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Performance characterisation of a stormwater treatment bioretention basin

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ABSTRACT

Treatment performance of bioretention basins closely depends on hydrologic and hydraulic factors such as rainfall characteristics and inflow and outflow discharges. An in-depth understanding of the influence of these factors on water quality treatment performance can provide important guidance for effective bioretention basin design. In this paper, hydraulic and hydrologic factors impacting pollutant removal by a bioretention basin were assessed under field conditions.

Outcomes of the study confirmed that the antecedent dry period plays an important role in influencing treatment performance. A relatively long antecedent dry period reduces nitrite and ammonium concentrations while increasing the nitrate concentration, which confirms that nitrification occurs within the bioretention basin. Additionally, pollutant leaching influences bioretention basin treatment performance, reducing the nutrients removal efficiency, which was lower for high rainfall events. These outcomes will contribute to a greater understanding of the treatment performance of bioretention basins, assisting in the design, operation and maintenance of these systems.

1. Introduction

Bioretention basins are among the most commonly used stormwater treatment measures using filtration as the primary mechanism for pollutant removal, supported by evapotranspiration, adsorption and biotransformation (Davis, 2007). Additionally, a bioretention basin attenuates runoff peak flow and reduces runoff volume through detention and retention. As noted by past researchers (Davis, 2008; Hunt et al., 2008), the water quality treatment performance of bioretention basins closely depends on hydrologic and hydraulic factors such as rainfall characteristics and inflow and outflow parameters. In this context, an in-depth understanding of the influence of hydrologic and hydraulic factors on treatment performance can provide important guidance for effective bioretention basin design.

Researchers using both, field and laboratory scale studies have assessed the performance of bioretention basins, highlighting the influence of hydrologic and hydraulic factors on pollutant removal processes (Dietz and Clausen, 2005; Heasom et al., 2006; Hsieh and Davis, 2005). In terms of field scale studies, past researchers have commonly evaluated the long term treatment performance rather than event-based performance (Hunt et al., 2006; Hatt et al., 2009a). This limits the detailed understanding of treatment performance, as only lumped characteristics of hydraulic and pollutant treatment processes are considered. Research studies focussing on developing an in-depth understanding of processes in bioretention basins have primarily been undertaken at the laboratory scale (Hatt et al., 2008). However, these studies can be far from reality in terms of replicating field conditions. This results in knowledge gaps relating to field performance, influential factors and event-based pollutant removal processes.

This research study was undertaken to create new knowledge relating to the influence of hydraulic and hydrologic factors on pollutant removal processes. The study was undertaken in a monitored bioretention basin in the field serving a small residential

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catchment. Detailed monitoring was conducted to characterise pollutant removal performance as a rainfall event progressed. A range of influential hydrologic and hydraulic parameters were investigated using a conceptual model which was calibrated using recorded rainfall event data. The study outcomes will contribute to a greater understanding of the treatment performance of bioretention basins and in turn enable improved design and operation and maintenance of these systems.

2. Materials and methods

2.1. Study sites

The bioretention basin selected for the study is located at 'Coomera Waters' residential estate, Gold Coast, South East Queensland, Australia. The bioretention basin receives stormwater from a catchment with a total area of 6530 m^2. About 52% of the area is impervious, consisting of roofs, road, and driveways, while the pervious areas mainly consist of lawns and yards (see Fig. 1). Design information on the bioretention basin is provided in the Supplementary Information.

2.2. Sample collection and laboratory testing

The inlet and outlet of the bioretention basin have been monitored since April 2008 using automatic monitoring stations to record rainfall and runoff data and to capture stormwater samples for water quality testing. Flow measurements were undertaken using calibrated V-notch weirs and samples were collected by stage triggered, peristaltic pumping. Discrete samples were collected during rainfall events to investigate the variation in water quality during a runoff event. The samples collected were tested for total nitrogen (TN), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), total phosphorus (TP), phosphate (PO_4^{3-}) and total suspended solids (TSS), which are the primary stormwater pollutants (Goonetilleke et al., 2005; Liu et al., 2012). Total pollutant loads and event mean concentrations (EMCs) at the inlet and outlet were determined for each rainfall event. Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS, 1998).

2.3. Development of bioretention basin hydraulic conceptual model

A conceptual model, where the bioretention basin was divided into 10 equal zones (Fig. 2a) was developed to replicate the hydraulic behaviour of the system. The stormwater movement over the surface was replicated as flow from Zone 1 where the inlet structure is located, to Zone 10 where the outlet structure is located. Each zone was considered to be a soil column in which the water flows downward to replicate the infiltration process. The stormwater flow within the bioretention basin was modelled according to the processes described in the following steps, which were replicated by a range of mathematical equations as shown by the numbered labels given in Fig. 2b.

- Stormwater runoff inflow (1) into the bioretention basin infiltrates into the soil column (2). This is replicated using an infiltration model;
- When the inflow rate is higher than the soil column infiltration capacity, the excess runoff becomes surface flow to the next soil column (3);
- The infiltrated water percolates until it reaches the drainage layer where the stormwater is temporarily stored (4);
- Part of the stormwater stored in the drainage layer percolates to the original soil layer underneath (5).
- Through perforated pipes, stormwater in the drainage layer flows to the outlet structure where the flow is monitored (6).

Details of the conceptual model development, calibration and simulation can be found in Mangangka (2012).

2.4. Rainfall event selection and hydrologic/hydraulic parameters

Twelve monitored rainfall events were selected for the analysis. The selected rainfall events were less than 1 year average recurrence interval (ARI). This ARI range is used for most urban stormwater treatment system design (Dunstone and Graham, 2005) due

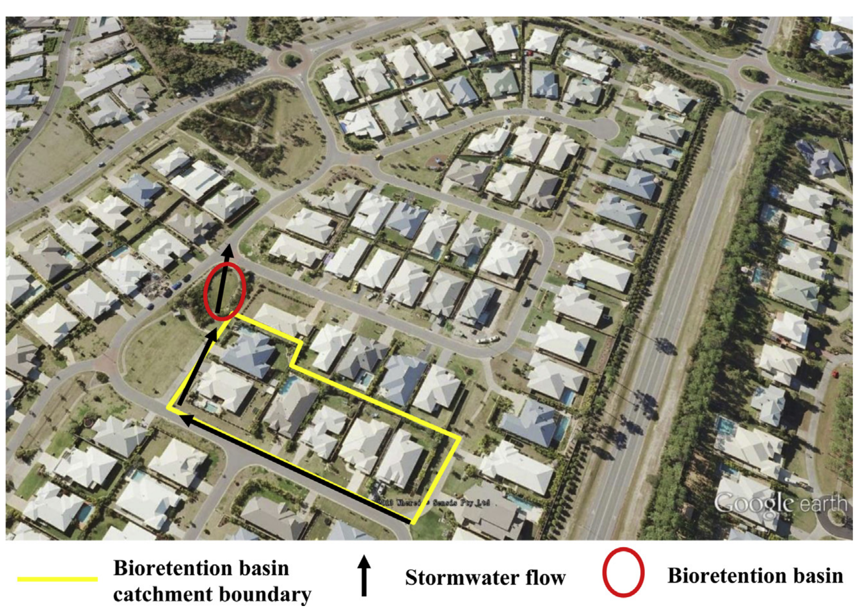

Fig. 1. Bioretention basin study site.

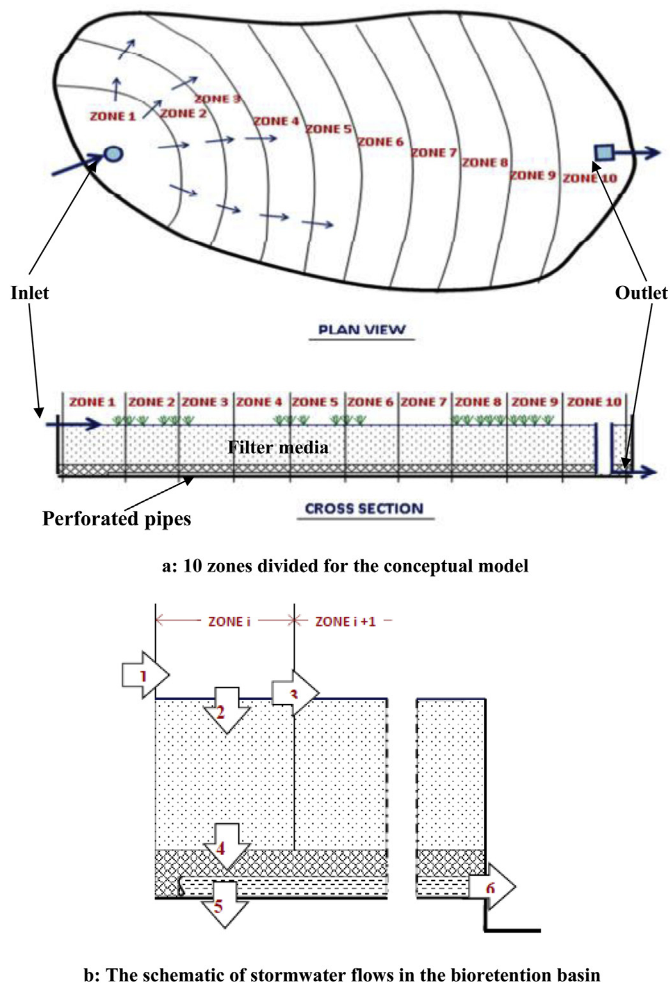

Fig. 2. The conceptual model.

to their relatively more frequent occurrence and being responsible for a high fraction of annual runoff volume from catchments (Liu et al., 2013). Additionally, the twelve rainfall events accommodated the mid-range of the rainfall depth (4.8–52.0 mm) typical to the study area and an appropriate number of stormwater runoff samples were captured by the installed automatic sampler. The characteristics of the rainfall events considered as hydrologic parameters included rainfall depth (RD), antecedent dry period (AD) and average rainfall intensity (RI) (see Table 1).

Table 2
PROMETHEE ranking.

Ranking	Rainfall events	φ value	Rainfall depth (mm)
1	B6	0.2955	51.8
2	B5	0.2926	44.6
3	B2	0.2712	52.0
4	B7	0.1507	25.8
5	B1	0.0141	20.6
6	B12	−0.0117	12.6
7	B10	−0.0801	9.60
8	B11	−0.1089	20.2
9	B8	−0.1246	19.4
10	B4	−0.1324	18.4
11	B3	−0.1526	12.0
12	B9	−0.4139	4.80

Hydraulic parameters generated by the conceptual model consisted of volume treated (VT), volume retained (VR), contributed wetted area (CA) and outflow peak (OP). VT indicates the actual stormwater quantity entering the treatment system while VR is the volume retained within the system at the end of a storm event. As noted by Parker et al. (2009), VR is an important parameter influencing stormwater treatment performance of bioretention basins. CA represents the percentage of the wetted area of the bioretention filter media. This parameter is important for small events where the complete surface area of the system does not contribute to the treatment. OP is the maximum outflow discharge recorded during a rainfall event. These parameters for each event are given in Table 1.

2.5. Data analysis

Firstly, a preliminary analysis was undertaken for identifying appropriate hydrologic and hydraulic factors prior to undertaking the detailed analysis and to prevent correlating parameters overshadowing critical relationships between hydrologic and hydraulic factors and treatment performance of the bioretention basin (Egodawatta et al., 2006). This was conducted using PROMETHEE, which is a multi criteria decision making method as well as the Pearson correlation analysis. Detailed information on PROMETHEE method is provided in the Supplementary Information.

Additionally, Principal Component Analysis (PCA) was used to investigate the relationship between the treatment performance and hydrologic and hydraulic factors. PCA is an effective technique to explore correlations among variables and objects (Kokot et al., 1998). The number of significant principal components was selected using the Scree plot method (Adams, 1995). StatistiXL software (StatistiXL, 2007) was used for PCA in this study. Finally, the original dataset was explored to further analyse the water quality treatment performance.

Table 1
Hydrologic and hydraulic parameters.

No.	Rainfall depth (mm) RD	Rainfall intensity (mm/h) RI	Antecedent dry period (day) AD	Volume treated (m^3) VT	Outflow peak (L/s) OP	Contributing area (%) CA	Volume retained (m^3) VR
B1	20.6	7.36	8.51	54.65	1.528	70	31.33
B2	52.0	14.86	3.05	87.73	3.417	100	22.00
B3	12.0	5.45	6.60	31.03	1.342	50	23.23
B4	18.4	3.91	6.83	51.69	1.258	40	24.81
B5	44.6	5.95	10.48	112.26	1.877	100	48.86
B6	51.8	8.22	13.05	79.06	3.032	70	38.47
B7	25.8	4.69	10.36	70.56	1.550	100	49.51
B8	19.4	8.08	4.24	49.33	1.458	40	20.38
B9	4.80	2.53	4.56	8.70	0.522	10	6.03
B10	9.60	8.73	10.50	31.87	0.933	50	28.41
B11	20.2	8.78	5.88	28.88	1.595	40	23.20
B12	12.6	6.63	13.07	38.82	1.303	60	31.17

3. Results and discussion

3.1. Selection of hydrologic and hydraulic factors

Table 2 gives the PROMETHEE ranking. The φ net value is the net ranking flow where a higher φ net value of an object indicates the higher position in the rank order. It can be noted that the higher ranked objects are those rainfall events with higher rainfall depth. For example, the top three events (B6, B5 and B2) have the highest rainfall depths (51.8 mm, 44.6 mm and 52.0 mm) among the twelve monitored events while the bottom ranked event has the lowest rainfall depth (B9, 4.8 mm). This suggests that rainfall depth is an important factor among the hydraulic parameters and hence could be critical to the overall hydraulic performance of the bioretention basin. Therefore, rainfall depth (RD) was selected for further investigation.

The Pearson correlation matrix (Table 3) showed that VT, OP and CA have very close correlations with RD as the coefficients are 0.887, 0.931 and 0.739, respectively. This essentially confirms that high rainfall depth (RD) leads to high stormwater volume entering the bioretention basin, high outflow peak and large filter media wetted area. Considering the strong correlations, only one factor (RD) was selected for further analysis. The other factors selected for further analysis were VR, RI and AD. AD is an independent factor by its definition since it represents the dry period prior to rainfall occurrence. VR is an important hydraulic factor for most stormwater treatment devices. RI is an independent factor since it shows a relatively weak relationship with the other factors except with OP (0.738).

3.2. Relationship between water quality treatment and hydrologic/hydraulic factors

In order to undertake detailed investigations into the treatment performance, the pollutant load removal and EMC reduction were analysed individually. Accordingly, two data matrices for load and EMC reduction were separately evaluated using PCA. For pollutant load removal, objects were the 12 rainfall events while the variables were the percentages of TSS, TP, TN, NH_4^+, NO_3^-, NO_2^- and PO_4^{3-} load removed and the selected hydrologic/hydraulic factors (RI, RD, VR and AD). For pollutant EMC reduction, objects were the 12 rainfall events while the variables were the percentages of TSS, TP, TN, NH_4^+, NO_3^-, NO_2^- and PO_4^{3-} EMC reduced and RI, RD, VR and AD. Fig. 3 shows the resulting PCA biplots.

3.2.1. Pollutant load removal

It can be observed in Fig. 3a that all pollutant load removal vectors are projected on the positive PC1 axis along with AD and VR vectors while RI and RD vectors are projected on the negative PC1 axis. This means that AD and VR are relatively more important factors influencing the bioretention basin treatment performance

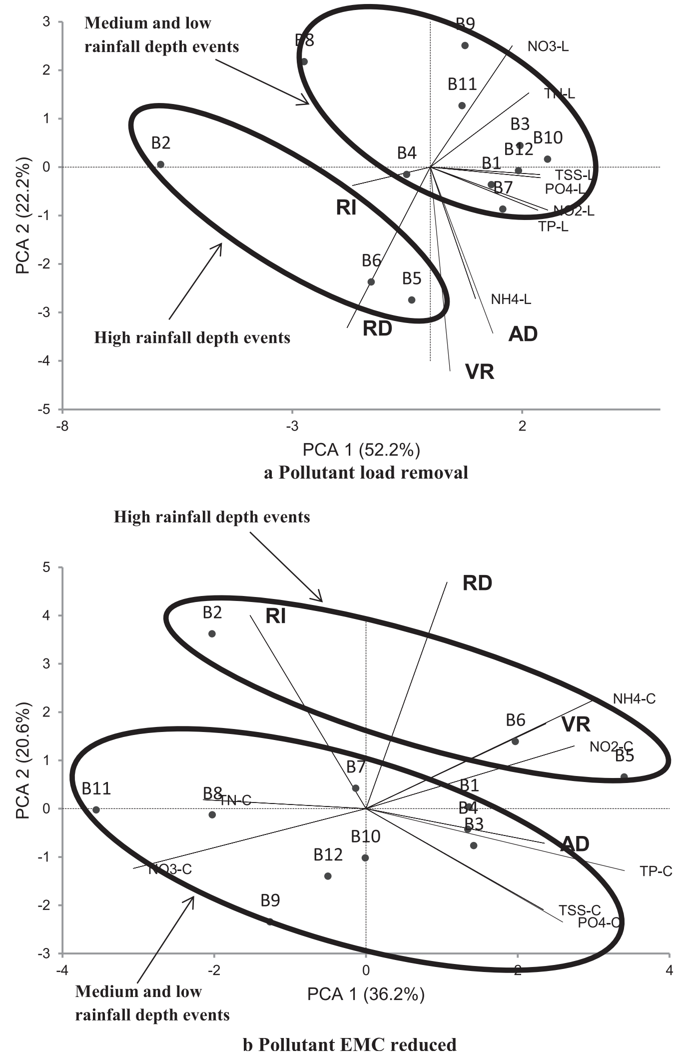

Fig. 3. PCA biplot of pollutant removal (AD = antecedent dry period; VR = volume retained; RI = rainfall intensity; RD = rainfall depth; pollutant-L = pollutant load removal percentage; pollutant-C = pollutant EMC reduction percentage).

in terms of pollutant load reduction. Furthermore, these outcomes imply that the longer dry periods and resulting lower filter media moisture content can enhance the capacity of the treatment system to retain higher stormwater volume and hence enhance the treatment performance.

Interestingly, nitrogen species show different characteristics of load removal with TN and NO_3^- load removal vectors projected on the positive PC2 axis while NO_2^- and NH_4^+ vectors are on the negative PC2 axis along with AD and VR, particularly the NH_4^+ vector having a close relationship with AD and VR. This means that the longer antecedent dry period results in a high percentage reduction in NO_2^- and NH_4^+ loads. This suggests the occurrence of the nitrification process in the case of events with relatively long antecedent dry periods.

It can also be noted that nearly all pollutant load removal vectors show a strong correlation with events having medium to low rainfall depth (<26 mm, see Table 2). This implies that the bioretention basin exhibits a relatively higher treatment capacity for these events due to the fact that low rainfall depth and the resulting small runoff volume can be effectively captured by the treatment system (Guo and Urbonas, 1996). However, relatively higher rainfall depth and resulting larger runoff volume may significantly by-pass

Table 3
Pearson correlation matrix for hydrologic and hydraulic factors.

	RD	RI	AD	VT	OP	CA	VR
RD	1.000	0.560	0.125	0.887**	0.931**	0.739**	0.495
RI		1.000	−0.211	0.355	0.738**	0.428	−0.018
AD			1.000	0.249	0.017	0.331	0.714**
VT				1.000	0.720**	0.871**	0.723**
OP					1.000	0.659*	0.309
CA						1.000	0.793**
VR							1.000

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

the treatment system without achieving the desired removal of pollutants and hence will not receive effective treatment.

3.2.2. Pollutant EMC reduction

It can be observed in Fig. 3b that the pollutant EMC reduction vectors are divided into two groups. TSS, TP, PO_4^{3-}, NO_2^- and NH_4^+ EMC reduction vectors are projected on the positive PC1 axis along with AD and VR vectors while NO_3^- and TN vectors are projected on the negative PC1 axis. This confirms that AD and VR are relatively the more important factors influencing treatment performance. However, it is noteworthy that the influence exerted by AD and VR are different on the two groups of pollutant EMC reduction vectors, namely (TSS, TP, PO_4^{3-}, NO_2^- and NH_4^+) and (NO_3^- and TN). Additionally, the EMC removal characteristics of the different nitrogen species are also different. This is in agreement with the results of the PCA for pollutant load removal (Fig. 3a).

The close relationship between AD and TSS, TP and PO_4^{3-} EMC reduction means that solids and phosphorus reduces in the bioretention basin with the increase in the antecedent dry period. This is attributed to the higher particulate load and associated phosphorus load during rainfall events associated with relatively long AD as the pollutant build-up on surfaces can be expected to be relatively high (Vaze and Chiew, 2002). Additionally, the average size of particulate pollutants can also be expected to increase with the increase in AD (Egodawatta and Goonetilleke, 2006). High particulate input load would enhance solids and phosphorus removal as phosphorus is primarily present in particulate form (Miguntanna et al., 2013). This can be supported by the fact that relatively larger particle sizes are more easily removed by stormwater treatment systems (Hsieh and Davis, 2005).

In the case of the differing removal characteristics of different nitrogen species, Fig. 3b shows that there is a strong positive correlation of AD and VR with NO_2^- and NH_4^+ EMC reduction percentage and negative correlation with NO_3^- and TN. This suggests that a longer dry period and the resulting higher volume retention capacity increases NO_2^- and NH_4^+ removal, but decreases NO_3^- removal. The possible reasons are that a longer antecedent dry period allows NH_4^+ and NO_2^- oxidation, thus reducing their concentrations, and increases NO_3^- concentration. As Davis et al. (2009) have noted, exposure of NH_4^+ and NO_2^- to the atmosphere during the dry period can lead to nitrification due to relatively abundant oxygen content, resulting in excess NO_3^- washout during subsequent events. This implies that nitrification occurs in the bioretention basin during the dry period.

The fact that particulate (TSS and phosphorus) and dissolved pollutants (nitrogen) show different removal characteristics in the bioretention basin can be attributed to different treatment mechanisms. Particulate pollutants would be primarily removed by filtration while dissolved pollutants would be primarily removed by biochemical processes such as denitrification.

Additionally, except for NO_2^- and NH_4^+ vectors, the other pollutant EMC reduction vectors point toward medium and low rainfall depth events. This means that the bioretention basin would have a relatively lower capacity for treating high rainfall depth events. This highlights the fact that the treatment of events with high rainfall depth may not be technically feasible in a bioretention basin. Treatment of large events would also not be economically feasible due to relatively more land and cost requirements.

3.3. Analysis of water quality treatment performance

As discussed in Section 3.2, antecedent dry period and resulting volume retained would exert influence on water quality treatment performance of bioretention basins. Therefore, the data matrix on water quality treatment performance (load removal and EMC reduction percentages) was prepared based on the antecedent dry period as shown in Table 4.

It can be noted that the mean pollutant reduction percentages for rainfall events occurring after a relatively long dry period (>6 days) are generally higher than the corresponding values for rainfall events after a relatively short dry period (<6 days) except for NO_3^- load, TN EMC and NO_3^- EMC reduction percentages. This

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
Hatt et al. (2009b)	Unit 1[b]	76 ± 25	64 ± 42	−13 ± 93[f]		−7 ± 72	/	−398 ± 559	/	/	/	/	/	/	/
	Unit 2[c]	93 ± 4	96 ± 7	−17 ± 35		37 ± 21	/	86 ± 3	/	/	/	/	/	/	/
Passeport et al. (2009)	Unit N[d]	/	78	43		56	/	53	/	70	33		54		63
	Unit S[e]	/	88	1		47	/	68	/	84	8		54		58

[a] Standard deviation.
[b] Bioretention unit in Monish University, Victoria, Australia.
[c] Bioretention unit in McDowall, Queensland, Australia.
[d] Bioretention unit in North, Graham High School, Alamance County, N.C., USA.
[e] Bioretention unit in South, Graham High School, Alamance County, N.C., USA.
[f] Values for NO_x.

confirms the important role played by the antecedent dry period which results in drying of the filter media and ability to retain an increased volume and thereby influencing the treatment performance. Additionally, the data presented in Table 4 also confirms that nitrification occurs in the bioretention basin. Longer antecedent dry period allows NH_4^+ oxidation, which increases the NO_3^- load and consequently reduces the overall NO_3^- removal percentage. Furthermore, the studies by Hatt et al. (2009b) and Passeport et al. (2009) also show the higher NH_4^+ reduction percentage than NO_x (NO_2^- and NO_3^-) for both loads and EMCs. This further confirms the occurrence of nitrification in a bioretention basin. This decreases the presence of ammonia, but increases the presence of nitrate. These outcomes imply that controlling redox conditions in bioretention basins would prove beneficial in areas where nitrogen pollution is a major concern.

As the study outcomes confirm that longer dry periods and resulting lower filter media moisture content can enhance the treatment capacity of bioretention systems by retaining a higher stormwater volume, the presence of vegetation would further contribute to enhancing the treatment performance (Davis et al., 2009). Vegetation will reduce the filter media moisture during dry periods as well as increase its porosity. This means that appropriate planting, particularly vegetation species with high water absorbing capacity can enhance the treatment capacity of bioretention basins.

It is noteworthy that Table 4 also shows negative values for pollutant reduction percentages, particularly nitrogen and phosphorus EMC. Similar results were reported by Hatt et al. (2009b) for nitrogen and phosphorus load removal (see Table 4). This implies the occurrence of nutrient leaching which can be attributed to the flushing of runoff retained in the filter media from the preceding rainfall event containing elevated concentrations due to evapotranspiration. Furthermore, nutrients present in the bioretention filter media itself could also contribute to pollutant leaching (Davis, 2007; Dietz and Clausen, 2005). This means that the increase in pollutant retention in the filter media over the long term can cause pollutant export. This highlights the importance of timely replacement of the filter media and the selection of appropriate filter media to enhance nutrient removal.

4. Conclusions

The key conclusions from the study are:

- Antecedent dry period plays an important role in influencing treatment performance of a bioretention basin. A long antecedent dry period will result in relatively low moisture content in the filter media which can enhance the runoff retention capacity and consequently improve treatment performance. In this context, planting of appropriate vegetation, particularly vegetation with a high water absorbing capacity would enhance treatment efficiency.
- A bioretention basin has a relatively lower ability for treating events with high rainfall depth. This should be taken into consideration in the design. This is also supported by the possible land and cost savings.
- Nitrification occurs within a bioretention basin leading to high nitrite and ammonium nitrogen reduction, but lower nitrate removal. This implies that controlling redox conditions in a bioretention basin could prove beneficial in areas where nitrogen pollution is a major concern.
- Pollutant leaching influences bioretention basin treatment performance, particularly reducing nutrients removal. This highlights the importance of the selection of appropriate filter media and its timely replacement.

Appendix A. Supplementary material

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jenvman.2014.11.007.

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