Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal

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ABSTRACT
Improved urban water management in Australia is of national importance. Water resources are stretched and urban runoff is a recognized leading cause of degradation of urban waterways. Stormwater recycling is an option that can contribute to easing these problems. Biofilters are effective structural stormwater pollution control measures with the potential for integration into stormwater treatment and recycling systems. However, premature clogging of biofilters is a major problem, with resulting decreased infiltration capacity (and hence the volume of stormwater the system can detain) and increased detention time. This paper presents preliminary findings with respect to the effect of clogging on pollutant removal efficiency in conventional stormwater filter media. A one-dimensional laboratory rig was used to investigate the impact of clogging on pollutant removal efficiency in a conventional biofiltration filter media (gravel over sand). Both the individual gravel layer and the overall multi-filter were highly efficient at removing suspended solids and particulate-associated pollutants. This removal efficiency was consistent, even as the filters became clogged. Removal of dissolved nutrients was more variable, with little reduction in concentrations overall. Although preliminary, these results challenge the concept that increased detention time improves the treatment performance of stormwater filtration systems.

KEY WORDS
Biofilters; clogging; stormwater treatment; water quality

INTRODUCTION
Runoff from urban areas is a leading cause of water quality degradation in surface waters (U.S. Environmental Protection Agency, 2000). Urbanization leads to increased frequency and size of flood flows, altered groundwater levels, increased stream bank erosion (Novotny and Olem, 1994), and increased pollutant concentrations and loads (Hatt et al., 2004), with resulting negative impacts on aquatic ecosystems (Paul and Meyer, 2001).

At the same time, the use of water is approaching, and in some cases exceeding, the limits of sustainability in Australia. As a result, there is an increased recognition of the need to utilise stormwater runoff for non-potable requirements, thus reducing demand on potable resources. However, water recycling is not yet widely practiced in many places, particularly with respect to general urban runoff. This is largely due to a paucity of technologies for reliable and affordable on-site treatment of stormwater runoff which can guarantee water quality fit for its intended use.
Biofilters (also known as bioretention systems and biofiltration systems) have been demonstrated to be effective structural stormwater pollution control measures (Fletcher et al., 2003). They are traditionally constructed as vegetated buffers on top of a soil, sand or gravel filtration medium in shallow trenches, basins or landscaped areas (Melbourne Water, 2004). Stormwater flows over the vegetation and slowly seeps through the filter – pollutant removal is achieved as a result of enhanced sedimentation in the vegetation zone, mechanical filtration, sorption and other chemical processes in the filter media, and plant and biofilm uptake of pollutants (Winogradoff, 2002). An underdrain collects the treated water, while some water infiltrates into the surrounding soil (depending on the design). Runoff entering the system may cause temporary ponding above the planting bed, however ponding depths are typically shallow and infiltrate over a short period of time.

However, there are two major issues that need to be resolved before biofilters can be reliably implemented as part of a stormwater recycling system:

1. current biofilter design is not tailored to treat stormwater to the consistently high standards required for safe water use; and
2. whilst eventual clogging of biofilters is inevitable, designs must be able to prevent premature clogging, so that biofilters can perform adequately over an acceptable lifespan.

Clogging is a process common to all types of water filters and occurs because sediment is deposited in the filter as water percolates through. These deposits build up over time, decreasing porosity and ultimately preventing water from passing through. Clogging has been identified as the primary cause of premature failure of stormwater infiltration systems (Lindsey et al., 1992). However, although clogging decreases the hydraulic capacity of a filter, it is possible that clogging may actually improve stormwater treatment efficiency, since lower flow rates lead to increased detention times. This paper presents preliminary findings with respect to the effect of clogging on treatment efficiency in conventional stormwater filter media, as part of a broader project developing novel biofilters for stormwater recycling.

METHODS

Data Collection

A fully automated, one-dimensional (1D) experimental rig was used to assess the performance of conventional biofilter media for different flow rates and wetting conditions (Figure 1). The filter consisted of a layer of gravel (as used in conventional infiltration systems) over a sandy loam layer (or sand with the same hydraulic conductivity, k). Stormwater was introduced through a rotating sprinkler system, at a rate controlled by software and pressure sensors. Outflow from the system was monitored using a tipping bucket rain gauge.

Since a fresh supply of stormwater was needed, a compromise was made between using real stormwater and readily available synthetic stormwater for testing. Sediment was collected from a stormwater retarding basin. The solids content of a slurry of the <300µm fraction (to reflect pre-treatment for coarse solids removal) was determined and added to a tank of tap water in known amounts to achieve suspended solids concentrations typical for Melbourne, Australia, stormwater (Duncan, 1999). This mixture also mainly achieved required nutrient and metal concentrations. These were topped up as required using chemicals. The particle size distribution of this sediment also matched that typical for sediment in stormwater. The semi-synthetic stormwater (termed so because it is a compromise between real stormwater and the completely artificial approach) was constantly mixed by bubbling air into the tank.
Five experiments have been conducted, each with a different hydrologic regime (Table 2). Either a constant water level was maintained in the gravel layer or was varied between the top and bottom of the gravel layer. Each experiment was run until the system was clogged (outflow was 10% of the initial outflow).

Water samples were collected on alternate days at the inflow, outflow, interface between the two filter media, and various other points through the filter media. These were analysed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), ammonia (NH₃), dissolved phosphorus (FRP), nitrate/nitrite (NOₓ), total dissolved nitrogen (TDN), and total and dissolved copper (Cu), lead (Pb) and zinc (Zn) using standard methods (Hosomi and Sudo, 1986; APHA/AWWA/WPCF, 1998). Cadmium is also usually considered as one of the four main heavy metals, however it is almost always below detection in Melbourne stormwater, hence it was decided not to analyse for this metal.

**Data Analysis**

Water quality samples were collected simultaneously, hence outflow concentrations do not directly correspond to inflow concentrations due to the detention time. Interpolation was therefore used to allow for the time delay between water entering and exiting the filter. The detention time was calculated according to the flow at the time of the sample collection:

\[ t = \frac{L}{v} \quad v = \frac{Q}{A} \]

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Suspended Solids</td>
<td>150</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>2.6</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>0.35</td>
</tr>
<tr>
<td>Copper</td>
<td>0.05</td>
</tr>
<tr>
<td>Lead</td>
<td>0.14</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.25</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0045</td>
</tr>
</tbody>
</table>

Table 1. Typical Melbourne stormwater pollutant concentrations (Duncan 1999)
Table 2. Experimental conditions

<table>
<thead>
<tr>
<th>Filter media</th>
<th>Stormwater</th>
<th>Water Level</th>
<th>Flow (l/day)</th>
<th>mean k (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 gravel on soil</td>
<td>sediment + tap water</td>
<td>constant</td>
<td>45</td>
<td>34.6</td>
</tr>
<tr>
<td>E2 gravel on sand</td>
<td>sediment + tap water</td>
<td>constant</td>
<td>45</td>
<td>130</td>
</tr>
<tr>
<td>E3 gravel on sand</td>
<td>sediment + tap water</td>
<td>constant</td>
<td>85</td>
<td>104</td>
</tr>
<tr>
<td>E4 gravel on sand</td>
<td>sediment + pond water</td>
<td>varying</td>
<td>5 - 85</td>
<td>51.8 - 104</td>
</tr>
<tr>
<td>E5 gravel on sand</td>
<td>sediment + tap water</td>
<td>varying</td>
<td>5 - 85</td>
<td>60.5 - 130</td>
</tr>
</tbody>
</table>

where \( t \) is the detention time, \( L \) is the length of the filter, \( v \) is Darcy’s velocity, \( Q \) is the flow, and \( A \) is the horizontal area of the filter. Linear interpolation between points was then used to calculate the outflow concentration that corresponded with the inflow concentration.

Inflow and corresponding outflow loads were then calculated:

\[
I = Q \times c
\]

where \( I \) is the load, \( Q \) is the flow and \( c \) is the pollutant concentration.

This allowed pollutant removal efficiencies to be calculated:

\[
EFF = \frac{l_{in} - l_{out}}{l_{in}}
\]

where \( EFF \) is the removal efficiency, \( l_{in} \) is the inflow load and \( l_{out} \) is the outflow load.

Individual pollutant removal efficiencies of gravel, sand and sandy loam (dissolved pollutants only), as well as their efficiency in combination as a multi-filter were determined for each of the stormwater pollutants analysed.

**First order kinetic model**

A number of physical processes contribute to pollutant removal in a filter, however the overall effect is that pollutant concentrations move by an exponential decay process towards an equilibrium value (CRCCH, 2003). The first order kinetic model describes this:

\[
EFF = e^{-\frac{k_t}{q}}
\]

where \( EFF \) is the removal efficiency, \( k_t \) is the rate constant and \( q \) is the hydraulic loading of the filter. In other words, the lower the flow rate, the higher the removal efficiency.

This model was tested by plotting efficiency against flow for the first day of each experiment (i.e. for a clean filter). This test is valid because flow is through saturated media (the filter was filled from the bottom up to the required water level) and has reached equilibrium (clean water is run through the system for several days prior to introducing stormwater).

**RESULTS AND DISCUSSION**

**Changes in water quality through the filter media**

Sediment levels in incoming stormwater rapidly decreased in the upper section of the filter, regardless of the hydrologic regime. This is illustrated in Figure 2, which presents the change in sediment concentration with depth. Particulate-associated pollutants (TP and heavy metals) and TN followed a similar trend. In contrast, FRP and NOx largely passed through the filter, with little to no reduction in concentrations. Ammonia behaved quite differently, with increasingly elevated outflow concentrations as each test progressed.
Changes in water quality with time

Gravel. Inflow concentrations of suspended solids fluctuated between 75 and 185 mg/l (E2 results), due to mixing variations in the dosing tank, however outflow concentrations from the gravel filter were steadily less than 10 mg/l (Figure 3). Outflow concentrations of TN were also steady, despite variable inflow levels. TP outflow concentrations followed a similar, but significantly reduced, pattern to inflow levels. Despite fluctuations in TSS concentrations, both within and between experiments (overall range: 75-255 mg/l), outflow TSS levels were consistently below 10 mg/l.

Sand. Pollutant outflow concentrations from the sand filter closely tracked the trend in inflow concentrations (Figure 4). However, it must be noted that the incoming water has already filtered through gravel layer, thus pollutant concentrations and the particles entering the sand are much smaller, both of which will influence relative reductions in pollutant concentrations. While the sand removed some sediment and phosphorus, it had little effect on nitrogen levels. This may be explained by the fact that most particles have already removed prior to filtering through the sand, so the incoming TN is more likely to be in dissolved form. Dissolved pollutants are removed by processes such as adsorption and biological activity, which are not promoted by either sand or gravel.

The maximum flow rate occurred on the first day of each test and steadily declined before leveling at a minimum flow (due to clogging). Surprisingly, this flow reduction (and resulting increase in detention time) did not have any discernible influence on outflow concentrations of TSS, TP or TN.

Pollutant removal efficiency of clean filter media

Surprisingly, there was either no difference in treatment efficiency at varying flow rates (range 27 - 121 l/day) or no discernible trend i.e. variations in removal efficiencies were not explained by flow. This is in contrast to the widely accepted first order decay model and further work is required to explain this. It may be that settling is not the primary pollutant removal mechanism and that perhaps instead it is mechanical straining of particles and their associated pollutants, which is less influenced by flow.

Pollutant removal efficiency with clogging of the filter media

Pollutant removal efficiency was reasonably steady for the duration of each experiment (Figure 5). The suspended solids removal efficiencies of the gravel and multi-filters did not change, while some variation in the efficiency of the sand filter was evident. For all three filter types, there was a slight decrease in TN removal efficiency with time, while the
efficiency of TP removal slightly increased with time. The likely reason for the increase in TP removal efficiency is that bound phosphorus is mainly associated with smaller particle sizes and as the filter clogs, it is able to trap smaller particles.

FRP and NO\textsubscript{x} concentrations were not reduced by the gravel, sand or multi-filters. However, the sandy loam filter used in the first test consistently removed almost all NO\textsubscript{x}. In contrast, significantly elevated levels of FRP were observed in the outflow. Although this remained significant for the duration of the experiment, outflow concentrations slowly decreased, suggesting that this was due to release of phosphorus already present in the sandy loam media. Elevated outflow concentrations of NH\textsubscript{3} were also observed for all filters, and increased with time. This implies that other forms of nitrogen trapped by the filter are being transformed to ammonia, particularly as the flow (and probably oxygen) decreases. It is likely that this is due to mineralization of particulate organic nitrogen, yet it is surprising that denitrification is not evident (it would be expected to occur in tandem); perhaps this is the result of using tap water that does not contain bacteria to make up the stormwater (which may also be precluding the earlier step of nitrification from occurring).

Results for filter performance with respect to heavy metal removal were available for only one of the five experiments (E1). A steady and high removal efficiency of total metals by the gravel filter was observed. Given that metals are mainly particulate associated, their high
removal rates reflect that of sediment. Interestingly, the removal efficiency of dissolved copper by the gravel filter follows the expected first order kinetic model i.e. removal increases as flow decreases (Figure 6; dissolved lead concentrations are not shown because they were almost always below the detection limit (0.1 µg/l)). The metals removal efficiency of the sandy loam ranged from high (0.8) to significant release (-0.8), with no apparent trend. This may be due to swinging of the two opposing processes of removal of incoming metals and release of metals already present in the sandy loam.

Flow does not influence pollutant removal efficiencies until the minimum flow is reached i.e. the system is clogged. At this point efficiency becomes variable. It is suggested that as flow decreases and the filter becomes dirtier, release of previously trapped pollutants may become a more important process. This is possible because there are more pollutants in the filter and more time for transformations and/or remobilization to occur.

Figure 5. Pollutant removal efficiencies for a gravel, sand and multi-filter (Note: results are for E2 but are reflective of all five tests, with the exception of the spiked decrease in TP removal efficiency in the sand filter)

Figure 6. Pollutant removal efficiencies for dissolved copper and zinc
CONCLUSIONS

Both the gravel and multi-filters were highly efficient at removing suspended solids and particulate-associated pollutants. This removal efficiency was consistent, even as the filters became clogged. Removal of dissolved nutrients was more variable, with little reduction in concentrations overall. The exceptions to this trend are ammonia, which was present at elevated levels in the effluent from all filters; dissolved phosphorus, which was released from the sandy loam filter; and nitrate/nitrite, which was almost entirely removed by the sandy loam filter.

Although preliminary, these results challenge the concept that increased detention time improves the treatment performance of infiltration systems. The experimental data demonstrated that increased detention time as a result of clogging did not enhance pollutant removal efficiency (with the exception of dissolved copper). Release of previously immobilized pollutants did not occur for the most part, apart from those exceptions described above.

These results have implications for stormwater filtration systems in terms of treatment performance. The importance of preventing clogging to maintain the hydraulic capacity of stormwater filters is well accepted, but some clogging may be desirable if clogging was found to improve the pollutant removal efficiency of the filter. However, the experimental data presented in this paper suggests that clogging does not improve removal efficiency, and so prevention of clogging remains essential to extend the life of stormwater filtration systems in terms of hydraulic capacity and treatment performance.

REFERENCES


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