EFFECTIVENESS OF BIORETENTION BASINS IN REMOVING POLLUTANTS FROM URBAN STORMWATER IN MANLY COUNCIL, SYDNEY

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ABSTRACT

A range of stormwater treatment techniques can be applied in urban areas to reduce pollutant loads in stormwater, and reduce stormwater volumes polluting the environment. Bioretention basins (also known as bio-filtration basins and raingardens) are a type of stormwater treatment device that mimics natural processes, reconnecting the built and natural environments. Interest, knowledge, and experience in the application of constructed bioretention basins is currently undergoing rapid growth in urban areas with increased emphasis on water sensitive urban design. This study aimed to estimate the effectiveness of bioretention systems in removing pollutants from urban stormwater, over a one-year period in the Manly Council area of Sydney. Sampling was undertaken at 10-15 minute intervals during rainfall events with stormwater samples collected and flow volumes measured both upstream and downstream of three bioretention basins. This enabled total load reduction to be estimated for pollutants total suspended solids and bacteria. Results indicate a high total suspended solids concentration reduction of 78%, and significant bacterial concentration reductions of 78% for faecal coliforms and 21% for enterococci. Our results suggest that bioretention basins are efficient at removing pollutants from stormwater, even with a small bioretention area to catchment ratio. This indicates that even in relatively space-constrained urban areas such as Sydney, significant potential exists for implementation of bioretention systems as one component of a well-planned stormwater treatment-train. For small ratio bioretention basins, the requirement for more frequent system maintenance, reduced lifetime of basin soil-media, and possible reduced hydraulic retention time may need to be considered.

INTRODUCTION

Urban Stormwater Pollution

Impervious surfaces in urbanised locations mean that a large percentage of rainfall cannot infiltrate into the soil and becomes runoff, mobilising deposited pollutants (Lee and Heaney, 2003). Pollutants commonly entrained in urban stormwater include suspended solids, nutrients, heavy metals and pathogenic bacteria. These pollutants are universally recognised to have detrimental impacts on aquatic environments, including smothering of benthic ecosystems, eutrophication, chronic toxicity, whilst pathogenic bacteria can cause risks to human health in recreational waterways (NSWEPA, 1997).

Sources of suspended solids include construction sites, residential gardens, and industrial activities. Sources of heavy metals include the weathering of paints, roofing, vehicle components and atmospheric deposition of industrial and vehicle exhausts (Davis et al., 2001). Sources of nutrients include gardens and fertiliser, while, sources of pathogenic bacteria includes faeces of domestic animals and birds and sewer leaks/overflows (Carroll et al. 2008).

Bioretention Systems as a Water Quality Improvement Tool

A range of stormwater quality improvement tools are available including gross pollutant traps, nets, booms, sand filters, sediment basins, vegetated swales, constructed wetlands, street sweeping, and source controls such as community education and regulation. Bioretention basins (also known as bio-filtration systems and raingardens) are a type of stormwater treatment device that mimics natural processes, reconnecting the built and natural environments. Bioretention basins contain a sand/soil/organic matter media with various reeds, grasses and shrubs. During rainfall events, stormwater drains into the bioretention media, and is vertically filtered through porous soil media, which removes pollutants through processes including filtration, adsorption and biological uptake (Heish et al., 2007). Interest, knowledge, and experience in the application of constructed bioretention basins is currently undergoing rapid growth in urban areas in south-east Queensland, Sydney, and Melbourne, with increased emphasis on water sensitive urban design.

This paper will be focusing on the removal of total suspended solids (TSS) and pathogenic bacteria by bioretention basins. The primary processes in bioretention systems for the removal of TSS and pathogenic bacteria are filtration and adsorption. Published results from previous bioretention studies have shown TSS removal to vary greatly, ranging from greater than 90% improvement to negative results (Hatt et al., 2009, Hunt et al., 2008, Line and Hunt, 2009, Hunt et al. 2005 and Hiesh and Davis, 2005). This disparity in bioretention efficiency is often caused by variations in age, structural design, media, catchment land uses and background stormwater TSS levels. Efficient bioretention basins are generally expected to reduce stormwater TSS concentrations by over 80% (Melbourne Water, 2005, Hatt et al., 2009).

Hunt et al. (2008) in a an extensive study of a large bioretention basin in North Carolina, USA, found TSS reduced by 60% from an average of 49.5 mg/L to 20 mg/L in runoff treated from a car park. It was also one of the few studies to monitor the bioretention basin's removal of faecal indicator bacteria. It found that faecal coliform concentrations were reduced by 69% and *E. coli* levels were reduced by 71%. Lab bioretention column studies have shown removal rates of faecal indicator bacteria to increase with less permeable soils, suggesting fine soil particles may physically remove faecal indicator bacteria by filtration and adsorption (Meschke and Sobsey, 2003).

Size Constraints on Bioretention Systems in Developed Urban Areas

In highly urbanised catchments, existing developments severely limit the placement and area available for stormwater treatment devices. Bioretention basins typically have a bioretention area to catchment ratio of 2%, which provides sufficient capacity for primary processes of filtration and adsorption, and provide sufficient capacity to treat design rainfall events without overloading (Melbourne Water, 2005). However, many developed urban city areas suffer from a lack of sufficient open space suitable for large bioretention basins. The design of the basins has accommodated this constraint by maximising the bioretention area in the available site and incorporating a media with a high hydraulic conductivity.

Given the opportunities for construction of new bioretention systems in existing urban areas, an important research question exists as to what the water quality improvement performance is in size constrained bioretention systems. This has implications for the decision by local government authorities to invest in the construction and establishment of bioretention systems in size constrained locations. The extremely large loads of suspended solids entering waterways and the potential public health risks caused by pathogenic bacteria makes these water quality parameters of particular concern to authorities in the Manly Local Government Area. The study results presented here show the effectiveness of three size-constrained bioretention basins in an urban area at removing total suspended solids and faecal indicator bacteria from stormwater.

METHODS

Study Site – Manly, NSW, Australia

Three bioretention basins were identified, which were draining developed residential catchments in the suburb of Balgowlah Heights. Balgowlah Heights is located in the Manly Local Government Area, about 12 km northwest of the Sydney CBD (Figure 1). All three basins were size-constrained and restricted to a very small bioretention area in relation to the catchment area (<1%). These basins were known respectively as Jellicoe St Basin, Beatty St Basin, and Tutus St Basin (Figure 2).

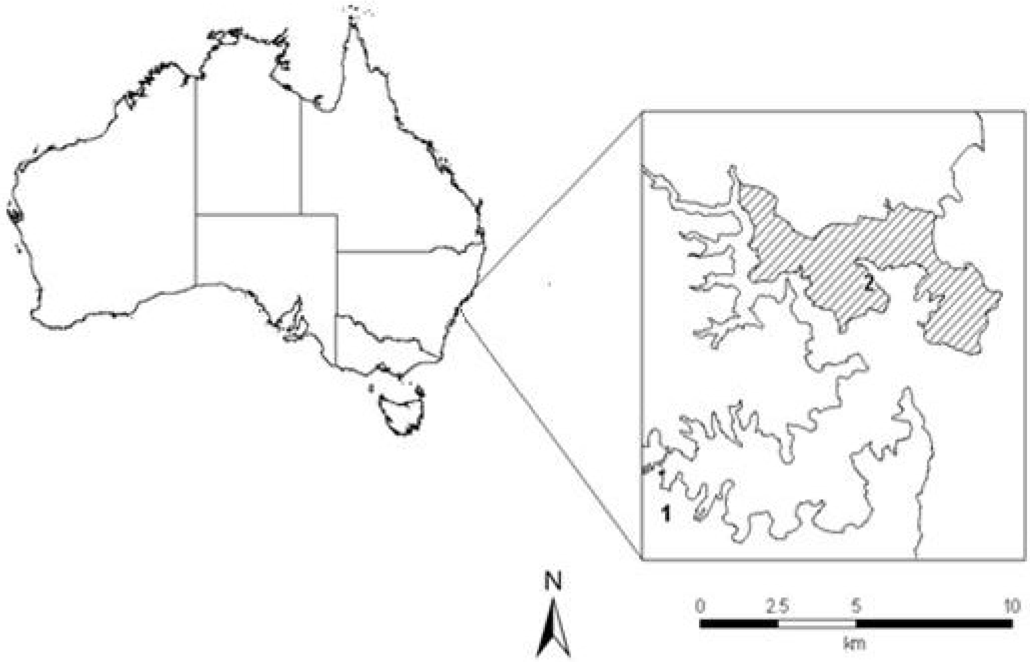

Figure 1: The studied bioretention basins are located in Balgowlah Heights, Sydney, Australia. Indent: Sydney Harbour, 1: Sydney CBD. 2: Location of the bioretention basins. Shaded area: Manly Local Government Area.

The Jellicoe St Basin was constructed in 2003 and treats an area of 5,000 m^2. The area of the bioretention basin is approximated 50 m^2 (1% of the catchment). The Beatty St Basin was constructed in 2006, it treats an area of 5,000 m^2 and has a bioretention area of 8 m^2 (0.16% of the catchment). The Tutus St Basin was constructed in 2007 and treats an area of 11,000 m^2. The bioretention area of the Tutus St basin is approximated 40 m^2 (0.36% of the catchment).

All three basins contain a dense growth of *Carex appressa* and *Juncas usitatus*. Dye testing of the basins found them to have an approximate retention time of 10-15 minutes.

Figure 2: Location of the studied bioretention basins and the catchment treated by each basin.

Figure 3: Top left – Beatty St Basin one year after construction. Top Right – Tutus St Basin two years after construction. Bottom – Jellicoe St Basin one year after construction.

Water Quality Monitoring

Water quality sampling of three bioretention basins was conducted during rainfall events between August 2009 and August 2010. In all rainfall events, only one bioretention basin was monitored during each event. Sampling was conducted by hand without the aid of an auto-sampler. The Australian Government Bureau of Meteorology Online Weather Watch Radar Network was used so that the sampler could arrive on site at the start of the rainfall event. Sampling could not be undertaken at night for safety reasons, therefore, when a rainfall event started over night; sampling would begin when the next day as soon as possible. Sampling continued throughout a rainfall event until it stopped raining or other constraints as exceeding number of bottles (generally after 3 to 3.5 hours of sampling). The event duration, sampling duration, antecedent period, and approximate rainfall of the sampled storms are shown in Table 1.

Total Suspended Solids samples were collected every 10-15 minutes starting at the inflow point of the bioretention basin, followed by the outflow, then again at the inflow, and so on. At each time interval, three replicate total suspended solids samples were taken and individually analysed. Clean 1.2L polyethylene bottles were rinsed 3 times with sample water before the collection of each sample. Each total suspended solids sample was analysed at the University of Technology, Sydney, using the standard method of vacuum filtration with glass fibre filter papers.

Faecal coliforms and enterococci samples were also collected every 10-15 minutes throughout certain rainfall events. However, only 1 sample was collected every 10-15minutes (rather than the 3 replicate collected at each time interval for TSS). Samples to be analysed for faecal coliforms and enterococci bacteria concentrations were collected in sterile 500ml polyethylene bottles and stored on ice. Samples were transported to a NATA accredited laboratory as soon as possible (within 12 hours) and bacteria were analysed using standard membrane filter procedures. Faecal coliforms and enterococci were chosen because of their extensive use in stormwater monitoring projects as an indicator of faecal contamination, which is a source of pathogenic bacteria. In total, TSS was sampled for 16 storms and faecal coliforms and enterococci bacteria were sampled in 7 of those storms.

Flow Volume Estimation

Flow was estimated every time a sample was collected (every 10-15 minutes) at the inflow and outflow of each bioretention basin. This was measured at all inflow and outflow sampling locations, except one, by measuring the time taken for the stormwater flows to fill to a container of known volume. From this flow rate was determined. At the Jellicoe inflow sampling location the container could not be used to capture the flow. Instead ruler measurement markings were drawn on the street gutter walls allowing the cross-sectional area of the water flow to be measured at the time of sampling. The area was then multiplied by the flow velocity, which was found by measuring the time taken for a buoyant object to travel a set distance without being impeded.

Event Mean Concentration Calculation

The event mean concentration (flow weighted concentration) at the inflow and outflow of each bioretention basin was calculated for each event using the flow estimations and TSS/enterococci/faecal coliform sample concentrations. Event loads are the event mean concentration multiplied by the stormwater volume (EPA, 1986). CEach rainfall event was also weighted according to flow volume in order to calculate the overall concentration reductions by each basin.

RESULTS

Observed Hydraulic Conductivity and Flow Characteristics

Total stormwater flow volume for the three bioretention basins decreased by an average of 18.6% from the inflow to the outflow (Table 2). This means that the bioretention basin or the local soil and groundwater absorbed a proportion of the stormwater flows. The heaviest of the monitored rainfall events usually resulted in little reductions in stormwater flow volume between the inflow and outflow. There were also minimal reductions in peak flow rates by the basins during heavy rainfall conditions, especially at the Tutus St and Beatty St Basins (Table 1). This implies the flood mitigation and peak flow reduction benefits seen in large bioretention basins are not being observed in the size-constrained Basins.

Water Quality Improvement Performance – Total Suspended Solids

Strong TSS concentration reductions were seen across all 3 bioretention basins with a 70.1% concentration reduction being observed at the Tutus St basin, 78.8% reduction at Beatty St and 73% reduction at Jellicoe St (Table 2). The difference in pollutant concentration between inflow samples and corresponding outflow samples is, not surprisingly, correlated to the initial pollutant concentration of the stormwater at the inflow. This suggests that if there is more pollution coming into the bioretention basin, more can be removed.

Figures 5 and 6 illustrate the difference between corresponding inflow and outflow concentrations. The timing of the outflow data series has been adjusted to match the corresponding inflow sample. The highest TSS concentrations generally occur at the start of the rainfall event during the first flush. The clearly visible first flush is the period when most TSS was removed from stormwater by the bioretention basins.

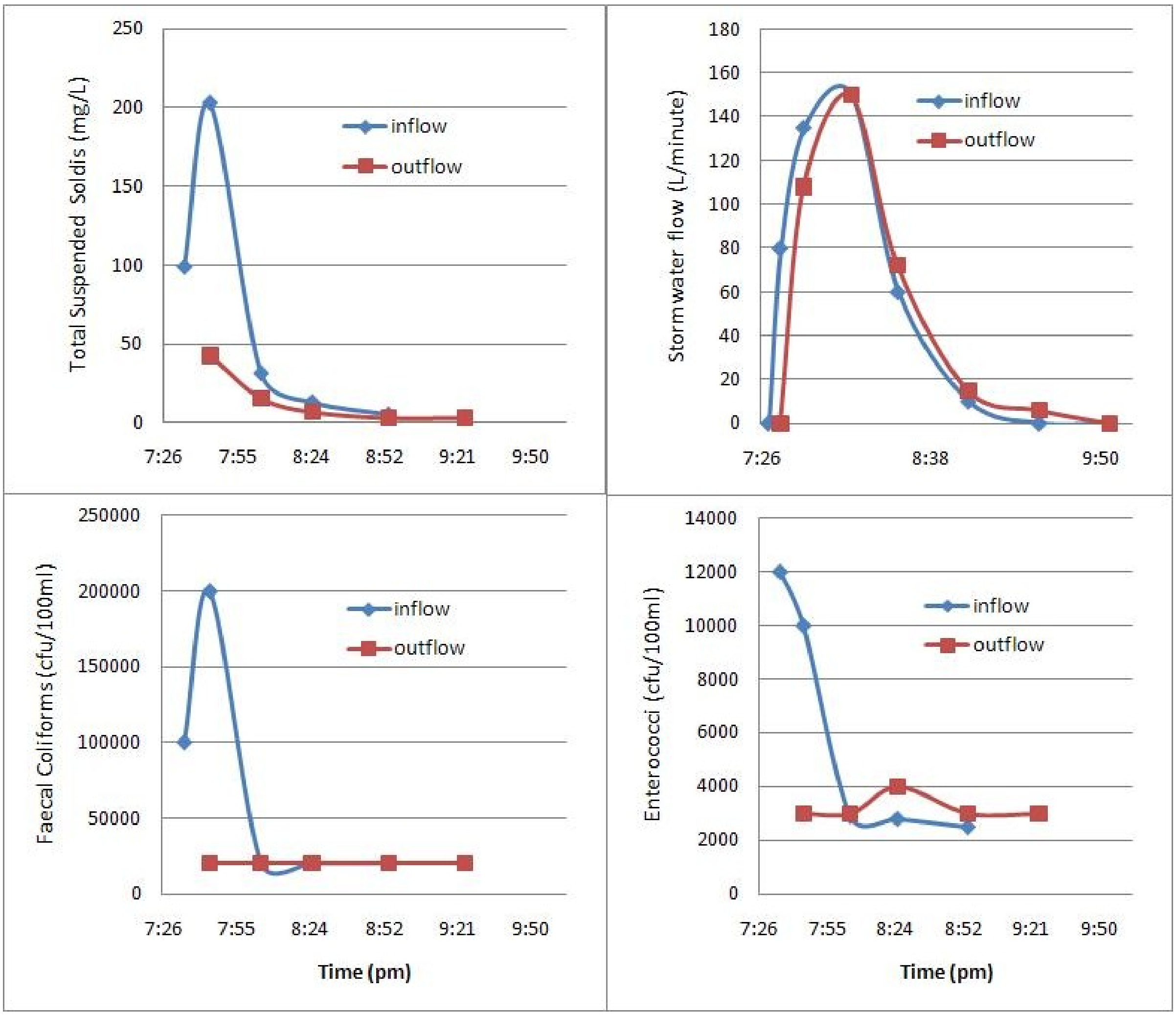

Figure 4: Inflow and outflow concentrations of TSS, faecal coliforms, enterococci, as well as flow volumes, at Tutus St on 28/2/2010

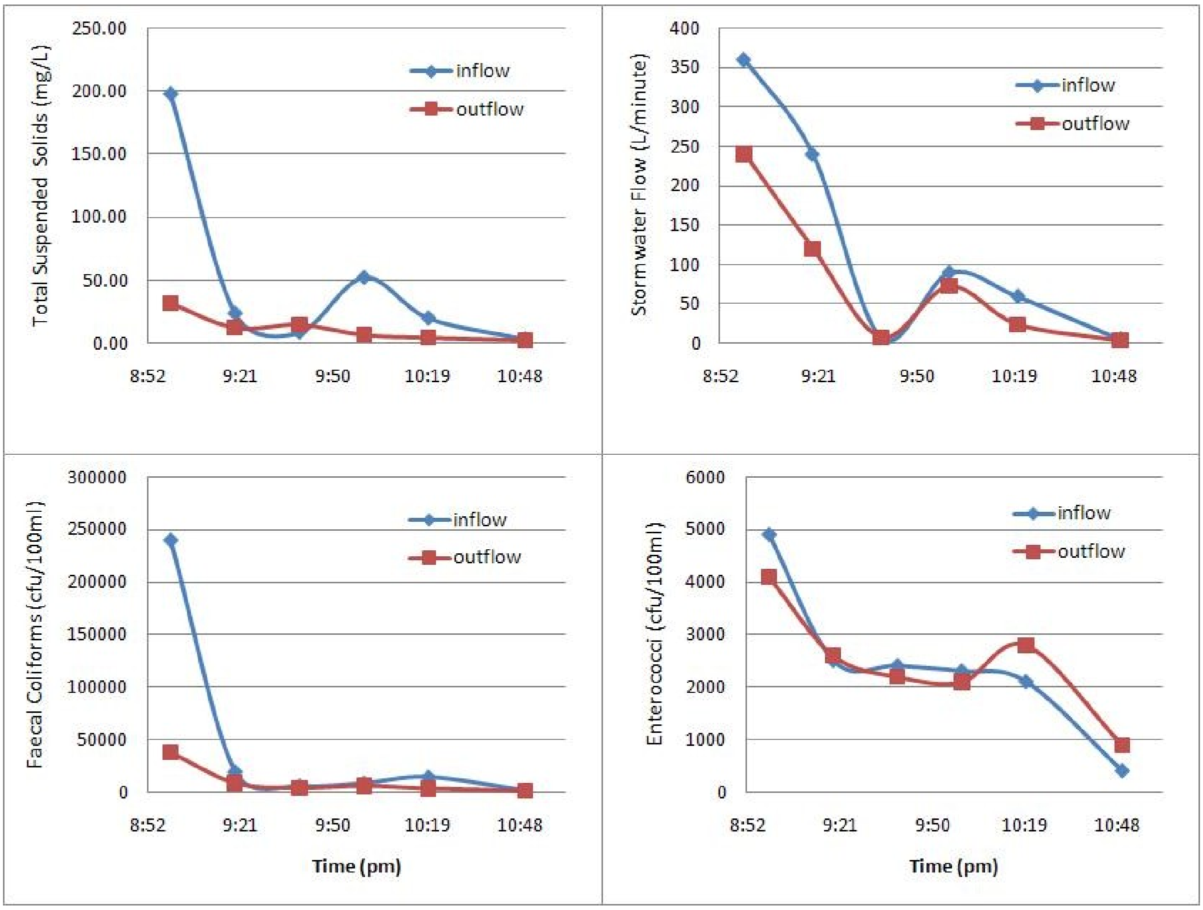

Figure 5: Inflow and outflow concentrations of TSS, faecal coliforms, enterococci, as well as flow volumes, at Beatty St on 16/5/2010

Water Quality Improvement Performance - Faecal Indicator Bacteria

Faecal coliforms and enterococci are microbiological parameters that indicate the presence and concentration of pathogenic bacteria. On average, the 3 basins recorded average reductions of 8.7% and 10.7% for faecal coliforms and enterococci, respectively (Table 3 and 4). However, only one rainfall event was able to be monitored at Jellicoe St for faecal indicator bacteria. Unfortunately, the event was small, resulting in flows reaching the outflow during only one 15 minute period. This suggests the concentration results for Jellicoe St are unreliable and may not represent the true efficiency of the bioretention basin. The Tutus St and Beatty St basins recorded respective concentration reductions of 74% and 81% for faecal coliforms and 41% and 0% for enterococci.

DISCUSSION

Removal of suspended solids by bioretention basins

Strong TSS concentration reductions were seen across all 3 bioretention basins (Table 2), with a 70.1% concentration reduction being observed at the Tutus St basin, 78.8% reduction at Beatty St and 73% at Jellicoe St. These TSS reductions compare well to results published in other field bioretention studies. Line and Hunt (2009) recorded a 79% reduction in TSS concentration, while the Hunt et al (2008) study of a bioretention basin, also in North Carolina, USA, observed a 60% reduction in TSS. The basins in North Carolina have a bioretention area to catchment area of 7.65% and 6.19%, whereas the Tutus, Beatty and Jellicoe St basins have bioretention area to catchment areas of <1%.

Despite being undersized, none of the basins overflowed during the monitored storm events indicating that the hydraulic conductivity of the basin was fast enough to convey the encountered stormwater flows. Hydraulic conductivity of the basin is generally related to the porosity of the soil media. Highly porous soil means the basin is less likely to overflow. However, it also means there are fewer fine particles in the media for pollutants to adhere to, reducing the potential water quality improvement of the bioretention basin.

Removal of faecal indicator organisms by bioretention basins

The Tutus St and Beatty St basins had respective concentration reductions of 74% and 81% for faecal coliforms and 41% and 0% for enterococci. Faecal coliforms have a faster die-off rate compared to enterococci, which could explain difference between concentration reductions (NSWDECCW, 2009). Faecal coliform removal rates have been monitored in bioretention column studies and found to have very high removal rates, while enterococci is less commonly used (Rusciano and Obropta, 2007; Hunt et al., 2008). Hunt et al., (2008) recorded an average faecal coliform concentration reduction of 69% by their studied bioretention basin in North Carolina.

The high faecal coliform removal efficiencies of the Tutus and Beatty basins is supported by studies that showed sand filters to reduce faecal coliform concentrations by 65%. Bioretention column studies by Meschke and Sobsey (2003) found removal rates of faecal indicator bacteria to increase with less permeable soils, suggesting pathogenic bacteria may be physically removed by bioretention basins. This could explain why the Tutus and Beatty basins had high faecal indicator bacteria removal rates despite very short retention times.

CONCLUSIONS

Existing literature indicates bioretention basins provide significant benefits in water quality improvement for typical pollutants of concern for aquatic waterways and for faecal indicator bacteria of concern to human health. They provide a valuable additional tool for use in urban areas as part of a stormwater treatment train to reduce pollutant loads to urban waterways.

This research highlights that significant water quality benefits can be obtained from construction of bioretention basins even in size constrained environments, where greater hydraulic conductivity media is used and basin size is below the standard 2% of the catchment size.

This suggests that investment in construction and establishment of bioretention basins in size constrained locations is warranted by local government authorities as a means to improve stormwater quality. Additional potential considerations where basins are significantly below the typical 2% of catchment area may include a reduced lifespan of the basin until harvesting and replacement of media is required, and greater monitoring potential and maintenance.

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Table 1: Antecedent period, sampling time, estimated rainfall and peak flow for each monitored rainfall event.

		Peak Flow (L/min)		**Antecedent period**	**Sampled at start of Event?**	**Approx. Event Duration**	**Total sampling Time**	**Estimated Rainfall While Sampling**
		Inflow	Outflow	days	Yes/No	hrs : mins	hrs : mins	(mm)
Tutus	11/08/2009	74	72	15	yes	3:10	3:10	0.8
	24/11/2009	34	0	4	yes	0:40	0:40	0.2
	28/01/2010	150	150	4	yes	2:00	2:00	1.8
	29/03/2010	180	18	16	yes	1:40	1:40	1.1
	30/03/2010	300	270	<2	yes	22:00	2:00	5.0
	23/06/2010	660	690	<2	no	2:00	1:15	7.5
	Total	**1397**	**1200**	**39**		**31:30**	**10:45**	**16.3**
Beatty	13/02/2010	10	10	<2	no	9:00	1:00	0.3
	28/02/2010	60	40	13	yes	1:10	1:10	0.9
	6/04/2010	24	15	<2	yes	8:00	2:50	0.7
	16/05/2010	360	240	11	yes	2:30	2:30	6.5
	26/05/2010	400	420	<2	no	13:00	3:15	10.4
	Total	**854**	**725**	**24**		**33:40**	**10:45**	**18.8**
Jellicoe	20/11/2009	10	10	8	no	1:25	1:15	0.2
	5/02/2010	198	84	<2	yes	1:30	1:30	5.2
	5/05/2010	126	36	5	yes	1:35	1:35	1.5
	19/05/2010	175	108	<2	no	1:20	1:00	1.9
	28/7/2010	1008	480	<2	no	16:00	3:30	22.7
	Total	**509**	**238**	**5**		**21:50**	**5:20**	**8.8**

Table 2: Estimated stormwater volume, TSS load and TSS event mean concentration at the inflow and outflow for each monitored rainfall event. Percentage reductions are the flow weighted average reductions, with the overall percentage reduction being the average of the three basins.

		Volume Total (KL)		**Total Suspended Solids**			
				Load (g)		Concentration (mg/L)	
		Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Tutus	11/08/2009	3.3	3.3	192	42	58.6	12.8
	24/11/2009	1.0	0.0	41	0	42.6	-
	28/01/2010	7.8	7.8	609	155	77.9	20.0
	29/03/2010	4.7	0.7	1170	8	247.6	11.0
	30/03/2010	21.9	20.2	318	118	14.5	5.8
	23/06/2010	33.0	33.5	618	481	18.8	14.4
	Reduction (%)	**8.7**		**72.7**		**70.1**	
Beatty	13/02/2010	0.6	0.6	16	3	26.3	4.7
	28/02/2010	2.2	0.6	167	5	77.3	7.6
	6/04/2010	1.7	1.0	30	5	17.9	5.3
	16/05/2010	15.6	9.8	1668	200	106.7	20.3
	26/05/2010	25.0	29.1	267	202	10.7	6.9
	Reduction (%)	**8.8**		**80.7**		**78.8**	
Jellicoe	20/11/2009	0.3	0.3	11	3	37.8	10.5
	5/02/2010	10.4	4.6	208	30	19.9	6.6
	5/05/2010	3.1	0.8	268	12	87.2	16.1
	19/05/2010	3.8	2.7	42	23	11.2	8.4
	28/7/2010	45.4	30.4	2642	2242	58.2	7.3
	Reduction (%)	**38.4**		**87.1**		**85.1**	
Overall	**Reduction (%)**	**18.6**		**80.2**		**78.0**	

Table 3: Estimated faecal coliform load and event mean concentration at the inflow and outflow for each monitored rainfall event. Percentage reductions for each basin are flow weighted, with the overall percentage reduction being the average of the three basins.

		Faecal Coliforms			
		Load (cfu)		Concentration (cfu/100ml)	
		Inflow	Outflow	Inflow	Outflow
Tutus	28/01/2010	5,810,000,000	1,551,000,000	74,325	20,000
	29/03/2010	3,934,800,000	357,975,000	83,276	48,212
	30/03/2010	629,550,000	514,710,000	2,875	2,544
	% Reduction	**77**		**74**	
Beatty	28/02/2010	766,800,000	84,000,000	35,500	14,000
	16/05/2010	18,644,960,000	2,163,852,000	119,213	21,988
	% Reduction	**88**		**81**	
Jellicoe	5/05/2010	12,797,070	7,260,300	417	955
	28/7/2010	232,943,000	275,976,000	513	907
	% Reduction	**-15.3**		**-87.2**	
Overall	**Reduction (%)**	**49.9**		**22.6**	

Table 4: Estimated Enterococci load and event mean concentration at the inflow and outflow for each monitored rainfall event. Percentage reductions for each basin are flow weighted, with the overall percentage reduction being the average of the three basins.

		Enterococci			
		Load (cfu)		Concentration (cfu/100ml)	
		Inflow	Outflow	Inflow	Outflow
Tutus	28/01/2010	435,000,000	254,250,000	5,565	3,279
	29/03/2010	238,106,250	5,895,000	5,039	794
	30/03/2010	243,975,000	234,759,000	1,114	1,160
	% Reduction	**46**		**41**	
Beatty	28/02/2010	29,310,000	20,400,000	1,357	3,400
	16/05/2010	550,260,000	317,029,000	3,518	3,222
	% Reduction	**42**		**0**	
Jellicoe	5/05/2010	47,942,200	12,964,500	1,561	1,705
		497,624,000	749,340,000	1,095	2,463
	% Reduction	**-39.7**		**-188.5**	
Overall	**Reduction (%)**	**16**		**-49.1**	