Factors that affect the hydraulic performance of raingardens: Implications for design and maintenance

Facteurs influençant la performance hydraulique des jardins de pluie : implications pour la conception et l’entretien

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ABSTRACT

Raingardens are becoming an increasingly popular technology for urban stormwater treatment, however, their hydraulic performance is known to reduce due to clogging from deposition of fine-grained sediments on the surface. This impacts on their capacity to treat urban runoff. It has been recently hypothesised that plants can help to mitigate the effect of surface clogging on infiltration. A conceptual model is therefore presented to better understand key processes, including those associated with plant cover, which influences surface infiltration mechanisms. Based on this understanding, a field evaluation is carried out to test the hypothesis that plants increase the infiltration rate, and to investigate factors which influence the deposition of fine-grained sediments within raingardens. The results show that infiltration rates around plants are statistically higher than bare areas, irrespective of the degree of surface clogging. This suggests that preferential flow pathways exist around plants. Sediment deposition processes are influenced by design elements of the raingardens such as the inlet configuration. These findings have implications for the design and maintenance of raingardens, in particular the design of inlet configuration, as well as maintenance of the filter media surface layer and vegetation.

KEYWORDS

Clogging, Hydraulic performance, Raingarden, Sediment deposition, Vegetation

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1 INTRODUCTION

The negative impacts of urbanization on the hydrology and water quality of receiving waters are well documented (Hatt et al., 2004). There are a broad range of technologies available to treat urban stormwater runoff prior to discharge to receiving water bodies, such as raingardens (also known as biofilters, biofiltration or bioretention systems). A raingarden incorporates a vegetated filter media through which stormwater passes, and it may have an underlying perforated underdrain that collects the treated water and delivers it to a stormwater drainage network or waterway (Hatt et al., 2007).

Both plants and the filter media have been shown to contribute to pollutant removal in various ways (Bratieres et al., 2008). The filter media is particularly effective in removing suspended solids and attached pollutants through sedimentation and filtration processes (Houng and Davis, 2008) and is therefore typically designed to have a fine texture to support plant growth and remove pollutants. It is also important, however, that it has a high infiltration rate to optimise the runoff volume treated (Le Coustumer et al., 2009). The filter media therefore commonly ranges from fine sand to sandy loam.

The overall treatment performance of raingardens has been shown to reduce with time as the infiltration rate decreases due to clogging of the filter media, causing the system to increasingly overflow thus discharging untreated water. Clogging occurs from the surface and interstitial deposition of fine-grained sediments, comprised mainly of silt and clay particles in the incoming catchment runoff (Hatt et al., 2008), that based on observations at operational sites, is likely to occur closest to the inlet (Asleson et al., 2009). Observations of faster infiltration rates in proximity of plants in operational systems and in vegetated treatments in an experimental study (Le Coustumer et al., 2012) suggest that plant cover can alleviate the impact of surface clogging on infiltration.

There are a number of mechanisms by which plants may improve the infiltration rate. Archer et al (2002) suggest that growth of coarse roots can create macropores resulting in preferential flow pathways. Root senescence and turnover can also have the same effect (BARLEY, 1954). An alternate mechanism is that wind-induced movement of stiff foliage or stem of plants could break open the surface clogging layer, forming surface macropores which channel water through to the root network (Martinez-Meza and Whitford, 1996). Although not directly associated with plants, compaction due to hydraulic loading as well as construction activity is known to modify the surface porosity and reduce infiltration rates (Hatt et al., 2009, Brown and Hunt, 2010).

![Figure 1 - Factors influencing the surface porosity, pore size distribution and infiltration mechanism](image)

The conceptual model in Figure 1 illustrates the key factors which influence the porosity and pore size distribution of the surface layer in raingardens. Preferential flow around plants may exist from macropore development within the surface layer; however this is likely to depend on the degree of surface clogging and level of compaction. In testing the hypothesis that plants create preferential flow pathways, we address the following questions: 1) Is infiltration rate increased by plants? 2) Does this effect of plants depend on the degree of surface clogging? We also aim to identify design elements of a raingarden which influence the sediment deposition process by assessing 3) the importance of distance and elevation relative to the raingarden’s inlet in controlling sediment deposition. Based on the findings, this paper discusses implications for design and maintenance of raingardens.
2 METHODS

Measurement of infiltration rate was carried out at seven operational raingardens in Melbourne, constructed during the last ten years. Sites were selected to have both vegetated and unvegetated areas, to enable surface infiltration rate measurement around plants and on bare ground. Plant species varied across and within sites, but were all monocots and herbaceous (Table 1). These included grasses, sedges and rushes, which generally have an extensive and fibrous root system with a high proportion of fine roots (Read et al., 2010). Raingardens with fine gravel mulch were avoided to minimise disturbance to the soil surface during infiltration measurements. The selected sites also varied in age and in design configuration (Table 1). All sites selected were constructed of a similar fine sandy filter media with an original infiltration rate around 150-300 mm/hr. However, site 3 had a layer of top soil (10cm) above the filter media to comply with AS 4419 (Standards Australia, 2003), and therefore would have had a lower original infiltration rate, possibly between 20-100 mm/hr.

2.1 Sampling

A stratified random sampling approach was used to select positions for infiltration measurements. Each raingarden was divided into two approximately equally-sized zones, based on the distance from the inlet or surcharge pit which was furthest to the overflow pit. Six random positions were selected in each zone, with 3 positions on bare ground and 3 positions around plants. The surface condition at the sampling positions was visually inspected for biological clogging, such as presence of biomass or biofilms (Bouwer, 2002, Gonzalez-Merchana et al., 2012), as well as evidence of cracking. Distance and elevation of each position were measured relative to the closest inlet. Distance was measured in a straight path and elevation was measured using a dumpy level.

Figure 2 – Schematic of a typical raingarden

2.2 Infiltration rate measurement

Steady infiltration rate was measured by ponded infiltration with a single ring method (Reynolds and Elrick, 1990). This approach was chosen due to (i) its ability to minimise disturbance to the soil surface and (ii) it being the only method that allows infiltration around plants to be measured. The rings were 400 mm in diameter to enable macropores, or other preferential flow pathways, associated with plants to be sampled within the infiltrating volume.

At the sampling positions, the infiltration ring was carefully pushed into filter media to a depth of 100 mm. For measurements around plants, care was taken to hold the plants’ foliage in place while passing the ring over, to avoid excessive movement and soil disturbance. The infiltration rate was expressed as saturated hydraulic conductivity, $K_{SAT}$, which was obtained from the one dimensional analytical solution of steady ponded infiltration (Reynolds and Elrick, 1990), Equation 1.

$$K_{SAT} = \frac{\alpha G Q_s}{r (\alpha H + 1) + G \alpha \pi r^2}$$  

Equation 1

$$G = 0.316 \left( \frac{d}{r} \right) + 0.184$$  

Equation 2

Where $\alpha$ is a soil parameter to do with structural/textural considerations, mm$^{-1}$; $d$ is the depth of ring insertion, mm; $r$ is the ring radius, mm; $G$ is a dimensionless shape factor based on the depth of ring insertion and ring radius; $H$ is depth of ponding (mm); and $Q_s$ is the steady infiltration rate, mm$^3$/hr.
Table 1 – Description of sites used in field study (‘Ratio’ represents the ratio of biofiltration system area to catchment impervious area)

<table>
<thead>
<tr>
<th>Site Number</th>
<th>Site Name</th>
<th>Size (m²)</th>
<th>Impervious Area (m²)</th>
<th>Ratio (%)</th>
<th>Age (Years of operation)</th>
<th>Plant species</th>
<th>Design configuration (Inlet/Overflow design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hagenauer reserve</td>
<td>30.1</td>
<td>859.8</td>
<td>3.5</td>
<td>4</td>
<td>Carex appressa</td>
<td>2 curb cut inlets 1 overflow pit</td>
</tr>
<tr>
<td></td>
<td>Box Hill</td>
<td></td>
<td>Car park</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Corona street</td>
<td>115</td>
<td>3620</td>
<td>3.2</td>
<td>4.5</td>
<td>Juncus amabilis</td>
<td>Tiered design with overflow from zone 1 directed into zone 2 and so on 1 main PVC pipe inlet into zone 1 1 overflow pit in zone 3</td>
</tr>
<tr>
<td></td>
<td>Kew</td>
<td></td>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Walker street</td>
<td>100</td>
<td>14286</td>
<td>0.7</td>
<td>5</td>
<td>Mix but mainly Poa labillardieri</td>
<td>1 main PVC pipe inlet with upstream sediment trap 1 overflow pit</td>
</tr>
<tr>
<td></td>
<td>Clifton Hill</td>
<td></td>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ricketts point</td>
<td>144.4</td>
<td>1836.1</td>
<td>7.8</td>
<td>4.5</td>
<td>Ficinea nodosa</td>
<td>No curb along one edge, with raingarden receiving direct road runoff No overflow pit</td>
</tr>
<tr>
<td></td>
<td>Beaumaris</td>
<td></td>
<td>Car park</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Power Avenue</td>
<td>55</td>
<td>993.1</td>
<td>5.5</td>
<td>5.5</td>
<td>Juncus amabilis</td>
<td>Tiered design with steep gradient 2 surcharge inlets 1 overflow pit</td>
</tr>
<tr>
<td></td>
<td>Hawthorn</td>
<td></td>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cremorne street</td>
<td>18.4</td>
<td>245.8</td>
<td>7.5</td>
<td>9.5</td>
<td>Gahnia sieberiana, Carex gaudichaudiana</td>
<td>1 curb cut inlet 2 overflow pits</td>
</tr>
<tr>
<td></td>
<td>Richmond</td>
<td></td>
<td>Commercial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Hambledon road</td>
<td>99.1</td>
<td>1630.2</td>
<td>6.1</td>
<td>1</td>
<td>Juncus flavidus, Ficinia nodosa, Dianella longifolia</td>
<td>Multiple inlets - 1 PVC pipe inlet and 4 surcharge pits 1 overflow pit</td>
</tr>
<tr>
<td></td>
<td>Hawthorn</td>
<td></td>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The height from the soil surface to the rim was measured at four locations to obtained an average depth of insertion, \(d\). The ring was ponded to a height, \(H\), and maintained for 20 minutes, which is sufficiently long for an equilibrium infiltration rate to be attained in sandy soils (Elrick et al., 1990). The ponded water was also measured at four locations to obtain an average \(H\). After 20 mins, the inflow volume, \(Q_s\) was measured for 5 mins. A hose attached to a water drum sitting on a scale of 10 g accuracy was used to deliver water into the ring (Figure 3). The weight difference was converted into the inflow volume. This was repeated until the last 3 inflow volumes had a coefficient of variation (CV) of less than 3% to ensure a quasi-steady state flow has been achieved. Water temperature was also recorded at every measurement. For this work, the \(\alpha\) value was kept constant at 0.012 mm\(^{-1}\). This value corresponds to most structured soils from clay to clay loams, and also unstructured medium and fine sands and sandy loams (Elrick et al., 1989). This value is therefore suitable for the surface layer.

Figure 3 – Infiltration rate measurements at bare and vegetated positions

### 2.3 Soil sampling and Analysis

Once infiltration measurement was completed at each position, the ring was carefully removed and 3 soil samples (50g) were collected from the uppermost 3 cm. The soil samples were dried at 105\(^\circ\)C for 24 hours, dry sieved using a 2mm mesh size and a composite sample made.

Laser diffraction was used to measure the particle size distribution (PSD) using a Malvern Mastersizer 2000. As the organic matter content was generally small, based on Loss On Ignition (LOI) measurements of less than 0.5%, no treatment was applied to remove the organic matter prior to laser diffraction, a procedure also adopted by Loizeau et.al (1994).

Each composite sample was well mixed and a small subsample, of approximately 1 g, was transferred to the fluid module. The suspension was ultrasonically dispersed for 5 mins which is sufficiently long to achieve dispersion (Chappell, 1998). The particle refractive index was set at 1.58 (zeolite) and the Mie theory was used to estimate PSD (Malvern Worcs, 1999). Particle size distribution was expressed as particle diameter percentiles.

### 2.4 Statistical Analysis

\(K_{\text{sat}}\) measurements were corrected at 20.0 \(^\circ\)C using a viscosity correction factor (Constantz and Murphy, 1991). Statistical analysis was carried out with the R statistical package. \(K_{\text{sat}}\) data was tested for normal distribution using the quantile-quantile plot (QQ plot), and data for the two groups, vegetated and bare positions, were tested for equality of variance based on Levene’s homogeneity of variance Test.

Multilinear regression was carried between \(K_{\text{sat}}\) and particle diameter percentiles (d10 and d20) and age of raingarden. Particle diameter percentiles d10 and d20 were selected because they are more likely to be related to the deposited sediments than the original filter media (Dechesne et al., 2005), and therefore a good measure of clogging. Different combinations of the predictor variables were tested to assess their impact on the model.

Analysis of covariance (ANCOVA) was carried out on \(K_{\text{sat}}\) data with a categorical variable cover type representing vegetated or bare positions, and d20 as a covariate to test for significant difference between vegetated and bare positions. Finally, a multilinear regression was used to investigate the influence of distance and elevation relative to closest inlet on d20.
3 RESULTS AND DISCUSSION

Visual assessment of the surface condition at the raingarden sites, particularly at the sampling positions, found that the surface was generally free of cracks or biological clogging such as biomass and biofilms. Therefore, any clogging was likely to be physical due to sediment deposition.

Box plots of \( K_{SAT} \) measurements at each raingarden (Figure 4) show that the median values around plants are generally higher than on bare ground, although a significant difference by cover type was only detected at site 4 \((p=0.016)\) and site 5 \((p<0.001)\). In part, this lack of significant difference is explained by the high level of intra-site variability. Plants at site 4 were observed to be consistently more elevated than the surrounding bare areas. This is likely to be due to regular foot traffic in the raingarden by car park users resulting in greater compaction in bare areas, hence the much larger \( K_{SAT} \) for vegetated positions.

When \( K_{SAT} \) data is grouped together across all sites, mean \( K_{SAT} \) for vegetated positions and bare positions is 534 mm/hr and 392 mm/hr respectively. This difference is significant \((p=0.004)\) using a t-test. \( K_{SAT} \) data is also normally distributed and both groups have equal variance.

![Figure 4 – Box plot of \( K_{SAT} \) (mm/hr) by cover type at each raingarden](image)

Multiple linear regression on \( K_{SAT} \) data across all sites shows that a 2 parameter model with particle size diameter percentiles (\( d_{10} \) and \( d_{20} \)) results in an \( r^2 \) value of 0.43 (Table 2). This suggests therefore that the texture of the uppermost layer of the raingarden is moderately related to the measured infiltration rate. This observation is supported by several laboratory-based studies, which have found good correlation between infiltration rate and cumulative sediment inflow (Hatt et al., 2008, Houng and Davis, 2008). In this study, the relationship between surface texture and infiltration rate at the operational raingardens is likely to also be influenced by factors such as compaction from hydraulic loading and foot traffic, presence of plants and micro-organisms such as worms, as well as the presence of water repelling compounds such as motor oil. Nevertheless, metrics based on surface soil texture, such as \( d_{20} \) or a combination of \( d_{10} \) and \( d_{20} \), appear to be good indicators of the degree of surface clogging.

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{10} )</td>
<td>0.28</td>
</tr>
<tr>
<td>( d_{20} )</td>
<td>0.40</td>
</tr>
<tr>
<td>( d_{10} + d_{20} )</td>
<td>0.43</td>
</tr>
<tr>
<td>( d_{20} + d_{10} + Age )</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table 2 - Adjusted \( r^2 \) values for model with \( K_{SAT} \) as response variable and different combination of predictor variables (All regressions were significant, \( p<0.05 \))
ANOVA on $K_{\text{SAT}}$ data with d20 as a covariate shows a significant difference by cover type ($p<0.001$) as shown in Table 3. The same result is obtained when $K_{\text{SAT}}$ data from site 4 is excluded because of the possible difference in compaction between the two sampling positions. Based on the linear regressions intercepts in Figure 5a, the infiltration rates around plants is found to be higher than on bare ground by approximately 170 mm/hr, with a standard error of ± 120 mm/hr. Infiltration rates could therefore be at least 50 mm/hr higher around plants in raingardens constructed of a fine sandy media. Interestingly, this positive effect of plant cover appears to exist with various degrees of surface clogging, as suggested by the parallel regression lines in Figure 5a, and even when clogging is quite severe e.g when 20% of particles are less than 50 microns (d20<50).

However, the role of vegetation in mitigating the effect of clogging found here is not consistent with a laboratory study which found that Carex appresa, a monocot commonly used in raingardens in Australia, reduced the infiltration rate (Le Coustumer et al., 2012). This was hypothesised by the authors to be due to its fine root system blocking the filter media pores, but no empirical testing was undertaken to test this hypothesis. It is also possible that the laboratory study was not undertaken for a sufficiently long time to capture the effect of fine root senescence and turnover known to improve porosity over time (Archer et al., 2002).

<table>
<thead>
<tr>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>1</td>
<td>468016</td>
<td>468016</td>
<td>12.878</td>
</tr>
<tr>
<td>d20</td>
<td>1</td>
<td>2387612</td>
<td>2387612</td>
<td>65.698</td>
</tr>
<tr>
<td>Cover : d20</td>
<td>1</td>
<td>419</td>
<td>419</td>
<td>0.012</td>
</tr>
<tr>
<td>Residuals</td>
<td>79</td>
<td>2871017</td>
<td>36342</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5a - Plot of $K_{\text{SAT}}$ (mm/hr) versus d20 (microns) with regression lines for vegetated and bare positions ;
Figure 5b - Plot of d20 with distance from single piped inlet (m) for site 2 and site 3

Based on the observations above, we can hypothesise that preferential flow pathways exist around plants as a result of macropores created from such mechanisms as proposed in the conceptual model (Figure 1). Furthermore, these mechanisms are likely to exist in various degree of surface clogging. It is not possible to confirm in this study the exact mechanisms by which plants modify the infiltration rate, that is whether it is the influence of plant roots, stem/foliation movement or a combination of both. A dye tracing experiment will be conducted in the future to investigate the exact mechanisms responsible for preferential flow around plants.

The ANCOVA in Table 3 also confirms that the covariate d20 (the degree of clogging) has a significant effect on $K_{\text{SAT}}$ ($p<0.001$). $K_{\text{SAT}}$ is positively related to d20 (Figure 5a), which suggests, not surprisingly, that the infiltration rate decreases as the proportion of fine-grained sediments in the surface layer increases. Regarding the deposition of sediment within the raingardens, the spatial variability of d20 differs across sites (Figure 6). The regression with distance from closest inlet is significant only for site
2 (p<0.001, \(r^2 = 0.83\)) and site 3 (p=0.002, \(r^2 = 0.60\)). Therefore distance only explains the variability in d20 at these two sites, with greater deposition of particles occurring closer to the inlet (Figure 5b). Including elevation relative to closest inlet as a variable does not improve the \(r^2\) value for any site.

Site 2 and 3 are both around 5 years old and are relatively larger, with a single point source inlet (PVC pipe), unlike the other sites which have multiple inlets or a diffused source such as site 4 where no curb is built along one edge of the raingarden. Therefore, it seems that the single inlet and longer flow path within these two raingardens promote sediment deposition with distance. The relationship between sediment deposition and distance is stronger at site 2 than site 3. This may be due to the tiered design of site 2, which allows ponding in the first zone closest to the inlet before overflow into the second zone and so on. This design element is likely to promote deposition with distance. Site 2 also has a much larger variability in d20 (CV=64%) compared to site 3 (24%), as shown in Figure 6. This may be due to the fact that site 3, unlike site 2, has a layer of top soil above the sandy filter media, which has a much finer composition and is closer to the PSD of the fine-grained sediments in the incoming runoff.

Site 6 was 10 years old, and although it has a single curb cut inlet, it has an even distribution of very fine-grained sediment (d20<50 microns) across the raingarden’s surface (Figure 6). Therefore the importance of distance on sediment deposition may decrease with age, as enough sediments become spread over the entire surface to reduce overall permeability. Site 7 is only 1 year old which explains why there is no evidence of fine-grained sediment deposition (d20 equals 220 microns) across the entire surface. Site 1, 4 and 5 display large variability in d20 (Figure 6), however neither distance nor elevation explains this variability. The lack of significant regression may be due to the limited sampling positions per site.

It seems therefore that distance from the inlet is important in controlling sediment deposition within a raingarden, particularly when there is a single source inlet and a relatively long flow path from the inlet to overflow pit. This combination of design elements tends to promote sediment deposition closer to the inlet, which may have been responsible for similar observation at sites by Asleson et.al (2009). A tiered design as at site 2 would further help to promote sedimentation closer to the inlet. On the other hand, a distributed inlet system such as site 7 would evenly distribute the infiltrating volume, and therefore sediment deposition over the entire raingarden surface. However, with increasing years of operation, it is expected that the importance of distance in controlling sediment deposition becomes less important as the surface texture becomes homogeneous over the entire raingarden. Elevation relative to inlet does not control the sediment deposition process at the field sites in this study but this is because most sites are flat. However, it is expected that raingardens with an uneven topography could influence the sediment deposition process.
CONCLUSION

This work has important implications for design and maintenance of raingardens. Firstly, it supports the early suggestions that incorporation of vegetation can help to maintain media filter permeability. We have found that infiltration rates around plants are at least 50 mm/hr higher in raingardens constructed of a fine sandy media, even when the degree of surface clogging is quite severe (e.g. d20<50 microns). There should thus be consideration of using vegetation, at least in parts of these systems, to increase their longevity. It is also important to avoid foot traffic within raingardens to minimise compaction of the filter media, which can be achieved by planting arrangement e.g larger plants located on the outside perimeter, or by fencing.

Pre-treatment of runoff for fine-grained sediments is preferable (e.g sediment traps) but where this is not possible, maintenance of raingardens should consider scraping the surface clogging layer. Hatt et.al (2008) recommends that the top 2-5 cm is scraped off every 2 years, a periodicity supported by this field evaluation. It is also apparent that the configuration of the inlet will influence the spatial deposition of fine-grained sediments from the incoming runoff, and that sediments will accumulate most quickly in the areas closest to the inlet when there is a single source inlet. A partitioned maintenance regime may thus be appropriate, where the inlet zone and surrounds have regular sediment removal. To facilitate such a stratified maintenance regime, the inlet area and immediate surrounds may be kept free of vegetation and configured to allow easy sediment scraping and removal.
LIST OF REFERENCES


