Supplementary information

Ranking three Water Sensitive Urban Design (WSUD) practices

based on hydraulic and water quality treatment performance:

Implications for effective stormwater treatment design

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Table S1(a) Characteristics of rainfall events selected and hydraulic performance of the bioretention basin

Sampling date	Rainfall events selected	Antecedent dry hours	rainfall depth (mm)	30min intensity (mm/h)	Peak flow reduction%	Volume reduction%
10/25/2007	B1	318	22.4	16	92.57	38.03
10/31/2007	B2*	63	8.4	14	92.50	44.83
11/6/2007	B3	122	4.6	4	90.00	92.86
11/7/2007	B4	30	25.4	36	74.55	6.90
11/11/2007	B5	63	7.2	14	92.50	52.63
11/17/2007	B6*	119	7	10	91.18	77.27
12/1/2007	B7	126	18	32	95.67	25.00
12/8/2007	B8*	59	8.4	10	95.13	51.85
1/29/2008	B9*	207	20.2	16	95.12	38.46
3/5/2008	B10*	231	1.8	10	100.00	100.00
3/8/2008	B11*	42	1	8	100.00	100.00
3/17/2008	B12*	220	11.2	16	91.74	65.52
4/5/2008	B13*	216	6	10	100.00	100.00
4/17/2008	B14	167	16.4	14	89.41	26.67
5/14/2008	B15*	632	3.6	12	100.00	100.00
5/29/2008	B16	951	42.8	32	94.49	26.12
10/9/2008	B17*	598	21.8	30	95.00	31.43
12/29/2008	B18*	26	14.4	18	96.46	16.67
1/22/2009	B19	315	50	46	96.10	9.86
2/11/2009	B20*	361	6.2	16	96.49	70.00
2/14/2009	B21	68	63.2	48	96.38	3.82
3/16/2009	B22	51	25	38	96.67	11.24

*Rainfall events selected for water quality analysis because only these events have complete water quality data required for this study.

Table S1(b) Characteristics of rainfall events selected and hydraulic performance of the constructed wetland

Sampling date	Rainfall events selected	Antecedent dry hours	rainfall depth (mm)	30min intensity (mm/h)	Peak flow reduction%	Volume reduction%
3/8/2008	W1*	231	1.8	8	98.51	22.50
3/17/2008	W2*	220	11.2	16	98.61	3.63
4/5/2008	W3*	216	6	10	98.25	-8.70
4/17/2008	W4*	167	16.4	14	98.21	2.41
5/14/2008	W5*	632	3.6	12	98.61	60.87
5/29/2008	W6*	951	42.8	32	99.18	52.04
5/31/2008	W7	14	92.6	46	98.57	68.54
11/16/2008	W8	696	31.2	22	98.68	35.69
11/25/2008	W9	119	93.6	54	99.55	82.07
12/29/2008	W10	26	14.4	18	99.59	21.70
1/3/2009	W11	122	8.6	14	99.32	6.02
1/22/2009	W12	315	50	46	99.45	55.13
2/11/2009	W13*	361	6.2	16	99.54	11.57
2/17/2009	W14	8	4	8	96.67	-14.81
3/4/2009	W15	133	3.2	10	98.51	40.68
3/16/2009	W16	51	25	34	99.49	52.00
5/6/2009	W17	105	16	14	97.53	11.55

*Rainfall events selected for water quality analysis because only these events have complete water quality data required for this study.

Table S1(c) Characteristics of rainfall events selected and hydraulic performance of the roadside swale

Sampling date	Rainfall events selected	Antecedent dry hours	rainfall depth (mm)	30min intensity (mm/h)	Peak flow reduction%	Volume reduction%
1/29/2008	S1	207	20	16	60.32	15.79
3/5/2008	S2*	231	1.8	10	90.91	75.00
3/8/2008	S3	42	1	8	100.00	100.00
3/10/2008	S4*	36	2.4	10	80.00	54.55
3/17/2008	S5	220	11.2	16	62.65	21.43
4/5/2008	S6	216	6	10	62.22	28.57
4/17/2008	S7*	167	16.4	14	74.17	22.22
5/14/2008	S8*	632	3.6	12	89.52	88.24
5/29/2008	S9	951	42.8	32	19.72	-11.93
12/29/2008	S10*	26	14.4	18	43.88	14.71
1/22/2009	S11*	315	50	46	17.47	-8.27
2/11/2009	S12	361	6.2	16	81.92	46.43
3/16/2009	S13*	51	25	38	38.48	-3.28

*Rainfall events selected for water quality analysis because only these events have complete water quality data required for this study.

Table S2(a) Water quality performance of the bioretention basin

Rainfall events selected	TSS		TN		TP	
	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)
B2	24.3	0.59	1.6	0.039	0.108	0.003
B6	12.1	0.09	1.14	0.009	0.113	0.001
B8	39	0.78	1.83	0.036	0.2	0.004
B9	24.5	1.21	1.16	0.057	0.098	0.005
B10	-*	0	-	0	-	0
B11	-	0	-	0	-	0
B12	57.3	0.92	2.19	0.035	0.163	0.003
B13	-	0	-	0	-	0
B15	-	0	-	0	-	0
B17	20	1.46	1.35	0.098	0.104	0.008
B18	24.4	1.49	1.26	0.077	0.132	0.008
B20	25.7	0.25	1.38	0.014	0.179	0.002

*no data due to sampling failure

Table S2(b) Water quality performance of the constructed wetland

Rainfall events selected	TSS		TN		TP	
	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)
W1	9	0.05	0.89	0.004	0.167	0.001
W2	15.4	0.6	0.75	0.029	0.101	0.004
W3	6.4	0.08	0.37	0.005	0.034	0
W4	8.7	0.72	0.47	0.039	0.023	0.002
W5	16.3	0.05	0.56	0.002	0.025	0
W6	11.4	-	0.46	-	0.052	-
W13	15.7	0.32	0.75	0.015	0.066	0.001

Table S2(c) Water quality performance of the roadside swale

Rainfall events selected	TSS		TN		TP	
	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)	Outflow EMC (mg/L)	Outflow load (kg/ha)
S2	5.6	0.011	0.69	0	0.072	0
S4	5	0.016	0.36	0	0.02	0
S7	10.3	0.524	0.57	0.03	0.061	0.03
S8	23	0.058	1.02	0	0.105	0
S10	13.5	0.874	1.11	0.07	0.18	0.011
S11	10.9	3.026	0.67	0.19	0.056	0.015
S13	9.9	1.264	1.17	0.15	0.087	0.011

Pollutants testing methods

TSS testing

TSS concentration/load was measured by filtering a 20 mL volume of sample through a 1 μm glass-fibre filter paper and measuring the weight of the residue retained on it. The filter papers were pre-washed using deionised water and oven dried before use. Samples were filtered through the pre-weighed filter papers and the filter paper together with the residue retained was oven dried at 103-105 ºC. The increase in weight of the filter paper was determined to obtain the TSS weight in the volume filtered. The method complied with the Standards Methods for Water and Wastewater Method No. 2540 D (APHA 2017).

TN and TP testing

TN and TP were tested using a SmartChem 140 Discrete Analyser (Figure S1). Additionally, a block digestion system was used for digestion of samples for total kjeldahl nitrogen (TKN) and TP. SmartChem 140 Discrete Analyser was used for nitrite nitrogen (NO_2^-), nitrate nitrogen (NO_3^-) and TKN testing. TN was obtained by the addition of TKN, NO_2^- and NO_3^-.

A number of test methods are included in a single run by the SmartChem 140 Discrete Analyser. The calibration of each test method was inspected separately while the instrument was in operation. When the concentration of the analyte in the sample was above the method detection range, the samples were diluted automatically. In addition, sample blanks and quality control solutions were included during the testing process. In terms of SmartChem 140, the range of measurement for NO_2^-, NO_3^- and TKN are 0.01-1.00mg/L, 0.02-20 mg/L and 0.10-20.0 mg/L, respectively, while the ranges of measurement for TP were 0.063-5.0 mg/L. The test methods for NO_2^-, NO_3^- ,TKN and TP were 4500-NO2-B, 4500-NO3-E, 4500-Norg-B and 4500-P-B, respectively, specified in the Standards Methods for Water and Wastewater (APHA 2017).

Figure S1 SmartChem 140 Discrete Analyser

PROMETHEE method

PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) is an unsupervised method for rank-ordering objects (Keller *et al.* 1991). Each variable (such as average values and CV values of peak flow reduction, runoff volume reduction, outflow pollutant EMCs and outflow pollutant loads in this study) has to be modelled by; (i) supplying a preference function (Linear, V-shape and Usual functions) and thresholds to indicate how objects are to be compared; (ii) indicating how the objects are to be ordered: top-down (maximised) or bottom-up (minimised) and, (iii) supplying a weighting to reflect the importance of one criterion over another (this was set as 1 in this study, as all variables were equally important).

A set of net ranking outflow values, Φ, are computed for each object (the three WSUD systems in this study) on the basis of the partial ranking outflow indices, $+\Phi$ and $-\Phi$. The objects are rank-ordered from the most preferred one (the most positive *(+) Φ* value) to the least well performing one (the most negative *(–) Φ* value). A large difference between two net ranking outflow values, Φ, indicates that the two objects are dissimilar. Generally, 10% of the difference of Φ values between the most preferred objects and the least well performing object is considered as the threshold to compare the two objects. Two objects are seen as similar if the difference in Φ values between them is smaller than 10% of the difference between the highest and lowest Φ values. DecisionLab software (DecisionLab 2000) was used for PROMETHEE analysis in the research study.

Information about the three WSUD systems

Constructed wetland

The constructed wetland contains a sedimentation pond, two wetland cells and an overflow bypass system (see Figure S2). There were two pipes which conveyed stormwater to the wetland from two separate sub-catchments. The larger pipe (750 mm diameter) conveyed stormwater from the larger sub-catchment while the smaller pipe (300 mm diameter) conveyed stormwater from the smaller sub-catchment. Consequently, two stormwater monitoring stations were required for the wetland inlets. Stormwater entering the constructed wetland was pre-treated in the sedimentation pond prior to receiving further treatment in the wetland cells. A cell inlet control pit at the pond outlet ensures that the stormwater enters the cells slowly because high flow might disturb the cells and vegetation. Additionally, the maximum inflow rate which was allowed to enter the wetland cells was controlled by the bypass weir. A 7 m wide bypass with a broad crested weir controlled the runoff level in the pond and once the level was exceeded, the excess runoff entered the receiving water through the bypass channel. Stormwater passing the sedimentation pond was further treated as it flows through wetland cells 1 and 2, before it overflows through a PVC riser. From the outlet control pit, the runoff flows though the outlet pipe to the wetland outlet station where the flow was measured and the samples were collected.
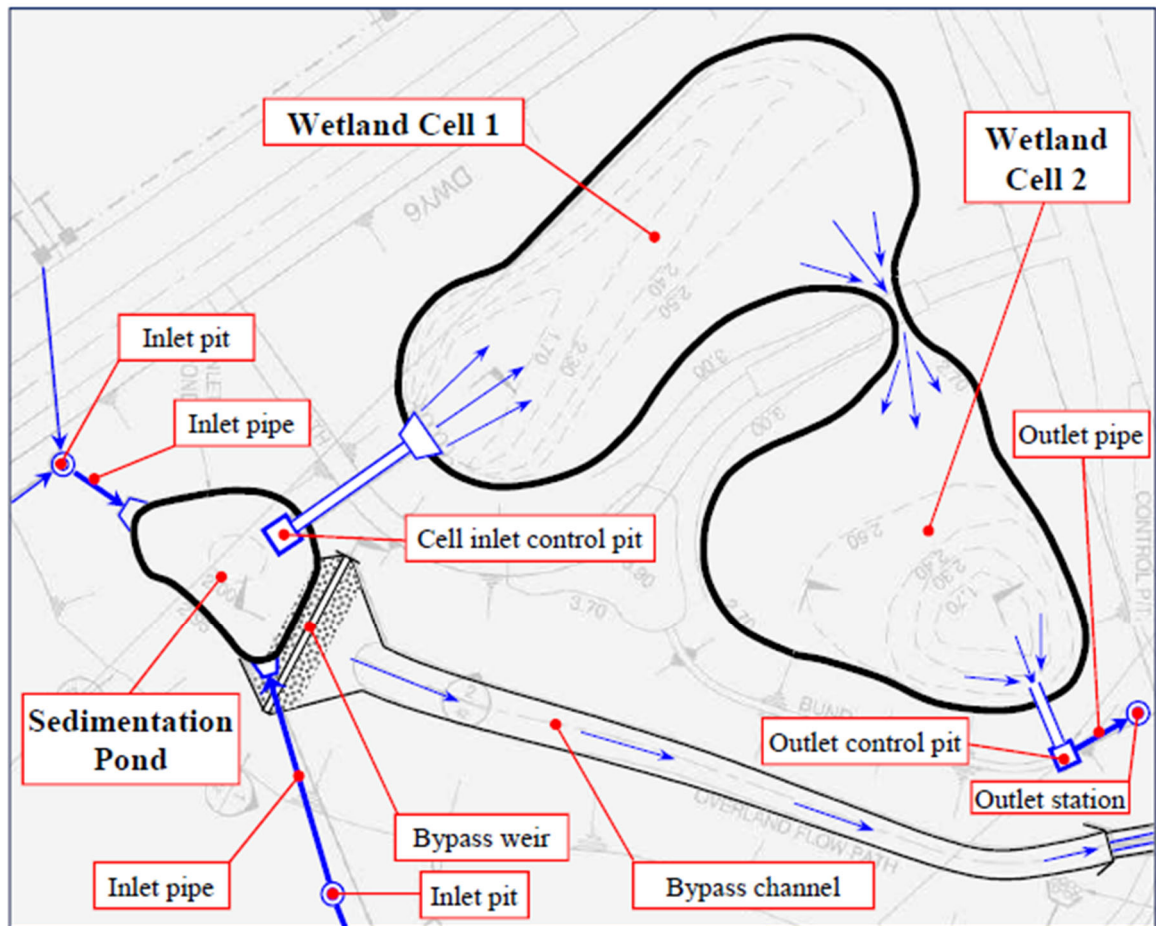
Figure S2 Constructed wetland configuration (Adapted from Mangangka, 2013)

Bioretention basin

The stormwater from the contributing catchment flows through a drainage network to the bioretention basin inlet where the stormwater was monitored. A v-notch weir was set-up at the bioretention basin inlet to monitor the stormwater flow, and an automatic sampler was used to collect samples for water quality analysis. The inlet drained the stormwater from the catchment into the bioretention basin where it receives treatment by filtration through the engineered filter media.

The bioretention basin area was 248 m^2 with a grass bed surface. The grass maintained the porosity of the bioretention surface. The filter media with 0.8 m thickness promoted stormwater treatment through infiltration. The treated stormwater which infiltrated and passes through the filter media drains to the 0.2 m thick drainage layer underneath the filter media consisting of granular material (see Figure S3). The bioretention basin has a network of perforated pipes in the drainage layer which

conveyed infiltrated stormwater to the bottom part of the outlet control pit. Perforated pipes are installed at the bottom of the drainage layer with 0.5% slope. The top weir of the outlet control pit is designed 10 cm above the elevation of the surface of the bioretention basin. This allows stormwater ponding up to 10 cm on the surface of the bioretention basin. The outlet control pit is utilised to be a bypass control. When the depth of stormwater exceeds 10 cm, it bypasses into the pit and no treatment is provided.
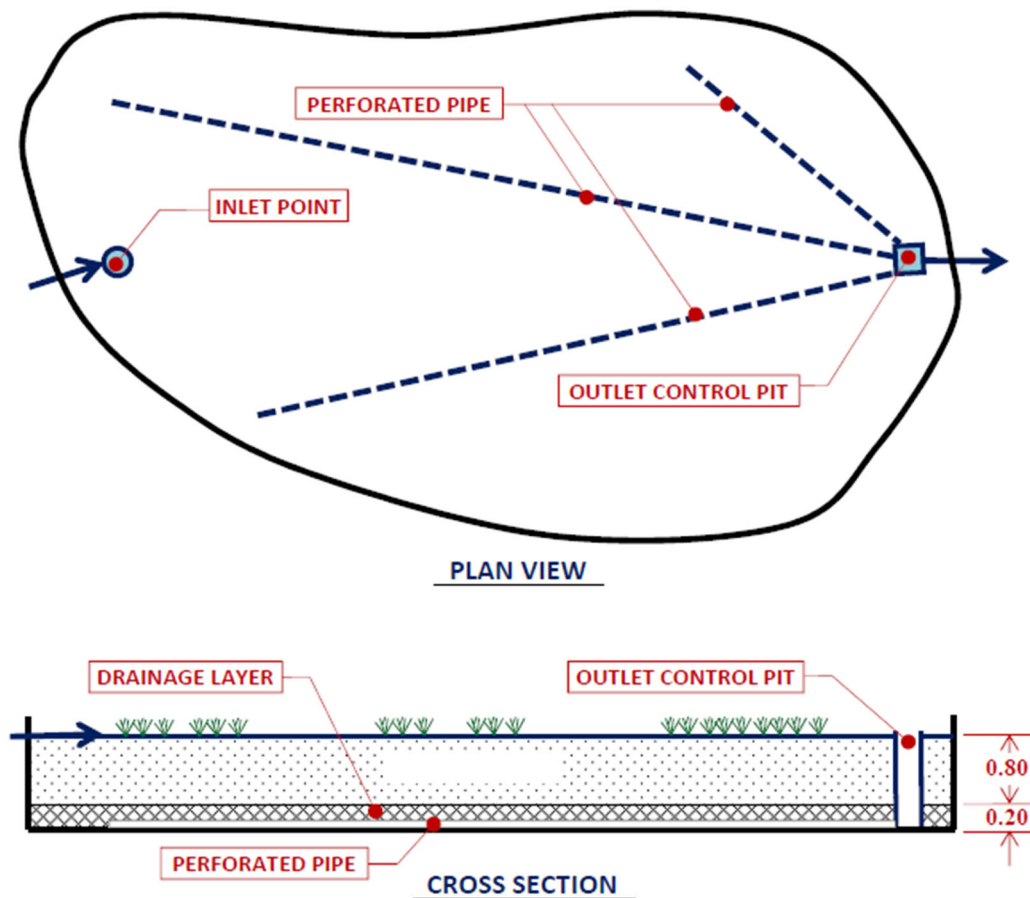

Figure S3 Bioretention basin configuration (Adapted from Mangangka, 2013)

Roadside swale

Bioretention swales are 1 m wide (see Figure S4) and run down either side of the street. They receive stormwater from houses, gardens and the road. In total, the bioretention swales are 2.9 % of the contributing catchment area (9560 m^2), of which 51% is impervious area. Flush kerbing allows stormwater to flow from the road into the swale for treatment. Runoff from roofs is conveyed via a PVC pipe to a small bubbler pit in the middle of the swale where stormwater exits into the swale. A culvert receives all stormwater inputs from the swales.
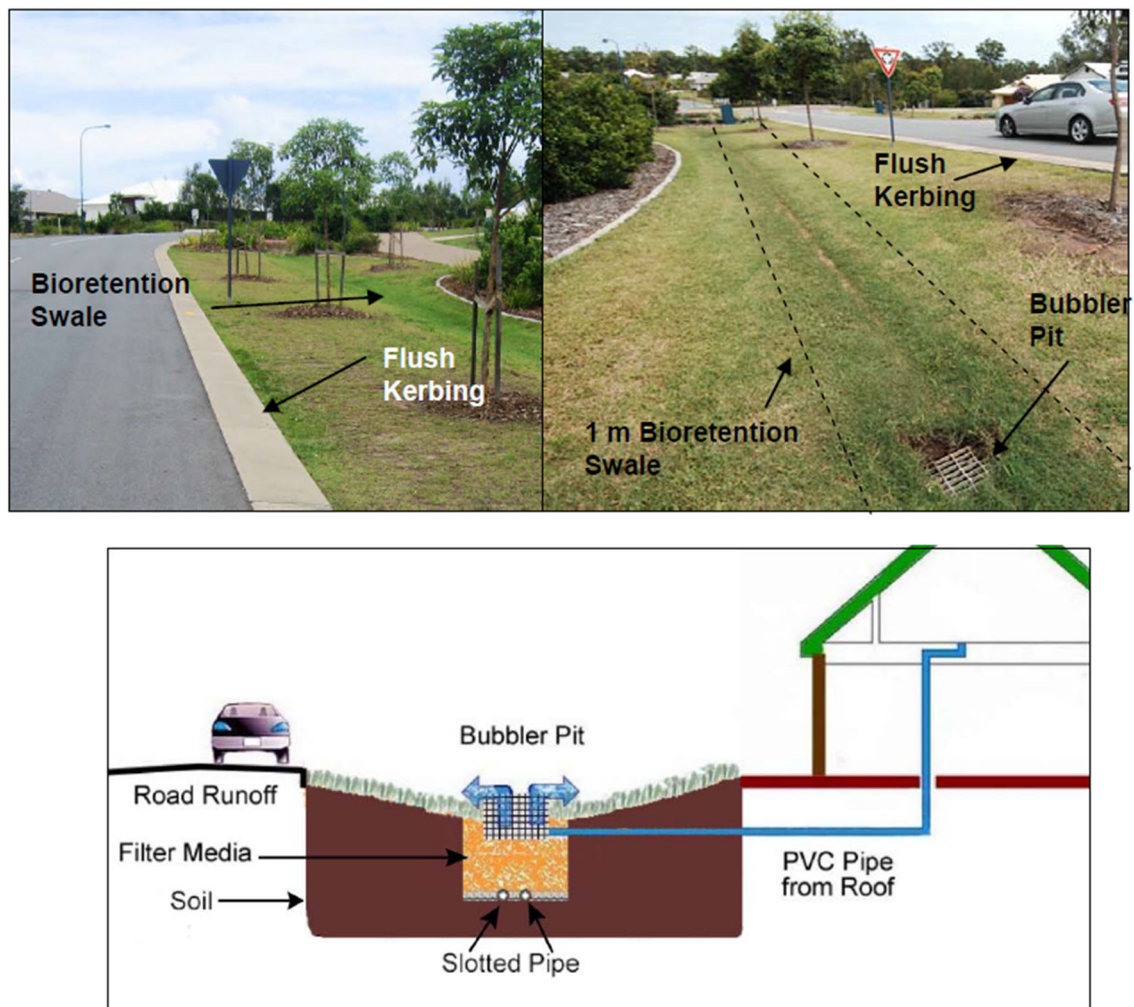

Figure S4 The roadside swale (Adapted from Parker, 2009)

References

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