Does bioretention actually work ?

Ocean Protect Webinar
3 February 2021

Brad Dalrymple & Michael Wicks

Zoom poll

1. Do you believe that bioretention systems typically provide a sustained, effective stormwater treatment function consistent with their design intent ?

2. Do you believe that MUSIC provides an appropriate method to predict the stormwater treatment performance of a bioretention system, assuming that the bioretention system has been appropriately designed, constructed, established and managed ?

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Concflict of interest declaration

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EPA VICTORIA | Environment Protection Authority Victoria

Review of stormwater science

Prepared for: EPA Victoria

Publication 1919 October 2020

"Analysis of the performance of biofiltration systems suggest treatment performance is variable"

Agenda

- Objectives of bio
- How do they work ?
- Lab-scale studies of conventional bio
- "Transition" of data from the lab to the field
- Field-scale studies of conventional bio
- Field-scale studies of high-flow bio
- Recommendations


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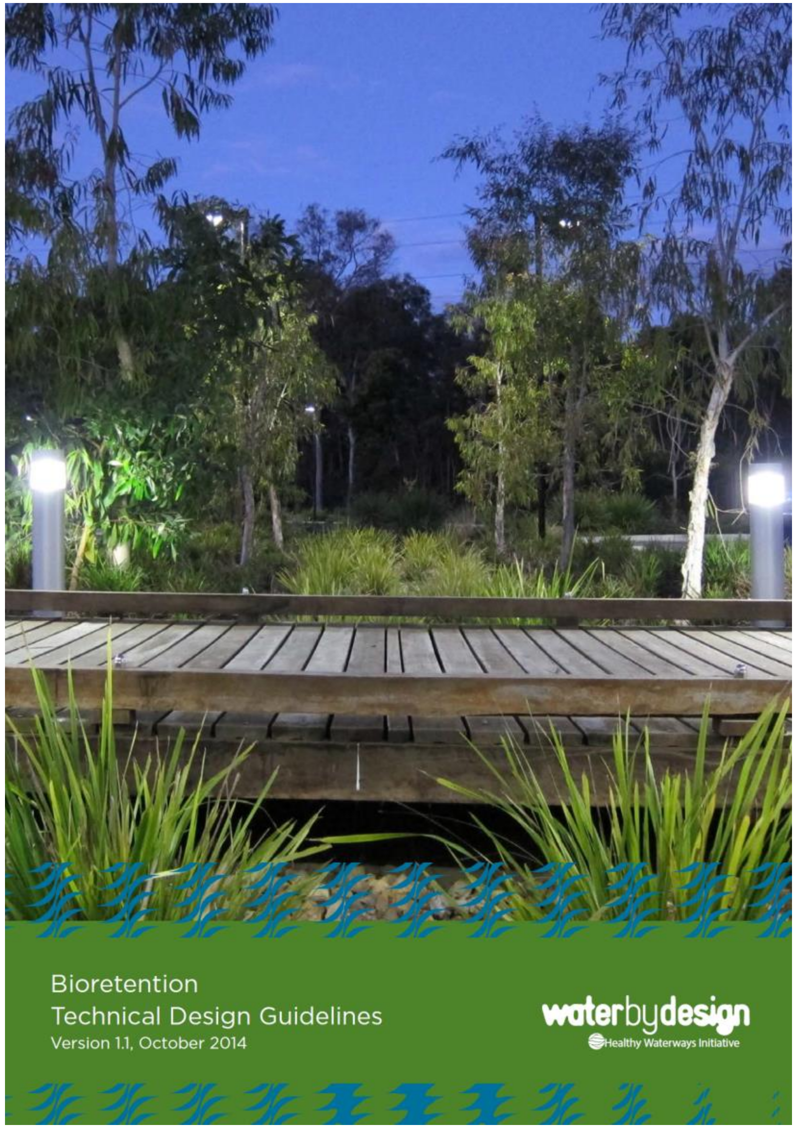
Objectives

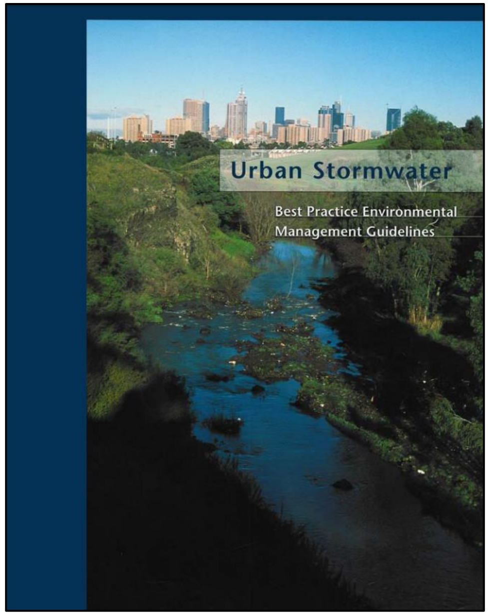


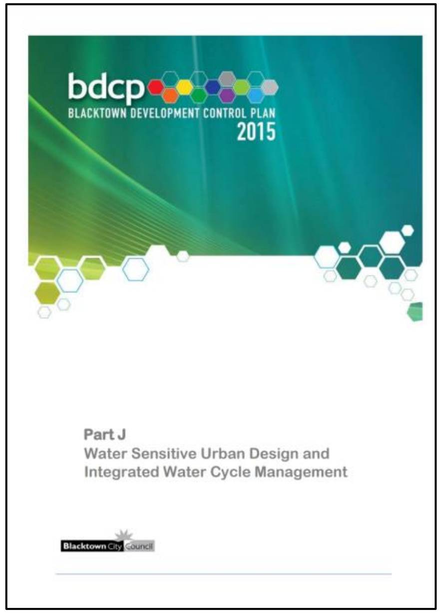
- *"The key function of biofiltration systems is to remove pollutants from stormwater"*
- *"… also contribute to managing hydrology by slowing the rate of discharge of stormwater to the receiving environment and reducing volume through evapotranspiration"*
- Other benefits (e.g. passive irrigation, amenity)

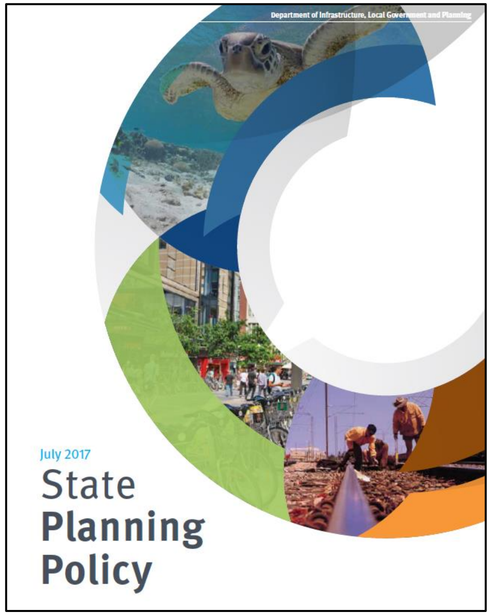
Average annual load removal targets:

- TSS: 80-85%
- TP: 45-65%
- TN: 40*-45%
- GPs: 70-90%

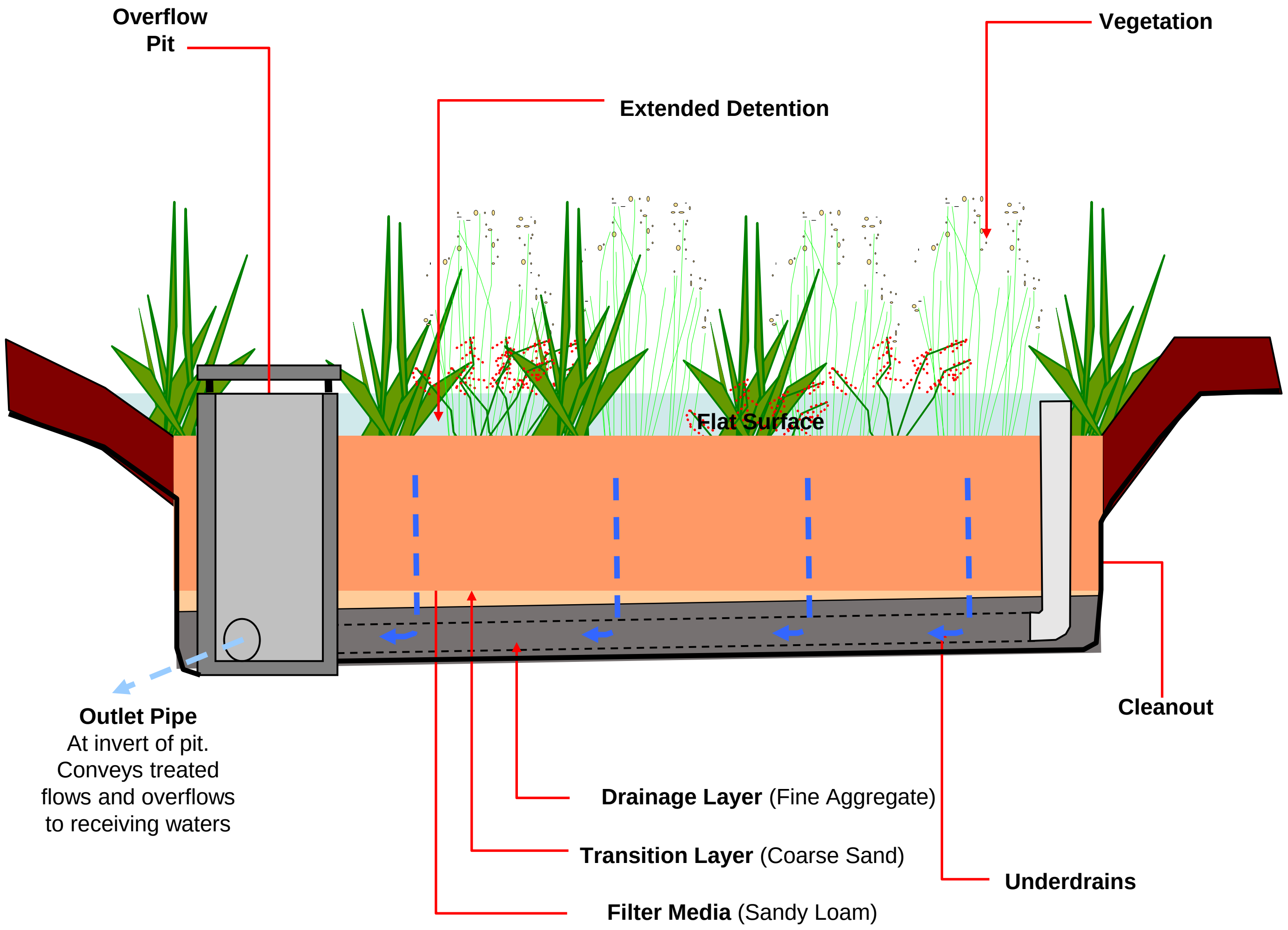
*: 35% TN target for Mackay Region







How do they work ?



Adapted from Water by Design (2009)

Stormwater pollutant	Key treatment processes
Sediment	• Settlement during ponding • Physical filtration by media
Nitrogen	• Nitrification • Denitrification • Biotic assimilation by plants and microbes • Decomposition • Physical filtration of sediment-bound fraction • Adsorption
Phosphorus	• Physical filtration of sediment-bound fraction • Adsorption • Biotic assimilation by plants and microbes • Decomposition
Heavy metals	• Biotic assimilation by plants and microbes • Physical filtration of sediment-bound fraction • Oxidation/reduction reactions
Pathogens	• Adsorption-desorption • Physical filtration by media • Die-off
Organic micropollutants*	• Adsorption • Biodegradation

*: Hydrocarbons, pesticides/herbicides, polycyclic aromatic hydrocarbons (PAHs), phenols, phthalates

Source: Payne et al (2015)

Water ‘losses’

- Bioretention act like ‘filters’ (and NOT ‘sponges’)
- Observed ‘losses’ in bioretention are dominated by exfiltration in most cases
- Exfiltrated water is not ‘lost’ but rather seeping into the surrounding soils or groundwater
- Losses evapotranspiration are reliably predicted by long-established equations

❖ MUSIC predicts ~2-5% ET ‘loss’ for bioretention
(sized to achieve typical targets, modelling in accordance with guidelines)


Lab* studies
*: mecosom & "not real world" mesocosms

Lab studies

- Lab studies referenced in MUSIC User Guide (eWater 2014):

  - Bratieres K, Fletcher T D, Deletic A, Zinger Y, 2008, *Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study*, Journal of Water Research
  - Hatt, B. E., T. D. Fletcher, et al. 2007, *Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes*. Water Science & Technology 56(12): 11-19.
  - Hatt, B. E., T. D. Fletcher, et al. 2008, *Hydraulic and pollutant removal performance of fine media stormwater filtration systems*. Environmental Science and technology 42(7): 2535-2541.
  - Henderson, C., C. Greenway, et al. 2007, *Removal of dissolved nitrogen, phosphorus and carbon from stormwater by biofiltration mesocosms*. Water Science & Technology 55(4): 183-191.
  - Read, J., T. D. Fletcher, et al. 2009, *Plant traits that enhance pollutant removal from stormwater in biofiltration systems*. International Journal of Phytoremediation.
  - Read, J., T. Wevill, et al. 2008, *Variation among plant species in pollutant removal from stormwater in biofiltration systems*. Water Research 42: 893-902.
  - Zinger, Y., A. Deletic, et al., 2007, *The effect of various intermittent dry-wet cycles on nitrogen removal capacity in biofilters systems*. Rainwater and urban design. Sydney, Australia.

- Other lab studies

  - Deletic, A., McCarthy, D., Chandresena, G., Li, Y., Hatt, B., Payne, E., Zhang, K., Henry, R., Kolotelo, P., Randjelovic, A., Meng, Z., Glaister, B., Pham, P., Ellerton, J., 2014, *Biofilters and wetlands for stormwater treatment and harvesting*. Cooperative Research Centre for Water Sensitive Cities, Monash University, Melbourne, p. 67 (October).
  - Glaister B J, Fletcher T D, Cook P L M, Hatt B E, 2014, *Co-optimisation of phosphorus and nitrogen removal in stormwater biofilters: the role of filter media, vegetation and saturated zone*, Water Science and Technology
  - Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., Poelsma, P., 2012, *The influence of design parameters on clogging of stormwater biofilters: a large-scale column study*. Water Res. 46 (20), 6743–6752.
  - Payne E G I, Pham T, Cook P L M, Fletcher T D, Hatt B E, Deletic A, 2014, *Biofilter design for effective nitrogen removal from stormwater – influence of plant species, inflow hydrology and use of a saturated zone*, Water Science and Technology
  - Randall M T, Bradford A, 2013, *Bioretention gardens for improved nutrient removal*, Water Quality Research Journal of Canada, 48.4.

Lab studies - Methods

- "Young" systems
- Semi-synthetic stormwater
- Dosing frequencies varied
- Range of media types
- With & without submerged zones
- Range of vegetation species
- HLR ~ for Monash University systems sized approx. 2-2.5% of catchment

Source: Zinger et al (2007)

Source: Randall et al (2013)

Lab studies - Results

Generally:

- High TSS, TP & heavy metal concentration reductions
- ‘Variable’ TN concentration reductions, but high for sandy loam media with effective plants (and with removal enhanced by saturated zone)

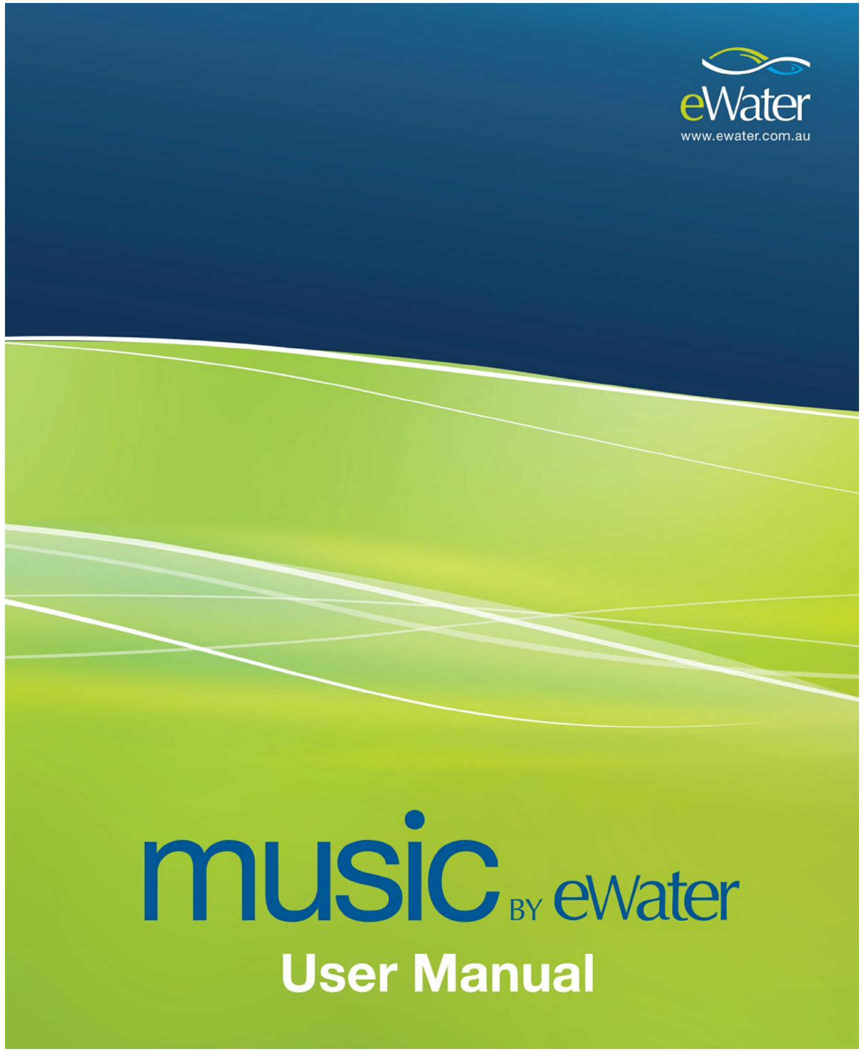
Lab studies – Recommendations

- Recommendations from studies:
  - Plant with species which maximise nutrient removal
  - Saturated zone may assist with nitrate (and TN) removal
  - Sandy loam filter media (without any additional organic matter)
  - Be sized to at least 2% of catchment area

- *"The magnitude of reductions reported in the current paper cannot be extrapolated to field conditions without validation"* (Payne et al 2014)

Source: Soberg et al (2020)

Modelling



- Appendix E: Modelling Bioretention System Treatment Performance
- Two 'components' modelled:
    - Detention modelled using USTM
    - Media modelled using 'lookup table'
- Zero reference to any study after 2009
- Zero reference to any field study
- Validation ?

Application of lab data

Bioretention

Field studies

Conventional* biofiltration

*: standards vary over time/ area, & may not be representative of current recommended best practice in Australia

High flow (Filterra) biofiltration

Field studies

'Conventional' biofiltration:

- Birch, G F, Fazeli, M .S, Matthai, C, 2005, *Efficiency of an infiltration basin in removing contaminants from urban stormwater*, Environmental Monitoring and Assessment, I0I, 23-38.
- Hunt, W. F., A. R. Jarrett, Smith J T, Sharkey L J, 2006, *Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina*. Journal of Irrigation and Drainage Engineering 132(6): 600-608.
- Davis, A.P., 2007. *Field performance of bioretention: water quality*. Environ. Eng. Sci. 24, 1048e1064.
- McKenzie-McHarg A, Smith N, Chapman B, 2008, *Stormwater Gardens to Improve Stormwater Quality in Brisbane*.
- Hatt B E, Fletcher T D, Deletic A, 2009, *Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale*, Journal of Hydrology.
- Parker N, 2010, *Assessing the effectiveness of Water Sensitive Urban Design in Queensland*. Thesis, Queensland University of Technology
- Roberts S J, Fletcher T D, Garnett L, Deletic A, 2012, *Bioretention saturated zones: do they work at the large-scale?* WSUD 2012 Conference, Melbourne, Australia.
- Mangangka, I. R., Liu, A., Egodawatta, P., & Goonetilleke, A., 2015, *Performance characterisation of a stormwater treatment bioretention basin*. Journal of Environmental Management, 150, 173-178.
- Lucke T, Nichols P W B, 2015, *The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation*, Science of the Total Environment
- Lucke T, Dierkes C, Boogaard F, 2017, *Investigation into the long-term stormwater pollution removal efficiency of bioretention systems*, Journal of Water Science and Technology.
- Peljo L, Dubowski P, Dalrymple B, 2016, *The Performance of Streetscape Bioretention Systems in South East Queensland*, Stormwater Australia Conference 2016, Brisbane.
- Johnson J P, Hunt W F, 2019, 2019, *A Retrospective Comparison of Water Quality Treatment in a Bioretention Cell 16 Years Following Initial Analysis*, Journal of Sustainability.

Field studies

- Birch et al (2005):
  - Sydney, NSW; constructed ?; ~420m^2 area (~4% of catchment); up to 1.1m deep filter media (1:6 mixture of zeolite and coarse, pure quartzitic sand with a mean diameter of 2 mm.); planting ?
  - WQ data from 9 real events between Oct & Dec 1999
  - Weighted Average CR's: TSS ~50%, TP 51%, TKN 65%, Cu 68%, Fe 93%, Zn 52%
  - No change or substantial increase in effluent conc.'s for Cr, Fe, Mn & Ni

Field studies

Hunt et al (2006) – Greensborough:

- Greensborough, North Carolina, USA; constructed 2000-01; two cells, 10m^2 each (5% of catchment); both with 1.2m 'organic sandy soil' filter, cell G1 included 0.45 to 0.6m internal water storage, ~20m^2 area; planted with river birch, common rush, yellow flag iris & sweetbay
- 11 real events 2002-03; flow & WQ monitored
- Volume 'loss': 46% (winter) to 93% (summer)
- Mean CRE (G1 & G2): TP -409% & -2900%, TN -224% & -312%

- Young system (<1-2 years)

- *See Johnson (et al 2017) for Chapel Hill, North Carolina*

Table 6. Inflow and Outflow Concentrations (Flow Weighted) for Greensboro cells G1 and G2

Analyte	Inflow/ outflow	Concentration: Mean (mg/L)	Concentration: Standard deviation (mg/L)	Significant? ($p<0.05$)
(a) Cell G1 (IWS configuration)[a]				
TKN	Inflow	1.0	0.75	Yes (p=0.0001)
	Outflow	4.1	2.0	
NH_4	Inflow	0.24	0.20	Yes (p=0.0001)
	Outflow	2.82	1.77	
NO_3	Inflow	0.34	0.17	No
	Outflow	0.28	0.43	
TN	Inflow	1.35	0.70	Yes (p=0.0001)
	Outflow	4.38	2.07	
TP	Inflow	0.11	0.13	Yes
	Outflow	0.56	0.39	(p=0.00003)
Ortho-P	Inflow	0.05	0.09	Yes
	Outflow	0.52	0.37	($p<0.00001$)
(b) Cell G2 (conventional configuration)[b]				
TKN	Inflow	0.76	0.47	Yes (p=0.0007)
	Outflow	4.90	3.50	
NH_4	Inflow	0.22	0.18	Yes (p=0.0015)
	Outflow	1.54	1.26	
NO_3	Inflow	0.50	0.32	No
	Outflow	0.30	0.42	
TN	Inflow	1.27	0.55	No
	Outflow	5.23	3.42	
TP	Inflow	0.10	0.083	Yes (p=0.013)
	Outflow	3.0	3.4	
Ortho-P	Inflow	0.056	0.063	Yes (p=0.020)
	Outflow	2.20	2.90	

Note: All significant increases in concentration from inflow to outflow are noted.

[a] $n=17$.

[b] $n=15$.

Field studies

Davis (2007):

- Maryland, USA, constructed QLD; constructed 2003; 2 parallel cells, 26m^2 area each (2.2% of catchment), Cell A 0.9m filter (50% sand, 30% topsoil, 20% hardwood mulch) with 80mm surface hardwood, Cell B as per Cell A but with 0.3m anaerobic sump (sand & newspaper mix); vegetated
- 12 real events 2003-04; WQ monitored
- Mean CREs (for Cells A & B): TSS 22 & 41%, TP 74 & 68%

- Young system (<1-2 years)

Table 2. Summary of water quality EMC data for University of Maryland bioretention cells.

Pollutant	n	*Median percent removal* Cell A	*Median percent removal* Cell B	*Mean percent removal* Cell A	*Mean percent removal* Cell B	*Median (mg/L) Discharge* Input	*Median (mg/L) Discharge* Cell A	*Median (mg/L) Discharge* Cell B	*Statistical significance* t-test Cell A	t-test Cell B	U-test Cell A	U-test Cell B	Log t-test Cell A	Log t-test Cell B
TSS	12	43	47	22	41	34	18	13	No	Yes	No	Yes	No	Yes
Total phosphorus	12	80	75	74	68	0.61	0.15	0.17	No	No	Yes	Yes	Yes	Yes
Copper	9	59	55	51	57	0.010	0.004	0.003	No	Yes	Yes	Yes	Yes	Yes
Lead	9	83	83	79	86	0.058	<0.002	0.004	Yes	Yes	Yes	Yes	Yes	Yes
Zinc	12	47	70	28 57[a]	63	0.107	0.048	0.044	No Yes[a]	Yes	Yes	Yes	No Yes[a]	Yes
NO_3-N	3	78	88	79	86	0.13	0.02	0.02	ND	ND	ND	ND	ND	ND

[a]With one outlier point sequestered. ND, no statistical analysis done on NO_3-N due to small sample size.

Field studies

McKenzie-McHarg et al (2008):

- Brisbane, QLD; constructed ~2006; ~20m^2 area; 0.4m deep SL filter media
- 4 simulated events 2006-2007; 3000L (3-month?) dose per event; flow & WQ monitored
- Volume 'loss' 23% average
- Peak flow rates reduced 73-80%
- Mean CREs: TSS 87%, TP 83%, TN 28%

- Young system (<1-2 years)
- High TN influent conc. (~2.7-2.9mg/L)

Table 1 Treatment performance of stormwater garden in Brisbane (mean ± max range)

	Constituent	Percent Reduction in Pollutant Concentrations	Percent Reduction in Pollutant Loads
	Total Suspended Solids	87 ± 9	92 ± 5
Nutrient Species	Total Phosphorus	83 ±13	88 ± 6
	Ortho Phosphorus	87 ± 21	90 ± 15
	Total Nitrogen	28 ± 33	45 ± 28
	Total Soluble Nitrogen	18 ± 37	37 ± 31
	Nitrite + Nitrate	-39 ± 51	-7 ± 40
	Ammonia	94 ± 14	85 ± 10
	Dissolved Organic Nitrogen	94 ± 12	63 ± 19
	Particulate Organic Nitrogen	71 ± 23	80 ± 19
Heavy Metals	Cadmium	89 ± 1	91 ± 2
	Copper	96 ± 2	97 ± 2
	Lead	97 ± 1	98 ± 1
	Zinc	99 ± 0	99 ± 0

Field studies

Hatt et al (2009) – Site 1:

- Monash Uni, VIC; constructed 2005; 3 cells, each 1.5m^2 area (1% of catchment); 0.5m deep filter media (Cell 1 SL; Cell 2 SLVP; Cell 3 SLCM); Dense planting (native sedges & rushes)
- Flow & WQ monitored 2006-2007; real events; flow data for 28 events; WQ data for 38 events
- High conc. reductions for TSS, NH_4 & HMs
- TP & FRP conc.'s increased in all cells
- TN & NOx conc.'s increased in cells 1 & 2 (& decreased in Cell 3)
- 11 overflow events (of 28)
- 27% flow 'loss'
- Young system (~1-2 years)
- Low TSS/TP/TN influent conc.'s, high DIN%

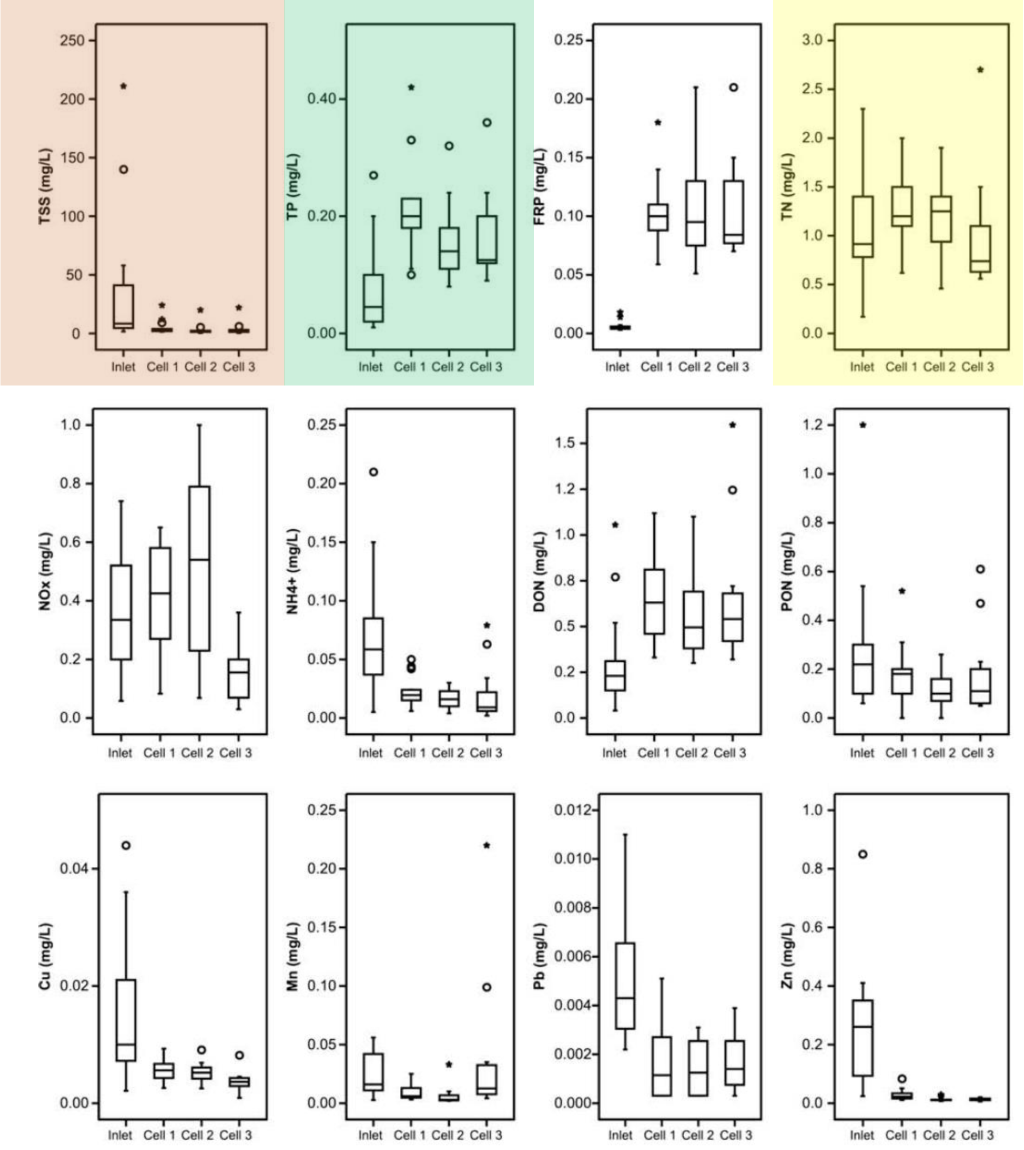


Fig. 8. Range of pollutant EMCs for 14 rain events at the Monash University site.

Field studies

Hatt et al (2009) – Site 2:

- McDowall, QLD; constructed 2006; 20m^2 area (2% of catchment); 0.4m deep SL filter media; Re-planted with Carex in 2007
- 4 simulated events in June & Oct 2007
- "Substantial reductions of TSS, TP, FRP, NH_4, DON, Cd, Cu, Pb, and Zn" (Hatt et al 2009)
- "TN & NOx effluent concentrations were largely equal to or greater than influent concentrations" (Hatt et al 2009)

❖ Young system (~1 year)

Table 3
Pollutant concentrations (mean ± standard deviation) for four stormwater simulations at McDowall. Pearson correlation coefficients (*R*) indicate the relationship between effluent pollutant concentrations and flow. Concentrations for heavy metals were largely below the detectable limit, hence maximum values only are reported and correlations for these parameters were not determined.

	Concentration (mg/L)		*R*
	Stormwater ($n = 4$)	Effluent ($n = 59$)	
TSS	128 ± 32	14 ± 19	0.49[**,a]
TP	0.4 ± 0.3	0.07 ± 0.06	0.34[**,a]
FRP	0.1 ± 0.2	0.01 ± 0.01	−0.39[**,a]
TN	2.7 ± 0.2	2.2 ± 0.7	0.34[**]
NO_x	1.0 ± 0.2	1.6 ± 0.7	0.26[*]
NH_4^+	0.5 ± 0.2	0.02 ± 0.03	0.14
DON	0.9 ± 0.2	0.5 ± 0.2	0.11
PON	0.4 ± 0.1	0.1 ± 0.1	0.01
Cd	0.005 ± 0.001	<0.001[b]	–
Cu	0.06 ± 0.01	0.005[b]	–
Pb	0.11 ± 0.02	0.007[b]	–
Zn	0.33 ± 0.06	0.013[b]	–

Significant correlations are shown in bold type.
[*] $p < 0.05$.
[**] $p < 0.01$.
[a] Log-transformed.
[b] Maximum concentration.

Field studies

Hatt et al (2009) – Site 3:

- Bracken Ridge, QLD; constructed 2001; 860m² area (5% of catchment); 0.4m deep SL filter media; *L.longifolia* & *M.quinquinerva*
- WQ monitored Dec 2005 to March 2006; data for 9 real events
- Reductions in TP, NH_4 & HMs
- No significant reduction in TSS, TN, & NOx

- Low TSS/TP/TN influent conc.'s

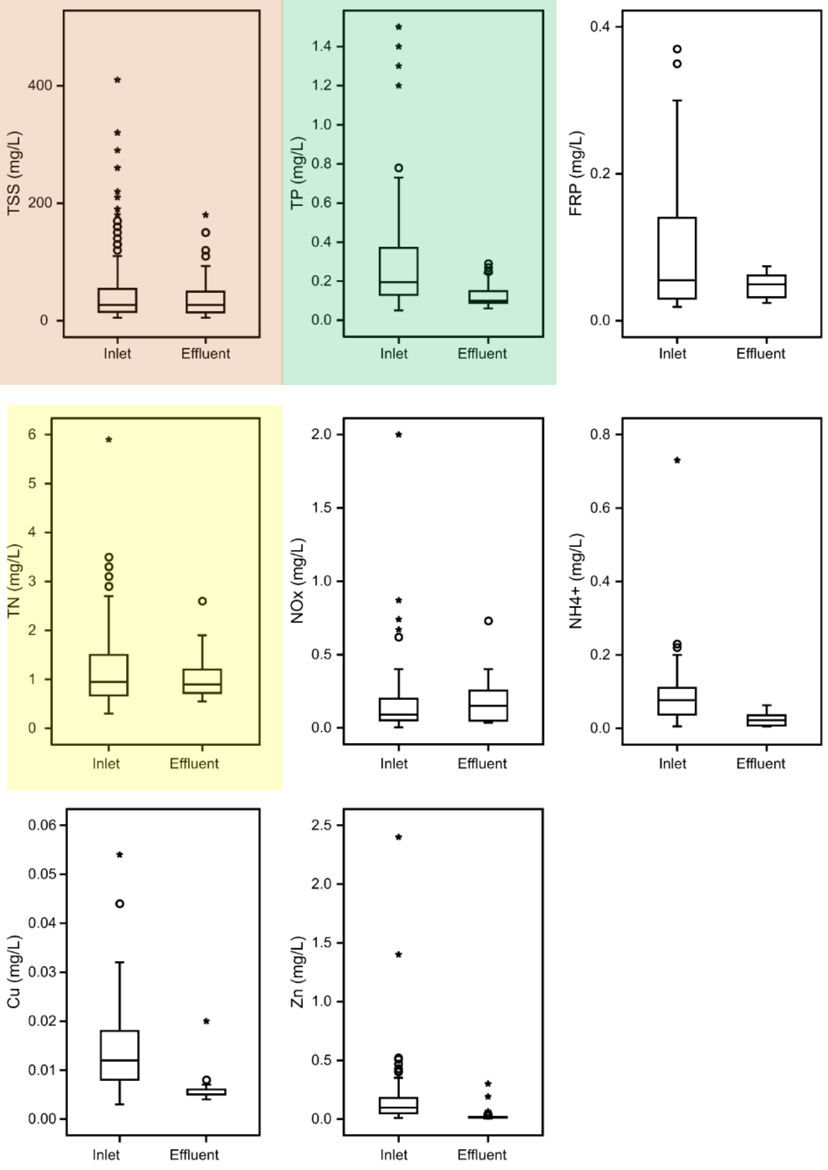


Fig. 11. Range of pollutant concentrations at Bracken Ridge.

Field studies

- Parker (2010), Mangangka et al (2015):
  - Coomera Waters QLD; 248m^2 bio basin (3.8% of catchment); 0.8m depth media (~70% sand, 14% clay, 6% loam, 10% organic matter); Geotextile, topsoil, & turf over filter media

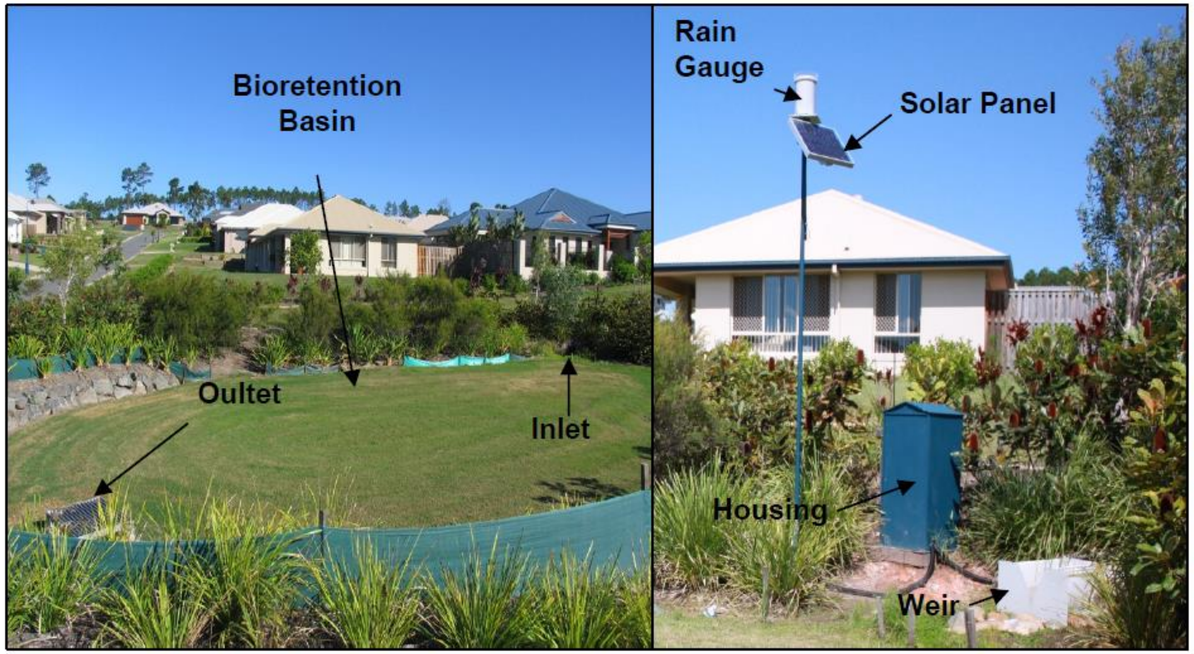


Figure 4.28 - Bioretention basin and bioretention basin inflow monitoring site

Field studies

Parker (2010):

- Flow & WQ monitoring Oct 2007 to Mar 2009
- 34% flow volume bypassed bio
- Peak flow reduction 94% average (for events with no bypass)
- Volume reduction 42% average (for events with no bypass)
- Reduced runoff frequency
- Mean CRE's: TSS 45%, TP -3%, TN – 13%, NH_4 77%, NOx -71%, Org N -20%, FRP -62%, Org P 23%, TDN -7%, Al -74%, Cu -11%, Pb 53%, Zn 64%

- System **not** established (filter media covered with geotextile, topsoil & turf)
- Filter media has **high organic matter %**

Appendix 11 continued: Water quality results for the bioretention basin

Total Suspended Solids (TSS) Results for the Bioretention Basin

Event Date	Inlet EMC (mg/L)	Inlet SMC (mg/L)	Outlet EMC (mg/L)	Outlet SMC (mg/L)	Concentration Reduction	Load In kg/ha	Load Out kg/ha	Load Reduction
31/10/2007	24.2	47.3	24.3	26.0	-0.3%	1.07	0.59	45%
17/11/2007	33.1	47.3	12.1	26.0	64%	1.11	0.09	92%
8/12/2007	41.8	47.3	39.0	26.0	7%	1.71	0.78	55%
29/01/2008	47.2	47.3	24.5	26.0	48%	3.72	1.21	67%
5/03/2008	98.3	47.3		26.0	No Outflow	0.64	0.00	100%
8/03/2008	29.7	47.3		26.0	No Outflow	0.10	0.00	100%
17/03/2008	76.2	47.3	57.3	26.0	25%	3.33	0.92	73%
5/04/2008	15.4	47.3		26.0	No Outflow	0.45	0.00	100%
14/05/2008	72.9	47.3		26.0	No Outflow	1.34	0.00	100%
9/10/2008	62.3	47.3	20.0	26.0	68%	6.65	1.46	78%
29/12/2008	27.6	47.3	24.4	26.0	11%	2.05	1.49	27%
11/02/2009	64.5	47.3	25.7	26.0	60%	2.00	0.25	87%
Average	49.4	47.3	18.9	26.0	45%	24.16	6.77	72%
± SD	25.3		17.8					

Total Nitrogen (TN) Results for the Bioretention Basin

Event Date	Inlet EMC (mg/L)	Inlet SMC (mg/L)	Outlet EMC (mg/L)	Outlet SMC (mg/L)	Concentration Reduction	Load In kg/ha	Load Out kg/ha	Load Reduction
31/10/2007	0.99	1.24	1.60	1.40	-61.4%	0.044	0.039	11%
17/11/2007	0.87	1.24	1.14	1.40	-32%	0.029	0.009	71%
8/12/2007	0.78	1.24	1.83	1.40	-135%	0.032	0.036	-14%
29/01/2008	0.88	1.24	1.16	1.40	-32%	0.070	0.057	17%
5/03/2008	1.26	1.24		1.40	No Outflow	0.008	0.000	100%
8/03/2008	1.02	1.24		1.40	No Outflow	0.003	0.000	100%
17/03/2008	1.10	1.24	2.19	1.40	-99%	0.048	0.035	27%
5/04/2008	1.49	1.24		1.40	No Outflow	0.043	0.000	100%
14/05/2008	2.39	1.24		1.40	No Outflow	0.044	0.000	100%
9/10/2008	1.62	1.24	1.35	1.40	17%	0.173	0.098	43%
29/12/2008	1.23	1.24	1.26	1.40	-3%	0.091	0.077	16%
11/02/2009	1.49	1.24	1.38	1.40	7%	0.046	0.014	71%
Average	1.26	1.24	1.49	1.40	-13%	0.632	0.365	42%
± SD	0.45		0.37					

Total Phosphorus (TP) Results for the Bioretention Basin

Event Date	Inlet EMC (mg/L)	Inlet SMC (mg/L)	Outlet EMC (mg/L)	Outlet SMC (mg/L)	Concentration Reduction	Load In kg/ha	Load Out kg/ha	Load Reduction
31/10/2007	0.055	0.123	0.108	0.127	-95.5%	0.002	0.003	-7%
17/11/2007	0.037	0.123	0.113	0.127	-211%	0.001	0.001	31%
8/12/2007	0.064	0.123	0.200	0.127	-213%	0.003	0.004	-52%
29/01/2008	0.098	0.123	0.098	0.127	0%	0.008	0.005	37%
5/03/2008	0.218	0.123		0.127	No Outflow	0.001	0.000	100%
8/03/2008	0.086	0.123		0.127	No Outflow	0.000	0.000	100%
17/03/2008	0.120	0.123	0.163	0.127	-36%	0.005	0.003	50%
5/04/2008	0.081	0.123		0.127	No Outflow	0.002	0.000	100%
14/05/2008	0.170	0.123		0.127	No Outflow	0.003	0.000	100%
9/10/2008	0.255	0.123	0.104	0.127	59%	0.027	0.008	72%
29/12/2008	0.064	0.123	0.132	0.127	-106%	0.005	0.008	-69%
11/02/2009	0.162	0.123	0.179	0.127	-10%	0.005	0.002	65%
Average	0.117	0.123	0.137	0.127	-3%	0.063	0.032	49%
± SD	0.069		0.039					

Field studies

Mangangka et al (2015):

- Flow & WQ monitoring 2008 to 2011 (12 events)
- Mean CRE's: TSS 34%, TP 7%, TN -37%
- Loss (excluding bypass) = 61%; Loss (including bypass) = 39%
  - (bypass information from Mangangka thesis, cited in CRC for Water Sensitive Cities 2020)

- System **not** established (filter media covered with geotextile, topsoil & turf)
- Filter media has **high organic matter %**

Table 4
Pollutant removal data.

Dry period	Rainfall events	Load removal %							EMC reduction %						
		TSS	NH_4^+	NO_2^-	NO_3^-	TN	PO_4^{3-}	TP	TSS	NH_4^+	NO_2^-	NO_3^-	TN	PO_4^{3-}	TP
Long dry period (>6 days)	B1	75.56	88.58	72.21	44.06	64.88	89.98	87.63	18.09	61.73	6.85	−87.50	−17.73	66.42	58.54
	B3	85.90	98.13	84.66	62.00	62.62	91.95	83.09	43.91	92.56	38.99	−51.16	−48.69	67.97	32.72
	B4	86.49	85.30	56.44	−10.54	11.42	27.85	48.90	74.03	71.73	16.23	−112.57	−70.34	−38.74	1.73
	B5	81.11	83.65	48.93	−38.42	7.92	71.46	75.05	66.54	71.05	9.57	−145.10	−63.04	49.47	55.82
	B6	67.34	80.22	28.43	−1.73	6.28	62.09	57.95	36.39	61.47	−39.39	−98.14	−82.55	26.17	18.10
	B7	71.32	65.54	90.66	82.04	76.05	58.68	78.41	3.87	−15.52	68.69	39.79	19.71	−38.49	27.63
	B10	94.03	84.67	82.23	81.54	88.03	96.78	90.18	44.99	−41.25	−63.65	−69.99	−10.29	70.38	9.54
	B12	84.50	71.61	56.05	90.24	66.27	91.69	81.43	21.36	−44.06	−123.02	50.49	−71.14	57.84	5.74
	Mean	80.78	82.21	64.95	38.65	47.93	73.81	75.33	38.65	32.21	−10.72	−59.27	−43.01	32.63	26.23
	SD[a]	8.26	9.39	19.82	46.03	31.44	22.14	13.60	22.46	52.36	57.51	65.72	33.87	43.20	20.40
Short dry period (<6 days)	B2	27.50	73.33	−2.17	−17.85	1.82	−26.79	−18.44	3.23	64.40	−36.36	−57.30	−31.04	−69.23	−58.09
	B8	49.69	0.60	13.39	41.46	12.07	40.89	22.95	14.26	−69.38	−47.59	0.24	−49.83	−0.73	−31.30
	B9	84.73	57.72	38.01	58.24	56.53	76.79	65.05	50.26	−37.78	−102.00	−36.06	−41.66	24.38	−13.88
	B11	85.31	65.59	43.72	88.22	84.38	60.34	76.14	25.30	−74.94	−186.18	40.11	20.58	−101.63	−21.31
	Mean	61.81	49.31	23.24	42.52	38.70	37.81	36.42	23.26	−29.42	−93.03	−13.25	−25.49	−36.80	−31.15
	SD	24.50	28.66	18.57	38.67	33.44	39.40	37.38	17.43	55.99	59.23	37.05	27.42	50.74	16.74

Field studies

Roberts et al (2012):

- Wakerley, QLD; constructed 2007; 3 cells (955m^2 each, 0.3% of catchment); upstream sed basin; 'standard' filter media; 0.9m saturated zone in Cell 3; variety of plant species
- WQ monitoring 2009-10; 53-74 events

Photo source: ideanthrowater.com

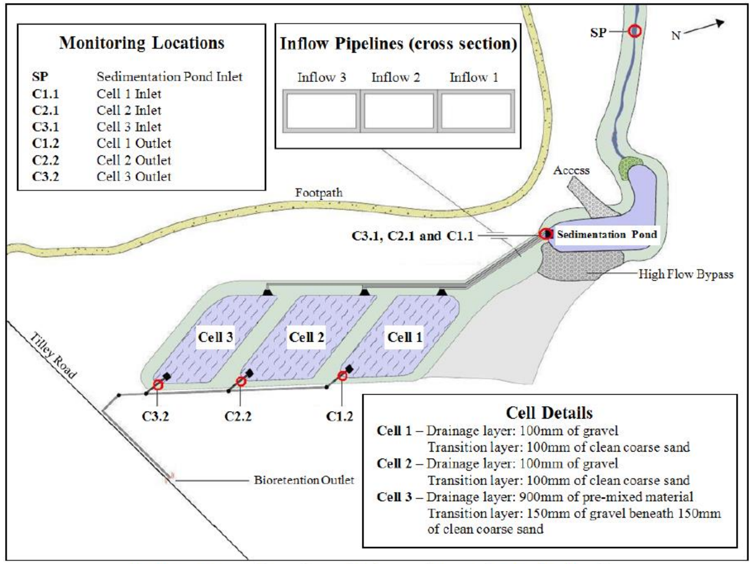
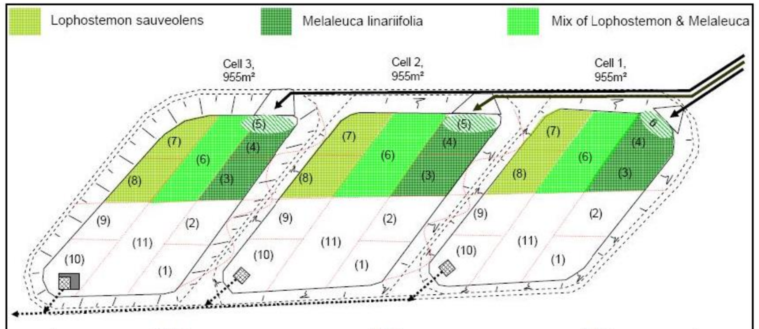


Figure 1. Location of monitoring points at the Wakerley site. (Modified from Water Management City Design, 2007)



Cell 3		Cell 2		Cell 1	
Vegetation	Zone	Vegetation	Zone	Vegetation	Zone
Carex appressa	5	*Carex appressa*	4, 6, 8	*Juncus usitatus*	4, 5, 8
Carex fasicularis	5	*Juncus Sp.*	5	*Dianella caerullea*	3, 6, 7
Cymbopogon refractus	4, 6, 8	*Lomandra longifolia*	3, 6, 7	*Ficnia nodosa*	2, 10, 11
Microlaena stipoides	3, 6, 7	*Lomandra hystrix*	1, 9, 11	*Cyperus exaltatus*	1, 9, 11
Eragrostis elongata	2, 10, 11	*Gahnia sieberiana*	2, 10, 11		
Imperata cylindrica	1, 9, 11				

Figure 2. Vegetation layout for each bioretention cell.

Field studies

Roberts et al (2012):

- Mean CREs (for Cells 1, 2 & 3):
  - TSS: 36%, 53%, 44%
  - TP: 25%, 34%, 38%
  - TN: -28%, -11%, 19%

- Low TSS/TP/TN influent conc.'s

Table 2. Bioretention cell inflow and outflow pollution levels.

Pollutant	Parameter	**Inlet**	**Cell 1 outlet**	**Cell 2 outlet**	**Cell 3 outlet**
	Median	23.0	12.0	10.0	11.0
	Mean (μ)	29.6	18.9	13.8	16.5
TSS [mg/L]	Coefficient of Variation (CV)	0.093	0.135	0.125	0.128
	Recorded Range	6.0 - 120.0	2.5 - 73.5	2.5 - 60.0	2.5 - 120.5
	Skewness	2.06	1.82	1.91	2.99
	Median	0.83	1.10	0.97	0.74
	Mean (μ)	0.98	1.26	1.09	0.79
TN [mg/L]	Coefficient of Variation (CV)	0.058	0.069	0.056	0.053
	Recorded Range	0.36 - 2.30	0.51 - 4.20	0.41 - 2.20	0.30 - 2.4
	Skewness	1.09	2.44	1.06	1.64
	Median	0.069	0.050	0.053	0.034
	Mean (μ)	0.087	0.065	0.057	0.054
TP [mg/L]	Coefficient of Variation (CV)	0.609	0.710	0.636	1.429
	Recorded Range	0.020 - 0.260	0.020 - 0.230	0.014 - 0.210	0.005 - 0.620
	Skewness	1.34	2.22	2.38	5.84
Approximate Standard Error of Skewness		0.30	0.34	0.32	0.28

Field studies

- Lucke et al (2015, 2017):
  - Caloundra, QLD; constructed 2005; 3 bio's ($7m^2$ each, sized to achieve 80/60/45); 0.9m depth SL media; *L.longifolia*
  - 12 simulated events (4 tests at each of the 3 bio's) between April & August 2014; ~2-year 30-min events @: A – no pollution; B – typical TSS/TP/TN; C – 2 x typical; D – 5 x typical

Fig. 1. One of the bioretention basins evaluated in the study.

Field studies

Lucke et al (2015, 2017):

- Peak flow rates reduced 80-94%
- Outflow volumes reduced 33-84%

- *"The results of this study suggest that the long-term pollution removal performance of these systems may not be as effective as previously thought and further research is needed"* (Lucke et al 2017)

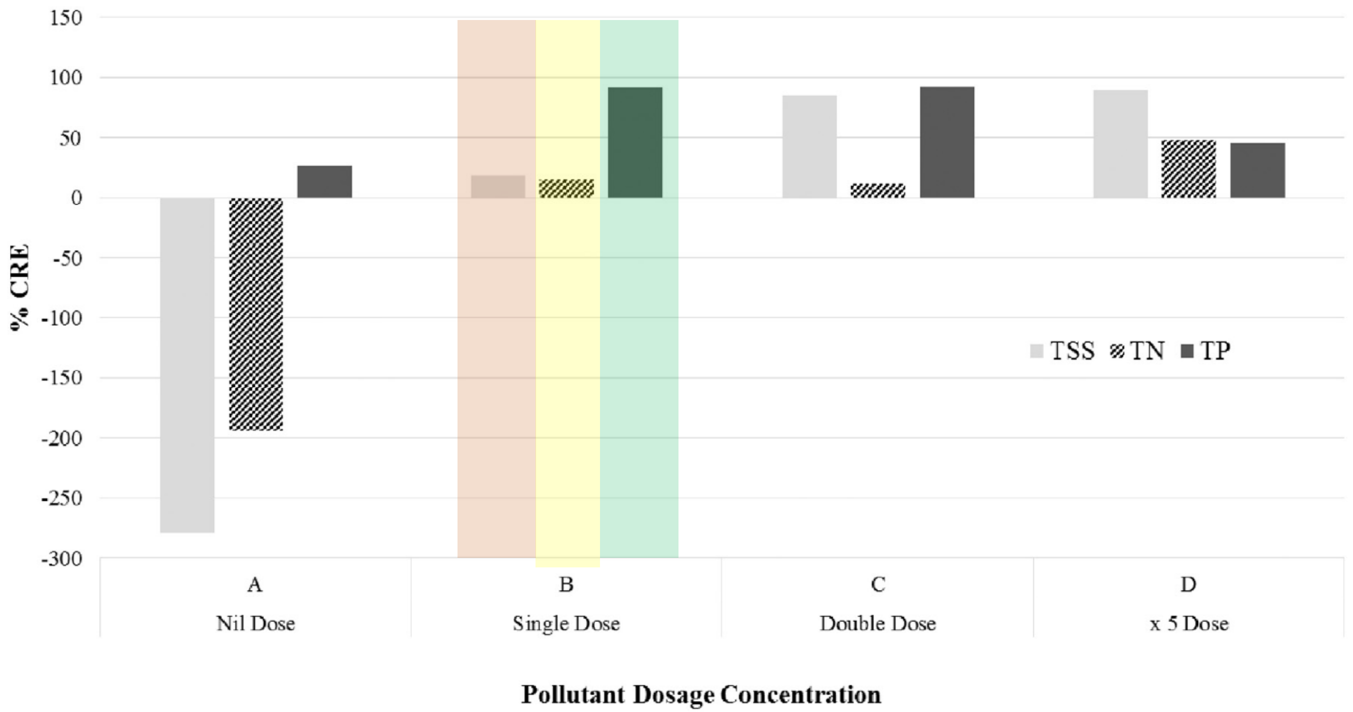


Fig. 7. Average bioretention pollution removal performance (CRE) across basins.

Field studies

- Peljo et al (2016):
  - Caloundra, QLD; constructed 2013; 4 systems ~10m^2 each (~1% of catchment); 0.4m deep SL filter media; *Juncus & Carex* spp.
  - 2 simulated events at each of 4 systems in June 2015

Field studies

Peljo et al (2016):

- Mean CRE: TSS (91%), TP (83%), TN (33%)
- High HM CRE's
- Reductions in flow (mean 67%)

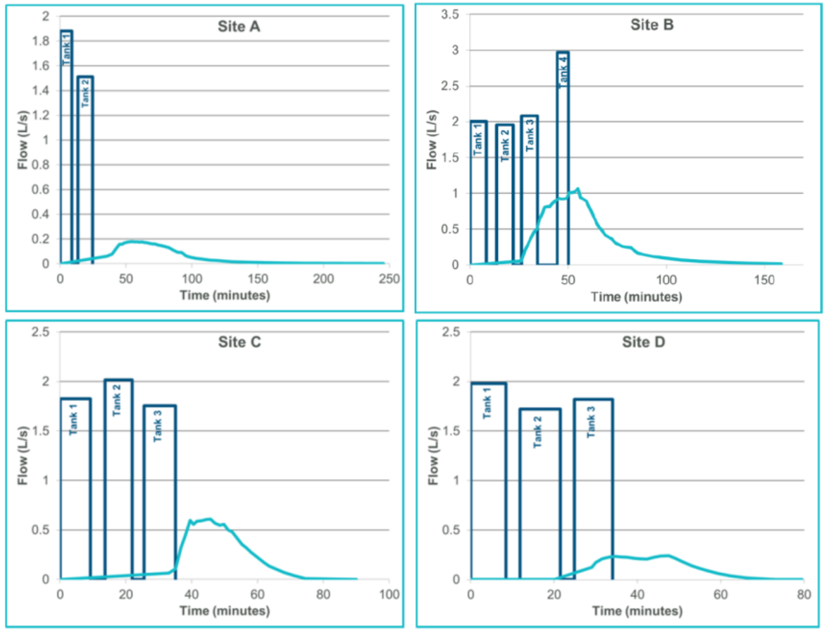


Figure 1 Hydrographs of Inflow and Under-Drainage for Each Bioretention System

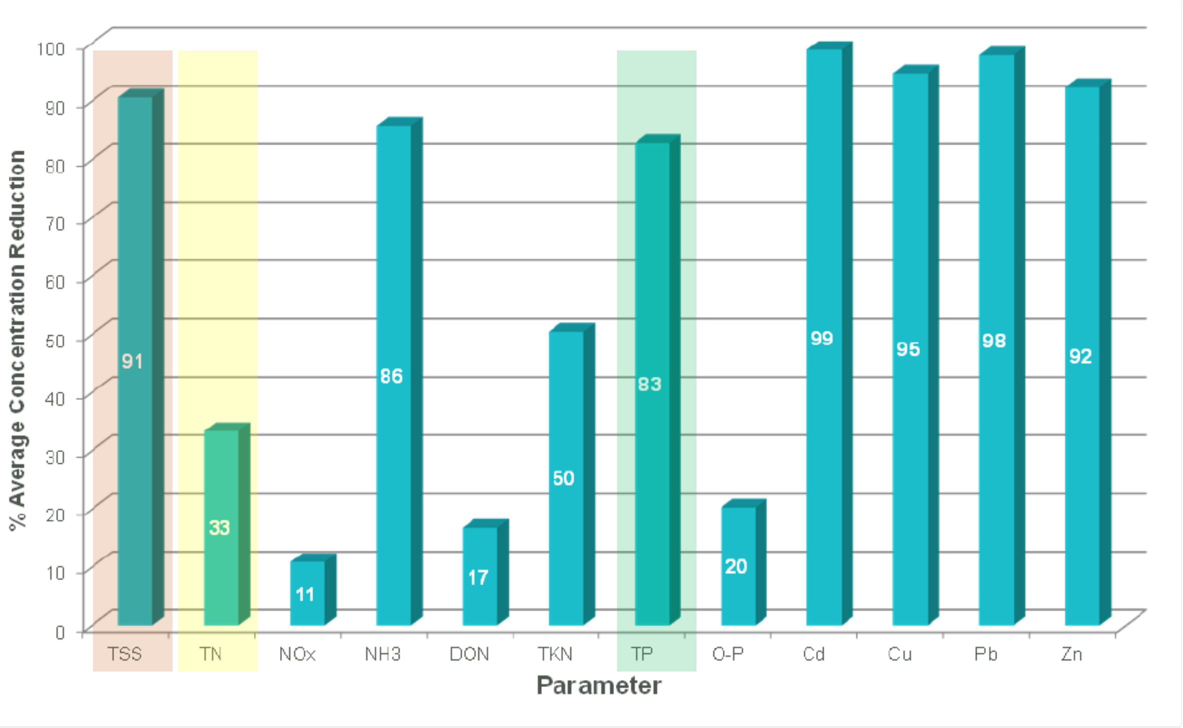


Figure 2 Graph of Average Flow-weighted Pollutant Concentration Reduction

Field studies

Johnson et al (2019):

- Chapel Hill, North Carolina, USA; constructed 2001; 90m^2 area (14% of catchment 2002-03; 8% of catchment 2003-now); 1.2m deep sandy filter media; Perennial grasses, trees & shrubs
- 1st **monitoring:** Flow & WQ monitored June 2002 to April 2003 (10 real events)
- 2nd **monitoring:** Feb 2017 to March 2018 data (18 real events)

Figure 1. Bioretention cell during initial monitoring period (**left**) and return monitoring period (**right**).

Example studies

Johnson et al (2019):

- N & P removal improved over time
- 2nd monitoring CRE: TP 39%, TN 26%

Table 3. Median EMCs and efficiency ratio (ER) for sampled analytes during each monitoring period.

Pollutant	Initial Monitoring Period EMC In (mg/L)	Initial Monitoring Period EMC Out (mg/L)	Initial Monitoring Period Change (%)	Second Monitoring Period EMC In (mg/L)	Second Monitoring Period EMC Out (mg/L)	Second Monitoring Period Change (%)
TN	0.89	1.23	+37.6 *	1.51	1.12	−25.8 *
TKN	0.74	1.41	+90.5 *	1.29	0.95	−26.4
TAN	0.17	0.05	−70.6	0.19	0.06	−68.4 *
NO_3-N	0.15	0.18	+20.0 *	0.23	0.08	−67.4 *
ON	0.56	0.70	+25.0 *	0.95	0.84	−12.1
TP	0.14	0.17	+21.4	0.14	0.09	−39.3 *
OP	0.07	0.05	−28.6	0.02	0.03	+50.0
PBP	0.04	0.04	0.0	0.11	0.04	−63.6

* denotes statistical significance ($p < 0.05$).

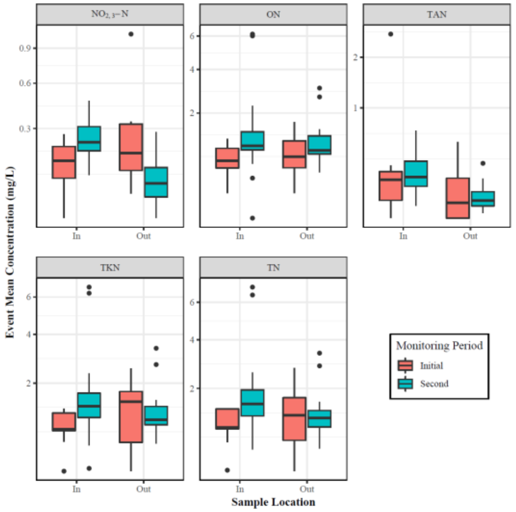


Figure 2. Event mean nitrogen species concentrations for sampled storm events at the inlet (ir outlet (out) of the Chapel Hill bioretention cells (BRC) during each monitoring period.

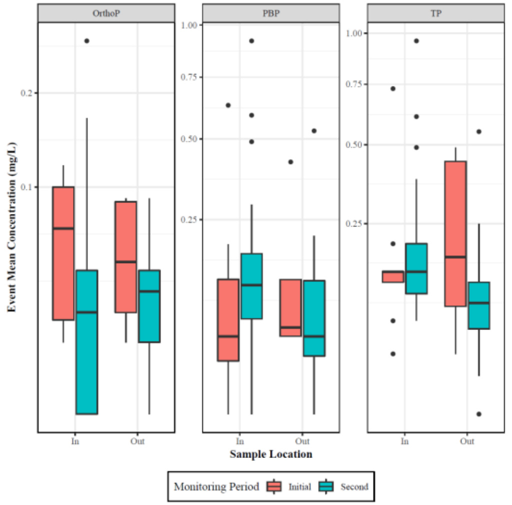


Figure 3. Event mean phosphorus species concentrations for sampled storm events at the inlet (in) and outlet (out) of the Chapel Hill BRC during each monitoring period.

- *"If designed, built, and maintained correctly, bioretention appears to provide sustained treatment of stormwater runoff for nitrogen and phosphorus for nearly two decades, and likely longer."* (Johnson et al, 2019)

Example studies

- High flow biofiltration:

  - Smolek A P, Anderson A R, Hunt W F, 2018, *Hydrologic and Water-Quality Evaluation of a Rapid-Flow Biofiltration Device*. Journal of Environmental Engineering 144(2), February 2018.
  - Herrera Environmental Consultants, 2014, *Technical Evaluation Report – Filterra® System Phosphorus Treatment and Supplemental Basic Treatment Performance Monitoring*. Prepared for Americast Inc.
  - Dalrymple B, Wicks M, 2021, *Stormwater treatment performance for a high flow rate biofiltration system at Western Sydney, Kingswood, NSW, Australia* (pending publication).

Example studies

Smolek et al (2018):

- North Carolina State University, Fayetteville, North Carolina, USA; activated 2012, 2.2m^2 area (0.22% of catchment); 0.53m deep Filterra filter media; Crepe myrtle *(Lagerstroemia spp)*
- Flow & WQ monitored 2013-14; data for 34 real events
- Mean CRE: TSS 92%, TP 54%, TN 33%
- 56% median peak flow reduction
- 6% of unaccounted runoff volume loss

Table 9. Summary Statistics for Event Mean Concentrations of All Pollutants

Pollutant	Location	<MDL (%)	Event mean concentration (mg/L)							
			n	Range	$\tilde{x}$	$\bar{x}$	SD	In versus out significance p-value	Median removal efficiency $\widetilde{RE}$	Mean removal efficiency $\overline{RE}$ [95% CI]
TSS	IN[a]	0	29	20–730	68	122	137	**< 0.00001**[b]	**94**	**92 [90–94]**
	OUT[a]	0		1–16	4	5	4			
SSC	IN[a]	0	22	12–353	82	118	95.46	**< 0.00001**[b]	**97**	**94 [92–97]**
	OUT[a]	0		1–12	3	4	2.78			
TP	IN[a]	0	33	0.03–0.59	0.100	0.132	0.115	**< 0.00001**[c]	**62**	**54 [43–65]**
	OUT[d]	27		< MDL–0.14	0.038	0.047	0.031			
TP (TAPE)	IN[a]	0	16	0.11–0.30	0.185	0.208	0.121	**< 0.00001**[c]	**70**	**66 [57–75]**
	OUT[e]	6		< MDL–0.09	0.052	0.063	0.037			
TDP	IN[f]	58	31	< MDL–0.39	0.018	0.049	0.077	0.352[c]	0	−3 [−25 – 21]
	OUT[d]	61		< MDL–0.08	0.016	0.024	0.021			
OP	IN[f]	94	32	—	—	—	—	—	—	—
	OUT[e]	100		—	—	—	—			
TN[g]	IN[a]	—	34	0.35–2.62	1.06	1.17	0.63	**0.0002**[b]	**35**	**33 [21–44]**
	OUT[a]	—		0.26–2.10	0.53	0.71	0.46			
TAN	IN[d]	32	34	< MDL–0.57	0.09	0.15	0.16	**0.0299**[c]	**39**	**13 [−17 – 44]**
	OUT[d]	47		< MDL–0.42	0.05	0.07	0.09			
TKN	IN[a]	0	34	0.34–2.40	0.99	1.08	0.57	**< 0.00001**[c]	**44**	**43 [34–53]**
	OUT[d]	12		< MDL–1.40	0.46	0.56	0.32			
$NO_{2,3}$—N	IN[d]	15	34	< MDL–0.45	0.11	0.13	0.10	0.0974[c]	−53	−97 [−168 to −28]
	OUT[d]	12		< MDL–0.80	0.15	0.18	0.16			
Cu	IN[a,e]	8	13	< MDL–0.027	0.0073	0.0080	0.0069	0.5954[b]	28	−10 [−54 – 31]
	OUT[a]	0		0.002–0.012	0.0049	0.0062	0.0034			
Zn	IN[a,e]	8	13	< MDL–0.180	0.049	0.059	0.047	**0.0019**[c]	**74**	**66 [53–79]**
	OUT[d]	46		< MDL–0.035	0.013	0.018	0.010			

Example studies

Herrera (2014) :

- Bellingham, Washington, USA; 2.2m^2 area (0.13% of catchment); installed in 2007, 0.53m deep Filterra filter media
- WQ monitored 2013; data for 22 real events
- Mean CRE: TSS 90%, TP 73%

Example studies

Dalrymple et al (2021):

- Kingswood, NSW, Australia; activated 2018, 1.45m^2 area (0.34% of catchment); 0.53m deep Filterra filter media; 'Bush Christmas' Lilly pilly *Syzygium australe*
- WQ monitored 2018 to present; data for 28 real events (17 post establishment)

Dalrymple et al (2021):

	No. of events	TSS Influent	TSS Effluent	TP Influent	TP Effluent	TN Influent	TN Effluent
Mean - first 12 months	11	31	8.6	0.111	0.044	1.897	1.215
Mean - after 12 months	17	46	9.0	0.134	0.023	1.217	0.620
ER % - first 12 months	11	72%		60%		36%	
ER % - after 12 months	17	80%		83%		49%	

Field studies - Results

Conventional biofiltration:

- Typically high TSS, TP & heavy metal concentration reductions
- Variable TN reductions
    - No field study with TN CRE's >33%
- Possibly no field study to date for 'real' events with currently recommended specifications for Australia

High flow biofiltration:

- Mean CRE's: TSS 80-92%, TP 62-83%, TN 33-49%

Generally:

- Treatment performance likely to improve over time IF system is appropriately maintained
- Significant exfiltration of flow (to groundwater/ baseflow)

On-line poll

1. Do you believe that bioretention systems typically provide a sustained, effective stormwater treatment function consistent with their design intent ?

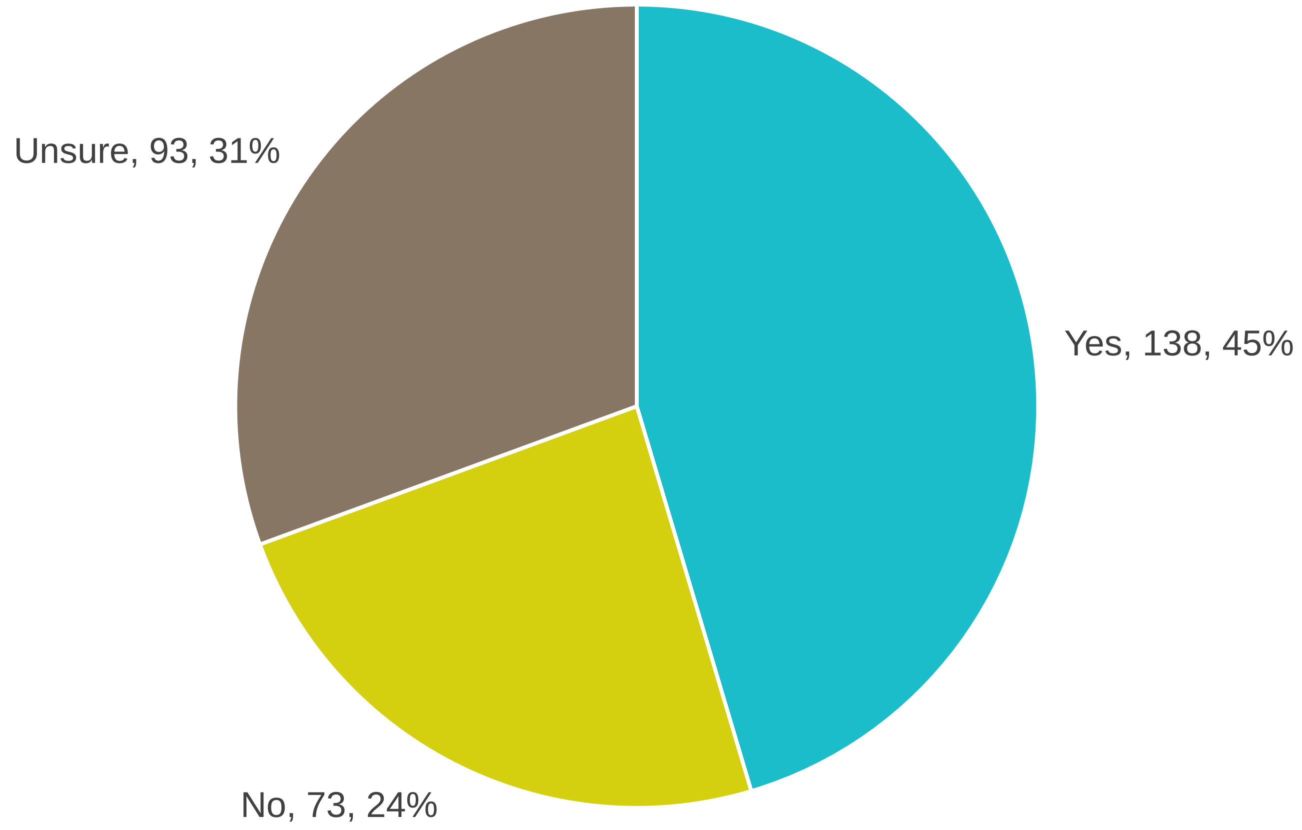
2. Do you believe that MUSIC provides an appropriate method to predict the stormwater treatment performance of a bioretention system, assuming that the bioretention system has been appropriately designed, constructed, established and managed ?

On-line poll results

www.oceanprotect.com.au

- 304 respondents

Poll results to Question 1:
"Do you believe that bioretention systems typically provide a sustained, effective stormwater treatment function consistent with their design intent ?"

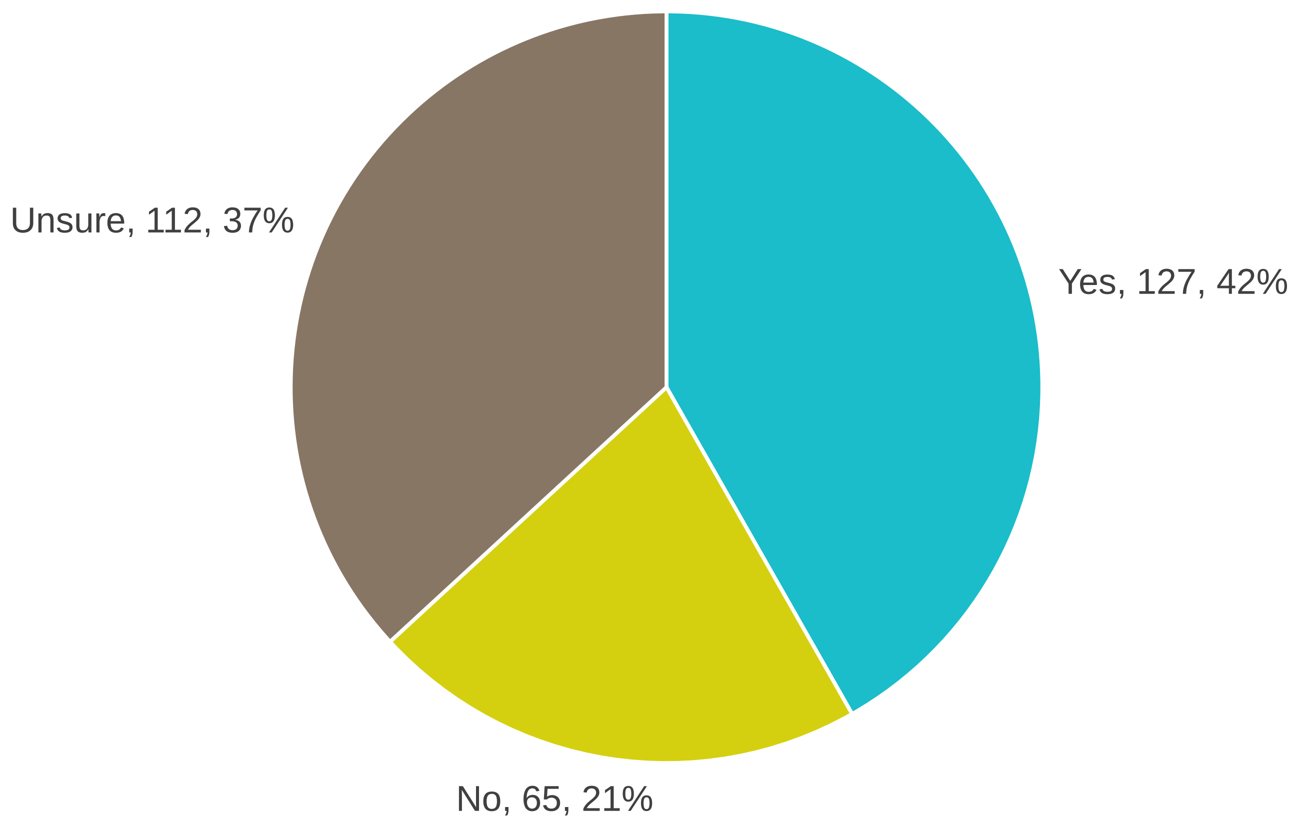


On-line poll results

304 respondents

Poll results to Question 2:

"Do you believe that MUSIC provides an appropriate method to predict the stormwater treatment performance of a bioretention system, assuming that the bioretention system has been appropriately designed, constructed, established



Our thoughts

- If designed, installed, established, and maintained correctly, bioretention should provide appropriately sustained treatment of stormwater runoff for nearly two decades, and likely longer

Now what are we supposed to do ?

Recommendations

- Do your own review of biofiltration performance monitoring (or seek advice from suitably qualified personnel/ groups)
- Ensure any biofiltration systems are appropriately designed, installed, established & maintained
- Consider undertaking appropriate ‘real world’, long-term performance monitoring

Further studies

Blacktown City Council

- Blacktown City Council to undertake the *"Basin F6.1 Water Quality and Quantity Data Acquisition Project"*
- 5-year stormwater treatment performance evaluation of:
  - 2 x GPTs
  - 6 x biofiltration systems

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THANK YOU