Insights From The Design, Construction And Operation Of An Experimental Stormwater Biofiltration System

B.E. Hatt, J. Lewis, A. Deletic, T.D. Fletcher
Facility for Advancing Water Biofiltration, Department of Civil Engineering, Monash University, Victoria, 3800, belinda.hatt@eng.monash.edu.au

Abstract
Biofiltration systems are being installed on an ever-increasing scale, both for stormwater quality improvement and as a component of stormwater reuse systems. However, there is currently a general lack of knowledge regarding their design, implementation and performance. This paper reports on the issues encountered and lessons learnt during the installation and operation of an experimental biofiltration system. While the water industry familiarizes itself with biofiltration technologies, effective communication and clear guidance is required to ensure successful construction and operation of biofilters. The studied biofiltration system consisted of three separate cells, each containing a different, soil-based media type. Compaction of filter media, organic matter and moss growth significantly reduce hydraulic conductivity, however root penetration and the addition of vermiculite and perlite appear to assist in maintaining porosity. Preliminary treatment performance results indicate that all three cells effectively remove sediment and heavy metals (lead, copper and zinc), however they are all net producers of nitrogen and phosphorus. However, biofiltration systems appear to be promising technologies for treatment of stormwater, both for reuse and aquatic ecosystem protection.

Introduction
In recent years, there has been a shift from traditional water management strategies to the sustainability principles that underpin Water Sensitive Urban Design (WSUD). One objective of WSUD is to manage urban stormwater as a resource and to protect the ecological value of receiving waterways. This has resulted in the development of a suite of structural and non-structural techniques.

Biofiltration systems (also commonly referred to as biofilters and bioretention systems) are a structural treatment technique that are designed to remove a range of pollutants, from sediment and its associated pollutants down to dissolved pollutants. Their basic design is a trench or basin filled with a porous, soil-based filter media underlying a vegetation layer. An extended detention zone temporarily detains stormwater, which then percolates through the filter media, where pollutants are removed by processes such as mechanical straining, sorption and biological uptake. Perforated pipes underneath the filter media collect the treated water for conveyance to receiving waters or for storage prior to reuse.

In addition to their potential pollutant removal capabilities, biofiltration systems are flexible in their configuration, and so are particularly useful for urban areas, which often have tight space constraints. As a vegetated system, they can also improve the urban landscape. However, as is the case with all new technologies, there is currently a general lack of knowledge regarding their design, implementation and their hydraulic and treatment performance, particularly at the field scale.

The aim of this paper, therefore, is to report on the design, construction, maintenance and performance of a full-scale biofiltration system, constructed to treat water from a large carpark. Both quantitative and qualitative findings are presented.

System Design & Construction
**Objectives and constraints**

The purposes of constructing the biofiltration system were two-fold. Firstly, we aimed to treat runoff from a large carpark, prior to discharging it to an open storage pond, where the water could be drawn for irrigation of public open space (sports grounds). Secondly, we wanted a system which allowed us to test stormwater biofiltration at full-scale, in a way that allowed us to rigorously monitor the flow and pollutants flowing in and out of the system. For this reason, we required that the system be fully lined, to ensure that there would be no seepage losses.

Our original intention was to construct a system sized at approximately 1.5% of the catchment area. However, we were restricted by the requirements of the site owner (Monash University) not to remove existing trees.

**Construction**

An experimental stormwater reuse system was constructed at the Clayton campus of Monash University in Melbourne. Runoff from the top level of a multi-level car park (approximately 4500 m$^2$) is collected and passed through a treatment train consisting of two 15 kL pre-treatment tanks (for coarse sediment removal) and a biofilter. The treated water is stored in an adjacent ornamental pond prior to being used to irrigate a nearby sports oval.

The biofilter is partitioned into three cells (each 1.5 m wide, 10 m long, and 0.7 m deep (0.5 m of filter media plus a 0.2 m drainage layer)) to allow for performance testing of three separate soil-based filter media (Table 1). The idea was to test the sandy loam currently recommended by design guidelines (e.g. Melbourne Water, 2005) as well as add other media that may enhance the hydraulic and pollutant removal capabilities (these filter media types have also been tested in non-vegetated, laboratory-scale system, Hatt *et al.*, 2007).

Table 1. Biofilter media details

<table>
<thead>
<tr>
<th>Cell</th>
<th>Filter Media Details</th>
<th>Rationale for selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (SL)</td>
<td>Sandy Loam</td>
<td>Currently recommended by design guidelines</td>
</tr>
<tr>
<td>2 (SLVP)</td>
<td>80% Sandy Loam 10% Vermiculite 10% Perlite</td>
<td>High cation exchange capacity for increased retention of heavy metals</td>
</tr>
<tr>
<td>3 (SLCM)</td>
<td>80% Sandy Loam 10% Composted Pine Bark 10% Hardwood Mulch</td>
<td>Provision of a carbon source to enhance nutrient removal via biological processes</td>
</tr>
</tbody>
</table>

Each cell was planted with the following species: *Carex apressa*, *Carex tereticaulis* *Lomandra longifolia*, *Isolepis nodosa*, *Caleocephalus lacteus*, and various *Juncus* species. These species are recommended species for biofiltration systems (e.g. Melbourne Water, 2005). However, a planting density of 10-12 plants/m$^2$ was used (higher than the recommended densities given in Melbourne Water, 2005), in order to minimize the time taken for plants to fully occupy the site. This had two motivations; firstly we wanted to ensure that the system would be performing as a “mature” system as soon as possible, and secondly we wanted to reduce the invasion of weeds within the soil media. To assist with the first objective, we installed a large transparent cover over the system for a period of four months, to increase growth rate during winter. The planting arrangement was as close as possible to...
identical in each cell, to ensure that any variation in treatment and hydraulic performance is due to the filter design rather than vegetation differences.

Construction was completed in January 2006, and the system was fully vegetated in February 2006.

**Monitoring Setup**

A fully automated monitoring system was installed to evaluate the hydraulic and pollutant removal performance of the biofilter. Three levelled V-notch weirs were installed in the covered inflow chamber (which acts to reduce flow velocities and deliver equal flows to each cell) to monitor the inflow rate to the biofilter. The outflow rate from each cell was also monitored by a V-notch weir. The water heights over the weirs were monitored by ultrasonic depth sensors (Siemens Miltronics) and continuously logged (one minute time step). Autosamplers (Sigma 900) collected flow-weighted water quality samples at both the inflow and three outflow points. Samples were analysed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), ammonium (NH₄⁺), dissolved phosphorus (FRP), nitrate/nitrite (NO₃⁻), dissolved organic nitrogen (DON), and total heavy metals (copper – Cu, cadmium – Cd, lead – Pb, and zinc – Zn) using standard methods (Hosomi and Sudo, 1986; APHA/AWWA/WPCF, 1998). Flow monitoring commenced in September 2006, and water quality monitoring in January 2007.

**Preliminary Results**

**Evolution of hydraulic conductivity**

Hydraulic conductivity of the uncompacted soil was estimated at approximately 300mm/hr (Table 2). Within two weeks, after planting this had settled down to an estimated value of around 180 mm/hr. Subsequently, the hydraulic conductivity dropped substantially. Upon inspection, it was apparent the biofilter had a thick layer of dense moss growing all over it. We surmise that this was an artifact of having placed a “hothouse” over the biofilter. In late August, the biofilter was thoroughly weeded, resulting in removal of some (but not all) the moss. There was an immediate increase in hydraulic conductivity following this. As the moss has grown back, the hydraulic conductivity has again decreased.

Interestingly, the cell with vermiculite and perlite added has maintained a consistently higher hydraulic conductivity than the other two cells. This is consistent with behaviour observed in laboratory biofilter columns (Le Coustumer et al., 2007), and suggests that addition of this material is a worthwhile investment.

<table>
<thead>
<tr>
<th>Date</th>
<th>kₙ (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cell 1 (SL)</td>
</tr>
<tr>
<td>12/02/2006 (initial)</td>
<td>≈300</td>
</tr>
<tr>
<td>26/02/2006</td>
<td>≈180</td>
</tr>
<tr>
<td>20/07/2006</td>
<td>24</td>
</tr>
<tr>
<td>10/08/2006</td>
<td>18</td>
</tr>
<tr>
<td>01/09/2006</td>
<td>205</td>
</tr>
<tr>
<td>02/10/2006</td>
<td>31</td>
</tr>
</tbody>
</table>
Treatment performance

Seven storm events have been monitored since January 2007. Inflow concentrations of TSS are generally well below reported values for typical urban catchments (Figure 1, Duncan, 2005), with the exception of Event 3, which was a summer thunderstorm that resulted in high flows and high subsequent TSS concentrations at the inlet. Given that the catchment is a sealed carpark, it was expected that it would be relatively “clean”, however these low inflow concentrations also indicate that the pre-treatment tanks are effectively removing sediment (and its associated pollutants) and thus protecting the biofilter from clogging. On average, outflow concentrations of TSS were less 10 mg/l (Figure 1). TSS was effectively removed, regardless of the storm size. It is also likely that any TSS in the outflow is fine particulate matter that is washed from the bottom of the filter media, and not inflow sediment that has migrated through the filter.

![Figure 1. TSS event mean concentrations (EMCs) at the inlet and outlets for seven events](image)

Concentrations of TP (and FRP) at the inlet were also well below reported values for typical urban catchments (Figure 2, Duncan, 2005). Outflow concentrations of TP range from similar to inflow concentrations to significantly higher; on average outflow is five times higher than inflow and there is never any removal. Interestingly, only around 50% of the P in the inflow is dissolved, suggesting that one source of P in the outflow is the fine particles that form outflow TSS. The dissolved component of P at the outlets may be from the inflow, or may have been desorbed from the filter media under anaerobic conditions; further testing is required to check this.
Incoming concentrations of TN and its species (NH$_4^+$, NO$_x$, DON) were generally all well below reported values for typical urban catchments, although inflow concentrations during Event 3 approached typical values (Figure 3, Duncan, 2005). Outflow concentrations of TN range from similar to inflow concentrations to slightly elevated. There was low to moderate removal of NH$_4^+$ and NO$_x$, suggesting nitrification-denitrification is occurring, however this is largely negated by leaching of DON (on average, outflow concentrations of DON were three times higher than inflow concentrations).

Heavy metals data was only available for the first four events. Cadmium concentrations at the inlet and outlets were always below detection. Not surprisingly, mean inflow concentrations of Cu (0.013 mg/l) and Pb (0.0059 mg/l) were generally well below typical reported values, however mean Zn concentrations (0.20 mg/l) were closer to typical reported values. Cu, Pb and Zn were effectively removed, with mean outflow concentrations less than 0.007, 0.0026 and 0.026 mg/l, respectively.

Comparing effluent quality to water quality guidelines. In the absence of guidelines specific to stormwater reuse, the Australian and New Zealand Guidelines for Marine and Fresh Water Quality provide water quality trigger values for irrigation (Table 3). Overflows from the
storage pond are directed into the stormwater drainage system and ultimately to local streams, therefore the guidelines for aquatic ecosystem protection are also pertinent.

Outflows from each of the three biofilter cells are always of a quality suitable for irrigation, with all pollutant concentrations well below the trigger values for long-term irrigation. On the other hand, outflow pollutant concentrations almost always exceed the guidelines for aquatic ecosystem protection, particularly for nutrients. It is anticipated that concentrations of heavy metals in the outflow will decrease as the supply of fine particles that can be washed from the bottom of the filter media is exhausted. However, further work to improve the nutrient retention capacity is required and is currently being undertaken. On the other hand, the aquatic ecosystem protection guidelines are for slightly disturbed ecosystems, and so not entirely suitable, given that the receiving waters are likely to be more highly disturbed urban streams. Regardless, the ultimate aim of biofiltration systems is to be able to produce water quality to sustain intact aquatic ecosystems, and laboratory experiments suggest that with appropriate design and vegetation selection, this may be achievable (Fletcher et al., 2007).

Table 3. Water quality guidelines for various end-uses (ANZECC and ARMCANZ, 2000)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Irrigation(^a) (mg/l)</th>
<th>Aquatic Ecosystem Protection(^b) (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>n/a(^b)</td>
<td>0.05</td>
</tr>
<tr>
<td>FRP</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>TN</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>NO(_3)</td>
<td>-</td>
<td>0.04</td>
</tr>
<tr>
<td>NH(_4)</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>Cd</td>
<td>0.01</td>
<td>0.0002</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2</td>
<td>0.0014</td>
</tr>
<tr>
<td>Pb</td>
<td>2</td>
<td>0.0034</td>
</tr>
<tr>
<td>Zn</td>
<td>2</td>
<td>0.008</td>
</tr>
</tbody>
</table>

\(^a\)Long-term use – up to 100 years  
\(^b\)Guideline of 0.05 mg/l set to prevent bio-clogging of irrigation equipment only and not applicable here  
\(^c\)Guideline for slightly disturbed lowland rivers in south-east Australia

**Lessons**

**Construction**

Effective communication between designers and construction contractors is essential, throughout all stages of the project. It is imperative that quality control issues are addressed in planning and design, construction and maintenance throughout the life of the bioretention system, and that the design intent is communicated to the contractors, at a pre-construction briefing.

**Filter media specification**

*Hydraulic Performance.* Filter media compaction over time has an important influence on the eventual hydraulic performance of a biofilter, and therefore has implications for specification and testing of filter media properties. Hydraulic conductivity specifications should be based on tests that are relevant for field conditions i.e. tests that take compaction over time into account. It is recommended that a ‘repeated-drop’ measurement, such as that recommended by McIntyre and Jakobsen (2000), be used to specify soil filter media, as this method allows the asymptote conductivity to be determined.
Preliminary findings from this study suggest that vermiculite and perlite assist in maintaining porosity of the filter media. Conversely, compost and mulch appear to limit the hydraulic capacity due to swelling of organic matter upon wetting and so reduce porosity. Findings from a related study suggest that specifications must be strictly adhered to in terms of both composition and hydraulic conductivity in order to ensure reliable operation of biofiltration systems. Interim soil specifications have been developed (FAWB, 2006) and it is recommended that these be followed.

Treatment Performance. Water flowing into the biofilter is already fairly clean, as a result of a relatively clean catchment and effectively pre-treatment. Overall, this is a good result for the stormwater reuse system, however it does limit the assessment of the pollutant removal performance of the biofilter. Further experiments, including by-passing pre-treatment tanks to allow “dirtier” water to flow into the biofilter are being undertaken.

Vegetation selection and planting density
Of the species planted, most have grown very well (Isolepis nodosa, Lomandra longifolia, Juncus spp. and Carex spp.), however most of Caleocephalus lacteus have died, appearing to be smothered by the other taller, more vigorous plants. It seems also that different species have tended to “self-select” within the biofilter, along a moisture gradient. Near the inlet, which is more frequently wet, Carex and Juncus tend to dominate, whilst near the outlet (where water may not reach during small storms), L. longifolia is vigorous. There appears to be some benefits in using a diversity of plants, in order that the overall vegetation ‘community’ will be able to adapt to the wetting and drying regime for the particular filter. On the other hand, laboratory trials have shown that not all species perform equally in terms of nutrient removal (Fletcher et al., 2007), with Carex appearing to be give particularly high levels of nitrogen removal.

The dense planting used at this site, whilst offering advantages in terms of weed suppression, may have also assisted in promoting the moss growth which contributed to reductions in hydraulic conductivity. Planting density may need to be a compromise between these considerations, although further research is required before definitive guidance on this can be provided.

System maintenance
Maintenance requirements are likely to be high immediately following construction (i.e. during the establishment phase); frequent weed removal is required and the juvenile vegetation may require watering during extended dry periods. However the need for this level of maintenance reduces significantly as the vegetation matures. The development of mosses on the surface should be discouraged, as these can reduce the hydraulic capacity of the system. Dense planting of the preferred plants at the time of construction will help to minimise the extent of weed invasion.

Conclusions
Until the industry becomes more familiar with biofiltration technologies, effective communication and careful guidance is required to avoid problems and ensure successful implementation. Selection of a variety of plant species may allow the vegetation community to self-adapt, and planting at a high density may also assist in reducing invasion of weed species and subsequent maintenance requirements. The hydraulic capacity of the biofilter was
reduced by compaction of the filter media, the addition of organic matter to the media, and thick moss growth on the surface, however these mechanisms were countered to some extent by root penetration and the addition of vermiculite and perlite. In terms of pollutant removal, all three biofilter cells were able to effectively and reliably remove sediment and heavy metals, however they were all net producers of nitrogen and phosphorus, partly as a result of the artificially low inflow concentrations at this site. Further investigations will be undertaken to determine the system performance for more typical pollutant levels.

References


