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Dynamics of Clay Particles in Non-vegetated Stormwater Biofilters

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Abstract Stormwater biofilters manage quantity and quality of urban stormwater runoff. Particulate solids from natural and anthropogenic sources accumulate on paved surfaces and eventually reach receiving waters. Retention of suspended solids in stormwater management systems ensures the quality of stormwater runoff to water resources. Stormwater biofilters are similar in most of design parameters to sand filters employed in water treatment systems. The understanding and design of stormwater biofilters are often based on generic models of sand filters. Unlike water treatment sand filters, which are continuously fed, stormwater biofilters operate intermittently with spontaneously alternating wetting and drying cycles. This results in dynamic pollutant removal pattern that employs different mechanisms during and across rainfall events. As such, pilot scale biofilter columns fabricated with a layer of organic material were operated. Removal of suspended solids was very dynamic, where impact of age of filter, antecedent dry days, and inflow quality varied during and across events. Flush of retained solids and filter material occurred during the stabilisation period during each event while very high removal percentages (more than 90%) were observed after stabilisation, during an event. Clogging was not observed due to re-entrainment, redistribution, and flush of retained solids during intermittent wetting and drying cycles.

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Keywords Stormwater biofilters · Antecedent dry days · Turbidity · Total suspended solids · Clogging · Solids retention

Abbreviations

ADD	Antecedent dry days
EN	Event number
TUIN	Turbidity of inflow of current event
TUPRE	Turbidity of inflow of previous event
TUOUT	Turbidity of outflow
min(t) [min2, min7, etc.]	TUOUT at “t” minutes during an event (2 min, 7 min, etc.)
TSS	Total suspended solids
PSD	Particle size distribution

1 Introduction

Stormwater biofilters are an element of Water Sensitive Urban Design (WSUD) that manage the quantity and quality of stormwater runoff in urban catchment. Urbanisation of catchments includes paving of surfaces, that while objecting percolation of stormwater and hence increasing surface runoff acts as a platform for pollutant build-up (Ellis and Revitt 2008; Walsh 2000). Significant amount of suspended solids are observed to accumulate on paved surfaces that eventually get washed off with runoff. Suspended solids increase the turbidity of water that substantially restricts penetration of sunlight that affects the aquatic plants and other life forms (Bilotta and Brazier 2008). In addition, suspended solids provide surfaces for adsorption of other toxic pollutants such as heavy metals and organic pollutants (Hoffman et al. 1982; Shinya et al. 2000). Loading of suspended solids in water resources is therefore required to be reduced, and hence, stormwater management systems should essentially enhance suspended solids removal.

Removal of suspended solids in filters occurs mainly due to two mechanisms, cake filtration and in-depth (deep) filtration (Newcombe and Dixon 2006). Sand filters employed in water treatment systems that are fed continuously remove suspended solids primarily due to cake filtration (while depth filtration also contributes significantly to the removal of solids). Cake filtration mechanism retains solids that are smaller than the pore size (straining), that progressively removes smaller particles as the size of the pores decrease during a run (Kim and Whittle 2006; Siriwardene et al. 2007). This phenomenon eventually leads to clogging of the filter, when the top layer of the filter (cake formed during the run) is scraped from the surface of the filter to revive the performance of the filter in removing solids. Similar theory is adopted to design and model the performance of stormwater biofilters that were operated under either continuous feeding or extended ponding conditions (intermittent) (Li and Davis 2008a, b). These models were observed to explain the removal of solids during an event in stormwater biofilters. Stormwater biofilters, however, are specifically different to conventional sand filters employed in water treatment systems in primarily two characteristics. Stormwater biofilters operate necessarily under intermittent wetting and drying conditions, the dry periods (antecedent dry days) vary depending on the catchment rainfall characteristics. Antecedent dry days (ADD) and the age of filter have been shown to impact the stabilisation of the filter during and event (phase I stabilisation) that subsequently affect the performance of the filter (Subramaniam 2015; Subramaniam et al. 2014a, b, 2015). The factors that destabilise the filter material during dry days may potentially play a crucial role in the solids retained in the system during an event. The fate of retained solids and the mechanism of removal of solids in stormwater biofilters under intermittent wetting and drying is scarcely analysed in the literature. In addition, the solids loading (inflow concentrations) in stormwater biofilters vary significantly during and across events. For example, the first flush phenomenon in wash off of solids in stormwater runoff would lead to high concentrations of pollutants in the inflow of a stormwater biofilter compared to the pollutant concentrations towards the end of the rainfall event. In the same way, the pollutant concentration may also vary depending on the number of antecedent dry days and the characteristics of the environment where as in a water treatment system, the inflow water quality to a sand filter would comparatively be invariant. Filtration in a porous medium depends on several factors related to characteristics of the filter including hydraulic conductivity of the medium, particle concentration in the inflow, particle size distribution of the medium, pore size distribution, geometry and surface roughness of the grains, and charged sites on the filter material (Lee and Koplil 2001; Reddi et al. 2005). In addition, retention of solids also depends on other processes including hydrodynamics, physicochemical interactions, and physical straining (Ahfir et al. 2007; Sen and Khilar 2006). The distribution and retention of solids in stormwater biofilters is therefore more dynamic in character in stormwater biofilters, where the models will need to be developed more specifically to incorporate the spontaneity and dynamics of solids retention. In addition, the models will have to incorporate the dynamics of retained solids across events as well (in addition to the dynamics within an event) to understand the total removal of solids in the system as stormwater biofilters are seldom maintained (backwashing or scraping the top layer) and that the age of the filter affects the processes in the filter (Subramaniam et al. 2014b, 2015).

This study is designed to understand removal of suspended solids in stormwater biofilters under intermittent wetting and drying conditions, and analyse the removal dynamics incorporating the phenomenon of stabilisation observed in intermittent operations of the filters. The study also analyses the total mass of solids retained in the system over the experimental period and hence analyse the longevity of the lifespan of the filter.

2 Methodology

2.1 Laboratory-Scale Stormwater Biofilters

Five Perspex™ columns of 94-mm internal diameter and of length 1.6 m were constructed as experimental bioretention columns. The columns were packed according to standard guidelines as described below (Gold Coast City Council 2003; South East Queensland Healthy Waterways 2010). Material incorporated in bioretention columns (filter zone, transition zone, and drain zone) was obtained from an industry standard material supplier in Brisbane and the Gold Coast, Australia (Fig. 1).

Filter zone—engineered filter media Engineered filter media consisted of primarily loamy sand. The particle size distribution was engineered to include particles with diameter less than 1 mm (D_{60} = 300 μm). The engineered mix was intended to have a hydraulic conductivity of 50–500 mm/h (180–200 mm/h optimum) according to the guidelines, and the observed saturated hydraulic conductivity varied between 300 and 450 mm/h as monitored during the experiment. Engineered filter media also included approximately 8% of a mixture of natural organic matter (by weight) added to enhance nitrate-nitrogen removal. Organic matter added, however, had negligible levels of total nitrogen and total phosphorus.

Drain zone Drain zone had two layers (transition layer and gravel layer).

a. Transition layer: a transition zone is included if the ratio between particle size of gravel media and filter media are more than an order of ten. A transition zone was therefore included in this laboratory-scale stormwater biofilters using transition media supplied by the industrial supplier. Transition media provided by the supplier was engineered to have particles of diameter between 1 and 2 mm (D_{60} = 1.18 mm).
b. Gravel layer: primary purpose of drain zone is to rapidly transport infiltrated (treated) stormwater to drain channel that followed or to temporarily store infiltrated stormwater prior to infiltrating in the native soil in systems that were designed to recharge groundwater. In this experiment, drain zone operates to rapidly transport infiltrated stormwater into the drain channel that was also a water sampling port in this study. Gravel media provided by the supplier was engineered to comprise of particles of sizes between 2 and 5 mm in diameter (D_{50} = 4 mm).

Ponding zone Ponding zone is included in design specifications to provide temporary storage of stormwater runoff, to control over flow quantities, and to provide head to initiate and facilitate infiltration process through the filter.

Vegetation Based on the argument that phytoremediation is not a nitrate-nitrogen removal process in stormwater biofilters as the plants are not removed from the system, and the fact that there are several field-scale installations designed without any vegetation other than surface turf-grass, nitrate-nitrogen removal in this study is based in the filter zone only (Raskin et al. 1997). Impact of vegetation on nitrate-nitrogen removal is therefore beyond the scope of this study.

2.2 Experiments

2.2.1 Stabilisation of Stormwater Biofilters

The columns were fed with tap water for five designed experimental events, with two events per week (the antecedent dry days (ADD), were 3 or 4 days for all events). All five columns were fed with five events each. The details of designed experimental events are given below.

Feed rate—100 ml/min (875 mm/h) A simulated rainfall event was designed according to the 3-month ARI (annual recurrence interval) for South East Queensland, Australia. From the data, it was computed that a 3-month ARI was a rainfall event with 34 mm/h intensity that lasted for approximately 30 min (Parker 2010). The other assumption considered was that the area of bioretention basins (stormwater biofilters) covered approximately 3% of the catchment area with a catchment runoff coefficient of 0.8.

Event duration—3 h Even though the events are designed to 3-month ARI, 30-min rainfall, the events in this experimental study were prolonged to 3 h (at the same feed rate). The longer duration was required to run the experiment to monitor and understand the process of stabilisation of stormwater biofilters.

Ponding and overflow The ponding level above the filter zone was maintained at approximately 350 mm, in order to provide a temporary storage for inflowing stormwater and also to provide sufficient head for the process of infiltration of stormwater through the biofilter. This was attained by reducing the feed rate to match the hydraulic conductivity when the ponding reached 350 mm, so that the ponding level stayed constant while inflow rate and outflow rate were equal.

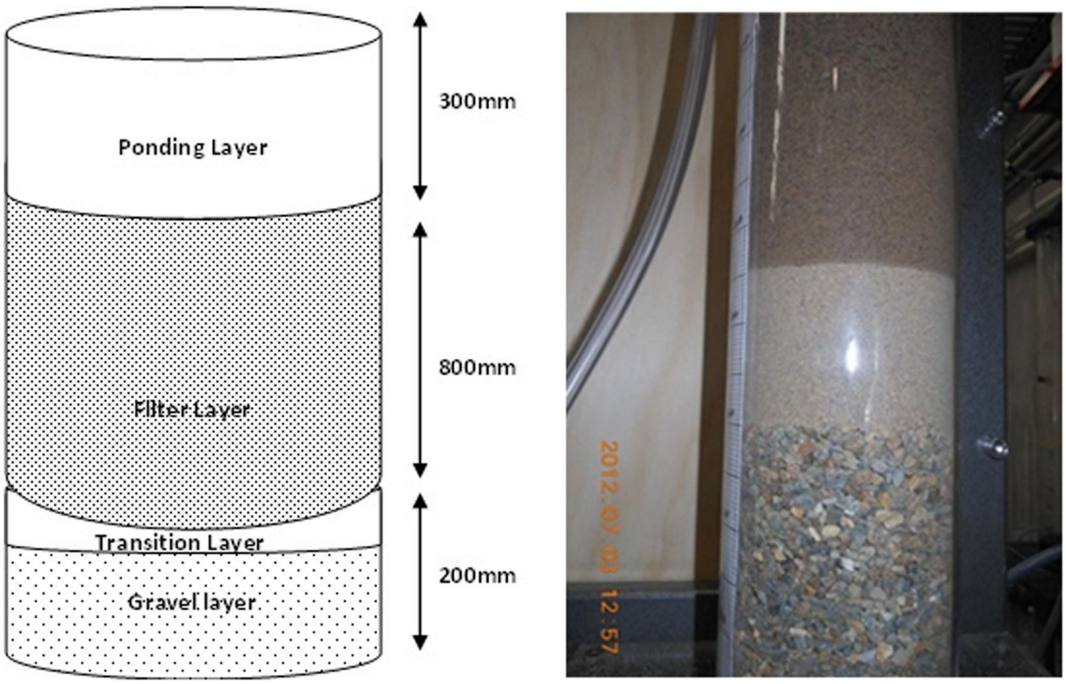


Fig. 1 Schematic diagram and photograph of the laboratory-scale stormwater biofilter

The age of filter Since this was an experiment to study the stabilisation of stormwater biofilters over age, the columns were not re-packed in between designed storm events. The sequence of events were, therefore, numbered with an increment of one for each event (EN—event number) to represent the operational parameter of age of the filter under field-scale operations. The first event was there for EN = 1 while the second event bore the EN = 2 and so on.

Intermittent wetting and drying The designed events were carried out in intermittent wetting and drying regime with an antecedent dry days of 3–4 days in between events. Stormwater biofilter columns were observed to take approximately 16 h to complete draining after an event, and therefore, zero antecedent dry day was considered as an event that occurred approximately 24 h following the previous event.

2.2.2 Simulated Experiments

After the process of designed filter-stabilisation events, the experimental events were scheduled. The nature of this study requires a controlled environment since dynamics of suspended solid concentrations need to be monitored for varied EN, ADD, and inflow concentrations (TUIN and TUPRE). In addition, several storm events had to be simulated within a short period of time that required large amounts of feed. The quality of stormwater feed to the experimental biofilter columns, therefore, had to be consistently regulated across the experimental schedule. In such occasions, it has been a common practice to use simulated stormwater for laboratory studies (Blecken et al. 2009; Bradford et al. 2003; Davis et al., 2003, 2006; Hsieh et al., 2007; Li and Davis 2008a, b). Simulated stormwater for this study was prepared by mixing the following materials in tapwater:

1. Ammonium nitrate (NH_4NO_3): to represent ammonium-nitrogen and nitrate-nitrogen in stormwater
2. Glycine ($C_2H_5NO_2$): to represent organic-nitrogen in stormwater
3. Montmorillonite and kaolinite (1:1 by weight): to represent solids in suspension in stormwater

Insignificant level of chlorine was observed in tapwater from tests using DPD tablets and therefore, dechlorination was not considered. Since stormwater quality in various studies in South East Queensland varied extensively based on several factors including catchment characteristics and land use, standard simulated stormwater in this study was designed for 5.0 ppm of total nitrogen (TN, with NO_3-N: 2.0 mg/L, NH_4-N: 1.5 mg/L and organic-N: 2.5 mg/L) and 100 mg/L suspended solids (kaolinite: montmorillonite—1:1 by weight) (Liu, 2011; Miguntanna, 2009; Parker 2010).

Events were fed with stormwater on the first four biofilter columns (C01–C04) and with tapwater alone on the fifth biofilter column (C05). Events were simulated according to the description given under preliminary stabilisation (feed rate and length of an event). Experiments were conducted in two stages, the first with standard synthetic stormwater with a turbidity of 56.12 ± 5.87 NTU that corresponds to 100 mg/L of suspended solids, while varying antecedent dry days (ADD) from 0 to 56 days (Table 1). In experiment 1, different ADD's were randomly scheduled for each biofilter column ensuring that it did not follow a pattern. For example, C1 had events with 4, 0, 2, 21, 56, 12, 7, and 13 days while C2 had events with 0, 2, 7, 12, 21, 0, 4, and 31 days. Events were simulated this way to avoid any impact of certain pattern affecting performance of a column in a unique way. This is to contrive field-scale condition to laboratory-scale study where events are subjected to spontaneous ADD and inflow quality. During experiment 2, the first four columns were fed with varying concentration of pollutants and ADD, and variations in inflow turbidity were spontaneously varied in each column similar to variation of ADD in experiment 1. The range of ADD's and inflow turbidity are given in Table 1. During experiments 1 and 2, the fifth column was continued to be fed with tapwater alone that had turbidity less than 0.1, with different ADD and increasing EN.

2.2.3 Sampling and Testing

Four filter material samples were taken from each column and the particle size distribution (PSD) was analysed using Malvern Mastersizer S. Three water samples of the inflow from each column were taken at three different times during an event and the turbidity and PSD of the samples were determined. Turbidity of the samples were monitored using HACH - 2100N Laboratory Turbidimeter. A calibration was done to convert turbidity to total suspended solids (TSS) concentration (ppm). A linear calibration was obtained.

Outflow samples were collected at 2, 7, 12, 20, 30, 60, 90, 120, and 150 min from the start of outflow, and were tested for turbidity; 2nd, 7th, 12th, 20th, and 30th minutes samples were also tested for PSD (other samples had very low turbidity and determination of PSD was not possible at lower concentrations). The hydraulic performance of the columns were also monitored by measuring the outflow rate at each sampling time, monitoring the feed rate and recording the ponding level in each column.

2.3 Data Analysis Techniques

Experiment 1 was conducted by maintaining inflow turbidity at a constant level, and varying ADD and EN. Initially graphical representation techniques were used to interpret general trend in data obtained from experiment 1. Trends in stabilisation, occurrence of peak concentrations, and variability in removal of pollutants with time were some of the common observations made from graphical techniques. In contrast, all four variables were varied in experiment 2, where interpretation of

Table 1 Summary of experimental runs

Column number	Feed	Turbidity (NTU)		ADDs (days)
		Experiment 1	Experiment 2	
C1	Synthetic stormwater	56.12 ± 5.87*	10–250**	0–56
C2	Synthetic stormwater	56.12 ± 5.87	10–250	0–56
C3	Synthetic stormwater	56.12 ± 5.87	10–250	0–56
C4	Synthetic stormwater	56.12 ± 5.87	10–250	0–56
C5	Tapwater	< 0.1	< 0.1	0–56

*Corresponds to 100 mg/L of suspended solids

**Corresponds to a range of approximately 25–500 mg/L of suspended solids graphical representation of data was limited. However, general trends on the impact of PRE (the previous event: EN-1) and IN (the current event: EN) were identified and observations were made on variation of their impacts on outflow quality depending on ADD and EN. For a comprehensive analysis of data to confirm the variation in the impacts of each variable on the outflow quality, multivariate and statistical modelling tools were required to be employed.

For statistical analysis, nitrate-nitrogen concentration in the outflow at different times (2, 7, 12, 20, 30, 60, 90, 120, and 150 min) were considered as individual dependent variables (min2, min7, min12, min20, min30, min60, min90, min120, and min150, respectively). These dependent variables were analysed statistically with independent variables, ADD, EN, TUIN (turbidity in the inflow of the current event), and TUPRE (turbidity in the inflow of the previous event). Principal component analysis was used in this exercise to identify the patterns and also to identify redundant variables. In addition, correlation analysis (bivariate) was utilised to define correlations between the variables and to confirm the patterns.

3 Results and Discussion

Figure 2 shows variation of turbidity and removal percentage of turbidity during events of different EN and ADD. Turbidity in initial outflow (min2) varied widely between 150 and 700 NTU, indicating significant leaching of filter material (turbidity higher than inflow). This corresponds to the effect of stabilisation which was also observed by Subramaniam et al. (2016, 2014b, 2015). Beyond the first 30 min of stabilisation (phase I), the levels of turbidity were observed to be constant at very low levels, indicating very high percentage of removal.

However, the computation of percentage removal during stabilisation highly varied and was exaggerated or trivialised depending on the initial turbidity (for example, low inflow turbidity resulted in higher negative percentage removal compared to a high inflow turbidity, for the same outflow turbidity). Since initial outflow is affected by stabilisation, the impact of EN and ADD would have mostly been present as it was observed by Subramaniam et al. (2015). Therefore, the impact of turbidity of the inflow in the current and previous event was analysed.

Figure 3 shows variation in outflow turbidity with time, across events with different inflow concentration of current (TUIN) and previous (TUPRE) events together with varying ADD and EN. Phase I stabilisation observed earlier was evident in all events, irrespective of EN, ADD, TUPRE, or TUIN. Although duration of phase I stabilisation was unaffected by the variables mentioned above, turbidity in the outflow during stabilisation varied widely with events. Due to the complexity of the impacts observed, it was not possible to identify the individual impact of each independent variable on TUOUT from the figure in isolation. Unlike observations on nitrogen species removal after stabilisation that varied depending on inflow concentrations(Subramaniam et al. 2016, 2014a, b, 2015), turbidity in contrast was almost a constant in the outflow after phase I stabilisation irrespective of TUIN. In order to investigate the impact of each variable on outflow turbidity over time, this was examined separately and is discussed below.

Outflow turbidity at different times (min2–min150) for all events with simulated stormwater feed was considered for statistical analysis. Events fed with tapwater alone had less than 0.1 NTU of TUIN, and therefore, any turbidity in outflow of those events was considered a washoff of filter material. A strong negative correlation (with coefficients greater than 0.7) with high significance ($p < 0.01$) was observed between EN and TUOUT at all times, while weaker negative correlation (coefficients between 0.25–0.5) was observed between TUPRE and TUOUT. While correlation analysis on the data revealed no impact of ADD on TUOUT, variance observed in initial TUOUT suggested that there may be some impact of ADD on TUOUT. A potentially significant impact of ADD on TUOUT may thus have been over shadowed by stronger impact from other variables including EN. In order to understand the impact of ADD on TUOUT, events were analysed grouped into two groups, one with events with EN less than 10 and the second with events with EN greater than or equal to 10.

A significant difference was observed between two groups of events in the impact of ADD and EN on TUOUT. Very strong (coefficient greater than 0.5) and significant ($p < 0.01$) impact of EN was evident for young filters (events with EN less than 10). In contrast, for older filters (events with EN greater than or equal to 10), the impact of ADD becomes more pronounced while the impact of EN was not significant. It was concluded therefore that the impact of ADD was

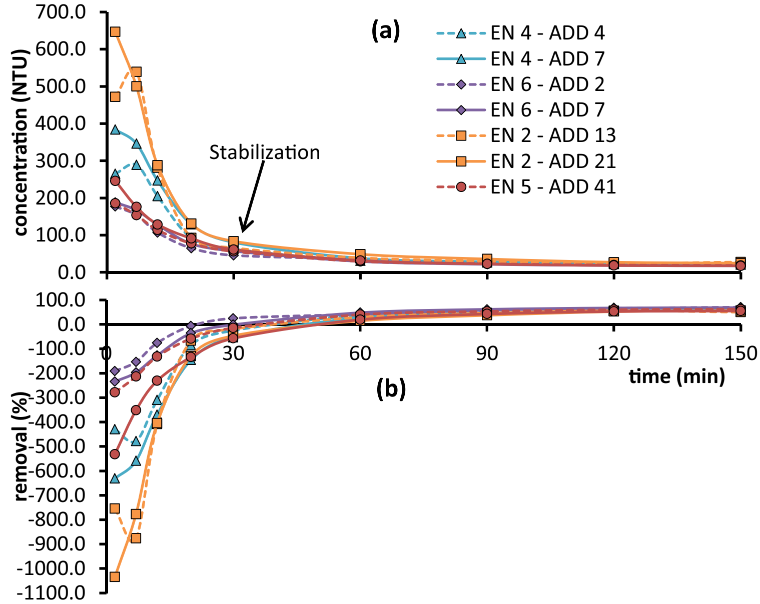


Fig. 2 Turbidity (**a**) and turbidity removal (**b**) percentage in stormwater biofilters during events with varying EN (event number) and ADD (antecedent dry days)

dwarfed by the strong impact of EN on TUOUT in young filters, while the effect of EN subsided with ageing of filter, the impact of ADD became more pronounced.

3.1 Removal of Suspended Solids in Filter

Prior to the analysis of the impact of suspended solids retained in the filter during the previous events on phase I stabilisation of current event, it is important to analyse solids retention and mechanisms of retention during an event. It was observed in Figs. 2 and 3 that there was a significant removal of turbidity that occurred after phase I stabilisation. This indicated retention of solids in the filter. TUOUT was significantly correlated to TUIN (beyond 60 min of outflow), while no impact of EN, ADD, or TUIN was observed.

For effective retention of solids by straining, the ratio between particle diameter (suspended solids) and medium particle diameter (filter medium) should be greater than 0.005 (Bradford et al. 2003). Therefore, stormwater biofilters with typical D_{50} of approximately 0.3 mm should be capable of removing particles larger than 1.5 μm in diameter, which is in the range of clays. The current study had kaolinite and montmorillonite clay in the inflow that have approximately 1–40 μm of particle sizes, which would therefore potentially be retained in the filter due to straining. Higher removal of solids observed in this study could be therefore attributed to cake filtration (straining) on the top layer of the filter. Continuously operated biofilters show formation of cake on the top layer of the filter in such occasions that continued to grow until the system failed due to clogging (Li and Davis 2008a). Distinctively different colour of kaolinite and montmorillonite (white) to the colour of the filter medium (brown) made observation of the formation of a thin cake on the top layer of the filter clear in this study, as shown in Fig. 4. The figure shows the top layer of the filter after four events fed with simulated stormwater with strength of 100 mg/L solids. A very thin layer of deposited clay (kaolinite and montmorillonite) was observed on the top of the filter, with no significant colour difference in the filter with depth. As the experiments continued, the thickness of this layer of clay on top of the filter did not vary, where other studies on continuously wet system observed the contrary (Li and Davis 2008a; Siriwardene et al. 2007). This is evident by comparing Figs. 4 and 5 (after 4th and 12th events, respectively) where the growth of the cake layer was not significant. One of the reasons for this observation could be due to the fact that the events in this study were comparatively shorter in duration.

A significant difference in the colour of the filter layer, more specifically of the top layer of the filter, however (10–15 cm), became more apparent with time. Colour of the top layer of the filter gradually started to

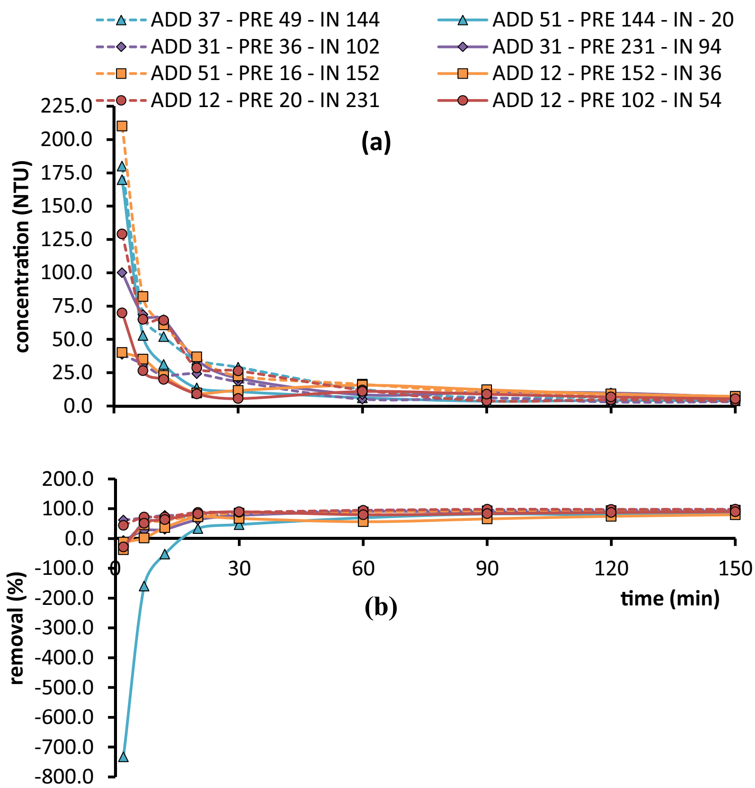


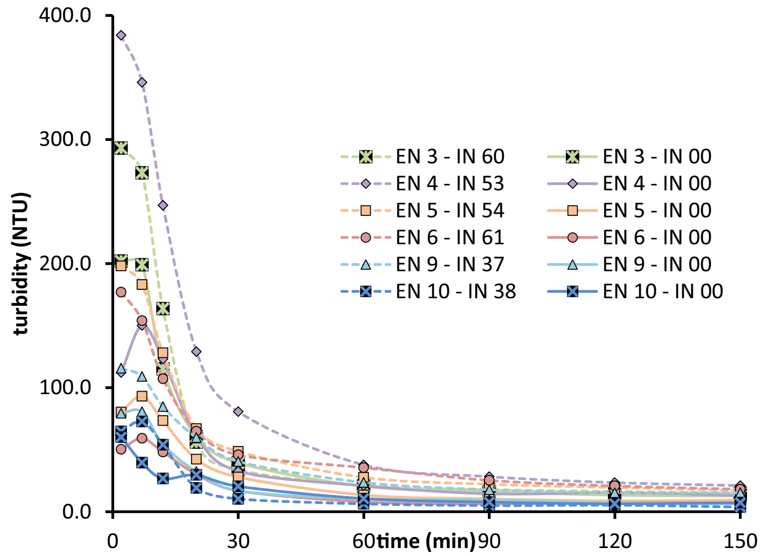
Fig. 3 Turbidity (**a**) and turbidity removal (**b**) percentage in stormwater biofilters during events with varying TUIN (inflow turbidity of current event) and TUPRE (inflow turbidity of previous event)

turn into a greyer shade, indicating increased presence of clay material due to retention from percolating stormwater. A similar study that used kaolinite was conducted on a filter with a length of 400 mm and made similar observations (Alem et al. 2013). They also observed significant amount of solids being retained in deeper areas of their filter layer, increasing with increasing flow rates through the system. They also reported that for a flow rate comparable with the flow rate in this study, significant amounts of solids were retained to a depth of approximately 10 cm after a feed of approximately 83 pore volumes. The other important factor that determined the depth to which solids were retained due to straining was the total amount of feed (number of pore volumes), where the depth of retention increased with increasing pore volumes of feed. The current study has employed approximately 4–5 pore volumes of feed in each event, with a total of approximately 90 pore volumes of feed over the whole experimental schedule. The depth to which straining occurred here was comparable with or more than the depth observed by Alem et al. (2013), although that experiment had much higher concentration of solids in the feed (1000 mg/L) and was operated continuously for 90 pore volumes of feed. Another important difference between these two studies was the intermittent wetting and drying mode of operation employed in the current study, which potentially would have caused the differences in observations. Significant amounts of solids were lost in the flush during phase I stabilisation in the study. It is important to analyse the characteristics of this flush to understand the impact of intermittent wetting and drying on the dynamics of fines (clay) retention in the filter.

As it was evident that flush of solids caused increased turbidity in the initial outflow, it was important to identify if this flush is due solely to material wash off from the filter itself. TUOUT in events that were fed with simulated stormwater was compared with outflow TU from events that were fed with tapwater alone (that had no inflow TU). Figure 4 shows six events using both simulated stormwater (shown in dashed lines) and tapwater (shown in solid lines) that had similar ADD's and EN's where IN represented inflow TU concentrations (TUIN).

It is evident from Fig. 4 that events fed with simulated stormwater had a higher flush compared with corresponding EN-number events that were fed with tapwater alone. There was a trend, however, that showed a

Fig. 4 Variation of concentration of TU with time, for events with tapwater alone as the feed (IN 00) and simulated stormwater, for events with same EN and approximately similar ADD



decrease in the flush with ageing of the filter. This was discussed earlier. Significantly higher flush in biofilter columns fed with simulated stormwater indicated that the solids removed during the wet phase of the preceding events in fact may have potentially got washed off in the subsequent event during stabilisation, causing an increased flush of solids. The analysis of total removal of solids, therefore, should consider the possible flush of captured solids from the previous event in the outflow of the following events. In order to analyse the composition of outflow suspended solids, the PSD of the solids in the outflow of columns fed with synthetic stormwater was compared with the PSD of the solids in the outflow of the column fed with tapwater alone.

Figure 5 shows particle size distribution (PSD) of simulated stormwater inflow and outflow of events using both simulated stormwater and tapwater feeds, at different times (min2, min7, min12, and min30). Initial outflow (min2) of both tapwater and simulated stormwater fed events were very similar to each other in PSD, while both being significantly different from the PSD of simulated stormwater inflow, indicated by D_{50} (was approximately 1.2 μm for outflow of all events and 4.5 μm for inflow). With time (through min7, min12, and min30), however, the PSD of outflow for events with simulated stormwater gradually deviated from PSD of outflow from tapwater fed events, and approached comparable to the PSD of simulated stormwater inflow. As turbidity continued to decrease with time, as seen earlier, the PSD analysis was seen to vary evenly between repetitions probably due to insufficient presence of solids in the sample for instrument detection capability. The trend however is in line with the arguments developed earlier from statistical analysis, that the flush of filter material decreased with time in the first 30 min (phase I stabilisation), indicating lesser presence of filter particles in the outflow in min30 compared to min2. Hence, outflow PSD from events with simulated stormwater feed were more similar to outflow PSD from events with tapwater feed in the beginning of outflow, indicating dominant presence of filter particles in the outflow. Outflow PSD from simulated stormwater events then became more similar to PSD of simulated stormwater inflow, indicating dominant predominance of inflow particles in the outflow by the end of phase I stabilisation.

Due to possible flush of solids retained (clay from inflow) during phase I stabilisation, it is also important to identify how much of the solids retained had been flushed out of the filter in the subsequent events, since retained clay particles could not be removed from the system otherwise. A conservation of mass analysis was employed to quantify the total mass of solids (kaolinite and montmorillonite) retained, from computations of total mass of solids fed to the system and total mass of solids that left the system in the outflow. In order to quantify the mass of solids, mass of total suspended solids (TSS) was calibrated against turbidity (TU) using standard solutions. Cumulative amount of mass retained were quantified for each experimental column, as EN increased. It was assumed that wash of filter material did not contribute to solids in the outflow, although significant amount of solids from the filter material was

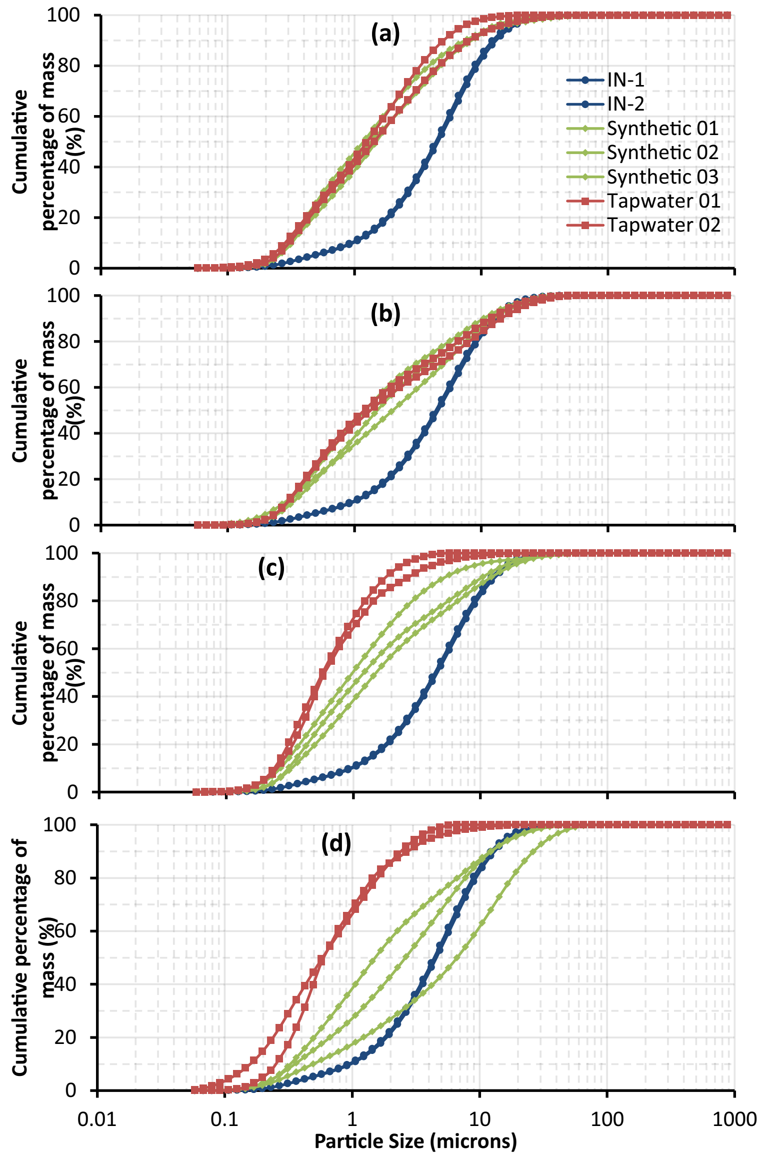


Fig. 5 Particle size distribution (PSD) of simulated stormwater inflow (blue circles) and outflow of events fed with simulated stormwater (green diamonds) and outflow of events fed with tapwater (red squares), at different times (**a**) min2, (**b**) min7, (**c**) min12, and (d) min30

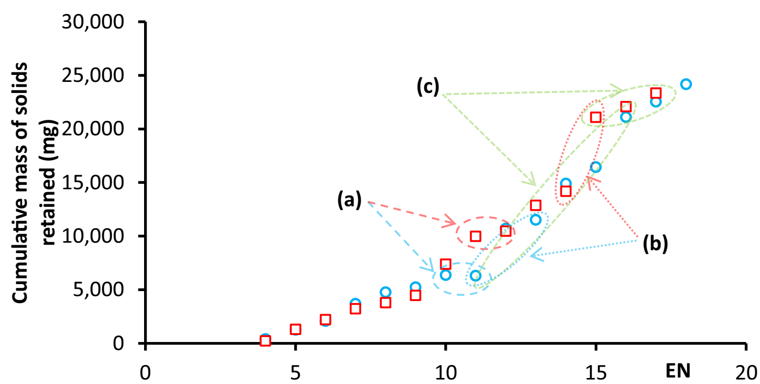


Fig. 6 Cumulative mass of solids (clay from inflow) retained in the filter with increasing EN for all events on two different columns (one shown in red and the other in blue)

flushed at the beginning of each event. The cumulative mass of clay (inflow solids) retained computed in this analysis is potentially less than actual amount of clay retained from percolating stormwater, indicating higher removal efficiency of the system.

An increasing trend in cumulative mass of solids retained was observed for all three columns monitored, more importantly in a very similar way with similar amounts of solids getting retained in all the columns in each event. Another important observation from this analysis was that the mass of solids retained in each event was constant for all events in all three columns. Amidst flush of filter material contributing to outflow solids in this analysis, a very significant removal of solids was observed. This cumulative removal analysis is highly subjective to the length of operation, as the impact of flush of solids in first 30 min would become more or less significant depending on the length of the event.

Figure 6 shows cumulative mass of solids (clay from inflow) retained in the filter with increasing EN for all events: corresponding to ageing of filter (standard and varied strength simulated stormwater) for two different columns. Strength of simulated stormwater varied after the tenth event for both the columns. Significant changes in the strength of the inflow were reflected with corresponding retention of solids. When low strength simulated stormwater was used as shown by (a), less retention of solids was observed while when very high strength inflow was applied as shown by (b), higher retention of solids were observed. Following events with higher strength inflow, the filter were capable of efficiently retaining solids for events with lower strength or higher strength as shown in (c). Irrespective of the schedule of alternating strengths of inflow used on events on a particular column, the cumulative mass of solids retained were comparable for different columns, that depended only on the total mass of solids supplied, as shown for the two columns in this figure.

3.2 Clogging of Filter

According to the discussion above, it was evident that significant amounts of solids were retained in the filter, during each event and across events as the filter aged. Observations in this study, however, did not confirm any significant levels of occurrence of clogging, as the flow rates were almost uniform during and across all events on all the experiments on different columns. Compared to the study by Alem et al. (2013) where they observed significant impact of clogging after 30 pore volumes of feed for a flow rate comparable to this study, significantly lower concentration of solids in this study would have been a reason for no apparent impact of clogging during the experimental schedule.

It was argued in past studies that considering amount of solids retained alone to analyse clogging is not sufficient rather, the deposit morphology is more crucial in determining the impact of clogging on performance of the filter (Alem et al. 2013; Boller and Kavanaugh 1995; Mays and Hunt 2004; Veerapaneni and Wiesner 1997). Clogging is mostly caused by the reduced permeability in the cake layer that is formed and grows with time on top of the filter layer removed periodically in water treatment sand filters. The layer on top of the filter that caused cake filtration in other studies did not grow with progressing EN in this study, while retention of clay was apparently deeper in the filter than in other studies as discussed earlier. Therefore, there must be another factor that influenced the process of clogging in the current study that hindered formation of cake layer on top and thereby dispersing the otherwise clogging particles.

Intermittent wetting and drying causes variations in flow rates in the filter, where very high infiltration rates were observed at the progression of wetting front. Hydrodynamic forces are crucial in assisting and obstructing retention of particles in the filter where attachment and detachment of particles are more dynamic under varying hydraulic conditions in the filter. Detachment of retained solids is highly affected by the hydrodynamic forces including drag and shear on retained solids that assist detachment and Derjaguin-Landau-Verwey-Overbees (DLVO) force that resists detachment (Alem et al. 2013; Johnson et al. 2007; Torkzaban et al. 2007). Intermittent wetting and drying, therefore, caused re-entrainment of retained or settled clay both in the thin cake layer on top as well as those clay particles retained in the top layer of the filter and redistributed them deeper in the filter layer. Re-entrainment of attached particles under varied hydraulic conditions constantly change the morphology of the pore space occupation by retained particles that in turn prohibited formation of clogging in the pore space. This is the same process that destabilises the filter layer eventually causing the flush in phase I stabilisation. In terms of clogging, intermittent wetting and drying favours enhanced functionality and lifespan of bioretention filters by delaying the process of clogging. Since retention of solids in the filter does not transform retained particles, the particles continue to accumulate in the filter, eventually reducing pore space. At some point of time, the filter will eventually clog, yet unlike water treatment sand filters, scraping the top layer would not resolve the issue of clogging in stormwater biofilters, rather a whole replacement of the filter would be required.

The dynamics of suspended solids in a stormwater biofilter analysed in this study may significantly be different to stormwater biofilters with vegetation, due to the influence of the root system of the vegetation. Depending on the development of the root system, even the species of the plant used in the column would affect the analysis.

4 Conclusion

Removal of suspended solids in stormwater runoff could efficiently be removed in stormwater biofilters with a removal efficiency as high as 95% after phase I stabilisation of the filter during an event (beyond first 30 min of the event). Even though the concentration of suspended solids in the outflow after phase I stabilisation is constantly irrelevant to inflow concentrations, ADD or EN, the removal efficiency may significantly vary depending on the inflow concentrations (mainly because removal efficiency is relative to inflow concentrations). Despite the significant amount of flush of solids from the filter during phase I stabilisation, the amount of suspended solids systematically removed from percolating stormwater was observed to be very high (cumulative mass of retention in the filter). The retention of suspended solids in the filter, however, was not observed to be induced by the cake filtration mechanism as observed in continuously fed sand filter systems. Contrastingly, the intermittent nature of the feed in stormwater biofilters re-entrained and redistributed trapped or settled particles deeper in the filter. This phenomena ensured that the clogging of the filter did not affect the performance of the filter throughout the entire study period (lifespan of the filter was prolonged).

The mechanism of removal of suspended solids in filters plays a crucial role in the design and maintenance procedure of the system. Distribution of retained solids in the deeper layer of the filter while prolonging the lifespan of the filter, which is an advantage, simultaneously reduces the maintenance of the filter by scraping the top layer due to formation of cakes. However, when the clogging finally occurs due to optimal retention of solids in the pore spaces spread throughout the filter, the whole system will need to be replaced. The future designs of stormwater biofilters may consider the dynamics of retained suspended solids under intermittent wetting and drying, to determine the design parameters to enhance the removal efficiency and the lifespan of the filter.

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