Pollutant removal performance of field-scale stormwater biofiltration systems
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ABSTRACT

The pollutant removal performance of three separate stormwater biofiltration systems in two different climates was assessed. At one of the sites, rain events were simulated, while actual runoff events were monitored at the other two sites. In all cases, concentrations of total suspended solids (TSS), copper, lead and zinc were effectively and reliably reduced, despite variations in inflow concentrations. Two biofiltration systems also effectively reduced phosphorus concentrations, however the third system discharged elevated phosphorus concentrations relative to inflow; this is attributed to poor specification of filter media properties. Effluent nitrogen concentrations were more variable at all sites and ranged from being substantially lower to considerably higher than inflow concentrations. Flow was also measured at two sites, where it was determined that volumetric reductions in runoff further improved pollutant removal. TSS and heavy metals will be reliably removed by a wide range of soil-based filter media, as will phosphorus, as long as the phosphorus content of the filter media is low. However, nitrogen removal remains a challenge because it is easily transformed to soluble forms and is influenced by wetting and drying. These results are essentially consistent with related laboratory studies.

Key words | biofiltration system, treatment, urban runoff, water quality

INTRODUCTION

Uncontrolled stormwater discharges are detrimental to the health of receiving waters (Leopold 1968; Hatt et al. 2004; Walsh et al. 2004; Meyer et al. 2005). We therefore need to better manage the quality and quantity of urban runoff in order to both protect and (ideally) restore the ecological health of urban waterways. At the same time, climate change is increasing the frequency of extreme storm events (Hegerl et al. 2004; Tebaldi et al. 2006) and thus the risk of flooding. Therefore, it is likely that augmentation of existing drainage systems will be required in order to prevent flood damage to urban areas.

Biofiltration systems (also known as biofilters, bioretention systems, and rain gardens) are a low-energy treatment technology with the potential to provide both water quality and quantity benefits. They work by filtering diverted runoff through dense vegetation followed by vertical filtration through a porous soil-based filter media. Pollutants are removed via a combination of physical (e.g. sedimentation, straining), chemical (e.g. sorption) and biological (e.g. plant and microbial uptake) processes. Biofiltration systems are being installed on an ever-increasing scale because they are flexible in their design and have a small footprint. In addition, they offer other benefits such as aesthetic improvements and are potentially beneficial to the local micro-climate because their vegetation increases evapotranspiration. Extensive performance testing of biofilters at the laboratory scale has demonstrated their effectiveness at removing suspended solids, heavy metals, phosphorus, and moderate effectiveness at removing nitrogen (e.g. Davis et al. 2003, 2006; Fletcher et al. 2007; Henderson et al. 2007;
Zinger et al. 2007b; Hatt et al. 2008). However, to date, little validation of these results through testing at the field-scale has been undertaken.

This paper reports on the findings of three separate pollutant removal performance studies of fieldscale biofiltration systems in Australia. At one site, another objective was to assess the hydrologic performance of the biofiltration system; preliminary results of this component of the study are reported in Lewis et al. (2008). Improved understanding of the long-term behaviour of biofilters will lead to better design guidance and hopefully contribute to more sustainable urban water management.

METHODS

Study sites

Three field-scale biofilters, varying in age, size and catchment characteristics (including climate) were studied. One site was in Melbourne, south-eastern Australia, and the other two in Brisbane, eastern Australia.

Bracken ridge

The first study site was an 860 m² biofiltration basin that was installed in 2001 to treat runoff from a 1.74 ha catchment, made up predominantly of roadway. The depth profile of this biofilter is as follows: 50 mm shredded hardwood mulch, 400 mm sandy loam, 250 mm sand and 200 mm gravel. The system is vegetated with Lomandra longifolia (a rush species) and Melaleuca quinquina (a small tree species) and a layer of geotextile separates the sand and gravel layers.

McDowall

The second study site was a 20 m² biofilter that was retrofitted in a 900 m² residential catchment (treating primarily runoff from roads, and some roof areas) in McDowall, Brisbane, in 2006. The filter media is a 400 mm deep sandy loam material (overlaying a 100 mm sand and 200 mm gravel drainage layer) and was originally vegetated with Dianella (native sedge) species, however this failed to establish well and was replaced with Carex appressa (another native sedge) in early 2007.

Clayton

The third study site was a 45 m² biofilter that was constructed in early 2006 at the Clayton campus of Monash University, Melbourne, to treat storm runoff from the top level of a 4,500 m² multi-level carpark. The biofilter is partitioned into three parallel cells to allow for performance testing of three types of soil-based filter media: Cell 1, 100% sandy loam; Cell 2, 80% sandy loam, 10% vermiculite, 10% perlite; and Cell 3, 80% sandy loam, 10% composted pine bark, 10% hardwood mulch. The depth profile is 500 mm filter media, 100 mm sand and 100 mm fine gravel. Each cell was planted as homogeneously as possible with the following native sedge and rush species: C. appressa, Carex tereticaulis, L. longifolia, Isolepis nodosa, Caleocephalus lacteus, and Juncus spp.

Data collection

Bracken ridge

Twenty-one runoff events were monitored at the Bracken Ridge site from March 2003 to September 2006, most during the summer months. Automatic samplers were used to collect time-weighted water quality samples from each of the three inlets and from the outlet. Water quality samples were analysed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), copper (Cu) and zinc (Zn).

McDowall

Five simulated runoff experiments were conducted during the period October 2006 to April 2008, where the biofilter was loaded with semi-synthetic stormwater equivalent to a 3-month rainfall event (the design storm). The rationale and method for preparing semi-synthetic stormwater has been described previously (Hatt et al. 2007b). Outflow was measured and water quality samples were collected at regular intervals to create a time-series of flow and water quality. Water quality samples were analysed for TSS, TP, filterable reactive phosphorus (FRP), TN, ammonium
(NH$_4^+$), nitrate/nitrite (NO$_x$), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), cadmium (Cd), Cu, lead (Pb) and Zn.

**Clayton**

Levelled V-notch weirs and ultrasonic depth sensors were used to continuously monitor inflow and outflow rates. Automatic samplers were used to collect flow-weighted water quality samples at the inflow and from the outflow of each of the three cells during runoff events. Water quality samples were analysed for TSS, TP, FRP, TN, NH$_4^+$, NO$_x$, DON, PON, Cd, Cu, Pb and Zn; for three runoff events, all water quality samples were analysed individually, however flow-weighted composite samples were analysed for all other runoff events. Seventeen runoff events were monitored from January 2007 to November 2007.

**Data analyses**

**Pollutant concentrations**

While percentage removals are often used as a measure of treatment performance, they are generally not reported here because they are mathematically dependent on inflow concentrations and therefore not necessarily transferrable from one system to another. Instead, boxplots were used to compare the range of stormwater and outflow pollutant concentrations at each site and so assess the reliability of treatment. Percentage reductions can be readily calculated from these figures. The change in pollutant concentrations from inflow to outflow was assessed. In the case of nutrients, both total and individual species are assessed in order to understand the processes occurring within the media and the bioavailability of nutrients in the filter discharge. Since water quality data was collected over a period of 3.5 years at the Bracken Ridge site, it was possible to assess whether there was a change in treatment performance with time. Hydrologic data was available for the Clayton site, therefore it was also possible to assess the influence of flow and the antecedent dry weather period on pollutant removal performance.

**Pollutant loads**

Pollutant loads over the duration of a storm event were estimated for each sampling point at the McDowall and Clayton sites as the integral over time of the product of measured flows and concentrations at each timestep:

\[
l = \sum_{i=1}^{N} Q_i C_i \Delta t
\]

where \(l\) is the load, \(Q_i\) and \(C_i\) are the flow rate and concentrations, respectively, measured at time \(i\), \(\Delta t\) is the time interval between the two measurements, and \(N\) is the total number of samples taken for each simulation or runoff event. The proportion of inflow that passed through each cell at the Clayton site could not be calculated, therefore it was assumed that equal flows passed through each cell; the loads from the three outlets were then summed to give a total load out. This approach is reasonable, given that the Clayton biofiltration system had inlet weirs set at identical levels, fed by a large stilling basin designed to maximise the uniformity of flows over the three weirs. Pollutant loads were only determined for runoff events at the Clayton site where the high-flow bypass was not engaged.

**RESULTS AND DISCUSSION**

**Pollutant concentrations**

**Bracken ridge**

Concentrations of TSS, Cu, Zn, TP and FRP were effectively and reliably reduced, despite variation in inflow concentrations (Figure 1). The effluent concentrations were also much less variable than influent concentrations, resulting in an effective ‘buffering’ of the catchment discharge by the biofiltration system. While the range of effluent TN concentrations was narrower than that for influent stormwater, median concentrations were essentially the same, indicating that nitrogen (N) removal only occurred when incoming concentrations were high. This suggests the presence of a ‘background concentration’, below which effective treatment will not occur (Wong et al. 2009).
With respect to bioavailable N species, \( \text{NH}_4^+ \) concentrations were effectively reduced, however leaching of \( \text{NO}_x \) often occurred.

There is no influence of time on effluent concentrations of TSS (\( r^2 = 0.04 \)), heavy metals (\( r^2 = 0.00 \), Cu; \( r^2 = 0.26 \), Zn) or TN (\( r^2 = 0.01 \)). However, effluent TP concentrations declined over the monitoring period (Figure 2) and, while there was a moderate correlation between stormwater TP and effluent concentrations, this relationship was not significant (\( r^2 = 0.58 \), \( p = 0.38 \), Figure 2). This suggests that leaching of phosphorus (P) from the filter media may have occurred in the early stages of operation. Regardless, effluent TP concentrations were always lower than the influent stormwater. An exponential model provides a good fit of this behaviour and suggests that the system was approaching its optimal treatment capacity at the end of the monitoring period.

**McDowall**

The range of stormwater concentrations at the McDowall site were generally substantially narrower than those observed at the Bracken Ridge biofilter, due to the use of semi-synthetic stormwater, however the results still indicate reliable removal of TSS, heavy metals and P (Figure 3). Effluent concentrations of all species of N except \( \text{NH}_4^+ \) were
again highly variable. This may have significant implications for small flowing downstream receiving waters, which have little capacity to buffer high concentration inputs of nitrogen. However, median concentrations of all N species except NO\textsubscript{x} were reduced in comparison to stormwater concentrations, resulting in a small reduction in TN concentrations (Figure 3).

**Clayton**

Consistent with the Bracken Ridge and McDowall biofilters, TSS, Cu, Pb, Zn, NH\textsubscript{4} and PON concentrations were effectively reduced at the Clayton site (on average, by 76, 51, 68, 84, 40 and 37%, respectively). However, TP, FRP, NO\textsubscript{x} and DON were consistently leached from all three cells (Figure 4); given that this always occurred, it is likely that this was due to the properties of the filter media rather than a failure to trap incoming N and P. It is important to note also that at the Clayton site, influent concentrations of most pollutants were generally quite low (Figure 4), and lower than typical urban stormwater quality (Taylor *et al.* 2005; Duncan 2006). Given this, and the afore-mentioned observation of a “background concentration” in the behaviour of stormwater biofiltration systems, it is not surprising that net production of these components was often observed.

Effluent event mean concentrations (EMCs) of P and FRP were not influenced by inflow rates or the antecedent dry weather period (ADWP), nor were there any clear temporal trends across the monitoring period (data not shown). Similarly, inflow rates did not influence effluent EMCs of N (total or species). It can be seen, however, that effluent TN concentrations increased steadily over the monitoring period, largely as a result of increased NO\textsubscript{x} concentrations (Figure 5). Concentrations of TN also increased with the ADWP, this time as a result of increased DON concentrations (Figure 5). The density and biomass of the plant community increased substantially over the monitoring period, therefore the observed temporal influence may be due to increased decomposition of N-containing compounds as a result of increased biological activity. The influence of the ADWP on effluent TN concentrations is consistent with a related laboratory study conducted by Hatt *et al.* (2007a), although that study identified the cause as increased NO\textsubscript{x} concentrations after periods of drying. The reason for this difference may be attributable to the filter media composition; Hatt *et al.* hypothesised that PON was being transformed to NO\textsubscript{x} (via mineralisation and nitrification) and accumulating in the filter media during dry periods, only to be washed out upon rewetting. The TN and total organic carbon content of the filter media in the Clayton biofilter is 2–4 times that of the filter media used in the laboratory study, therefore the amount of DON (desorbed PON) may be overwhelming the mineralisation capacity of the biological community, and hence accumulating in the filter and being washed out upon rewetting.

**Pollutant loads**

**McDowall**

Runoff volumes were reduced by 11–30%. This, in combination with reduced pollutant concentrations, resulted in generally high pollutant load reductions (Table 1).
Figure 3 | Range of pollutant concentrations at the McDowall biofilter (n = 5, stormwater; 74, effluent). ●, mild outlier; *, extreme outlier.
Even where N concentrations increased, largely through leaching of NO\textsubscript{x}, pollutant loads were at least partially reduced because the system retained water.

**Clayton**

Runoff volumes were reduced by an average of 33% (Hatt et al. submitted). Loads of TSS and heavy metals were effectively reduced (Table 1), however the volumetric reduction was not enough to counter leaching of N and P, and so loads of these increased through the system.

**Implications for biofilter design**

These studies clearly demonstrate the importance of specifying appropriate filter media properties for biofilters. While other studies have suggested that a higher organic content is beneficial for P retention (e.g. Hsieh & Davis 2005), the results from the Clayton study are in direct contrast. It would appear that, while TSS and heavy metals will be removed by a wide range of soil-based filter media, use of a material with a low organic matter content is important for P removal.
Reliable removal of N remains a challenge, in that current design is unable to buffer against the deleterious effects of dessication on N removal. Laboratory-scale performance testing of biofilters with a permanently submerged zone at the bottom of the system has been undertaken. This design feature was initially incorporated to try to improve the retention of NO$_x$, by providing conditions conducive to denitrification and, while this has proven successful (Kim et al. 2003; Zinger et al. 2007b), it has been shown to have another important role in buffering against the deleterious effects of dessication, because the submerged zone provides a constant water source for the biological community (Zinger et al. 2007a). A number of field-scale biofiltration systems incorporating this design have recently been constructed and will be monitored to validate the results of the laboratory studies.

![Graphs showing effluent nitrogen concentrations vs. time and antecedent dry weather period at the Clayton biofilter.]

**Figure 5** Relationship between effluent nitrogen concentrations, time, and the antecedent dry weather period at the Clayton biofilter.

**Table 1** Pollutant removal performance (mean ± Coefficient of Variation) for four storm simulations at McDowall and seven storm events at Clayton.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Load reduction (%)</th>
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<tbody>
<tr>
<td>TSS</td>
<td>95 ± 4</td>
<td>76 ± 33</td>
<td></td>
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<tr>
<td>Cu</td>
<td>98 ± 1</td>
<td>67 ± 31</td>
<td></td>
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<tr>
<td>Pb</td>
<td>98 ± 0.5</td>
<td>80 ± 19</td>
<td></td>
<td></td>
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<tr>
<td>Zn</td>
<td>99 ± 0.1</td>
<td>84 ± 28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>86 ± 4</td>
<td>-398 ± 140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRP</td>
<td>81 ± 19</td>
<td>-1271 ± 84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>37 ± 56</td>
<td>-7 ± 1096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_x$</td>
<td>-17 ± 201</td>
<td>-13 ± 711</td>
<td></td>
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<tr>
<td>NH$_4$</td>
<td>96 ± 7</td>
<td>64 ± 65</td>
<td></td>
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<tr>
<td>DON</td>
<td>58 ± 19</td>
<td>-129 ± 180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PON</td>
<td>58 ± 19</td>
<td>38 ± 146</td>
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CONCLUSIONS

This study confirms the findings of previous laboratory studies, that is, biofiltration systems efficiently and reliably remove TSS and heavy metals. Retention of P will also be high, provided the organic content of the filter media is low. However, even if the filter media properties are correctly specified, N removal will still be variable because extended dry periods are detrimental to the effectiveness of N retention; this is also consistent with recent laboratory findings. The key challenge in improving biofilter design therefore lies in managing the effects of variable wetting and drying. A related laboratory study of biofiltration systems that incorporate a permanent pool of water at the bottom of the system has demonstrated the potential for buffering against desiccation. A field-scale study to validate this finding is currently underway. Once this adaptation is perfected, the next challenge will be to address both flow and water quality objectives, enabling the maximum infiltration to occur, whilst maintaining the permanently wet zone which appears to improve N removal.

ACKNOWLEDGEMENTS

This project was funded by the Victorian Government’s Science, Technology and Innovation grant scheme, and a number of industry partners. Brisbane City Council, particularly City Design (Stormwater Planning and Investigation) and Water Resources are thanked for their assistance.

REFERENCES


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