Desalination and Water Treatment
www.deswater.com
1944-3994/1944-3986
doi: 10/5004/dwt.2012.4084

Taylor & Francis
Taylor & Francis Group

45 (2012) 361–369
July

Two stage filtration for stormwater treatment: a pilot scale study

Benjamin Kus[a], Jaya Kandasamy[a], Saravanamuthu Vigneswaran[a,*], Hokyong Shon[a], Glen Moody[b]

[a]*Faculty of Engineering and IT, University of Technology, Sydney, P.O. BOX 123, Broadway, NSW 2007, Australia*
Tel. +61 2 9514 2641; Fax: +61 2 9514 2633; emails: s.vigneswaran@uts.edu.au, Vigid.Vigneswaran@eng.uts.edu.au
[b]*Kogarah Municipal Council, 2 Belgrave Street, Kogarah, NSW 2217, Australia*

Received 31 December 2011; Accepted 13 April 2012

ABSTRACT

This paper presents the results of the granular medium filter and membrane (Ultra Flo membrane) filter experiments conducted with raw stormwater collected from a stormwater canal at Carlton, in Sydney. The filter medium experimented were granular activated carbon (GAC), anthracite and sand. Each was used as a single medium in a 1 m filter column. The filter columns were operated at filtration velocity 10 m h^{-1}. The GAC filter column was capable of significantly reducing the influent dissolved organic carbon (DOC) concentrations. After GAC filtration of stormwater, the average concentration of DOC was 1.76 mg l^{-1}, measured using LC-OCD, which represents a 70% removal of all types of organic. Membrane filtration removed a small additional amount of organics. The GAC filter as a pre-treatment to membrane filtration performed effectively with significant removals in most heavy metals although their influent concentrations were low. The treatment train of GAC filter column followed by membrane filtration was able to reduce the turbidity by 99%. The GAC filter by itself was able to reduce turbidity to an average of 84%. The GAC filter by itself and with the membrane filter both achieved turbidity levels below the ADWG (2004) limits of 5 NTU.

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

1. Introduction

Australia is the driest continent, and has one of the most variable rainfall intensity in the world. In the last 100 y, Australia has suffered six major droughts and 15 other droughts, the most recent one being the worst on record. The last drought and concerns about climate change have all highlighted the need to manage water resources more sustainably. Expanding the beneficial reuse of stormwater runoff lowers the demand placed on municipal water supplies and reduces water pollution. The average annual volume of urban stormwater runoff in Australian cities is almost equal to the average annual urban water usage, of which at least 50% is for non-potable use [1]. Stormwater is now recognised as a valuable resource which could be harvested, where previously it was thought of as a waste stream.

Stormwater runoff is the main source of pollution to receiving water such as lakes and waterways. The chemical characteristics of stormwater are dependent on the nature of surfaces runoff passes on such as roads, roofs, etc. 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 [4]. Such discharges of urban stormwater may cause numerous adverse impacts including the export of heavy metals, organic compounds and pathogens to the receiving waters. Best management practices (BMPs) or sustainable urban drainage systems (SUDs) such as filter strips

*Corresponding author.

and swales; infiltration systems (soakaways, infiltration trenches and infiltration basins); and storage facilities (detention basins, retention ponds, lagoons) are widely used as treatment of stormwater to reduce the amount of stormwater based pollutants entering the receiving water as well as the urban runoff peak flows, [5].

The high potential for continued proliferation of organic and inorganic contaminants pose substantial challenges to the recycle and reuse of stormwater. As Australia enters an era of recycling of stormwater and wastewater, it is essential to identify treatment systems that effectively remove emerging contaminants of concern in urban stormwater [5,6]. Deep bed filtration is an effective process in removing suspended particles of various nature and sizes that are present in water and wastewater. Rapid filtration finds its greatest application in the clarification of dilute suspensions of particles ranging from 0.1 to 50 μm [7]. Further, the use of membrane filtration as post treatment helps to remove pathogens and suspended solids. Advances in low pressure driven membrane technologies such as microfiltration (MF) and ultrafiltration (UF) have permitted their use in water and wastewater treatment due to their high efficiency, ease of operation and small footprint [8]. However, low pressure membrane filtration (MF, UF) cannot efficiently remove the natural organic matters (NOM) from. Thus it is important to incorporate a treatment process to remove organics and heavy metals.

This study assessed the performance of filtration using different media such as granular activated carbon (GAC), sand and anthracite to determine the effectiveness of filtration as pretreatment in removing suspended solids, organics and heavy metals from stormwater. The importance of membrane filtration as a post-treatment was also studied using raw stormwater collected from a stormwater canal at Carlton, Sydney.

2. Experimental methodology

Raw water samples were collected from a stormwater harvesting plant facility located at the Lower West Street Reserve, Carlton, Sydney. The stormwater that was harvested was predominantly 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 through a control valve pit which monitors the turbidity levels for filtration suitability. If the turbidity is greater than 50 NTU, the water was diverted back through a return pit to the canal. Otherwise it proceeds to the stormwater filtration plant at a rate of 0.7 L s^{-1} or 2.5 kL h^{-1}.

2.1. Filter configuration

Experiments were conducted with granular medium filter packed with different media and a membrane filter (Fig. 2a). The media used were GAC, anthracite and sand and the membrane was the Ultra Flo membrane. The characteristics of GAC, anthracite and sand are given in Tables 1 and 2. The membrane characteristics are given in Table 3. The raw water was pumped to the filter column. The effluent from the filter column was passed through the membrane filter. The membrane filter was under

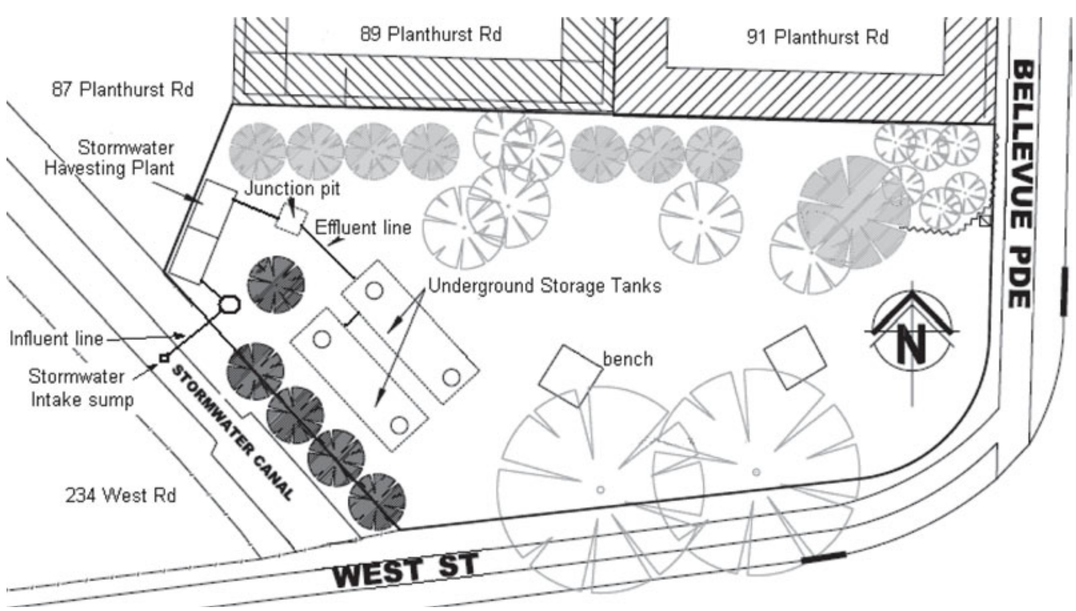

Fig. 1. Carlton Stormwater Harvesting Plant, Kogarah, Sydney.

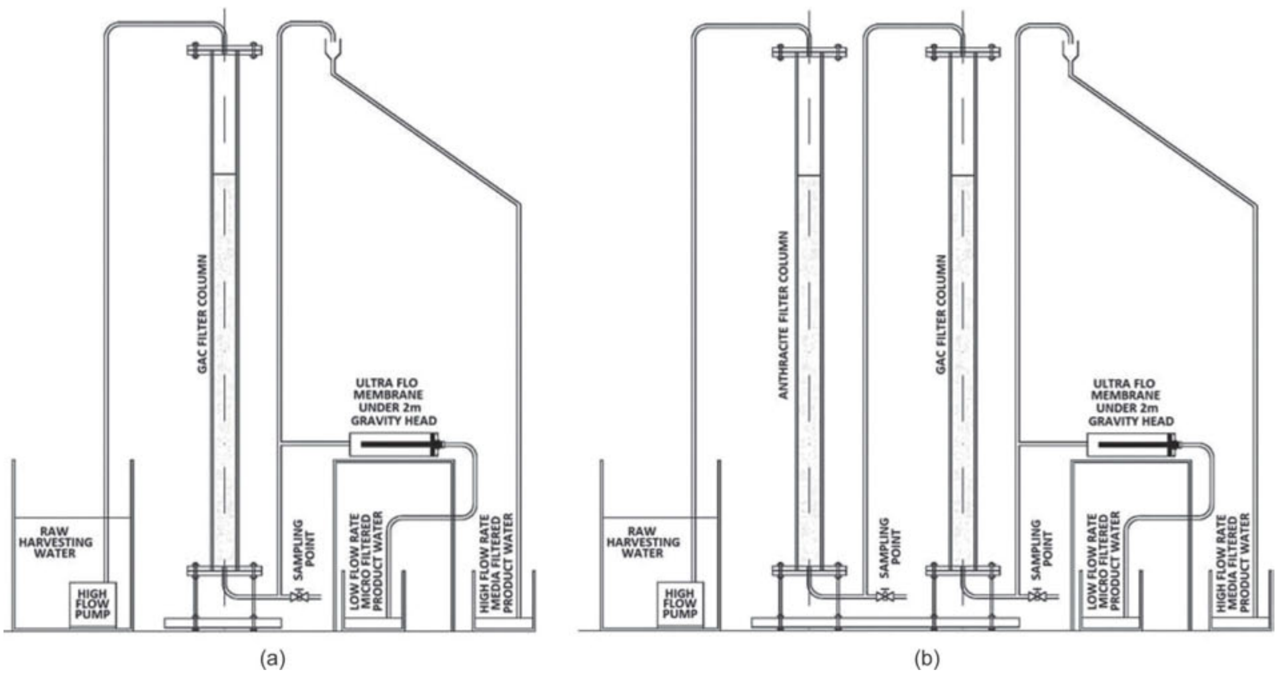

Fig. 2. Schematic diagram of GAC media filtration (media filtration flux = 10 m h^{-1}, media depth = 1 m) and Ultra Flo hollow fibre micro-filtration membrane (operated under gravitational head).

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%
Bulk density, kg m^{-3}	748
BET surface area, m^2 g^{-1}	748

Table 2
Physical properties of anthracite and sand (manufacturer: RiverSands P/L, Australia)

Parameter	Anthracite	Sand
Effective size (mm)	1.0–1.1	0.55–0.65
Uniformity coefficient	1.30	<1.5
Acid solubility	1%	<2%
Specific gravity	1.45	2.65
Bulk density (kg m^{-3})	660–720	1500

a 2 m of gravity head. The membrane operated under crossflow conditions. Further experiments were conducted with two filter columns (anthrachite filter and GAC filter in series, Fig. 2b) and three columns in series (anthrachite filter, sand filter and GAC filter in series) to see the necessity of sand and anthracite filters as pre-treatment to the GAC filters in order to reduce the suspended solids load to GAC filter.

Table 3
Physical properties of Ultra Flo hollow fibre micro-filtration membrane

Name	Characteristics
Membrane manufacturer	MANN + HUMMEL ULTRA-FLO P/L, Singapore
Material	Polysulfone
Pore Size	0.1 µm
Outer diameter	1.9 mm
Inner diameter	0.7 mm
No. of fibres	40
Length of fibre	400 mm
Filter Area	0.3 m^2
Method	Out-in

The height of the medium in the column was 1 m. The flow rate through the columns was 10 m h^{-1}. The columns were run continuously for 4 h d^{-1} for three consecutive days. The filter columns were backwashed at the end of each day of operation for 60 s which proved to be satisfactory in maintaining less than 1 bar of pressure across the columns. Fig. 3 shows the granular medium column filtration system.

Fig. 3. Flow column filtration system in harvesting plant cabinet.

The granular medium filter (GAC, anthracite or sand) column can typically operate at a relatively high filtration rate (10 m h^{-1}). By contrast, the flux of the submerged membrane filtration (Ultra Flo membrane) is slow. The characteristics of the Ultraflo membrane are given in Table 3. To facilitate the much lower rate of membrane filtration, while maintaining a contact driving head of 2 m, an overflow system was installed as shown in Figs. 2 a, b. The experimental configuration of a possible prototype high rate stormwater treatment system is shown in Fig. 4. In this system stormwater pumped from a channel is treated by a granular medium filter at a relatively high filtration rate. After treatment water is stored for uses that are compatible with its quality. This water is good enough for non-potable purposes such as gardening. The stored water can undergo further membrane treatment for uses that typically require higher quality of water.

Detailed laboratory analyses were carried out to determine individual pollutants. The pollutants analysed and the water quality parameter measuring methods were according to standard methods [9]. Total organic carbon (TOC) concentration of raw water and treated water was measured by using the Multi N/C 2000 analyzer (Analytik Jena AG). The measurements were made thrice each time and the deviation was less than +/–0.03 mg l^{-1}.

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

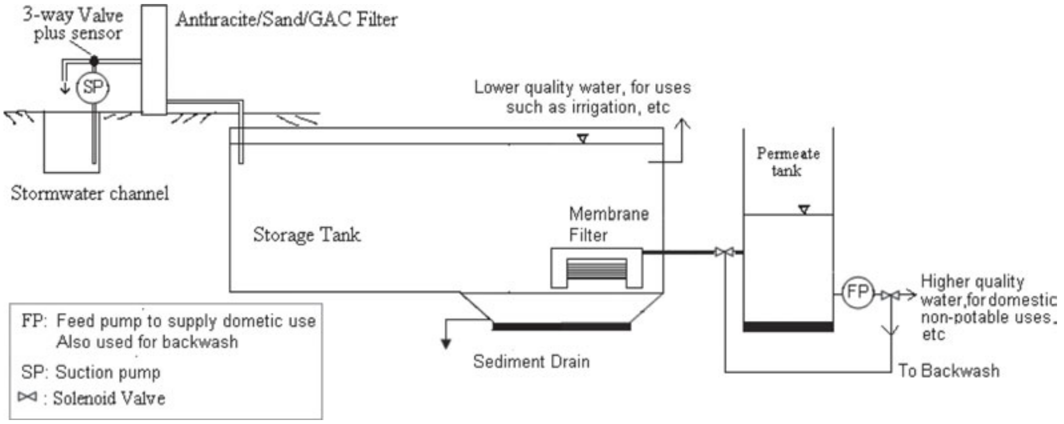

Fig. 4. Possible prototype application of high rate media filtration followed by membrane filtration membrane (operated under gravitational head).

Table 4
TOC results (based on 7 samples taken daily for 3 consecutive days)

Treatment train	Influent (mg l^{-1})	Anthracite (mg l^{-1})	Sand (mg l^{-1})	GAC (mg l^{-1})	Membrane (mg l^{-1})
GAC filter and membrane post-treatment	2.3–6.9 4.6	NA	NA	ND–1.0 0.1	ND–1.0 0.1
Anthracite + GAC and membrane post-treatment	2.3–6.9 4.6	2.3–6.4 4.1	NA	ND–1.7 0.1	ND–1.7 0.1
Anthracite + sand + GAC and membrane post-treatment	2.2–6.6 4.6	2.3–6.4 4.1	2.1–6.3 3.9	ND–0.9 0.1	ND–0.8 0.1

NA – not applicable.
ND – below detection limit.

3. Results

3.1. TOC

The details of the concentration of TOC in the influent stormwater is given in Table 4. The treatment train of GAC filter column followed by membrane filtration demonstrated that the GAC treatment was capable of reducing the influent TOC concentrations minimum of 86% (0.95) to more than 99.9% (Table 4 and Fig. 5). The latter value corresponded to detectable limits. The average concentration of TOC was reduced down to 0.1 mg l^{-1} or a removal rate of 99%. The submerged membrane filter system used as post-treatment to GAC filter gave negligible improvement to the TOC removal. The GAC adsorbed a majority of organic matter. The slight improvement of TOC removal by the post-treatment of the membrane was due to the adsorption of organics on the membrane.

Two other treatment trains were tested. One treatment train was anthracite filter column followed by a GAC filter column and then by membrane filtration. The other treatment train was anthracite filter column followed by a sand column, then a GAC filter column and then followed by membrane filtration. The addition of anthracite filter column and the sand filter did not provide any additional benefit to the overall removal of TOC. The average TOC removal rates were 10.8 and 15.2% corresponding to reduction in concentration of 4.1 mg l^{-1} and 3.9 mg l^{-1} for anthracite filter and the anthracite and sand filters in sequence respectively (Table 4 and Figs. 6, 7). The sand and anthracite filters were used to mainly to remove the suspended solids. The sand and anthracite filters had a minimal capacity in adsorbing the organic matter.

3.2. Turbidity

The details of the concentration of turbidity in the influent stormwater is given in Table 5. The treatment train of GAC filter column followed by membrane filtration was able to reduce the turbidity by 99%, (Table 5, Fig. 8). The GAC filter by itself was able to reduce turbidity to an average of 84%. The membrane had a pore size of 0.1 µm, which removed practically all the

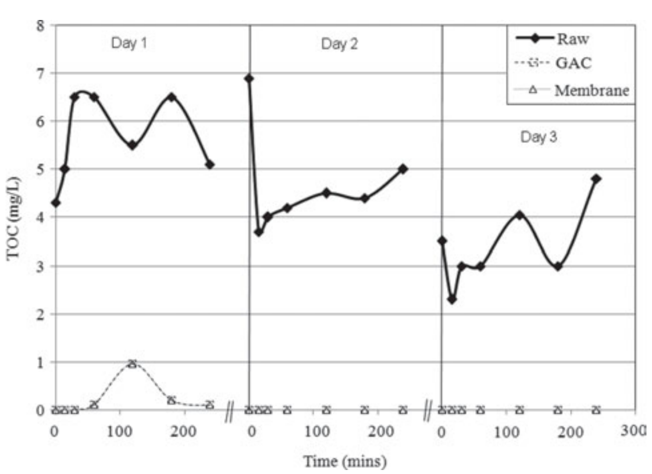

Fig. 5. TOC results with GAC filter followed by membrane filter filtration.

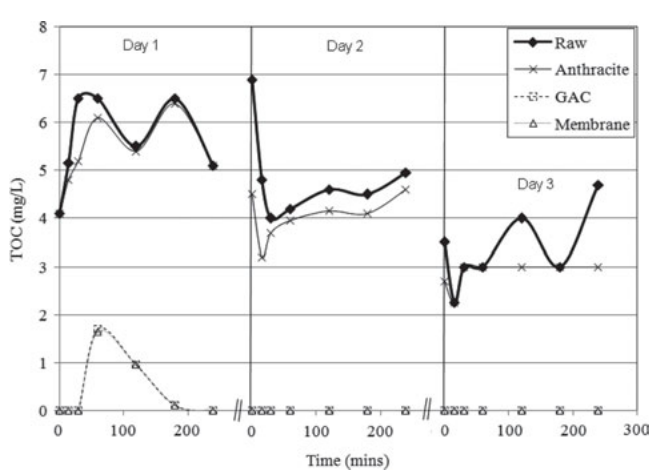

Fig. 6. TOC results with anthracite, GAC and membrane filter treatment.

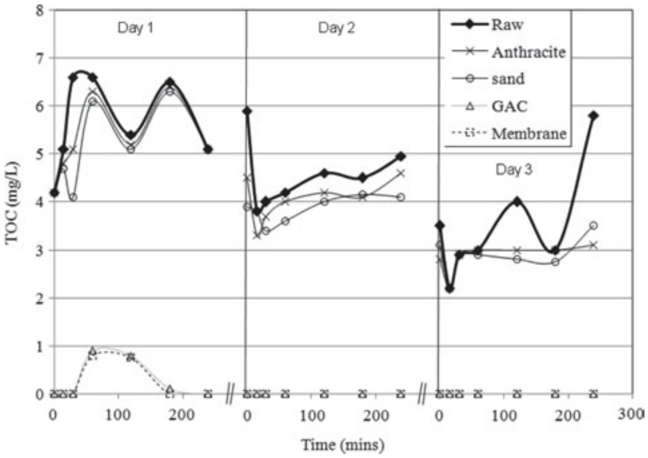

Fig. 7. TOC results with anthracite, sand, GAC and membrane filter treatment.

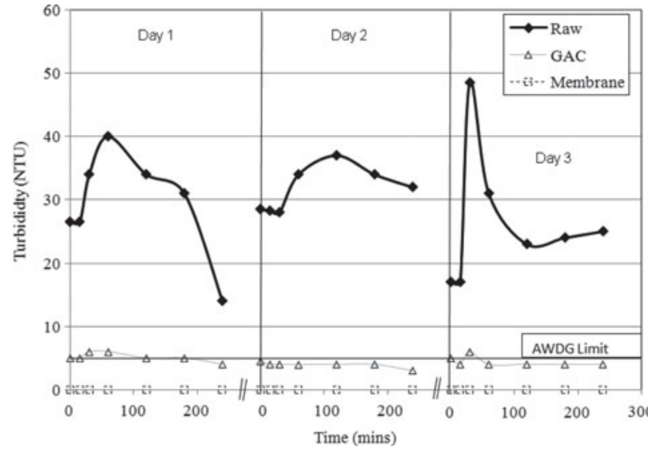

Fig. 8. Turbidity with results GAC filter followed by membrane filter.

suspended matter. The average turbidity levels of influent raw water, and GAC filter effluent was 29.2 and 4.5 NTU, respectively. The turbidity following membrane filtration was below detection levels. The GAC treatment and membrane treatment both achieved turbidity levels below the Australian Drinking Water Guideline limits of 5 NTU [10].

The addition of the anthracite filter in the treatment train (anthracite filter column followed by a GAC filter column and then followed by membrane filtration) achieved an average turbidity removal performance of 71% reducing it from 28.9 NTU down to 8.5 NTU, (Table 5, Fig. 9). This allowed the GAC filter to reduce the turbidity down to 4.2 NTU. The membrane again reduced the turbidity down to below detection limits. The anthracite filter alone could not reduce the turbidity levels to below the ADWG limit of 5 NTU, but the subsequent GAC and membrane treatment both achieved turbidity levels below the ADWG limit [10].

The addition of the sand filter after the anthracite filter in the treatment train (anthracite filter column followed by a sand filter column, then a GAC filter

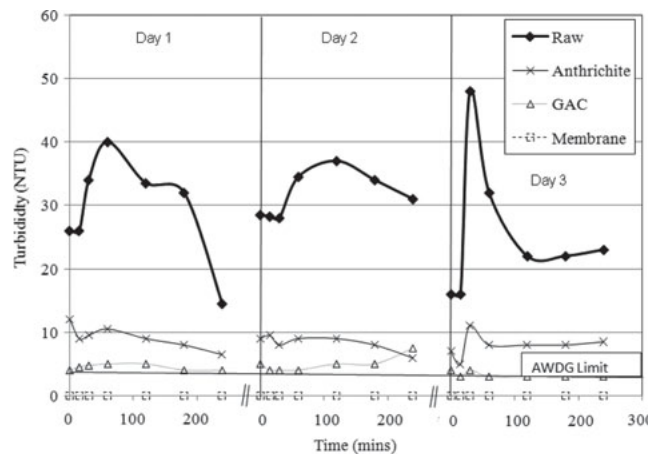

Fig. 9. Turbidity results with anthracite, GAC and membrane filter treatment.

column and then followed by membrane filtration) gave a small improvement to the turbidity removal which reduced down to 5.5 NTU following the sand filter (Table 5, Fig. 10). This further improved the GAC

Table 5
Turbidity results (based on 7 samples taken daily for 3 consecutive days)

Treatment train	Influent (NTU)	Anthracite (NTU)	Sand (NTU)	GAC (NTU)	Membrane (NTU)
GAC Filter and membrane	14.0–48.5	NA	NA	3.0–6.0	ND
post-treatment	29.2			4.5	ND
Anthracite + GAC and	14.5–48.0	5.0–12.0	NA	3.0–7.5	ND
membrane post-treatment	28.9	8.5		4.2	ND
Anthracite + sand + GAC and	14.5–48.0	5.0–17.0	4.0–8.0	2.0–5.0	ND
membrane post-treatment	28.9	8.8	5.5	3.5	ND

NA – not applicable.
ND – below detection limit.

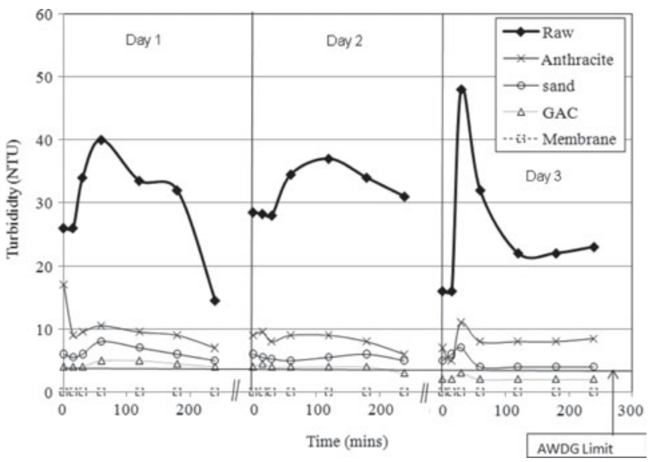

Fig. 10. Turbidity results with anthracite, GAC and membrane filter treatment.

filter performance which reduced the average turbidity to 3.5 NTU. Following membrane filtration, the turbidity was reduced to below detection levels which represent an average total removal of 99%. The sand filter could not reliably reduce the turbidity levels to below the ADWG limit of 5 NTU, but the subsequent GAC and membrane treatment both continued to achieve levels below the ADWG limit [10].

The benefit of using these other filter media before GAC filtration is to provide a screening barrier for sediments and other suspended solids which might otherwise clog and reduce the life of the GAC.

3.3. Heavy metals

The details of the concentration of heavy metals in the influent stormwater are given in Table 6. The influent raw stormwater itself had generally low concentrations of heavy metals, (Table 6). There were no traces of arsenic, cadmium, chromium, selenium, silver or mercury detected in the samples. The concentration of copper and zinc were below ADWG limits [10].

The GAC filter as a pre-treatment to membrane filtration performed effectively with significant reductions in most heavy metals. The GAC filters removed the majority of heavy metals by adsorption mechanism. An average of 85% of aluminium was removed, 94% of iron, 80% of manganese and 64% of zinc (Table 6). The GAC filter followed by membrane filtration reduced the concentration of all heavy metals to very low levels and to well within the ADWG limit (Table 6) [10].

3.4. Organic matter characterisation

Categorization of organic matter was conducted for raw influent stormwater and after pre-treatment (Table 7). 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%). For comparative purpose, Table 7 gives values of raw rainwater.

After GAC filtration of stormwater, the concentration of DOC was 1.76 mg l^{-1} which represents a 70% removal. It was found that 61% of organic matter was hydrophobic and 38% was hydrophilic. The GAC filter removed more than 75% of hydrophobic substances. The hydrophilic portion consists of biopolymers (15%), humic substances (52%), building blocks (27%) and lower molecules neutrals and acids (7%).

After pre-treatment of raw stormwater through GAC filtration followed by membrane filtration, the concentration of DOC was found to be 1.17 mg l^{-1} which represents an 80% removal. It should be noted that the majority of organic removal is by adsorption onto GAC. An additional removal of organic matter by the membrane may be due to adsorption onto the membrane. The majority of organic matter was hydrophobic (75%) compared to 25% of hydrophilic organic matter. In hydrophilic portion, the majority of the substances were humic substances (52%), building blocks (32%) and lower molecules neutrals and acids (14%).

3.5. Practical implication of the study

The media filter performed at a high rate of 10 m h^{-1}. It was able to remove suspended solids, organic matter and heavy metals in a consistent manner despite fluctuation in the influent concentration of these pollutants, Figs. 5–10 and Tables 4–7. It was able to do this over a period of 5 h for three consecutive days. This type of operation and experimental set-up mimics a stormwater harvesting system. In urban areas rainfall event and the stormwater arsing from it does not last for more than several hours. However the stormwater needs to be treated at a high rate. The effluent from the media filtration is suitable for not-potable purposes such as street washing, irrigation of parks, etc.

Effluent from the media filter can be stored in a manner shown in Fig. 4. The stored water can be filtered under gravity through membrane filter. Though the filtration rate is slower the water quality of the effluent is high and for many parameters achieves drinking water standard, Figs. 5–10 and Tables 4–7. The volume of water required for potable purposes is less compared to non-potable uses. This system can be suitably configured to meet these different demands.

Table 6
Removal of heavy metals with various treatment trains

Parameter	Raw canal (mg l^{-1})	Treatment train									ADWG limit (mg l^{-1})
		GAC filter and membrane filter			Anthracite filter, GAC filter membrane filter			Anthracite filter, sand filter GAC filter and membrane filter			
		Pre Treatment[a] (mg l^{-1})	Effluent (mg l^{-1})	% Removal	Pre Treatment[b] (mg l^{-1})	Effluent (mg l^{-1})	% Removal	Pre Treatment[c] (mg l^{-1})	Effluent (mg l^{-1})	% Removal	
Aluminium	0.25	0.038	>0.005	>98%	NA	0.062	75%	NA	>0.005	>98%	<0.2
Copper	0.025	NA	0.01	60%	0.019	0.003	88%	0.025	0.002	92%	<2
Iron	1.277	0.082	0.005	99%	NA	>0.005	>99%	NA	>0.005	>99%	<0.3
Manganese	0.478	0.098	0.084	82%	0.053	0.035	93%	0.048	0.035	93%	<0.1
Lead	0.003	NA	0.003	0%	0.002	>0.001	>67%	0.002	>0.001	>67%	<0.01
Zinc	0.058	0.021	0.004	93%	0.038	0.002	97%	0.017	0.001	98%	<3

[a]Following GAC filtration.
[b]Following anthracite and GAC filtration.
[c]Following anthracite, sand and GAC filtration.
NA – not available.

Table 7
Fractionation of organic compounds by LC-OCD

Sample	DOC dissolved mg l^{-1}, % DOC	HOC hydrophobic mg l^{-1}, % DOC	CDOC hydrophilic mg/l, % DOC	BIO-polymers mg l^{-1}, % DOC	Humic substances (HS) mg l^{-1}, % DOC	Building blocks mg l^{-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	1.76	1.08	0.68	0.10	0.35	0.18	0.05
	70%	61%	38%	15%	52%	27%	7%
GAC filter and membrane 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 (for comparison)	1.63 NA	1.26 77%	0.37 23%	n.q.	0.2 54%	0.1 27%	0.06 16%

LMW – low molecular weight.

4. Conclusions

The GAC filter column was capable of significantly reducing the influent TOC concentrations. The addition of anthracite filter column and the sand filter did not provide any additional benefit in the overall removal of TOC.

The treatment train of GAC filter column followed by membrane filtration was able to reduce the turbidity by 99%. The GAC filter by itself was able to reduce turbidity to an average of 84%. The GAC filter by itself and with the membrane filter together achieved turbidity levels below the ADWG limits of 5 NTU [10]. With respect to turbidity removal, the addition of the anthracite and sand media did provide effective reduction in turbidity levels before reaching the GAC filter media. The benefit of using these other filter media before GAC filtration is to provide a screening barrier for sediments and other pollutants which might otherwise clog and reduce the life of the GAC.

The influent raw stormwater had generally low concentrations of heavy metals. The GAC filter as a pre-treatment to membrane filtration performed effectively with significant removals in most heavy metals. The inclusion of anthracite and sand filters in the treatment trains did help to reduce heavy metal concentration. Following membrane filtration the concentration of all heavy metals were reduced to very low levels and well within the ADWG limit [10].

After GAC filtration of stormwater, the concentration of DOC was 1.76 mg l^{-1} which represents a 70% removal and removed all types of organic. Membrane filtration removed a small additional amount of organics.

Acknowledgements

The research is funded by an Australian Research Council Linkage Project Grant (LP0776705) and Kogarah Council.

References

[1] V.G. Mitchell, R.G. Mein and T.A. McMahon, The reuse potential of urban stormwater and wastewater resources in urban areas. Australian Journal of Water Resources, 6(1) (1999) 31–43.
[2] S. Beecham, D. Pezzaniti and J. Kandasamy, Treatment and Retention of Stormwater Pollutants Using Permeable Pavements, Proceedings of the Institution of Civil Engineers-Water Management, WATER-D-10-00097 (accepted and in press), 2011.
[3] J. Kandasamy, S. Beecham and A. Dunphy, Effectiveness of Stormwater Sand Filters in Water Sensitive Urban Design, Proceedings of the Institution of Civil Engineers-Water Management, April 2008 WM2, pages 55–64.
[4] A.T. Abbasi and S.A. Abbasi, Sources of Pollution in Rooftop Rainwater Harvesting Systems and Their Control, Critical Reviews in Environmental Science and Technology, 41:23 (2011) 2097–2167.
[5] R. Aryal, S. Vigneswaran, J. Kandasamy and R. Naidu, Urban stormwater quality and treatment. Korean J ChemEng, 27 (2010) 1343–1359.
[6] G.F. Birch and A. Scollen, Heavy metals in road dust, gully pots and parkland soils in a highly urbanised sub-catchment of Port Jackson, Australia. Aust J Soil Res, 41 (2003) 1329–1342.
[7] S. Vigneswaran, J.S. Chang and J.G. Janssens, Experimental investigation of size distribution of suspended particles in granular bed filtration, Wat. Res. 24(7) (1990) 927–930.
[8] J.J. Qin, M.H. Oo, K.A. Kekre, F. Knops and P. Miller, Reservoir water treatment using hybrid coagulation–ultrafiltration. Desalination, 193 (2006) 344–349.
[9] A. Eaton, L. Clesceri, E. Rice and A. Greenberg, Standard Methods for the Examination of Water & Wastewater. 21st ed. 2005, Published jointly by: American Public Health Association, American Water Works Association, Water Environment Federation, 2005.
[10] ADWG, Australian Drinking Water Guidelines, National Health and Medical Research Council, Australian Water Resources Council. 2004. p. 615.