Clogging of stormwater filters with high filtration rates

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Abstract

Hydraulic performance of granular filter media and its evolution over time is a key design parameter for stormwater filtration and infiltration systems that are now increasingly used in management of polluted urban runoff. Clogging of filter media is recognised as a limiting factor of these stormwater treatment systems. However, very limited studies have been undertaken to understand clogging processes in the context of stormwater treatment systems. Of particular interest are non-vegetated high-flow rate filtration systems, which have the potential of maintaining high rate treatment at the same time as providing consistent and high pollutant removal. This thesis therefore focuses on the clogging of stormwater filters with high infiltration rates.

The impacts of both design and operational variables on clogging have been studied in controlled laboratory environments using a compressed-timescale approach. Laboratory investigations have also been made to assess the importance of biological clogging for these stormwater filters. Finally, observations from a field and modelling study of a filtration system located in Melbourne were compared with the findings from the laboratory studies.

It was found that while angularity and smoothness of filter media may not be important for design, the flow rate through the stormwater treatment system is a key design aspect that needs to be considered. The infiltration rate of a system should be guided by the objectives of the system - whether to treat more volume of stormwater or to achieve better treatment performance, longevity and maintenance. The size of the filter media particles significantly impacted the clogging process, as well as the overall sediment removal performance of the filters. Deeper systems were found to have longer lifespan compared to shallower ones, even though the deeper systems removed more sediment over their life span. Having two layers of distinct sized media in the filter bed improved performance over the single-layered systems.

Results suggest that sediment concentration in stormwater and size of sediments stormwater are important parameters that affect the performance and eventually longevity of these treatment systems. While hydraulic loading rate was found to be a significant parameter affecting the performance of these systems, any variation in the stormwater composition and loading regime had a limited effect. This study therefore developed an understanding of the effect of catchment characteristics on design of filters and hence their longevity and maintenance needs.

It was also found that filters with enhanced biological conditions clogged faster as compared to filters with suppressed biological activity. Although the evidence was not overpowering, the variations observed in this study suggest that more attention should be given to biological clogging in stormwater filters, which is mostly ignored at present.

Data from a field system using granular filters was collected and observations were compared with findings from laboratory studies. Similarities in evolution of infiltration performance in field based systems were observed. An exponential relationship between decline of infiltration rate and cumulative volume of treated stormwater to predict the system's hydraulic performance was developed.

This research has provided both theoretical and practical insights which will be useful in the application of stormwater infiltration systems that use filters with high infiltration rates for both stormwater harvesting and protection of receiving waters from stormwater pollution.

Declaration

In accordance with Monash University Doctorate Regulation 17 Doctor of Philosophy and Research Master's regulations the following declarations are made:

This statement is to certify that, to the best of my knowledge, the thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other institution, and that the thesis contains no material previously published or written by any other person, except where due reference is made in the text of the thesis. The length of this thesis is less than 100,000 words, exclusive of figures, tables and references

This thesis includes 4 original as leading author papers submitted to peer reviewed journals and 4 original conference publications. The core theme of the thesis is to understand the clogging processes in stormwater filters with high infiltration rates. The ideas, experimental design, development and writing up of all the papers in the thesis were the principal responsibility of myself, the candidate, working within the Civil Engineering, under the supervision of Professor Ana Deletic and Dr David McCarthy.

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Harpreet Singh Kandra

Dedicated to my parents and my wife

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Details of publications submitted

S No	Publication Title	Publication status	Nature and extent
1	Assessment of clogging phenomena in granular filter media used for stormwater treatment	Kandra H.S., McCarthy D., Fletcher T.D., Deletic A., 2014. Assessment of clogging phenomena in granular filter media used for stormwater treatment. Journal of Hydrology, 512, pp. 518-527	Initiation, ideas, experimental design and works, data interpretation, write up. 60%
2	Assessment of impact of filter design variables on clogging in stormwater filters	Kandra H. S., McCarthy D., Fletcher T.D., Deletic A., 2014. Assessment of impact of filter design variables on clogging in stormwater filters. Journal of Water resources management, 28, pp. 1873-1885.	Initiation, ideas, experimental design and works, data interpretation, write up. 60%
3	Assessment of the impact of stormwater characteristics on clogging in stormwater filters	Submitted *Journal of Water Resources Management*	Initiation, ideas, experimental design and works, data interpretation, write up. 60%
4	Investigation of biological clogging in stormwater filters	Kandra H. S., Callaghan, J., Deletic A., McCarthy D., 2014. Biological clogging in stormwater filters. Journal of Environmental Engineering, ASCE (in press)	Initiation, ideas, experimental design and works, data interpretation, write up. 60%

Details of conference papers

1. Kandra, H.S., McCarthy, D.T., Deletic A. and Fletcher T.D., 2010. Assessment of clogging phenomenon in granular filter media used for stormwater treatment. Proceedings NOVATECH Conference, Lyon, France, 27 June - 1 July.
2. Kandra H., McCarthy D., and Deletic A., Investigation of biological clogging in stormwater filters. 12th International Conference on Urban Drainage, Porto Alegre/RS – Brazil, 11th to 16th September, 2011
3. Kandra, H.S., McCarthy, D.T. and Deletic A., 2012. Impact of filter design variables on clogging in stormwater filters. 7th International Water Sensitive Urban Design Conference, Melbourne, Australia, February 21-23, 2012.
4. Kandra H.S., McCarthy D.T. and Deletic A., 2013. Assessing nature of clogging in zeolite based stormwater filters. 8th International Water Sensitive Urban Design Conference, Gold Coast, Australia, 21st to 25th November, 2013

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Abbreviations used

ASTM	American Society for Testing and Materials
BoM	Bureau of Meteorology
BMP	Best management practice
BOD	Biological Oxygen Demand
Cd	Cadmium
Cl	Chlorine
COD	Chemical Oxygen Demand
Cr	Chromium
Cu	Copper
FAWB	Facility for Advancing Water Biofiltration
Fe	Iron
GPT	Gross pollutant trap
IIR	Initial infiltration rate
IR	Infiltration rate
ks	Hydraulic Conductivity
L	Litres
LID	Low-Impact Development
LoI	Loss on ignition
mg/L	milligram per litre
mm/hr	millimeter per hour
m/hr	meter per hour

Mn	Manganese
Ni	Nickel
ON	Organic nitrogen
Pb	Lead
PSD	Particle size distribution
PP	Porous pavement
SS	Suspended Solids
SUDS	Sustainable Urban Drainage Systems
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
WSUD	Water Sensitive Urban Design
Zn	Zinc
μ/ μm	Micron/Micrometer

1 Introduction

1.1 Background

Urbanisation activities (clearing of vegetation, compaction of soils, changes in drainage and introduction of impervious surfaces) all affect the hydrology of a catchment, engendering the following results (Vlachos and Braga, 2001; Walsh et al., 2004):

- increased stormwater runoff volumes, by preventing infiltration and reducing evapotranspiration;
- increased peak flood discharges, owing to an increase in urban drainage efficiency (i.e. reduced detention); and
- pollution of catchment discharges, due to an increase in the erosive and mobilisation potential of stormwater flow.

Therefore, stormwater runoff from urban catchments is becoming an important environmental issue (Makepeace et al., 1995; Novotny, 2003). Traditionally, stormwater has been considered a nuisance that has to be disposed off directly into receiving waters. The conventional solutions to stormwater management have ranged from collection to channelling and final disposal to water bodies.

Recent management practices, however, emphasize consideration of stormwater as an overlooked resource. Consequently, emerging stormwater management concepts focus on holistic management of the urban water cycle, aimed at (Wong, 2006a):

1. treating urban stormwater to meet water quality objectives for reuse and/or discharge to surface waters;
2. using stormwater in the urban landscape to maximise the visual and recreational amenity of developments and;
3. reducing potable water demand through seeking alternative sources of water, such as rainwater and stormwater, guided by

the principle of “fit-for-purpose” matching of water quality and end uses.

Various stormwater treatment technologies have been employed for urban stormwater runoff management. Filtration-based treatment systems have been found to be more acceptable in comparison with the other technologies, due to their effective treatment of particulate and dissolved pollutants, including both microorganisms and chemicals (Fletcher et al., 2004). Another advantage of these filtration based systems is that they can be engineered for site-specific requirements, for example with respect to objectives of treatment, water quality standards for end-use, space availability and site specific pollutant characteristics.

Once treated, stormwater can also be harvested from these systems and used for a range of non-potable urban water uses in Australia, including toilet flushing; gardening and open space irrigation; fire fighting; environmental flows; washing of vehicles and windows; industrial recycling; water features; ornamental ponds; and groundwater recharge (Hatt et al., 2006). Furthermore, given the uncertainties associated with the amount of rainfall and its pattern, stormwater harvesting options could support adaptation to climate change. Systems used for stormwater treatment and harvesting can additionally provide flood protection and restore flow regimes and water quality in water bodies (Fletcher et al., 2007).

However, the acceptance of filtration-based systems to manage urban stormwater is impeded due to a range of concerns, including maintenance and longevity issues (Ellis and Marsalek, 1996). Numerous studies have highlighted that clogging of these systems is a key operational issue affecting their longevity and performance (Lindsey et al., 1992; Warnaars et al., 1999 and Bardin et al., 2001).

1.2 Objectives and scope of research

Clogging of filters that can be potentially harnessed for stormwater treatment and harvesting is an important operational issue, which affects the longevity of systems that use filtration processes to treat stormwater. As such, it requires further investigation. Hydraulic performance of the system can also affect its treatment capability. This research is therefore aimed at improving our understanding of clogging processes in filter media that can potentially be used for stormwater treatment and re-use.

While there is some understanding of clogging processes in the context of other water treatments and/or filter media with very low infiltration rates and those using vegetation, knowledge gaps exist for non-vegetated stormwater filters with high infiltration rates. Given that most clogging studies in other disciplines such as civil engineering, soil science and membrane research have found clogging to be very discipline-specific (Schubert, 2002; Mays and Hunt, 2005; Mays, 2010), it is pertinent to understand clogging processes in the context of non-vegetated stormwater filters with high infiltration rates. For instance, influent residence time in subject filters is less as compared to fine media filters and therefore treatment dynamics, such as size of particles removed and treatment efficiency, could vary.

As such, the scope of this laboratory-based research is to understand the process of clogging in this type of filter media (i.e. non-vegetated, high infiltration rate) that can be used for stormwater infiltration and treatment. This thesis also investigates the interplay between clogging and sediment removal. The understanding developed in this study will enable incorporation of granular filter media in a wide range of stormwater treatment systems, including those which harvest stormwater.

1.3 Thesis outline

Figure 1.1 shows the investigations in the various chapters of this thesis. Chapter 2 of the thesis provides a review of the existing literature on clogging and pollutant removal processes. The aim is to identify current knowledge gaps in relation to clogging and treatment performance of granular filter media with high infiltration rates in the context of stormwater treatment. The chapter also aims to identify factors that could affect performance of these filters. It then lists the key research aims and hypotheses of this research.

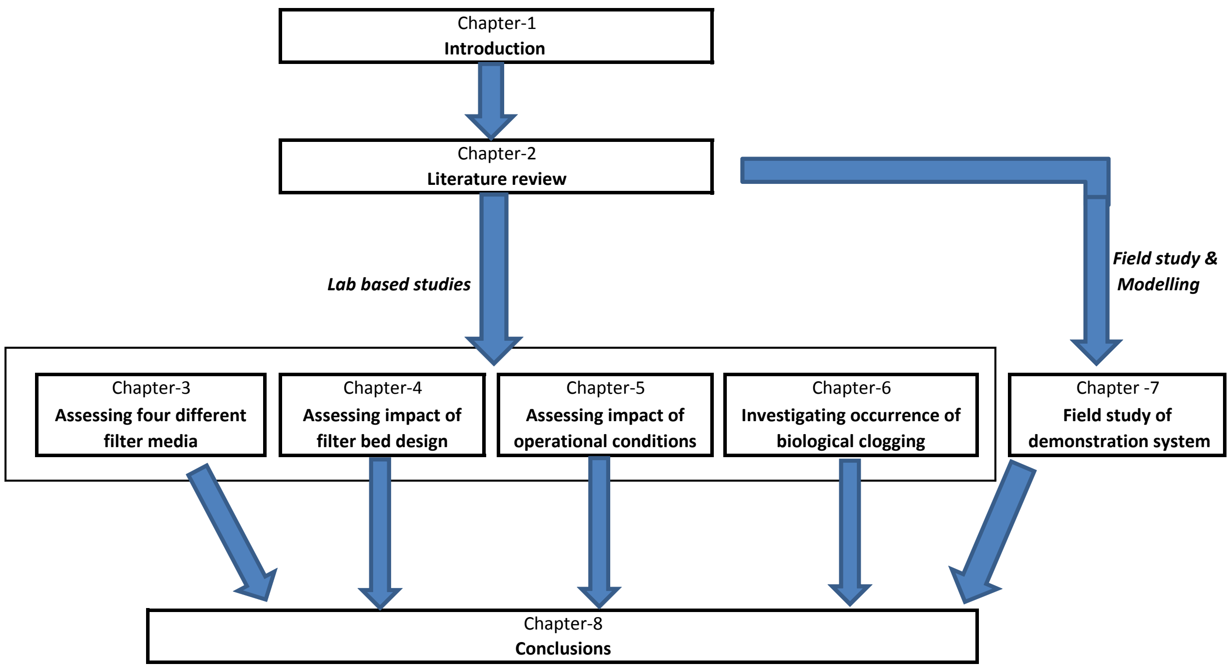

Figure 1.1: Flowchart of the research plan

Chapter 3 compares four filter media over a range of outflow rates, aiming to identify the impact of physical characteristics (such as filter media's shape and smoothness) on its hydraulic and treatment performance. The learning from these experiments and conclusions guide experimental work carried out in the following chapters.

The impact of the filter bed's design and construction on hydraulic and treatment performance of granular filter media has been investigated using zeolite media in Chapter 4. An understanding of the latter may inform design and maintenance of systems using such filters and their performance (e.g. sediment removal performance and/or reducing maintenance intervals).

Chapter 5 presents the impact of operational conditions (stormwater inflow characteristics) on the clogging performance of the subject granular filter media. This fosters understanding of how these systems may behave in various catchments with differences in composition of stormwater and stormwater application patterns.

While it is generally assumed that physical clogging may be the main reason for clogging of stormwater filters, an investigation has been made to assess the prevalence of biological clogging in subject filters. Results from investigation of the impact of biological clogging on stormwater filter media's infiltration and treatment performance are presented in Chapter 6.

Chapter 7 provides results from a field demonstration site where a modular filter system with granular filter media has been installed and monitored for about 2.5 years. These findings have been compared with those of the laboratory studies. A model to predict the performance of the field system has also been developed.

Chapter 8 concludes this project by discussing the strengths and limitations of this research, while also providing recommendations for further research.

2 Literature review and Research aims

2.1 Introduction

This chapter reviews current knowledge on clogging processes that occur in filter media used for urban stormwater treatment and identifies the key knowledge gaps for which further research is required. The first section provides background information on urban stormwater flows and pollutants followed by a discussion on urban stormwater management approaches. The subsequent sections discuss types of clogging processes and factors influencing clogging in filter media. The concluding section identifies knowledge gaps and research required to understand clogging processes in non-vegetated filter media used for stormwater treatment. The research aims of the project and hypotheses are delineated accordingly in the last section.

2.2 Urban stormwater flows and pollutants

Urbanisation, including clearing of natural vegetation, compaction of soils, introduction of impervious surfaces and changes in drainage pathways, causes significant changes to the hydrology of these systems. These changes are highlighted in Figure 2.1, which compares the hydrology of pre-developed and developed conditions. These changes result in an increase of stormwater runoff volumes, flow frequency and peak flood discharges (Walsh, 2000; Roesner et al., 2001; Hatt et al., 2004; Line and White, 2007). The latter (i.e. increased peak flows) has been the core focus of urban drainage design, to protect urban dwellers against flooding by providing hydraulically effective transport of surface runoff from urban areas into local receiving waters (Butler and Davies, 2004; Rauch et al., 2005). This traditional approach to stormwater management also changes patterns and volume of infiltration, evapotranspiration and surface and subsurface flows, causing further changes to flow regimes, thereby degrading our precious ecosystems (Burton and Pitt 2002; Walsh et al, 2005).

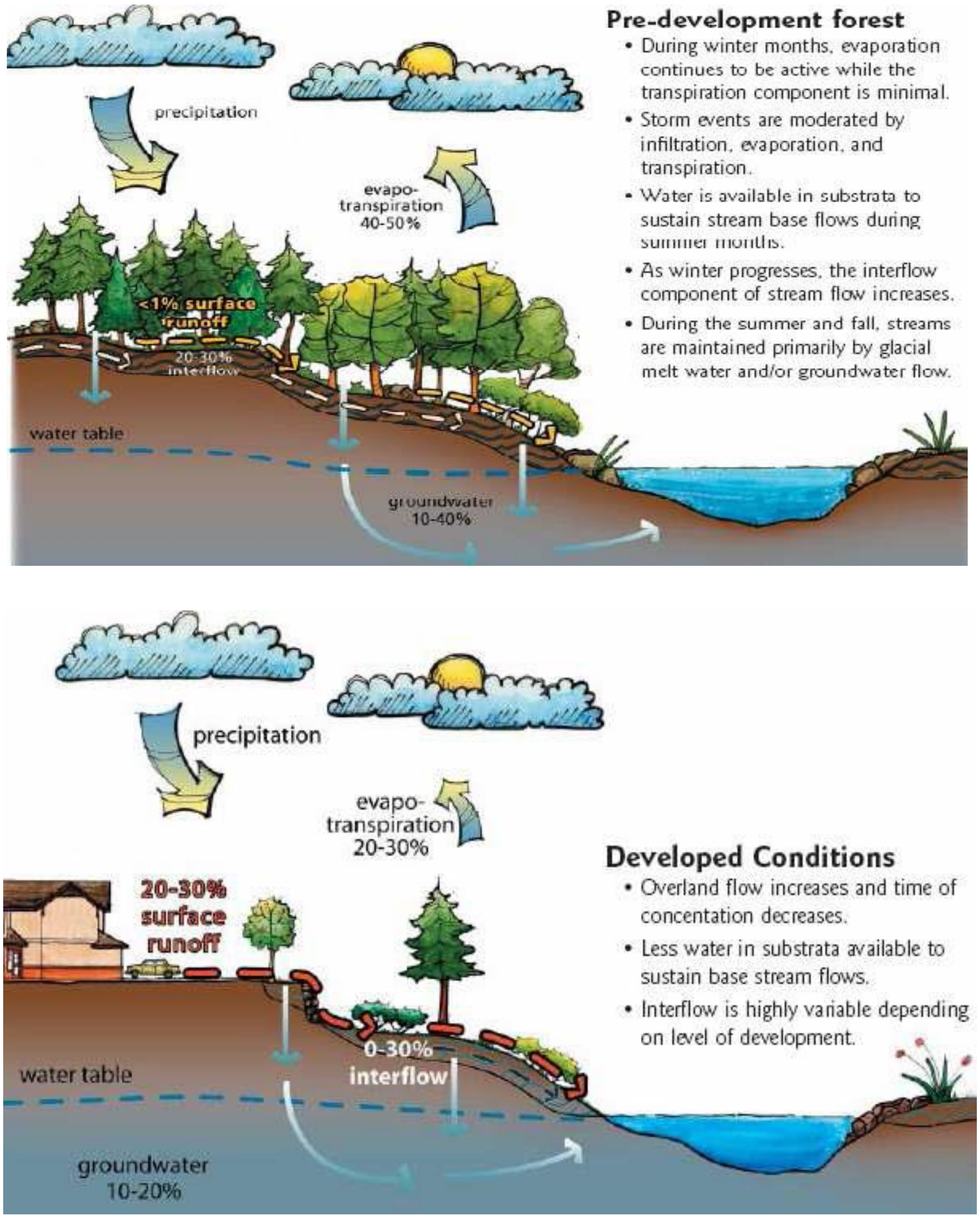

Figure 2.1: Comparison of pre-urban and an urban catchment (Hinman, 2005)

Urbanisation also influences the water quality of our receiving water bodies. A large U.S. EPA survey showed that urban stormwater is the most important pollutant source in U.S. coastal waters (Burton and Pitt, 2002). Similarly, stormwater has been recognized as the major source of pollution in streams and coastal waters of Australian cities (Commonwealth of Australia, 2002). The resulting degradation affects the aquatic life and its diversity because of the changes in photosynthesis processes; oxygen depletion (by decomposition of waste) and; toxicity changes. It also affects usability of water as bacteria and viruses are introduced in stormwater and visual amenity of waterways is also affected. Besides, these pollutants in stormwater also affect groundwater resources (Burton and Pitt, 2002). The key pollutants in urban stormwater are discussed below (Wong, 2006b).

Sediments and suspended solids: These are the particles that remain in suspension in stormwater and are a generic indicator of urban pollution and usually result from the erosion in the catchment. Sediment is, by weight, the greatest pollutant of water resources (Burton and Pitt, 2002). It carries most of the pollutants (attached to the sediment itself), in particular heavy metals and hydrocarbons. For instance, studies have also found that solids are the major carriers of pollution with on average 70% of heavy metals and phosphorus being attached to fine particles (Duncan, 1999; Deletic and Orr, 2005).

Suspended sediments decrease light penetration and photosynthesis, clog gills and filtering systems of aquatic organisms, reduce prey capture, reduce spawning, and reduce survival of sensitive species. Moreover, there are several mechanisms whereby stormwater exposure can cause potential human health problems. These include exposure to stormwater contaminants at swimming areas affected by stormwater discharges, drinking water supplies contaminated by stormwater discharges, and the consumption of fish and shellfish that have been contaminated by stormwater pollutants (Burton and Pitt, 2002). Sediment can also plug underground injection systems when stormwater is discharged underground instead of to surface waters. Excessive sediment deposition over time can fill in navigation channels, increasing the maintenance and safety costs of shipping.

(www.oeconline.org/our-work/rivers/stormwater/stormwater%20report/impacts)

Nutrients: Phosphorus and nitrogen result in stormwater from different sources such as soil erosion; agricultural and domestic waste; atmospheric deposition and vehicular emissions (Makepeace et al., 1995; Mayer et al., 1996). Excessive nutrient levels in waterways stimulate the growth of plants and algae, which can reduce dissolved oxygen levels and harm the entire aquatic ecosystem.

(www.oeconline.org/our-work/rivers/stormwater/stormwater%20report/impacts)

Most studies of coastal eutrophication consider surface runoff as the major pathway of nutrient inputs (Lapointe and Matzie, 1996). Nutrients have a low to moderate groundwater contamination potential for both surface percolation and subsurface infiltration/injection practices because of its relatively low concentrations found in most storm waters (Burton and Pitt, 2002).

Metals: Metals that pollute stormwater commonly include cadmium, chromium, copper, nickel, iron, lead, manganese, sodium and zinc. These pollutants result from the catchment infrastructure such as roofs, buildings and other infrastructure and activities such as operation of vehicles and waste disposal (Pitt et al., 1995; Makepeace et al., 1995; Brown and Peake, 2006). The effects of metals on human and aquatic health can be far reaching. Lead, which is often used as an indicator for other toxic pollutants in stormwater, can be harmful or deadly for human and aquatic life. Zinc, although not harmful to humans at concentrations normally found in stormwater, can be deadly for aquatic life. Cadmium can bio-accumulate in an ecosystem- soil microorganisms are especially sensitive to it, and it is harmful to human health. Chromium damages fish gills, causes birth defects in animals, and is also dangerous to human health. Low levels of copper inhibit the olfactory systems of fish species, decreasing their ability to hide in response to warning signals.

(www.oeconline.org/our-work/rivers/stormwater/stormwater%20report/impacts)

<u>Oils and Surfactants:</u> These are transport-related pollutants that are washed off from the road surfaces, where they are deposited because of leaks from vehicles, vehicle braking and manufacturing operations in case of industrial catchments (Makepeace et al., 1995; Brown and Peake, 2006). High levels of hydrocarbons and surfactants are toxic to fish, invertebrates and macrophytes; result in reduction in photosynthesis which affects growth of algae and seagrass; may hinder fish respiration and feeding; can stimulate microbial activity during oil decomposition which may depress oxygen levels (US EPA, 2005).

<u>Organic matter:</u> This refers to the contaminants in stormwater that can be oxidised readily and produce simpler end products such as carbon dioxide, nitrates, sulphates and water (Makepeace et al., 1995; Francey et al., 2010). Higher organic matter content can reduce dissolved oxygen concentrations, affect the diversity of fish and invertebrates, hinder respiration of fish, increase the levels of bacteria and increase growth of some algae. Very low oxygen levels may increase the release rate of nutrients and metals from sediments (US EPA, 2005).

<u>Micro-organisms:</u> These are added to stormwater from domestic pet and bird faeces and wastewater overflows, leakages and cross-connections (Burton and Pitt, 2002, McCarthy et al., 2009). Pathogens in stormwater are a significant concern, potentially affecting human health. Epidemiological studies have shown significant health effects associated with stormwater-contaminated marine swimming areas. Protozoan pathogens, especially associated with likely sewage-contaminated stormwater, are also a public health concern (Burton and Pitt, 2002). Good correlations between the incidence of gastroenteritis in swimmers and E. coli and enterococci concentrations in water have resulted in new recreational water criteria (EPA, 1986). Viruses have been detected in groundwater

where stormwater recharge basins are located short distances above the aquifer (Burton and Pitt, 2002).

Several large compilations of worldwide data sets of urban water quality suggest that characteristics of urban stormwater are site-specific (Duncan, 1999; Smullen et al., 1999; Fuchs et al., 2004). The composition of stormwater is influenced by many factors, such as the extent of urbanisation, type of collection surface (e.g.- roads, roofs, car parks, etc.), atmospheric conditions, population density, waste disposal and sanitation practices, soil type, climatic conditions (i.e. dry and wet weather flows) and the presence of construction activities (Duncan, 1999; Wong, 2000a; Marsalek and Chocat, 2002; Goonetillekea et al., 2005). The variations in characteristics of stormwater in space and time have also been documented by different studies (Smullen et al., 1999; Francey et al., 2010).

Studies suggest that the majority of stormwater pollutants are attached to Total Suspended Solids (TSS). For instance, Han et al. (2006) analysed highway stormwater runoff characteristics for three years in California. The analysis suggested that suspended solids were associated with most particulate-bound metals such as chromium, copper, nickel, lead and zinc. Other studies (Liebens, 2002; Pitt et al., 2004; Stead-Dexter and Ward, 2004; Gnecco et al., 2005; and Weiss et al., 2006) have also shown that these metals are largely associated with sediments in stormwater runoff. Taylor et al. (2005) found that the proportion of nitrogen in particulate form was higher during storm events. Similarly, correlation between TSS and Total Phosphorous has been found to be strong in study of seven urban catchments in South Eastern Australia (Francey et al., 2010).

Therefore, as many pollutants associate with sediment, it has been suggested that the removal of suspended sediment from urban stormwater flows could help improve our downstream water quality. This is particularly the case for nutrients (such as phosphorus) and heavy metals (such as zinc), which can cause eutrophication and toxicity to fish, respectively (EPA, 1986; Burton and Pitt, 2002).

2.3 Urban stormwater management

2.3.1 Introduction

Urban stormwater management strategies are based on both structural measures (a physical device) and; non-structural measures[1] (Department of Water and Swan River Trust, 2007). These are often termed: Best management practices (BMPs), Sustainable Urban Drainage Systems (SUDS), Low Impact design (LID), Water Sensitive Urban design (WSUD) (Mikkelsen et al., 1996; Wong, 2006b; Roy et al., 2008). The aim of these strategies is to control stormwater flows and pollutants by removing, reducing, retarding, or preventing urban stormwater runoff quantity and pollutants from reaching receiving waters (Strecker et al., 2001). Additionally there is a focus on integration of urban water cycle management and urban planning and design, based on sustainability principles such as water conservation, waste management and environmental protection (Lloyd et al., 2002).

The use of treated stormwater could potentially reduce pressures 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 can be harvested and used for a range of non-potable urban water uses and is of better quality as compared with untreated sewage or industrial wastewater discharge (Mitchell et al., 2002; Brown et al., 2007), as shown in Table 2.1. 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).

[1]Non-structural controls are institutional and pollution-prevention practices designed to prevent or minimise pollutants from entering stormwater runoff and/or reduce the volume of stormwater requiring management. They do not involve fixed, permanent facilities and they usually work by changing behaviour through government regulation (e.g. planning and environmental laws), persuasion and/or economic instruments.

Table 2.1: Characteristics of different water sources

Quality parameter	Untreated stormwater[a]	Potable supply[b]	Untreated grey water[b]	Untreated wastewater[b]	Treated wastewater[b]
BOD_5 (mg/L)	3-73		90-290	100-500	8-80
Total Suspended Solids (mg/L)	8-1622		45-330	100-500	11-250
Total dissolved solids (mg/L)	44-208	500	284-1700	250-850	520-4940
Total phosphorus (mg/L)	0.02-9		0.6-27.3	4-30	
Total nitrogen (mg/L)	0.44-32.6		2.1-31.5	20-85	6.1-44.2
Heterotrophic plate count (CFU/mL)	6.9×10^4–4.9×10^5 [e]	< 0.02 to 10^4 [g]	11–10^6 [f]	10^8 [h]	
E. coli (MPN/100 mL)	542-19496 [c] 5- 84853 [d]		< 1 – 236 x 10^6 [f]		
Cadmium (µg/L)	0.2-46	2	<10		0-2
Copper (mg/L)	0.005-0.56	1	0.018-0.39	0.001-0.2	0.001-0.12
Iron (mg/L)	2.4-7.3	0.3	0.094-4.37	0.3	0.03-1.6
Lead (mg/L)	0.007-2.04	0.01	<0.05-0.15	0.05	0-0.03
Manganese (mg/L)	0.04-0.11	0.1	0.014-0.075	0.0003	0.02-0.08
Sodium (mg/L)	12-116	180	29-230	70-300	41-1540
Zinc (mg/L)	0.026-2.4	3	<0.01-0.44	0.055	0.0-0.26

[a] Mitchell et al., 2002; Duncan, 2005; Francey et al., 2010; [b] Mitchell et al., 2002; [c] McCarthy et al., 2012; [d] International stormwater BMP database 2007 (www.bmpdatabase.org); [e] Makepeace et al., 1995; [f] Eriksson et al., 2002; [g] Allena et al., 2004;[h] Mara & Horan, 2003

2.3.2 Overview of different systems

Structural stormwater treatment technologies, known as Water Sensitive Urban Design (WSUD) systems, employed for urban stormwater runoff management could be categorised in a number of ways, with the main distinction being that some are water-body based (e.g. wetlands or ponds), whereas others are filter media based (e.g. biofilters or infiltration systems). A brief overview of commonly used stormwater treatment technologies is provided in Figure 2.2 (CWSC, 2010). Table 2.2 compares the pollutant removal performance of different technologies based on a review of field and lab based performance of these systems (CWSC, 2010).

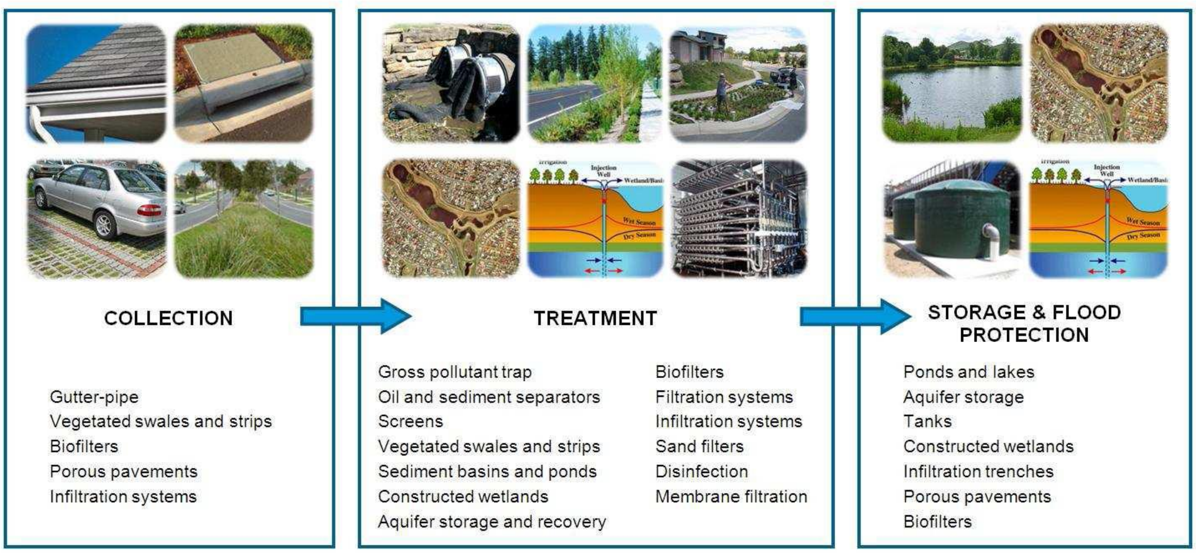

Figure 2.2: Technologies used for stormwater management (CWSC, 2010)

<u>Non Filtration-based systems</u>

Gross pollutant traps, Oil separators and Sediment separators/traps

Gross pollutant traps (GPTs) are generally provided for limited treatment before stormwater is discharged into the receiving waters. They range from simple screens to structures that use various combinations of screens, stalling flow, settlement, floatation and flow separation. These systems are not effective in the removal of fine or dissolved pollutants (Hatt et al., 2004a).

Oil separators are used to remove hydrocarbons which are derived in urban stormwater from motor vehicles and roads. They are usually installed at the sources of spills (e.g.- petrol stations and airports), before the oil emulsifies in large volumes of urban runoff (Wong, 2006b). The main purpose is to remove free-floating oil to minimise the effects on receiving waters and surrounding environment. In certain cases, they may also be provided to reduce load on downstream treatment systems such as biofilters or wetlands.

Sediment separators prevent discharge of coarse sediment to downstream treatment measures. They range from simple earthen or concrete basin designs to complex structures using vortices and secondary flows. Sediment traps are seldom effective in the removal of fine or dissolved pollutants (Hatt et al., 2004a).

These systems have high hydraulic loading rates of 50-100 m/hour as the aim is to drain the stormwater as quickly as possible (Allison et al., 1998 as citied in CWSC, 2010). However, there is hardly any removal of key pollutants such as solids, nitrogen, phosphorous, heavy metals possible (CWSC, 2010) as shown in Table 2.2.

Table 2.2: Summary of hydraulic load and percentage pollutant removals for different technologies (adapted from CWSC, 2010)

Pollutants		Treatment Technology							
		GPT; Oil & Sediment separators	*Swales; Filter Strips*	*Biofilters*	*Sand Filters*	*Engineered Filters*	*Infiltration systems Porous pavement*	*Wetland*	*Ponds*
Hydraulic load [mm/h]		(50 000-100 000)	20-60	100-200	30-130	2000-8000	From (10-80) to 40,000	3 to 32	20-100
Solids	TSS	background level	80-90%	57-93%	75-90%	93-96%	36-100%	58-85%	47 to 80
	TN	Nil	(-10)-50%	30-55%	20-61%	61-79%	8 to 85%	16-30%	22-25%
	NOx	3-10%	(-5)-40%	(-17)-43%	(-14)-74%		(-126)-0%	39-67%	3.5-63%
Nitrogen	NH3	(-6)-14		64-96%				10-55%	83%
Phosphorus		Nil	3-65%	5-80%	39-59%	55-67%	40-80%	46-60%	19-51%
Hydrocarbons					27%	74-84%			
	Aluminium					70-77%			
	Cadmium		40%	90%		90-97%	69-88%		
	Chromium		11%			80-87%	(-29)-94%		
	Copper		8-50%	54-98%	37-50%	83-88%	35-87%	40-65.5%	5-9%
	Iron		(-10)-70%			80-85%	-81%		
	Manganese			38%			4%		
	Nickel		50%				(-65)-92%		
	Lead		15-60%	31-98%	87%	67-81%	78-98%	75%	
Heavy Metals	Zinc		60-90%	61-99%	79-87%	83-94%	52-97%	35-44%	26-66%
	Faecal coliform		Leaching	69-90%	65-79%		96%	78-85%	(-2.5)-86%
	E. coli					>99%			
Pathogenic Indicators	FRNA-phages					>99%			
	C. perfringens					98%			

Wetlands are used in stormwater management either as standalone facilities or in combination with other WSUD systems, such as stormwater detention ponds. These are relatively shallow vegetated water-body treatment systems that are designed to detain water for treatment on a periodic or permanent basis. They are designed to trap sediment, nutrients, bacteria and toxins, and also promote oxygen recovery (Ellis, 1993). Water treatment is performed as a combination of sedimentation, filtration and biological nutrient uptake.

Wetlands, whether natural or constructed, additionally offer landscape amenity, recreational opportunities, habitat provision and flood retention (Mitchell et al., 2007). The role of vegetation in wetland performance is critical, and they can be quite effective in the removal of fine sediment and dissolved pollutants (Hatt et al., 2004a). These systems have very low hydraulic loading rates of 0.003–0.03 m/hr (Wadzuk et al., 2010, Yi et al., 2010). Several studies report variable performance of these systems dependent on construction features and climatic conditions. Studies suggest TSS removal rates varying between 58-85%; TN removal: 16-30%; TP removal: 46-60%; huge variation in removal of heavy metals and limited removal of hydrocarbons (also listed in Table 2.2) (Winer, 2000; Carleton et al., 2000 as reported in Fletcher et al., 2004; Wadzuk et al., 2010; Yi et al., 2010). These systems have long life but also need a lot of space and maintenance (CWSC, 2010).

Stormwater management ponds are designed to intercept the runoff before it reaches a stream and detain the water for a longer period. This allows more time for the sediment and attached nutrients to settle out. These are artificial open water bodies, usually deeper than 1.5 m, that treat stormwater mainly by sedimentation and detention, with some nutrient uptake from emergent vegetation along the margin (Wong, 2006b). System type and design may vary depending on the nature/size of pollutants treated by these systems (sedimentation basins and ponds) and other features offered such as urban lakes. The treatment train provided by lakes includes sedimentation, biological uptake and exposure to ultraviolet disinfection. Lakes design and maintenance is important to avoid the risk of algal blooms and pre-treatment is a requirement to avoid this risk (Wong, 2006b).

Performance of these systems is listed in Table 2.2. While the hydraulic loading rate is 0.02-0.1 m/hr, solids removal ranges between 47-80%. TN removal has been found to be considerably less (22-25%); TP removal (19-51%); Heavy metals (Cu: 26-57% and Zn: 26-66%) (Winer, 2000; Mallin et al., 2002). In some cases these systems may increase the concentration of pathogenic indicators (Davies and Bavor, 2000)

Vegetated swales are open, grassed surfaces that both collect and treat stormwater by filtration before discharging it to drainage system or receiving water. These technologies aim to reduce runoff velocity and retain coarse sediments (Hatt et al., 2004a). Depending on the end use objectives, such as, providing water for re-use, ground water recharge or discharge to receiving waters, they may either promote or discourage infiltration. They can also be adopted as a pre-treatment measure preceding other WSUD technologies.

Vegetated swales have low hydraulic loading rates of 0.02-0.06 m/hr, which implies large areas are required for treatment. These systems are effective in removal of suspended solids, but have lower and variable removal performance for nutrients (some species) and some heavy metals (refer Table 2.2) (Barrett et al., 1998; Fletcher et al., 2004; CWP, 2007). In particular, pathogenic indicators seem to show a consistent increase in concentrations, even when access of animals and faecal bacteria to the swales was limited (CWSC, 2010).

It can therefore be concluded from the above review that the non-filtration based systems have very low hydraulic loading rates thereby reducing their capacity of flow attenuation. These systems are not very effective in removal of pollutants such as nutrients, heavy metals and micro-organisms. Further a lot of variation has been observed in their pollutant removal performances.

Filtration/Infiltration based systems

Biofiltration systems are also known as bio-retention systems, biofilters (especially for large scale applications), rain gardens (at the household scale) or tree pits biofilters (at street scale). Biofilters are vegetated buffers on top of a filtration medium (e.g. sandy loam, sand and/or gravel). Biofilters facilitate flow attenuation, sediment and pollutant removal (CWSC, 2010).

Stormwater runoff from close catchments flows across the vegetation before percolating through the soil media (FAWB, 2009a and 2009b). By flowing through the vegetation and filter media, stormwater is subjected to a number of physical, chemical and biological processes. As stormwater enters the dense vegetation in a biofilter, its velocity diminishes, enhancing sedimentation of particulates. Physical filtration continues as stormwater percolates down through the filter media, which also enhances binding of dissolved contaminants. Additionally, the vegetation and especially the soil microbial community take nutrients (nitrogen) and, to a lesser extent, other contaminants (heavy metals), ensuring both their growth and survival (CWSC, 2010). Depending on the design of the system, effluents reaching the bottom of the filter media might either infiltrate the underlying soil or be collected in a drainage pipe for conveyance to the receiving waters.

Biofiltration systems have higher hydraulic loading rates of 0.1-0.2 m/hr but there is considerable variability in the field performance of these systems, which is likely due to different design characteristics. Solids removal, for instance, has been found to range between 57-93%; Phosphorous removal ranges between 5-80% (CWP, 2007; Hunt et al., 2008; Hatt et al., 2009) as shown in Table 2.2. Pre-treatment may be required to reduce clogging risks of these systems as operational problems such as overflowing could result because of clogging (i.e. reduced hydraulic performance) (Hatt et al., 2012). However, the presence of plants is one of the main reasons why clogging is maintained in biofilters.

Infiltration and porous pavement systems are similar to filtration systems but allow water to percolate in the underlying soil. They are usually located near the point of discharge. These practices have been found as advantageous towards achieving better receiving water quality as they maintain the natural local hydrology and water table levels, and reduce pollution discharges to receiving waters (Duchene et al., 1992).

Depending on the nature and location of storage, these may be differentiated as Infiltration trenches, Infiltration basins and Leaky well systems. These systems have low hydraulic loading rates of 0.01-0.08 m/hr and solids removal rate of 36-50%. However, nitrogen removal rates are low and leaching of NO_x has been observed (Landphair et al., 2000 and; Birch et al., 2005).

Porous pavements are permeable surfaces that promote infiltration at high flow through rates. Depending on their construction, all these pavements could be grouped into monolithic structures that include porous concrete and porous pavement (asphalt) and modular structures that include porous pavers or modular lattice structures with a gap in between each paver (Yong, 2008).

The treatment processes that occur in these systems include sedimentation, straining, adsorption, and biological degradation, etc. Their infiltration rates can range between 50 mm per hour to up to 40 m per hour depending on the pavement design (Bean et al., 2007). There is a huge variation in the performances amongst different designs of porous pavements but consistent for a given design. Porous pavements may leach metals such as Chromium, Iron and Nickel and nutrient species such as NOx (Landphair et al., 2000; Birch et al., 2005; and Emerson et al., 2010).

Non-vegetated filters enable stormwater treatment by letting stormwater runoff flow through a porous non-vegetated medium (CWSC, 2010). These may be further categorised depending on the type of filter media used such as sand, coarse gravel, engineered media and their combinations. These systems are effective in removal of sediment and adsorbed pollutants (Hatt et al., 2004a). Like the biofiltration systems, pollutant removal in these systems results from sedimentation and filtration. These filters may require more maintenance as compared with biofiltration systems, to ensure that the top layer remains porous and does not clog with accumulated sediments. This is because of the much higher infiltration rate of these systems and non-availability of vegetation. Maintenance involves removal of the top layer of filter media, where contaminants such as oils and sediments are retained (Hatt et al., 2004a).

These systems can be engineered for example by using soils containing naturally occurring and/or bio-engineered microorganisms that degrade toxic pollutants and organic materials that remove nutrients as stormwater infiltrates through the soil (Hatt et al., 2004a). Various novel filter media, such as Zeolites and activated carbon (Clark and Pitt, 1999; Bratieres et al., 2012) are available on the market and can be used for treatment of stormwater runoff by either incorporating the media in traditional WSUD technologies, or as stand-alone treatment systems (CWSC, 2010).

While sand based systems have low hydraulic loading rates of 0.03-0.13 m/hr and lower nutrient removal rates, engineered media based systems can be designed to have high loading rates with better treatment performance, as listed in Table 2.2 (Poelsma et al., 2010; Schang et al., 2010).

Additionally, the space requirements for the high flow rate systems are considerably less. For instance, Schang et al. (2010) state the enviss™ systems can be sized seven times smaller than biofilters for a given impervious catchment area. On the contrary, systems such as biofilters need to wait for plant establishment periods; require water to maintain plant health (which can be an issue during extensive dry periods) and; have very low infiltration rates because of which they are not suited for confined urban environments. High flow rate systems that could fit into highly urbanised areas could be beneficial for both discharge applications and possibly reuse scenarios, especially if their treatment performance could exceed current technologies (Schang et al., 2010; Bratieres et al., 2012).

However, high infiltration performance and non-availability of any vegetation makes these systems more prone to clogging. The treatment performance of such systems may be lower as compared to filters with lower hydraulic performances because of shorter residence time within the filter bed. Therefore, better understanding of clogging and treatment processes would help design better systems that could maintain high flows while treating stormwater contaminants effectively.

2.3.3 Summary

Compared to the other WSUD technologies, filtration-based systems have been found to be more acceptable. They are commonly used, due to their effective treatment of particulate and dissolved pollutants, including both microorganisms and chemicals (Fletcher et al., 2004). Another advantage of these filtration based systems is that they can be engineered for site-specific requirements, such as with respect to the objectives of treatment, water quality standards for end-use, space availability and site specific pollutant characteristics. For these reasons, filtration type stormwater treatment technologies are gaining traction around the globe as reported in studies conducted in different countries (e.g.- Warnaars et al., 1999; Barraud et al., 1999; Raimbault et al., 1999; Dierkes et al., 2002; Fujita, 1994; Nozi et al., 1999; Tan et al., 2003; Mikkelsen et al., 1997; Lindsey et al., 1992; and Pitt et al., 1999).

However, it is also acknowledged that filtration based stormwater filters have some disadvantages. The acceptance of filtration-based systems to manage urban stormwater is impeded due to a range of concerns, including maintenance and longevity issues (Ellis and Marsalek, 1996). Numerous studies have highlighted that clogging of these systems is a key operational issue affecting their longevity and performance. Field studies to evaluate performance of infiltration-based systems, such as infiltration basins and trenches, have been undertaken by Veenhuis et al. (1988), Lindsey et al. (1992), Schueler et al. (1992), Warnaars et al. (1999), and Bardin et al. (2001). These studies observed a decline in hydraulic performance and/or failure of these systems over time. For instance, a field survey of a number of infiltration systems, conducted by Lindsey et al. (1992) showed that only 38% of infiltration basins were functioning as designed after 4 years of operation, with 31% considered to be clogged. Similarly, field-based investigations of permeable pavements show a reduction in permeability by a factor of 10 to 100 due to clogging (Pratt, 1995; Illgen et al., 2007; Yong et al., 2008). Laboratory based studies for stormwater treatment using soil based filter media Hatt et al. (2008) and gravel stormwater filters (Siriwardene et al., 2007) have also observed clogging.

For instance, Figures 2.3 shows picture of ponded biofilter at Banyan Reserve stormwater treatment system (Melbourne) after a storm event (Hatt et al., 2012). Figure 2.4 presents results of hydraulic performance, over a period of 12 months, as observed for this biofilter, as compared with the design infiltration rate (IR). By contrast, the designed hydraulic performance was more than 100 mm/hr, the observed hydraulic performance of the system dropped significantly to around 20 mm/hr.

Figure 2.3: Picture of the Banyan Reserve stormwater treatment system after storm event in April 2010 (Hatt et al., 2012)

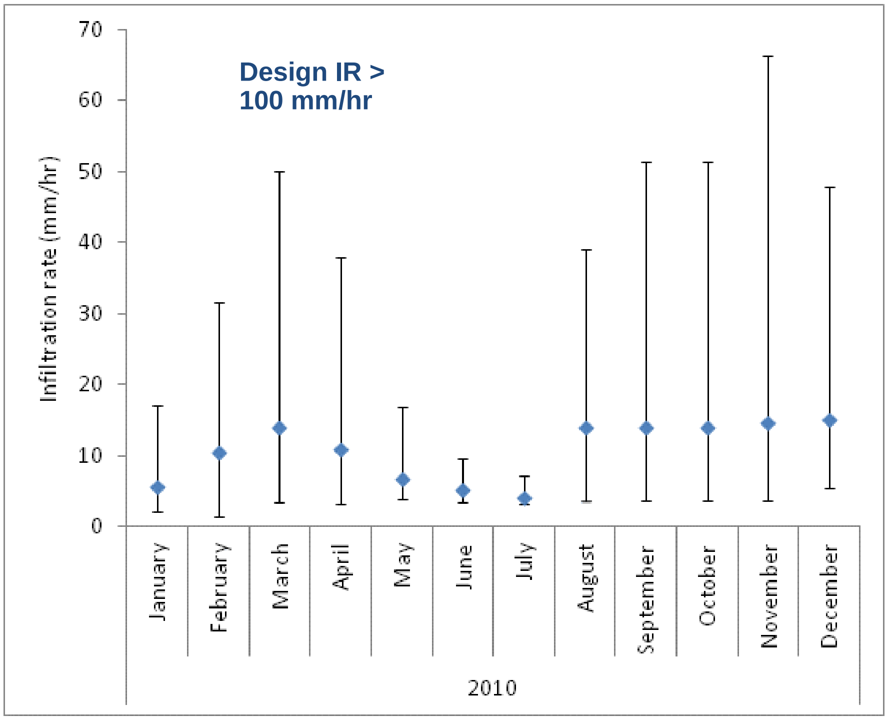

Figure 2.4: Hydraulic performance results of the Banyan Reserve stormwater treatment system measured in 2010 as compared with design IR of 100 mm/hr (Hatt et al., 2012)

Notwithstanding, due to the benefits of filtration based systems, such as smaller footprint and their ability to attenuate flood events, this research will focus on infiltration and/or filtration-based stormwater treatment systems. Of particular interest are ***non-vegetated high-flow rate filtration systems****, which have the potential of maintaining high rate treatment at the same time as providing consistent and high pollutant removal.*

2.4 Clogging of filtration/infiltration based WSUD systems

Clogging of infiltration systems is the decrease in permeability of a filtration system and occurs due to the accumulation of materials associated with treatment/ sediment removal processes (Perez-Paricio, 2001; Bouwer, 2002). This trapped material could accumulate both in the surface and/or subsurface of the filter, thereby preventing infiltration (Siriwardene et al., 2007; Hatt et al., 2008). As a consequence, either the infiltration rate (also called as hydraulic performance or hydraulic conductivity or permeability) of the system diminishes or the piezometric head increases, depending on the boundary conditions.

The phenomenon of clogging has also been observed and studied in other filtration systems and for other influents, such as fine sand clogging by septic tank effluent (Spychala and Blazejewski, 2003), sewage flow in vertical flow constructed wetlands (Winter and Goetz, 2003) and; municipal wastewater filtration using different types of geotextile (Yaman et al., 2006).

The development of a clogging layer(s) leads to problems such as increased overflows and long periods of ponding, which eventually result in a range of concerns: from public safety to aesthetics, health, hygiene and reduction in operational efficiency (Le Coustumer et al., 2007; Knowles et al., 2011). Advanced clogging may eventually necessitate remediation of the clogged media; thus limiting the asset lifetime of the system, or the system may just become a wetland.

In order to take clogging into account in the design of a treatment system, therefore, conservative values of hydraulic performance are generally used and a safety factor is generally applied to the measured hydraulic conductivity. For instance, New Jersey Department of Environmental Protection, 2004 suggests a safety factor of 2. However, such safety factors are chosen arbitrarily, since no study has been undertaken to quantify the actual evolution of the hydraulic conductivity over time.

Clogging has been observed in potable water treatment and supply and has been effectively managed in these systems by regular backwash/ back flushing processes. Backwashing operations involve reversing the flow and increasing the velocity at which water passes back through the filter. This, in effect, blasts the clogged particles off the filter. However, de-centralised stormwater treatment and harvesting systems have limited infrastructure and resources and;

normally operate without backwashing.

Based on review of literature on clogging processes, it has been found that most of the field studies have simply reported the existence and importance of clogging. However, these studies have failed to go beyond quantifying the extent or rate of clogging, and none have been able to explain the nature of the clogging process. This is because clogging was generally not the desired outcome or focus of the research conducted. In some studies where clogging was observed, insufficient detail was recorded to evaluate the conditions leading to clogging for the applied dosing regime. A greater understanding of the conditions that cause clogging may therefore lead to improvements in operation and design for optimal treatment efficiency and improved system reliability.

2.5 Clogging processes

As discussed above, clogging occurs as a result of the accumulation of materials associated with treatment/sediment removal processes. In general, clogging occurs because of three main processes: chemical, biological and physical (Rinck-Pfeiffer et al., 2000). Each clogging process is discussed below.

2.5.1 Chemical clogging processes

Chemical clogging processes are caused by the precipitation of calcium carbonate, gypsum, phosphate and other chemicals within the filtration media. Chemical reactions can occur within the filter bed during the filtration of any influent and this may lead to continuous deposition of matter on the surfaces of the pores (Rice, 1974; Rinck-Pfeiffer, 2000; Larroque and Franceschi, 2011). For instance, many natural and altered hydro-geologic systems are characterized by chemical disequilibrium, which is caused by the changes in temperature, pressure, and oxidation/reduction potential. The resulting chemical reactions then result in either precipitation of a mineral phase or transformation of one mineral phase into another (Baveye et al., 1998).

Clogging is known to depend on chemical factors which control the colloidal stability of the particles (Mays and Hunt, 2007). The factors affecting chemical clogging include the characteristics of influent (such as pH, its ionic strength, fraction of organic compounds, mineralogical composition) and; operational conditions (such as temperature and pressure changes that assist precipitation/dissolution). For instance, Schubert (2002) states that high loads of biodegradable substances in the river water can lead to chemical clogging beneath the infiltration areas due to strong changes in redox-potential and pH values which may cause precipitation of substances (e.g. Iron carbonate (FeCO3)) in the pores of the soil.

For instance, Rinck-Pfeiffer et al. (2000), while investigating bore clogging at a South Australian recycled water aquifer storage and recovery site, found that chemical processes had a role to play. But this investigation was carried using recycled water with high COD (165-170 mg/l), high alkalinity (140-150 mg/l) and high heavy metal concentrations. On the contrary, stormwater has been found to have very low concentration of these chemical constituents.

Chemical clogging has not been studied in context of stormwater systems. However, based upon the above literature and the known physical (i.e. neutral pH) and chemical characteristics (low levels) of urban stormwater (refer Table 2.1), it is hypothesised that the likelihood of chemical clogging in stormwater systems is minimal. The scope of this study consequently does not include investigation of chemical clogging in these systems.

2.5.2 Biological clogging processes

Biological clogging has earlier been established as a significant operational issue in the case of wastewater treatment systems (Chang et al., 1974; De Vries, 1972; Rice, 1974). Biological clogging processes are caused by the accumulation of algae and bacterial products in water and the formation of bio-films and biomass due to the growth of micro-organisms. Taylor et al. (1990) state that the growth of a biofilm in a porous medium reduces the total volume and average size of pores. 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.

It has been found that biological growth contributes to the reduction of the hydraulic conductivity via several mechanisms. One clogging mechanism is the physical presence of the microbes itself. Experiments by Vandevivere and Baveye (1992) saw a distinct connection between increasing biomass accumulation and the rate of hydraulic conductivity reduction in experiments using bacteria in sand filters. The secretion of polysaccharides by adsorbed bacteria is another mechanism that contributes to the clogging phenomenon. Vandevivere and Baveye (1992) measured the occurrence of polysaccharides in sand filters and concluded that this compound had a significant contribution to the reduction in hydraulic conductivity. Polysaccharide accumulation also enables the development of biofilms, which assist in the treatment of water by removing pathogens (Stevik et al., 2002). In certain cases, micro-organisms also produce chemicals (including gases such as nitrogen and methane) that block pores and accumulate below the clogging layers to create vapour barriers to infiltration (Baveye et al., 1998; Seki and Miyazaki, 2001).

Given that stormwater flows are intermittent in nature, with high sediment load and low levels of organic matter and nutrients in comparison to other water types (refer Table 2.1), it is usually perceived that biological clogging may not be prevalent in these stormwater infiltration systems. Some studies indirectly support this hypothesis. For instance, Pavelic et al. (1998) investigated the nature and extent of clogging by injecting wetland-treated stormwater to a confined aquifer in South Australia over four years. They reported that clogging occurred due to injected sediments, especially where sediment concentrations were high and was not a result of any biological activity. Similar results can be drawn from Bouwer and Rice (1989). They investigated the effect of clogging material and of increasing the water depth, on infiltration rate, using two columns filled with sandy loam soil samples. They conducted two similar types of experiments with inorganic and organic suspension of clogging layers by varying water depth from 20 cm to 85 cm. The findings suggest that the inorganic clogging layer is more prominent in decreasing hydraulic conductivity and has relevance for urban stormwater, which is relatively low in organics.

However, the abundance and nature of microbes in stormwater (McCarthy et al., 2012), as shown in Table 2.1, does imply that biological clogging could be an important process which needs investigation. This may be the reason previous studies, such as Bratieres et al. (2012), observed that provision of disinfection in granular stormwater filter media enhanced filter performance, indicating that biological clogging may be present. Since adsorption is a dominant removal mechanism in granular filter media, it can be speculated that microbes trapped within the media during wet weather can grow between events, leading to biological clogging.

However, limited research has been conducted thus far to investigate biological clogging in stormwater treatment filters. The abundance and nature of microbes in stormwater do imply that biological clogging should not be neglected altogether and needs investigation.

2.5.3 Physical/mechanical clogging processes

Physical/mechanical clogging may result from the migration of fine-grained materials into coarse-grained materials, consequently resulting in their entrapment and accumulation in soil pores. This entrapment of solids results mainly from three mechanisms - size exclusion, sedimentation and adsorption, as shown in Figure 2.5 (Changhong, 2008).

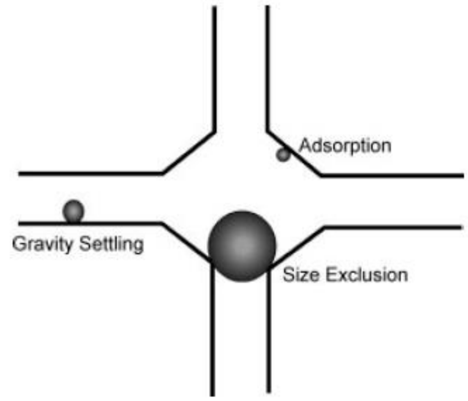

Figure 2.5: Particle capture mechanisms in porous media (Changhong, 2008)

Deposition of the suspended particles within the filter bed depends on many factors such as the type of filter, particle size of filter media (Perez-Paricio, 2001, Changhong, 2008). Since there is a diverse range of particles in stormwater, the deposition of retained particles within the filter bed may be in more than one of the following ways:

1. *Blocking filtration* wherein the deposited particles reduce the flowing path inside the porous media, thus increasing the possibility of bridging (Figure 2.6a). This may be more pertinent for smaller sized particles that can be removed within relatively large pores if numerous particles arrive simultaneously and block the pore by bridging (Knowles et al., 2011).

2. *Cake filtration* may occur when the particles are too large to penetrate into the media or other particles are deposited on existing blocked particles. This cake layer may also be described as the clogging layer which limits flow through the filter medium (Figure 2.6b). Depending on the age of cake, it may be compressed due to accumulation of the particles. The hydraulic performance of such as system is a direct function of particle aggregation at the surface of the filter medium (McDowell-Boyer et al., 1986).

3. *Deep bed filtration or internal cake formation* occurs when small particles may invade the formation, bridge and form an internal filter cake (Figure 2.6c). Straining is a common particle removal mechanism in the case of deep filters. Bradford et al. (2007) describe straining as "the retention of colloids in the smallest regions of the soil pore space formed adjacent to the points of grain-grain contact". Herzig et al. (1970) stated that straining is purely a geometric process involving mechanical removal of particles in small pore spaces. Bradford et al. (2007) found that both solution chemistry and hydrodynamic forces influence straining and, therefore, both physical and chemical mechanisms may be involved. Deep bed filtration may be preferable for stormwater applications so as to limit failure due to formation of an impermeable cake layer.

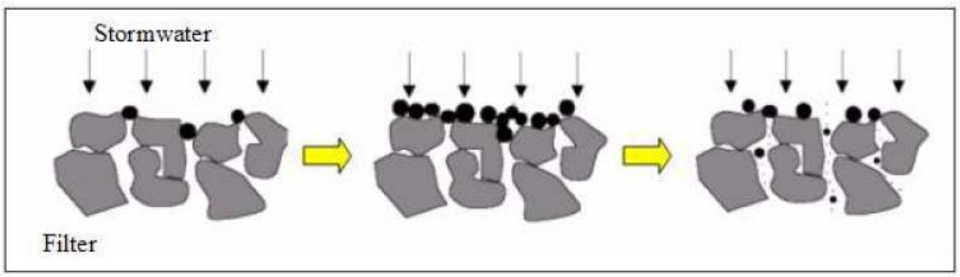

Figure 2.6a: Blocking filtration; **Figure 2.6b**: Cake filtration; **Figure 2.6c**: Deep bed filtration (as citied in Siriwardene, 2008)

Siriwardene (2008), in a review of clogging processes, concluded that stormwater has less organic contents than the treated wastewater sources and hence physical nature of clogging is more prevalent for stormwater systems. In general, it is hypothesised that the importance of chemical and biological clogging in stormwater filters will be less important than physical clogging. Furthermore, in some cases, it has been found that physical clogging initiates the process of decline in hydraulic conductivity and creates an environment conducive for biological and chemical clogging. For instance, 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. Hence, physical clogging is a very important clogging process to be considered in the context of systems treating stormwater influent that has high and variable sediment loads.

Even though physical clogging in stormwater systems has been investigated in biofilters (e.g. Coustumer et al., 2007 and 2012), infiltration systems (e.g.- Abbott and Comino-Mateos, 2001; Dechesne et al., 2004; Dechesne et al., 2005; Siriwardene, 2008), porous pavements (e.g. Pratt et al., 1995; Sansalone et al., 2011); physical clogging processes in high-rate filtration systems needs further investigation. This includes systems that use zeolites or coarse sands (like enviss™ filters that have been discussed earlier).

Given that the focus of this study is the (non-vegetated) filters that treat urban stormwater and the operational conditions are more conducive for physical clogging, the scope of this review is narrowed to physical clogging only. The next section therefore focuses on the processes and factors affecting physical clogging. However, some of the factors discussed therein may have relevance for chemical and biological clogging as well.

2.6 Factors affecting physical clogging

The physical process of filtering/trapping particles through filtration media is impacted by a range factors. Firstly, it is the filter design such as the type of filtration media and its physical characteristics, in construction of filter beds that can affect performance. Next, there are significant variations in the quantity and timing of influent applied to stormwater treatment systems, as they are only active during wet weather periods (i.e. intermittent operation) and have highly variable inflow rates (caused from variability in rainfall rates). Finally, there are significant fluctuations in the water quality in urban stormwater between wet weather events, as described in Section 2.2 (Table 2.1), partly attributable to the variations in rainfall rates, dry weather periods etc.

This section therefore reviews how physical clogging is influenced by filter media design and operational conditions (water quantity and quality). However, as there are few studies directly reporting how design and operational factors influence clogging in stormwater systems, this review also includes some evidence from potable water treatment and wastewater treatment fields. While these studies will provide some understanding of how these factors influence physical clogging in stormwater systems, it is noted that direct transfer of knowledge is not possible as drinking and wastewater treatment systems experience very different operational dynamics (i.e. they are continually inundated, often with a fairly consistent water quality and inflows).

2.6.1 Filter Design

Filter media differ from each other on the basis of type of material and their shape (which relates with their angularity and surface texture). This may be of consequence for the hydraulic and treatment performance of granular media. The material of filter media has been found to affect the hydraulic and treatment performance of the system. For instance, Hatt et al. (2008) compared six different types of filter media with low infiltration rates (ranging between 7 to 65 x 10^{-5} m/s) for stormwater treatment application. These media (fine sand, sandy loam and its different combinations with hydrocell, vermiculite, perlite, compost and mulch) had different initial hydraulic performances. Further, it was observed that significant reduction in hydraulic performance occurs overtime but at very different rates for different filter media types. Similarly, Knowles et al. (2011), while studying subsurface flow wetlands for wastewater treatment, recognised that significant differences exist between sand filters and bio-retention facilities because of the difference in media used in these facilities. However, these studies have been undertaken for fine filter media with low infiltration rates. The validity of the effect of filter media material needs to be assessed for coarser filter media that have higher infiltration rates.

The shape of filter grains has also been found to affect the overall performance of the system. For instance, improved performance of crushed grains (jagged and angular, collected from crushing of larger pieces of rock) over spherical grains (rounded and smooth, collected from river beds or glacial outwash) has been demonstrated for drinking water filtration using fine filters (Suthaker et al., 1995; Evans et al., 2002). Knowles et al. (2011) also observed that particle shape influences media hydraulic conductivity for wastewater treatment. Non-spherical or angular media may aggravate clogging as it reduces porosity and increases the specific surface area available for bio-film growth. Similarly, in a review of retention and removal of pathogenic bacteria in wastewater percolating through porous media, Stevik et al. (2002) also state that the rate of biological clogging (due to accumulation of bacteria) is dependent on the size and shape of the filter media and the bacterial cells. However, these experiments did not investigate the role of captured particles on the filtration and clogging performance. Further, the effect of filter grain shape needs investigation especially in the context of filters used for stormwater treatment.

The size of filter media has also been found to impact the hydraulic performance of a system as it controls the flow through rates. Knowles et al. (2011) found that the hydraulic conductivity of porous media was very sensitive to media size for wastewater treatment in vertical and horizontal subsurface flow treatment wetlands. Indeed, the smaller the particle size, the higher specific surface area available for bio-film establishment, and surface chemistry; and the greater the likelihood of suspended solids interception due to narrower pore diameters. This therefore made the fine media prone to rapid clogging by pore occlusion from filtration and bridging of surface accumulations. Similarly, McIsaac and Rowe (2007) compared clogging performance of different sized gravel media for leachate collection systems in real time and real scale. The coarse gravel bed (38 mm; initial hydraulic conductivity: 2800 m/hr) performed much better than the 19 mm gravel (initial hydraulic conductivity: 1330 m/hr and maintained a hydraulic conductivity that was higher than the 19 mm gravel even after operating for twice as long. In a study of natural sedimentation in laboratory based water columns, Skolasinska (2006) found that trapping of influent particles in case of riverbeds was controlled by infiltration rate, suspension viscosity and shape and size of both the porous media.

Rodgers et al. (2011) undertook a laboratory study to investigate the effect of sand filter depth on wastewater treatment performance of four intermittently dosed fine sand filters with a grain size of 1 mm. The performance of the shallower filter (0.3 m deep) appeared to diminish over time as the effluent COD and SS concentrations rose gradually as the study progressed. However, the 0.4 m deep filter did not exhibit the same effects. Farizoglu et al. (2003) studied the effect of filter depth on wastewater pollutant removal using sand and pumice (0.5-1 mm grain size) as a filtration media under rapid filtration conditions (7.64 m/hr and 15.28 m/hr) in laboratory conditions. The change of suspended solids removal rate with time for1000 mm, 750 mm and 470 mm of bed depths suggests that increasing bed depth increases the available surface area for the capture of particulate matter. Thus, more particulate matter can be retained in the filtration bed, so the removal rate of the particulate matter is improved by increasing the bed depth. Even though these studies are in context of water and wastewater treatment, these do highlight the significance to investigate the effect of filter depth on pollutant removal and clogging.

Changhong (2008) observed that high flow rate (velocity) can carry particles further inside a porous medium, but no studies have been undertaken to assess the effect of infiltration rate on clogging performance. This may be consequential for nature/extent of filter bed clogging (whether it is at the surface or deep interstitial in nature) and hence could guide maintenance protocols of these systems. However most of studies to date are limited to media that have relatively low conductivity; Suthaker et al. (1995) tested filter media for drinking water filtration at filtration rates of 12.5 m/hr, 8 m/hr and 3.5 m/hr; Pavelic et al. (2011) studied soil aquifer treatment at filtration rates of 0.004 m/hr (loam) and 0.96 m/hr (sand). This therefore necessitates the need to undertake specific studies for urban stormwater filtration using filters with comparatively higher infiltration rates.

It can therefore be concluded from the above review that there are a number of factors related to the characteristics of filter media and filter bed design that affect filtration and clogging processes. However, limited studies have been undertaken to understand the impact of these on clogging processes, especially in context of stormwater treatment involving gravity flow at high infiltration rates that operate intermittently. Most of the stormwater treatment systems are currently being designed using knowledge and experience acquired from other water treatment systems. Given the specific nature of clogging, it is important to understand clogging processes in the context of non-vegetated filter material that can be potentially used for stormwater treatment. It is therefore pertinent to test the effect of filter media characteristics such as the type of media; shape and size of grains; and the way filter media is packed within the filter bed (i.e. filter bed design) on the overall performance of filters that have high infiltration rates.

2.6.2 Operational conditions – water quantity characteristics

The influence of hydraulic loading rates on hydraulic performance of filtration systems has been studied but the results are conflicting. Ruppe (2005) observed that sand filters loaded with identical hydraulic loading rates and influent wastewater source, but with different dosing frequencies clogged at different times. However, Reddi et al. (2000) in their experiments found that difference in flow rates did not cause any noticeable change in the clogging behaviour of sandy soils (using fluids containing polystyrene or kaolinite particles; initial permeability: 108-144 m/hr). This is despite the fact that particle deposition is generally known to be less likely at higher flow rates. Other wastewater studies, for instance, Leverenz et al. (2009), also highlight different variables of importance, including hydraulic loading rate, time of operation, and dosing frequency(based on the results of a model sensitivity analysis). Knowles et al. (2011) also recognised significant differences between sand filters and bio-retention facilities. It was found that sand filters usually have relatively steady inflow rates and ponding heads, while the variability of incoming runoff renders bio-retention behaviour much more dynamic. Similarly, flow rate and duration of injection were found to affect the rate of clogging when injection of wetland-treated stormwater to a confined aquifer was studied by Pavelic et al. (1998) in a constant temperature glasshouse environment using sand and loam.

Hatt et al. (2008) compared six different fine filter media using stormwater. The authors found that the infiltration capacity of the filters recovered following an extended dry period, before declining again during wet periods. This may indicate that clay particles and organic matter swell during wet periods (reducing the porosity of the filter media) and develop cracks and macropores as water content decreases during dry periods (increasing porosity). Similar patterns were evident for all other filter media types, although the variation in infiltration capacity was much less for some of the filters. Li and Davis (2008a) also found that bio-retention filters exhibited higher solids loading capacity under intermittent flow conditions before clogging than under continuous flow conditions(low flow rates between 0.048-0.208 m/hr). Similarly, Knowles et al. (2011) state that intermittent operations may be beneficial for reversing clogging in the wetlands. The periodicity of loading to resting determines the ability of the system to operate without clogging and the recovery period depends on climatic conditions. Systems in cold and wet climates will require a longer recovery period than those in hot and arid climates (Knowles et al., 2011). Studies undertaken for intermittent sand filters used in wastewater treatment also suggest that variations in hydraulic loading regimes had significant effects on clogging. However, Yong et al. (2010), while investigating the effect of drying and wetting regimes on the clogging behaviour and pollutant removal efficiency of three porous pavement types found that drying has a direct influence on the longer lifespan of these systems with higher solids loading capacity. These studies therefore suggest that intermittent loading regimes involving some resting periods do affect longevity of filtration systems in different ways but this would need more investigation specifically for non-vegetated filters with high infiltration rates.

Effect of operational conditions on clogging, such as hydraulic head, has been studied. Reddi et al. (2005) compared the clogging performance of sandy soils under constant flow rate and constant head conditions. Similar permeability reduction with respect to time was observed in both cases. However permeability reduction under constant head occurred in much fewer pore volumes as compared to under constant flow rate. Siriwardene et al. (2007) in their study of gravel stormwater filters also found that dynamics of water application, and in particular the presence of a constant water level in a gravel infiltration system, affects its hydraulic performance. However, it is not possible to operate stormwater treatment systems under a constant flow regime. The methods designed to investigate the clogging processes of systems in this study will therefore focus on constant head conditions only.

Based on this review, it can be concluded that loading rates and regimes have a mixed effect on clogging of filtration systems. Specific studies therefore need to be undertaken to investigate the effect of hydraulic loading rate and regimes on clogging in context of stormwater treatment using non-vegetated filters with high infiltration rates.

2.6.3 Operational conditions – water quality characteristics

There could be a significant variation in the stormwater characteristics depending on a number of factors such as the catchment type and its size; nature and extent of pre-treatment; climatic conditions and so on (refer Section 2.2). These may all eventually affect the way filtration systems behave.

Haselbach (2010) found that extreme storm events deposit large quantities of clay on pervious concrete pavements leading to a reduction in the infiltration capacity of the system. The rate of this reduction was found to increase with the density of the clay suspensions. Gautier et al. (1999) in a field study of two low flow rate basins used to drain industrial areas found that the particles present in the stormwater or their concentration (based on the land use) have an influence on the clogging process. Similarly Pavelic et al. (1998), while studying injection of wetland-treated stormwater to a confined aquifer at very low infiltration rates (sand: 23 m/day and loam: 0.1 m/day), also suggest that the rate of clogging is dependent on concentration of suspended solids and temperature.

In a review of clogging phenomenon in wetlands for wastewater treatment, Knowles et al. (2011) found that influent characteristics, such as solids content and pollutant characteristics are vital for understanding clogging processes in the subject systems. The size of particles in the influent has also been found to affect hydraulic performance of the system. Siriwardene et al. (2007) undertook a laboratory study to understand physical clogging processes in coarse gravel stormwater filters. It was found that physical clogging is mainly caused by the migration of sediment particles less than 6 μm in diameter. Li and Davis (2008a) conducted a series of laboratory column experiments and field observations for bio-retention filters and found that clay-sized components of the incoming total suspended solids (TSS) exerted a controlling effect on media clogging as compared with components of other particle sizes. Similarly, Kaminski et al. (1997) state that influent particle size distribution plays an important role in wastewater filtration (with flow rates varying between 5-25 m/hr) and the particle removal efficiency varies for different particle size groups. It was also observed that filters with high rate of filtration were more sensitive to particle size, as compared with low rate filters. However, Changhong (2008) in a review of different studies (using media such as sandstone, glass beads, sand and passing particles such as alumina, clay, latex, bentonite) found that bigger influent particles caused more damage as they have higher tendency to settle down and block or bridge.

Flocculation could also affect blocking processes within the filter bed. Reddi et al. (2000), compared influents made of fine and uniform sized kaolinite particles (size: 2-12 μm) with relatively larger particle sized influent made of polystyrene spheres (size: 1-35 μm). Permeability reductions for both influents were observed to be comparable. This was attributed to be an effect of flocculation, which may as well have a role to play in the case of stormwater systems.

Spychala and Blazejewski (2003) studied factors affecting fine sand clogging by septic tank effluent and found that sewage temperature had a significant impact on the clogging process of fine sands with lower temperature resulting in lower hydraulic conductivity. However, for sewage ponding in study columns, the impact of temperature on the filter hydraulic conductivity was more significant for biological activity than for sewage viscosity. De Vries (1972), while testing the effect of primary wastewater effluent on different experimental columns (made of 0.1-0.5mm sand fractions; initial hydraulic conductivity: 600 cm/day) , also found that continuous effluent applications at the same rate, but at a temperature of 4 ± 3°C, while allowing the same daily rest periods, resulted in early failure because of pore clogging. Variations in stormwater temperature have been reported for Philadelphia, US: 4-26°C(Roseen et al., 2009); 9-32°C (Jones et al., 2009)and other geographical locations (Emerson and Traver, 2008).However, a limited variation in water temperature is expected in the case of stormwater treatment systems operating in Australia.

It can be concluded from the above review that the limited studies undertaken for stormwater systems and for other non-stormwater systems stress the significance of the effect of influent characteristics, such as concentration and type of pollutants and particle size of pollutants, on clogging phenomenon. Furthermore most of the studies have been undertaken for fine media filters and/or systems with low infiltration rates.

It is therefore pertinent to undertake specific studies to understand the effect of stormwater characteristics on clogging especially in context of non-vegetated filters with high infiltration rates.

2.7 Nature of clogging

An understanding of pollutant migration and location of clogged material could have important ramifications for design, operation and especially maintenance of filtration-based systems. However, conflicting information is available on the extent of clogging within the filter bed. For instance, in their comparison of six different filter media using stormwater Hatt et al. (2008) found that the accumulation of captured sediment was at or near the filter surface and was causing reduction in hydraulic performance. Similarly, Siriwardene et al. (2007), while studying gravel stormwater filters, found that a clogging layer forms at the interface between the filter and underlying soil. Literature on porous pavements, for instance Haselbach (2010), also states that most of the trapped material remains on the surface of the pavement and can be removed with simple maintenance procedures such as sweeping. However, Li and Davis (2008b) in their study of bio-retention filter media (tested in the lab using sandy soil media < 2 mm in size and hydraulic conductivity 45-131 cm/hr) observed that both depth filtration and cake filtration contribute to urban particle capture.

Similar contradictions related to the nature/extent of filter bed clogging exist in the case of wastewater systems. De Vries (1972), while testing the effect of primary wastewater effluent on columns filled with sand fractions, conclude that filter failure was caused by the surface sludge layer. Some of the field investigations of artificial recharge basins that use turbid or treated wastewater report that clogging from silt happened at the surface, while clay particles penetrated deeper (Schuh, 1988; Schuh, 1990). For instance, in an in-situ study of a 1.2m deep test pit on a coarse sandy site found variability in hydraulic properties and clay distribution with depth. Skolasinska (2006) undertook field and laboratory investigations to describe clogging microstructures by simulating natural conditions in a water column and using sand samples with low hydraulic conductivityof0.3-3 m/hr. The author found that while intensity of clogging decreased with depth, most of the suspended material was trapped near the surface. Goss (1973) tagged the suspended sediment in water used for recharge with a radioisotope to determine the extent of its movement into materials underlying recharge basins. 50% of the sediment suspended in the recharge water moved deeper than 18 inches when openings of naturally occurring large pores were allowed to remain at the basin surface.

Further, Herzig et al. (1970) reviewed different filtration studies and found that the ratio of sediment size (d_s) and filter media's grain size (d_p) was an important parameter that guides the nature of clogging. For $d_s/d_p > 0.15$, the porous medium is irreversibly blocked and a filter cake is formed; for $d_s/d_p < 0.065$, the retention remains always low and for the intermediate values a partial blocking of the porous bed may occur (this depends on particle shape and bed porosity).

Therefore, based on the existing literature, it can be concluded that the nature of clogging is different across systems and influents. It is specific to factors like the filter media characteristics, influent characteristics and the interplay between them. Given the diverse range of particle sizes in stormwater (which varies considerably), it is necessary to understand the nature of clogging processes specific to non-vegetated filters with high infiltration rates. This will eventually assist in informing design and reducing maintenance requirements.

2.8 Conclusions of literature review and Research Aims

As concluded from the review of literature, clogging processes have not been studied and understood for urban stormwater filtration systems, even though they are being adopted around the world. Therefore, understanding the processes and factors which influence these processes (filtration media, type of design, influent and nature/dynamics of stormwater application) is important. This would help in reducing clogging rates and eventually enhance longevity of these systems with reduce maintenance needs. As such our aim is to understand clogging processes and factors which influence them.

As understood from this review of literature, clogging is very specific to the characteristics of filtration media, influent and nature/dynamics of stormwater application. ***The aim of this research is therefore to study clogging processes in the context of non-vegetated granular filters with a high infiltration rate that can be used for stormwater treatment***.

The specific objectives of this research are:

1. To undertake evaluation and develop an understanding of the effect of basic filter media's physical characteristics (e.g. shape and material type of the media) on the clogging of the filters.
2. To undertake evaluation and develop an understanding of the effect of filter bed's design/construction (i.e. particle size and layered structure of media in filter bed) on the clogging of the filters.
3. To undertake evaluation and develop an understanding of the effect of the operational conditions, including characteristics of stormwater and the way it is applied to cloggingof these filters.
4. To evaluate if biological clogging could play a significant role in the clogging of these filters.

2.9 Research hypotheses

To achieve the research aims, the key hypotheses that will be tested are:

1. Hypotheses related to filter media characteristics

a. The physical characteristics of filter media, such as its structural strength, shape (angularity) and smoothness, have a significant impact on the rate of clogging and treatment performance.

b. The infiltration/flow-through rate of the filter has an important impact on filter clogging and treatment performance.

2. Hypotheses related to design features of the filter

a. The size of filter media particles in the filter bed affects its sediment/pollutant removal behaviour.

b. The constructional features of a filter bed, such as its depth and the way filter media particles are packed, affect the sediment trapping behaviour.

3. Hypotheses related to stormwater characteristics

a. The characteristics of sediment in stormwater, such as its concentration and the presence of pollutants other than sediment (such as heavy metals and nutrients), affect overall performance of the system.

b. The particle size distribution of the sediment in influent affects the rate of clogging and treatment performance.

4. Hypotheses related to dynamics of water application

a. Loading rates affect the hydraulic and treatment performance of the filter.

b. Intermittent loading i.e. the wetting and drying regimes affect the longevity of the filter.

5. Hypotheses related to clogging processes

Physical clogging processes, rather than biological clogging are the key mechanisms that reduce the hydraulic performance of filters used in stormwater treatment.

6. Hypotheses related to field study

a. Clogging of enviss™ filters in field will follow same trends as clogging of 2 and 3 layered systems studied in the laboratory.

b. It is possible to model the hydraulic performance of enviss™ filters using a simple regression curve between infiltration rate and cumulative treated volume of stormwater.

3 Assessment of clogging phenomena in granular filter media used for stormwater treatment

3.1 Introduction

This chapter describes the laboratory experiments carried out with the aim to gain an understanding of the effect of filter media's shape and size on clogging processes in non-vegetated filter media with high infiltration rates. As discussed in the previous chapter, current clogging studies in stormwater treatment systems have been limited to fine filter media (e.g. Hatt et al., 2008) or very coarse media (e.g. Siriwardene et al., 2007). Clogging of filter media of particle size range between 1 mm and 5 mm has not been studied, even though some commonly used stormwater filters use coarse filter media (Clark and Pitt, 1999; Bratieres et al., 2012).

Filter media differ from each other on the basis of material, shape (angularity and surface texture) and this may be of consequence for the hydraulic and treatment performance of granular media (e.g.- Suthaker et al., 1995; Evans et al., 2002; Hatt et al., 2008; and Knowles et al., 2011). Therefore, given that the type of filter media and its size (and hence the infiltration rate of the system) could be a key factor affecting clogging, it is important to study the overall performance of filter media of this size range for stormwater treatment.

The main purpose of this research is therefore to understand the process of clogging in filter media with high infiltration rates that are typical of stormwater infiltration and treatment systems. This chapter focuses on impacts of filter media type and flow operational conditions (i.e. filtration or flow-through rate). It also discusses the interplay between clogging and sediment removal performance. Effects of intermittent loading (i.e. the wetting and drying) regime have not been included in this chapter and have been presented in Chapter-5. Based on a review of the literature, the following hypotheses have been identified for investigation in context of stormwater treatment:

- physical characteristics of the media material such as its structural strength, shape (angularity) and smoothness have a significant impact on the rate of clogging and treatment performance;
- flow-through rate has a significant impact on filter clogging and treatment performance for a specific particle size of filtration media.

The main results of these experiments are presented in a paper published in *Journal of Hydrology* and a copy is attached as Appendix I-1 (Kandra et al., 2014a). The research findings were also presented in the Novatech Conference, Lyon, France, 27th June - 1st July, 2010.

3.2 Methods

3.2.1 Experimental setup

Four granular filter media were tested (Figure 3.1): zeolite, scoria, riversand and glass beads (made from a polymer material). These media were specifically selected to address the first hypothesis and cover a range of particle shapes (angularity), porosity, roughness, and structural strength (as shown in magnified picture of these media in Figure 3.2). These media are also representative of typically-used materials in filtration (Clark and Pitt, 1999; Kele, 2004; Bratieres et al., 2012; and River Sands Pty Ltd). Zeolite was chosen because of its cage like structure and its wide acceptability in the water treatment industry. Scoria particles were selected because they are the most uneven and have the lowest structural strength. Riversand was chosen because of its angular shape and as it is the one of the most widely available media. Glass beads were chosen as a theoretical material as they are the most spherical, impermeable and smooth.

Figure 3.1: Photographs of filter media grains with particle size of 2 mm (passing 2.36 mm sieve and retained on 2 mm sieve) (from left to right: zeolite, scoria, riversand and glass beads; same scale for all media)

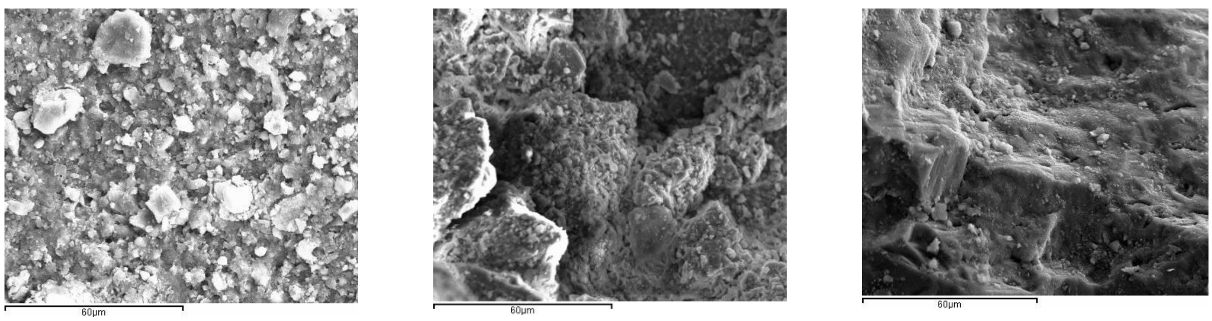

Figure 3.2: Photographs of zeolite, scoria, and riversand at a magnification level of 1000 times

A uniform filter media particle size of 2 mm (passing 2.36 mm sieve and retained on 2 mm sieve) was selected for all media. Sieving has been done to prepare a filter bed with particles sized between 2-2.36 mm as a preventative measure against a mixed filter bed with diverse set of particle sizes (which could create a new variable affecting performance of compared systems). Systems with a filter particle size lower than this size (such as 0.5 mm) were found to have a lower filtration rate, in a series of prior pilot experiments, whereas bigger particle sizes (such as 10 mm) had lower treatment performance. Therefore, the selected particle size range is something of a trade-off between the hydraulic and treatment performance. Further clogging of non-vegetated stormwater filter media that is made from particles sized between 1 mm and 5 mm has not been investigated even though they are often used in proprietary stormwater systems (e.g.- Clark and Pitt, 1999 and Bratieres et al., 2012).

Using the selected materials, 95 experimental columns of 150 mm diameter were constructed. The ratio of experimental column diameter to filter particle diameter was more than 50, as recommended for filtration studies (Lang et al., 1993). Figure 3.3 and Table 3.1 show the characteristics of the experimental column design wherein 300 mm of filter material was placed between a 50 mm layer of coarse gravel at the top (that protected the filter from the energy of water applied) and a 50 mm gravel layer at the bottom that prevented migration of the media out of the filter. A minimum of five replicates of each column configuration were built to allow statistical comparison of each configuration.

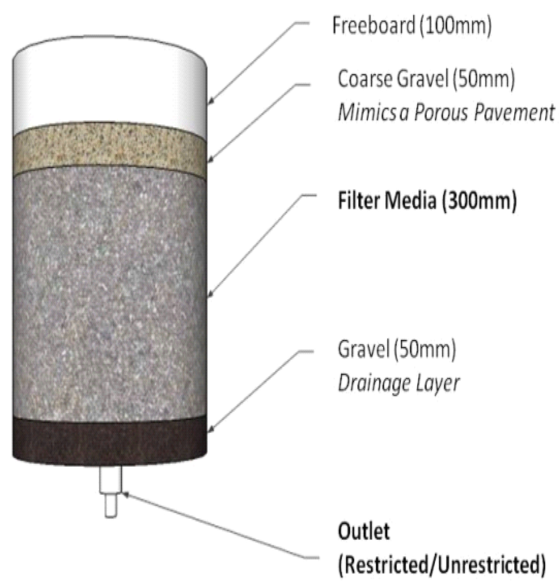

Figure 3.3: Design of experimental columns

Table 3.1: Design of Experimental column: details of filter media and column construction

Filter material type Layers	Depth (mm)	**Material and particle size** (media type coding shown in brackets)
Energy dissipation cover	50	Coarse gravel: 7 mm
Filter media (one of the four)	300	Zeolite (Z): 2-2.36 mm
		Scoria (S): 2-2.36 mm
		Riversand (RS): 2-2.36 mm
		Glass beads (GB): 2-2.36 mm
Drainage layer	50	Fine gravel : 6-7 mm

The objective of this study was to compare the performance of these four media across four different flow rates and study the impact of flow through rates on the media. However to achieve different flow-through rates, we used different outlet sizes. Columns were built with four different outlet sizes, the largest of which (79 mm outlet) assured unrestricted outflow with initial infiltration rate (IR) of 60-80 m/hr through the media. This corresponds closely to loading rates observed for coarse filters with a hydraulic conductivity of 10-1000 m/day therefore representing filters with high infiltration rates (Hosty and Mulqueen, 1996; Mulqueen, 2005). The other three outlets (sizes: 10 mm, 4.2 mm and 1.8 mm) caused restricted flows through the media as specified in Table 3.2 and were chosen to represent different orders of magnitude.

Table 3.2: Design of Experimental column: details of outlets and infiltration rates

Outlet characteristics		
Restriction type	**Diameter (mm)**	**Initial infiltration rate IR (m/hr)**
Unrestricted flow	79	60–80
Restricted flows	10	15–20
	4.2	1.5–3
	1.8	<0.5

During the construction of these columns, the layers were not compacted, to avoid damaging the media and to replicate natural (un-engineered packing) conditions. The treatments are named according to the filter material name and the outlet size. For instance, zeolite filter configurations with an unrestricted outlet size of 79 mm is referred to as Z79 and riversand with the smallest outlet size of 1.8 mm is referred to as RS1.8.

3.2.2 Experimental procedures

Two sets of experiments were conducted:

i. filter stability tests to investigate the impact of hydraulic compaction on media characteristics (in order to distinguish these influences on clogging from the impacts of sediment in stormwater), and
ii. clogging tests that focused on understanding a combined impact of sediment in stormwater and infiltration rates.

Stability of filter media to filtration forces

To investigate the structural strength of filter particles (i.e. whether particles break during filtration processes), the experimental columns prepared with zeolite, scoria and riversand (10 mm outlet sized design with IR 15-20 m/hr) were dosed with potable water. Polymeric glass beads were not tested as this media was known to be structurally stable. These experiments allowed us to investigate whether rearrangement and disintegration of its particles could contribute to clogging processes.

Each of the experimental columns was dosed manually with 22.5 m of potable water over 10 days, passing 1.7-2.8 m per day. In all, 4.5 m of water was dosed every two days while allowing a drying time of 12 hours in between events and maintaining same application rate to all experimental columns in these compressed-in-time experiments. The dosing volume of 22.5 m was selected since it was almost equal to the expected lifespan of the systems of this outlet size when typical stormwater is applied (see the results).

Using Melbourne's historical rainfall data (BoM), 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/yr, spread over 72 events). It was assumed that these systems represent 0.3% of its catchment's impervious area. For instance, to achieve treatment of over 90% of runoff from an impervious surface, as recommended by current Australian best practice (Wong, 2006b); high flow rate filters were sized by Bratieres et al. (2012) to be 0.3% of their impervious catchment area for Melbourne conditions. However they will be of different size for different climatic conditions. The average storm event was calculated (equals Rainfall per event x Cross sectional area of column/ Catchment impervious area) and mimicked by applying 1.7 m of stormwater (approximated to 30 litres per dosing event for each column). A constant head to the top of column was maintained manually during each dosing session by topping up water at a controlled pace and avoiding any spill (freeboard available on top of coarse gravel: 100 mm; depth of coarse gravel layer: 50 mm). It was ensured that stormwater was always applied up to the top of the column and any excess water would just spill out from the column. This volume of water may seem very high but given the high infiltration rate of these filters, the contact time of influent in the filter bed is very minimal.

The media were not pre-washed as it is expected that most of the intrinsic dust within the filter media is removed during the sieving process when the filter grains are passed through two sieve sizes of 2 mm and 2.36 mm. As potable water is passed through in these experiments further cleaning of filter bed occurs. The depth of filter bed was measured at the start and end of the experiment to ascertain any compaction of the filter bed.

Estimation of infiltration rates was made at regular intervals (after every 1 m of water was passed) by measuring outflow rate and then calculating hydraulic conductivity (normalised for standard temperature of 20°C). Water samples were obtained both for inflow (potable water) and outflow from the experimental column, after 0.5 m and 22.5 m of potable water was passed through, and analysed for total suspended solids (TSS) using Standard Test Method for Filterable and Non-filterable Matter in Water (ASTM D5907-09). The outflow TSS, named "*Background TSS*", resulted from dust in the filter bed that may be the result of particle breakage due to filtration hydraulic forces.

After allowing the columns to dry naturally for a period of 7 weeks, the columns were dismantled and filter media samples of approximately 200 grams were carefully removed from the top, middle and bottom layers of the column. The removed particles were then dried in an oven at a low temperature of 50°C for six hours to ensure there was no breakage of filter media from exposure to high temperature conditions. Sieve analysis of the media samples was then undertaken to determine the change in filter media particle size using mesh sizes of 2.36 mm, 2 mm, 1.40 mm and 1.18 mm and evaluating weight fractions finer than 2 mm size. Natural breakage in each layer caused by packing and unpacking was also identified. Similar sieve analysis experiments were repeated for blank columns but without passing any water through them so as to understand the net effect of particle breakage from water scouring.

Clogging experiments

The columns were dosed in-situ with 5.6 m of potable water (or 45-50 pore volumes of the media) at the very start of the clogging experiments. This ensured that the filter bed was free of any intrinsic dust prior to the testing for clogging. At the end of this cleaning process, TSS in the outflows of each configuration was also measured. Initial infiltration rates were determined during this washing phase by measuring flow rates after every 1.5 m of water application.

All columns were then dosed with semi-synthetic stormwater that was prepared using tap water and sediment harvested from a stormwater pond in Huntingdale (Melbourne, Australia), passed through a 1000 μm sieve. Once mixed, the particle size distribution (PSD) of the sediment collected from this pond was in the range of stormwater composition values, where d_{10}= 5.1 μm, d_{50}= 34.5 μm, d_{75}= 140 μm and d_{90}= 301 μm, respectively. This PSD is quite close to what has been observed in a study comparing urban roads in Melbourne, Sydney, Brisbane and Adelaide with d_{10}= 6 μm, d_{50}= 40 μm, d_{75}= 175 μm and d_{90}= 440 μm (Lloyd et al., 1998). This approach has been used in earlier clogging studies (e.g.- Hatt et al., 2007; Siriwardene et al., 2007; and Bratieres et al., 2012). It provides a good compromise between using natural stormwater sediments, while addressing the need to ensure consistency over the duration of experiments. The concentration of sediment in stormwater was targeted at 100-300 mg/L, which is in the range of stormwater composition (based on a review of international data (Duncan, 1999)). Within one dosing event, TSS was maintained at a constant concentration by a mixer installed in the stormwater tank, but despite this, it varied slightly between different events. Therefore, different experimental configurations were tested simultaneously to ensure that the same stormwater was applied to all media, thus avoiding artefacts due to varying concentrations between treatments.

The focus of these experiments is limited only to total suspended solids (TSS) in stormwater as studies suggest that majority of stormwater pollutants are attached to TSS. For instance, Han et al. (2006) analysed highway stormwater runoff characteristics for three years in California and suggested that suspended solids were associated with most particulate-bound metals such as chromium, copper, nickel, lead and zinc. Similarly, correlation between TSS and Total Phosphorus has been found to be strong in a recent study of seven urban catchments in south eastern Australia (Francey et al., 2010). Therefore, as many pollutants are associated with sediments, it has been suggested that the removal of suspended sediment is critical for the treatment of a wide range of stormwater pollutants. This is particularly the case for nutrients (such as phosphorus) and heavy metals (such as zinc) which can cause eutrophication and toxicity to fish, respectively (Ellis and Jacobsen, 1996; Walsh, 2000).

The experiments have been 'compressed in time', where months of operational life of the systems were compressed to several weeks due to time constraints, as has been done in previous clogging studies (Hatt et al., 2007; Siriwardene et al., 2007; Bratieres et al., 2008; Bratieres et al., 2012). However, to ensure more realistic behaviour, the systems were not continuously dosed, but storm events were simulated with some level of drying in between, which was chosen to be around 12 hours based on logistical reasons. The average storm event was calculated using Melbourne's historical rainfall data (BoM) and assuming that these systems represent 0.3% of its catchment's impervious area, as discussed in the previous section and equated to 30 litres per dosing event for each column. The columns were dosed twice a day with this volume because of logistical reasons in these compressed-in-time experiments. A constant head to the top of column was maintained manually during each dosing session by topping up water at a controlled pace and avoiding any spill. However, it is important to note that this procedure ignores drying influences in the field, meaning that the experiment serves as a comparison of the filter media, rather than a prediction of field behaviour.

The infiltration rate of each column was calculated by measuring the outflow volume per unit time using the constant head method (ASTM international D 2434-68) as per Darcy's Law. This was done after every 0.85 m of water was passed because we wanted to measure infiltration rate two times during the dosing event as due to logistic reasons we were not able to take more measurements. For each dosing event, composite water quality samples were obtained both for inflow water and outflow from the experimental column (at regular intervals after 0.56 m, 1.13 m and 1.7 m of stormwater was passed through the filters). However, outflow water quality samples representing first flush event (immediately after influent is applied to the filter bed after a drying period) have not been measured. Particle size distribution (PSD) to assess the range of particle sizes in the inflow and outflow from the columns was undertaken using a Beckham Coulter LS100Q Laser Diffraction Particle Size Analyser. Experiments were run until the infiltration rate was 5% of the initial infiltration rates, which was regarded as the clogged state of the columns.

3.2.3 Data analysis

The evolution of clogging was examined in relation to the cumulative volume of applied water. To compare results among different experimental runs (undertaken with somewhat different sediment inflow concentrations), the recorded inflow volumes were normalised and expressed as equivalent meters of 'typical stormwater' (with an assumed TSS concentration of 150 mg/L). The cumulative mass of sediment applied to the column was divided by 150 mg/L and the area of the column to obtain equivalent meters of stormwater applied.

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)
- Normalised volume of stormwater that causes clogging of the system, which is defined as when the infiltration rate dropped to 5% of the initial rate
- Overall pollutant treatment efficiency of the media over its life span, defined as the ratio between the total mass of TSS removed and the total mass applied to each column
- The percent of particles finer than 2 mm (by weight) in all media layers (that were sieved after completion of all experiments)

To test if there is a statistical difference between the above variables calculated for different treatments (e.g. media types and different flow rates) standard ANOVA tests were used, with significance accepted at $p<0.05$. Data has been tested for independence, normality and homogeneity of variances prior to undertaking the significance tests, as assumed for Standard ANOVA tests. Since the experimental design was fully factorial with four different filter media and four outlet sizes (i.e. 16 different configurations), full factorial statistical analysis has been undertaken to analyse the main effects of filter media and flow rate and their interaction on the above performance parameters using SPSS (SPSS, 2001).

3.3 Results and discussion

3.3.1 Stability of filter media to filtration forces

The initial infiltration rate (IIR) in experimental columns of different filter media (with outlet size of 10 mm) was found to vary around 30% within replicates (Figure 3.4). This can be attributed to the natural variability in media, its packing and the uncertainty associated with infiltration rate measurement techniques. These observed variations were within the ranges reported in the literature, e.g. Le Coustumer et al. (2012) found it to be around 49% for loamy-sand filters.

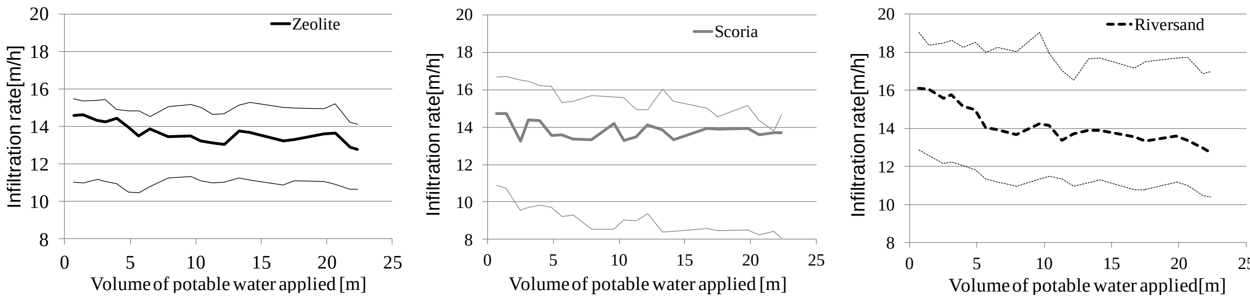

Figure 3.4: Evolution of infiltration rate on the application of potable water in zeolite, scoria and riversand filters with column outlet of 10 mm (IIR: 15-20 m/hr) *(Thick lines represent median values and thin lines represent 95% confidence interval)*

The infiltration rate (IR) of all the media types diminished initially, but then stabilised after the initial cleaning phase (Figure 3.4). Comparison of IR at the start and end of these experiments suggests a median decline in hydraulic performance of 7%, 16% and 16%, as measured in the five replicates of zeolite, scoria and riversand filter beds respectively. Maximum initial decline was observed in the case of experimental columns that had the highest infiltration rate at start, which may be caused by comparatively loose packing of the filter media. This suggests that there is an initial re-arrangement of filter grains in the filter bed due to disturbance provided by the inflowing water. However, no changes in the depth of filter bed were observed after all potable water was passed, implying limited compaction of filter media. Differences between IR of different media (compared after 0.7 m, 5.7 m, 11.3 m, 20.7 m and 22.3 m of water was applied) were not statistically significant since the p-value of ANOVA tests were 0.30, 0.44, 0.52, 0.81 and 0.83, respectively (all far above the 0.05 significance level).

To assess the impact of filtration forces on particle breakage, two sets of tests were done. Firstly, particle size distribution (PSD) of the raw filter media (i.e. having received no influent at all) at different depths was determined after emptying the packed columns and undertaking sieve analysis and results are shown in Figure 3.5a (dotted lines). Secondly, PSD of filter media in columns that received 22.5 m of potable water (which as shown in following discussion is approximately the volume of water that is treated during a column's normal operational life) was undertaken. The percentage of particles in the top layer with particle size less than 2 mm at the end of the experiment for zeolite, scoria and riversand were 28%, 39% and 18%, respectively, as shown in box plots (Figure 3.5a). We can therefore conclude (from the evidence in Figure 3.5a) that main processes responsible for change in particle size are breakage of filter particles during the packing and unpacking process and impact of filtration forces. Within the scoria bed, particle breakage was observed to be far greater in the top layer as compared to the bottom layer, indicating that the impact of scouring during dosing was significant. However, the extent of filter particle disintegration across layers of filter bed was relatively uniform for riversand and zeolite indicating consistent and better particle strength.

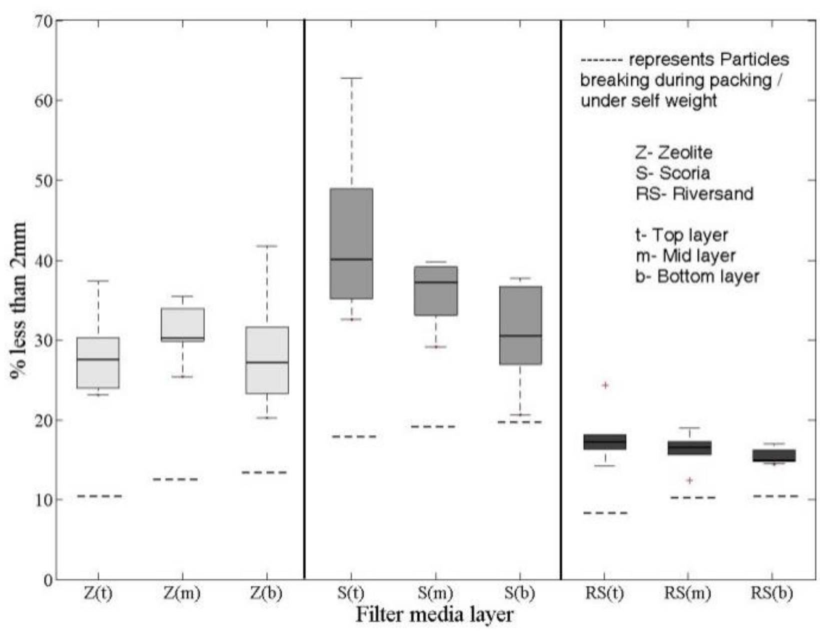

Figure 3.5a: Percent filter media breakage at different depths of the three filter media with outlet size of 10mm (IIR: 15-20 m/h)

Comparison of 'Background TSS' concentrations in the outflow (Figure 3.5b) suggests that while concentrations before and post cleaning of filter beds do not vary much for riversand, it is high and variable for scoria (the outflow TSS reduced by 90% over its lifespan). This indicates a high level of intrinsic dust in scoria filter bed which comes from its weaker particle strength and greater abrasion amongst scoria filter particles than is the case for other media.

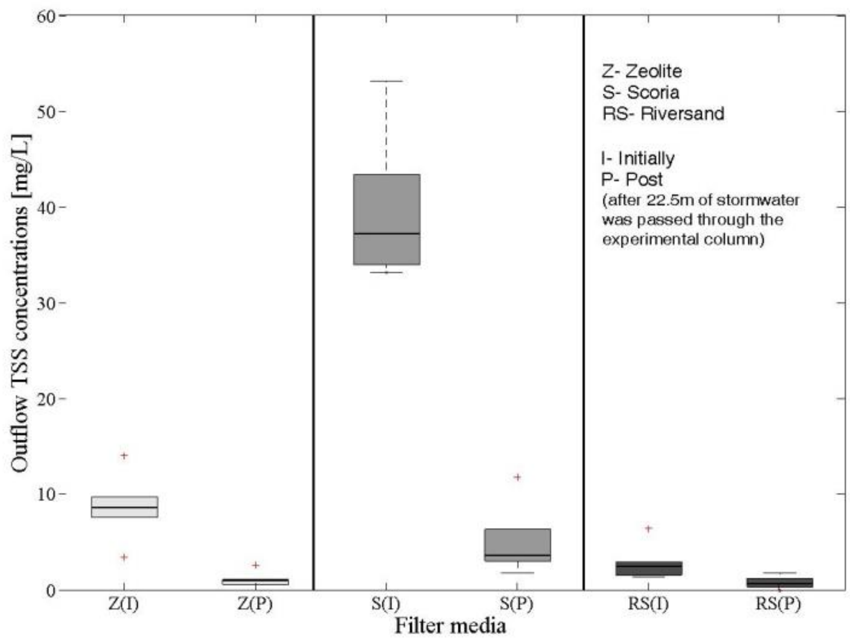

Figure 3.5b: Observed TSS concentrations in the outflow of these filters at the start (initial: **I**) and end (after 22.5 m of water was passed: **P**) of the potable water experiments

3.3.2 Evolution of clogging and sediment trapping over time

Infiltration Rate (IR) remained relatively constant initially and started to drop significantly only after certain amount of stormwater was passed through any of the designs tested (Figures 3.6a (zeolite), 3.6b (scoria)). The deflection point at which IR started to significantly drop and its rate of decline depended mainly on the outlet size (which governs the IIR). For instance, as shown in the log plots in Figure 3.6a, infiltration rate of Z79 design was almost constant for the first 30% of stormwater applied and then declined sharply. On the other hand, for Z1.8 design, the hydraulic performance varied around a narrow range for the first 75% of volume passed and then started to decline. Therefore, the pattern of drop in IR varied for columns with higher initial infiltration rate than for columns with lower initial infiltration rate. Trends in the evolution of infiltration rate for riversand and glass bead columns also suggest similar trends with the infiltration rate remaining constant at the start followed by decline (Figures 1a, 1b of Appendix II). Again the pattern of decline in infiltration rate depends mainly on the initial hydraulic performance of the filter bed, which is controlled by the size of outlet.

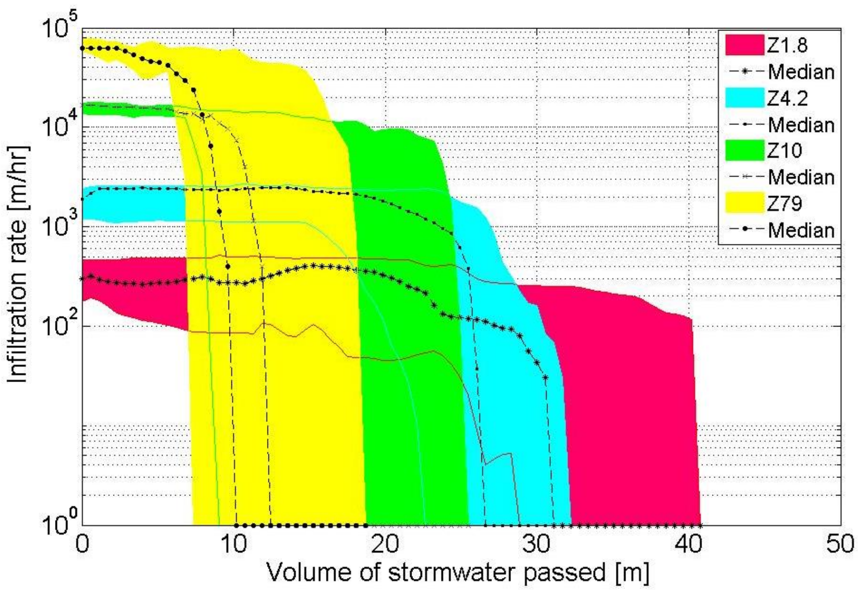

Figure 3.6a: Evolution of infiltration rate in zeolite filter bed with different initial infiltration rates that are linked to the size of outlet as per Table 3.2. *(95% confidence intervals are represented as area plots (log plots) and dark lines represent median values)*

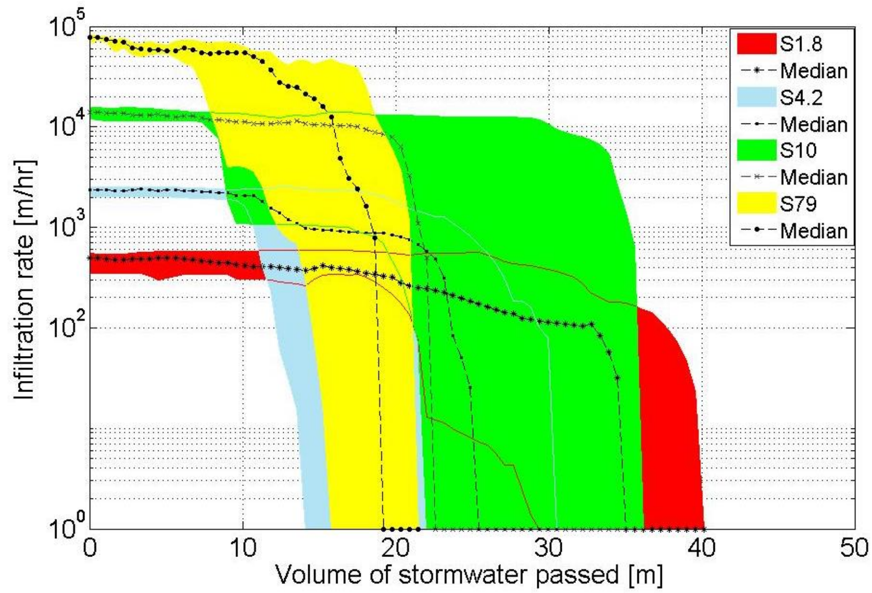

Figure 3.6b: Evolution of infiltration rate in scoria filter bed with different initial infiltration rates that are linked to the size of outlet as per Table 3.2. *(95% confidence intervals are represented as area plots (log plots) and dark lines represent median values)*

It can be concluded that any increase in the flow through rate by provision of wider outlet leads to faster clogging, as these designs clog with smallest amount of stormwater application. This is contrary to what was observed by Changhong (2008) and Mays and Hunt (2010) for fine filter material, wherein it was found that higher infiltration rate reduces clogging of filter bed. The difference may be because clogging in fine filters is mainly located at the surface as a 'clogged thin layer' (e.g. Hatt et al., 2008), while clogging in 2 mm filter media used in this study may be distributed over its depth and consequently can be interstitial in nature. According to McDowell-Boyer et al. (1986) and Li and Davis (2008b), deep clogging occurs if the ratio of media particle size to sediment particle size is greater than 10, which was the case for more than 75% of particles of the incoming sediment in these experiments.

As expected, the treatment efficiency improved consistently as clogging developed and infiltration rate dropped. Treatment efficiency at the start, mid and end of operational life of different outlet sizes of zeolite and scoria is shown in Figure 3.7. For instance, for Z79 the treatment efficiency improved from an initial 57% to 86% as the filter bed became fully clogged. It is logical that the trapped sediment material in filters enhances the removal efficiency of incoming sediment as straining improves because of the reduced pore spaces and reduced water velocity. This therefore increased the residence time of influent in the filter bed. All configurations treated stormwater with almost equal effectiveness once they were clogged, irrespective of any differences in their characteristics. This is because the clogging layer in different designs would be equally effective in removal.

The provision of restriction reduces the flow through rate and enhances treatment performance by increasing the residence time of influent in the filter bed. As shown in Figures 3.7, treatment performances of any filter media (at start, mid and end of operational lives) improve as the restriction increases. For instance, Z79 had lower treatment efficiency during different stages of its operational life as compared to Z4.2 and Z1.8. Similar treatment performance trends were observed for glass beads and riversand filter configurations (as shown in Figure 2 of Appendix II).

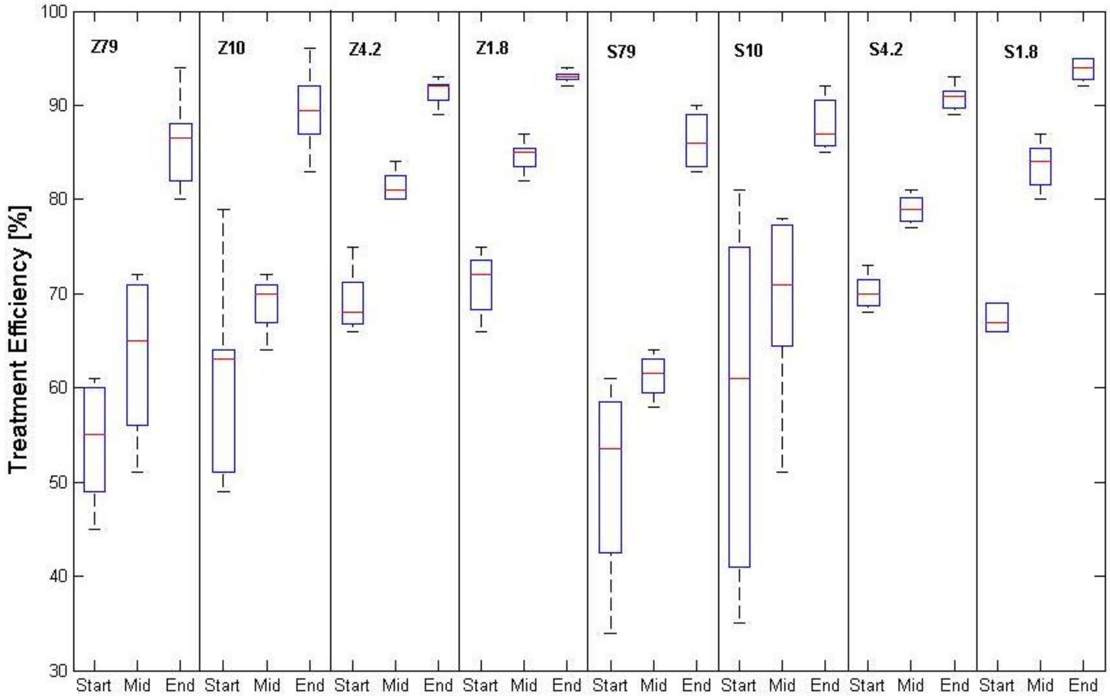

Figure 3.7: Treatment efficiency at the start, mid and end of operational life of the different outlet designs of zeolite and scoria filter media

The observed values for median particle size d_{50} in the outflow at the start, mid and end of the systems were compared to the stormwater inflow, which had d_{50} ranging between 25-55 μm (median value: 35 μm, Figures 3.8a, 3.8b). While zeolite columns produced outflow with relatively stable d_{50} over time (which was half of that in the stormwater inflow), scoria outflow experienced a significant drop in d_{50} over time, but was often similar or greater than that of the stormwater inflow, suggesting that particle disintegration rather than incoming sediment impacted on the PSD of the outflow sediment (see also Figure 3.5a). This also suggests that intrinsic dust in scoria filter bed may not be completely flushed during the initial cleaning phase and this cleaning process progresses during the operational life of the system. Analysis of d_{10} and d_{90} particle size distributions also show similar trends. d_{50} plots for riversand and glass beads are attached as Figures 3a, 3b of Appendix II.

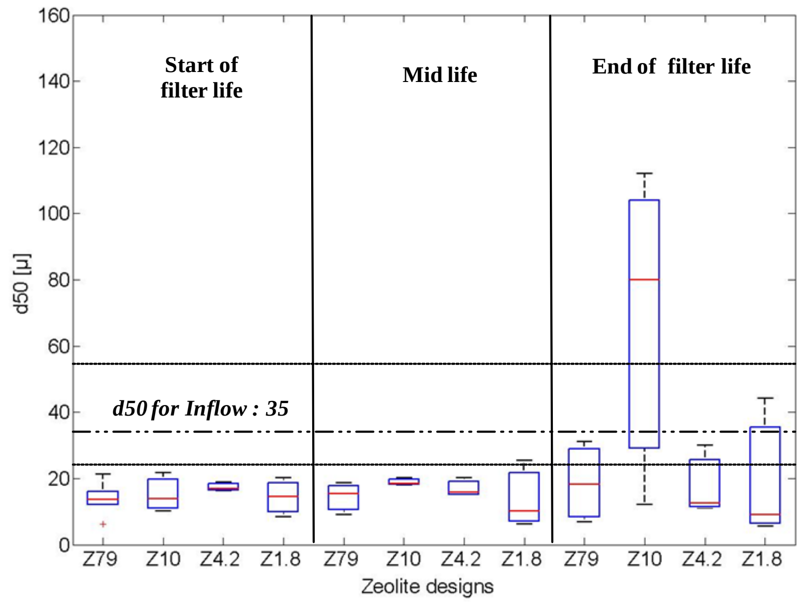

Figure 3.8a: d_{50} particle size distribution in outflow of zeolite during different stages of their operational life as compared to d_{50} in the inflows *(dark dotted lines represent median value of inflow and light shaded dotted lines represent range of observations)*

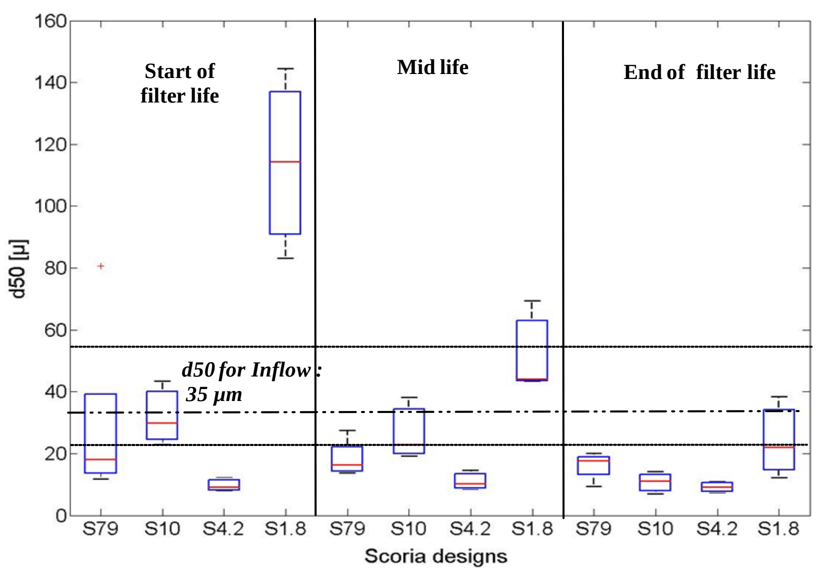

Figure 3.8b: d_{50} particle size distribution in outflow of scoria during different stages of their operational life as compared to d_{50} in the inflows *(dark dotted lines represent median value of inflow and light shaded dotted lines represent range of observations)*

3.3.3 Comparison of performance of different filter configurations

Table 3.3 presents the results of full factorial statistical analysis undertaken to analyse the main effects of filter media and outlet size on selected performance parameters: initial infiltration rate, treated volume over the system life span (i.e. the total normalised volume that causes clogging), and overall treatment performance (i.e. total mass removed as percentage of total mass applied).

Initial infiltration rate (IIR) – The outlet size fully controlled the initial infiltration rate, showing that the infiltration rates of the media were not limiting, relative to the inflow rate. As already discussed, no statistically significant differences were observed in the initial infiltration rates of the four media of a specific outlet size (Table 3.3 and Figures 3.6 a, b). Within the four different outlet restrictions, designs with most restricted outlets (4.2 mm dia outlet and 1.8 mm dia outlet) had comparable IIR (even though $p > 0.05$), which may suggest that these configurations should behave in comparable way.

Table 3.3: Results of full factorial ANOVA tests on impact of media type and outlet size on the performance parameters

Response Variable	Design factor(s)	Significance	Comments
Initial Infiltration rate	Outlet size	~0.00	Significance tests indicate that columns with 4.2mm and 1.8mm outlets had comparable IIR
	Filter material	0.97	IIR is similar for all filter medias of a given outlet size
	Outlet x Filter material	0.02	Significance tests therefore indicate that the outlet size controls IIR variations amongst different designs
Total volume of stormwater treated	Outlet size	<0.01	Post hoc tests indicate that only columns with 79mm and 10mm outlets treated comparable volume of stormwater
	Filter material	0.38	Volume of stormwater treated before clogging is similar for all filter media with same outlet size, except scoria
	Outlet x Filter material	0.04	Significance tests therefore indicate that the variation in outlet size controls the total volume of stormwater treated
Overall treatment efficiency	Outlet size	<0.01	Significance tests indicate that the outlet size strongly controls the treatment performance of the design
	Filter material	0.77	Treatment performance of filter media with same outlet size is similar with riversand performing slightly better than zeolite and scoria
	Outlet x Filter material	0.02	Significance tests therefore indicate that outlet size controls treatment performance

Total volume of stormwater treated over life span – The configurations with smaller outlets were able to treat more stormwater over their life spans compared to systems with larger outlets (Figure 3.9). E.g. configurations with 1.8 mm outlets (lowest IIR) treated 2-3 times more stormwater as compared to the unrestricted columns (with maximum IIR). However, the 79 mm outlet design and 10 mm outlet design had similar clogging performances (Figures 3.9, 3.10) showing that the nature of the impact of outlet restriction (or IIR) is not linear.

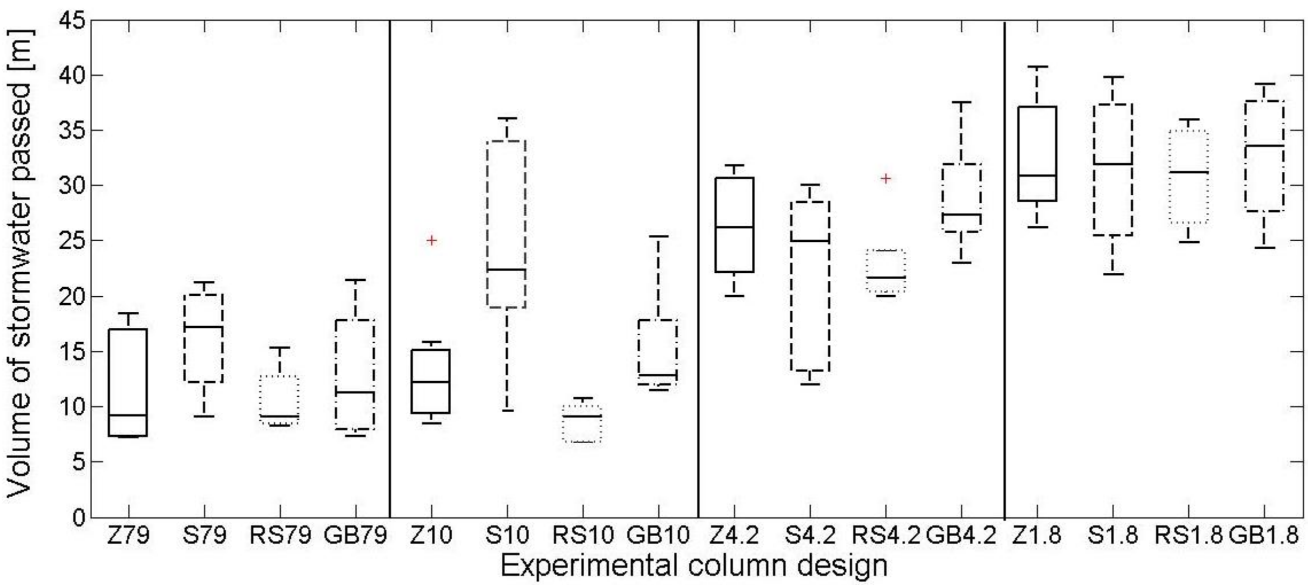

Figure 3.9: Total volume of stormwater treated over system's life span by different filter designs measured before clogging *(clogged state refers to when the measured infiltration rate is about 5% of the IIR)*

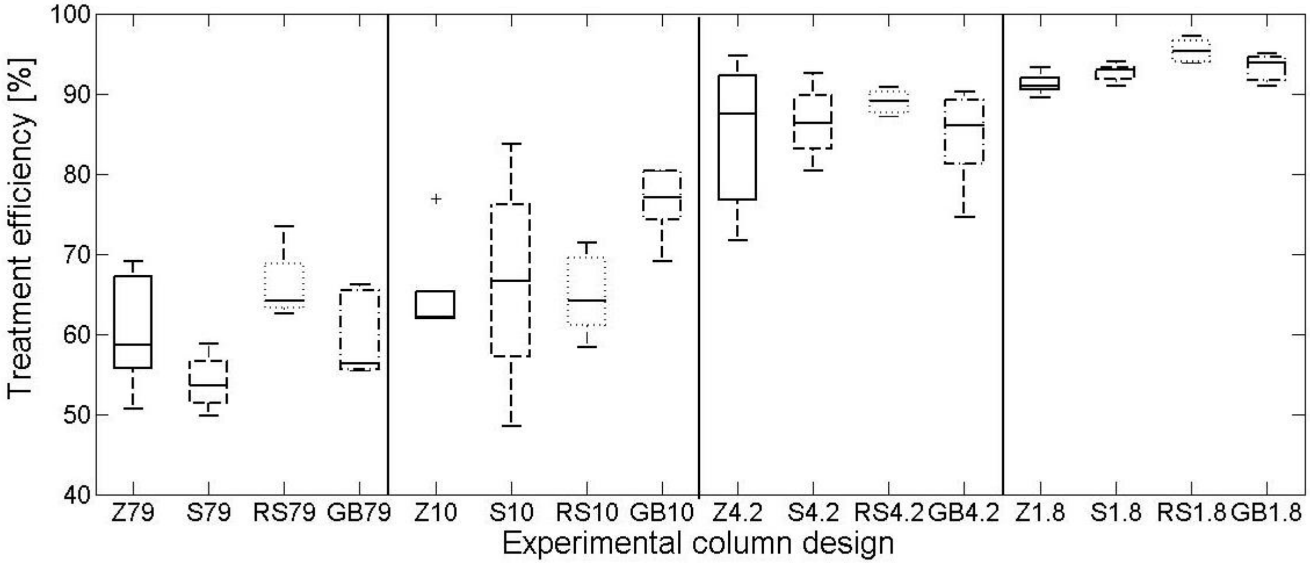

Figure 3.10: Overall treatment performance of different filter designs measured before clogging *(clogged state refers to when the measured infiltration rate is about 5% of the IIR)*

As shown in Figure 3.9, the volume of stormwater treated by all four filter media is comparable, especially for filter bed designs with smaller outlets. It was however observed that scoria treated more stormwater, especially for designs with bigger outlets; e.g. scoria with 79 mm outlet treated 70% more stormwater before clogging as compared to other three media types with the same outlet size.

This difference in scoria filter beds may be explained by the disintegration of its particles as water passes through the filter media (as discussed earlier, Figures 3.5a, b). This may eventually result in increased void spaces in the filter bed and/or regular re-arrangement of filter media grains within the filter bed that could lead to more porous systems. Further, since scoria had a high sediment load in the first flush outlet events due to its fragile nature, the actual treatment efficiency of scoria beds may be less than as shown in Figure 3.10. This implies that total sediment trapped by scoria filter beds may actually be less than other media types, despite its advantage in terms of the amount of water it passed before clogging.

Amongst replicates, it was observed that the coefficient of variation for total volume of stormwater passed before clogging was greatest for scoria columns. This may again be attributed to the fragile nature of scoria particles, which leads to variations in void spaces of each replicate and hence varied performance. A high coefficient of variation within replicates indicates that it may be difficult to predict the performance of such a material accurately and poses a challenge for designers. Higher coefficient of variation was observed in the performance of columns (total volume of stormwater passed and overall treatment performance) with bigger outlet sizes as compared to smaller outlet sizes of 4.2 mm and 1.8 mm. This suggests that with the decrease in outlet size, the residence time of stormwater in the filter increases and eventually any performance variations amongst the replicates reduces.

Overall treatment efficiency – Not surprisingly, as shown in Figure 3.10, filter designs with smaller outlets and therefore lesser filtration rates, had higher initial and overall treatment efficiency for all tested configurations. Since filter designs with smaller outlets passed a much larger volume of stormwater before clogging with greater treatment efficiency, they also removed a greater quantity of sediment over their lifespan. All materials had similar treatment efficiencies for a given outlet size. Riversand and glass beads however showed slightly better treatment efficiency for all flow rates.

3.4 Conclusions

This study of the impacts of both flow rate and media characteristics (e.g. angularity and smoothness) on stormwater filter media pollutant removal and clogging performance suggests that flow rate plays a dominant role. Although all filter media of a particular outlet flow rate were capable of treating comparable volumes of stormwater before becoming fully clogged, it appears that scoria may be able to treat a greater volume of stormwater (especially for designs with high infiltration rates). However, scoria-based filters were also found to be highly variable in performance, most likely due to breakdown of the particles.

There was strong evidence that low flow-through rates (due to restricted outlets) improves the overall performance of the filter system (and diminish the relative importance of the media characteristics), as the total volume of stormwater treated during the filter life increases. The treatment efficiency of filters with restricted outflow was also found to be greater than for filters with unrestricted flow rates, thereby leading to a greater removal of sediment over their lifespan.

Therefore, while angularity and smoothness may not be important for design, the flow rate through the stormwater treatment system is a key design aspect that needs to be considered as it controls the residence time of influent in the system and also guides pollutant removal. Further, while the choice of filter media may be guided by local availability, it is necessary to investigate the structural stability of filter media such as its breakage over time and its effect on the stability of filter bed. The infiltration rate of a system to be designed will be guided by the objectives of treatment - whether to treat more volume of stormwater or to achieve better treatment performance, longevity and reduced maintenance.

Whilst the effect of outlet restriction (hence flow through rate) and media characteristics on clogging and treatment performance have been demonstrated, further work is needed to understand the clogging phenomenon in granular filters. Further experiments need to be conducted to analyse the influence of filter bed design (such as filter media particle size in the filter bed; depth of filter; layered filter beds with particles of different sizes, compaction of the media during construction); stormwater inflow characteristics (such as its concentration, composition, particle size distribution of the sediment and rate of stormwater application) and drying and wetting regimes. An understanding of these factors and location of clogged material in filter beds are likely to provide useful insight into the way in which flow rates can be configured to extend filter lifespan. Ultimately, these insights could be used in the development of a model which predicts the hydraulic and treatment performance of filters over their lifespan. One of the main applications of such a tool would be in improved design of water treatment systems based on such granular filters, particularly for stormwater filtration for ecosystem protection or supply of filtered stormwater for harvesting purposes.

4 Impact of filter design variables on clogging in stormwater filters

4.1 Introduction

This chapter describes the laboratory experiments carried out with the aim to gain an understanding of the effect of filter bed's design on clogging processes in non-vegetated filter media with high infiltration rates.

As concluded from the literature review in Chapter-2, most studies on clogging suggest that hydraulic performance of filter media is specific to a number of filter bed design factors. Previous clogging studies in context of stormwater treatment have however focussed mainly on vegetated filters (Le Coustumer et al., 2009; Le Coustumer et al., 2012) and fine filter media (with low infiltration rates) (Hatt et al., 2008) or very coarse gravels (Siriwardene et al., 2007). Therefore, there is a limited understanding of the effect of filter bed design (such as filter bed's composition and construction) on its clogging and treatment performance; this is in particularly the case for stormwater filters with high filtration rates.

Furthermore, based on existing studies, it is not possible to ascertain the nature of clogging i.e. the location of clogged material within the filter bed of such filters with high infiltration rates. Conflicting information is available on the extent of clogging within the filter bed of stormwater treatment systems, e.g.- Siriwardene et al. (2007); Hatt et al. (2008); Li and Davis (2008); and even in case of wastewater systems. An understanding of pollutant migration and location of clogged material could have important connotations for the design, operation and especially maintenance of filtration-based systems.

The following hypotheses have therefore been proposed to understand the effect of filter bed design on clogging processes in context of high flow rate stormwater treatment using non-vegetated filters:

1. Size of filter media particles in filter bed affects sediment retention within the media and therefore directly impacts on clogging.
2. Depth of filter bed affects the sediment trapping performance of system and therefore clogging.
3. The way 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.

In order to investigate the hypotheses listed above, we studied the differences between the selected filter designs that do not include impact of drying/wetting regime or biological clogging, but only typical stormwater applications during wet weather periods.

The main results of these experiments have been published in *Water Resources Management* and a copy is attached as Appendix I-2 (Kandra et al., 2014b). The research findings were also presented in the 7th International Conference on Water Sensitive Urban Design, 21st – 23rd February 2012, Melbourne.

4.2 Methods

4.2.1 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 (as also concluded in Chapter 3 and Kandra et al, 2010). 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 Pengb, 2010) and its frequent use in stormwater filters (e.g. Clark and Pitt, 1999; Bratieres et al., 2012).

100 mm diameter[2] experimental columns were constructed (Figure 4.1). Zeolite was placed between a 50 mm layer of coarse gravel at the top (to protect the filter from the 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).

Figure 4.1: Design of experimental columns

[2]Columns used in the previous chapter had a diameter of 150 mm. However, smaller sized columns were used in experiments discussed henceforth because of logistical reasons involving sieving of 2-2.36 mm sized particles, larger stormwater needs and time constraints. Both sized columns were simultaneously compared for their performance prior to this change and were found to have similar performance as shown in Table 1 of Appendix III.

Filter media particle sizes, depth of filter bed and packing arrangement of filtration media were varied as shown in Table 4.1. 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 was avoided. Moreover this is 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 a full factorial experimental design.

4.2.2 Experimental procedures

The experiments were undertaken in two steps:

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

__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.

Table 4.1: Details of different experiments and experimental column designs (nomenclature mentioned in bold in brackets)

Tested effects	**Details of filter bed and nomenclature**
Base case	Zeolite, 2 mm sized particles, Single layer, 300 mm deep filter bed **(Base case)**
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)**

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 1000 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 practised in earlier clogging studies (e.g. Siriwardene et al., 2007 and; Bratieres et al., 2012). Particle size distribution of semi-natural stormwater used here (d50= 401 μm and d90= 448 μm) was in the range of stormwater composition (e.g. Lloyd et al., 1998). Concentration of sediment in the semi-natural stormwater was targeted at 150 mg/L, which is in the range of stormwater composition (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; Bratieres et al., 2012), 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 in between each event. 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/yr, 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., 2012). Therefore the average storm event should be mimicked by applying 15 litres (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 because we wanted to measure infiltration rate two times during the dosing event as due to logistic reasons we were not able to take more measurements.

During each dosing event, composite water samples were taken from the inflow and the columns' outlets; the entire outflow was collected in a 25 litre 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.

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 the clogged filters, a detachable column that opened longitudinally was constructed (Figure 4.2 (left)). The clogged column was inverted and the contents transferred into this detachable column. This transfer was undertaken carefully, so that 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 (Figure 4.2 (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 grams were removed, one of which was then oven dried to estimate moisture content and another used to measure sediment trapped in the respective layer.

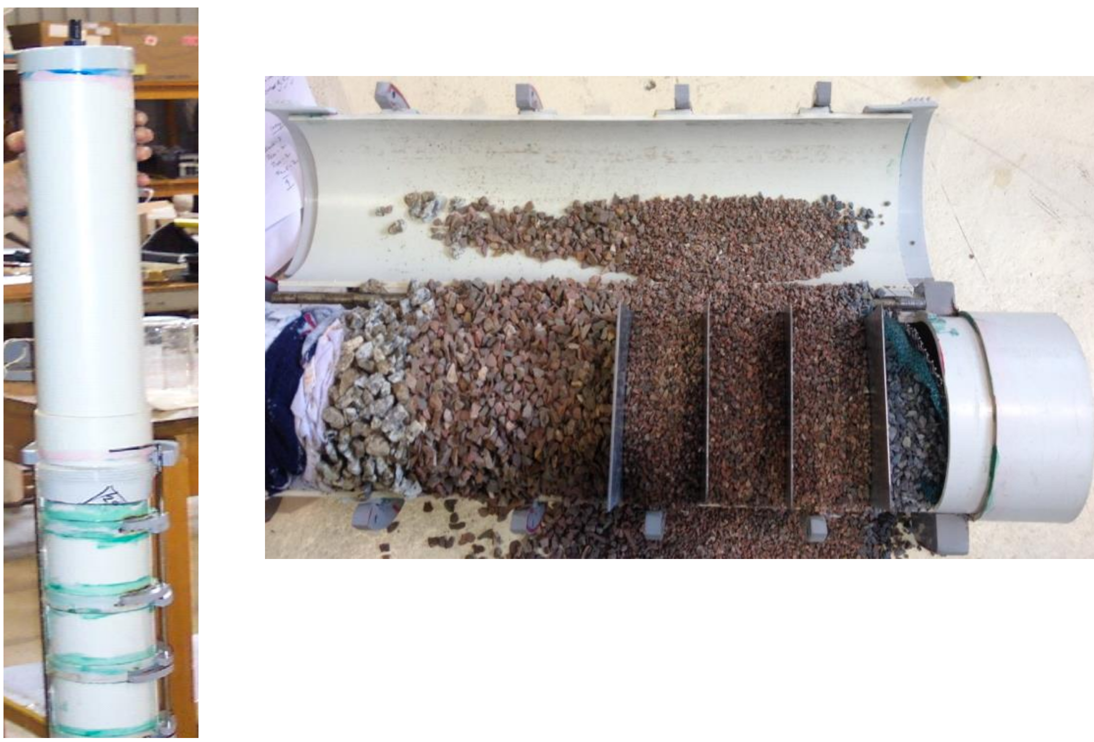

Figure 4.2: Method used to separate layers within a clogged column while it was still in vertical position (left), and the opened column separated into different layers (right)

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 seconds. 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 800-1000 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.

4.2.3 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 meters 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)
- Overall sediment removal efficiency of the media over its life span, defined as the ratio between the total mass of TSS removed and the 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.

4.3 Results and Discussion

4.3.1 Effect of filter media particle size

The initial infiltration rates of the three systems were different (Figure 4.3), 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 (Figure 4.3) because of the cumulative retention of particles in the filter media, causing the pore spaces to reduce, which also meant the sediment removal performances were enhanced (as shown earlier in Figure 3.7). 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, Figure 4.4, 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 was 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 very high flow through rate led to re-suspension of particles responsible for clogging.

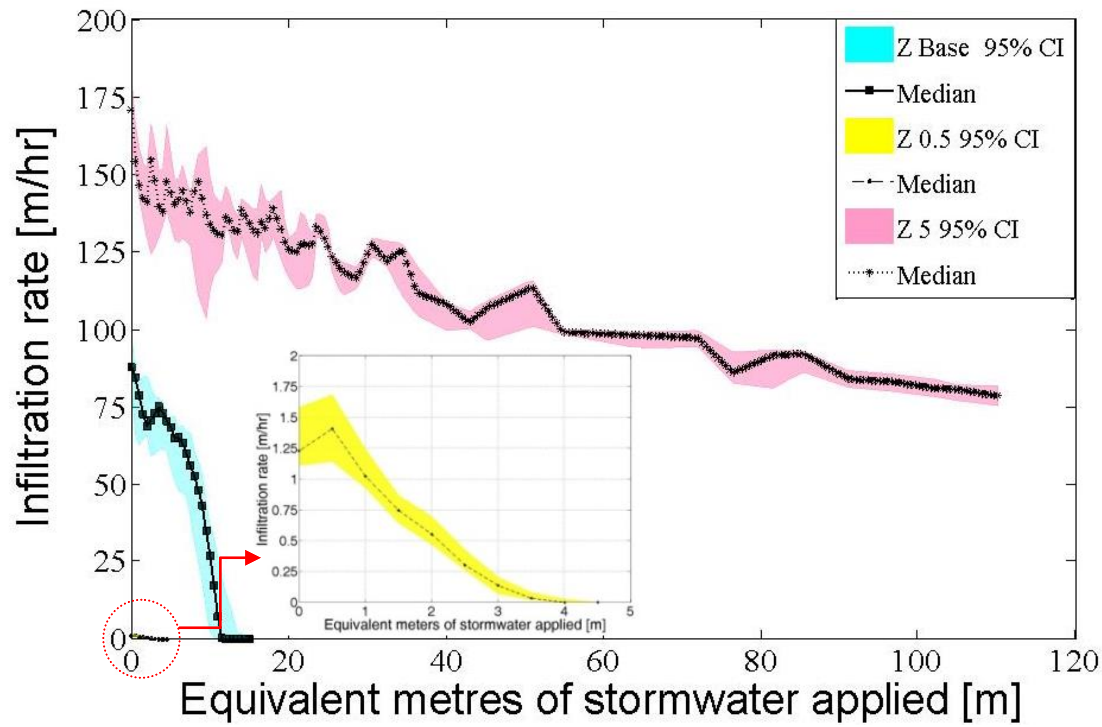

Figure 4.3: Evolution of hydraulic performance in the three configurations with different particle sizes over their lifespan *(lines represent median values and shaded areas represent 95%* confidence *intervals for the five replicates of this design)*

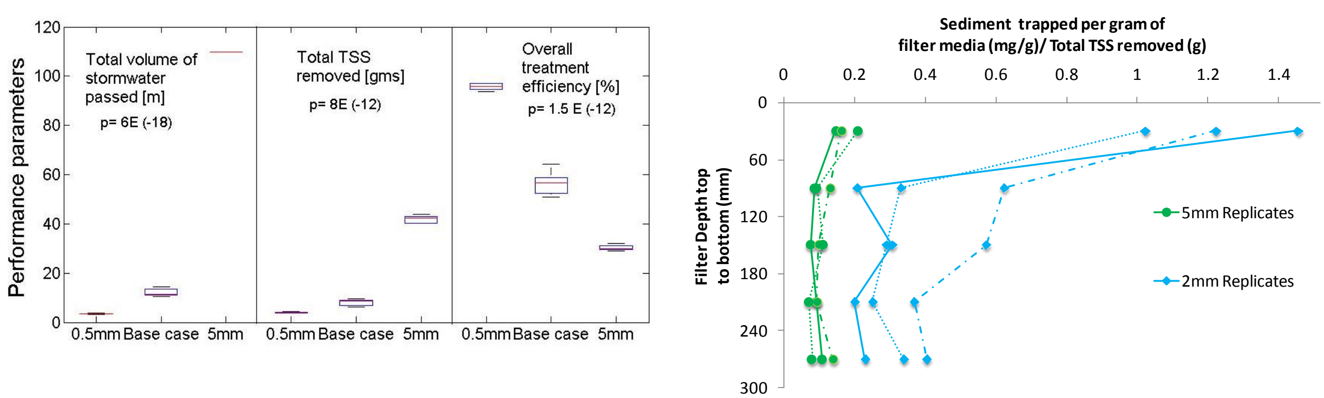

Figure 4.4: Box plots comparing performance of filter beds made with different particle sizes (left); Distribution of sediment within different depths/layers of filter bed with 2 mm and 5 mm sized particles (right). *(Note: Top-most layer of the 300 mm deep filter bed is represented as 0-60 mm section and bottom most layer as 240-300 mm section of the filter bed)*

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 11 μm upon clogging. These results align with the above discussion; indeed, as the systems clog, their pore 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 (refer Figure 1, Appendix III).

Profiling of the clogged columns suggests that most of the sediment removal occurs within the top-most layer (Figure 4.4, 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 (2008a). 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 system's objective, whether focussed towards flow control or treatment.

4.3.2 Effect of filter bed depth

Similar performance trends were observed for all three designs, as described above, infiltration rates decreased with time (Figure 4.5, left), while sediment removal efficiencies increased. Overall sediment removal performance increased with filter depth- 42% for 100 mm depths; 57% for 300 mm and; 62% for 500 mm (Figure 4.5, right). Particle size analysis of the outflows also suggests that the deepest filter bed was able to remove finer sediment as compared with the other configurations (refer Figure 2, Appendix III).

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

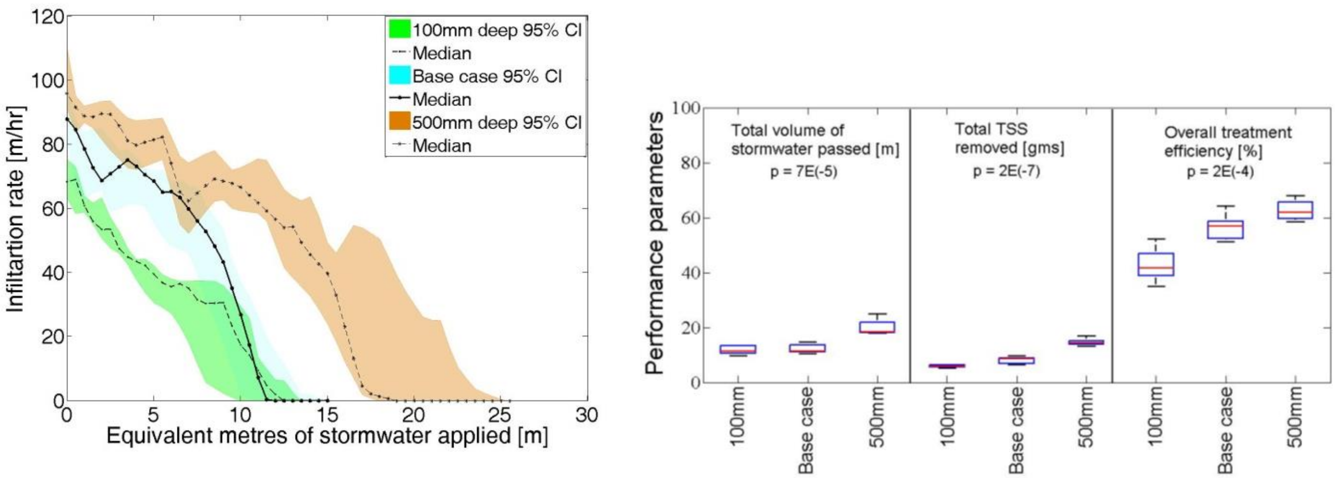

Figure 4.5: Performance of 100 mm, 300 mm (Base case) and 500 mm deep filters made from 2 mm Zeolite particles- Infiltration performance over filter lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right*) (lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this design)*

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 (Figure 4.5, right). The hypothesis is that the shallow systems fail *mainly* due to surface clogging. The deeper columns have the largest ponding depth (Table 4.1), 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 Figure 4.6, 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 configurations, respectively). Deeper systems should therefore be preferred in practice, especially if large hydraulic gradients (similar to those used here) are possible.

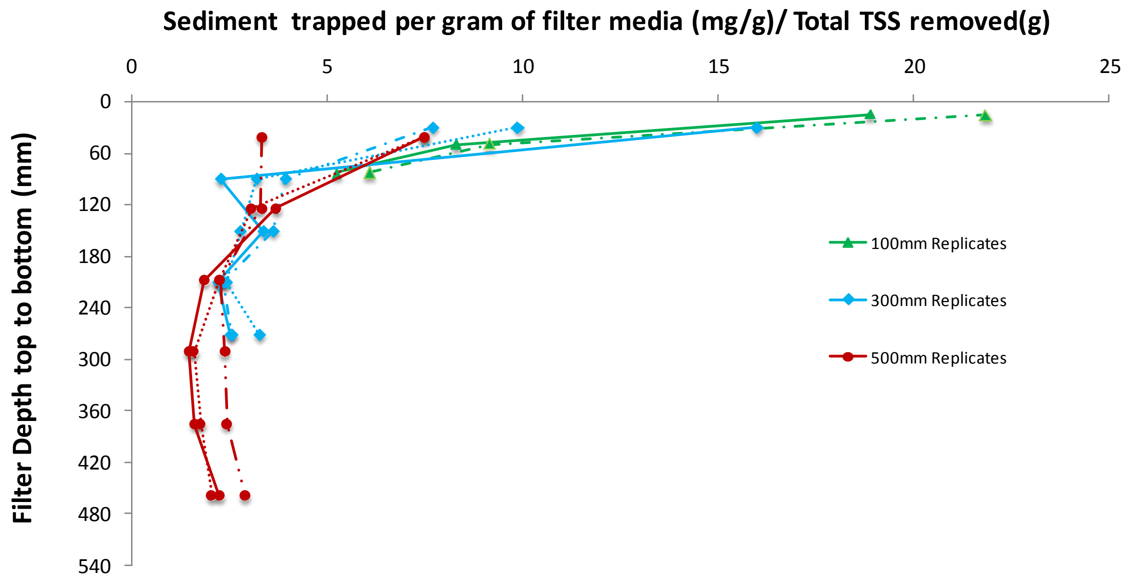

Figure 4.6: Distribution of sediment within different depths/layers of filter bed for 100 mm, 300 mm and 500 mm deep filters

4.3.3 Effect of packing arrangement

<u>Layering arrangement</u>

The initial infiltration performance 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 (Figure 4.7). For instance, Z 0.5,2 had similar initial hydraulic 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 (Figure 4.7), resulting in different lifespans of the multiple layered systems compared with single-layered systems (Figure 4.8). It is hypothesised that the enhanced performance of layered systems is due to sediment removal processes occurring mostly in the upper layer, which protects the bottom layer from clogging, as also found in patented air and gas filters (such as Carey Jr., 1977 and Osendorf, 1995). However, the two-layered system (Z 0.5,2) performed similarly to the three-layered system (Z 0.5,2,5) (Figures 4.7, 4.8). 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.

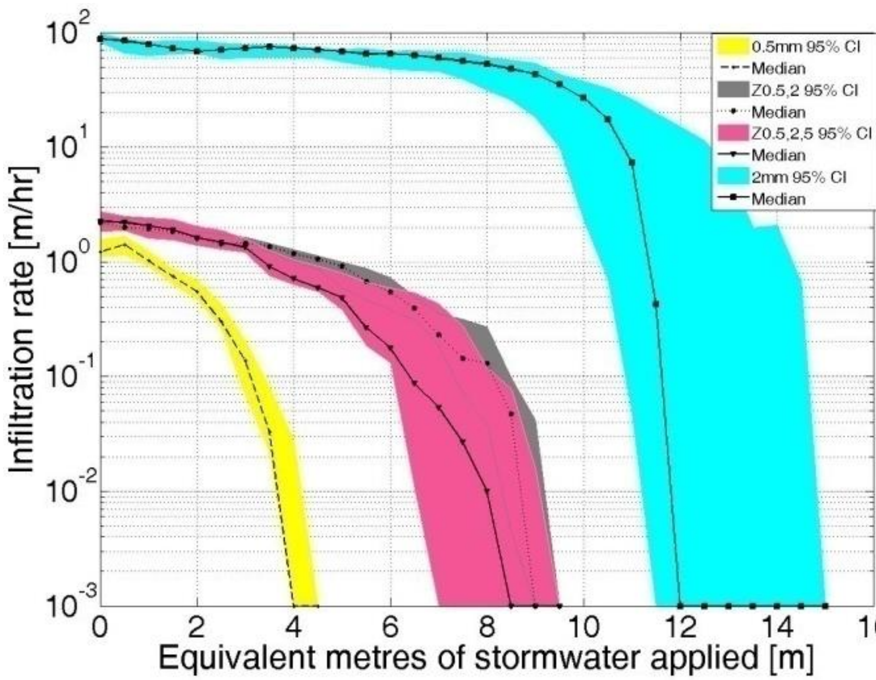

Figure 4.7: Comparison of hydraulic performance of filter bed with 1, 2 and 3 layers of filter media (log plots) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this design)*

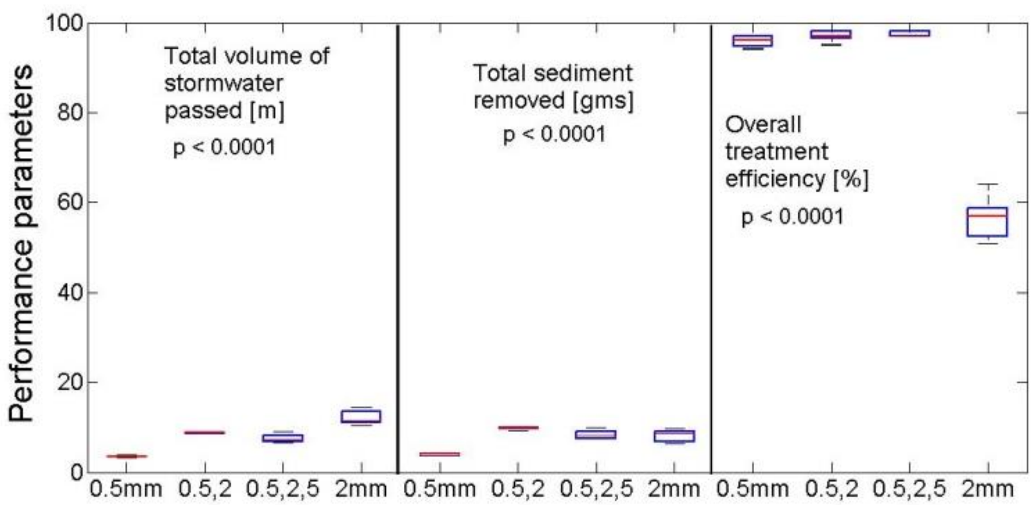

Figure 4.8: Box plots of the total stormwater volume passed, total sediment retained and overall sediment removal efficiency of the filter beds with 1, 2 and 3 layers of filter media

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 (Figure 4.9 and p-values in Figure 4.10). 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.

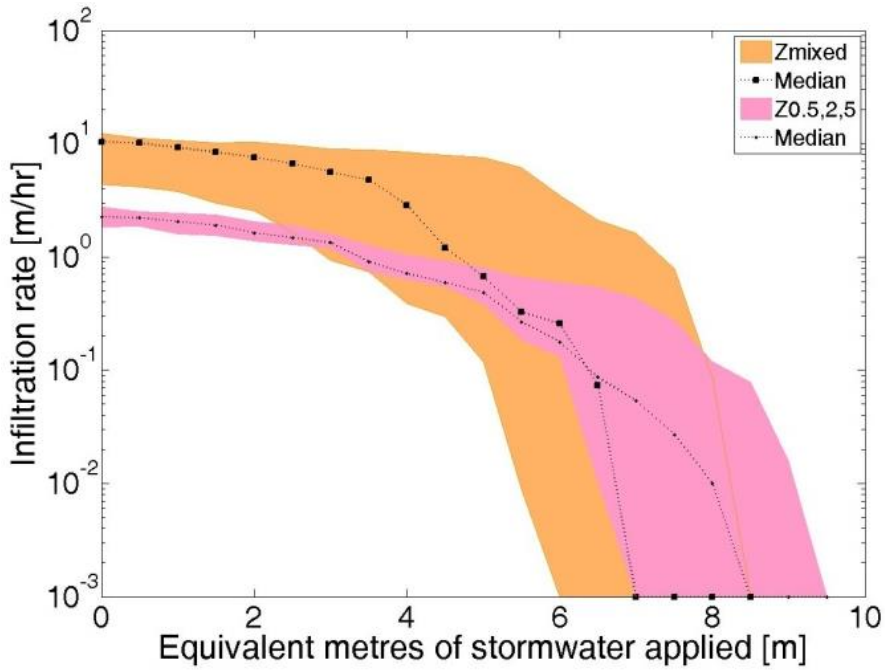

Figure 4.9: Comparison of hydraulic performance of filters with three layers and mixed filter bed over their lifespan (log plots)

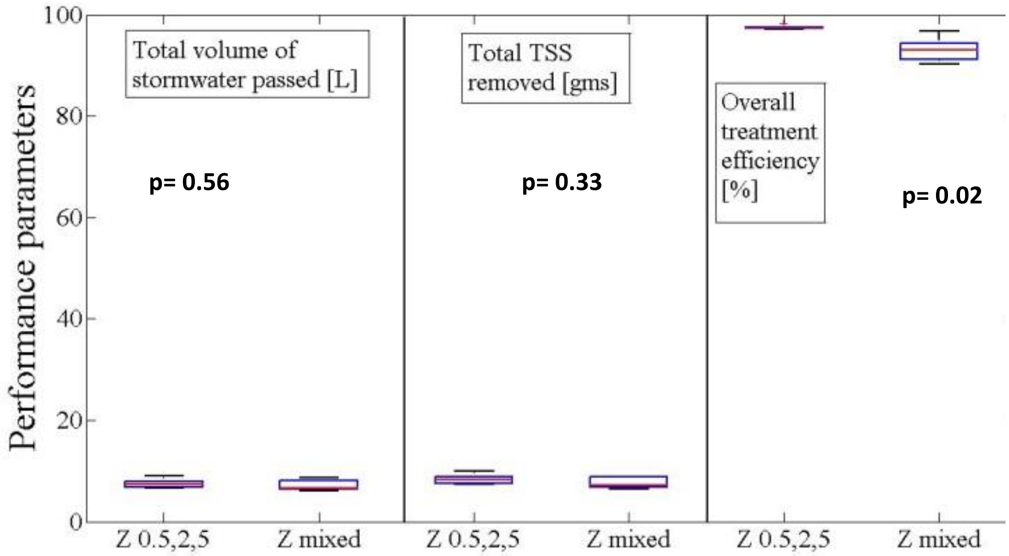

Figure 4.10: Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency performance of filters with three layers and mixed filter bed over their lifespan

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 (refer Figure 3, Appendix III).

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 seldom 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.

4.4 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 one-third 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 towards 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 5 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.

5 Assessment of the impact of stormwater characteristics on clogging in stormwater filters

5.1 Introduction

Literature on impact of operational conditions on clogging suggests that the hydraulic performance of filtration systems is impacted by a number of factors, such as influent and nature/dynamics of stormwater application, as discussed in Section 2.6. Operational conditions, such as the quality of stormwater inflows, their volumes and antecedent dry weather conditions, can vary significantly between stormwater events and catchments resulting from: differences in rainfall intensity and frequency, differences in catchment imperviousness and land use, duration of dry periods, etc. (e.g. Goonetillekea et al., 2005). These can eventually have an effect on the infiltration and treatment processes.

However most studies undertaken to assess the impact of operational conditions have been undertaken for either fine media filters (i.e. systems with low infiltration rates such as fine sand filters) or coarse gravel media (used in infiltration systems), and very rarely for stormwater applications (the majority of work is still focused on wastewater systems, e.g.- Reddi et al., 2000 and Ruppe, 2005). There is therefore a considerable lack of studies done on high infiltration rate granular media (of particles between 1-5 mm in diameter), that are becoming popular in stormwater treatment practice (e.g. Clark and Pitt, 1999; and Bratieres et al., 2012).

This chapter presents findings from a study, which was set up to investigate how operational conditions influence both the rate and the nature (deep versus surface) of clogging in zeolite-based stormwater filters. The following hypotheses were tested:

- The composition of stormwater, such as the concentrations of sediment, nutrients and heavy metals, as well as the size of sediment particles, all affect sediment retention processes and therefore the nature of clogging and lifespan of filters.
- Stormwater application patterns, such as the frequency and rate of application of stormwater, as well as duration of dry periods (in between two dosing) affect sediment trapping and hence filter longevity and nature of clogging.

The main results of these experiments are presented in a paper submitted to the *Water Resources Management* and a copy is attached as Appendix I-3. The research findings were also presented in the 8th International Conference on Water Sensitive Urban Design, 25th-29th November 2013, Gold Coast.

5.2 Methods[3]

5.2.1 Experimental setup

Zeolite is used as a representative media since it is commonly used in practice (e.g. Bratieres et al., 2012), due to its good treatment performance, low costs, and local availability (Booker et al., 1996; Wanga and Peng, 2010). Since shape and smoothness of filter media grains have been found to have a limited effect on the performance of stormwater filters (as found in Chapter 3 and Kandra et al., 2010), it is very likely that the findings from this study will be transferable to other media that have similar particle size and infiltration rates.

2 mm sized zeolite media (passing 2.36 mm sieve and retained on 2 mm sieve) was placed in 300 mm deep single layer and covered by porous/permeable pavement (coarse gravels) in a 100 mm diameter

[3] It is acknowledged that there is some repetition between Methods in this chapter and the previous chapters

testing column (as shown in Figure 4.1). The ratio of experimental column diameter to filter particle diameter was around 50 as recommended for similar laboratory studies (Lang et al., 1993). The 50 mm layer of coarse gravel at top protected the filter from the energy of water applied to the column and the 50 mm gravel layer at the bottom acted as a drainage layer and prevented migration of the media out of the filter. The columns have an outlet size of 73 mm which corresponded to a zero head loss at the outlet representing free flow conditions. During the construction of these columns, the layers were not compacted, to avoid damaging the media and to replicate natural (un-engineered packing) conditions.

Table 5.1 outlines five different operational regime effects that were tested. They ranged from how clogging is affected by:

- water quality characteristics i.e. sediment concentration, other pollutant concentrations; and stormwater sediment size to
- hydraulic/hydrology characteristics loading rate; and stormwater loading/dosing regime

They were all compared to the Base case, as explained in Table 5.1. For each operational condition, five column replicates were tested. The experiments have been to some extent 'compressed in time', where months of operational life of the systems were compressed to several weeks due to time constraints, as has been done in previous clogging studies (Hatt et al., 2007; Siriwardene et al., 2007; Bratieres et al., 2008; and Bratieres et al., 2012). Nevertheless impact of drying has been studied on this compressed time scale (Effect of dosing regime, Table 5.1). Cost and space constraints did not permit a full factorial experimental design.

Table 5.1: Details of different experiments with variations in the stormwater dosed (nomenclature shown in italics and brackets)

Tested effects	Operational conditions ***(text in bold italics shows differences in respective configuration as compared to the Base Case)***
Base case	*Inflow TSS of about 150 mg/L;* *Stormwater made of sediments only;* *Sediment particle size in stormwater < 1000 µm;* *Stormwater hydraulic loading of 15 L/day (1.91 m/d);* *Daily dosing*
1. **Effect of inflow sediment concentration** *(Low TSS and High TSS)*	***Inflow TSS: Low (about 25 mg/L) and; High (about 400 mg/L);*** Stormwater made of sediments only; Sediment particle size in stormwater < 1000 µm; Stormwater hydraulic loading of 15 L/day (1.91 m/d); Daily dosing
2. **Effect of other (than TSS) pollutant concentrations** *(Complete SW)*	Inflow TSS of about 150 mg/L; ***Complete (or Natural) stormwater made up of sediments, nutrients and heavy metals (using range ofstormwater composition)*** Sediment particle size in stormwater < 1000 µm; Stormwater hydraulic loading of 15 L/day (1.91 m/d); Daily dosing
3. **Effect of stormwater sediment particle size** *(Fine sediment)*	Inflow TSS of about 150 mg/L; Stormwater made of sediments only; ***Sediment particle size in stormwater < 75 µm*** Stormwater hydraulic loading of 15 L/day (1.91 m/d); Daily dosing
4. **Effect of loading rate** *(5 L/day and 45 L/day)*	Inflow TSS of about 150 mg/L; Stormwater made of sediments only; Sediment particle size in stormwater < 1000 µm; ***Low loading rate of 5 litres/day*** (0.6 m/d) ***and High loading rate of 45 litres/day*** (5.7 m/d) Daily dosing
5. **Effect of loading/dosing regime** *(Alternate day and Weekly)*	Inflow TSS of about 150 mg/L; Stormwater made of sediments only; Sediment particle size in stormwater < 1000 µm; Stormwater hydraulic loading of 15 L/day(1.91 m/d); ***Alternate day dosing and Once a week dosing with 15 L/day***

The columns exposed to the Base case operational regime were dosed with 15 litres (L) of stormwater on a daily basis. Using Melbourne's historical rainfall data (1999-2009, Bureau of Meteorology (BoM)), 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/yr, spread over 72 events). It was assumed that the system represents 0.3% of its catchment's impervious area, typical of stormwater filters (as used in Bratieres et al., 2012), and therefore the average storm event should be mimicked by applying 15 L (1.91 m) of stormwater daily (for most of the configurations).

For the Base case, the stormwater contained total suspended solid (TSS) concentrations of 150 mg/L, made up of particles which were less than 1000 μm in size; this is in line with characteristics of TSS, as found in a worldwide study done by Duncan (1999). The sediment was sourced from a nearby stormwater pond in Huntingdale (Melbourne, Australia). No additional pollutants were added to the stormwater.

TSS concentration in the inflows was varied between low TSS of 25 mg/L and high TSS of 400 mg/L (as against the Base case with a TSS of 150 mg/L). This selection of TSS ranges is based on a review of TSS stormwater quality data undertaken by Duncan (1999) and Francey et al. (2010).

The effect of pollutants other than sediments have also been tested because it is normally hypothesised that physical clogging is most pertinent in stormwater systems as stormwater has low organic content as compared to wastewater (Mitchell et al., 2002). To test this effect, filter columns were dosed with semi-synthetic stormwater which had target pollutant concentrations in the range of stormwater composition of a dense urban catchment- total nitrogen (TN)- 2.1 mg/L; total phosphorus (TP)- 0.35 mg/L; copper (Cu)- 0.05 mg/L; lead (Pb)- 0.14 mg/L and; zinc (Zn)- 0.25 mg/L (based on a review of stormwater quality data undertaken by Duncan, 1999).

Effect of stormwater sediment particle size was studied by using very fine sediment (maximum size < 75 µm; d_{50}= 31 µm) and coarser sediment (maximum size < 1000 µm; d_{50}= 391 µm). This variation was based on review of limited international literature available on particle size distribution (PSD) of suspended solids in stormwater. Diverse results have been reported for urban runoff. Roberts et al. (1998) suggest that most of particle sizes are less than 50 µm; Deletic and Orr (2005) reported median diameter of stormwater particles to be 23 µm and; Lloyd et al. (1998) found that 65% of the suspended solids collected in Australian sites were less than 100 µm.

The effect of loading rate on clogging has been investigated by varying daily dosing rates between a low loading rate of 5 litres/day (0.6 m/d) to a high loading rate of 45 litres/day (5.7 m/d). The low loading rate corresponds to the hydraulic conductivity recommended/observed for bio-filters; for example, guidelines for bio-filter design in Australia recommend hydraulic conductivity of 0.002-0.008 m/day (Melbourne Water, 2005) and those observed in lab/field studies suggest 0.013- 0.028 m/day (Le Coustumer et al., 2009; Hatt et al., 2009). The high loading rate corresponds closely to loading rates observed for coarse filters with a hydraulic conductivity of 10-1000 m/day.

The effect of loading regime has been investigated by varying the number of dry days in between dosing events, derived on the basis of the analysis of Melbourne's rainfall pattern over a 10 year period. The columns that were dosed daily and every alternate day represent frequency of rainfall in Melbourne during winters and the 'once a week' dosing regime represents dryer conditions. This sampling regime therefore abides by the logistical constraints of time and resources and also allows us to determine whether any climatic factors influence the performance of the filter.

5.2.2 Experimental procedures

Two sets of experiments were conducted:

1. filtration tests, that investigated the impact of inflow stormwater characteristics on infiltration rates and treatment performances; and
2. sediment profiling of the columns to identify the location of the clogged material and therefore to understand the nature/extent of clogging of the filter bed.

<u>Filtration experiments</u>

Column cleaning: 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. The media were not pre-washed as it is expected that most of the intrinsic dust within the filter media is removed during the sieving process when the filter grains are passed through the sieves. Initial infiltration rates (that represent the initial hydraulic performance of system) were determined during this washing phase by measuring flow rates after every 1.5 m of water application. The depth of filter bed depth was measured at the start and end of the experiment to ascertain any compaction of the filter bed.

Semi-natural stormwater: For dosing of Base case configurations, semi-natural stormwater was prepared using tap water and sediment harvested from a stormwater pond in Huntingdale (Melbourne, Australia). Although natural stormwater would have been preferred, this was not possible for logistical reasons – the high volume required for the tests and the timing of rainfall meant that using actual stormwater was not possible. The use of artificial stormwater also ensured a fairly consistent composition of inflow for the experiments. This approach has been used in earlier studies of clogging (e.g. Siriwardene et al., 2007; and Bratieres et al., 2012).

Sediment harvested from a stormwater pond was passed through 1000 μm and 75 μm sieves to test the effect of stormwater sediment particle size. Particle size distribution of semi-natural stormwater was in the range of stormwater composition. The diameters of sediment particles in stormwater (used for the Base case as in Table 5.1) was on average d_{50}= 391 μm, d_{75}= 428 μm and d_{90}= 451 μm, 50^{th}, 75^{th} and 90^{th} percentile, respectively. Average d_{50} particle size for stormwater with finer sediment (< 75μm) was 31 μm. This sediment size is within the range found in practice (e.g. Lloyd et al., 1998).

Monitoring hydraulic performance and water quality :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 because we wanted to measure infiltration rate two times during the dosing event as due to logistic reasons we were not able to take more measurements.

During each dosing event, composite water quality samples were taken from the inflow and the columns' outlets. The entire outflow from each column was collected in bucket measuring 25 litres and then a composite sample was withdrawn. This ensured that first flush events were also covered and gave a better estimate of treatment efficiency. All water samples were then analysed for suspended sediment concentrations using Standard Test Method for Filterable and Non-filterable Matter in Water (ASTM D5907-09). These results were then used to determine the total mass of sediment applied to and retained by each column. Nutrients and heavy metals were also analysed in those samples collected from the columns which were used to test the effect of other pollutant concentrations (group 2 in Table 5.1). Particle size distribution (PSD) was undertaken using AccuSizer V Autodiluter Particle Sizing Systems to assess the range of particle sizes in the inflow and outflow from the columns.

Profiling of sediment in clogged columns

These experiments were designed to study the location of the clogged material within the filter bed. Three replicates of each configuration listed in Table 5.1 were opened. To examine the contents of the clogged filters, a detachable column that opened longitudinally was constructed (as shown in Figure 4.2 left)). The clogged column was inverted and the contents transferred into this detachable column. This transfer process was undertaken carefully, so that the layers within the filter media were not disturbed significantly. The filter bed was then separated into five layers of equal depths (each with a depth of 60 mm) by carefully inserting metal sheets into the filter bed (Figure 4.2 right). A representative sample (1/6th of the entire volume) was removed from each sliced layer carefully using scoops. Two samples (each weighing about 80-100 grams) were removed, one of which was oven dried to estimate moisture content and other analysed to measure sediment trapped in the respective layer.

In order to measure the accumulated sediment in the sample drawn from each layer, thorough washing of the sampled media was undertaken. About 400-500 mL of de-ionised (DI) water was first added to the collected filter media and the solution was mixed thoroughly, both manually as well as using a Vortex for 30 seconds. This helped to separate the sediment from the filter media; the water (with sediment) was decanted and kept. 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, between 800-1000 mL of deionised water was used in the washing process (the exact volume was recorded). The water containing the sediment trapped in the samples of respective layer was then analysed for Total Suspended Solids (ASTM D5907-09). The total sediment load in the filter media sample was calculated based on the TSS observed in the sediment solution and the volume of DI water used for cleaning. This eventually helped in assessing mass of sediment load per mass of filter media (dried weight). This was repeated for all layers of each filter bed that were studied and then comparisons drawn.

5.2.3 Data analysis

The evolution of clogging was studied as stormwater was applied to these filter columns. Median values and 95% confidence intervals have been reported for the following variables for all tested effects:

- Hydraulic performance at the beginning of filter life has been measured using potable water and reported as Initial infiltration rate (IIR in m/hr)
- The normalised volume of stormwater (in meters/litres) that causes total clogging of the system, defined as the point when the infiltration rate dropped to 5% of the IIR. The normalisation is 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/litres of treated water* for same inflow sediment conditions
- Sediment removed by the configuration over the system life span has been reported in grams (g)
- Overall pollutant retention efficiency of the media over its life span is defined as the ratio between the total mass of TSS (or pollutant) removed and the 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 differences between replicates of different configurations for a particular performance parameter (such as the effect of size of sediment in stormwater on its life and the 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 amongst configurations.

5.3. Results and Discussion

5.3.1 Effect of inflow sediment concentration

The evolution of hydraulic performance with normalised volume of stormwater applied (150 mg/L) (Figure 5.1 (left)), suggests that sediment inflow concentrations impacts on clogging in a non-linear way. While the Base case and the High TSS concentration configurations (TSS > 400 mg/L) had comparable performance, the Low TSS concentration lasted much longer, passing 80% more stormwater (Figures 5.1 (right)). The Low TSS concentration configuration also removed more than double the amount of sediment (13.3 g) as compared with the High TSS concentration configuration (6.4 g; Figure 5.1 (right)). These performance differences could be impacted by a difference in the number of dosing events for each configuration (High TSS: 3 events; Base case: 7 events; and Low TSS: 69 events). It is therefore hypothesised that a greater number of dosing events helped push the sediment deeper in the filter bed. Every dosing event disturbs/re-suspends the sediments trapped within the pores of filter material and eventually allow them to move through the filter bed enhancing the life of the filter bed. This is somewhat confirmed in Figure 5.2, which shows profiling of the clogged columns. It was observed that per unit sediment trapped in the topmost layer of columns fed with Low TSS was lesser in comparison to the other two configurations.

PSD analysis of the particle sizes in treated effluent suggest that d_{50} particle sizes in the outflow of Base case reduced upon clogging to <100 μm, while it was less than 60 μm for the Low TSS configuration, and less than 190 μm for the High TSS configuration (refer Figure 1, Appendix IV). In other words the Low TSS was able to retain finer sediment as it clogged.

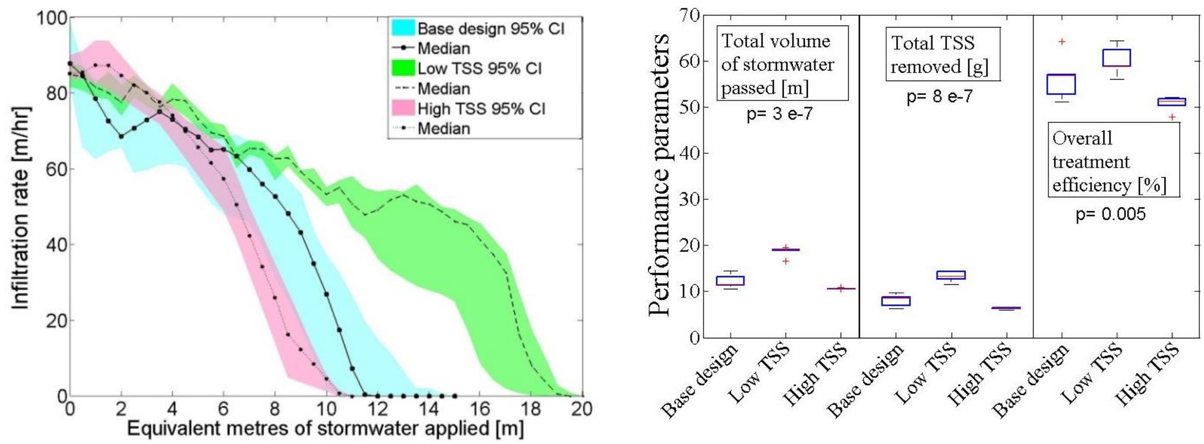

Figure 5.1: Comparative performance of columns with different TSS concentrations in the influent- Hydraulic performance over their lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this configuration)*

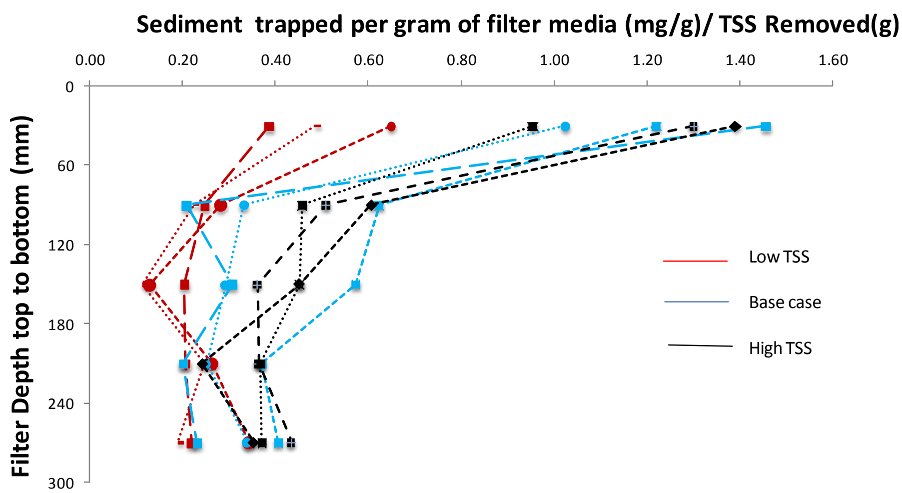

Figure 5.2: Profiling of sediment distribution in the three configurations with varying TSS concentrations in the influent

These results clearly imply that sediment concentration in stormwater is an important parameter affecting the hydraulic and sediment removal performance and eventually impacts the longevity of these stormwater treatment systems. This aligns with findings in the literature from other studies (mainly non-stormwater); e.g. Pavelic et al. (1998); Haselbach (2010); and Knowles et al. (2011).

Since influent sediment concentration is dependent on the type of catchment and the extent of its development, designs of non-vegetated stormwater systems need to factor this in adequately.

5.3.2 Effect of concentrations of nutrients and heavy metals

Columns dosed with *Complete stormwater* (wherein nutrients and heavy metals have been added to semi-synthetic stormwater) had comparable performance as compared to the Base case, as shown in Figure 5.3 (left). These columns passed 10.6 m of stormwater as compared to the Base case (11.5 m) and consequent to their lower treatment efficiency, they removed less sediment (6.5 g) as compared to the Base case (8.6 g). However, these performance differences are not statistically significant (see p-values in Figure 5.3 (right)). PSD of particles in effluent also suggest no differences in the two configurations (shown in Figure 2, Appendix IV). Figure 5.4 also shows that the pattern of accumulation of sediment in different layers of these two configurations is same with most sediment in the topmost layer and relatively lower sediment entrapment by the other layers.

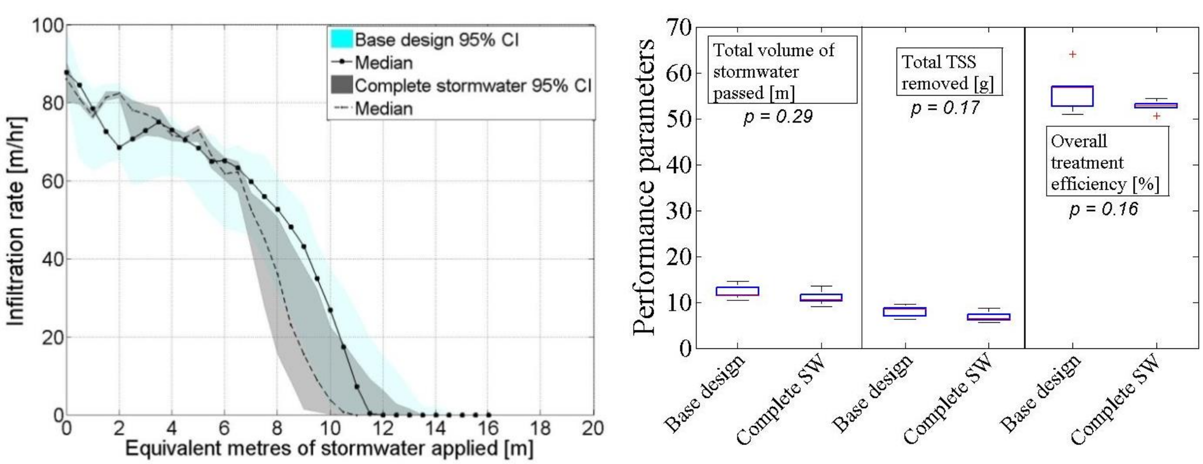

Figure 5.3: Comparative performance of columns with variations in stormwater composition- Hydraulic performance over their lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this configuration)*

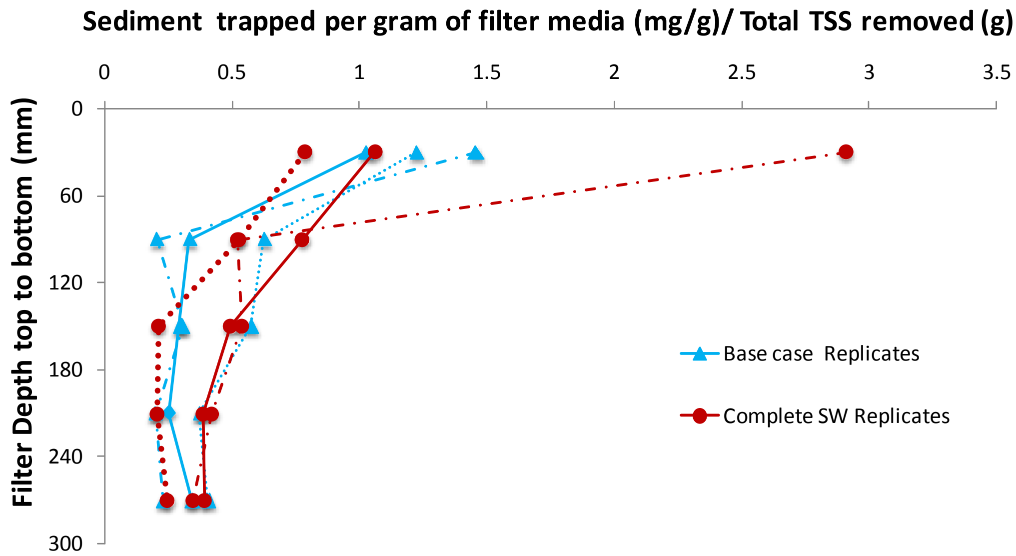

Figure 5.4: Profiling of sediment distribution in the configurations with different stormwater composition

It was observed that heavy metal removal improved as the filters clog, as shown in Table 5.2, with removal rates varying for different heavy metals. This trend is similar to sediment removal performance of these filters which is in agreement with Han et al. (2006) who found that suspended solids were associated with most particulate-bound metals. However, nutrient removal for both nitrogen and phosphorous (as TN, TP) was very low and ranged between 4-29% with treatment performance improving overtime (Table 5.2). This low removal performance may be related to the poor residence time of influent within the filter bed because of the high infiltration rate of these filters.

Table 5.2: Details of percent pollutant removal during different stages of filter operational life for the columns dosed with *Complete stormwater*

Pollutant	Stage of filter operational life		
	Start	*Mid*	*End*
	Removal rates (%)		
Heavy metals			
Cadmium	47	46	80
Chromium	22	20	23
Copper	11	20	46
Iron	44	42	45
Lead	31	29	57
Manganese	54	51	70
Nickel	52	49	71
Zinc	50	48	73
Nutrients			
Total Nitrogen	4	12	29
Total Phosphorous	14	11	27

It could be concluded that metals and nutrients have limited or no contribution to changes in hydraulic and treatment performance of the studied stormwater filters. This is in contrast with the other stormwater studies such as Gautier et al. (1999) and Knowles et al. (2011), wherein the authors found that influent characteristics, such as other pollutants are vital for understanding clogging processes in stormwater systems. However, it is important to understand that our experiments were compressed in time. The effect on clogging processes of pollutants other than sediment may be different under the influence of drying and wetting regimes and/or higher pollutant concentrations, when chemical and/or biological clogging may come into play.

5.3.3 Effect of sediment particle size

Columns of the *Very fine sediment* configuration (with sediment particle size< 75 μm) experienced a very gradual decline in hydraulic performance overtime, as shown in Figure 5.5 (left). It is important to note that dosing of these columns had to be discontinued after about 1 year of equivalent rainfall was passed through due to logistical reasons. The infiltration rate when dosing was stopped in these columns was about 68% of the IIR, even after about ten times more stormwater had been applied to the columns as compared to the Base case, as shown in Figure 5.5 (right). Because of the poor sediment removal performance of this configuration (with initial treatment efficiency of 20%), the pores in its filter bed hardly clogged and the system passed much more stormwater without clogging (109 m). However, as a result of the interaction between total volume passed and treatment efficiency, the total TSS removed by this configuration was more (26.6 g) as compared to the Base case (8.6 g).

PSD analysis of the particles in treated effluent suggests that while d_{50} particle sizes in the outflow of Base case reduced steadily, as discussed earlier, but was around 25 μm throughout the life of configuration fed with *very fine sediment* (refer Figure 3, Appendix IV).

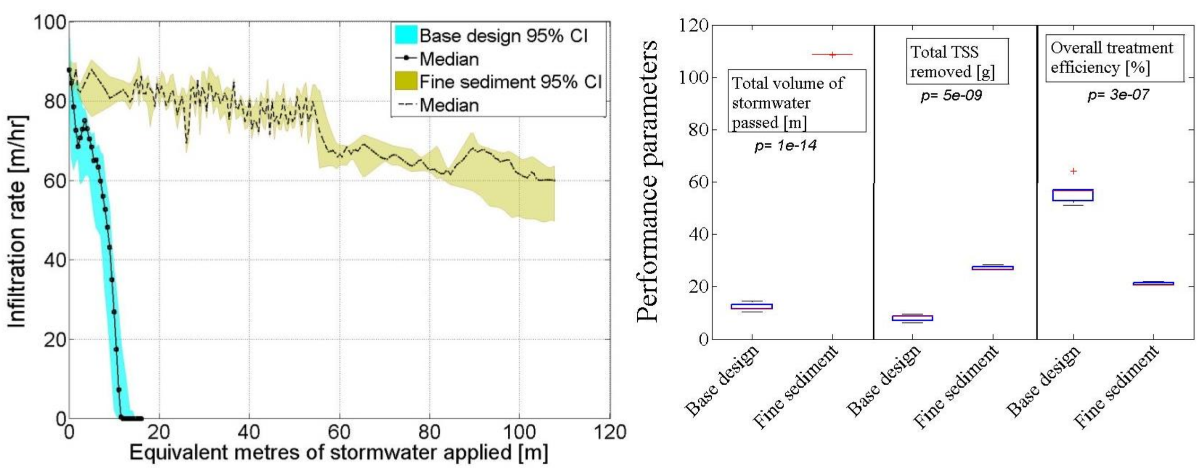

Figure 5.5: Comparative performance of columns with different variations in sediment particle size in the influent- Hydraulic performance over their lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this configuration)*

Figure 5.6 shows sediment trapped in different layers of the Base case and configuration fed with very fine sediment (sized < 75 µm). The accumulation of sediment in the < 75 µm configuration is fairly constant across layers. This suggests that finer particles were moving deeper into the filter bed because of the difference in size of the interstitial pore spaces between filter grains and particles in stormwater. Another possible reason for this, even though not very significant, could be the difference in number of dosing events between the two configurations (Base case: 7 events; and *Very fine sediment configuration*: 55 events).

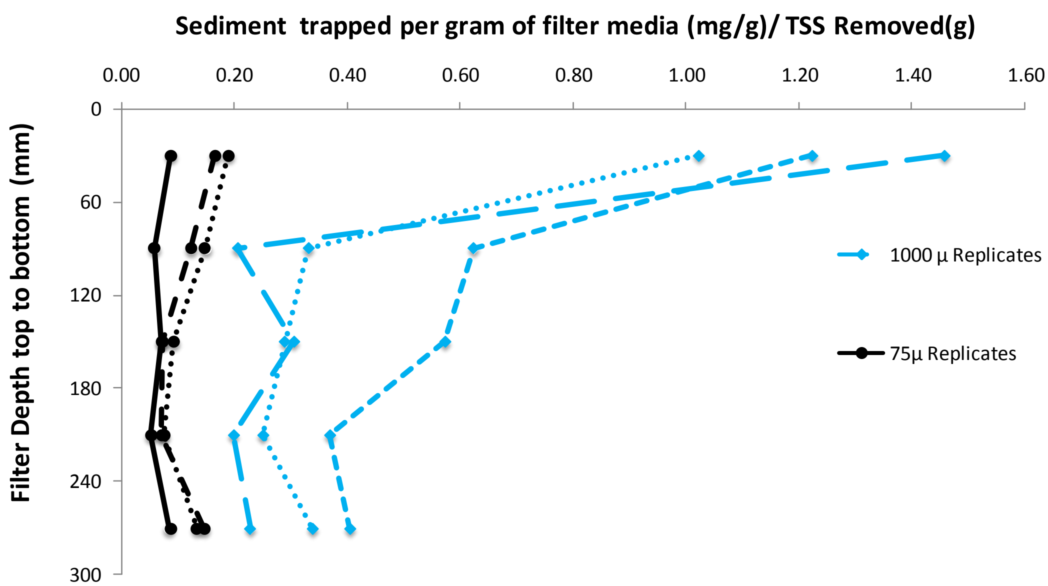

Figure 5.6: Profiling of sediment distribution in configurations with variations in sediment particle size in the influent

These differences in performance (Figures 5.5 and 5.6), especially in sediment removal performance, suggest that these coarse filters may not be effective in trapping very fine sediment because of the relative difference between sizes of filter pores and sediment in influent. These findings therefore clearly imply that the size of sediment in stormwater (and its relation with the size of filter media grains) is an important parameter to be considered in the design of coarse filters with high infiltration rates that are used for stormwater treatment.

The results from this study are in line with some studies on wastewater, such as Kaminski et al. (1997), wherein it was found that filters with high rates of filtration were more sensitive to particle size, as compared to low rate filters. On the other hand, wastewater studies such as Reddi et al. (2000) suggest that flocculation could affect blocking processes. Flocculation however may not be relevant for the subject stormwater systems as either the sediment particles in inflow may be too fine for considerable flocculation to occur or the process of flocculation was too slow in these high flow rate filters. These results therefore suggest that these systems perform differently compared to those treating water and wastewater.

5.3.4 Effect of stormwater loading rate

The configuration with high loading of 45 L/d passed 19% less stormwater as compared to the Base case (15 L/d), whereas configuration with low loading rate of 5 L/d passed 25% more stormwater compared with the Base case (Figures 5.7 (left)). All performance differences between these configurations were statistically significant (Figures 5.7 (right)).

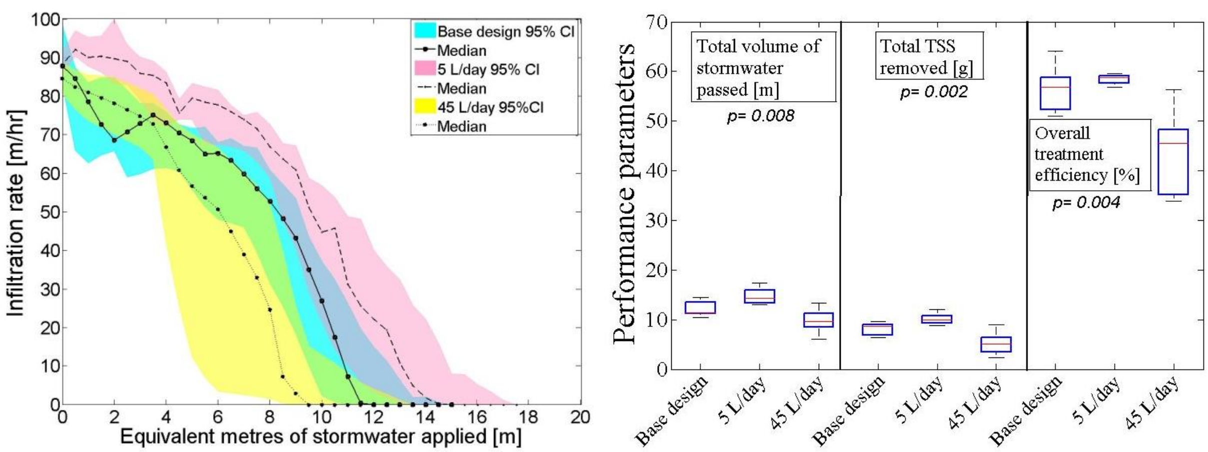

Figure 5.7: Comparison of configurations with different loading rates– Hydraulic performance over their lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this design)*

These differences in performance could be the result of the difference in number of dosing events across each configuration. While the columns dosed with 45 L/day of stormwater clogged within 3 dosing events; it took 29 dosing events to clog the columns with daily loading rate of 5 L (Base case: 7 events). It is therefore hypothesised that every dosing event disturbs/re-suspends the sediments trapped within the pores of filter material pushing the sediment deeper in the filter bed and eventually enhancing the life of filter bed. This hypothesis was reinforced by the particle sizes of the effluent in each of these configurations at the end of their operational life: d_{50} particle sizes in the outflow of Base case (with 15 L/day) reduced to <100 μm, while it was less than 80 μm for the Low loading rate (with 5 L/day), and 160 μm for the High loading rate (with 45 L/day) (refer Figure 4, Appendix IV). In other words the low loading rate allows a more even distribution of sediment in the column, which therefore is better at removing finer particles and hence causes lower d_{50} whereas the higher daily loading rate was able to push out larger particles.

However, as shown in Figure 5.8, profiling of the clogged columns suggests only minor variations in the amount of sediment trapped by different layers of these configurations. These variations amongst the configurations diminish in the lower layers of the filter bed. These results therefore provide limited evidence on the relation between location of clogged material and effect of loading rate or number of dosing events.

The findings imply that loading rate is an important parameter affecting the hydraulic and sediment removal performance of systems with high infiltration rates. Since hydraulic loading rate is dependent on the climatic conditions and location of treatment system in the catchment, the design of non-vegetated stormwater systems needs to account for this factor.

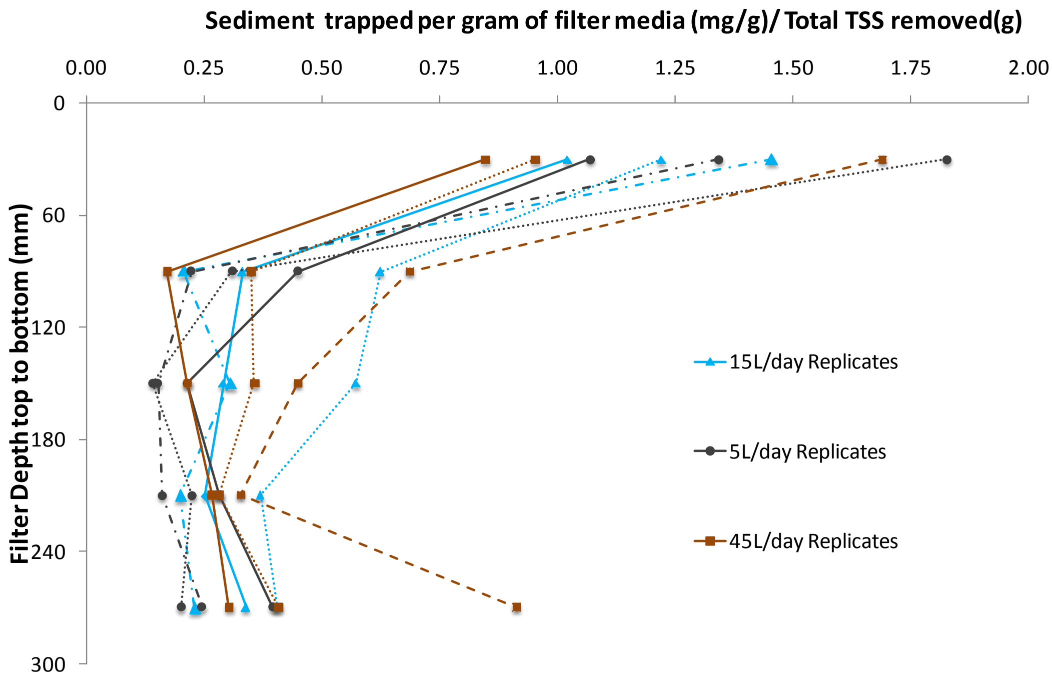

Figure 5.8: Profiling of sediment distribution in designs with variation in loading rates

5.3.5 Effect of stormwater dosing regime

The hydraulic performance evolution curves for three configurations with different frequency of stormwater dosing regimes (daily, alternate day and weekly dosing) show similar patterns of decline with stormwater application (Figure 5.9 (left)). Consequently all configurations had similar overall performances with statistically insignificant p-values (Figure 5.9 (right)). For instance, the configuration wherein stormwater was dosed on a weekly basis passed 11.3 m of stormwater as compared to the configurations wherein stormwater was dosed on alternate day (12.1 m) and daily basis (11.5 m) (Figure 5.9 (right)). As shown in Figure 5.9 (right), statistical differences were observed only for sediment removal performance but the magnitude of difference is not considerable.

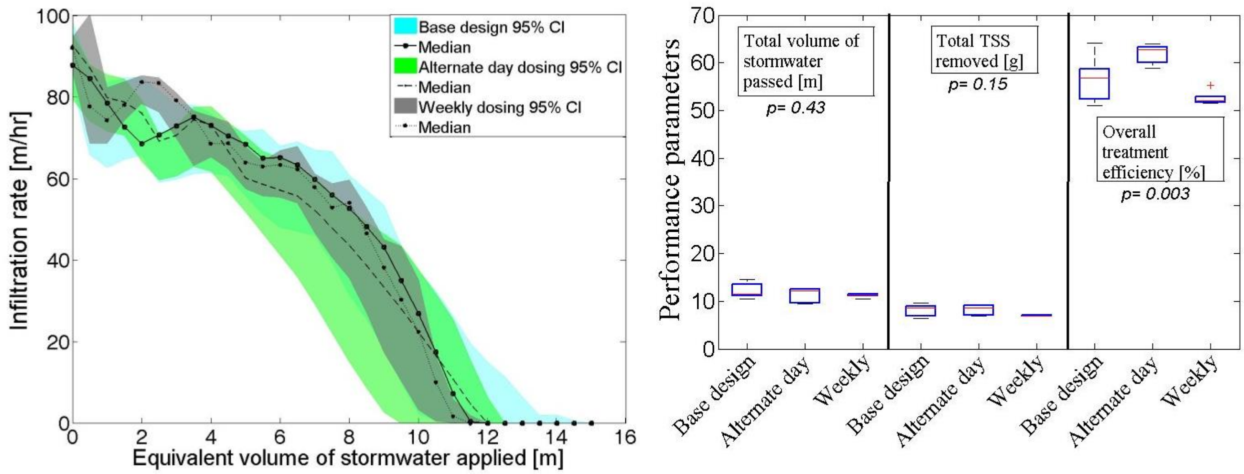

Figure 5.9: Comparison of configurations with different stormwater dosing regimes- Hydraulic performance over their lifespan (left) and; Box plots of total stormwater volume passed, total sediment retained and overall sediment removal efficiency over their lifespan (right) *(lines represent median values and shaded areas represent 95% confidence intervals for the five replicates of this design)*

At the same time, d_{50} particle sizes in the outflow of all configurations were comparable at the end of operational lives (shown in Figure 5, Appendix IV). Finally the comparison of sediment trapped in different layers of filter bed for the three configurations suggest similar trends across all layers with most of the sediment trapped by the top-most layer (shown in Figure 5.10).

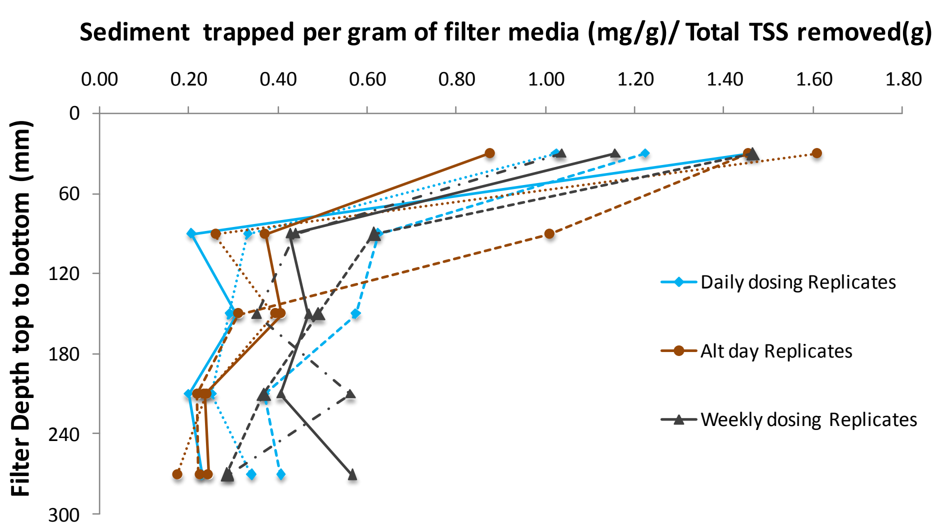

Figure 5.10: Profiling of sediment distribution in designs with different stormwater dosing regimes

These results suggest that any variation in the stormwater dosing frequency had limited effects on the volume of stormwater treated and sediment removed for non-vegetated filters with high infiltration rates. This in contrast to findings of studies of fine filter media used in stormwater filtration systems (Hatt et al. (2008), Li and Davis (2008) and Knowles et al. (2011)), where intermittent operations had been found to be beneficial for reversing clogging. Results of this study therefore suggest that there is limited or no swelling of the filter media in case of high flow zeolite filters, and therefore no cracks or macropores were formed in media with high infiltration rates and eventually porosity was not affected. However, given the fact that drying and wetting regimes may be extreme in the field, effects of this variable need to be verified further in field conditions.

5.4 Conclusions

Clogging of granular stormwater filters have been studied for a range of inflows with variations in stormwater: quality of stormwater (sediment load, type of pollutants, particle size of sediment) and; loading regime (loading rate and regime/frequency of loading). Analysis of comparative performances of these configurations suggests that these variations in stormwater characteristics have a mixed effect on the clogging rate and sediment removal performance of non-vegetated high flow rate filters that treat stormwater.

Sediment concentration in stormwater has been found to affect the hydraulic and sediment removal performance and eventually affects the longevity of these stormwater treatment systems. It is very likely that the impact is not linear (the effect is lost if sediment concentrations in inflows are over a certain value), but further work is needed to confirm this hypothesis. However, the presence of metals and nutrients has limited or no effect on performance of the studied stormwater filters. However, it is important to understand that our experiments were compressed in time. The effect on clogging processes of pollutants other than sediment may be different under the influence of drying and wetting regimes and/or higher pollutant concentrations, when chemical and/or biological clogging may come into play. Further, experiments suggest that these coarse filters may not be effective in trapping very fine sediment because of the difference between size of pores and sediment in influent. Therefore, the size of sediments in stormwater (and their relation with the size of filter media grains) is an important parameter to be considered in design of coarse filters with high infiltration rates that are used for stormwater treatment. Finally since influent characteristics are dependent on the type of catchment and the extent of its development, design of stormwater systems using media with high infiltration rates need to account for these variations.

The configuration with low hydraulic loading rate passed more stormwater and removed more sediment as compared to the Base case suggesting that stormwater loading rate is an important parameter affecting the hydraulic and sediment removal performance of systems with high infiltration rates. However, any variations in the stormwater dosing regime had a limited effect on the hydraulic and sediment removal performance of non-vegetated filters with high infiltration rates. Since the loading rate and dosing regime are dependent on the climatic conditions and location of treatment system in the catchment, the design of non-vegetated stormwater systems need to consider these design factors.

This study therefore suggests that stormwater characteristics have a mixed effect on the clogging performance and longevity of non-vegetated, high flow-rate stormwater filters. But nonetheless, this study enforces that clogging is specific to type of water treated and location of treatment system. Therefore, there is a need to understand stormwater characteristics in context of the catchment's features and to design the treatment system accordingly.

6 Investigation of biological clogging in stormwater filters

6.1 Background

Clogging of a filtration system can be due to physical, biological and chemical processes (Bouwer, 2002). However, limited research has been conducted to date to investigate biological clogging in stormwater treatment filters, even though biological clogging has earlier been established as a significant operational issue in the case of wastewater treatment systems (De Vries, 1972; Chang et al., 1974; Rice, 1974).

Given that stormwater flows are intermittent in nature, with high sediment load and low levels of organic matter and nutrients in comparison to other water types (as presented earlier in Table 2.1), it is usually perceived that biological clogging may not be prevalent in these stormwater infiltration systems. However, the abundance and nature of microbes in stormwater (McCarthy et al., 2012), as shown earlier in Table 2.3, does imply that biological clogging could be an important process which needs investigation. Bratieres et al. (2012) has also observed that the provision of disinfection in granular stormwater filter media enhanced filter performance, indicating that biological clogging may be present. Since adsorption is a dominant removal mechanism in granular filter media, it can be speculated that microbes trapped within the media during wet weather can grow between events, leading to biological clogging.

It is therefore pertinent to investigate the occurrence of biological clogging in context of non-vegetated stormwater filters with high flow rates. It is hypothesised that physical clogging is more pronounced than chemical or biological clogging; and the abundance and nature of microbes in stormwater imply that biological clogging should not be neglected altogether.

This article 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. However, we do not study impact of organisms that could live in stormwater filters and their impact on clogging (e.g. invertebrates whose movement may impact clogging).

The main results of these experiments have been accepted by the *Journal of Environmental Engineering* and the article is in press. A copy is attached as Appendix I-4 (Kandra et al., 2014c). The research findings were also presented in the *12th International Conference on Urban Drainage (ICUD)* held at *Porto Alegre, Brazil, 11th – 16th September, 2011*.

6.2 Methods

6.2.1 Experimental setup

To investigate the above hypotheses, zeolite media was combined with a coarse gravel layer on top (which mimics porous/permeable pavement based systems) in a testing column, forming a filtration system as shown in Figure 6.1. A combination of zeolite with porous pavement is one of the ways these systems have been used in practice (Poelsma et al., 2010; Bratieres et al., 2012). Presence of un-compacted coarse stones at the top also protects the filter media beneath and avoids any disturbance to the clogging layer formed during the filters' operation.

As observed in earlier experiments (Chapter 3), filter media selection is not critical for these experiments. Filter media characteristics such as shape and smoothness of filter media grains have been found to have a limited effect on clogging performance of filters with high infiltration rates. Therefore, zeolite was selected as a representative of similar granular media, because of its good treatment performance and wide use in the water filtration industry, low costs and local availability (Booker et al., 1996; Wanga and Peng, 2010).

Figure 6.1: Design of experimental columns

Experimental columns of 100 mm diameter were constructed according to the design shown in Figure 6.1, wherein zeolite (2 mm particle size) is located underneath a porous pavement to create an effective treatment train and treated stormwater is collected from the outlet of the column. 300 mm deep zeolite filter bed was placed between a 50 mm layer of coarse gravel at the top and a 50 mm gravel layer at the bottom that prevented migration of the media out of the filter. The coarse gravel layer used at the top had a median particle size of 7 mm, which is comparable to some of the porous pavements used in practice. These coarse stones not only protected the filter from the energy of water applied at the top but would also assist in some removal of sediment (even though with very low treatment efficiency as found in earlier experiments (Chapter 5). During construction of these columns, none of the layers were compacted, thus avoiding any damage to the filter media and reflecting construction practices. The ratio of experimental column diameter to filter particle diameter was around 50 to avoid any wall effects, as recommended for filtration studies (Lang et al., 1993).

The total head on top of the filter bed is 150 mm, comprising the free board of 100 mm and the 50 mm head available in the coarse gravel layer. A restricted outlet, as shown in Figure 6.1, has been provided in the experimental columns to allow a greater residence time of the influent stormwater within the filter bed. This therefore creates a favourable environment for any microbial growth. These filters have high infiltration rates, hence have very small area in relation to their catchment size and can therefore treat considerably high volumes of water. Clogging of non-vegetated stormwater filter media that is made from particles of this size range has not been investigated, even though they are often used in proprietary stormwater systems (Clark and Pitt, 1999 or Bratieres et al., 2012).

Four different configurations of experimental columns, with five replicates each, were prepared to indirectly investigate the role of biological clogging in filtration media by either promoting or hindering biological growth, as outlined in Table 6.1.

Two 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 case, chlorine tablets were left on top of the porous pavements. Alternatively, chlorine could have been added to the synthetic stormwater but that could affect the chemical composition of stormwater (including the sediment).For the filters that required sterilized stormwater, the sediment was autoclaved at a steam pressure of 1 bar at 121°C for 20 minutes (Salle, 1967) prior to adding it to the stormwater mixture. Alternatively stormwater could have been sterilized but this was not possible logistically, given that each dosing event required 75 litres of stormwater.

Table 6.1: Details of different tested configurations

Experiment details	**Experimental configuration**	**Details of stormwater**	**Hypothesised nature of biological activity**
Typical operational conditions	Base case	Typical stormwater quality	Natural conditions
Hypothesized to enhance biological activity	Nutrient loaded case	Stormwater with high nutrient load	Higher nutrient load enhances normal biological activity
Hypothesized to inhibit biological activity	Chlorinated case	Typical stormwater quality dosed over chlorine tablets placed on the top of Porous pavement	Chlorination disinfects any biological activity in the system
	Sterilized sediment inflow case	Sterilized stormwater	Sterilizing the sediment curbs natural biological activity in the stormwater

6.2.2 Experimental procedures

Clogging experiments

The columns were dosed in-situ with 6.4 m of potable water (or 45-50 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. The media were not pre-washed as it is expected that most of the intrinsic dust within the filter media is removed during the sieving process when the filter grains are passed through two sieve sizes of 2 and 2.36 mm. As potable water is applied in these experiments, further cleaning of filter bed occurs. This dosing with potable water ensured that no microbes were dosed into the experimental columns. During this washing phase, infiltration rates were measured after every 1.5 m of water application, to record the initial infiltration rate before stormwater is dosed.

The columns were then 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 ensured a fairly consistent composition of inflow for the experiments. This approach has been applied in earlier studies to investigate clogging and treatment phenomena (e.g. Siriwardene et al. 2007, Bratieres et al., 2012; Yong et al, 2013; Kandra et al., 2014; and Kandra et al., 2014a); stormwater was prepared using tap water and sediment harvested from a stormwater pond, sieved to select particles less than 1000 µm in diameter.

The sediment concentration in the stormwater was targeted around 150 mg/L based on a review of international data (Duncan, 1999; Francey et al, 2010) and was maintained at a relatively constant concentration for each experiment by mixing regularly. For all but High nutrient dosed filters, nutrients are added to target typical concentrations of Total Nitrogen (TN) = 2.1 mg/L and Total Phosphorus (TP) = 0.35 mg/L (Duncan, 1999; Duncan, 2005; Francey et al, 2010). The High nutrient loading configuration was dosed with typical sediment concentrations and almost double typical nutrient concentrations (TN= 5 mg/L and TP= 1.5 mg/L). For the Chlorinated case, chlorine tablets were used with residual chlorine ranging between 1-3 mg/L at the outlet of the column. The presence of free chlorine residual in treated stormwater indicated that a sufficient amount of chlorine was added to inactivate most bacteria.

The particle size distribution (PSD) of sediment used matched typical stormwater values; diameters of 10, 50 and 90 % of weighted sediment was d10= 4.8 μm, d50= 32 μm and d90= 317 μm, respectively. This compares well with a study for urban roads in Melbourne, Sydney, Brisbane and Adelaide, wherein the PSD was observed as d10= 6 μm, d50= 40 μm and d90= 440 μm (Lloyd et al. 1998). 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.

All four experimental configurations were tested simultaneously. Although an attempt was made to have constant concentrations for each round of dosing, the level of inflow TSS varied between 98-193 mg/L between events, resulting in some variation in the number of dosing events between different configurations. This TSS range emulates what is observed in practice. These variations in sediment content occur because even though stormwater in the tank is mixed continuously, there could be some settling of the sediment that affects its concentration, hence it is not possible to accurately achieve a TSS concentration of 150 mg/L in the artificial stormwater. Inflow TSS was most consistent for the sterilized sediment configuration, ranging between 142-184 mg/L, but varied between 98-193 mg/L for other configurations.

The dosing experiments have been designed following Melbourne's rainfall pattern for wet periods, which represents a worst-case operational scenario. These wet conditions should be favourable for growth of most microbes since the latter die off in dry soils (Schimel et al., 2007). Moreover, it was found that following a dry period, hydraulic conductivity of stormwater filters increases due to soil cracking (Hatt et al,. 2007). To design the dosing regime, an analysis of Melbourne's historical rainfall data (last 10 years- 1999 to 2009) was conducted. It was determined that the average amount of rainfall during each event was 5.9 mm; for an annual rainfall of 512 mm; total rainfall contributing to runoff equals 422 mm/year and number of events contributing to runoff constitutes 72 events per year. As such, during each dosing event, each column was dosed with 15 L (1.91 m) of stormwater, which equates to a sizing of this system of 0.3 % of the catchment's impervious area. For instance, as recommended by current Australian best practice (Wong, 2006), to be able to treat over 90% of runoff from an impervious surface, high flow rate filters have been sized to be 0.3% of their impervious catchment area for Melbourne conditions in studies such as Bratieres et al. (2012).

The columns were dosed every alternate day; i.e. storm events were simulated with about 2 days of drying in between, which is similar to the frequency of rainfall in Melbourne during winters (BoM, 2010). It is acknowledged that real time weather events should have been used to determine the dosing regime in these laboratory based experiments but here, in this initial study, we wanted to understand prevalence of biological clogging under constant inflow conditions and worst field conditions as in wet weather. The columns were dosed manually while maintaining a constant head to the top of column during each dosing session by topping up water at a controlled pace and avoiding any spill. The authors therefore suggest that any future investigation of this subject should entail design of a dosing regime, considering the stochastic nature of rainfall events and allowing drying in between dosing events, such as for the summer season.

The infiltration rate of each column was calculated by measuring the outflow volume per unit time using the constant head method (ASTM international D 2434-68) as per Darcy's Law, after every 0.75 m of water was passed. Composite water quality samples were taken for each dosing event. The experiments were run until the infiltration rate was about 5% of initial infiltration rates, which was regarded as the clogged state of the columns.

Loss on ignition (LoI) experiments

To assess the extent of biological activity in each configuration, experiments were undertaken to evaluate the amount of biodegradable organic matter in clogged columns. Organic matter was estimated by weight loss measurements in clogged filter media (e.g. Ball, 1964; Muller et al., 1998; Bianchi et al., 2008). The authors acknowledge that other methods such as elemental analyzers (EA) are better as compared to the LoI method to ascertain specific percentages of carbon and nitrogen but could not be undertaken in this study because of logistical reasons. Future investigations should consider using EA or better methods to assess the amount of biological matter in clogged filter media.

Three of the five replicate columns were randomly selected from each configuration for use in the LoI tests. From each of these columns, triplicate samples of filter media were collected using the top 25 mm layer of each column (below the interface between porous stones and filter media). For comparisons, filter media was also collected from the top layer of blank columns which were dosed with 50 L of potable water. Filter media in the topmost layer was used in these experiments because most of the clogged material is likely to be concentrated in the topmost layer next to the interface between coarser porous stones and filter media (for instance, as found by Siriwardene et al., 2007; Hatt et al., 2008; and Haselbach, 2010).

Moisture content of these samples was measured by leaving the samples in an oven at 105° C. This was done repeatedly to ensure that all moisture was dried and involved re-heating in the oven and re-measuring weights. The dried sample from this process was then weighed and placed in a muffle furnace at a temperature of 550° C for 24 hours to burn the organic matter. At the end of this 24-hour period, the samples were allowed to cool slowly to room temperature and re-weighed, giving the final organic matter content of the sample, calculated as weight lost (Equation 6.1).

$LoI = ((DW_{105} - DW_{550}) / DW_{105}) * 100$…………………………….Equation 6.1

where,

LoI represents Loss on Ignition (of organic matter) at 550° C (as a percentage);

DW_{105} represents the dry weight of the sample before combustion (in grams) and;

DW_{550} represents the dry weight of the sample after heating to 550° C (in grams).

Microscopic analysis of microbial counts

Microscopic examination of clogged filter media was undertaken to assess the extent of biological activity in each configuration at the end of its life (i.e. once clogged). Using confocal microscopy, microbial counts were made on samples of the filter media removed from the top most layers of the clogged columns. Since no standard procedures were available, the method for this study has been adapted from others (Wright and Jong (1986) and; Voyich and DeLeo (2002)).

Three replicates of accumulated sediment were taken from each column, as in the LoI measurements (i.e. 15 replicates per configuration) for this analysis. The samples of the top layer of the filter media were first prepared for microscopic examinations by refrigerating them at 4° C for about four hours; this was done to reduce microbial activity post its removal from the clogged columns. Representative samples of clogged filter media were taken in pre-weighed 1.5 ml Eppendorf tubes and weighed. 750 μL of PBS (Phosphate Buffered Saline) and 0.05% Sodium azide solution were added to the media to maintain constant pH and to avoid any contamination of the sample. Each sample was then mixed thoroughly using a Vortex mixer to re-suspend the cells. After this thorough mixing, the sample was gently sonicated for 5 minutes to disrupt the biological material from clogged sediment material. Each tube was then mixed again using a Vortex mixer. 100 μL of the dispersed sample was transferred to an Eppendorf tube with 100 μL of fixative (8% Paraformaldehyde), mixed and kept on ice. 50 μL of each sample was centrifuged for 1 minute at 1800 rpm to concentrate the biological matter for further processing. After removal of the supernatant, 500 μL of 0.2 mg/ml Fluorescein Isothiocyanate (FITC) (Sigma, St Louis, USA) /1% BSA (Bovine serum albumin) in PBS were added to each sample to label the biological material. BSA was added to prevent non specific binding to filter media. Even if the BSA was stained with the FITC, it would be washed away as it is in the supernatant. The samples were incubated for 10 minutes on a rocking platform. The tubes were centrifuged; the supernatant removed and replaced with PBS 4 x to remove the unbound dye and any very small particles. 50 μL of PBS/Sodium azide was added to the final pellet, whereupon the samples were stored at 4°C.

A 7 μL of the sample was put on 18 mm x 18 mm cover slip and mounted on a slide. The samples were imaged using a Nikon C1 confocal microscope (Nikon, Japan) with a Plan Apo VC 100 x with NA = 1.4 objective. A 4x4 tiled image was collected to ensure a statistically relevant number of cells were imaged. Images were analyzed using FIJI and Metamorph (Molecular Devices Inc.), counting total cell numbers within a size range of 0.5-3 μm, which is the expected size of microbes in stormwater. Total cell count per gram of clogged filter media was calculated considering the dilution factor, volume of sample used (7 μL) and weight of filter media. The results have been reported as microbial cell counts per gram of filter media.

6.2.3 Data analysis

The following variables have been studied:

- Initial infiltration rate (IIR) in m/hr representing hydraulic performance at the beginning of filter life (measured using potable water).
- Normalized volume of stormwater that causes clogging of the system (when the infiltration rate dropped to 5% of IIR)- The normalization has been undertaken by first calculating the total mass of sediment applied to an experimental design over its life and dividing this by 150 mg/L (the standard target inflow TSS concentration for all experimental designs to allow comparisons).

The results are then expressed in 'Equivalent meters of stormwater passed' (for a same inflow sediment concentration of 150 mg/L).

- Total TSS removed over time (in grams).
- Overall treatment efficiency of the media over its life span, which equals the ratio between the total mass of TSS removed and the total mass of TSS applied to each column (in %).
- Results of the Loss on ignition (LoI) tests to identify percent organic matter in the clogged samples have been normalized per unit sediment removed by the filter media.
- Cell count in clogged filter media was normalized and reported as the ratio of cell count per gram.

The data was analyzed 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 and inter-comparison of replicates, has been performed. Statistical analysis, to test the statistical difference between different configurations of results for different configurations, has also been carried out using ANOVA tests, at $p = 0.05$. Data has been tested for independence, normality and homogeneity of variances prior to undertaking the significance tests, as assumed for Standard ANOVA tests.

6.3 Results and discussion

6.3.1 Initial Infiltration Rate

The initial infiltration rate (IIR) of the different configurations was found to vary between 10–32% within replicates (Figure 6.2), as also shown in earlier chapters. This can be attributed to the natural variability in media, its packing and the uncertainty associated with hydraulic permeability measurement techniques. These observed variations were, however, within the ranges reported in the literature; e.g. Le Coustumer et al. (2012) found it to be around 49% for loamy-sand filters.

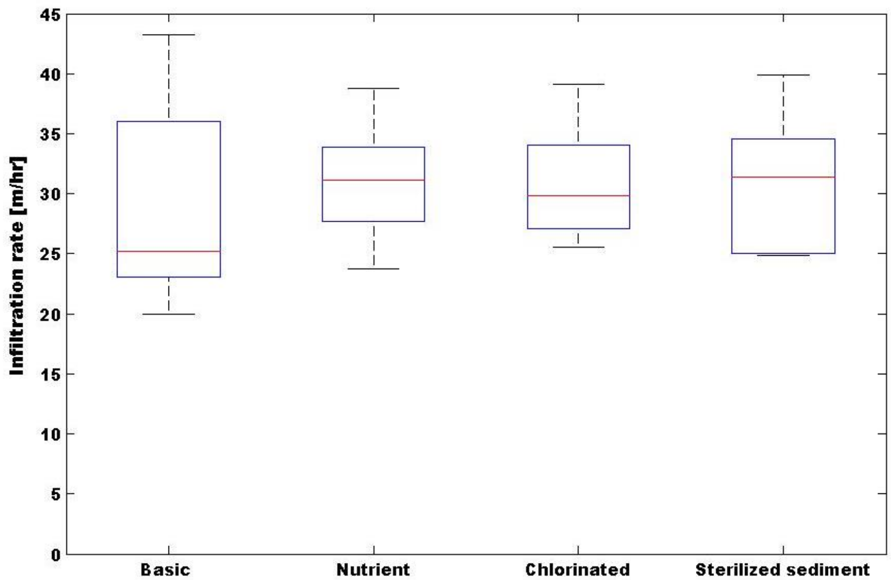

Figure 6.2: Initial infiltration rate of all configurations

Statistical analysis of the comparative IIR (using ANOVA with significance level of 0.05) suggests that initial hydraulic performance does not vary amongst the different configurations ($p = 0.97$). It may appear that the Base case has a slightly lower initial infiltration rate (Figure 6.2), but variation amongst its replicates is considerably 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 the same initial infiltration rates.

6.3.2 Clogging Experiments

The infiltration rate (IR) for all configurations decreases steadily over time as more stormwater is passed through the filter bed. For instance, as shown in Figure 6.3, IR for the Base case in these experiments 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 150 mg/L (which represents 6 dosing events or about 2 weeks of filter life during wet weather in Melbourne). Similar trends were observed for all other experimental configurations. As expected, it was also found that the sediment removal efficiency (also referred to as treatment efficiency) improved consistently as the filters became clogged; e.g. treatment efficiency for the different replicates of the Base case improved consistently from an initial value of 40% to 90% on clogging.

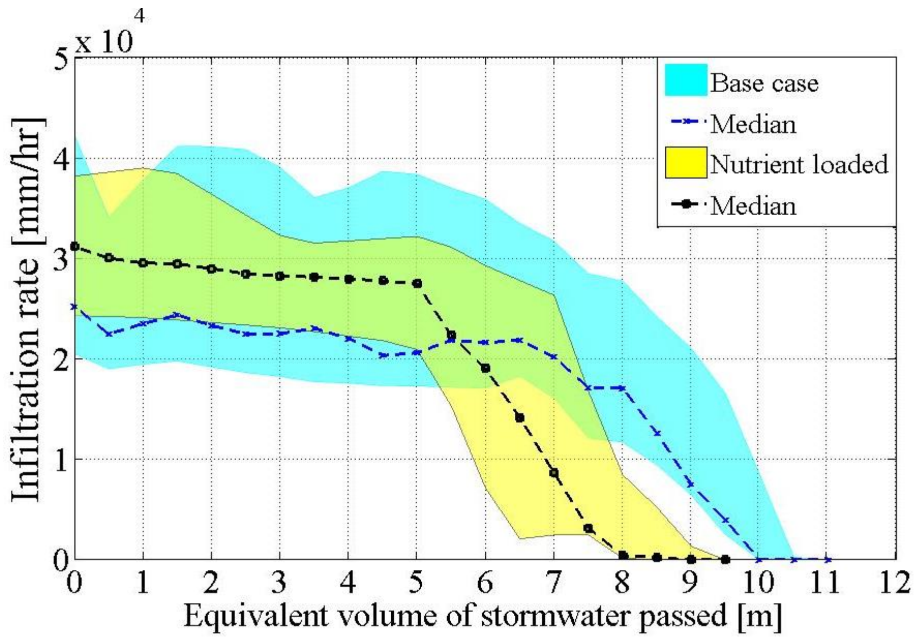

Figure 6.3: Evolution of hydraulic performance in the Base case and configuration with High nutrient loading

Effect of enhancing biological activity

Effect of enhancing biological activity: Comparison of evolution of hydraulic performances of the Base case and High nutrient loading case (where biological activity was enhanced by dosing stormwater containing high nutrient load) suggest that, although the initial infiltration rates did not differ significantly ($p= 0.73$), the pattern of decline in hydraulic performance and longevity were rather different (Figure 6.4). 'High-nutrient' columns clogged after around 20% less stormwater was applied than in the, Base case ($p= 0.001$). This may suggest that an increase in nutrient loading in stormwater may have enhanced the microbial activity within the filter bed, which could have increased the level of biological clogging within the filter. This 'enhanced clogging' could also have been the cause for the slightly higher TSS treatment efficiency found in 'High-nutrient' columns, even though statistically they are similar to the Base case (p= 0.18) (the shorter life of the 'High-nutrient' columns resulted also in lower sediment removal than in the Base columns). It is pertinent to mention that literature does not suggest that addition of any additional chemicals, as in this case, would lead to any chemical clogging.

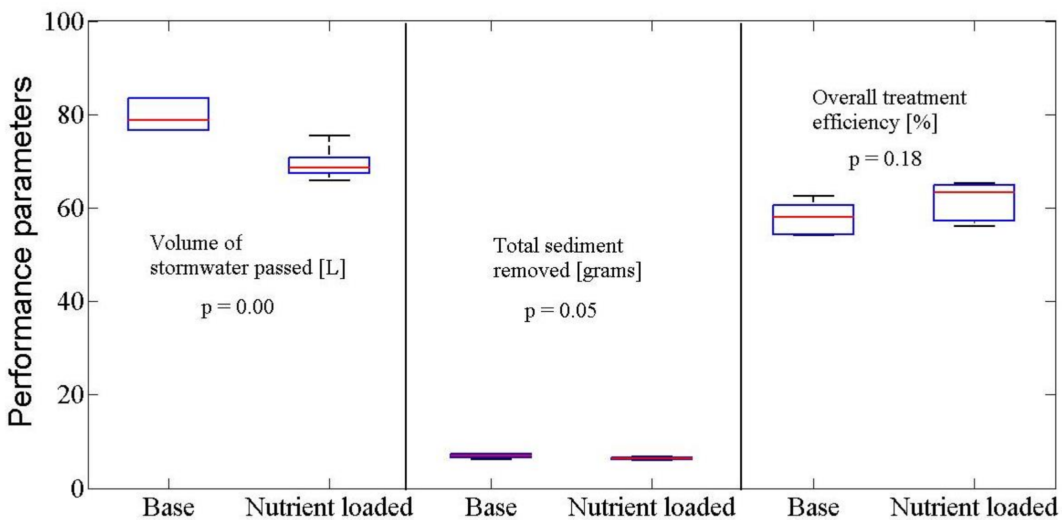

Figure 6.4: Comparison of performances for the Base case and configuration with High nutrient loading (total volume of stormwater passed (L), total sediment removed (grams) and overall treatment efficiency (%))

Effect of inhibition of biological activity

As shown in Figures 6.5 and 6.6, not only did the 'Chlorinated' filters pass significantly more stormwater before clogging as compared with the Base-case (30%; p= 0.0002), they also removed significantly more sediment (40%; p= 0.002) with a comparable overall treatment efficiency (p= 0.12). These results suggest that addition of Chlorine (Cl) can significantly change the behaviour of the treatment system. It is acknowledged that the addition of Cl to the columns could have various consequences on the filtration process. However, it is hypothesized that the differences observed here pertain to the reduced microbial activity in the stormwater and filtration media, caused by provision of chlorine tablets, thereby minimizing biological clogging layer formation. However, since these columns still clogged, it is concluded that other dominant processes (i.e. physical clogging) were still occurring.

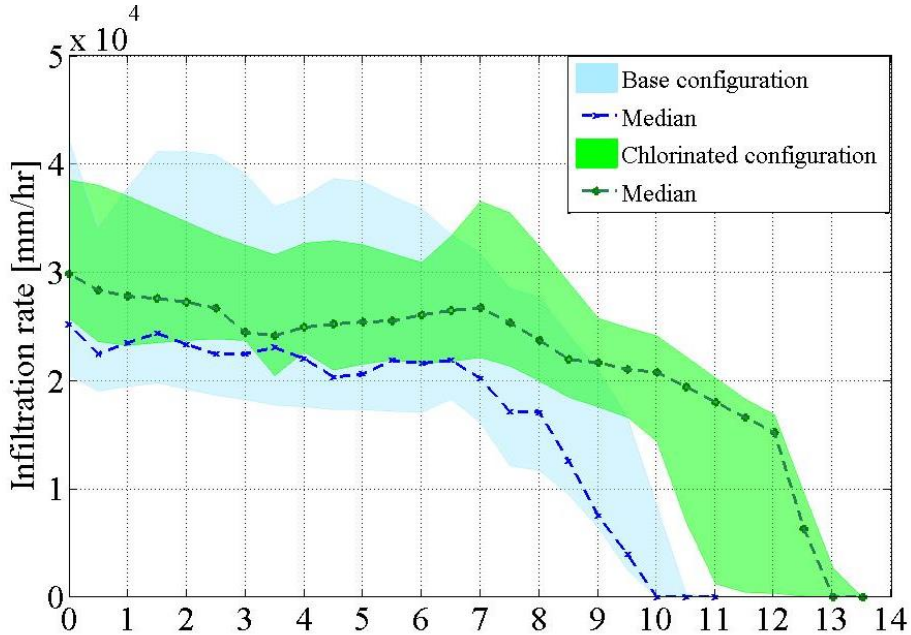

Figure 6.5: Evolution of hydraulic performance in the Base case and Chlorinated case

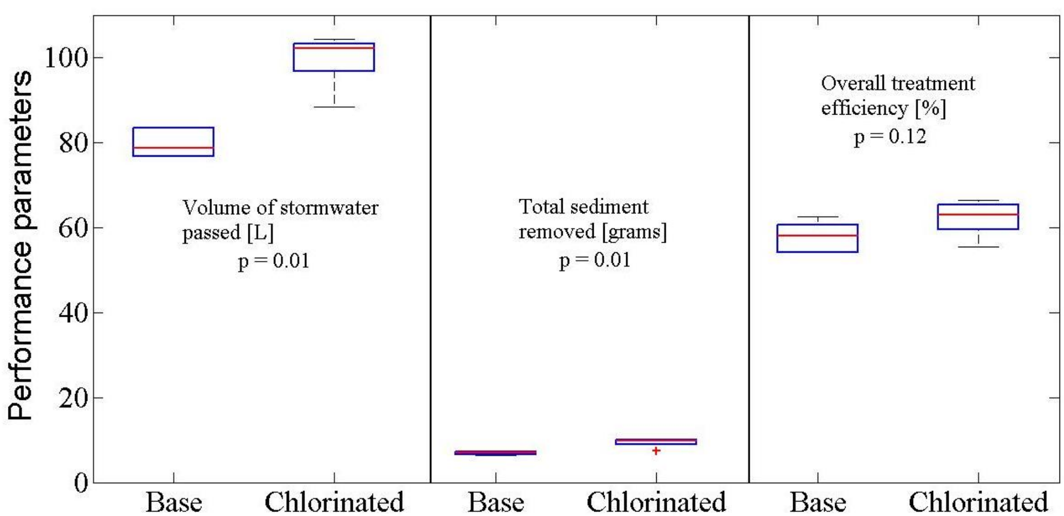

Figure 6.6: Comparison of performances for the Base and chlorinate configurations (total volume of stormwater passed (L), total sediment removed (grams) and overall treatment efficiency (%))

The ‘Sterilized sediment configuration’ treated almost the same volume of stormwater as the Base case configuration, but removed 37% more sediment with significantly higher treatment efficiency as shown in Figures 6.7, 6.8. Unfortunately, because of a methodology error, these columns were inadvertently dosed with slightly higher influent sediment concentrations as compared to the Base case. As observed by the author in other experimental work (Kandra et al., 2013), differences in inflow sediment concentrations can influence the clogging process. It was found that a 2-3 fold increase in inflow sediment concentration reduced the amount of water treated by around 25%, as higher inflow concentrations lead to higher sediment removal rates, hence faster clogging. This therefore implies that Sterilized sediment columns would have passed more stormwater before clogging had we applied stormwater with the same sediment concentrations.

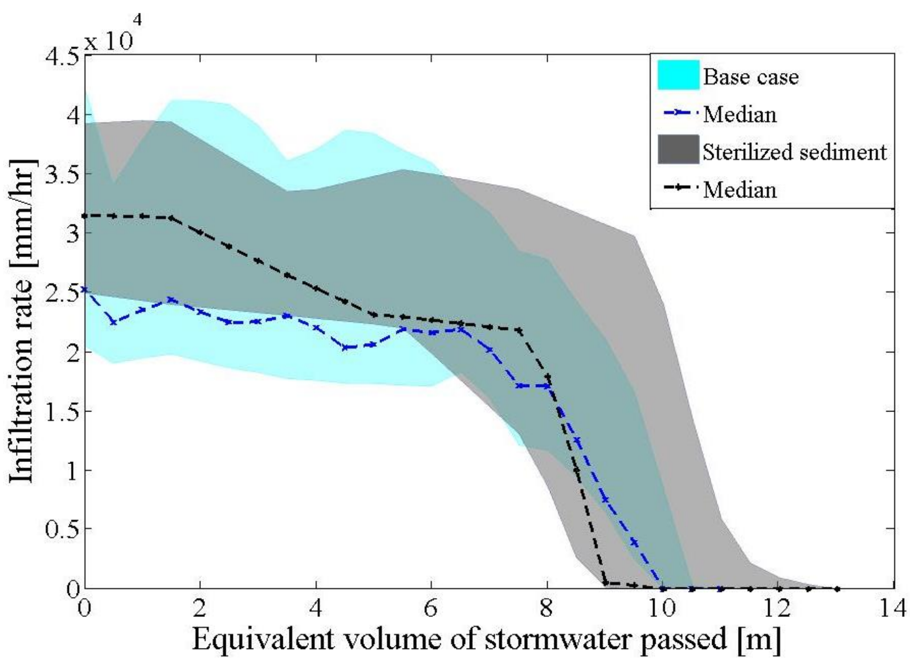

Figure 6.7: Evolution of hydraulic performance in the Base case and Sterilized sediment configuration

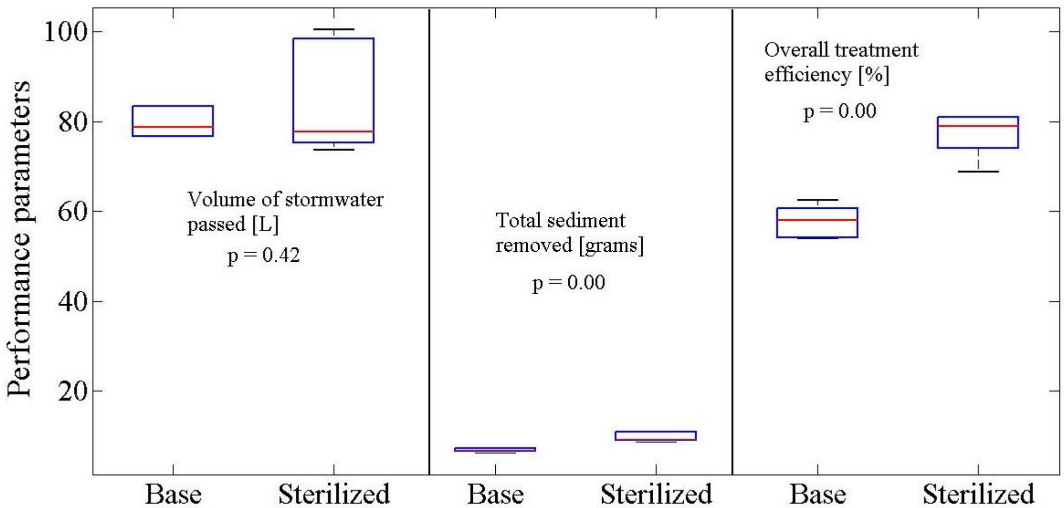

Figure 6.8: Comparison of performance (total volume of stormwater passed (L), total sediment removed (grams) and overall treatment efficiency (%)) for the Base and Sterilized configurations

6.3.3 Loss on ignition (LoI) experiments

Effect of enhancing biological activity

Figure 6.9 presents the comparisons between the Base case and Nutrient loaded cases suggesting that the 'nutrient-loaded' configurations had significantly higher organic matter content (p= 0.00). This high concentration of organic matter in the Nutrient loaded case could be present due to the higher biological growth in filters as compared to the Base case. However, it could also be a direct result of the fact that these columns were fed with a very high nutrient load (TN of around 5 mg/L), in contrast with other columns (TN of around 1 mg/L). As suggested by Taylor et al, (2005), Organic Nitrogen (ON) on average makes 28% of stormwater TN. Since Zeolite filters can adsorb ON (Bratieries et al., 2012), the high LoI results could be solely due to high inflow TN concentrations. Unfortunately, we were not able to estimate whether biological clogging or high inflow TN levels are the primary cause of high LoI levels.

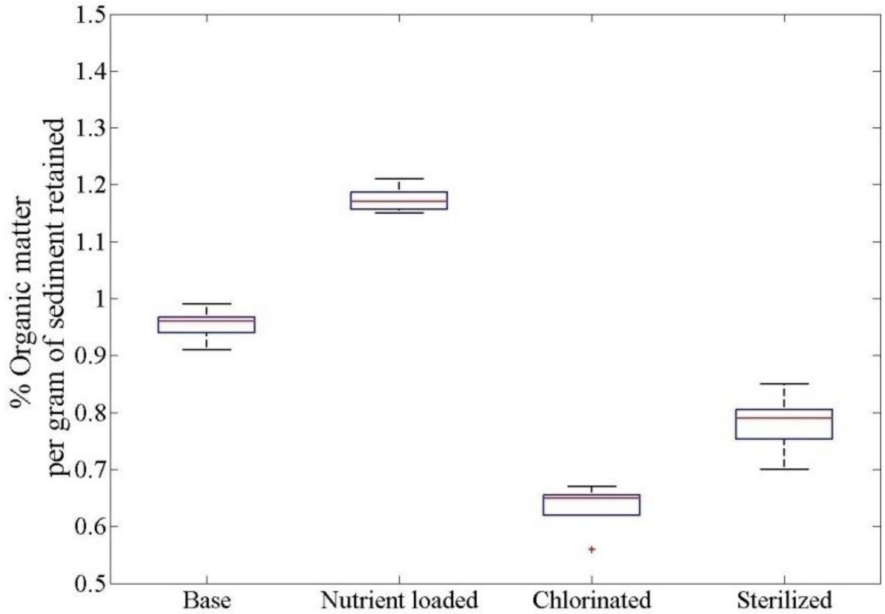

Figure 6.9: Comparison of percent organic matter (LoI) present in clogged filter media of the different configurations (expressed per unit sediment retained by the filter media) Note: The Nutrient loaded columns were fed with a very high nutrient load (Total N= 5 mg/L) as compared to other columns (Total N~ 1 mg/L).

Effect of inhibition of biological activity

The normalized results from LoI tests, as shown in Figure 6.9 above, suggests that the configurations with inhibited biological activity (by chlorination and sterilizing inflow) had lower organic matter contents as compared to the Base case. These differences were statistically significant with p-values close to zero. The results suggest that addition of Cl was either suppressing biological activity in filter beds of this case or chlorination was inducing chemical de-clogging in some way. Similarly, the sterilization of sediment fed to the experimental columns was inhibiting the biological activity: hence a reduced content of organic matter is observed in filter media removed from the clogged columns.

6.3.4 Microscopic analysis

Effect of enhancing biological activity

Results of microscopic examination of clogged samples, as shown in Figure 6.10, suggest that normalized cell counts (median values reported as cell count per gram of sediment removed by the filter) in the Base and Nutrient-loaded cases are comparable (p = 0.61). This therefore may suggest that both configurations eventually clog at almost the same level of microbial activity. However, it is noteworthy that the variability of the nutrient loaded systems was significantly lower than the base case, which could suggest some impact of higher nutrient levels on the microbial cell count. It is pertinent to mention that microbial count in the blank samples were only 2% of what was observed in the Base case.

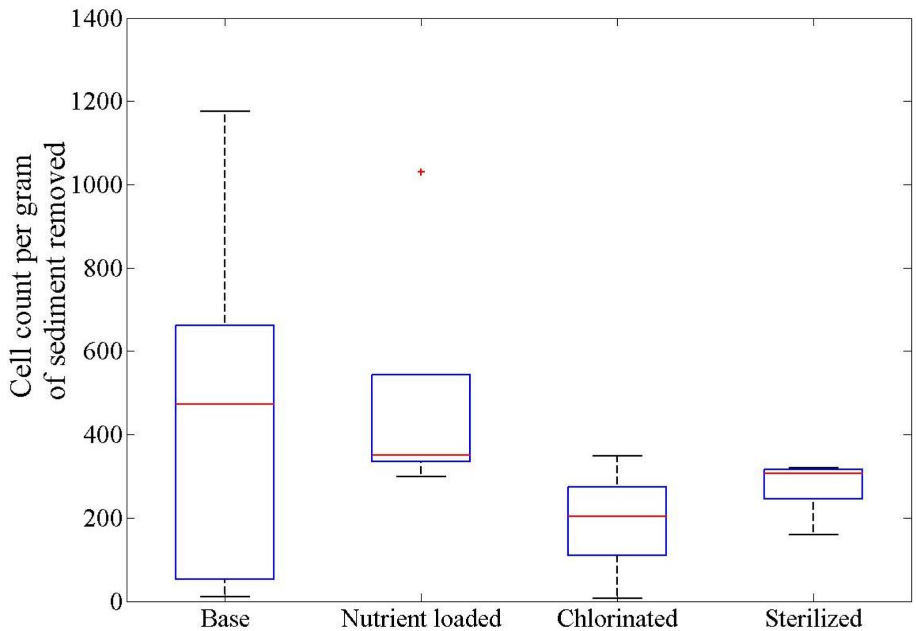

Figure 6.10: Comparison of microbial cell counts present in clogged filter media of different configurations (expressed per unit sediment retained by the filter media)

Effect of inhibition of biological activity

Results of microscopic examination of clogged samples (Figure 6.10) suggest that median cell count in chlorinated columns was lower than in the Base case. While these results are not statistically significant, they nevertheless indicate some differences. They suggest that regular addition of chlorine may have either suppressed the biological activity in filters or induced chemical de-clogging. It is also important to note that addition of Cl does not kill all bacteria, while some chlorine resistant microbes may still have survived and even grown. Comparing the Cl columns to the nutrient loaded columns reveals that the Cl systems had significantly lower microbial concentrations ($p < 0.05$).

Appendix V shows images from microscopic examination of the different configurations tested in this study. As already acknowledged in the methods section, due to the lack of any standard procedures, the developed method may have some errors. For instance, the presence of clumps of microbial cells and/or interference by minute-sized particles of filter media could affect the cell count. However, it is assumed that since the same method was used consistently for testing of all the configurations and their replicates, comparisons between the configurations should be acceptable.

6.4 Conclusions

Comparison of clogging of zeolite based stormwater filters for four different cases: (i) dosed by typical stormwater (Base case) (ii) stormwater loaded by a high level of nutrients, (iii) chlorinated stormwater, and (iv) sterilized stormwater, has been carried out. Results demonstrate that biological clogging may be present in stormwater filtration systems. This was clear from the results on the rates of clogging and sediment treatment, where filters dosed by high nutrient stormwater clogged faster than in the Base case, while the chlorinated dosed filters lasted for the longest duration. The results of Loss on ignition partially confirmed these findings. However it was not clear whether the higher organic content in the high-nutrient dosing case is due to biological growth or rather to simple media adsorption of inflow organics (organic N). Results of microbial cell counts suggest that the nutrient loaded configuration had significantly more microbes than the Chlorinated configuration. However the evidence of biological clogging is limited, which could be entirely due to high uncertainties of methods used.

Although the evidence was not overpowering, variations observed in this study suggest that more attention should be given to biological clogging in stormwater filters. These laboratory based experiments reflect wet weather conditions, however field conditions such as prolonged drying in the summer season could exert an impact upon biological activity. Similarly, facilities located in areas receiving more rainfall will have favourable conditions for microbial growth and may experience greater biological clogging. Even though drying and wetting regimes was found to have a limited effect on clogging in laboratory based columns using similar filter media (Kandra et al., 2013), studies undertaken for coarser filtration media such as porous pavements indicates significant impact of drying (Yong et al, 2013).Therefore, it is important for future studies to investigate the impact of other factors, such as drying and wetting; stormwater composition; or rainfall patterns on biological clogging in stormwater filters.

Future work should be done on quantification of biological clogging in relation to physical clogging. This preliminary work suggests that the former could comprise up to 30% of the total clogging in non-vegetated stormwater filters (zeolite-based) with high infiltration rates. This therefore implies that clogging models used for design should consider biological clogging in addition to physical clogging. Any future work that investigates biological clogging should design a real-time dosing regime and harness better methods to analyze organic matter in clogged filter media.

7 Field study

7.1 Introduction

Laboratory experiments are generally undertaken in controlled environments and hence not burdened with the problems that arise in real world. This may therefore lead to less valid data/findings. MacDonald (1993) states that lack of field validation implies lack of appreciation for the spatial and temporal variability of most hydrologic processes. This eventually leads to an excessive reliance on theory and concepts and the lack of field experience could potentially affect technology development when confronted with different problems or new environments.

This research therefore studied a stormwater harvesting system that includes an enviss™ filtration system installed at South Syndal State Primary School (SSSPS), Melbourne. The aim of this study was to understand the evolution of infiltration rate in the enviss™ filtration systems in field conditions and to test the following hypotheses:

1. Clogging of the enviss™ filters in field follows same trends as clogging of layered systems studied in the laboratory.
2. It is possible to model the infiltration rate of enviss™ filters using a simple regression curve between infiltration rate and cumulative volume of stormwater treated by the filters.

7.2 Methods

7.2.1 Description of site and treatment system

Figure 7.1 shows the location of the South Syndal State Primary School in Melbourne, where the enviss™ filters have been installed. This treatment system treats runoff from a 5000 m^2 catchment area consisting of roofs and paved areas in the school. The location of the porous pavement enviss™ filter system (PP) in relation to the school buildings can be seen in Figure 7.1. The system is located in between a soccer field to the east which contains storage tanks underneath and a children's sand pit in the west. Treated water from the filters is conveyed to underground storage tanks with a capacity of 140 m^3 and is used within the school for irrigation and toilet flushing.

Figure 7.1: South Syndal Primary School set up

The enviss™ filters have been developed recently (Bratieres et al., 2012), with an advantage to other WSUD measures when stormwater needs to be treated within space constrained urban environments (Yong et al., 2010). The enviss™ system was specifically designed to remove the key pollutants from stormwater (e.g. microorganisms, heavy metals and PAHs) (Bratieres et al., 2012). Although enviss™ filter media has moderate infiltration rate (around 2,000 to 2,500 mm/hr when installed), which is lower than the media studied in the laboratory conditions, an attempt was made to use this system to verify the findings from the laboratory in field conditions. Indeed enviss™ filters are amongst systems with the highest flow rate that are used in Australian practice, and hence are a logical choice for study in this thesis (which focuses on high-flow rate filters). Furthermore, since Monash University stormwater researchers were involved in the development of these filters, the author benefited from in-house knowledge of the systems and this was another reason to select this field system.

The filters are modular (Figures 7.2 and 7.3) and consist of the following (Poelsma, 2010, Bratieres et al., 2012):

1. A trafficable porous pavement grate that removes gross pollutants and could be used a part of a path, car park or light trafficable road;
2. A replaceable sediment trap that removes sediment and protects the underlying filter from premature clogging by removing most of the sediment;
3. A fine media filter that removes finer sediment and dissolved pollutants;
4. Chlorine tablet in the sediment traps;
5. A drainage layer at the bottom to prevent filter media migration and outlet clogging; and
6. A box/cell that contains the above and is used for the collection of treated water.
7. An under collection system that transports the treated water to storage tanks for non-potable water supplies to the school.

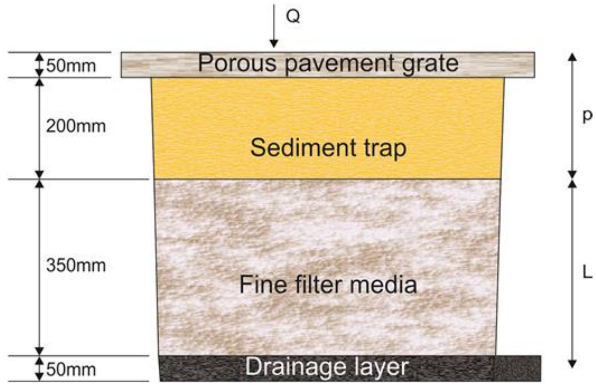

Figure 7.2: The enviss™ stormwater treatment module

The system installed in the Syndal School grounds have a total filter area of 8m^3, or 0.2% of the impervious catchment area, and is made up of sixty treatment modules or pits (Figure 7.3). These are arranged in two rows of thirty pits with the inlet at one end. The length of system is 20 m and its width is 1.12 m. The ponding depth on top of the porous pavements (before the water overflows to the side collection chamber) is 0.15 m. One collection chamber is shown in Figure 7.3 and the other one is located at the other end of the system, next to cells in Row 30. Sand pit play area is also shown in Figure 7.3.

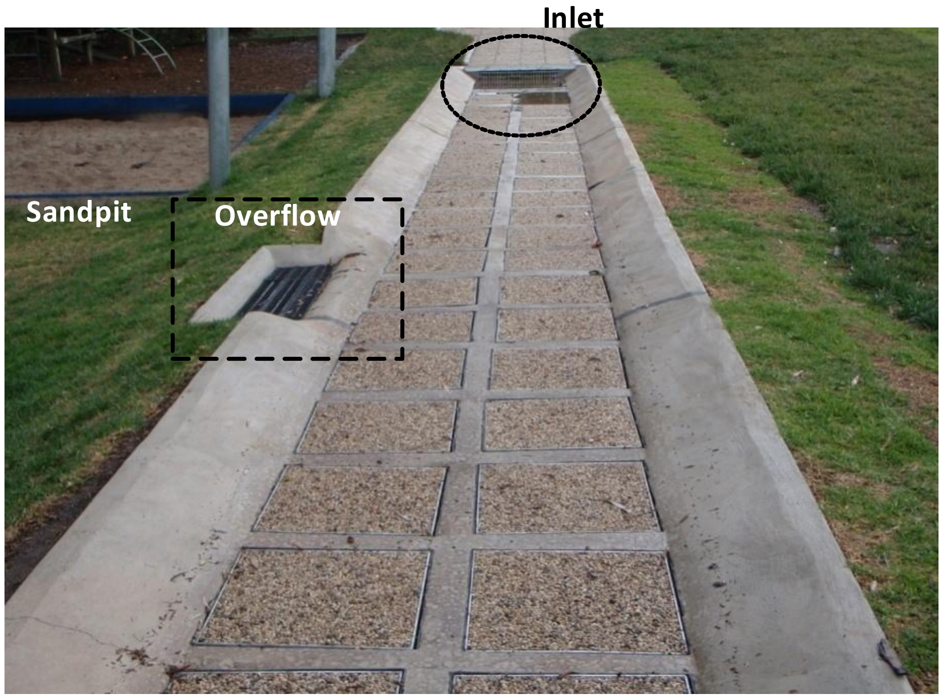

Figure 7.3: Stormwater treatment system at Syndal South Primary School

At a design filtration rate of 2000 mm/hr (conservative estimate), a filter of this size is designed to be able to treat 80-90% of flows expected from the catchment. The design of the system has been changed once since October 2008. The new system has been operational since end November 2009 when new improved media was installed, including chlorine in the sediment traps. The system was designed and installed in collaboration with Monash University research group with full details on the site development discussed in the industry (confidential) report developed by Monash University (2010).

7.2.2 Field measurements

<u>Monitoring of infiltration rate in the field</u>

The filtration rate of the modules (cells) of this system was calculated using field trials, wherein in-situ infiltration performance tests were undertaken using tap water. Field measurements were undertaken for 13 of the 60 pits that were located at various distances from the inlet.

Figure 7.4 shows the cells that have been tested after the new system was installed in November 2009. Nomenclature of the monitored cells has been done based on the number of the cell and its location (left or right hand side), as per Figure 7.4; e.g. the filter cell located in the 8th row on the left side of the system has been named as L8 and vice-versa.

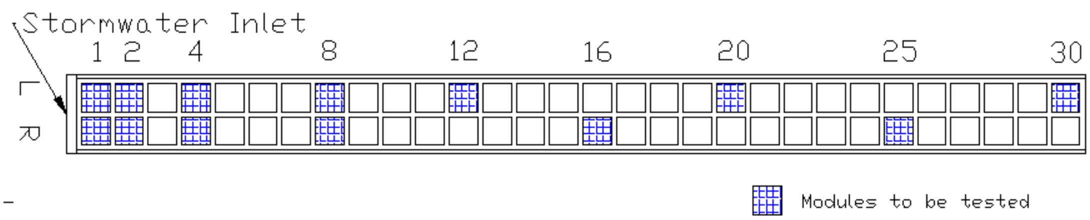

Figure 7.4: A schematic of the treatment system and the pits tested

Infiltration rate measurements have been conducted six times for each of the 13 cells over a 2.5 year period. The following days have been selected so as to allow comparisons both over shorter and longer time intervals and for logistical reasons:

- 17th April 2010
- 19th April 2011
- 10th May 2011
- 31st May 2011
- 14th May 2012, and
- 7th June 2012.

The field measurement process began with the removal of dirt, sand and tanbark from the top of porous pavement. Following this the porous pavement lid was removed from all cells (indeed, it was only the intent of this project to study the underlying filter media, not the porous pavement). Poly-ethylene sheets were then placed on the top of the cell covering the sediment trap media so that water is dispersed and the surface layer of the filter media is not disturbed and clogging in the media is not affected during the field measurement process. The filter cell was then filled with tap water and kept saturated for 2 hours before the field measurements could be undertaken, as shown in Figure 7.5. Therefore water was applied to each of the tests pits over a period of 4-5 hours. While maintaining a constant ponding depth, the inflow rate was measured three times using a 9 litre bucket and stop watch. Temperature was also recorded regularly.

Figure 7.5: Saturating cells and maintain a constant head

Throughout the field testing there are some limitations which restrict the ability to get accurate results. The majority of these limitations can be due to human error and were minimised by making sure that great care and diligence is taken when testing and taking an average of three observations. The limitations include, but are not restricted to:

- the ability to keep a constant head of water (ponding depth) throughout the whole testing period;
- filling the testing bucket with exactly 9 litres of tap water;
- knowing when the system is fully saturated;

- keeping cells fully saturated for testing period;
- ability to keep a steady flow into system; and
- ability to measure the time with stopwatch accurately.

<u>Data analysis</u>

Once the field testing was completed, data for monitored cells was analysed and compared. In order to convert the time taken for 9 litres of water to pass through the filter bed into an appropriate infiltration performance value, Darcy's law was used, as per the following equations:

$$Q = k\frac{dH}{L}A = k\frac{L+p}{L}A \qquad \text{Equation 7.1}$$

$$k = \frac{QL}{A\,(L+p)} \qquad \text{Equation 7.2}$$

wherein,

k = Infiltration rate [m/s converted to mm/hr]

Q = Flow rate through the system [m^3/s]

(equals *Volume of water added* i.e. 9 litres divided by *Time taken* to treat this volume)

L = Depth of filter material [m]

A = Cross sectional area [m^2]

P = Ponding depth [m]

Infiltration rate (IR) at a standard temperature of 20°C was calculated using Equation 7.3 below and reported:

$$\mathbf{k(at\ 20^{\circ}C)} = ((\mathbf{-0.0239} * \mathbf{ks} + \mathbf{1.571}) * \mathbf{temp(^{\circ}C)}) \text{...............Equation 7.3}$$

wherein,

k (at 20°C) = Infiltration rate at standard temperature

k = k at tested temperature

temp = temperature of potable water (°C) during testing

Further since three observations of flow rate were taken for every cell on a particular day, an average of the corresponding infiltration rates was reported for every event. The following data has been analysed:

- Variability in infiltration rate (k) between different events on a particular day
- Variation in infiltration rate (k) over a period of time and/or with volume of stormwater treated
- Variation in infiltration rate (k) with distance from the inlet to the system

Average infiltration rate of the entire system was estimated using field data. As it was not logistically feasible to measure the infiltration rate of all 60 cells in the field, IR of these cells was estimated through an extrapolation of IR of the nearby cells (whose field measurements has been undertaken). Trend lines were plotted to identify best fit line and nature of slope/fit across the length of the system and overtime.

7.2.3 Model development

A model was developed to investigate the rate of decline in infiltration rate (i.e. rate of clogging development) of these filter cells as stormwater was treated by the system. This model will help compare field performance trends with results from the laboratory experiments. Given that this is a demonstration system, the findings will also contribute to the future development of this technology and guide design of systems using such filter media. This can also be helpful to ascertain maintenance schedules of such systems in the field.

The model consists of following components (Figure 7.6) that are used in sequence:

1. the rainfall-runoff model simulates inflow into the system
2. the water balancing model that includes:
   - *water distribution model* to assess how much water is treated within a given time step; its distribution across different rows of the entire filter system; and cumulates total volume treated until a particular event; and
   - *infiltration rate regression model* that predicts decline of infiltration rate as simple function of cumulative treated volume and infiltration rate of filter and assesses the new infiltration rate of the system for the next time step using a decline rate.

Therefore this is continuous simulation of the infiltration rate decline over time, where the model inputs are rainfall at given time step of 6 minutes; system dimensions and; initial value of infiltration rate.

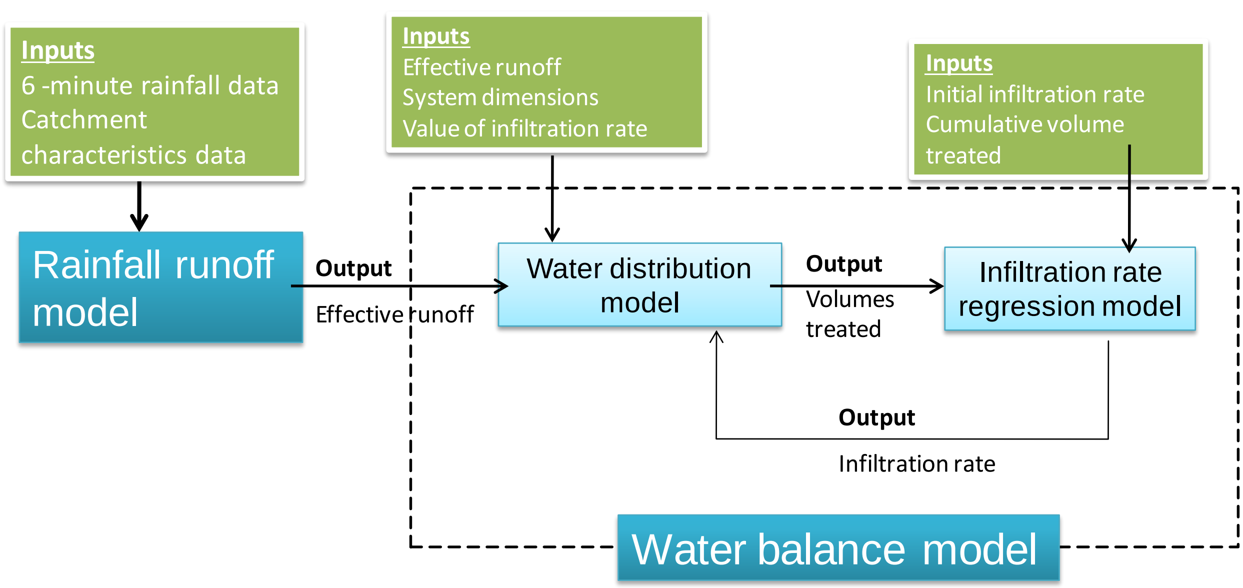

Figure 7.6: Inter-relation between the three components of model

Rainfall/Runoff model

A rainfall runoff model was developed using 6-minute rainfall data from the Melbourne Water's Notting Hill gauging station (2.8 km south-east of the site). This model converts rainfall into effective runoff considering an initial runoff loss of 1.0 mm and a routing bucket coefficient of 0.05 mm, as shown in Figure 7.7. Catchment area for the demonstration facility has been estimated to be 5000 m^2 when the filter system was designed in 2008 and includes roof areas (R1 to R6) and paved areas (P1 to P3), as shown earlier in Figure 7.1. All surfaces were observed to be directly connected to the system and were impervious. The imperviousness factor has therefore been assumed to be 100%.

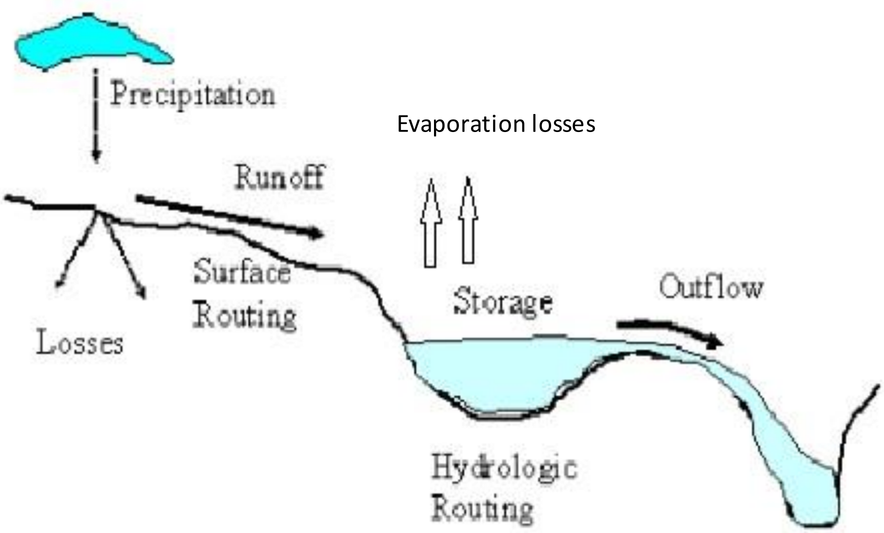

Figure 7.7: Rainfall runoff in the catchment

Total rainfall observed at this station (2592 mm) was comparable to total rainfall observed at Bureau of Meteorology's Glen Waverley (2695 mm) and Oakleigh weather stations (2412 mm) (BoM, 2014) for the duration of monitoring period (8th December 2009 to 7th June 2012).

The equations used for calculations in this model are as below:

i. Effective runoff (t) = Initial loss bucket (t)– Initial infiltration loss

   (if Initial loss bucket (t) > Initial infiltration loss, else zero)

ii. Routing bucket (t)= Effective runoff + Routing bucket (t-1) - Routed outflow (t-1)

iii. Routed outflow (t)= Routing bucket (t)x Routing coefficient (=0.05)

iv. Runoff created (t)= Routed outflow (t)x Catchment area

wherein,

Initial infiltration loss = 1 mm (eWater CRC, 2012);

Routing coefficient =0.05 (eWater CRC, 2012);

Catchment area = 5000 m^2

Water balancing model

Water distribution model: The following assumptions were made to model and analyse water flow within the system:

1. Any flow resistance within the porous pavement part of the filter (the top 50 mm of the filter) was ignored, since it is negligible in relation to the resistance within the other parts of the filter (Figure 7.2). This assumption is in line with the findings from our laboratory work for layered systems[4] (Figures 4.7-4.10), as discussed in Section 4.3.3, where it was found that hydraulic performance of the finest media controls overall performance of the layered system.
2. It was assumed that all 30 rows perform similarly and have an initial infiltration rate of 2000 mm/hr. This also means that any effect of longer drying period on the cells located at the remote end of this system is neglected and all cells perform with same/comparable treatment efficiency. Thus we can group two cells to form one row and likewise club a few rows to make the computational process efficient and easier.

[4]Since the field systems resembled the layered configurations tested in the laboratory, they have been compared with layered systems

3. The size of the system and each cell is given in Figure 7.8.The maximum volume of stormwater that each row (2 cells) can hold was calculated to be 53 litres assuming 35% porosity of fine filter media layer (e.g. as found in Yao et al., 1971; Mays and Hunt, 2005) and 50% porosity of upper coarse media (Siriwardene, 2008).
4. As discussed earlier, a part of the system is located next to a sandpit in the school play area (cells 4-12 are immediately next to the sand pit as shown in Figure 7.3). It is however assumed that any sand that gets into the system from the play area is not impacting the hydraulic performance of the system.
5. A row of system (that comprises of two cells, Figure 7.4) starts filtering water only when its upstream rows cannot process all the incoming inflow. An overflow from the system to the stormwater drainage system occurs once ponding on top of the entire systems exceeds 0.15 m.
6. As water overflows through to the downstream cells, no treatment occurs in the upstream cells (i.e. sediment concentration in stormwater entering the different cells across all rainfall events are similar/ comparable).

Following these assumptions, the water balance analysis was undertaken for the field system, as per conceptual model shown in Figure 7.8. Two cells of a given row were combined assuming that they treat the same amount of stormwater in a similar way. Effective runoff first reaches Row 1 (comprising of cells L1 and R1) and fills in the cell volume comprising of voids in the filter bed, sediment trap and the free space in each of the cells. The cells treat stormwater at a rate proportional to the infiltration rate of the respective cell (i.e. in accordance with Darcy's Law). When the cells in a particular row are full, they start discharging/ overflowing to downstream rows. Any excess volume of untreated flow from Row 1 (i.e. the volume of inflow minus treated outflow and storage in this cell for a given time step) flows into the cells in Row 2 and so on and so forth.

Stormwater available in each cell percolates and gets treated within the filter bed and treated water flows into the storage tanks through the collection system. Therefore, in case of an event that creates runoff, there is a continuous process of filling, treating, emptying and overflowing. During a rainfall event, once all rows are in operation and effective runoff is greater than the capacity of the system (equal to volume of water held by all cells minus outflow), water start ponding on top of permeable pavement. Once ponding exceeds 0.15 m depth, an overflow occurs from the system to the stormwater drainage system. As the cells clog overtime (i.e. with the volume of stormwater treated), their infiltration rate drops and therefore the volume of water treated drops. The model was run for 6 minute time intervals, since that was the lowest time resolution of the rainfall data.

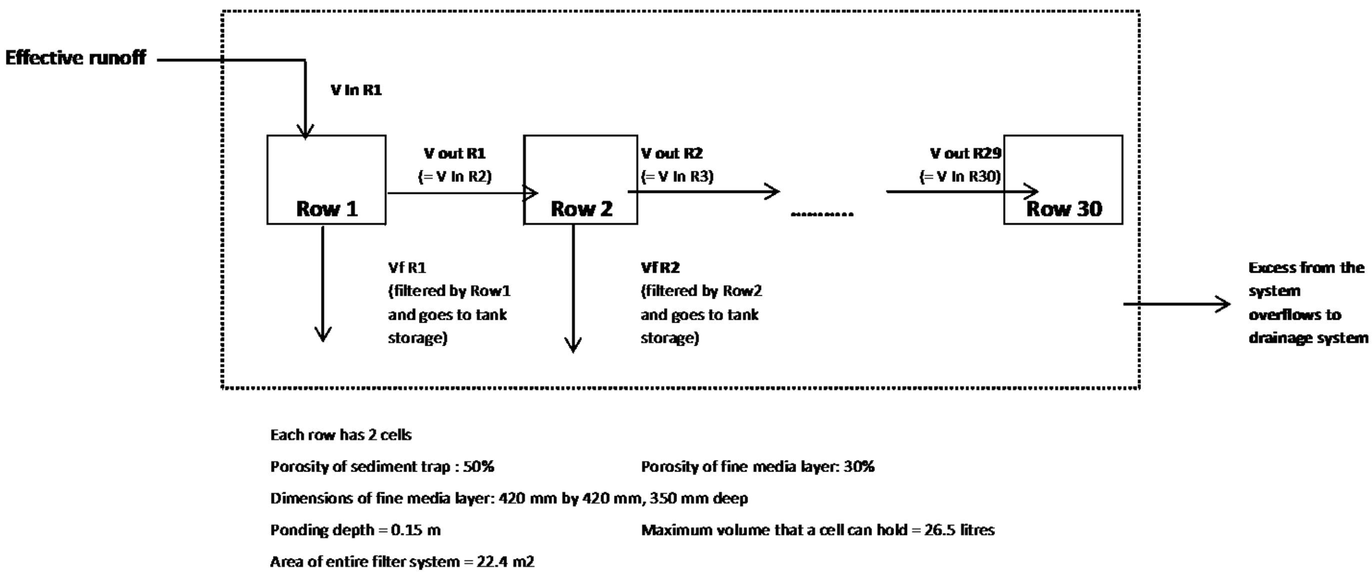

Figure 7.8: Water balance for the filter system

The equations used for calculations in this model (as an illustration for Row 1) are as below (also refer Figure 7.8):

i. $\text{Volume IN}^{Rj}(t) = \text{Volume IN}^{Rj}(t-1) + \text{Runoff created}(t) - \text{Volume filtered}^{Rj}(t-1) + \text{Volume Out}^{Rj}(t-1)$

ii. $\text{Volume Out}^{Rj}(t) = \text{Volume IN}^{R1}(t) - \text{V max}^{Rj}$ (if $\text{Volume IN}^{R1} > \text{Vmax}$)

wherein,

Volume IN ^{Rj} = Volume in the two cells of Row j

Volume Out ^{Rj} = Volume leaving Row j and entering Row j+1

Runoff created (t)= Obtained from rainfall runoff model

Volume filtered ^{Rj} = Volume filtered by two cells of Row j (and is proportional to the instantaneous infiltration rate *(obtained from the Infiltration rate regression model)*

V max ^{Rj} = Maximum volume that the two cells in Row j can hold (= 53 litres)

Infiltration rate regression model: The decline in infiltration rate is related to the mass of sediment retained by the filter bed, as also observed from laboratory experiments. The amount of sediment trapped is in turn a function of the amount of water treated by the system and its treatment efficiency. Since the treatment efficiency of a modular system like this is rather constant with time, the main assumption for this component of the model is that decline in infiltration rate of each infiltration cell is a simple function of the total volume treated by the cell.

Analysis of decline in infiltration rate for the column configurations tested in the laboratory suggests that the decline trends can be linear or exponential (refer Figures 4.3, 4.5 (left), 4.7). Accordingly, following two different approaches have been assumed and tested for field based system:

- Linear relationship between infiltration rate and the cumulative treated volume, and
- Exponential relationship between infiltration rate and the cumulative treated volume.

Linear regression model: The coefficients of linear decline in infiltration rate with cumulative treated volume were calculated for all tested experimental designs. This was done by using data from the start of the column's operations until they reached 80% of their initial infiltration capacity. 80% threshold has been selected as replicates have huge variations in their infiltration rate for the last 20% life and measurement errors/uncertainty in measuring low values of infiltration rates will be higher. The linear regressions between infiltration rate and cumulative treated volume for lab columns are shown in Table 7.1. Decline values for enviss™ systems, obtained from a past laboratory study for improved filter design (Monash University, 2010), have been also included.

Table 7.1: Decline rates for different filter designs tested in the laboratory

Experimental design (tested in lab)	Initial Infiltration Rate (mm/hr)	Linear decline		Exponential decline	
		Decline Rate (mm/hr per Normalised volume of stormwater treated in meter)	R^2 value	Decline Rate (mm/hr per Normalised volume of stormwater treated in meter)	R^2 value
Base case	87689	−5123	0.85	−0.100	0.71
100 mm deep filter bed	68225	−4458	0.95	−0.110	0.91
500 mm deep filter bed	95645	−3837	0.90	−0.070	0.72
Particle size of filter media: 0.5 mm	1227	−425	0.91	−0.730	0.89
Particle size of filter media: 5 mm	170434	−667	0.90	−0.006	0.94
2-layered system: 0.5 mm and 2 mm	2195	−267	0.99	−0.230	0.91
2-layered system: 2 mm and 5 mm	118265	−2939	0.89	−0.046	0.74
3-layered system: 0.5 mm, 2 mm and 5 mm	2256	−393	0.98	−0.320	0.94
Mixed filter bed	10395	−1998	0.97	−0.390	0.80
enviss™ systems in lab	2525	−48	0.95	−0.030	0.97

The following simple equation was then used to assess infiltration rate of each cell at the end of each event and this then is the new infiltration rate for the next rainfall event:

$$k_{t+1} = k_t + a * (V_{t+1} - V_t) \qquad \text{Equation 7.4}$$

wherein,

k_{t+1} = Infiltration rate of cell at time t+1 (mm/hr)

k_t = Infiltration rate of cell at t (mm/hr)

V_{t+1} = Normalised volume of stormwater treated till event t+i (m) *(calculated as Volume of stormwater treated (m^3)/ Area of cell (m^2))*

V_t = Normalised volume of stormwater treated till event t (m)

a = Rate of linear decline (negative value; mm/hr per normalised volume (meter) of stormwater treated)

k_t at the start was assumed to be 2000 mm/hr (based on data from the laboratory (Monash University, 2010))

Exponential regression model: Similar approach was followed for developing a model with an exponential rate of decline and tested using same laboratory data. The calculated exponential decline rates are listed in Table 7.1. Equation 7.5 was used to assess infiltration rate of each cell at the end of each event and this then is the new infiltration rate for the next rainfall event.

$$k_t = k_o * e^{-bV} \qquad \text{Equation 7.5}$$

wherein,

k_t = Infiltration rate of cell at event i (mm/hr)

k_o = Initial infiltration rate of the cell (assumed to be 2000 mm/hr based on data from the laboratory)

V = Normalised volume of stormwater treated till event t (m) *(calculated as Volume of stormwater treated (m^3)/ Area of cell (m^2))*

b= Rate of exponential decline (negative value) (mm/hr per normalised volume (meter) of stormwater treated)

<u>Model Application</u>

The model (Figure 7.6) was run for about 2.5 years of rainfall data; 6-minute rainfall data series from 8th December 2009 to 7th June 2012. During this period the catchment received 2.59 m of rainfall. For all cells, infiltration rate was assumed to be 2000 mm/hr at the start of the modelling period. Manual calibration of the decline rates (both linear coefficient: a, and exponential coefficient: b) was then undertaken by maximising the sum of squared errors (R^2 values) and the Nash-Sutcliffe model efficiency coefficient (E-value) between observed and modelled infiltration rates. The initial values of these parameters were first tested using decline values from laboratory columns and eventually assumed to be around the same values as the laboratory values found for the enviss™ system (Monash University, 2010) because of its comparable infiltration rate. These values were than varied in step changes until E and R^2 were optimised. In general around 50 runs of each model were performed before the optimised values were obtained. Although this is not an ideal approach to a model calibration (e.g. far more sophisticated methods could have been used to calibrate the model, e.g. Dotto et al., 2011), it was deemed sufficient since the proposed model had only one calibration parameter (either coefficient a or b).

7.3 Results and discussions

7.3.1 Field findings

Uncertainties in field measurements of infiltration rate

Field tests of infiltration on the same day clearly suggest uncertainties with the measurement of infiltration rate, as shown in Figure 7.9. Accordingly, three observations of infiltration rate were taken for each cell on a particular day. This observation is in line with findings of the laboratory studies, as mentioned in earlier chapters and shown in Figures 7.10 for a filter bed with layers of filter media. This reflects the natural variability in performance of filters using these media and reconfirms uncertainties associated with infiltration rate measurement techniques.

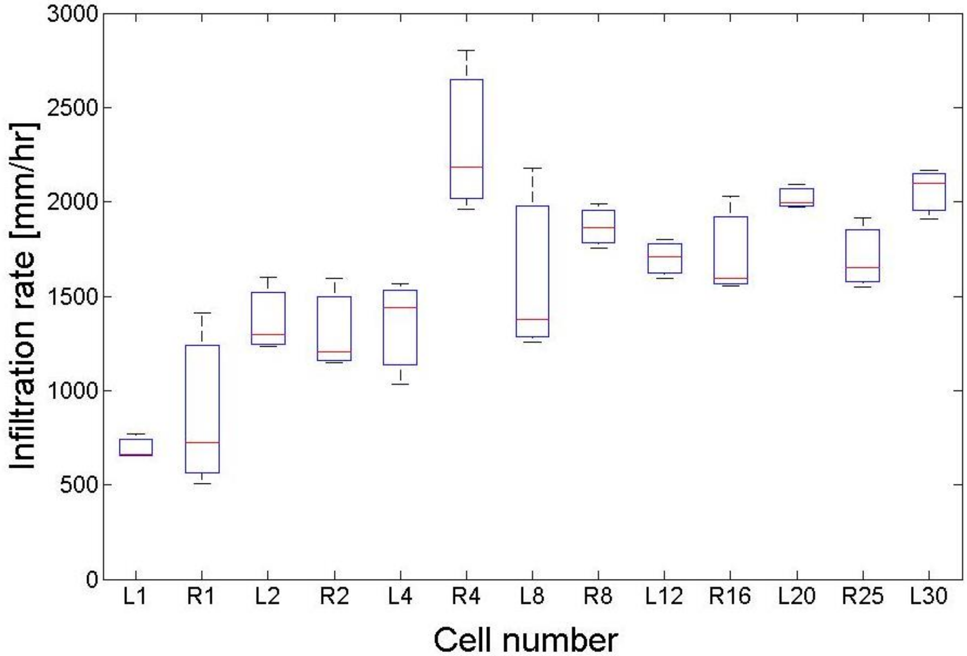

Figure 7.9: Variation in infiltration rate of different cells in the field as measured on 19th April 2011 (Note: L8 is cell in the 8th row to the left as per Figure 7.4 and likewise)

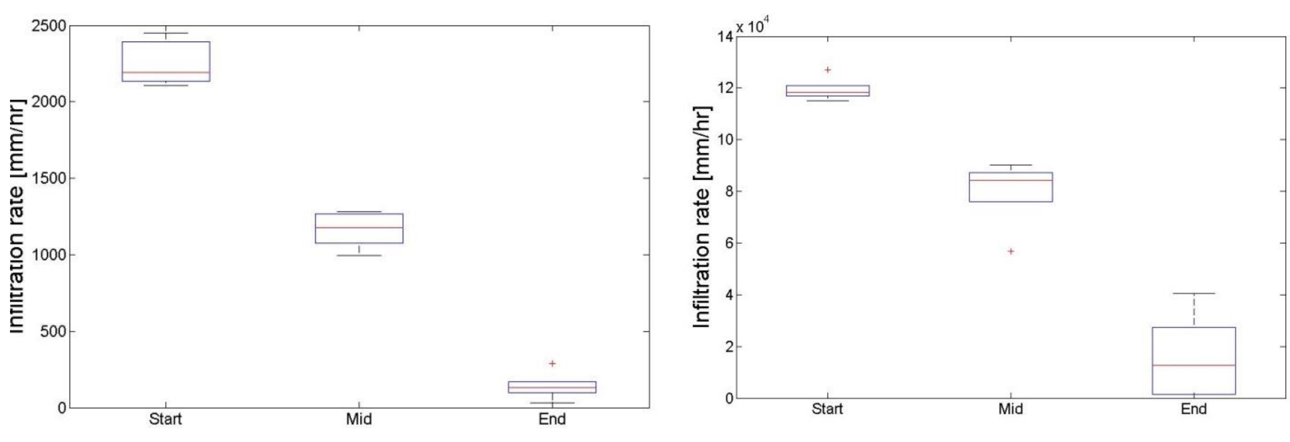

Figure 7.10: Variation in infiltration rate of the five replicates of laboratory columns with 2-layered filter design using: 0.5 mm and 2 mm sized filter media (left) and; 2 mm and 5 mm sized filter media (right)

Change of Infiltration rate over time

All field testing results clearly suggest that infiltration rate declines over a period of time. E.g. Figure 7.11 shows the evolution of the average infiltration rate of the entire system overtime. With time, the cells treat more stormwater, remove sediment and eventually get clogged as the removed sediment blocks the pores of the filter media. Interestingly, the decrease in filtration rate is not uniform. Possible explanations include uncertainties in the data collected; the effect of drying and wetting cycles on porosity of filter beds and irregular rainfall. Evolution of infiltration rate with volume of stormwater treated has been modelled and presented in the next section.

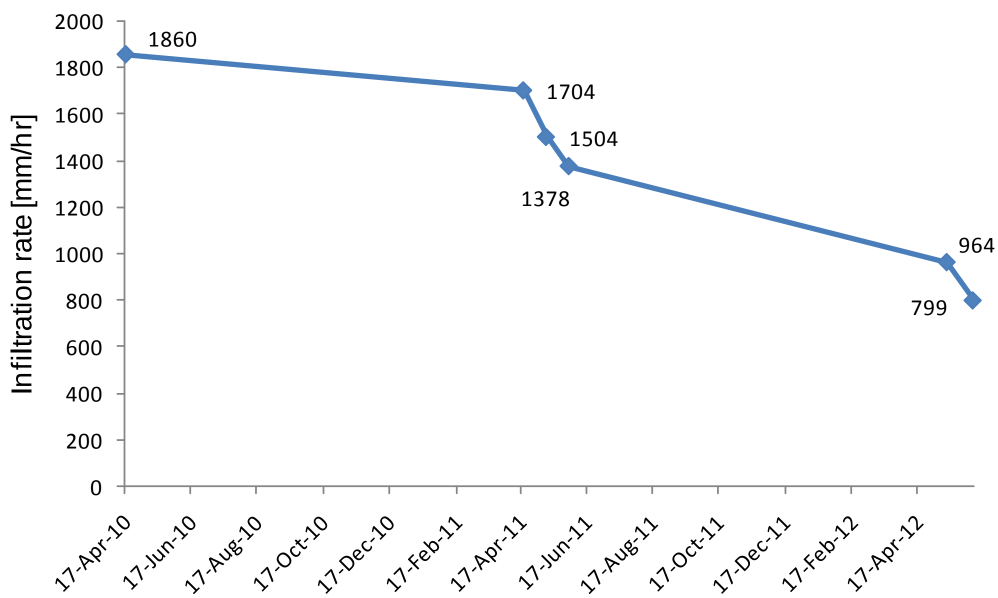

Figure 7.11: Change in average infiltration rate of the entire system overtime as observed in the field

Figure 4.7 shows the evolution of infiltration rate of layered systems in the laboratory, wherein it was observed that infiltration rate is constant initially and then declines steadily as stormwater is treated by these systems. Therefore comparison of the field systems with results from laboratory experiments suggests similar performances.

Change of infiltration rate with the distance from the inlet

It has been visually observed that the extent of clogging of the filter cells decreases as the distance of the cell from the stormwater inlet increases. Figure 7.12 shows pictures of the top of the cell and compares R1 and L30 on the same day to reflect this difference in extent of clogging.

(a) (b) (c)

Figure 7.12: Clogging of systems: **a)** Porous pavement in Row L-30; **b)** Porous pavement in Row R-1 and; **c)** Clogged filter media of cell R1 after porous pavement has been removed

Figure 7.13 shows the differences in infiltration rate of the first and last row from the inlet (R1 and R30) overtime. This directly reflects that cells closer to the inlet received comparatively more stormwater and hence clogged earlier than their counterparts located further from the inlet even though they have comparable infiltration rate at the start.

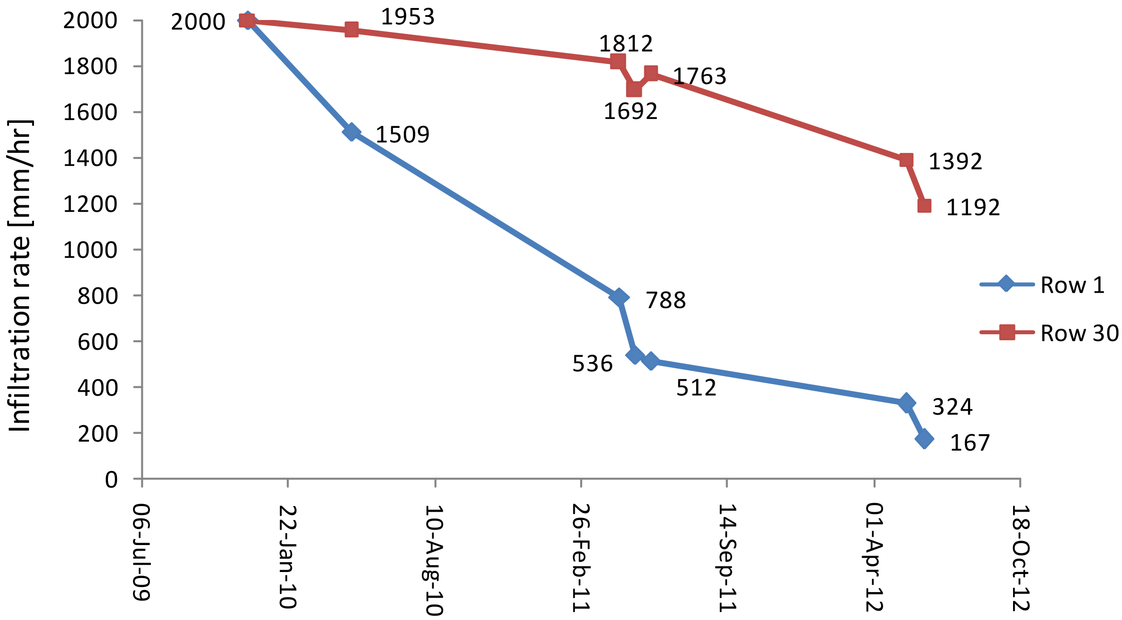

Figure 7.13: Evolution of infiltration rate of cells in Row 1 and Row 30 during the entire monitoring period (as observed in the field)

These findings from the field are similar to those observed in the laboratory wherein it was found that filters receiving more stormwater clog quickly as compared to those receiving lesser stormwater. Lab results, as discussed in Section 5.3.4, showed statistically significant performance differences for filters dosed with different volumes of stormwater as also shown in Figure 5.7 ($p=0.008$ for total volume of stormwater treated before clogging and $p=0.002$ for total sediment removed before clogging).

Plotting a trend line between the observed field infiltration rate for the entire length of system (all 30 rows) suggests that decline in infiltration rate across the system for each event can be expressed logarithmically (Figure 7.14). However, it was found that Row 4 is an outlier on the graph, which may be because R4 is next to the sandpit and may be getting influenced by sand from playing activity. As sand from external activities gets into the system, it is likely to get into the filtration cell during the next rainfall event and block filter pores, leading to clogging. Excluding results of R4 gave better coefficients of determination. There is therefore a good relationship that as the distance from the inlet increases the infiltration rate also increases. This is similar to observations from laboratory i.e. infiltration rate declines in proportion to the volume of stormwater treated (as discussed earlier, see Figures 5.7).

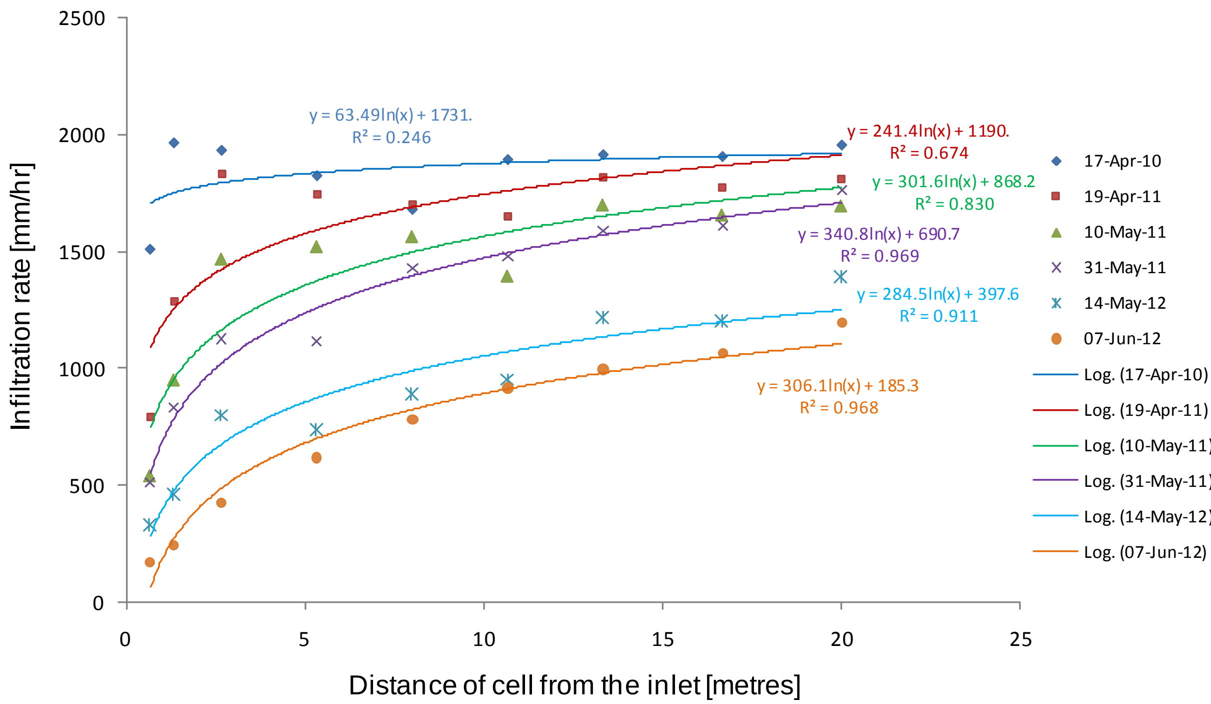

Figure 7.14: Change in average infiltration rate (field) of all rows with distance from the inlet

7.3.2 Model application

The findings from the models suggest that this system was able to treat around 85% of the effective runoff received by the system over the monitoring period. This is in accordance with the initial design estimate wherein the system was designed to treat up to 90% flows generated in the school catchment (Monash University, 2010). The calibrated linear and exponential decline rates are shown in Table 7.2.

Table 7.2: Linear and Exponential equations of decline for the field systems

Linear decline	Exponential decline
$k_t = 2000 - 0.84 * V_t$ ....Equation 7.6 wherein k t = Infiltration rate of cell at time t (mm/hr) V t = Normalised volume of stormwater treated by the cell (m) Infiltration rate at the start was assumed to be 2000 mm/hr Rate of linear decline (a) = (-) 0.84 mm/hr per metre (normalised volume) of stormwater treated	**$k_t = 2000 * e^{-0.0006527 * Vt}$** ....Equation 7.7 wherein k t = Infiltration rate of cell at event t (mm/hr) V t = Normalised volume of stormwater treated by the cell (m) Infiltration rate at the start was assumed to be 2000 mm/hr Rate of exponential decline (b) = (-) 0.0006527 mm/hr per metre (normalised volume) of stormwater treated

The figures below show the results of distribution of the values of infiltration rate as observed in the field and predicted by the linear decline model (Figure 7.15a) and exponential decline model (Figure 7.15b). Table 7.3 lists the calculated R^2 and E-values for different rows individually and the entire data set for both models developed here.

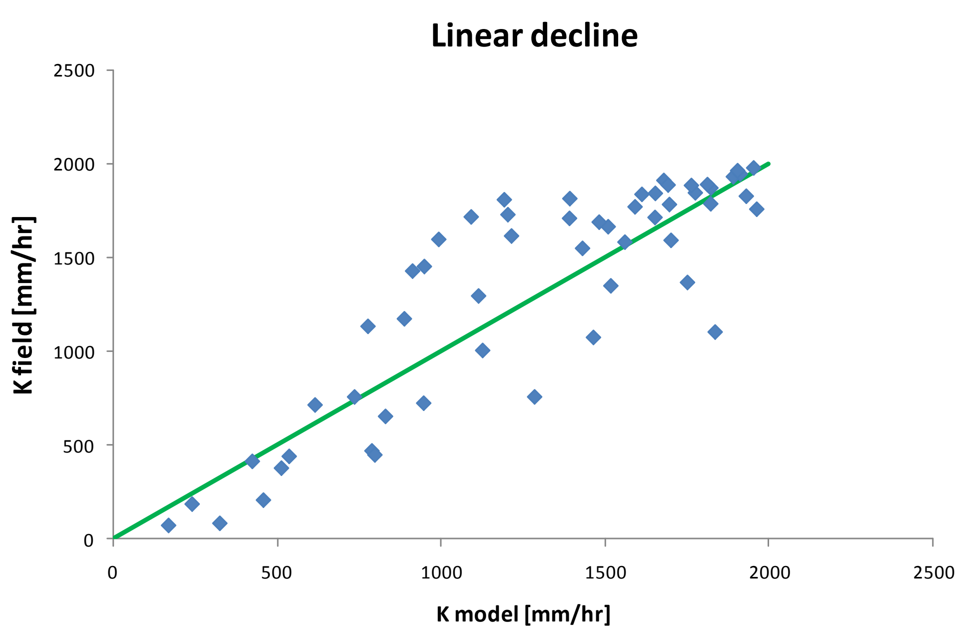

Figure 7.15a: Comparison of the results of infiltration rates observed in the field as against the infiltration rate calculated using the Linear decline model

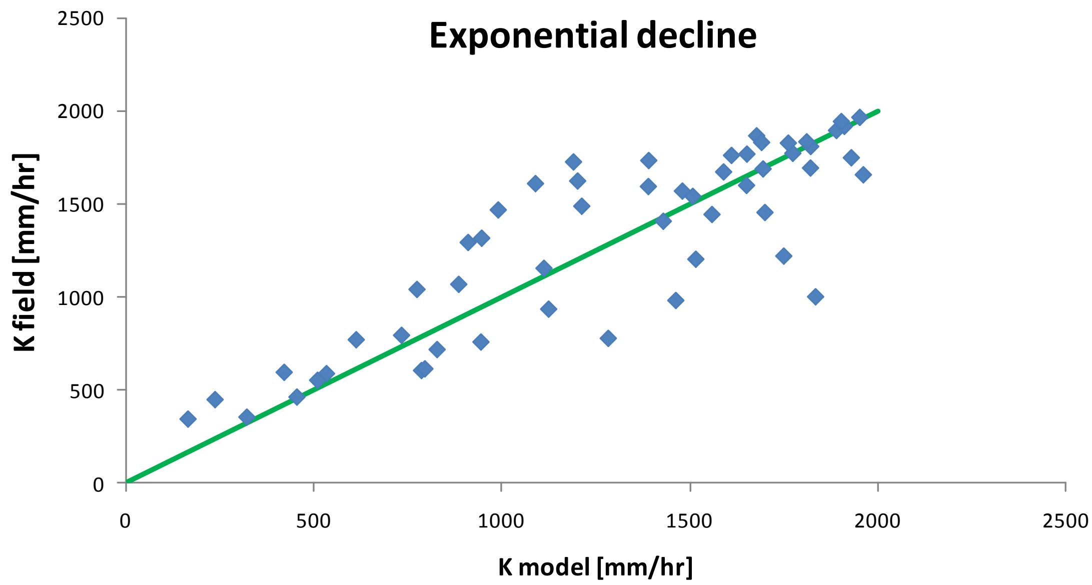

Figure 7.15b: Comparison of the results of infiltration rates observed in the field as against the infiltration rate calculated using the Exponential decline model

Table 7.3: R^2 values and E-values from comparison of field observations and modelling results (linear and exponential decline models) for infiltration rate

Row number	Linear		Exponential	
	R^2 value	E value	R^2 value	E value
R1	0.95	0.81	0.94	0.94
R2	0.94	0.76	0.89	0.77
R4	0.80	0.53	0.68	0.40
R8	0.85	0.83	0.76	0.69
R12	0.86	0.65	0.77	0.74
R16	0.95	0.10	0.93	0.56
R20	0.87	0.12	0.84	0.50
R25	0.91	-0.47	0.88	0.07
R30	0.85	-0.52	0.83	-0.05
R^2 value all rows	**0.76**		**0.74**	
E- value all rows	**0.67**		**0.73**	

Overall performance of the model: In general the model performed well in predicting the measured results. E-values of around 0.7 can be regarded as very good for a conceptual model with one calibration parameter only. However, the modelled infiltration rate of a few rows was not close to the measured; in particular Row R4 and a few rows towards the extreme end of the system were not modelled well. This model can therefore predict the performance of such system overtime and in relation to volume of water treated. This model could be customised and used both by designers and operational staff to design and maintain such filter systems.

The low model performance for Row 4 (please refer Figures 7.3 and 7.15) could be because of the presence of sandpit next to the filter system. As discussed earlier cells 4-12 were located immediately next to the sand pit that may be directly affecting the infiltration rate of the nearby cells. This suggests the need to adequately site such systems in the field to reduce interference from surrounding activities that may eventually clog/affect their longevity.

Low performance for Rows 25 and 30 could be because these cells experience extreme drying regimes (as compared to other cells), which is not taken into account by this model, although it was found to have a significant impact on porous pavement systems (Yong et al., 2013).Moreover these cells are likely to receive less sediment load for every event as compared to cells located upstream in the system because some sediment will be trapped in the porous pavement grates of the upstream cells before it reaches these cells. Therefore the assumption made earlier regarding ignoring the flow resistance within the porous pavement part of the filter is not accurate and therefore in an ideal case, the model should be developed for the complete system comprising of both top porous pavement section and fine filter system beneath.

Comparison of the Nash-Sutcliffe model efficiency coefficients obtained for two rates of decline suggests that the exponential model predicts performance of field system in a slightly better way. It is therefore proposed that an exponential rate of decline, as in Equation 7.7, be used to calculate the infiltration rate of these systems in the field. However, this equation needs to be used carefully calibrated as decline rates are very specific to the initial infiltration rate of the filter bed (as can be found based on a comparison of decline rates in Table 7.1).

Analysis of the decline of infiltration rate (as observed in the field) with volume of stormwater treated (calculated using an exponential decline rate) has been presented in Figure 7.16 and reconfirms similarities with findings from the laboratory (as made in earlier sections). This suggests that other factors such as the ingress of sand, role of porous pavement and drying and wetting regimes are affecting the system performance in some way.

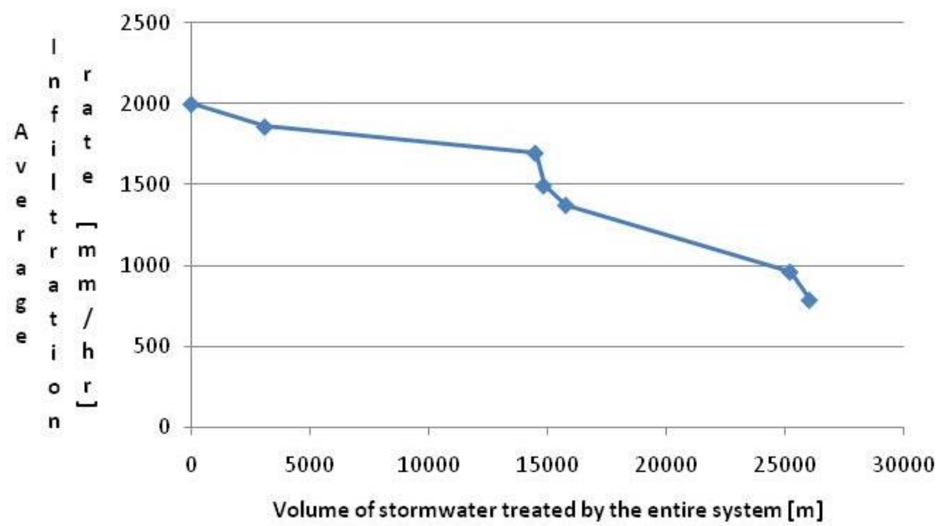

Figure 7.16: Change in average infiltration rate of the entire system (field observations) with modelled (exponential) volume of stormwater treated by the system

<u>*Comparison of decline rate with laboratory findings:*</u> The coefficients of declines for the field system were very different to various designs tested in the laboratory (listed in Table 7.1). These differences could be because of one or more of the following reasons:

1. The system in the field uses filters with fine media as compared to the coarser media used in the laboratory. This eventually affects the initial infiltration performance of the system in field. E.g. 2 mm sized filter media tested in the lab had a median IIR of about 98,000 mm/hr (which is 49 times that of the field system).
2. The presence of a continuous system in the field with 30 rows and 60 cells as against an individual column in the lab is likely to have some effect on overall decline patterns.

3. The sediment concentration in the inflow to the Syndal facility was found to be much lower (ranging from 3.3-178 mg/L and a median of 10 mg/L (Monash University, 2010)) than what has been used in laboratory experiments (150 mg/L). TSS concentrations in the inflow have been found to affect the longevity and the rate of decline of infiltration rate in granular filters as found and discussed in Section 5.3.1 (Figure 5.1).
4. The system in the field has chlorine tablets which impacts biological clogging processes as found earlier and discussed in Chapter-6.
5. Further experiments in the laboratory were undertaken with a compressed time scale, controlled conditions in a greenhouse and using synthetic stormwater. This may also contribute to the observed variations.

Even though no effect of drying and wetting regimes were observed in laboratory based columns (refer Section 5.3.5), modelling results indicate some impact of drying and wetting in the field. This is possible as field conditions are much different (complex and extreme as compared to the conditions in green house lab). Also since our lab systems use coarser media as compared to field systems, it is likely that effect of drying and wetting may be related with the particle size of filter media. However, these dissimilarities suggest that drying and wetting cycles may be an important factor affecting performances of these filters and needs further investigations in the field and modelling.

7.4 Conclusions

Analysis of decline of infiltration rate (as observed in the field) with time and/or volume of stormwater treated reconfirms laboratory observations that the infiltration rate is constant initially and then experiences a quicker decline. Analysis of infiltration rate across the length of the system suggests that when the distance from the inlet increases the infiltration rate also increases, as observed in the laboratory. These findings from the field are similar to those observed in the laboratory wherein it was found that filters receiving more stormwater clog quickly as compared to those receiving lesser stormwater.

Even though no effect of drying and wetting regimes were observed on laboratory based columns, modelling results indicate that this may be an important factor affecting performances of granular filters and needs further field investigations and modelling.

A simple model has been developed to predict the rate of decline in infiltration rate of these filters and results compared with field observations. Two approaches (linear decline and exponential decline) were used to estimate the nature and rate of decline of infiltration rate of these cells with volume of stormwater treated. Comparison of results of modelled infiltration rate with field observations was made using R^2 and Nash–Sutcliffe model efficiency coefficients. Results suggest that the exponential model predicts performance of field system in a better way and an equation was developed. However, this equation needs to be used carefully given that decline rates are very specific to the initial infiltration rate of the filter bed and site conditions such as sediment load in inflows.

The field study also suggests that the sand pit located next to the filter system was impacting the performance of this system (as observed for cells in Row 4). This suggests the need to adequately site such systems in field to reduce interference from surrounding activities that may eventually affect their longevity.

8 Conclusions and Recommendations for Future Research

8.1 Summary

The research plan for this PhD thesis has been based on findings from literature review, which suggest that clogging is very specific to the characteristics of filtration media, influent and nature/dynamics of stormwater application. The aim of this research was therefore to study clogging processes in the context of non-vegetated granular filters with a high infiltration rates that can be used for stormwater treatment operating intermittently.

In the first part of this research (Chapter 3), different granular filter media presenting various grain shapes from diverse materials have been tested across a range of flow-through rates to understand the impact of filter media's physical characteristics (e.g. shape and material type of the media) on the clogging of the filters. While, it was found that while angularity and smoothness of filter media may not be important for design, the flow rate through the stormwater treatment system is a key design aspect that needs to be considered. Since the shape and smoothness of filter media particles were found to have a limited effect on the clogging performance of most filter media, the next set of experiments were conducted using zeolite, which was selected because of its low cost; easy availability; and its frequent use in water treatment. These experiments (as in Chapters 4, 5, and 6) have been carried out under free flowing conditions, corresponding to a zero head loss[5].

[5]Due to logistical reasons, it was not possible to undertake these experiments (with 17 designs and 5 replicates each) for each of the 4 flow rates tested in Chapter 3.

The second part of this PhD research (as presented in Chapter 4) aimed at understanding the effect of filter bed's design/construction on the clogging of the filters. Different design parameters of the filter such as depth, particle size, number and composition of layering of the filter have been varied. Evolution of hydraulic performance and sediment removal performance overtime and the location of clogged material has been studied.

The next stage of this research (Chapter 5) aimed to develop an understanding of the effect of the operational conditions, including characteristics of stormwater and the way it is applied to clogging of these filters. Variations in hydraulic performance and sediment removal performance overtime and the location of clogged material have been investigated.

While clogging of a filtration system can be due to physical, biological and chemical processes, limited research has been conducted to date to investigate biological clogging in stormwater treatment filters. This part of research aimed to investigate the effect of biological clogging on the infiltration performance and longevity of high flow rate filters treating stormwater.

In the last part of this research, a field study was undertaken to assess and model the evolution of clogging of a multi-cell system using non vegetated filters for stormwater harvesting. Data from this field system was analyzed and observations were compared with findings from laboratory studies. An exponential relationship between decline of infiltration rate and cumulative volume of treated stormwater to predict the system's hydraulic performance was developed.

This research has therefore provided both theoretical and practical insights which will be useful in the development and application of stormwater infiltration systems that use filters with high infiltration rates for both stormwater harvesting and protection of receiving waters from stormwater pollution.

This following section provides key findings from different experimental studies undertaken in this study and recommendations for further work are discussed.

8.2 Strengths and weaknesses

Very limited studies have been undertaken to evaluate and understand clogging processes in the context of stormwater treatment systems (e.g. Le Coustumer et al., 2007; Siriwardene et al., 2007; Hatt et al., 2008; Le Coustumer et al., 2008; Li and Davis, 2008a; Bratieres et al., 2012; Yong et al., 2013). However, most of these existing studies have been undertaken either for vegetated filters or for filters with low infiltration rates. Given the importance and specific nature of clogging in stormwater filtration systems, it is necessary to understand clogging processes in context of non-vegetated systems that have high infiltration rates.

The major strengths of the present research program are discussed below and the novel findings have been presented in the next section:

- Current clogging studies in stormwater treatment systems have been limited to fine filter media (e.g. Hatt et al., 2008) or coarse gravel media (e.g. Siriwardene et al., 2007). Clogging of filter media of particle size range between 1 mm and 5 mm has not been studied, even though some commonly used stormwater filters use coarse filter media (Clark and Pitt, 1999; Bratieres et al., 2012). Given that the size of filter media (and hence the infiltration rate of the system) could be a key factor affecting clogging, this study assesses the overall performance of different filter media (zeolite, scoria, riversand and glass beads) of this size range for stormwater treatment using four different flow-through rates.
- This study undertook experiments to develop an understanding of the effect of filter bed design and operational conditions (i.e. stormwater characteristics) on the hydraulic and treatment performance of zeolite-based stormwater filters and the nature of its clogging. These studies thus aimed to understand the

processes behind the clogging phenomena in context of gravity fed high infiltration rate stormwater treatment filters that are operated intermittently (i.e. only during wet weather).

- It is usually perceived that biological clogging may not be prevalent in stormwater infiltration systems given that stormwater flows are intermittent in nature, with high sediment load and low levels of organic matter and nutrients in comparison to other water types. However, the abundance and nature of microbes in stormwater (McCarthy et al., 2012) does imply that biological clogging could be an important process which needs investigation. Therefore, it is pertinent to investigate the occurrence of biological clogging in context of non-vegetated stormwater filters with high flow rates. This study has used a laboratory based approach to investigate the effect of biological clogging on the infiltration performance and longevity of high flow rate filters treating stormwater.
- Field verification has also been attempted and confirms some of the main laboratory findings. A model to predict the performance of granular media in the field has also been developed.

These studies were undertaken in the lab using columns. There is a likelihood that side-wall effects may come into play i.e. increased flow near the smooth column wall due to decreased viscous resistance and tortuosity. However, these effects may be minimal at the high infiltration rates observed in this study. Further, the ratio of experimental column diameter to filter particle diameter was as recommended for filtration studies (Lang et al., 1993).

Similar to other studies (Hatt et al., 2007; Siriwardene et al., 2007; Bratieres et al., 2008; Bratieres et al., 2012), the experiments have been ‘compressed in time’, where months of operational life of the systems were conducted in several weeks due to time constraints. It is acknowledged that real time weather events should have been used to decide the dosing regime in these lab based experiments. The author recognises that long-term performance of stormwater filters is a critical issue but cannot be addressed in the timeframe of this research program. It is therefore suggested that any future work that investigates this subject further should design a dosing regime which accounts for the stochastic nature of rainfall events and allowing adequate drying in between dosing events.

Synthetic stormwater has been used instead of real stormwater in these laboratory based experiments. This is a weakness as real stormwater would best represent site conditions and constituents (physical, chemical and biological characteristics). Use of natural stormwater was not possible for logistical reasons – the high volume required for the tests and the timing of rainfall meant that using actual stormwater was not possible. The use of artificial stormwater also ensured a fairly consistent composition of inflow for the experiments and has been used in earlier clogging studies (e.g. Hatt et al., 2007; Siriwardene et al., 2007; and Bratieres et al., 2012). This also avoided any change in quality of real stormwater with time after collection.

The focus of these experiments is limited only to sediment/ total suspended solids (TSS) in stormwater. A possible shortcoming is that other pollutants of concern associated with stormwater such as microorganisms, oil and grease, and heavy metals have not been studied. However, earlier studies suggest that majority of stormwater pollutants are attached to sediment (Han et al., 2006; Francey et al., 2010). Therefore, removal of suspended sediment is critical for the treatment of a wide range of stormwater pollutants.

It is acknowledged that other methods such as elemental analysers (EA) are better as compared to the Loss on Ignition (LoI) method used to ascertain specific percentages of carbon and nitrogen for biological clogging experiments but could not be undertaken in this study because of logistical reasons. Future investigations should consider using EA or better methods to assess the amount of biological matter in clogged filter media.

An attempt was made to verify the lab work in field conditions, however with a mixed success. It was hard to find a high flow stormwater filter in Melbourne that we could monitor, so we focused on a system that have medium flow through rate (much lower than system studied in the lab). So the field work component has strengths and weaknesses: (1) at least some form of field verification was attempted confirming some of the main laboratory findings, but (2) unfortunately the monitored system had some differing characteristics than the media studied in the laboratory.

8.3 Key findings and contributions to practice

Review of existing literature suggests that the nature of clogging is different across systems and influents. It is specific to factors like the type of filter media, filter media characteristics, influent characteristics and the interplay between them. Further, limited research has been conducted to date to investigate biological clogging in stormwater treatment filters. Therefore, an understanding of the processes and factors which influence these processes (filtration media, influent and nature/dynamics of stormwater application) is important. This would help in reducing clogging rates and eventually enhance longevity of these systems with reduced maintenance needs. The aim of this research therefore was to study clogging processes and factors which influence the performance of non-vegetated granular filters with high infiltration rates that can be used for stormwater treatment.

<u>**Effect of type of filter media and flow through rate**</u>

Impacts of both flow rate and media characteristics (e.g. angularity and smoothness) on stormwater filter media pollutant removal and clogging performance suggests that flow rate plays a dominant role. There was strong evidence that low flow-through rates (due to restricted outlets) improves the overall performance of the filter system and diminishes the relative importance of the media characteristics. The treatment efficiency of filters with restricted outflow was also found to be greater than for filters with unrestricted flow rates, thereby leading to a greater removal of sediment over their lifespan. Therefore, while angularity and smoothness may not be important for design, the flow rate through the stormwater treatment system is a key design aspect that needs to be considered as it controls the residence time of influent in the system and also guides pollutant removal. The infiltration rate of a system to be designed will be guided by the objectives of the system – whether to treat more volume of stormwater or to achieve better treatment performance, greater longevity and less frequent maintenance.

Further, while the choice of filter media may be guided by local availability, it was necessary to investigate the structural stability of filter media such as its breakage over time and its effect on the stability of filter bed. For instance, scoria-based filters were found to be highly variable in performance, most likely due to the breakdown of its particles.

Effect of design of filter bed

Design parameters were varied to study the effect of filter bed design on clogging and sediment removal performance of granular stormwater filters (filter media particle sizes; depth of the filter bed and; different filter media packing configurations). The results showed the design of filter bed affects the hydraulic performance and sediment removal performance of non-vegetated high flow rate stormwater filters.

A decrease in the size of filter media's particle size eventually reduces hydraulic conductivities of the filter and improves its sediment removal performance. 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 it was 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 the particles responsible for causing clogging. Selection of filter media's particle size therefore needs to balance the objectives of flow control and treatment.

The longevity and sediment removal performance of a filter bed was enhanced with an increased depth. 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 important process that occurs. Indeed, the better performance of the deeper filter configurations is the result of an increased contact time with the media, which may enhance processes such as adsorption/adhesion or particle interception. Deeper systems should be preferred in practice, especially if large hydraulic gradients (similar to those used here) are possible.

It was found that layering in filter beds with different particle sizes offered a greater resistance to the flow and the improved design passed more stormwater while also removing much more sediment before clogging as compared to single-layered systems. The enhanced performance of layered systems is because of the protection to the bottom layer with most of removal processes/sediment removal occurs in the upper layer. However, provision of three layers in filter bed did not offer any benefit in comparison to two-layered systems, probably because the additional layer had a media size which was 5 times the maximum influent particle size. However, filter bed design 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 set of experiments therefore suggests that simple modifications to stormwater filter bed design can help improve the sediment removal performance and/or reduce maintenance intervals significantly.

Effect of stormwater characteristics

Clogging processes in granular stormwater filters have been studied by varying the stormwater: quality of stormwater (sediment load, type of pollutants, particle size of sediment); and loading regime (loading rate and regime/frequency of loading). The results suggest that variations in stormwater quality had a mixed effect both on the clogging rate and sediment removal performance of non-vegetated high flow rate filters that treat stormwater.

It was observed that the levels of sediment concentration in stormwater affect the hydraulic and sediment removal performance of these stormwater treatment filters and this eventually affects their longevity. On the contrary, the presence of metals and nutrients has limited or no effect on performance of the studied stormwater filters. However, it is important to understand that our experiments were compressed in time. The effect on clogging processes of pollutants other than sediment may be different under the influence of drying and wetting regimes and/or higher pollutant concentrations, when chemical and/or biological clogging may come into play.

Experiments also suggest that these coarse filters may not be effective in trapping very fine sediment because of the difference between the pore sizes of the media and the size of the sediment in the influent. Therefore, the size of sediments in stormwater (and their relation with the size of filter media grains) is an important parameter to be considered in design of coarse filters with high infiltration rates that are used for stormwater treatment. Since influent characteristics are dependent on the type of catchment and the extent of its development, designs of non-vegetated stormwater systems need to account for these variations.

The configuration with lower loading rate treated more stormwater and retained more sediment before clogging as compared to the Base case suggesting that loading rate is an important parameter affecting the performance of systems with high infiltration rates.

However, any variations in the stormwater dosing regime/frequency had a limited effect on the hydraulic and sediment-removal performance of non-vegetated filters with high infiltration rates. Since loading rate and dosing regime are dependent on the climatic conditions and location of treatment system in the catchment, the design of non-vegetated stormwater systems need to consider these design factors.

This study therefore suggests that stormwater characteristics have a mixed effect on the clogging performance and longevity of non-vegetated, high flow-rate stormwater filters. But nonetheless, this study enforces that clogging is specific to type of water treated and location of treatment system. Therefore, there is a need to understand stormwater characteristics in context of the catchment's features and to design the treatment system accordingly.

Importance of biological clogging for stormwater filters

The results demonstrate that biological clogging may be present in stormwater filtration systems. This was clear from the results on the rates of clogging and sediment treatment, where filters with enhanced biological conditions clogged faster than the filters with suppressed biological activity and normal filters. The results of Loss on Ignition partially confirmed these findings. Results of microbial cell counts suggest that filters with enhanced biological conditions had significantly more microbes than the filters with suppressed biological conditions. However, the evidence of biological clogging is limited, which could be entirely due to high uncertainties of methods used.

These results suggest that biological clogging could make up to 30% of the total clogging in non-vegetated stormwater filters (zeolite-based) with high infiltration rates. This therefore implies that using only physical clogging models for predictions would lead to serious underestimation of the clogging phenomena. In general the results from this rather preliminary work on biological clogging suggest that more attention should be given to biological clogging phenomena in stormwater filters.

Findings from the field study

Observations from field study of a demonstration system located in Melbourne suggest similarities with findings from laboratory studies. The infiltration rate of finer media filters in the field was observed to be lower in comparison to the coarse media tested in the lab. Filter cells located closer to stormwater inlet received more stormwater and more frequently as compared to filters located downstream in the system. These systems, which had higher loading rates, were found to clog earlier, similar to those observed in the lab. The presence of a coarse layer of sediment trap on the top of the fine media layer in the cells suggest that layering with coarser media was protecting the finer media beneath in the filter bed. As a result, these filter cells had a longer life. For instance, filters in first few cells lasted for more than 2.5 years of operation (about 90% decline observed in their infiltration rate during the monitoring period).

The key finding from this part of the study was that an exponential relationship between decline of infiltration rate and cumulative volume of treated stormwater could be used to predict the system's hydraulic performance over time. The field study also suggests that the sand pit located next to the filter system was impacting the performance of this system (as observed for cells in Row 4). This suggests the need to adequately site such systems in field to reduce interference from surrounding activities that may eventually affect their longevity.

8.4 Recommendations for Future Research

Based on the findings of this thesis, following recommendations are made for future studies:

1. The work undertaken in this thesis provides the basis for further research on investigating biological clogging processes. Any

future work that investigates biological clogging should design a real-time dosing regime and harness better methods to analyze organic matter in clogged filter media. Investigations should also consider effect of dry weather, prolonged drying and natural aspects such as temperature (of water and filter), and solar energy in relationship to humidity. Future work should be done on quantification of the biological clogging in relation to the physical clogging.

2. This thesis has tested four media individually for their hydraulic and treatment performance. It is important to test some other locally available filter media and complex filter beds (made from two or more different media, such as combining river sand and zeolite) in a mixed form or as separate layers.
3. The investigation of physical clogging processes in this study focuses on typical Melbourne conditions. However, the range of applicability of these findings should be investigated further for other rainfall conditions such as tropical weather with different drying and wetting regimes and stochastic rainfall events or cities with high rainfall such as Brisbane.
4. It would also be interesting to investigate the simultaneous effect of two or more variables such as filter layering and stormwater sediment particle size on hydraulic and treatment performance of non-vegetated filters with high infiltration rates.
5. Comparison of laboratory and field studies suggest that drying and wetting cycles may be an important factor affecting performances of these filters and needs further investigation in field conditions and incorporated in design models.
6. A model needs to be developed which can predict the hydraulic and treatment performance of filters over their lifespan using different variables that have been tested in this study (filter bed design, operational conditions). One of the main applications of such a tool would be in improved design of water treatment systems based on granular filters, particularly for stormwater filtration for ecosystem protection or supply of filtered stormwater for harvesting purposes.

8.5 Closing Remarks

In itself, this thesis has provided both theoretical and practical insights which will be useful in the application of stormwater infiltration systems that use filters with high infiltration rates. Findings from this study can be used to design systems with smaller footprint, less maintenance and longer life using locally available filter media. These findings will help waterway managers treat stormwater more effectively and efficiently, harvest treated stormwater and reduce impacts of urbanization and restore the hydrologic regime. This study has also provided recommendations for future research.

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APPENDIXES

APPENDIX– I

Research articles submitted

This appendix contains four research articles submitted to Research journals

Appendix I-1

Article published in Journal of Hydrology

Kandra H.S., McCarthy D., Fletcher T.D., Deletic A., 2014. Assessment of clogging phenomena in granular filter media used for stormwater treatment. Journal of Hydrology, 512, pp. 518-527

Appendix I-2

Article published in Journal of Water resources management

Kandra H. S., McCarthy D., Fletcher T.D., Deletic A., 2014. Assessment of impact of filter design variables on clogging in stormwater filters. Journal of Water resources management, 28, pp. 1873-1885.

Appendix I-3

Article under review: Submitted to the Journal of Water resources management

Kandra H., McCarthy D., Deletic A., Assessment of impact of stormwater characteristics on clogging in stormwater filters

Appendix I-4

Peer reviewed article submitted to Journal of Environmental Engineering, ASCE

Kandra H. S., Callaghan, J., Deletic A., McCarthy D., 2014. Biological clogging in stormwater filters. Journal of Environmental Engineering, ASCE (in press)

APPENDIX II – V

Supplementary information

Appendix II

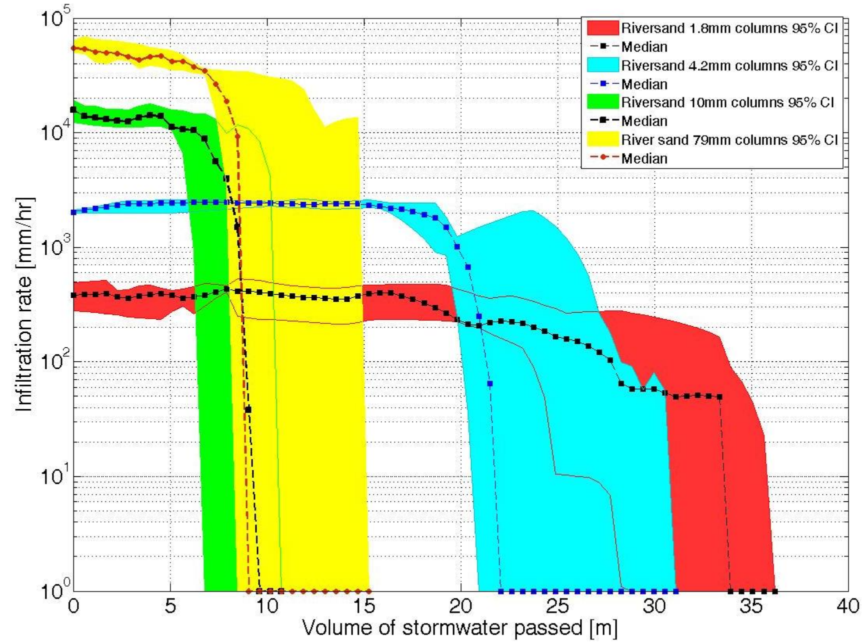


Figure 1a: Evolution of infiltration rate in Riversand filters with different outlet sizes

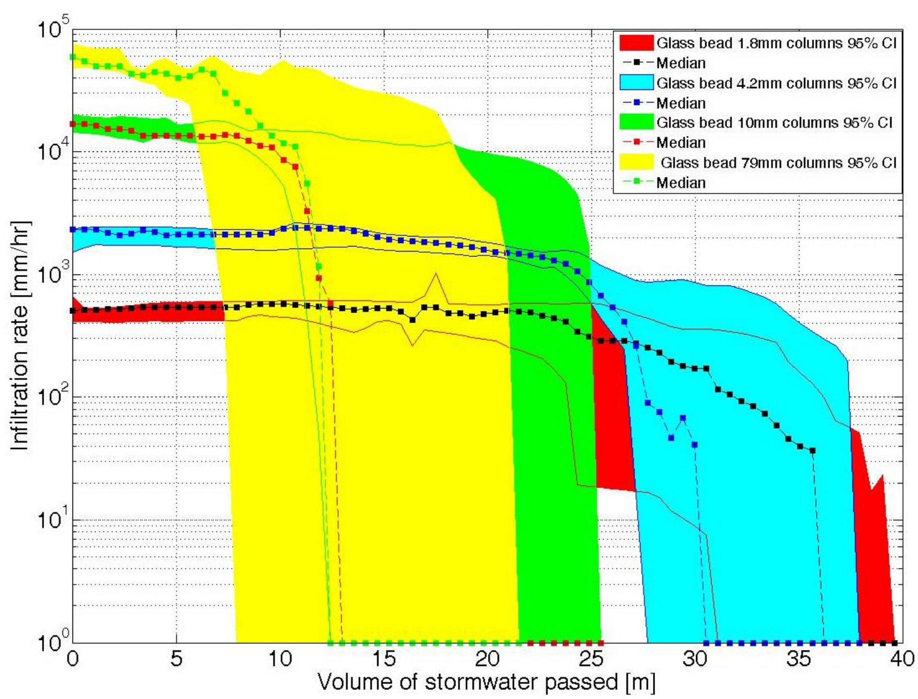


Figure 1b: Evolution of infiltration rate in Glass bead filters with different outlet sizes

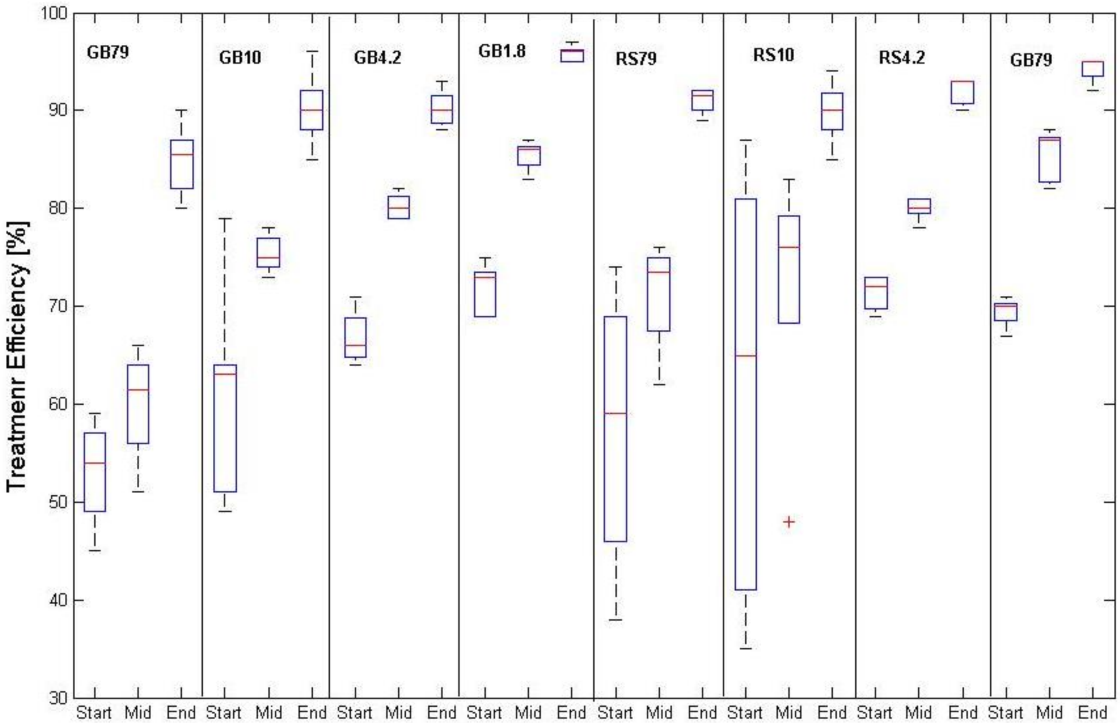


Figure 2: Treatment efficiency at the start, mid and end of operational life of the different outlet designs of glass beads and riversand filter media

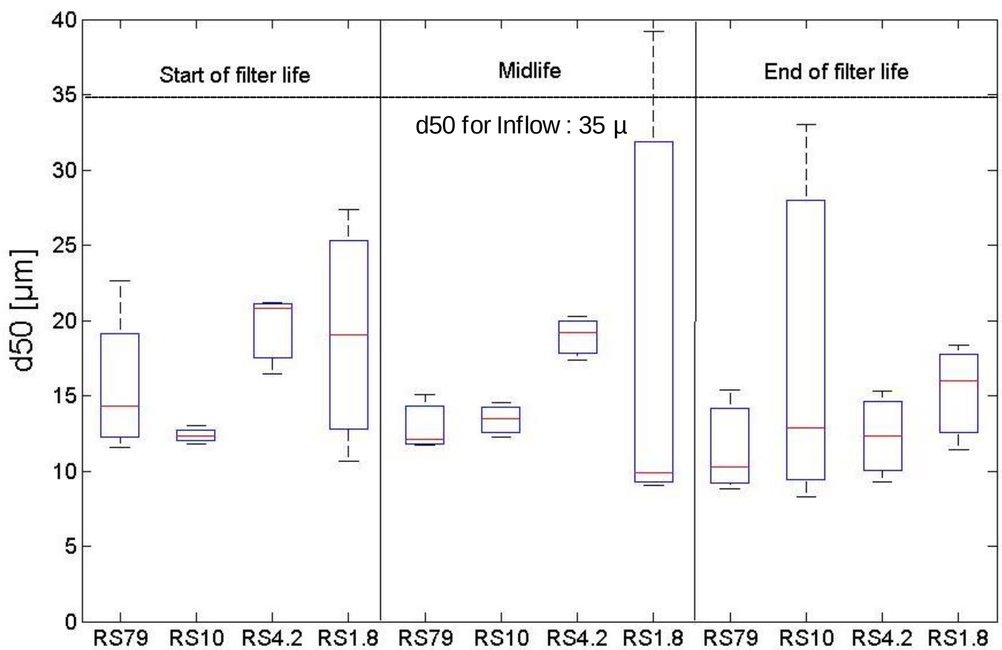


Figure 3a: d_{50} particle size distribution in outflow of riversand during different stages of their operational life as compared to d_{50} in the inflows

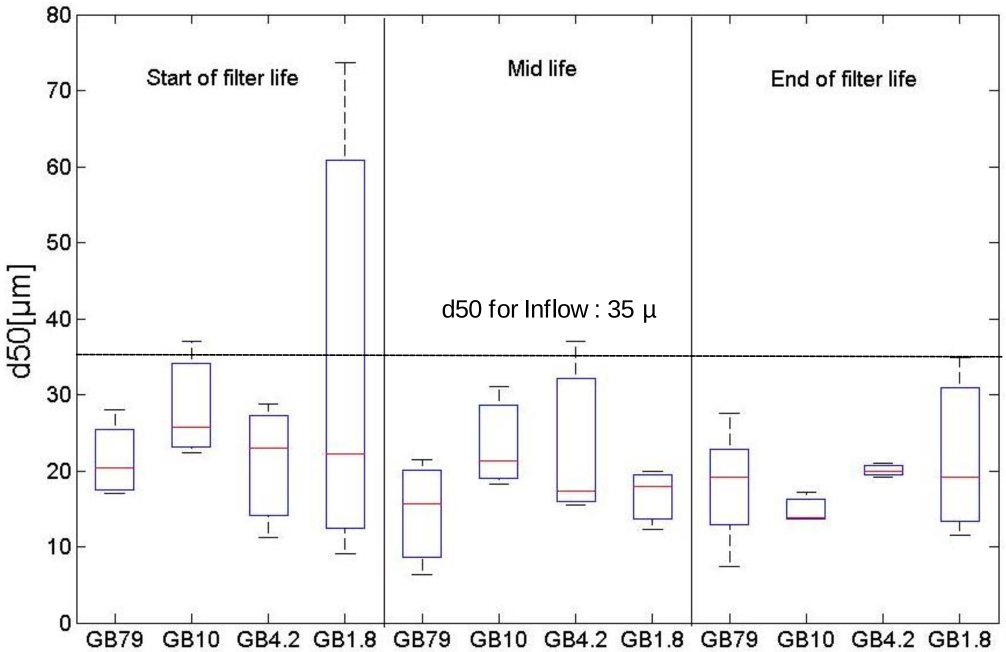


Figure 3b: d_{50} particle size distribution in outflow of glass beads during different stages of their operational life as compared to d_{50} in the inflows

Appendix III

Table 1: Performance results for Z-150mm dia and Z-100mm dia columns

Equivalent metres of stormwater passed		
Replicate number	Z-150mm dia	Z-100mm dia
1	12.94	13.80
2	12.18	11.11
3	11.57	10.89
4	11.82	16.24
5	12.10	11.22
Median values	**12.10**	**11.22**
p-value	**0.64**	

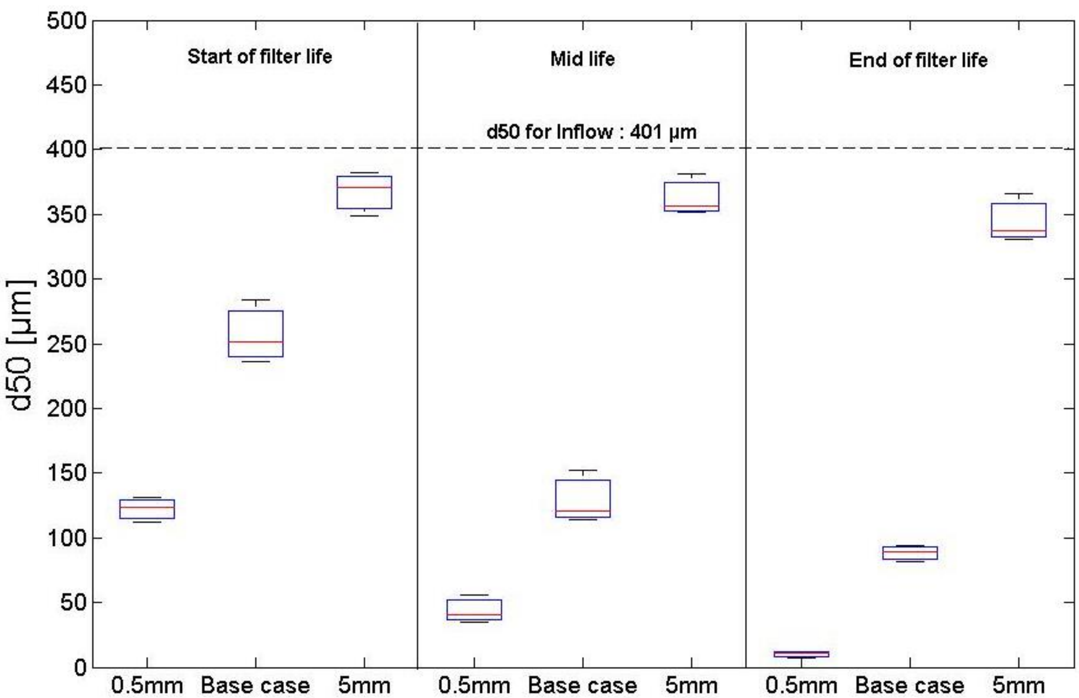


Figure 1: d_{50} particle size distribution in outflows of configurations with different particle sizes as compared to d_{50} in the inflows

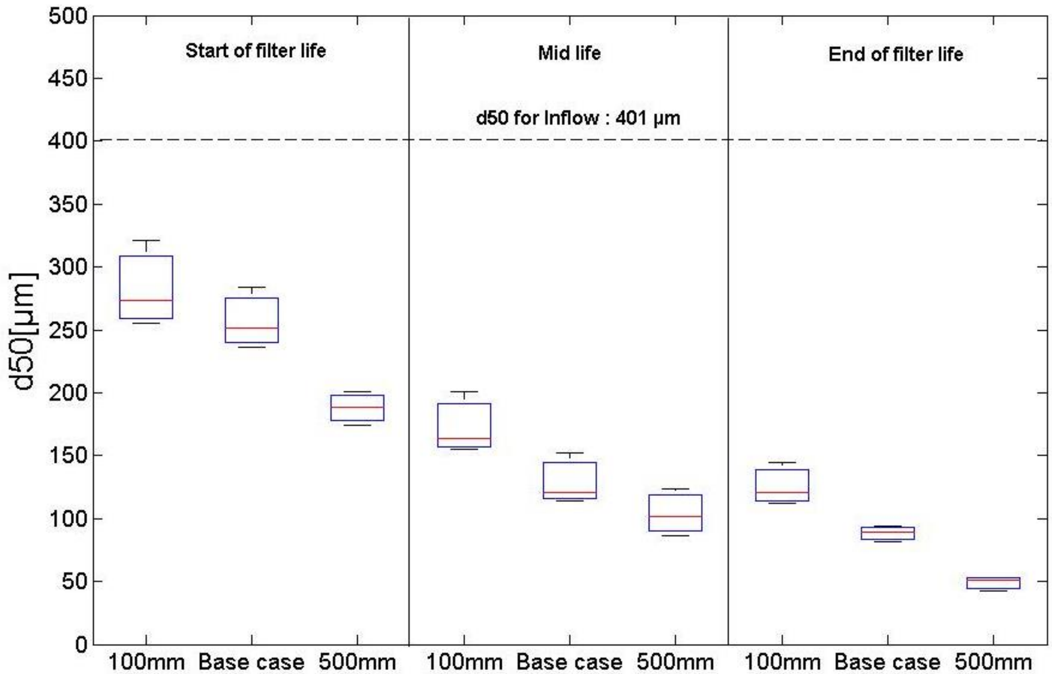


Figure 2: d_{50} particle size distribution in outflows of configurations with different depths of filter bed as compared to d_{50} in the inflows

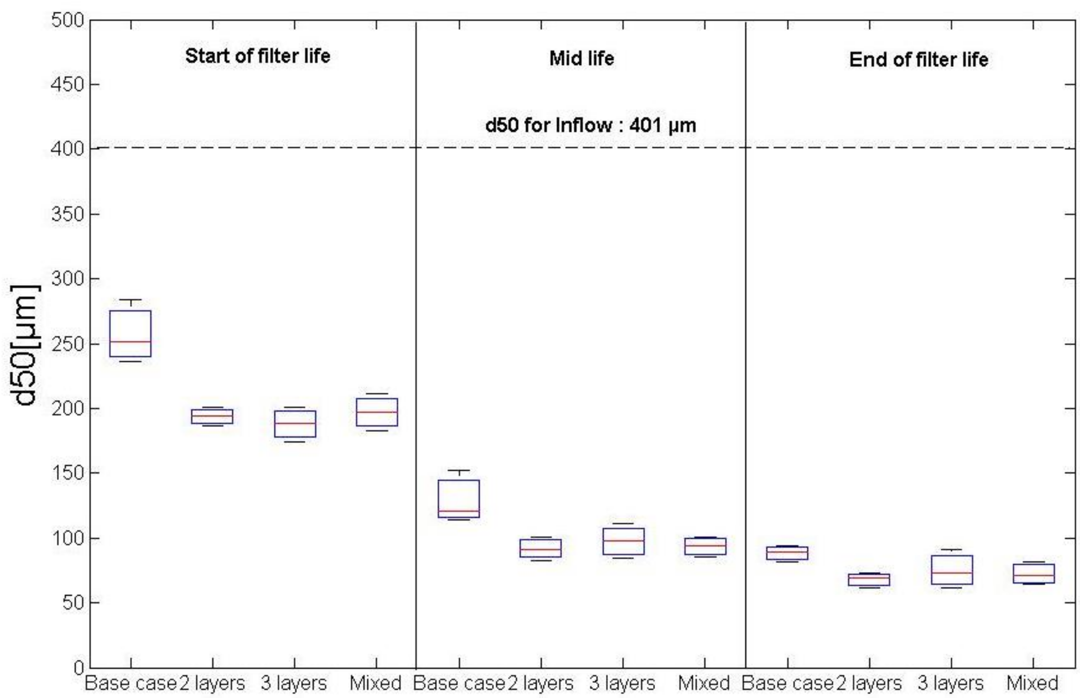


Figure 3: d_{50} particle size distribution in outflows of configurations with different packing configurations of media in the filter bed as compared to d_{50} in the inflows

Appendix IV

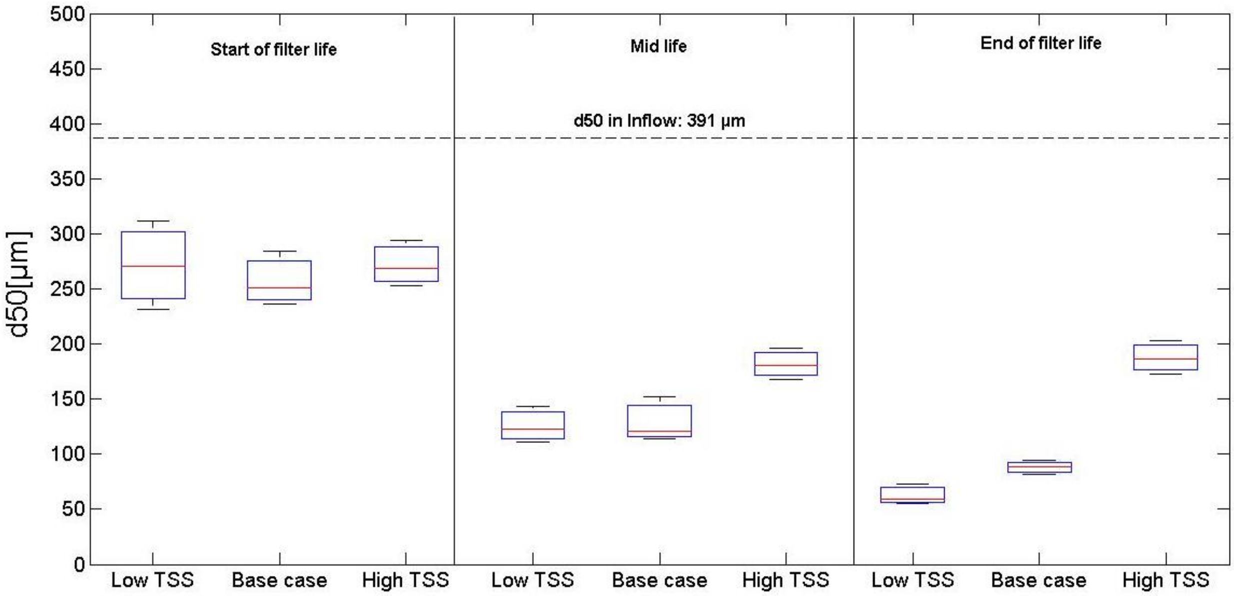


Figure 1: d_{50} particle size distribution in outflows of configurations with different inflow sediment concentrations

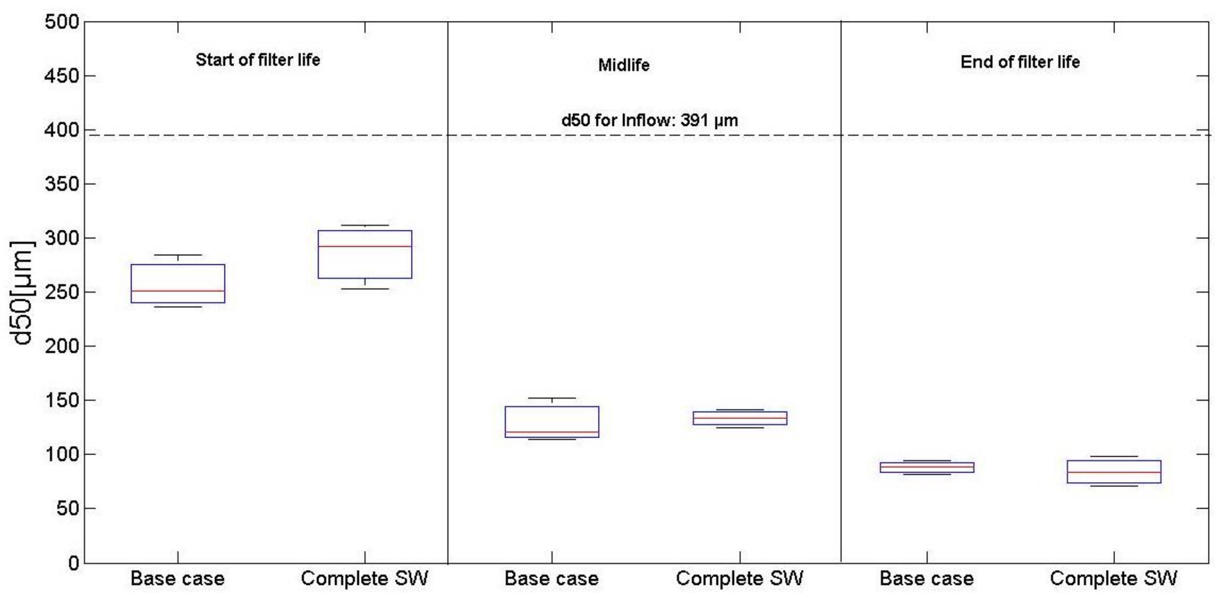


Figure 2: d_{50} particle size distribution in outflows of configurations with different variations in stormwater composition

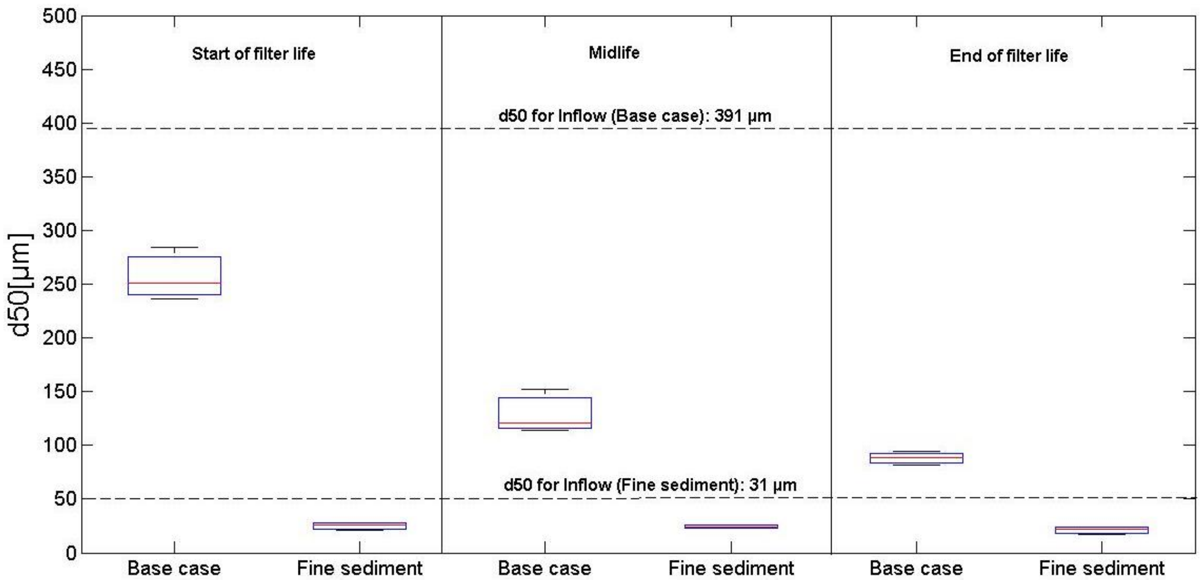


Figure 3: d_{50} particle size distribution in outflows of configurations with different variations in sediment particle size in stormwater influent

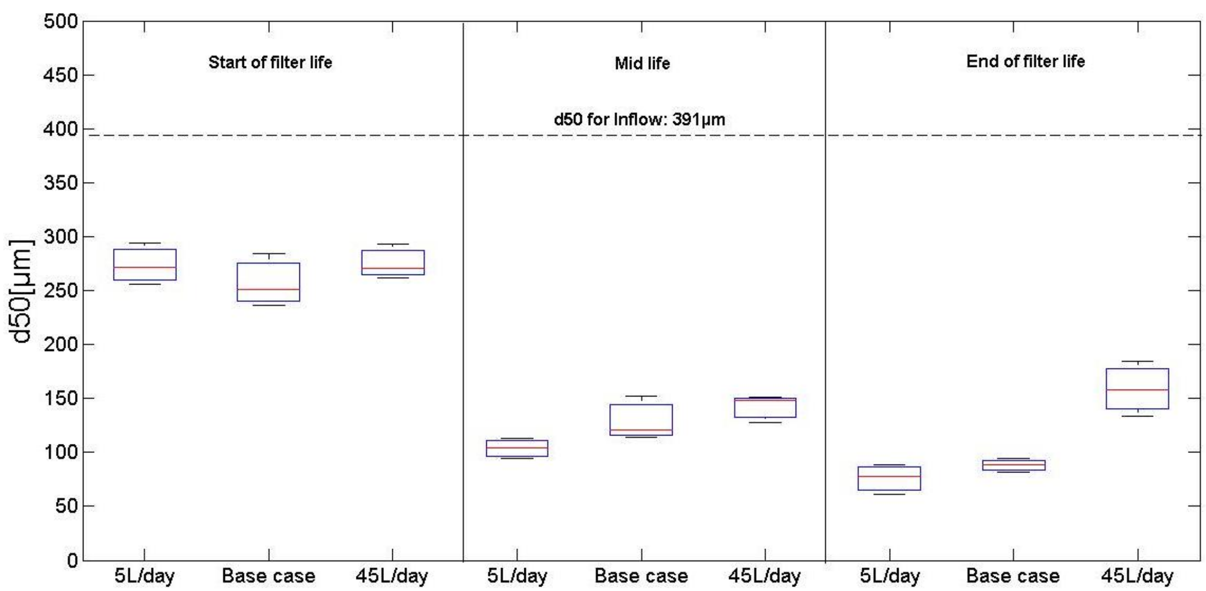


Figure 4: d_{50} particle size distribution in outflows of configurations with different stormwater loading rates

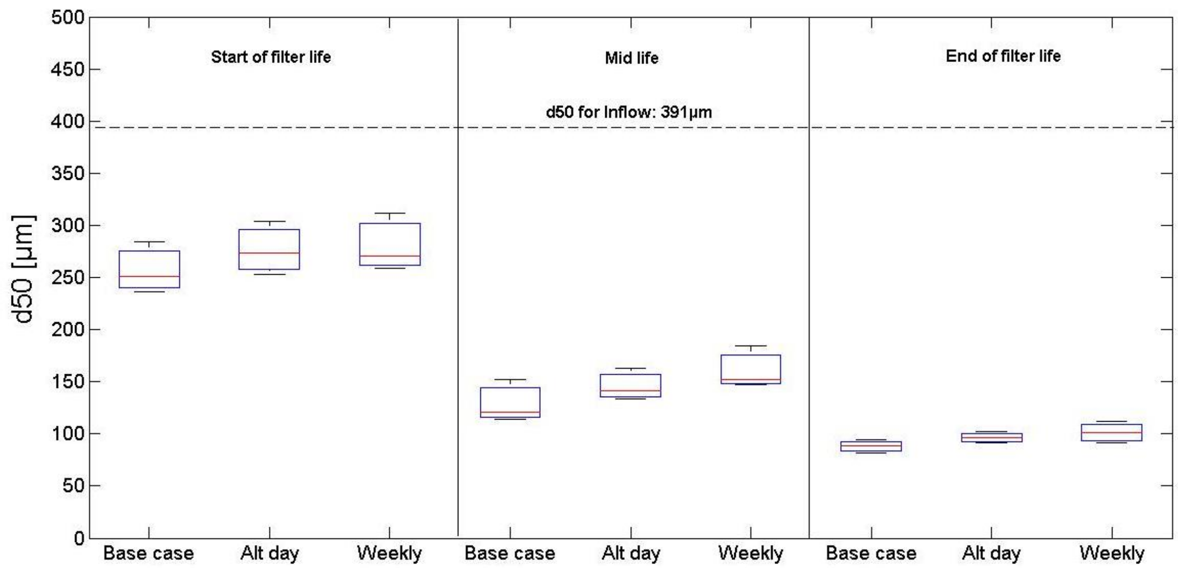
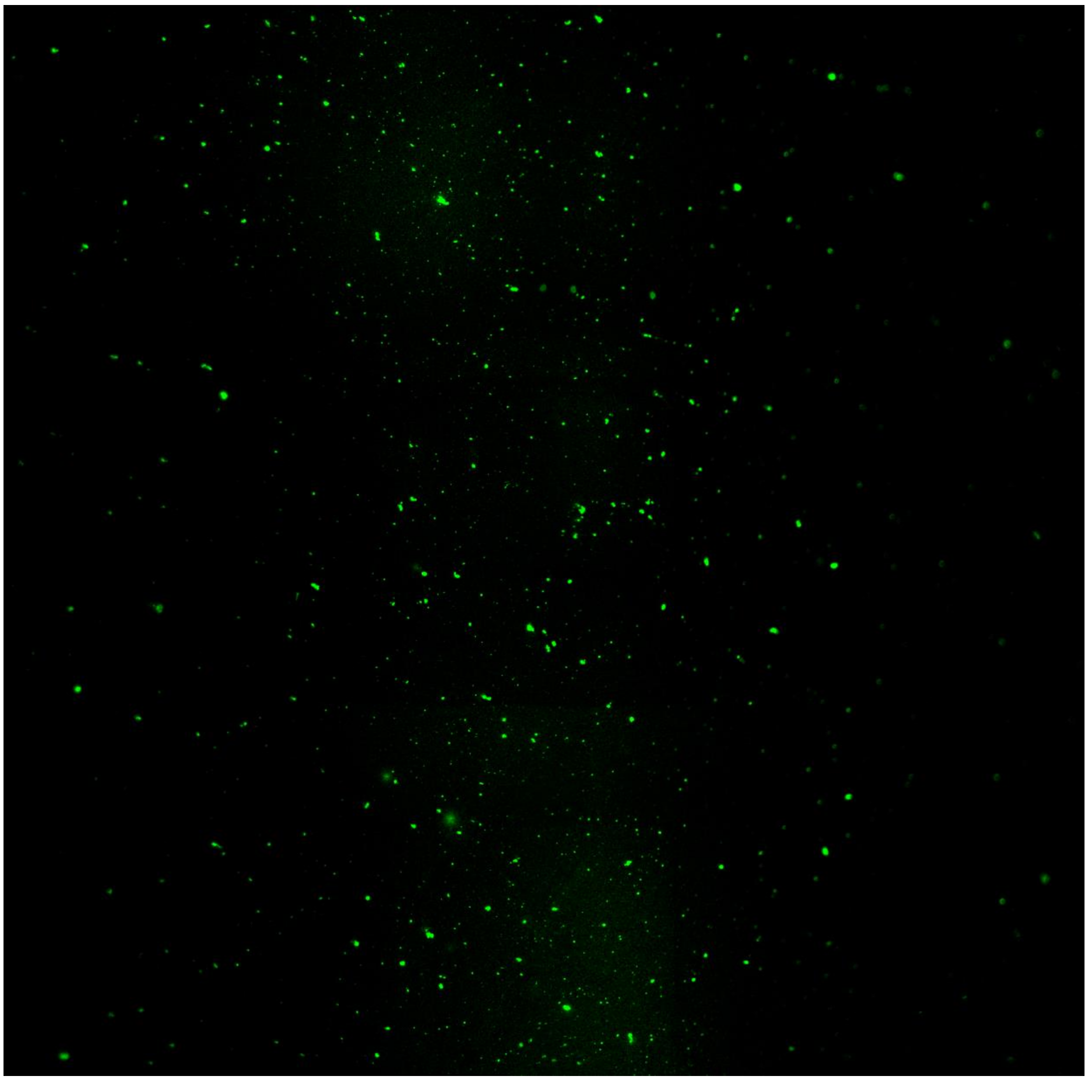


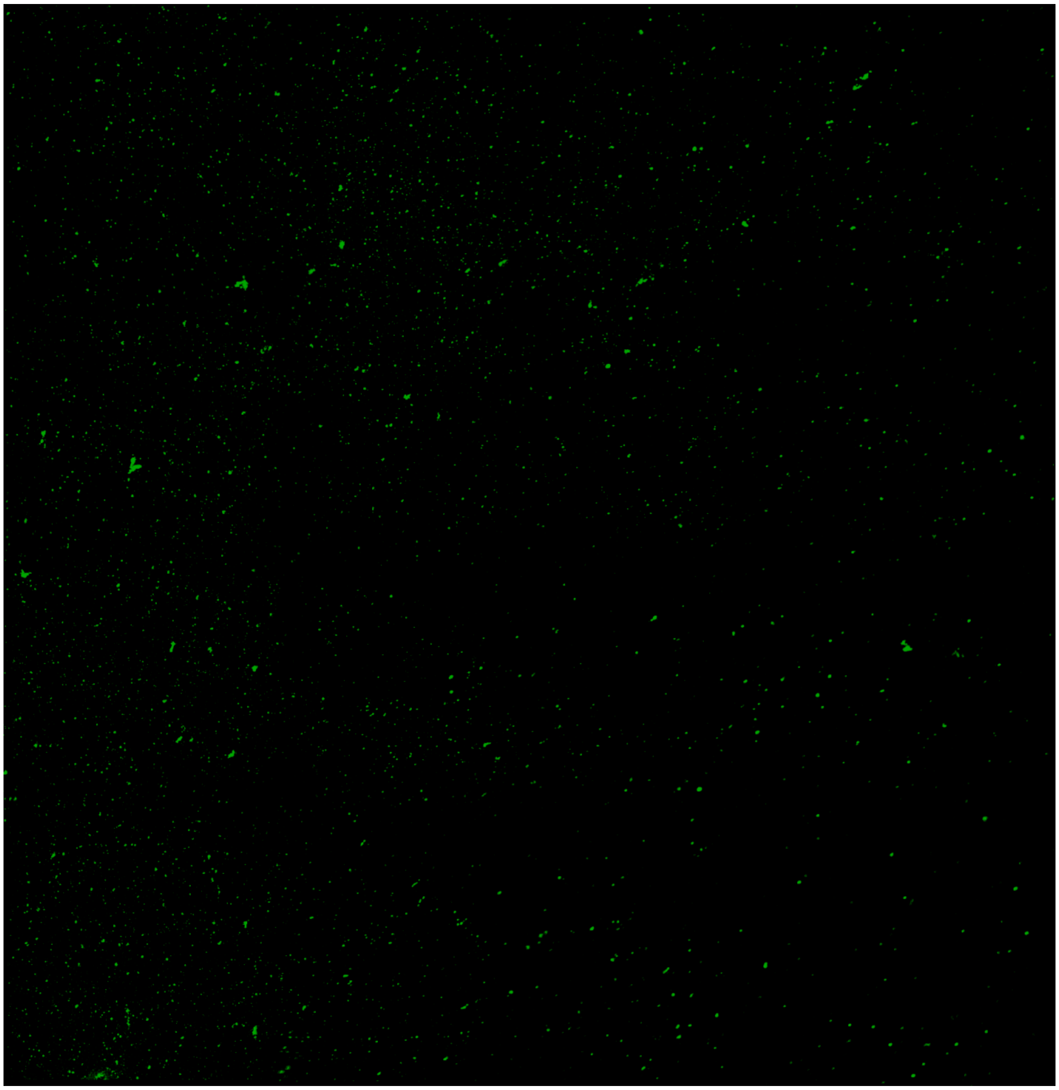
Figure 5: d_{50} particle size distribution in outflows of configurations with different stormwater dosing regimes

Appendix V

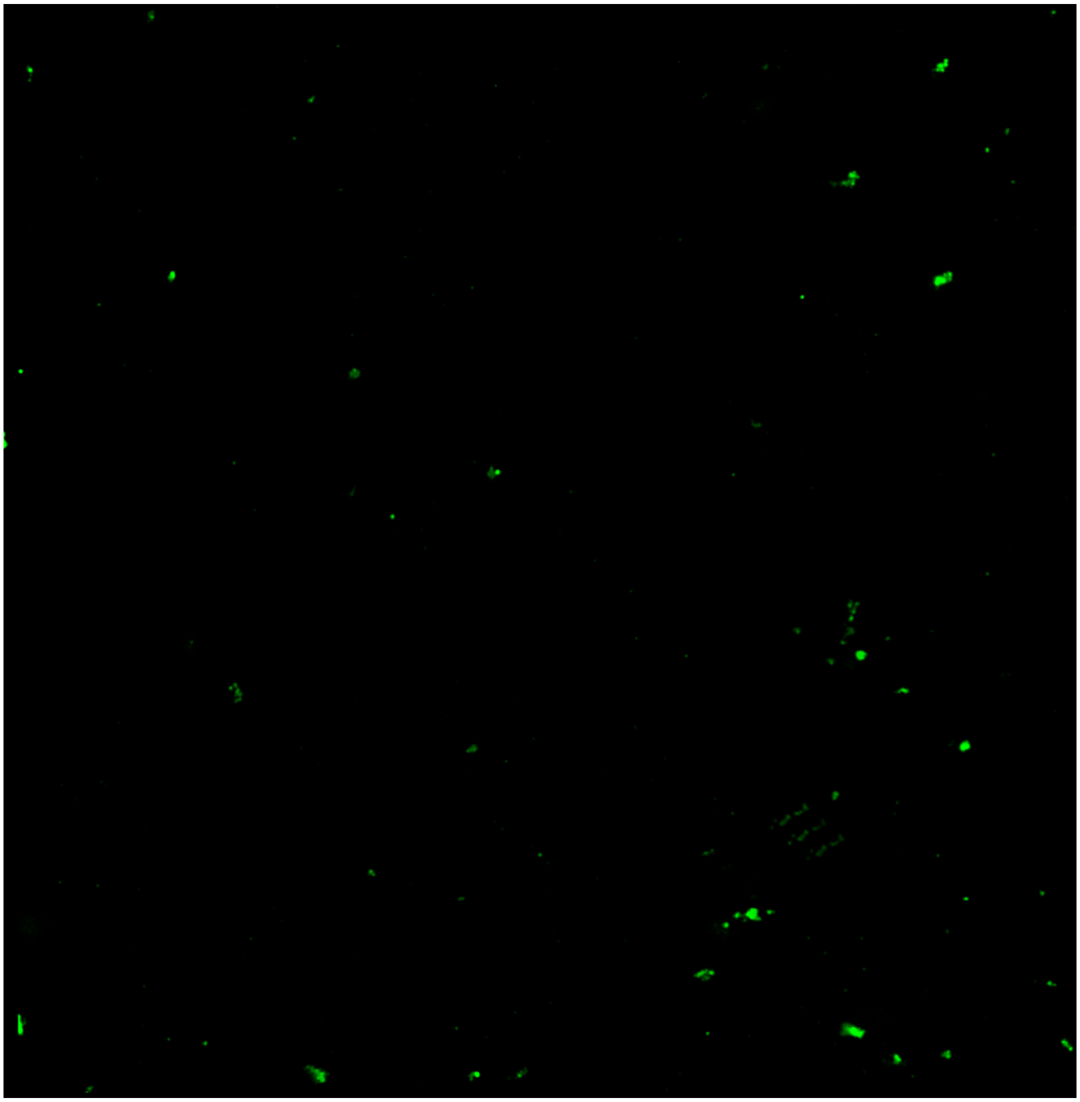
Pictures of images from microscopic examination of different tested configurations



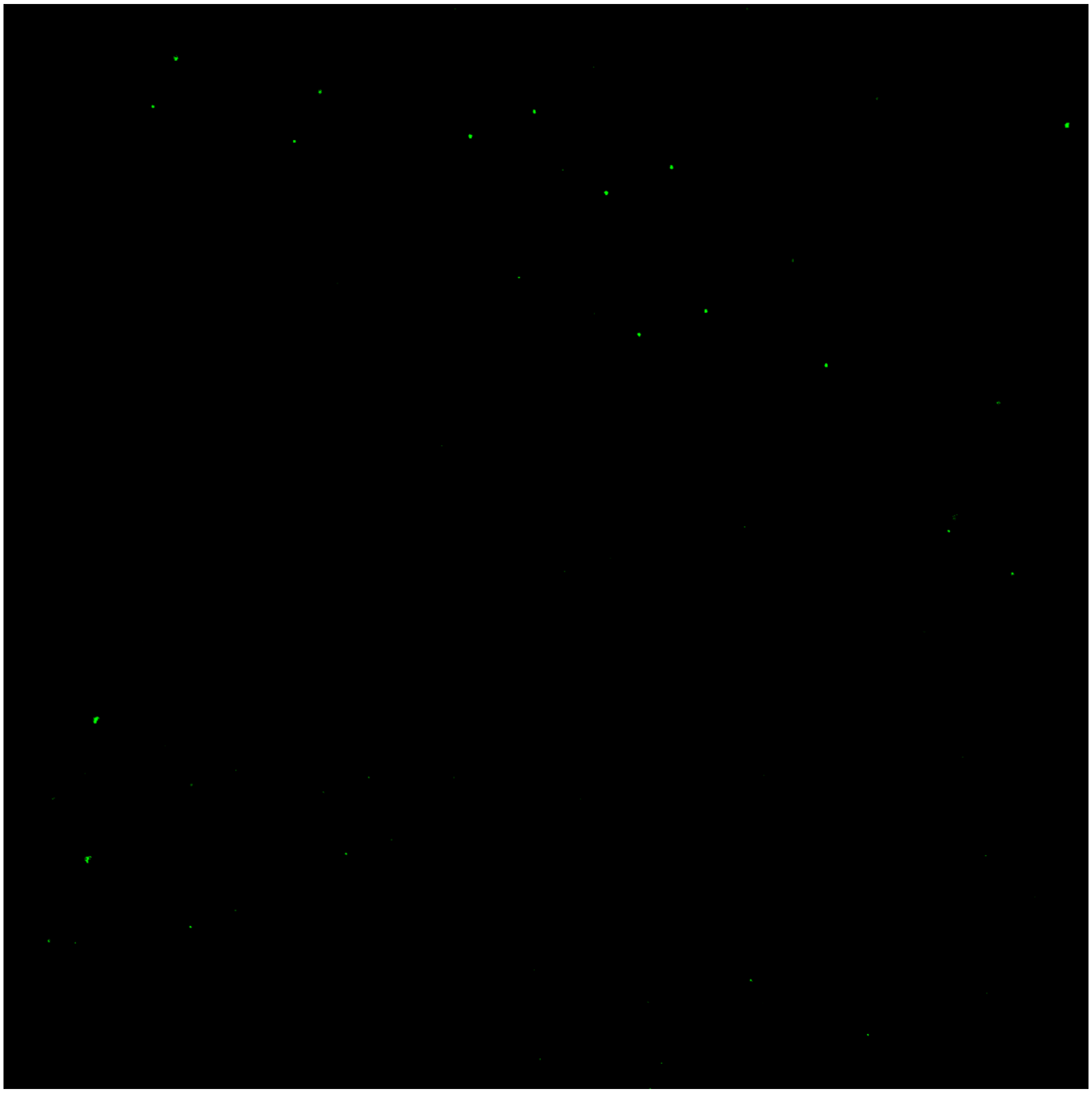
Picture 1: Image from microscopic examination of the Base case



Picture 2: Image from microscopic examination of the configuration with enhanced biological activity (Nutrient loaded case)



Picture 3: Image from microscopic examination of the configuration with inhibited biological activity (Sterilized sediment inflow case)



Picture 4: Image from microscopic examination of the configuration with inhibited biological activity (Chlorinated case)