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Performance of granular medium filtration and membrane filtration in treating stormwater for harvesting and reuse

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ABSTRACT

This paper discusses laboratory scale and pilot scale treatment systems used to in treat water from a stormwater canal in Carlton, Sydney. The laboratory scale pre-treatment systems investigated included flocculation, GAC filtration and fibre filter prior to laboratory scale steriflow stainless steel membrane filter. The results showed that these pre-treatments improved the quality of the filtrate as measured by the turbidity and TOC removal efficiency. The use of pre-treatment improved the TOC removal efficiency from 10% to 90%. Among the three pre-treatment methods, GAC filter resulted in the highest TOC removal efficiency (88%). Pilot scale experiments were also carried out using stainless steel membrane filtration and GAC filtration at Carlton, Sydney. Pilot scale experiments showed that the Steri-Flow membrane filter treatment without any pre-treatment achieved an effluent filtrate turbidity of between 0.79–0.99 NTU which were well below the 5 NTU ADWG (2004) limit [1]. The influent raw stormwater had generally low concentrations of heavy metals. Following membrane filtration the concentration of all heavy metals were reduced to very low levels and well within the ADWG (2004) [1] limits. The membrane filter could not remove TOC in significant amounts. GAC adsorption used as post-treatment following Steri-flow membrane treatment effectively reduced the TOC influent feed levels. GAC filtration of stormwater provided a 70% removal of organics. It removed all types of organic. The GAC filter did not provide any further improvement to the turbidity level or heavy metal concentration following treatment with the Steri-flow membrane system.

Keywords: Filtration; Membranes; Flocculation; Stormwater; Water harvesting; Organics

1. Introduction

Apart from recycling of wastewater, stormwater can become an alternative source of potable water to mitigate the water shortage problem. However, as recycled waste water has not yet been fully accepted by the consumers, stormwater treatment has become an important strategy for improving urban water cycle management, given the current and increasing stresses on water resources throughout urban centres of Australia, and much of the world. Expanding the use of stormwater to add to the water supply and reducing water pollution are important objectives in the face of the water crisis. Stormwater is now acknowledged as a valuable resource, rather than an irritant to be disposed of quickly, especially in large urban centres. Harvesting and reusing stormwater

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offers both a potential alternative water supply for non-potable uses and a means to further reduce stormwater pollution in our waterways.

Studies have shown that a large number of pollutants, both organic and inorganic, may be present in stormwater, [2,3], both in their dissolved and colloidal forms and associated with particles. Stormwater harvesting and reuse offers a potential alternative water supply for at least non-potable uses. It complements other approaches to sustainable urban water management such as rainwater tanks, the reuse of wastewater and greywater and demand management. Collectively these areas form the basis of developing sustainable water technologies.

In Australia, water recycling is increasingly a valuable contributor to the conservation of drinking water although stormwater harvesting has been neglected [4]. The consequences of urbanisation are the increase in impermeable area (roads, carparks, paved areas) and there is more runoff. The average annual volume of urban storm water runoff in Australian cities is almost equal to the average annual urban water usages, of which at least 50% is for non-potable use [5]. Urban stormwater is perceived to be of better quality than grey water and wastewater and its reuse has a better public acceptance. The benefits of a successful stormwater harvesting scheme are reductions in (i) demand for town water, (ii) stormwater pollution loads to downstream waterways and estuaries, and (iii) stormwater volumes and discharges. Stormwater pollution is a major source of pollution in receiving water eg. Sydney Harbour and Melbourne's Port Phillips Bay. Stormwater contributed 94% of sediments and 50–60% of nutrients to Sydney Harbour, [6].

Advances in low pressure driven membrane technologies such as microfiltration (MF) and ultrafiltration (UF) have permitted their use in water, seawater and wastewater treatment due to their high efficiency, ease of operation and small footprint [7]. Flocculation and adsorption are becoming attractive pre-treatments before the application of membrane filtration. Earlier studies found that flocculation and membrane (microfilter, MF; ultrafilter, UF) filtrations could efficiently remove the natural organic matters (NOM) from water [7,8].

High rate fibre filters were successfully used in tertiary treatment of wastewater. In fibre filter, in place of the sand, fibre media consisting of bundles of U-shaped fine polyamide fibres are used. Compared with the conventional rapid sand filter, the filtration velocity of a fibre filter is more than five times and the specific surface is more than twice [9,10]. The fibre packing combines the two advantages of a large specific surface area and very large porosity (more than 90%) which results in high removal efficiency and low pressure drop despite the high filtration velocity [10]. In-line additions of flocculants enhance the pollutant removal capacity for both dissolved organics and trace metals.

This paper discusses laboratory scale and pilot scale treatment systems used to in treat water from a stormwater canal in Carlton, Sydney. The laboratory scale pretreatment systems investigated included flocculation, GAC filtration and fibre filter prior to laboratory scale Steriflow stainless steel filter. The capability of these filters as the various treatments was studied in terms of turbidity, heavy metal concentration and organic removal. Pilot scale experiments were also carried out using pilot scale stainless steel membrane filtration and GAC filtration at Carlton, Sydney.

2. Experimental methodology

Raw water samples were collected from a stormwater harvesting plant located at the Lower West Street Reserve, Carlton, Sydney. The stormwater is normally harvested from base flow which constantly flows in the stormwater canal between rainfall events (Fig. 1). The stormwater drains by gravity through a sump pit in the floor of the stormwater canal to an adjacent wet well. It is then pumped at a rate of 0.7 $l\ s^{-1}$ or 2.5 $kl\ h^{-1}$ through a control valve pit which monitors the turbidity levels for filtration suitability. There is an optional facility to return raw stormwater back to the canal should the turbidity be greater than 50 NTU.

2.1. Laboratory scale treatment experiments

Different types of pre-treatment methods were used to treat raw stormwater collected from the stormwater harvesting plant Carlton, Sydney. These were

1. Flocculation: Flocculation was carried out using $FeCl_3$ as flocculant at a dose of 30 mg l^{-1}. The optimum flocculant dose (30 mg l^{-1}) was pre-determined using standard jar jest. $FeCl_3$ were added into beakers. The samples were stirred rapidly for 1 min at 130 rpm to represent rapid mixing followed by 30 min of slow mixing at 30 rpm to represent flocculation and a final 30 min to allow the flocs to settle.
2. GAC filtration: Short term (5 h) GAC filtration experiment was carried out using a filtration velocity of 5 m h^{-1}. The particle size of GAC used in this study was 0.30–0.76 mm. Other properties are given in Table 1. The height of filter media inside the filter column was 80 cm.
3. In line flocculation and fibre filtration: Filter column packed with fibre filter at a packing density of 115 kg m^{-3} were operated at a filtration velocity of 20 m h^{-1} to evaluate the efficiency of the fibre filter. The configuration of the fibre filter experimental set up is given elsewhere [11]. $FeCl_3$ at a dose of 15 mg l^{-1} was

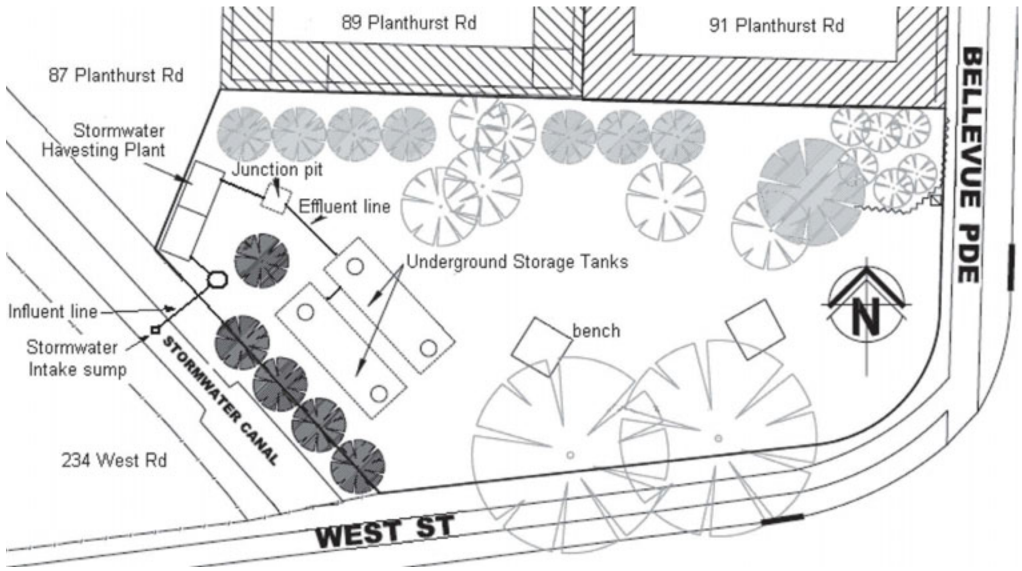


Fig. 1. Carlton stormwater harvesting plant, Kogarah, Sydney.

used as in-line flocculant. The fibre media consisting of bundles of U-shaped fine polyamide microfibres. Compared with the conventional rapid sand filter, the filtration velocity of the fibre filter is more than five times faster and the specific surface is more than twice [9,11,12]. The fibre packing combines the two advantages of a large specific surface area (6800 m^2 m^{-3}) and very large porosity (more than 90%) which results in high removal efficiency and low pressure drop despite the high filtration velocity employed. The details of fibre filter experiment are available elsewhere [9,11,12].

Membrane filtration: Membrane filtration experiments were carried out initially using the laboratory scale Steri-flow stainless steel filtration system (Fig. 2, Table 2). The membrane has a surface area of 0.03 m^2 and pore size of 0.3 μm.

2.2. *Pilot scale experiments*

Pilot scale experiments were carried out using stainless steel membrane filtration and GAC filtration at Carlton, Sydney.

Filter Configuration: Experiments were conducted with a membrane filter and a granular activated carbon (GAC) filter (Fig. 3b). The membrane was the steriflow stainless steel membrane (Table 2).

The Steri-Flow membrane filter was operated under a 2 m of gravity head in crossflow mode. The Steri-Flow filtration system utilised automated cleaning procedures including a back pulsing and back flushing. The back pulsing operated for 0.08 s every 3 s and back flushing operated for 1 s every 4 min. The circulation bleed

Table 1
Physical properties of GAC (manufacturer: james cummins P/L, Australia)

Specification	Estimated value
Iodine number, mg (g min)$^{-1}$	800
Nominal size, m	3×10^{-4}
Maximum moisture content	5%
BET surface area, m^2 g^{-1}	750

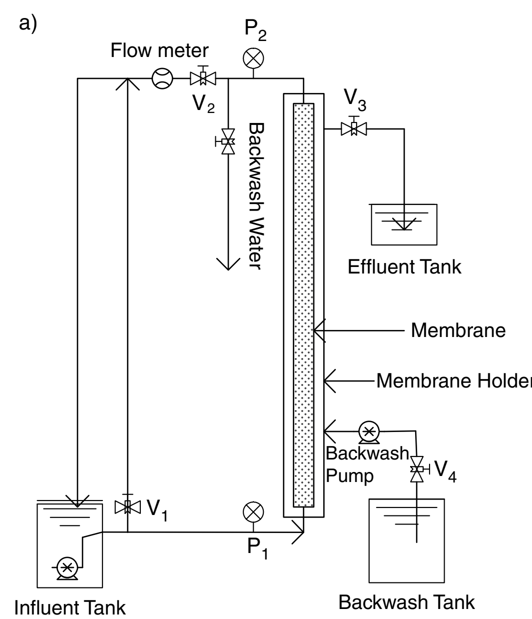


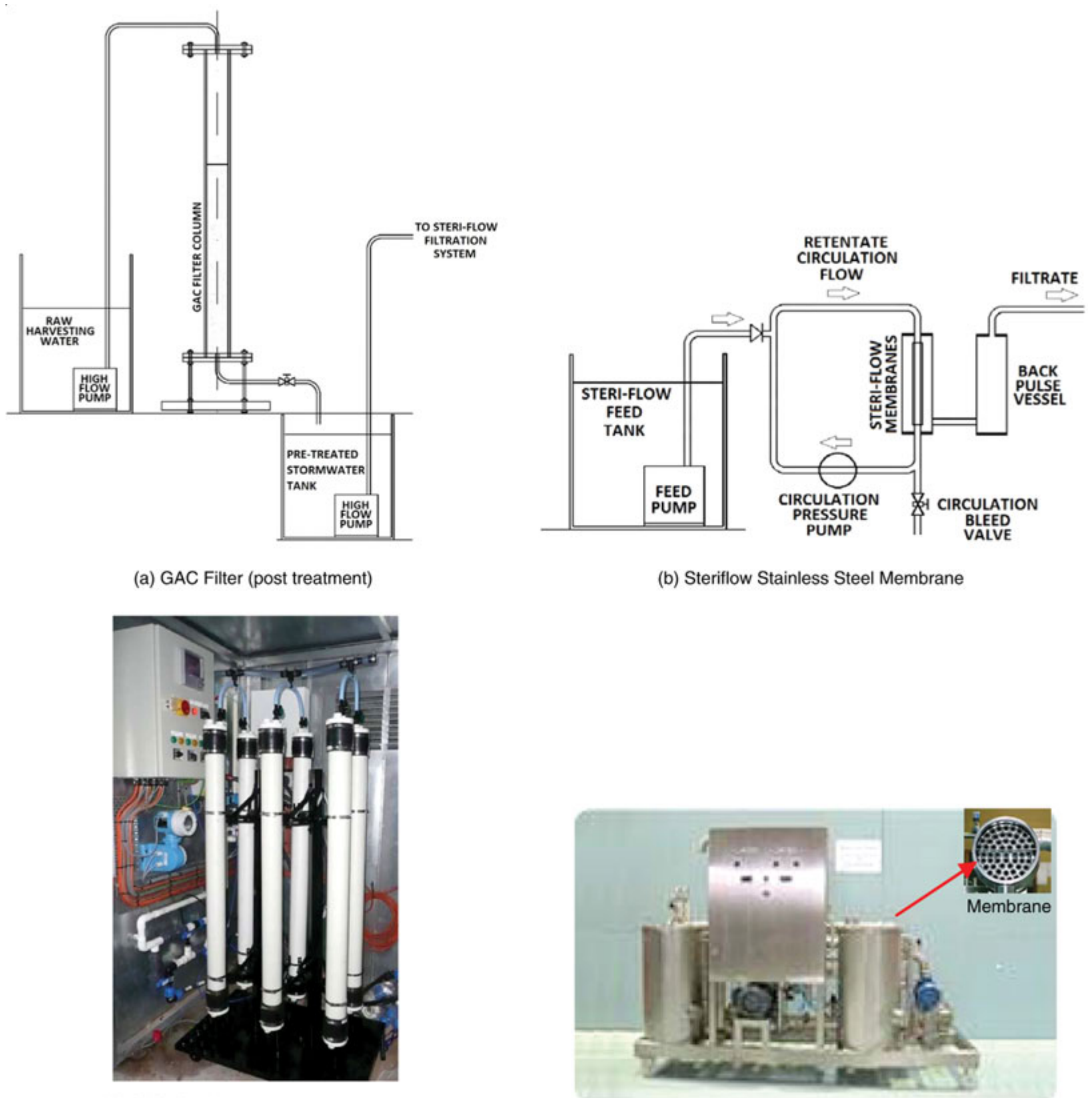
Fig. 2. Schematic diagram of laboratory scale Steriflow membrane system (membrane area = 0.03 m^2; pore size = 0.3 μm).

Table 2
Physical properties of steri-flow filtration systems stainless steel micro-filtration membrane

Name	Membrane
Manufacturer	Steri-flow filtration system
Material	Stainless steel
Pore size (um)	0.3
Membrane dimensions (mm)	450 long, 20 dia.
Filter area (m^2)	0.03 (laboratory scale) 3 (pilot scale)
Method	In – out

valve was partially opened to prevent the retentate's cross-flow concentration from continuously increasing (Fig. 3b). Following the completion of an experiment the entire filtration system was purged of pre-treated feed water and retentate water, then cleaned and back-washed with clean tap water to ensure virgin starting conditions for each subsequent experiment.

The height of the GAC in the filter column was 1 m. The flow rate through the columns was 10 m h^{-1}. The filter columns were backwashed at the end of each day of operation for 60 s which proved to be satisfactory to maintain less than 1 bar (100 kPa) of pressure across the columns. Fig. 3c shows the GAC filter column system.



(a) GAC Filter (post treatment)
(b) Steriflow Stainless Steel Membrane
(c) GAC filtration system in stormwater harvesting plant cabinet
d) Steriflow filtration unit

Fig. 3. Schematic diagram of pilot scale pilot scale stormwater plant comprising steri-flow filtration system and post treatment of GAC filter (a) GAC filter (post treatment), (b) steriflow stainless steel membrane, (c) GAC filtration system in stormwater harvesting plant cabinet, (d) Steriflow filtration unit.

The pilot scale experiments were conducted with raw stormwater collected from the stormwater canal in Carlton treated with the Steri-Flow membrane system followed by a post-treatment of GAC media filter. The Steri-Flow system operated in a cross-flow configuration. The Steri-flow filtration system's treated water was stored in a stormwater tank which was then pumped to provide the GAC filtration system's feed tank with the required feed supply (Fig. 3b).

2.3. Water analyses

Detailed laboratory analyses were carried out to determine individual pollutants. The pollutants were analysed and the water quality parameters were measured according to standard methods [13]. Total organic carbon (TOC) concentration of raw water and treated water was measured by using the Multi N/C 2000 analyzer (Analytik Jena AG).

Dissolved organic carbon (DOC) matter was measured using Liquid chromatography-organic carbon detection (LC-OCD). LC-OCD categorizes the classes of organic compounds in raw and treated water. It gives qualitative results regarding molecular size distribution of organic matter as well as quantitative information on NOM. Quantification was done on the basis of carbon mass determination, similar to TOC analysis which is performed with a special organic carbon detector. The qualitative analysis was based on size exclusion chromatography (SEC) and it separates organic matter according to their molecular size. All samples were filtered through a 0.45 micro-filtration as a pre-filter before being analysed in the LC-OCD.

3. Results and discussion

3.1. Laboratory scale experiments

Laboratory experiments were undertaken to investigate the effect of various pre-treatments prior to membrane filtration. Three different treatment methods were examined: (i) flocculation using $FeCl_3$, (ii) GAC filtration, (iii) in-line flocculation-fibre media filtration. It was found that all treatments improved the performance of membrane filtration.

The TOC of the influent was about 5.35 mg l^{-1} and the average TOC removal by the membrane alone was only about 10%. The MF alone cannot remove the TOC due to its large pore size (0.3 μm). The marginal removal is due to adsorption of organics on the membrane. The use of pre-treatment improved the TOC removal efficiency from 10% to 90% (Table 3). Among the three pre-treatments, GAC filter resulted in the highest TOC removal efficiency (88%, Table 3). The next highest TOC removal efficiency was with in-flocculation using $FeCl_3$ followed by fibre filtration. Flocculation alone had a TOC removal efficiency of 55% (Table 3).

The turbidity following different treatments was between 0.5–1.2 NTU (Table 3) except with GAC filtration where the effluent turbidity was 5 NTU. This may be due to the fact the particles are too small to be removed without any flocculation.

The flux decline of raw water (without pre-treatment) was between 35–40%, whereas after pre-treatment it reduced to about 8–30% (Fig. 4). In terms of flux decline in-line flocculation-fibre media filtration showed the lowest flux decline of 8–9% of the MF followed by GAC (24–30%) and flocculation (28–30%). The GAC filter showed higher TOC removal efficiency but had higher rate of fouling of the MF compared with in-line flocculation fibre filtration. The rationale behind this is that GAC filter was not able to remove colloidal particle from the water resulting in a higher turbidity value (5 NTU) compared with in-line flocculation fibre filtration which gave better removal of turbidity (0.5 NTU). The membrane flux was restored by chemical cleaning (with NaOH solution at pH of 12 for 2 min) and 1 min backwash with filtrate water.

Table 3
Filtrate water quality after different pre-treatments (raw water turbidity = 25.3 NTU; TOC = 5.35 mg l^{-1})

Pre-treatment option	Turbidity (NTU)	TOC removal efficiency (%)
Flocculation ($FeCl_3$ = 15 mg l^{-1})	1.23	55.7
GAC filtration (particle size = 0.3–0.67 mm, velocity = 5 m h^{-1})	5.0	88.2
In-line floculation-fibre filtration ($FeCl_3$ = 15 mg l^{-1}, v = 20 m h^{-1})	0.5	62.0
Flocculation ($FeCl_3$ = 15 mg l^{-1}) with MF as post-treatment	0.12	58.1
Microfiltration alone (MF, pore size=0.3 μm)	0.13	10
GAC filtration (particle size = 0.3–0.67 mm, velocity = 5 m h^{-1}) with MF as post-treatment	0.10	90.0
In-line floculation-fibre filtration ($FeCl_3$ = 15 mg l^{-1}, v = 20 m h^{-1}) + MF	0.10	62.0

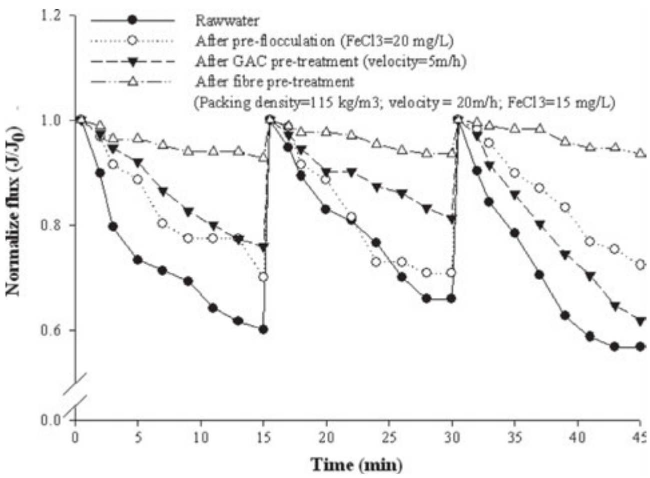


Fig. 4. Comparison between pre-treatments to cross-flow microfiltration (stormwater; membrane area = 0.03 m^2, pore size = 0.3 µm, cross flow velocity = 0.5 l min^{-1}, pure water flux at IP = 125 ± 3 and OP = 100 ± 3 kPa is 0.44 m^3 m^{-2} h^{-1}, IP = inlet pressure and OP = outlet pressure).

3.2. Pilot scale experiments

3.2.1. Steri-flow membrane filtration without pre-treatment

TOC: The concentration of TOC in the influent raw stormwater feed was between 3.94–9.73 mg l^{-1} (Fig. 5). Although micro-filtration membranes do not normally remove TOC without any other pre-treatment, the Steri-Flow system was able to reduce TOC levels in the filtrate to between 1.49–6.15 mg l^{-1}. This could be partly due to the high removal of turbidity from the feed on which some of the organic matter was associated. The TOC reduction by the membrane filter could also have been due to the adsorption onto the membrane.

Turbidity: The influent stormwater feed contained turbidity levels in the range of 72–575 NTU (Fig. 6). The turbidity levels of influent raw stormwater during this experiment were high coinciding with a period of rainfall and heavy stormwater runoff. The Steri-Flow membrane filter treatment without any pre-treatment achieved an effluent filtrate turbidity of between 0.79–0.99 NTU which were well below the 5 NTU ADWG (2004) limit.

Heavy Metals: The influent raw stormwater itself had generally low concentrations of heavy metals (Table 4). There were no traces of cadmium or mercury detected in the samples. The Steri-Flow filtration performed effectively with significant reductions in removing most heavy metals. The concentration of all sampled heavy metals in the effluent were below the ADWG (2004) limits. The removal rates for aluminium, copper, iron and zinc were high (Table 4). Lead was removed to below detection limits. The Steri-Flow system provided a

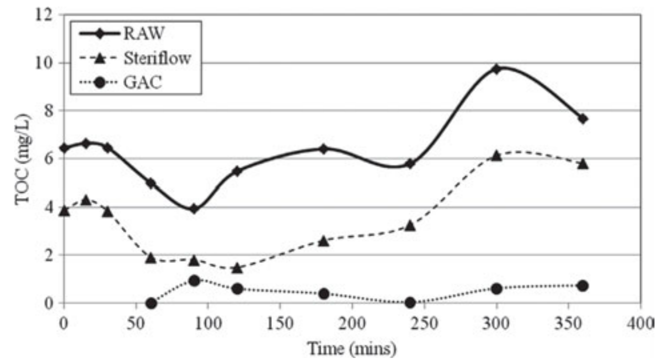


Fig. 5. TOC with results steri-flow membrane filter followed by post treatment with GAC.

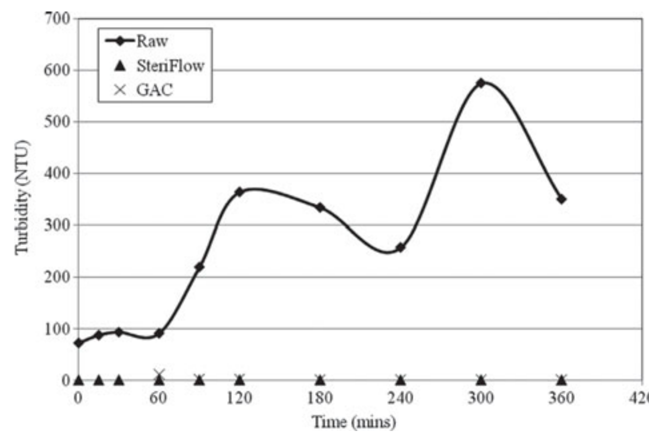


Fig. 6. Turbidity with steri-flow membrane filter treatment followed by post treatment with GAC.

smaller improvement for manganese with an average reduction of 42%. The sampling indicated that there was minor removal of chromium and selenium although the concentrations of both these in the raw stormwater were very low. The removal of heavy metals by the membrane filtration may have been due to the fact that a majority of heavy metals would have been associated with sediment particles.

3.2.2. Steri-flow membrane filtration with GAC adsorption as post-treatment

The results of the experiment with GAC adsorption as post-treatment following Steri-flow membrane treatment demonstrate that the GAC treated stormwater effectively reduced the TOC influent feed levels to between 0.61–0.81 mg l^{-1} and an average concentration of 0.68 mg l^{-1} (Fig. 5).

The GAC filter did not provide any further improvement to the turbidity level following treatment with

Table 4
Heavy metals results of steri-flow filtration system

Parameter	Raw (mg l^{-1})	Steri-flow filtration + GAC (mg l^{-1})	%Removal	ADWG (2004) (mg l^{-1})
Aluminium	1.077	0.007	99%	<0.2
Arsenic	0.005	0.002	62%	<0.007
Chromium	0.002	0.001	0%	<0.05
Copper	0.041	0.008	80%	<2
Iron	2.684	0.013	99%	<0.3
Manganese	0.109	0.063	42%	<0.1
Lead	0.013	ND	>20%	<0.01
Selenium	0.002	ND	0%	<0.01
Zinc	0.080	0.007	89%	<3

ND – not detected.

the Steri-flow membrane system, which were already well below the 5 NTU ADWG (2004) limit. The GAC filter provided a small additional improvement to the removal of heavy metals.

3.3. Organic matter characterisation

Categorization of organic matter was conducted for raw stormwater and after GAC treatment (Table 5). It was found that the concentration of DOC of the canal water was 5.86 mg l^{-1} out of which 66% was hydrophobic and remaining 34% was hydrophilic. In hydrophilic portion, the majority of the substances are humic substances (52%), building blocks (23%) and biopolymers (8%), and lower molecules neutrals and acids (16%).

After GAC filtration of stormwater, the concentration of DOC was found to be 1.17 mg l^{-1} which represents an 80% removal. The majority of organic matter was hydrophilic (75%) compared to 25% of hydrophobic organic matter. In hydrophilic portion, the majority of the substances were humic substances (52%), building blocks (32%) and lower molecules neutrals and acids (14%). For comparative purpose, Table 5 gives values of raw rainwater.

It was found that stormwater treated with the GAC filter had a majority of organic substances removed. GAC filter removed all types of organic.

3.4. Membrane flux decline

The experiment where the Steri-flow membrane system treated raw stormwater (without any pre-treatment) showed a large flux decline. The turbidity levels of influent raw stormwater during this experiment was

Table 5
Fractionation of organic compounds by LC-OCD

Sample	DOC Dissolved mg l^{-1}, %DOC	HOC Hydrophobic mg l^{-1}, %DOC	CDOC Hydrophilic mg l^{-1}, %DOC	BIO-polymers mg l^{-1}, %DOC	Humic substances (HS) mg l^{-1}, %DOC	Building blocks mgl^{-1}, %DOC	LMW substances mg l^{-1}, %DOC
Raw stormwater	5.86	3.87	1.99	0.17	1.04	0.46	0.32
	100%	66%	34%	8%	52%	23%	16%
GAC filter	1.17	0.88	0.29	n.q.	0.15	0.09	0.04
	80%	75%	25%	n.q.	52%	32%	14%
Raw rain water	1.63	1.26	0.37	n.q.	0.2	0.1	0.06
(for comparison)	NA	77%	23%	n.q.	54%	27%	16%

LMW – low molecular weight.

high in the range of 72–575 NTU (Fig. 5) coinciding with a period of rainfall and heavy stormwater runoff. The fluxes recorded at the initial stages of the experiment were consistently between 60–66 l m^{-2} h^{-1}. The flux decreased continuously over the 6 h duration of the experiment to a final flux of 37 l m^{-2} h^{-1}.

4. Conclusions

Laboratory studies showed that pre-treatment improved the quality of the filtrate as measured by the turbidity and DOC removal efficiency resulting in a lower fouling of the MF and a smaller decline of flux. The use of pre-treatment improved the TOC removal efficiency from 10% to 90%. Among the three pre-treatment methods, GAC filter resulted in the highest TOC removal efficiency (88%). The turbidity following different treatments was between 0.5–1.2 NTU (Table 3) except with GAC filtration where the effluent turbidity was 5 NTU. The flux decline of raw stormwater (without pre-treatment) was between 35–40%, whereas after pre-treatment it reduced to between 8–30%. In-line flocculation-fibre media filtration showed the lowest flux decline of 8–9% of the MF followed by GAC (24–30%) and flocculation (28–30%).

Pilot scale experiments showed that the Steri-Flow membrane filter treatment without any pre-treatment achieved an effluent filtrate turbidity of between 0.79–0.99 NTU which were well below the 5 NTU ADWG (2004) limit. The influent raw stormwater had generally low concentrations of heavy metals. Following membrane filtration the concentration of all heavy metals were reduced to very low levels and well within the ADWG (2004) limits. The membrane filter could not remove TOC in significant amounts. GAC adsorption used as post-treatment following Steri-flow membrane treatment effectively reduced the TOC influent feed levels. GAC filtration of stormwater provided a 70% removal of organics. It removed all types of organics. The GAC filter did not provide any further improvement to the turbidity level or heavy metal concentration following treatment with the Steri-flow membrane system.

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