Household rainwater harvesting system – pilot scale gravity driven membrane-based filtration system
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ABSTRACT
This paper presents the results of a pilot scale study consisting of pre-treatment with a granular activated carbon (GAC) filter followed by membrane filtration. Detailed characterisation of rainwater tanks has highlighted that turbidity, dissolved organic carbon (DOC) and heavy metals, in particular lead, were not compliant with the 2004 Australian Drinking Water Guidelines (ADWG). Further, organic matter present in the water causes membrane fouling and leads to carcinogenic compounds upon chlorination. A GAC filter was used as a first step to remove dissolved organic matter (measured in terms of DOC) in particular and also to reduce the concentration, of turbidity and lead. Membrane filtration can remove any remaining solids reducing the concentrations of turbidity and microorganisms. In this study a pilot scale rainwater treatment system consisting of a gravity fed GAC filter and membrane filter (Ultra Flo) was operated for a period of 120 days. The performance of this system was assessed in terms of membrane flux and improvement in water quality measured against the 2004 Australian Drinking Water Guidelines. Determination of the flux especially in the later stages of membrane operation was important to be able to size the filters in a manner that meets the expected demand. The treatment system of GAC filter and membrane filter was effective in reducing the turbidity, DOC and heavy metals. The system reduced the turbidity to levels of 0.3–0.4 NTU, below the ADWG limit of 1 NTU. The concentration of DOC was reduced to below the 2004 Australian Drinking Water Guidelines limit of 0.2 mg/L. The concentration of lead was reduced to less than 0.005 mg/L, and below the ADWD limit of 0.01 mg/L. The concentrations of all other heavy metals were well within the ADWG limits. Further, the GAC filter removed a majority of the organic substances from raw rainwater collected from the roof. After the initial flux decline, the stable flux achieved was 0.47 L/m²/h consistently over the final 60 days of the experiment.

Key words | deep bed filter, membrane filtration, organics, pilot scale experiment, rainwater, water harvesting

INTRODUCTION
Research in membrane technology in recent times has increased exponentially leading to increases in operating efficiency by reducing pressure requirements, the improvement of engineered membrane materials leading to improved treated water quality, decreases in manufacturing costs through mass production, and the expanded adoption of membrane uses in new treatment applications. The combination of all these improvements has allowed widespread application of membrane treatment applications that were previously only available in large filtration plants operated by specialised water companies. Applications available today range from low-energy home-based membrane treatment systems such as under-sink cartridge filters or small reverse osmosis filters and other applications such as decentralised small scale filtration plants.

Rainwater harvested from roofs can contain animal and bird faeces, mosses and lichens, windblown dust, particulates from urban pollution, pesticides, inorganic ions from the sea...
(Ca, Mg, Na, K, Cl, SO₄), and dissolved gases (CO₂, NOₓ, SOₓ). Rainwater storage tanks also accumulate contaminants and sediments that settle on the bottom. In particular heavy metals have recently become a concern as their concentration in rain water tanks was found to exceed the recommended ADWG (2004) levels and therefore makes it unsuitable for human consumption (Simmons et al. 2001; Han et al. 2006; Magyar et al. 2007, 2008).

Detailed sampling of eleven residential rainwater tanks was undertaken in the Sydney Metropolitan area (Kus et al. 2010a, b). The results indicated that many of the water quality parameters complied with the ADWG (2004). The pollutants that did not comply were the heavy metals, in particular the concentrations of iron and lead, and turbidity. The average iron concentrations of the rainwater samples were generally under the ADWG (2004) iron limit of 0.3 mg/L, however each tank had at least one sample over this limit with individual results as high as 4.70 mg/L. The lead concentration was also of concern with most tanks exceeding the ADWG (2004) lead limit of 0.01 mg/L with samples as high as 0.067 mg/L. Although the average concentration of turbidity of each rainwater tank complied with the ADWG (2004) limit of 5 NTU, three rainwater tanks had samples with turbidity up to 12 NTU (Kus et al. 2010a, b). One of the rainwater tanks exceeded the minimum pH level of 6.5 with an average pH of 5.7 and a number of other tanks were close to the minimum pH level of 6.5. The rainwater tanks which contained low pH levels were harvested from colour bond or zinc alum metal roofing.

Detailed characterisation of rainwater tanks, (Kus et al. 2010a, b) has highlighted that turbidity and heavy metals concentrations, in particular lead, were not compliant with the ADWG (2004). These findings have been reflected in other studies (Magyar et al. 2007, 2008). Further, dissolved organic carbon (DOC) is known to cause membrane fouling and reducing its concentration will improve membrane performance and prolong membrane life in tank systems that incorporate membrane filtration as a treatment. A granular activated carbon (GAC) filter was used as a first step to remove DOC in particular and also to reduce the concentration of turbidity and lead. Membrane filtration can remove any remaining solids reducing the concentrations of turbidity and DOC associated with particulates.

Yeo et al. (2006) studied a reuse system using a membrane process treating rainwater runoff from an urban parking area that contained non-point pollutants. The rainwater reuse system consisted of a pre-filter, membrane, and disinfection. A hollow fibre membrane having a pore size of 0.4 μm made of PVDF (polyvinyl di-fluoride) was used in this system because of its stable flux and strength. The treated water met the parameters for the Korean standard guidelines for reclaimed water. Turbidity was less than 0.3 NTU in the final effluent. Chemical oxygen demand (COD) concentration decreased from 23.0 to 13.1 mg/L and biochemical oxygen demand (BOD₅) decreased from 5.3 to 1.7 mg/L after treatment by this pre-filter and membrane process. Escherichia coli was completely removed by this system (Yeo et al. 2006).

In this study, a pilot scale rainwater treatment system consisting of a gravity fed GAC filter and membrane filter (Ultra Flo) was operated for a period of 120 days. The performance of this system was assessed in terms of membrane flux, and the improvement in water quality compared against the ADWG (2004). Determination of the flux, especially in the later stages of membrane operation, was important to be able to size the filters in a manner that meets the expected demand.

**EXPERIMENTAL METHODOLOGY**

**Rainwater tank**

A typical domestic residential rainwater tank was selected for the operational simulation of a GAC filter and membrane filter system. The rainwater tank was located within the Sydney Metropolitan basin at Peakhurst near Padstow approximately 1 km south of a heavily trafficked motorway and 10 km west of Sydney’s domestic and international airport. A record of the daily precipitation over the duration of the pilot scale study is provided in Figure 1 with a summary of the rainfall data provided in Table 1. The tank and house are 5 years old with a typical concrete glazed tile roof with aluminium guttering. The rainwater tank was a PVC tank with a total volume of 3,000 L, PVC plumbing and brass fittings. For the duration of the pilot trial, the rainwater tank was connected directly to feed the treatment system (GAC filter and membrane filter) (Figure 2). Potable grade hose
lines were installed between the rainwater tank and the filter system connections.

Filter configuration

The GAC filter was used as a first step to remove DOC in particular and also to reduce the turbidity. The DOC and lead associated with particulates were also removed. Membrane filtration removed any remaining solids and reduced concentrations of turbidity, DOC and lead. Further, the membrane filter can screen coliforms although it is acknowledged that further disinfection treatment (with a very small dose) is required to guarantee complete removal while also targeting virus removal.

A pilot scale treatment system was developed and comprised of pre-treatment with a GAC filter (Watts) followed by a membrane filter (Ultra Flo). The characteristics of the GAC and membrane filter are given in Tables 2 and 3, respectively. GAC of 0.3 mm was packed in a column.

The volume of GAC was 0.4 L. The membrane had a surface area of 0.4 m² and pore size of 0.1 μm. This system was operated in dead-end mode. The raw water was passed through the two filters, each with a volume of 0.4 L. As the pilot scale system was operated under gravity head, the two filter columns were placed horizontally and located at the base of the rainwater tank to take advantage of the full water head available from the rainwater tank (Figure 2).

The raw rainwater was passed through the two filters in a continuous operating system where the effluent from the GAC filters passed through to the membrane filter. An available water head of up to 2 m in the rainwater tank drives the flow through the GAC filter and membrane filter. The pilot scale treatment system was operated continuously for 120 days. In this pilot scale study the GAC filter and membrane filter were not backwashed except on two occasions (days 8 and 12). This was done to determine the performance of the treatment system under low maintenance conditions, determine how long the filters would operate effectively without backwash and quantify the flux. Determination of the flux in the final stage of membrane operation (with no backwash) was important to be able to size the membrane area in a manner that meets the expected demand. Both filters were backwashed for 30 s on two occasions, on days 8 and 12, to observe the impact of backwashing on the flux and what improvement it made. During the backwashing process, the flow was passed through the two filters in the reverse direction from normal operation. The influent flow pipe was rerouted from the rainwater tank to a waste drain. Excess free particles were removed from the column filter along with the tap water.

Detailed laboratory analyses were carried out to determine the concentration of individual pollutants. The testing methods are given in Kus et al. (2010a, b) and summarised in Table 4. The water quality parameter measuring methods were in accordance with standard methods (Eaton et al. 2005). DOC concentrations of raw rainwater and the treated water were measured using the Multi N/C 2000 analyzer (Analytik Jena AG). Turbidity was measured using a 2100P turbidity meter (HACH, USA). Lead was measured using inductively coupled plasma – mass spectrometry (ICPMS).
Data logging equipment was utilised to monitor the flow rates (Endress & Hauser Promag 10 H) and the driving head on the membrane. The flow rate was only controlled by the flux limitation through the treatment system and the available driving head. The available head was monitored using a calibrated pressure transducer (Endress & Hauser PMC 131) connected to a data logger (Endress & Hauser Eco Graph T RSG30) which represented the head available from the membrane to the top of the water level in the rainwater tank. The water level in the tank only increased when there was rainfall.
RESULTS AND DISCUSSION

Flux decline

Membrane flux decline was monitored over 120 days as shown in Figure 3. During this period the membrane was backwashed twice (on day 8 and day 12) for a period of 30 s. On both occasions there was an increase in flux which lasted only several hours before it reduced to levels that existed prior to the backwash. No other backwash was undertaken. The flux reduced from 27 L/m²/h to a stable flux of 0.47 L/m²/h over a period of 60 days. The membrane filter ran at steady state conditions for the remaining 60 days where the flux was nearly constant. Determination of the flux, especially in the later stages of membrane operation, was important to be able to size the membrane area in a manner that meets the expected demand.

Turbidity

The treatment train of the GAC filter followed by membrane filtration reduced the turbidity by 78% or to levels of between 0.6 and 0.41 NTU, (Figure 4, Table 5). The GAC filter achieved significant reductions in turbidity (Figure 4). Membrane filtration provided additional turbidity removal of up to 20%. The turbidity following membrane filtration was small and below 0.4 NTU. The ADWG (2004) limit is 1 NTU.

DOC

The GAC treatment was capable of reducing the influent DOC concentrations from an average of 0.42 to 0.12 mg/L (Figure 5, Table 5). The ADWG (2004) limit for DOC is 0.2 mg/L. In the initial period, during the first 30 days of operation, the DOC in the effluent was higher at approximately 0.4 mg/L (Figure 5). This corresponds to a period of development of biofilms on the GAC. Beyond this initial period, after 30 days of operation, the concentration of DOC

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**Table 4 | Water quality parameters and measurement methods**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement method (Eaton et al. 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy metals (aluminium, arsenic, cadmium, copper,</td>
<td></td>
</tr>
<tr>
<td>iron, lead, manganese, mercury, nickel, selenium,</td>
<td></td>
</tr>
<tr>
<td>silver and zinc)</td>
<td>APHA 3120 ICPMS</td>
</tr>
<tr>
<td>Turbidity</td>
<td>APHA 2130 - Nephelometric Method</td>
</tr>
<tr>
<td>Total suspended solids</td>
<td>GPC equiv. filtr. - APHA 2540 - D - Total Suspended Solids</td>
</tr>
<tr>
<td></td>
<td>dried at 103–105 °C</td>
</tr>
</tbody>
</table>

*APHA - American Public Health Association.

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**Figure 3 | Membrane flux decline over the duration of the pilot scale study. Also shown is the water head in the rainwater tank and the volume of water treated.**
reduced down to below detectable limits. The removal rate of DOC during this period was at times more than 99%. The membrane filter system used as post-treatment to the GAC filter indicated only a small improvement to the DOC removal, particularly during the initial period of the first 30 days. DOC is known to cause membrane fouling (especially organic and subsequently bio-fouling) and reducing its concentration will improve membrane performance and prolong membrane life in treatment systems that incorporate it. Further, organic matter present in the water causes membrane fouling and leads to carcinogenic compounds upon chlorination.

### Heavy metals

The influent raw storm water itself had generally low concentrations of heavy metals (Table 5). There were no traces of cadmium, selenium, silver or mercury detected in the samples. The concentration of a range of heavy metals including aluminium, arsenic, copper, iron, manganese, and nickel were below ADWG (2004) limits. The concentration of lead was notably above the ADWG (2004) limit.

The treatment train of GAC filter followed by membrane filtration performed effectively with significant reductions in most heavy metals. The concentration of lead in the effluent was reduced to below 0.005 mg/L, which was below the ADWG limit of 0.01 mg/L. Aluminium, iron and manganese were reduced to below detection limits. The concentration of these heavy metals in the effluent was well within the ADWG (2004) limit (Table 5).

It was observed that the levels of both copper and zinc were not improved with filtration and actually increased from the initial raw rainwater samples taken from the tank. This is due to the in-situ connections of the rainwater tank and effluent tap comprising of brass fittings which is a copper/zinc alloy. As brass is the common material used for connections in domestic residential tanks in Australia, and also copper is used for the internal plumbing of houses, it is expected that higher levels of both copper and zinc are likely to be found in samples collected from a residential

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**Table 5 | Turbidity and DOC results based on samples taken during the pilot trial**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ADWG limit</th>
<th>Detectable limit</th>
<th>Tap water</th>
<th>Raw water</th>
<th>GAC filter</th>
<th>Pre-treatment + membrane</th>
<th>GAC + Membrane filter removed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity (NTU)</td>
<td>1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.2</td>
<td>&lt;0.5</td>
<td>0.58 (0.17–1.1)</td>
<td>0.34 (0.06–0.41)</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td>Dissolved Organic Carbon (mg/L)</td>
<td>0.2</td>
<td>0.001</td>
<td>0.13</td>
<td>0.42 (0.16–0.84)</td>
<td>0.12 (&lt;0.001–0.56)</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td>Aluminium (mg/L)</td>
<td>0.2</td>
<td>0.005</td>
<td>0.247</td>
<td>0.04</td>
<td>0.010</td>
<td>&lt;0.005</td>
<td>&gt;55%</td>
</tr>
<tr>
<td>Copper (mg/L)</td>
<td>2</td>
<td>0.001</td>
<td>0.007</td>
<td>0.06</td>
<td>0.010</td>
<td>&lt;0.005</td>
<td>No improvement</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>0.1</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.02</td>
<td>0.002</td>
<td>&lt;0.001</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Lead (mg/L)</td>
<td>0.01</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.011</td>
<td>0.005</td>
<td>0.005</td>
<td>55%</td>
</tr>
<tr>
<td>Zinc (mg/L)</td>
<td>NA&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.001</td>
<td>0.024</td>
<td>0.033</td>
<td>0.514</td>
<td>0.504</td>
<td>No improvement</td>
</tr>
</tbody>
</table>

<sup>a</sup>Average value followed by range of values.

<sup>b</sup>Insufficient data to set a guideline value based on health considerations. Water for aesthetic use has a guideline limit of 3 mg/L.

<sup>c</sup>To maintain effective disinfection a limit of 1 NTU is necessary.
tap. The concentrations of copper and zinc in the effluent remained below ADWG (2004) limits.

Organic matter characterization

Categorisation of organic matter was conducted for raw rainwater and after treatment (Table 6). It was found that the concentration of DOC of the raw rainwater was 1.74 mg/L of which 30.3% was hydrophobic and the remaining 69.7% was hydrophilic. In the hydrophilic portion, the majority of the substances were biopolymers (5.2%), humic substances (25.3%), building blocks (12%) and low molecular weight neutrals and acids (24.5% and 2.6% respectively).

After treatment of raw stormwater through GAC filtration followed by membrane filtration, the concentration of DOC was found to be 1.14 mg/L which represents a 34% removal. The majority of organic matter was hydrophilic (67.1%) compared with 32.9% of hydrophobic organic matter. In the hydrophilic portion, the majority of the substances were biopolymers (3.8%), humic substances (43.3%), building blocks (8.2%) and lower molecular weight neutrals and acids (9.7 and 2.1% respectively). It was found that rainwater treated with the GAC filter had the majority of organic substances removed. The GAC filter removed all types of organics. In general membrane filtration can remove only the small amount of organics that is associated with suspended particles.

CONCLUSION

This study reports the results of monitoring and evaluation of the improvement in rainwater quality, and quantified the flux decline from a gravity fed GAC and membrane filter system during a 120 day pilot scale trial at a residential household within the Sydney metropolitan area.

This study followed on from a detailed water quality characterisation of rainwater tanks within the Sydney metropolitan area (Kus et al. 2004a, b) which identified turbidity, DOC and heavy metals, in particular lead, as parameters that did not comply with the ADWG (2004). A comparison with tap water showed a similar result. A treatment system was configured to reduce the concentrations of these parameters.

The treatment system of GAC filter and membrane filter was effective in reducing the turbidity, DOC and heavy metals. The system reduced the turbidity by an average of 78% or to levels of 0.6–0.41 NTU, below the ADWG (2004) limit of 1 NTU. The concentration of DOC was

<table>
<thead>
<tr>
<th>Sample</th>
<th>DOC dissolved mg/L, % DOC</th>
<th>HOC hydrophobic mg/L, % DOC</th>
<th>CDOC hydrophilic mg/L, % DOC</th>
<th>Bio-polymers mg/L, % DOC</th>
<th>Humic substances mg/L, % DOC</th>
<th>Building blocks mg/L, % DOC</th>
<th>LMW neutrals mg/L, % DOC</th>
<th>LMW acids mg/L, % DOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw rainwater</td>
<td>1.74</td>
<td>0.53</td>
<td>1.20</td>
<td>0.09</td>
<td>0.44</td>
<td>0.21</td>
<td>0.43</td>
<td>0.05</td>
</tr>
<tr>
<td>100%</td>
<td>30.3%</td>
<td>69.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAC filter and membrane filter</td>
<td>1.14</td>
<td>0.38</td>
<td>0.77</td>
<td>0.04</td>
<td>0.50</td>
<td>0.09</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>100%</td>
<td>32.9%</td>
<td>67.1%</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

LMW – low molecular weight.
reduced to below the ADWG (2004) limit of 0.2 mg/L. The concentration of lead was reduced to an average of 0.005 mg/L, and below the ADWG limit of 0.01 mg/L. The concentration of all other heavy metals was well within the ADWG (2004) limit. The GAC filter was necessary to reduce the turbidity, lead and DOC. The use of micro-filtration as a security filter is relevant to achieve physical disinfection and removal of solids in emergency situations where there is a high turbidity load. The micro-filtration will reduce significantly the disinfectant dose. Further, the GAC filter removed a majority of the organic substances from raw rainwater. After an initial flux decline, the stable flux achieved was 0.47 L/m²/h over the final 60 days of the experiment.

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