PERMEABILITY OF RAINGARDENS – FIELD MEASUREMENTS AND OBSERVATIONS IN AUCKLAND

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ABSTRACT

The aim of this research was to assess the hydraulic performance of raingardens over time. Six Auckland raingardens were selected for permeability testing using a double-ring infiltrometer, based on the availability of historical data. Additionally, the state of maintenance and factors affecting the performance were assessed.

Raingardens, or bioretention cells (BRCs), are a popular Water Sensitive Design practice for at-source pollution control and have been used in Auckland for the last decade and a half. The Proposed Auckland Unitary Plan should result in a large-scale implementation of this practice, particularly in greenfield sites and along high contaminant-generating roads. To date, most BRCs in Auckland have been designed to be consistent with TP10 (Auckland Regional Council 2003) regulations. This specifies a minimum permeability of 12.5 mm/hr with no upper permeability limit, and a clay content up to 25%. However, post-construction monitoring of long-term permeability has been conducted at very few sites. Infiltration rate is a primary determinant of performance, as it controls the volume of stormwater treated. Permeability can also influence the effectiveness of some contaminant removal processes.

Half the BRCs had infiltration rates above the minimum permeability requirements. Prolonged periods of ponding, bypass flows, and variations in permeability over time were observed. Plant health and weed composition varied. Maintenance did not conform with guidelines at most sites, evidenced by, for example, blocked inlets and the absence of a mulch layer. The research shows that, whilst BRCs can be both an effective stormwater treatment device and provide aesthetic amenity, proactive monitoring and maintenance is needed to ensure that this outcome is realised.

KEYWORDS

Bioretention, Permeability, Hydraulic Conductivity, Maintenance, Water Sensitive Design

PRESENTER PROFILE

Ruben Roelofs is currently writing his Master's Thesis as a trainee at NIWA. Being passionate about the urban environment and freshwater ecosystems, he has focused his projects on Water Sensitive Design and the rehabilitation of polluted freshwater bodies.

1 INTRODUCTION

Raingardens, or bioretention cells (BRCs) have been implemented in the Auckland region for well over a decade. The Proposed Auckland Unitary Plan "[…] emphasises the reduction and management of contaminants at source" (Auckland Council 2013). Greenfield developments and major redevelopments should therefore have water sensitive design and green infrastructure at the core of their stormwater management.

A limited number of studies have been carried out in the past to assess the permeability of BRCs in Auckland, and no ongoing monitoring programmes have been reported. Auckland BRCs have generally been designed to confirm to TP10 (Auckland Regional Council 2003) which specifies a minimum permeability of 12.5 mm/hr and allows up to 25% clay content. Media with high clay content are highly vulnerable to compaction, and this vulnerability is enhanced at high moisture contents (consistent with low permeability). An early glasshouse study showed that a TP10-compliant media constructed with North Shore silt and clay-rich soils, amended with sand and subjected to a weekly simulated rain event over 6 months, resulted in a markedly reduced permeability. Additionally field trial of a broadly similar media on the North Shore also showed marked reduction in permeability over 2 years (Trowsdale & Simcock 2011).

If the hydraulic conductivity is below design rates, BRCs treat a smaller volume than intended, with the excess polluted stormwater bypassing the system. Low permeability can also impact plant growth and survival. On the other hand, if permeability is well above design rates, treatment quality might be impaired. This research therefore focuses on permeability of BRCs over time, by assessing the hydraulic performance of BRC systems in the field, and the potential causes of change in performance.

1.1 UNIVERSAL URBAN STORMWATER CHALLENGES

Urban stormwater challenges concern both water quantity and quality. Urbanisation causes an increase in peak runoff velocity and a decrease in lag time as a result of increased impervious surface area and efficient connections to surface waters (Arnold & Gibbons 1996; Ferguson 1998; Leopold 1968). The urban hydrograph is therefore characterised by large, sharp peaks, with low baseflow in between (Ferguson & Suckling 1990).

Stormwater quality can be poor in urban areas, as it picks up coarse litter, sediment, microbes, heavy metals, and nutrients along its flow path. The receiving water bodies are impacted by receiving these environmental contaminants, being a leading cause of habitat and water quality impairment (Novotny & Olem 1994; Walsh 2000). Suspended matter impacts water ecology by reducing light and water clarity, and non-degradable heavy metals build up over time, accumulating and affecting organism health through bioconcentration and bioaccumulation (Geffard et al. 2007; Hannah 2015; Moss 2014). A wide range of sources contribute to the contamination, such as construction activities, traffic, and wear and tear from roofs and road surfaces (Förster 1996; Shamseldin 2011; Zanders 2005).

Urban stormwater runoff can also affect stream temperature through thermal loading (Hathaway et al. 2016; Herb et al. 2008). For an Auckland case study see Afoa et al. (2013). The warmer temperature of stormwater runoff combined with contaminants, a decrease in dissolved oxygen and sometimes an increase in contaminant toxicity can negatively impact egg development, metabolism, resistance to disease and parasites, migration, spawning habits, and survival of aquatic animals (Armour 1991; Beschta et al. 1987; Caissie 2006; Hokanson et al. 1977).

1.2 BIORETENTION CELLS

BRCs are an internationally popular measure to tackle the urban stormwater challenges, as they can often be easily integrated into the existing landscaping at 1 to 8% of a catchment area (Davis et al. 2009). The main principle behind BRCs is the use of natural processes to filter and remove pollutants from stormwater runoff, and thereby protect downstream ecology. BRC cells can be sized to create buffer storage, decrease hydrograph peaks by delaying and reducing flow, reduce thermal loading, and enhance exfiltration into groundwater. The natural processes of pollutant removal are diverse and complex. Efficiency varies with the local conditions and design parameters such as filter media composition, media and rooting depth, surface area, ponding depth, device volume, vegetation and underdrain configuration (Davis et al. 2009).

A typical Auckland BRC has an external boundary, e.g. a liner or a concrete vault, defined inlets, an overflow, a drainage layer topped with a sandy protection layer, soil filter media, a mulch layer, and vegetation. Depending on the local conditions and purpose, an underdrain and impermeable base may or may not be present. When possible, one or more external boundaries are left out to promote exfiltration. Typically, the footprint of a BRC is around 3% of the impervious catchment area, but this can be higher or lower depending on the treatment volume and quality target, ponding depth, and the assumed hydraulic conductivity of the media (Couling & Stone 2016; Fassman et al. 2013).

1.3 PERMEABILITY AND CLOGGING

Permeability of BRCs is expressed in saturated hydraulic conductivity (K_s). Within BRC guidelines and literature, the terms permeability, hydraulic conductivity (K), and saturated hydraulic conductivity are sometimes used interchangeably. Saturated hydraulic conductivity can be universally compared without the need to specify a hydraulic gradient. Values of saturated hydraulic conductivity measured in the field are sometimes referred to as K_{fs}. They should be reported with a specific ‘head’ (depth of water) where a constant head is maintained, or the depths of water over which the test is performed (for a falling head test). Permeability is often derived from surface-infiltration based tests, such as a ring infiltrometer test. Thin films or seals, or crusting of the surface can greatly impact the infiltration rate, and thereby the permeability outcome of the test. These restrictive layers cause reduced biofiltration efficiency, whilst the underlying filter media may have adequate permeability.

Local guidelines specify a permeability range for the filter media. Hydraulic conductivity of a filter media is subject to its particle size distribution (PSD), porosity, grain angularity, degree of compaction, and organic component (Bell 1998). During the BRC construction, and shortly after, the hydraulic conductivity and infiltration rate of the filter media typically declines due to settling of the media, compaction from hydraulic loading, and formation of surface crusts. Additionally, incorrect construction and use of materials is noted as an important factor impairing bioretention performance (Ansen & Healy 2010).

Inflow of sediments is a main cause of clogging (Le Coustumer et al. 2012). Sediment particles carried by stormwater progressively accumulate at the surface interface of the filter media. If these particles are fine (e.g. silt or clay), this layer may have low permeability and clog the surface (Coulon et al. 2014; Siriwardene et al. 2007). BRCs that are relatively small compared to the catchment area are more prone to clogging than those of larger size, as small cells receive a higher load per area.

Using 125 biofiltration columns and 39 weeks of controlled loading, a linear relationship between K and the relative BRC size was established for BRCs sized ≥1% of the catchment area (Le Coustumer et al. 2008). Relatively smaller BRCs (<1% of the catchment area) had an exponentially lower K after the 39 weeks of testing. Additionally, increasing ponding depth will allow for more storage, but ponding is found to play an important role in compacting the sediment, further reducing surface porosity and K (Coulon et al. 2014).

The initial decline in hydraulic conductivity from settling, compaction, and clogging can be offset by plant growth (Le Coustumer et al. 2008; Limouzin et al. 2011). Vegetation with relatively coarse roots can increase the hydraulic conductivity. This theory is supported by the findings of Hatt et al. (2009), who found K recovery coinciding with vegetation growth. On the other hand, plants with thin and long roots may create a mat in the soil, causing a reduction of hydraulic conductivity (Archer et al. 2002).

Mulch, and possibly organic matter content, can play an important role in the prevention of clogging. Some mulch layers resist clogging as they trap stormwater sediments and reduce crusting, which essentially protects the filter media (Simcock & Dando 2013; Simcock et al. 2014). Organic matter can help maintain and improve the structure and hydraulic characteristics of a filter media (Emerson & Traver 2008). Organic matter also supports plant growth and attenuation of some contaminants (at least in the short term) (Fassman et al. 2012).

Heavy loading of fine sediments and/or a lack of vegetation cover with a permeability-promoting root system will result in clogging. Periodic maintenance of the mulch and replacement of the top filter media layer can remediate such degraded performance (Brown & Hunt 2012; Simcock & Dando 2013).

1.4 AUCKLAND CASE STUDY

1.4.1 DESIGN GUIDELINES

The Auckland region has multiple design manuals for BRC practice as a result of the merger between the regional council and five local councils, forming the Auckland Council in 2010. Technical Publication 10 (Auckland Regional Council 2003) (TP10) was the core standard. The North Shore City Council and Waitakere City Council created design guidelines specific for their local catchment characteristics (Malcolm & Lewis 2008; Waitakere City Council 2004). The North Shore City Council (NSCC) required a minimum permeability (saturated hydraulic conductivity) of 50 mm/hr versus 12.5 mm/hr for the TP10 (2003).

Since TP10, unpublished design guidelines associated with General Guidance 01 (GD01) have increased minimum K to 50, 100 or 160 mm/hr (Table 1). The Auckland Unitary Plan however continues to refer to TP10 guidelines, as GD01 for BRCs remains in development (November 2016).

Table 1: Permeability and organic matter specifications in local guidelines

Report	Min. K_s (mm/hr)	Suggested K_s (mm/hr)	Max. K_s (mm/hr)	Organic content (% w/w)
TP10 (2003)	12.5	-	-	-
NSCC (2008)	50	50-300	300	10-30
Unpublished draft (2010)	60	100-300	-	1.5-3
Unpublished draft (2011)	12.5	>160	400	-

1.4.2 MAINTENANCE

A 2010 Stormwater NZ Conference paper noted that experience showed many stormwater treatment devices were not functioning correctly due to poor design, inappropriate construction methodologies, or insufficient maintenance (Ansen & Healy 2010). TP10 (2003), focused primarily on the design, is supported by the later released technical reports on construction and maintenance, namely TR2010/052 and TR2010/053, (Healy et al. 2010). For maintenance, TP10 notes:

> "[…] maintenance is primarily concerned with:
> - Maintenance of flow to and through the biofilter
> - Maintaining planted vegetation and preventing undesired overgrowth vegetation from taking over the area
> - Removal of accumulated sediments
> - Debris removal
>
> […] Maintenance includes fertilising plants, removing noxious plants or weeds, re-establishing plants that die and maintaining mulch cover. […] Sediments accumulate in rain gardens and their removal may be the most expensive aspect of rain garden maintenance. Removal should occur when surface ponding lasts significantly longer than the one day drain time, which indicates surface clogging. […] Similar to other types of practices, debris removal is an ongoing maintenance function at all rain garden systems. Debris, if not removed, can block inlets or outlets, and can be unsightly if located in a visible location. Inspection and removal of debris should be done on a monthly basis, with debris also removed whenever it is observed on site."

TP10 (2003) and Healey (2010) indicate that a BRC should meet the following conditions:

- a mulch layer that covers the whole cell (TP10), until full vegetation cover is achieved (Healey);
- no dead plants, no domination of weeds or noxious plants;
- no prolonged ponding (well over a day after storm event);
- a permeability of ≥12.5 mm/hr; and
- inlets and outlets that are free of debris.

The Waitakere City Council (2004) has a short section on maintenance and notes to "check vegetation condition" and "check for overflow due to clogging" every six months. Maintenance actions are to "Prune, clear excess vegetation, and irrigate" as required, and to "Remove accumulated sediments" every five years.

The North Shore City Bioretention Guidelines (2008) recommends annual re-mulching to maintain a 50 and 75 mm-deep layer and notes that harvesting and pruning of excess or diseased growth vegetation needs to happen as for any garden area. Further, the top 100 mm of soil and mulch should be scraped off and replaced every five years. The guidelines suggest that clogging may be corrected by skimming off the top 50 mm of the media and re-establishing the mulch layer.

1.4.3 BIORETENTION CELL SELECTION

Six BRCs were selected for testing, of which five had historic data that indicated the cells met the minimum permeability requirements for TP10. The data is summarised in Table 4.

Table 4: Available historical data, either mean permeability, range of permeability or range of infiltration rates.

Location (year of installation), Coordinates	**Historical Permeability Data**		
Olympic Park (~2010) 36° 54' 38.0" S 174° 41' 25.0" E	K_{fs}: ~50 mm/hr (2010)[a] (calculated from percolation rate)		
Albany Centre (2006) 36° 43' 24.0" S 174° 42' 41.7" E	K_{fs}: 155 mm/hr (2010)[b] (infiltration rate)		
Paul Matthews (2006) 36° 45' 2.0" S 174° 42' 36.6" E	K_{fs}: 25 mm/hr (2009)[c]	K_{fs}: 139 mm/hr (2008)[c]	K_{fs}: 120 mm/hr (2007)[d]
Waitakere Vehicle Testing Station (2000) 36° 51' 54.6" S 174° 37' 57.7" E	K_{fs}: 80-100 mm/hr (2010)[e]	K_{fs}: 50-100 mm/hr (2006)[e]	
Wynyard Quarter (2011) 36° 50' 25.1" S 174° 45' 16.5" E	2800 – 3900 mm/hr (2015)[f] (infiltration rate)	2300 -6000 mm/hr (2012)[f] (infiltration rate)	
Rangitoto College (<2006) 36° 44' 10.8" S 174° 44' 13.2" E	n/a		

[a] Jayaratne et al. (2010), [b] Torbati (2010), [c] *Correspondence with Landcare Research (2016),* [d] Trowsdale (2008), [e] Skeen et al. (2010), [f] Simcock & Fassman-Beck (2016).

2 METHODS

2.1 DOUBLE RING INFILTROMETER

Double ring infiltrometers (DRIs) were used to assess permeability. The DRIs had a 100 mm diameter inner ring, and 300 mm diameter outer ring. Rings were inserted into the BRC media to 75 mm depth, which is within the suggested range of 50-150 mm (Lai et al. 2012). The ponding depth (head) was kept at 10 mm, within the range described by most methods (Angulo-Jaramillo et al. 2016). Prior to the test, the outer ring was placed and filled with water. The soil was then inundated for 60 minutes, with the aim to create saturated conditions for the test and to obtain a stable infiltration rate relatively shortly after the test had started.

Since the objective was to establish how the bulk of the cell is behaving, the following test routine was used:

- The test locations are spread evenly over the call area.
- At least three test locations per unit, or one every ~30 m^2 for units larger than 100 m^2.
- No test location closer than 0.5 m to the inlet or outlet of the cell.

Two methods were chosen to establish K_s from the infiltration data. The Philip's two-term equation (Philip 1957) and Reynolds and Elrick's relationship were used as described in Angulo-jaramillo et al. (2016). The average of both methods and all test locations was taken to establish the permeability of the whole cell.

2.2 PARTICLE SIZE DISTRIBUTION

For the particle size distribution (PSD) analysis, ~150 g of oven-dry sample was taken and prepared for a dry sieve analysis. The finest sieve available in-house was a 54 µm sieve, which is at the boundary between very fine sand and fines (silt and clay). As there was no hydrometer available, this was the smallest particle size that could be determined in the lab. The sieve mesh sizes were chosen to represent the fractions mentioned in the 2010 draft guidelines as closely as possible:

Table 5: Sieve setup for dry sieve analysis

Sieve mesh size [mm]	**Sieve no.**	**Representative particle size classification**	
2	10	> 2 mm	Gravel
1	18	1 - 2 mm	Very coarse sand
0.5	35	0.5 - 1 mm	Coarse sand
0.25	60	0.25 - 0.5 mm	Medium sand
0.15	100	0.1 - 0.25 mm	Fine sand
0.054	270	0.05 - 0.1 mm	Very fine sand
Bottom tray		< 0.05 mm	Silt and clay (fines)

A mechanical shaker was used for 20 minutes, after which the content in each sieve is weighed. The results are presented in a particle size distribution curve.

2.3 FIELD OBSERVATIONS

A field worksheet recorded observations relevant to the hydraulic performance and the maintenance state of the cell. These following aspects were assessed:

Catchment related:

- Land use
- Presence of green (grass, trees, shrubs, deciduous / evergreen)
- Cleanliness of catchment (inflow of mineral and organic matter)

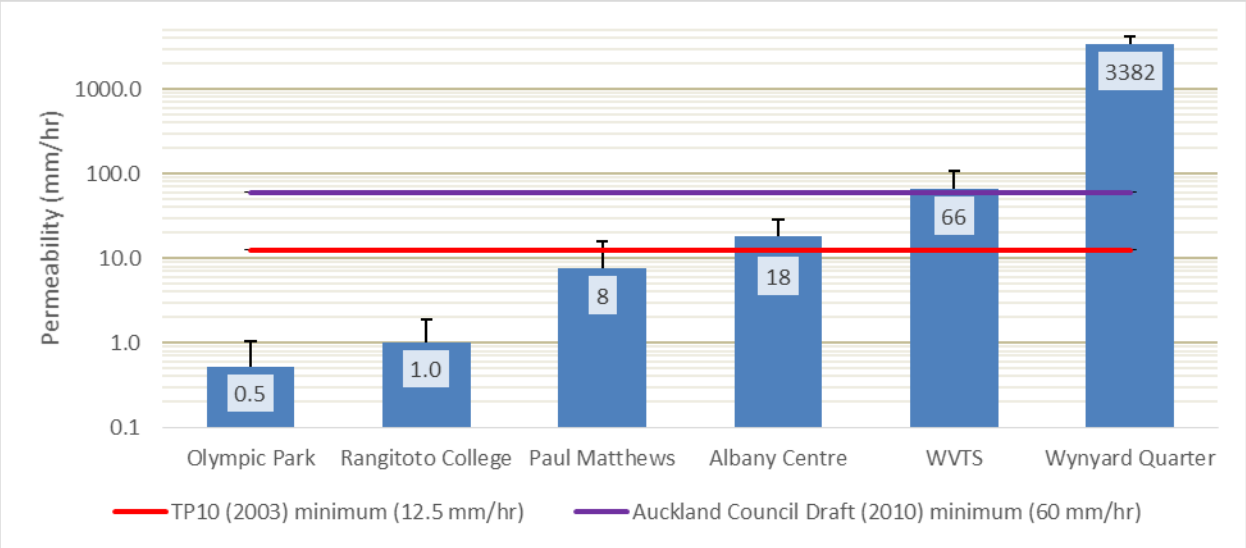
Cell related:

- Ponding depth
- Signs of unintentional bypassing
- Clogging of in- and/or outlet
- Vegetation health and coverage
- Coverage and thickness of mulch layer
- Signs of flow restricting layers, clogging, and endured ponding

3 RESULTS

3.1 PERMEABILITY

Figure 1: Average permeability value derived from infiltration, error bars indicate standard deviation



The results in Figure 1 show that three out of the six assessed BRCs had a mean permeability exceeding the minimum TP10 (2003) specification of 12.5 mm/hr. Two cells had parts that were above and below the specification, and two cells had no recorded areas above 12.5 mm/hr. Note that the vertical axis has a logarithmic scale.

3.2 PARTICLE SIZE DISTRIBUTION

Figure 2: Particle size distribution of the top layer (0-20 mm)

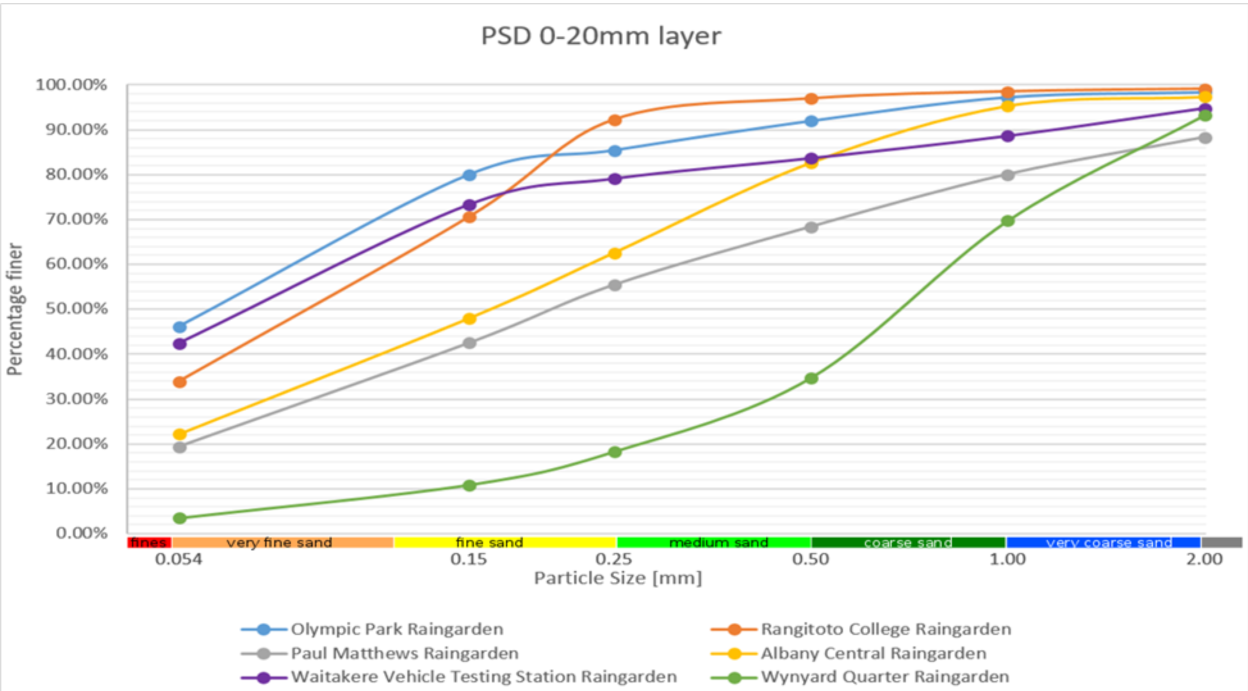
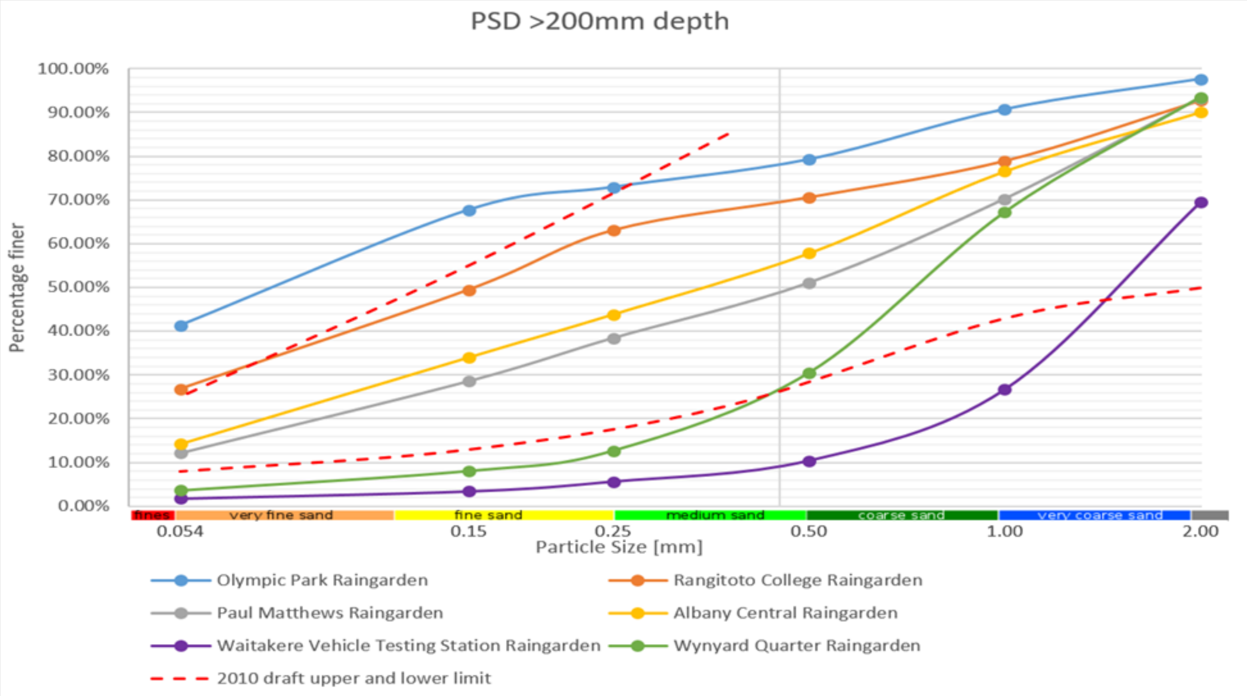


Figure 3: Particle size distribution of the filter media layer (>200 mm)



Figures 2 and 3 show the particle size distribution curves of the top layer and the filter media. The relatively fine media (e.g. Olympic Park) is positioned higher in the curve, whereas the coarser media are found below (e.g. Wynyard Quarter).

Figure 4: Permeability versus the weight percentage of fines at 0-20 mm and >200 mm depth. Fines (silt and clay) are defined as particles passing through 0.054 mm (54 µm) sieve.

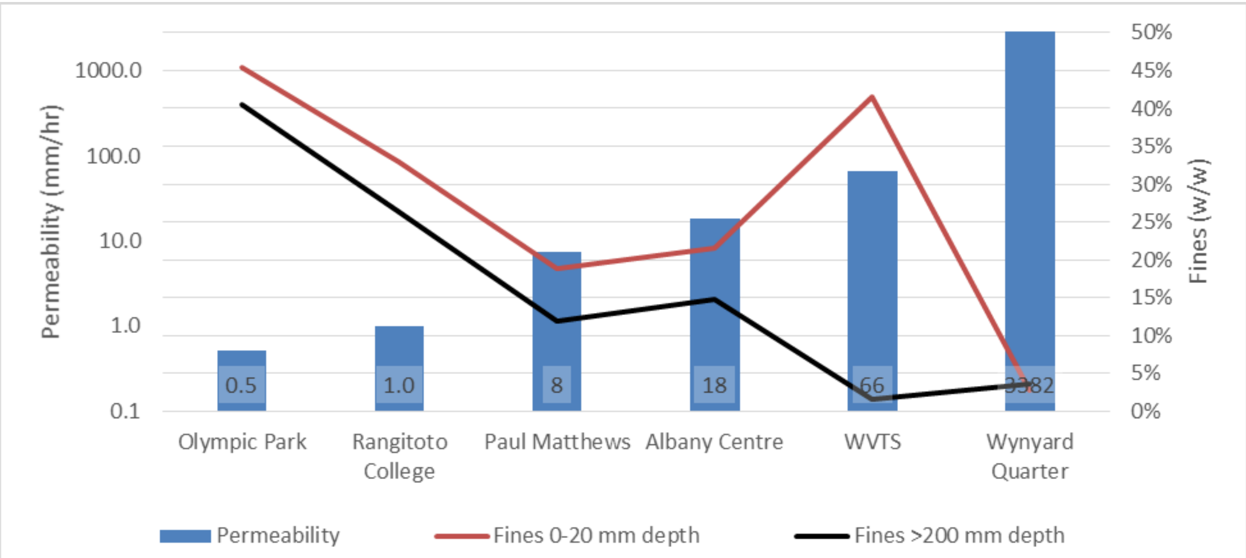


Figure 4 shows the content of fine particles in the top layer (0-20 mm depth) and filter media layer (>200 mm depth). As expected, the top layer had a higher content of fines, due to the inflow of sediments. Wynyard Quarter has a very low proportion of fines in both sediment and underlying media. Lower content of fines in the filter media generally corresponded with higher permeability.

3.3 OBSERVATIONS

The table below describes the most notable observations from the field work. The observations are categorised relating to the cell's catchment, the measured ponding depth and the state of the cell itself.

Olympic Park
• Catchment: High intensity road in area with commercial and low density residential land use. Some silt, sand, and gravel from the road catchment. High inflow of OM (mainly leaves and twigs) from trees, shrubs and grass clippings. • Average ponding depth: 33 cm • Cell: Planted with *Apodasmia similis* (Oioi), healthy and growing, first cell out of three had about double the vegetation density of the two lower ones. First cell was clearly enduring prolonged inundation (standing water and algae observed (70 m^2 / 39% of cell area)). The two lower cells were overgrown with weeds. Organic mulch layer was mostly degraded, present in patches around the edge of the cell (0-1 cm). Scour and erosion visible at the overflows. Signs of hydraulic failure at the overflows towards the subsequent cells, where filter media was flushed away.

Rangitoto College
• Catchment: High intensity road in area with low density residential land use. Inflow of silts, sand, and gravel from the road catchment. Little inflow of OM. • Average ponding depth: n/a (overflow at media level) • Cell: Various plants and shrubs, mainly healthy, few weeds. Some dead grasses. Inlet was recently maintained, but excavated silts and gravels deposited inside the cell. Organic mulch near the outlet (0-5 cm). Other areas of the cell without a mulch layer.

Paul Matthews
• Catchment: High intensity road in area with industrial and commercial land use. Very high inflow of silts, sand, and gravel from nearby industrial activity. Little inflow of OM. • Average ponding depth: 12 cm (design: 22 cm) • Cell: Planted with Oioi, healthy, although some dead leaves. Bare areas near the inlets and on the preferential flow path. Organic mulch was fully decomposed. Prolonged inundation indicated by standing water, algae and duckweed (36 m^2 / 18% of cell area). Thick sediment layer observed (1-20 cm), mainly gravels near the inlets, and finer particles on the outer edges. Two of the three inlets were clogged with solids and litter and erosion indicated unintentional bypass flow in some events.

Albany Centre
• Catchment: Low intensity road in partially developed commercial area. The road catchment seems clean, with some inflow of silts, sand, and gravel, and little OM. • Average ponding depth: 43 cm (design: 30 cm) • Cell: Planted with *Cordyline australis* and *Carex secta*. Some dead *Carex secta* in the lower part of the cell leaving open areas. Inorganic mulch (pebble gravel), in good condition at the lower end of the cell, but buried with sediment towards the inlet.

Waitakere Vehicle Testing Station
• Catchment: Carpark and paved area. Little inflow of solids, mainly OM from the trees and shrubs directly surrounding the cell. • Ponding depth: 12-42 cm (two overflows at different heights, one overflow clogged) • Cell: Densely planted with *Phormium tenax* (Flax), healthy. Organic mulch was fully degraded. Energy dissipating rocks at the inlets have been displaced. Some dead plant material in the actual cell. Thin organic topsoil with high root mass, and pumice filter media below. The lower overflow seemed clogged, and the underdrain seemed clogged where it connects to the manhole.

Wynyard Quarter
• Catchment: Low intensity road in a partially developed commercial area (brownfield development). Clean catchment, with no signs of sediment inflow. The catchment area is relatively small compared to the size of the BRCs. • Average ponding depth: 8 cm • Cell: Densely planted with a variety of groundcover plants and trees (over 20 species of tree and groundcover species were used in the establishment of the raingardens). Vegetation seemed healthy and growing. Inorganic mulch layer (pea gravel) was present throughout the cell, with a thickness between 2-5 cm.

4 DISCUSSION

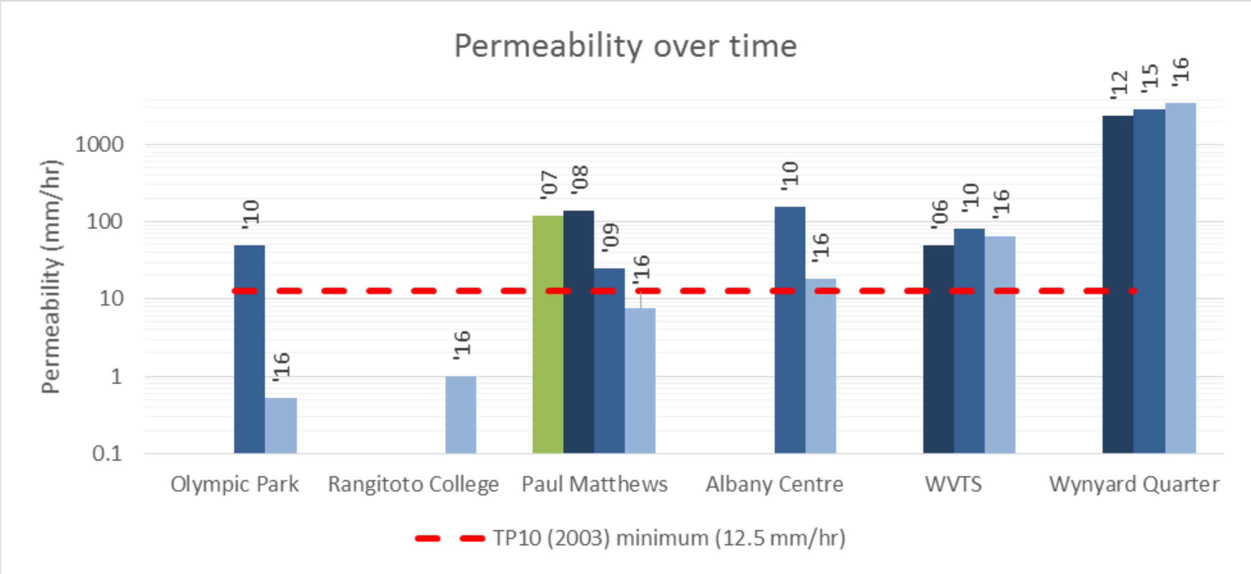
4.1 PERMEABILITY

As observed from Figure 5, three BRCs show a clear decrease in permeability over time, whereas the WVTS and Wynyard Quarter BRCs shows a stable permeability. Three BRCs do not meet the suggested TP10 minimum of 12.5 mm/hr; four do not meet the suggested North Shore City Council guideline permeability of 50 mm/hr. Note that the 50 mm/hr value came into force in 2008 and therefore does not operate retroactively on BRCs established prior to its release.

The case of WVTS, being the oldest of the BRCs, shows that increasing age is not necessarily connected with a decrease in permeability in the long term. The data shows that the permeability has been between 50 and 100 mm/hr for over a decade. The BRCs at Wynyard Quarter increased in permeability since their establishment, probably linked to vegetation development and little inflow of sediment (Simcock & Fassman-Beck 2016).

Over 6-7 years, permeability has decreased sharply at the Paul Matthews, Albany Centre, and Olympic Park BRCs. With a K_{fs} of 8 mm/hr, and 18% of the cell area practically impermeable, the performance of the Paul Matthews BRC is well below its 50 mm/hr target. The first of three sequential cells at Olympic Park has prolonged periods of ponding, with 39% of the total cell effectively non-functional, and the two following cells having an average K_{fs} of 0.5 mm/hr.

Figure 5: Change in permeability over time. Wynyard Quarter '12 and '15 data are minimum infiltration rates (mm/hr), closely resembling permeability. Sources in Table 4.



Field observations help explain the (change in) performance. WVTS and Wynyard Quarter have relatively clean catchments with low traffic intensities, and well established vegetation cover which seems to maintain or promote permeability. Coarse roots were abundant in the 0-20 mm layer. Perhaps importantly, these two BRCs are relatively large compared to their catchment (>4% of catchment area), lessening the rate of clogging. Although the BRC at Albany Centre was similar, it had reduced vegetation cover and root abundance in the 0-20 mm layer. The cell had received a significant inflow of sediments in the recent past. Ponding depth was measured to be 43 cm, whereas the original design value was 30 cm. This indicates compaction through settling may be the cause for the decline in permeability from well over 100 mm/hr to only 18 mm/hr.

The catchment of Paul Matthews is impacted from construction gravel and silts which have created a thick continuous sediment layer on top of the filter media. This observation is supported by the average ponding depth of 12 cm, compared with the 22 cm design and installation depth. Vegetation cover was lacking in some areas, but permeability was not found to be higher in parts with dense plant (Oioi) cover. In contrast, the catchment of Olympic Park did not seem to be especially dirty, and no continuous sediment layer was observed on top of the filter media. The plant cover (Oioi) was high in the first cell (which had prolonged inundation), but low in the two lower cells, overgrown with weeds.

The BRC at Rangitoto College had a patchy plant cover. Physical soil crusting was observed, which is known to reduce infiltration and can inhibit plant establishment (Belnap et al. 2001). The Rangitoto College cell was the only BRC tested that did not have any ponding depth. It is unclear whether this is per design or whether sediment has built up to the overflow level.

Overall, it should be noted that permeability measurements done shortly after the installation of a BRC may not be a useful indicator of performance of a cell on the long term. Performance can decrease rapidly, improve, or stabilise. Case-specific circumstances, such as relative cell size and cleanliness of the catchment, and the ability of plants to successfully establish in the years following the installation, will have a determining impact on the hydraulic performance.

4.2 PARTICLE SIZE DISTRIBUTION

The particle size distribution does include some permeability indicators and feedback for field observations. The weight percentage of fines in the 0-20 mm layer is strongly inversely correlated with permeability (r= -0.75). The two BRCs with the coarsest >200 mm layer are also the two with the highest permeability. However, the top layer at WVTS is likely to be restricting the flow, having over 40% fines in the 0-20 mm layer. Earlier research found that the filter media below the top layer has a permeability of 2000 mm/hr (Skeen et al. 2010). It is argued that the abundance of coarse roots in the upper layer results in that the permeability is still satisfactory and no further clogging over time is observed.

With 41% fines in the filter media, it is questionable whether the Olympic Park cell met TP10 requirements for clay content (<25%) during construction, and if it did, whether it could meet the 12.5 mm/hr permeability requirements. A double ring was inserted at 200 mm depth to compare to surface infiltration. After 40 minutes, no infiltration was observed, after which the experiment was stopped. Landcare Research provided data indicating that silt+clay weight percentage of the filter media was 60% shortly after establishment, having 22% clay. This does pose a question in terms of restorative approaches, as the filter media may be entirely unsuitable for bioretention purposes.

The Paul Matthews and Albany Centre BRC were both constructed in the same year, and have a PSD curve that closely match. Even though the Albany Centre BRC is relatively larger than Paul Matthews compared to its catchment, it has a higher weight percentage of fines. It is argued that at the Paul Matthews BRC, the coarse sediments found in its catchment offsets the weight percentage of fines. The loading of fines per area however, is likely to be higher than at the Albany Centre BRC. This results in more rapid clogging at the media interface, hence the lower permeability of the Paul Matthews BRC. This also follows the theory that the smaller the relative size of the cell, the more rapidly clogging occurs.

4.3 MAINTENANCE

Apart from the cell at Wynyard Quarter, all cells required some form of maintenance if TP10 guidelines were followed. Mulches were absent at Olympic Park, WVTS, Rangitoto College and Paul Matthews. Part of the inorganic mulch at Albany Centre was covered with sediment, at Rangitoto College accumulated sediments from the inlet were deposited into the cell, and the Paul Matthews cell had large areas with a thick layer of sediment.

Maintenance of a mulch layer may not be a fundamental part of BRC maintenance. Observations of these six BRCs indicate the necessity for mulch maintenance is case specific. BRCs with dirty catchments and/or a relatively small surface area would benefit from proactive removal of sediment and mulch layer maintenance, to prevent the cell from clogging. In other cases, establishing full plant cover with permeability-promoting vegetation can ensure long-term permeability without having to maintain the mulch layer. This does not imply that the mulch cover can be left out during the establishment of the BRC. The initial mulch layer helps plants establish, reduces the filter media drying out during plant establishment, and keeps weeds from competing with the selected plant cover.

In terms of planting, WVTS and Wynyard Quarter had extensive plant cover. Coarse roots were abundant in the 0-20 mm layer. The plants seemed proactively maintained, pruned, and dead growth removed on at least an annual basis. The Albany Centre cell had a sparser cover and dead sedges, but the *Cordyline australis* roots spread through most of the cell. Paul Matthews had dense *Adpodasmia similis* cover over about half the BRC. The Olympic Park cells had variable *Apodasmia* cover with some cells overgrown with weeds. Finally, the Rangitoto College cell had relatively low plant cover.

4.4 REMEDIATION

The North Shore City Council guidelines (2008) state that the top 100 mm of soil and mulch should be scraped off and replaced in the entire raingarden every five years. If this policy was carried out on the WVTS or Wynyard quarter BRC, irreparable damage would be done to the extensive plant cover, which would have to be re-established. Considering the good permeability of the cells and the condition of the plants, it would be a substantial waste of resources.

The guidelines also suggest skimming off the top 50 mm of the media in the case of prolonged ponding. Research by Brown and Hunt (2012) has shown that this method can be very effective, where two field studies reported an infiltration rate increase by up to a factor of 10 after the top 75 mm of the media was removed. However, the gains of this procedure will be case-specific and dependent on the permeability of the filter media below. It is important to identify why the cell clogged in the first place. If the causes of the cell clogging are not assessed and resolved, it seems likely that the long-term outcome will be a repetition of the identified problem: an underperforming cell.

The high percentage of fines in the filter media at the Olympic Park BRC, and the densely-aggregated media at the Rangitoto cell make it questionable if removing and replacing the surface 50 mm would be effective at improving permeability. Full replacement of the media is costly, but may be the only measure to achieve the stormwater treatment objectives in some remediation cases. Alternatively, research could be done into remediation through increased, permeability-promoting vegetation cover. The Olympic Park and Rangitoto College BRCs would make excellent case studies for this.

5 CONCLUSIONS

The results show that three out of six raingardens meet the minimum permeability requirement of 12.5 mm/hr. Over time, permeability remained stable for two BRCs, and sharply decreased for three BRCs. Observations in the field often helped in explaining these findings. Vegetation health and cover, root abundance in the 0-20 mm layer, and cleanliness of the catchment often backed up the test results.

The particle size distribution analysis can give additional feedback and a deeper understanding of field observations and permeability measurements. Weight percentage of fines in the 0-20 mm layer was strongly inversely correlated with permeability. A low weight percentage of fines (<5%) and fine sand in the filter media (measured at >200 mm depth) corresponded with good permeability.

Vegetation cover that promotes permeability has the potential to offset the negative effects of clogging from sediment and keep a BRC at desired permeability levels in the long term. This was observed at the Waitakere Vehicle Testing Station cell, where extensive flax cover with coarse roots in the 0-20 mm layer offset the negative effect of a high weight percentage of fines in the top layer.

Maintenance only met local guidelines at Wynyard Quarter BRC. Extended periods of ponding at the Paul Matthews and Olympic Park cells, the low permeability of the Paul Matthews, Olympic Park, and Rangitoto cells, and the clogged inlets at the Paul Matthews cell are considered the most pressing issues negatively affecting the volume of stormwater treated. The broad variability in raingarden designs and catchment types means a one-size-fits-all approach to maintenance could result in the asset not achieving its full potential.

The results suggest that cells receiving heavy sediment loading, due to their relative size or the catchment characteristics, need proactive maintenance to prevent clogging, e.g. by removing sediment and/or maintaining the mulch layer. In larger cells (e.g. >4% relative to catchment) and/or cells with a clean catchment, establishing full permeability-promoting vegetation cover can ensure satisfactory permeability on the long-term. This suggests that, compared to small or heavy loaded devices, larger BRCs would need less maintenance once full plant cover is achieved. An important condition is that the filter media itself can achieve the required hydraulic conductivity, which is possibly not the case at the Rangitoto College and Olympic Park BRC.

Six bioretention cells were randomly selected for testing based on the availability of historical data. Three cells did not meet the minimal permeability requirements. These requirements are at the basis of engineering and design calculations, put in place to achieve the desired volume of water treated. Results indicate that filter media that has particle size complying with TP10 may not achieve minimum permeability of 12.5 mm/hr on the long-term. If results of this small study are indicative of performance of similar devices across the Auckland region, there is reason for concern in terms of hydraulic performance and in achieving objectives for stormwater treatment.

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