Understanding the Hydrologic and Hydraulic Factors which Influence the Treatment Performance of Bioretention Basin

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Understanding the Hydrologic and Hydraulic Factors which Influence the Treatment Performance of Bioretention Basin

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Abstract. Bioretention basins are a common stormwater structural treatment measure used to remove stormwater pollutants. They perform as pollutant removal devices using filtration as the main mechanism, supported by evapotranspiration, adsorption and biotransformation. The effectiveness of bioretention basin on removing stormwater pollutants are influenced by factors such as hydrologic, hydraulic phsyco-chemical and biological factors. This paper presents outcomes from an in-depth study undertaken to define treatment characteristics of a bioretention basin highlighting the influence of hydrologic and hydraulic factors. The study included a comprehensive field monitoring of a well-established bioretention basin, development of a hydraulic conceptual model to simulate water infiltration process within the system and state-of-the-art multivariate analysis of stormwater quantity and quality data to understand correlations and define linkages between treatment performance and influential hydrologic and hydraulic factors. Samples collected at inlet and outlet was tested for Total Suspended Solid (TSS), nitrogen species i.e. Total Nitrogen (TN), Nitrite (NO_2), Nitrate (NO_3), Ammonium (NH_4) and phosphorus species i.e. Phosphate (PO_4) and Total Phosphorus (TP). The analysis results revealed that only TSS concentration was consistently reduced while the concentration of other pollutants was reduced for some rainfall events but increased for the others. While the antecedent dry period (AD) affects the concentration reduction of all pollutants, the other factors such as rainfall depth (RD), outflow peak (OP), contributed wetted area (CA) and volume of treated stormwater (VT) showed no correlation with any pollutant concentration reduction. Analysis results showed that AD reduces the concentration of NO_2 and NH_4 but increases the concentration of NO_3 and TN indicating that nitrification possibly occurs in the bioretention basin. The results also showed that the superior pollutant load reduction was in medium and low depth of rainfall events due to high fraction of runoff retain within the system.

Keywords:*use 10 pt; lower case; italic; Times; write alphabetically in 5-10 words.*

1 Introduction

A bioretention basin or also called biofilterperforms as a pollutant removal device using filtration as the main mechanism, supported by evapotranspiration, absorption and biotransformation. This is in addition to attenuation of runoff peak flow and reduction of runoff volume through detention and retention [1]. Past studies have reported that pollutant concentration reduction in bioretention basins is poor for a range of pollutant species particularly for nutrient species [1][2][3][4]. However, a substantial reduction in outflow volume can lead to significant reduction in pollutant loads [5].

A range of studies have been conducted for assessing bioretention basin performance and hydraulic and pollutant removal processes [6][7][8][9][10][11][12]. However, most of the past field studies have been conducted to evaluate the long term treatment performance while most of the studies which focused on developing an in-depth understanding of processes have been conducted using laboratory-scale models [13][14][15]. This paper presents the outcomes of a detailed study of an on-site bioretention basin which was monitored to understand the influence of hydrologic and hydraulic factors on bioretention basin treatment performance.

2 Methods

2.1 Study Site

The bioretention basin selected for the study was located at 'Coomera Waters' residential estate, Gold Coast, about 55 km South of Brisbane, the capital city of Queensland, Australia (Figure 1 (a)). This bioretention basin was selected due to the availability of historical rainfall, runoff and water quality data. The size of the bioretention basin was 248 m^2, approximately 3.8% of the contributing catchment area of 6,530 m^2 (Figure 1(b)). The basin consisted of 0.8 m thick filter media, covered by grass bed surface and 0.2 m thick drainage layer underneath the filter media consisting of granular material.The filter media promoted stormwater treatment through infiltration while the grass maintained the porosity of the basin surface. A network of perforated pipes in the drainage layer conveyed infiltrated stormwater to the outlet control pit. The inlet to the bioretention basin and the outlet 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.

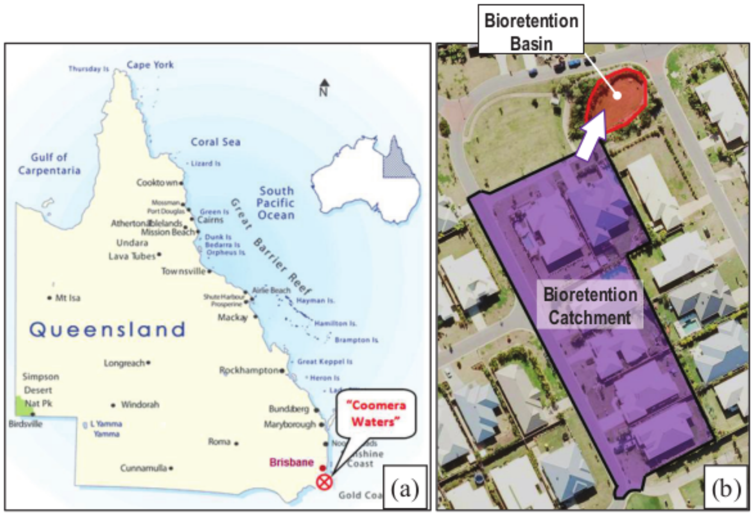

Figure 1 Study site (a), bioretention basin and contributing catchment (b)

2.2 Sampling and Testing

Only runoff samples from rainfall events with more than five antecedent dry days were tested. This was to allow an appreciable amount of pollutants to be built-up on catchment surfaces. Egodawatta et al. [16]have found that a minimum of five antecedent dry days can result in more than 75% of the maximum possible build-up on road surfaces. Samples were analysed for a suite of water quality parameters as shown in Table 1 given below. Further detail of the sampling protocol is explained in Mangangka et al. [17]and Parker et al. [18].

Table 1 Summary of physical parameters.

Parameter	Test Method	Comments
TSS	APHA No. 2540D	Filtered using 0.45µm glass fibre filter paper
TN as TKN + NO_2 + NO_3	TKN: US EPA No. 351.2 NO_2 : US EPA No. 353.2 NO_3 : US EPA No. 354.1	Smartchem 140 was used. For TKN, samples were digested using AIM600 block digester
TP	US EPA No. 365.1 and US EPA No. 365.4	Smartchem 140 was used. Samples digested using AIM600 block digester

2.3 Bioretention Basin Conceptual Model

A conceptual model was developed to replicate the hydraulic behaviour of the bioretention basin.Greater details on the conceptual model development, calibration and simulation areexplained in Mangangka[19]. Hydraulic characteristics of a bioretention basin are primarily based on infiltration and percolation of stormwater through the filter media which can be best replicated by 3-dimensional flow models. However, due to the complexity of the 3-dimensional flow models which are very complex and often require numerical analysis [20], an assumption was made to convert it to a 1-dimensional flow system. For this, the bioretention area was divided into a number of equal zones. A trial and error process used suggested that 10 equal zones were suitable for the model.The stormwater movement over the surface was as a flow from zone 1 where the inlet structure was located to zone 10 where the outlet structure was located (Figure 2).

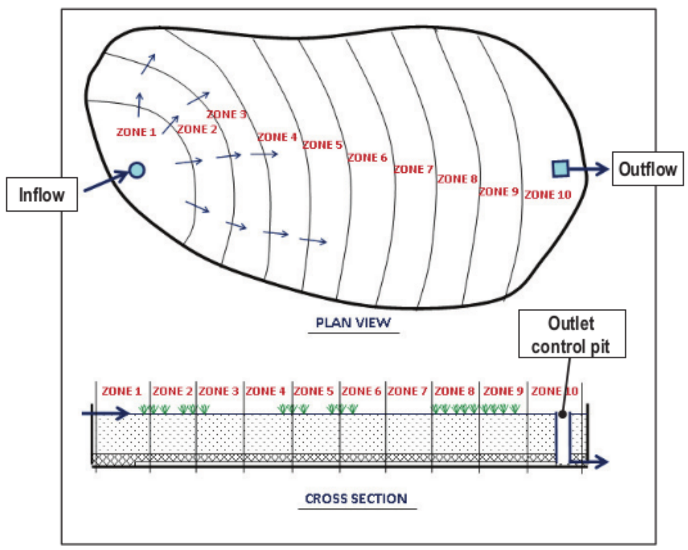

Figure 2 Simplifying 3-dimensional flow into 1-dimensional column based flow

The stormwater flow within the bioretention basin was modeled according to the processes described in the following steps:

- Stormwater runoff enters the bioretention basin through the inlet structure in zone 1 which is assumed as a soil column.

- The stormwater runoff then infiltrates into the soil column which is replicated using the Green-Ampt 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.
- The infiltrated water then percolates until it reaches the drainage layer in which the stormwater is temporarily stored.
- Part of stormwater stored in the drainage layer percolates to the original soil layer underneath.
- Through perforated pipes, stormwater in the drainage layer flows to the outlet structure where the outlet was monitored.

The conceptual model developed to replicate the bioretention basin was calibrated using measured data from inlet and outlet. For this purpose data from 12rainfall events which occurred from 29January 2008 to 29 March 2011 were used. The calibration was performed by adjusting coefficients in all the standard flow control equations using a trial and error approach. An example of the model performance is shown in Figure 3.

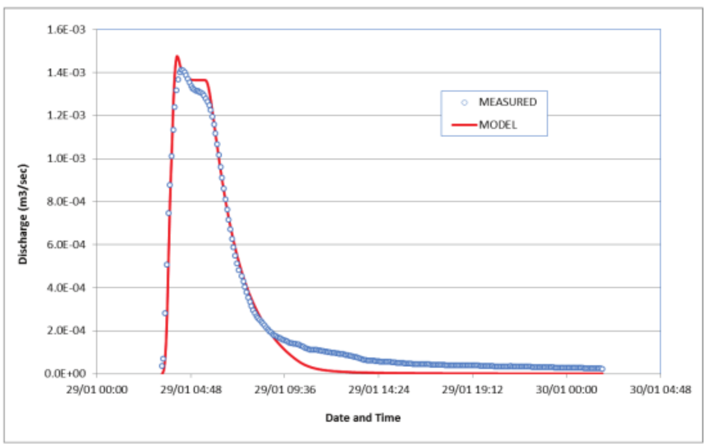

Figure 3 Bioretention basin measured and modeled discharge hydrograph

The model was used to obtain hydrologic and hydraulic parameters based on simulations to undertake performance evaluation of the bioretention basin. In this regard, four influential variables; contributed wetted area (CA), volume of runoff retained in the filter media (VR), volume of runoff treated (VT) and outflow peak (OP) were identified as being influential parameters.

2.4 Analytical Tools

The analytical tools were selected based on their ability for processing a multi variable dataset to investigate relationships between the objects and the variables. Among the range ofmultivariate techniques available, principal component analysis (PCA) was the mostappropriate for this analysis [21]. PCA is essentially a pattern recognitiontechnique which can be used to understand the correlations among different variables andclusters among objects. It has been used extensively as an analytical tool in water qualityresearch [22][23][24].

PCA transforms the original variables to a new orthogonal set of Principal Components (PCs)such that the first PC contains most of the data variance and the second PC contains thesecond largest variance and so on. Outcomes of PCA are typically presented as a biplot,which is a plot of two orthogonal PCs illustrating object scores and variable vectors[25]. The objects that exhibit similar variances for the analysedvariables have similar PCA scores forming a cluster when plotted on a biplot. Additionally,strongly correlated variables have the same magnitude and orientation when plotted, whereasuncorrelated variables are orthogonal to each other. Detailed descriptions of PCA can befound elsewhere [21][26].

3 Result and Discussion

3.1 Analysis of the Treatment Performance on Lumped Basis

PCA was initially undertaken to investigate the treatment characteristics of the bioretention basin using the event mean concentration (EMC) values at the inlet and the outlet. Water quality/ pollutant parameters used were; EC, TSS, NH_4, NO_2, NO_3, TN, PO_4 and TP. Data from 12 rainfall events were investigated which formed a matrix with 24 objects due to the occurrence of two sampling locations. The resulting PCA biplot is shown in Figure 4.

Figure 4 shows that the inlet and outlet samples tend to cluster into two separate groups based on the projected scores on PC2 axis. Most inlet samples (Cluster A) show negative scores on PC2, while most outlet samples (Cluster B) show positive scores on PC2. This indicates that inlet and outlet samples are significantly different in term of their pollutant concentrations suggesting that significant water quality changes occur when the stormwater flows from the inlet to the outlet through the bioretention basin.

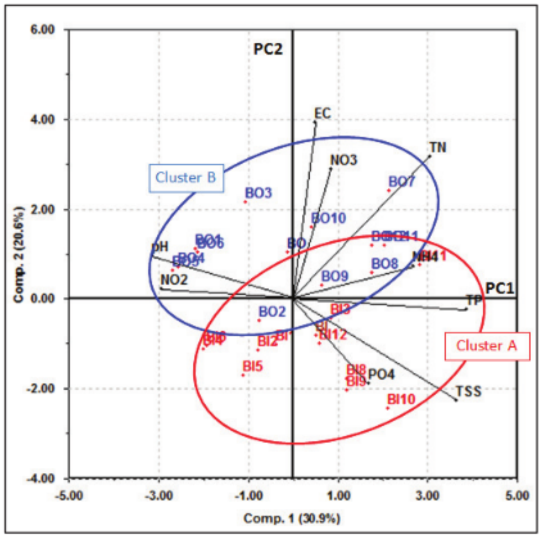

Figure 4 Biplot of water quality and pollutant event mean concentration at the inlet and outlet

As evident in Figure 4, that outlet sample objects (Cluster B) are generally located in the same direction where the vectors of EC and nitrogen compounds are directed, while the inlet sample objects (Cluster A) are generally located in the same direction as the vectors of TSS and phosphorus compounds are directed. This indicates that while the concentration of TSS and phosphorus species decreases, EC and nitrogen species concentrations tend to increase due to the processes in the bioretention basin. This agrees with the results of previous studies which reported that the concentration reduction of nitrogen species is poor [1][2][3][4]. Furthermore, similar trend in phosphorus compounds and TSS confirms that the phosphorus compounds are mostly available in particulate form, attached to suspended solids due to adsorption.

3.2 Influence of Hydrologic/Hydraulic Factors on Pollutant Concentration Reduction

Analysis of the performance of the constructed wetland was undertaken based on the reduction in EMC values. Table 2 shows the percentage concentration reductions (for example TSS-R is the percentage EMC reduction for TSS) for the 12 rainfall events. The percentage was calculated with respect to inflow water quality.

Table 2 Pollutant concentration reduction and hydrologic/hydraulic factors

Rainfall Event ID	EMC Reduction							Hydrologic and Hydarulic Parameters						
	TSS-R	NH4-R	NO2-R	NO3-R	TN-R	PO4-R	TP-R	Rainfall Depth (RD)	Rainfall Intensity (RI)	Antecedent Dry Period (AD)	Volume Treated (VT)	Volume Retained (VR)	Outflow Peak (OP)	Cont. Area (CA)
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(mm)	(mm/hr)	(day)	(m^3)	(m^3)	(m3/sec)	(%)
B1	18.09	61.73	6.85	-87.50	-17.73	66.42	58.54	20.6	7.36	8.51	54.65	31.33	0.00153	70
B2	3.23	64.40	-36.36	-57.30	-31.04	-69.23	-58.09	52.0	14.86	3.05	87.73	22.00	0.00342	100
B3	43.91	92.56	38.99	-51.16	-48.69	67.97	32.72	12.0	5.45	6.60	31.03	23.23	0.00134	50
B4	74.03	71.73	16.23	-112.57	-70.34	-38.74	1.73	18.4	3.91	6.83	51.69	24.81	0.00126	40
B5	66.54	71.05	9.57	-145.10	-63.04	49.47	55.82	44.6	5.95	10.48	112.26	48.86	0.00188	100
B6	36.39	61.47	-39.39	-98.14	-82.55	26.17	18.10	51.8	8.22	13.05	79.06	38.47	0.00303	70
B7	3.87	-15.52	68.69	39.79	19.71	-38.49	27.63	25.8	4.69	10.36	70.56	49.51	0.00155	100
B8	14.26	-69.38	-47.59	0.24	-49.83	-0.73	-31.30	19.4	8.08	4.24	49.33	20.38	0.00146	40
B9	50.26	-37.78	-102.00	-36.06	-41.66	24.38	-13.88	4.8	2.53	4.56	8.70	6.03	0.00052	10
B10	44.99	-41.25	-63.65	-69.99	-10.29	70.38	9.54	9.6	8.73	10.50	31.87	28.41	0.00093	50
B11	25.30	-74.94	-186.18	40.11	20.58	-101.63	-21.31	20.2	8.78	5.88	28.88	23.20	0.00159	40
B12	21.36	-44.06	-123.02	50.49	-71.14	57.84	5.74	12.6	6.63	13.07	38.82	31.17	0.00130	60

PCA was undertaken to assess the stormwater treatment performance of the bioretention basin based on the reductions in EMC values. For this analysis, hydrologic and hydraulic parameters were also included in order to investigate the linkage between treatment performance and the underlying flow scenarios in the bioretention basin. The parameters selected were rainfall depth (RD), rainfall intensity (RI), antecedent dry period (AD), volume of runoff treated (VT), volume of runoff retained in the filter media (VR), outflow peak (OP) and average retention time (RT), outflow peak (OP) and contributed wetted area (CA).The resulting PCA biplot is shown in Figure 5.

The biplot shows that the hydrologic and hydraulic factors and pollutant concentration reductions have formed the objects clustered with respect to rainfall depth. The clustering suggests that the rainfall events should beclassified into three categories; high, medium-high, medium and low rainfall depth. The biplot also shows a similar trend in the reduction of TSS, PO_4 and TP concentrations confirming that in stormwater runoff, phosphorus is mostly transported with particulates due to their tendency to adsorb to soil particles and organic matter [27][28][29].Furthermore, Figure 5 shows that the reduction of TSS, PO_4 and TP concentrations was correlated with the increase of the antecedent dry period. This could be attributed that longer antecedent dry period increases pollutant built-up on surfaces with higher particulate fraction [30][31].

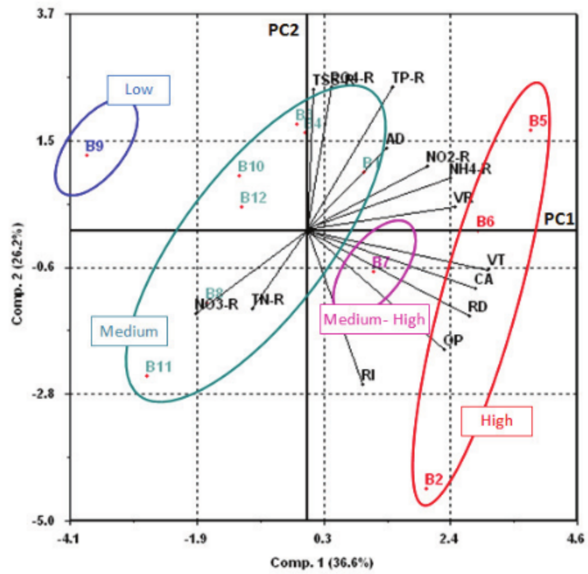

Figure 5 PCA biplot for pollutant concentrations reduction and hydrologic/hydraulic factors

Moreover, Figure 5 shows strong correlation of AD with NO2-R and NH4-R while showing a negative correlation with NO3-R and TN-R. This indicates that longer antecedent dry period reduces the concentration of NO_2 and NH_4, but increases the concentration of NO_3 confirming that nitrification possibly occurs in the bioretention basin. Longer antecedent dry period allows ammonium oxidation, which would reduce NH_4, and promote nitrite oxidation. This in turn reduces NO_2 and increases NO_3.

3.3 Hydrologic/Hydraulic Factors and Pollutant Load Reduction

Analysis of pollutant reduction in previous section shows that the concentration of some pollutant species decreased while the other pollutant species increased (negative reduction). However, this could provide misleading interpretation due to the significant reduction in the stormwater volume. Therefore, the actual amount of pollutant reduction should be best presented based on the load reduction.Similar data matrix as presented in Table 2 with TOC reduction replaced by pollutant loading reduction was analyzed using PCA. The resulting PCA biplot is shown in Figure 6.

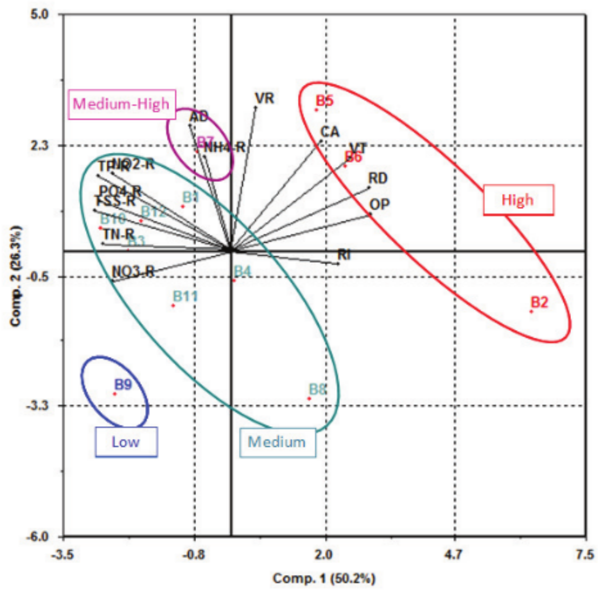

Figure 6 PCA biplot for pollutant loadsreduction and hydrologic/hydraulic factors

Similar with previous PCA result, Figure 6 shows that rainfall events with relatively high, medium-high, medium and low rainfall depths are clustered separately. Importantly, pollutant load reduction vectors, TSS-R, TN-R, NO2-R, NO3-R, TP-R and PO4-R are pointed towards medium rainfall depths. This suggests that the pollutant load reductions for these events are much superior compared to others. This is also supported by the negative correlation between pollutant load reduction vectors and influential hydraulic factors such as VT, CA and OP.

Some load reduction vectors are also correlated with AD and VR. Longer antecedent dry period typically leads to high retention of runoff volume within the bioretention basin filter media. This suggests that the higher percentage load reduction in medium and low events is due to high fraction of runoff retention within the system. All the percentage load reduction vectors are pointed in the same direction. This suggests a similar pattern in pollutant load reduction for all the pollutant species.

Figure 6 also shows very strong correlation between NH4-R and AD. This means that longer antecedent dry periodresults in higher reduction in NH_4 load. This suggests the possible contribution of the nitrification process in the treatment for rainfall events with long antecedent dry period.

4 Conclusions

The primary conclusions from the study are:

- The concentration reductions of TSS and phosphorus compounds were strongly correlated. Concentration of TSS and phosphorus compounds reduced in the outflow and the reduction is in line with the increase in antecedent dry period. When the antecedent dry period increased, the amount and average size of particulate pollutant also increased. This resulted in more solid particles being filtered and consequently reduced the TSS concentration and phosphorus bound to TSS.
- In bioretention basin, volume of runoff retained is an important factor, and is a function of antecedent dry period, volume of runoff treated and contributed wetted area. Since treatment in a bioretention basin is highly correlated with volume of runoff retained, other factors such as rainfall characteristics (rainfall depth and intensity) and outflow peakare not significant.
- Bioretention basin showed potential for pollutant leaching and to produce plug flow discharge of pollutants. This could be due to flushing of runoff retained in the filter media from the preceding rainfall event which could have contained elevated dissolved nutrient concentrations due to evapotranspiration.
- Longer antecedent dry period reduces the concentration of NO_2 and NH_4, but increases NO_3 concentration. This is an indication of the nitrification process occurring within the bioretention basin. A longer antecedent dry period allows ammonium oxidation which reduces NH_4 and promotes nitrite oxidation which reduces NO_2 and increases NO_3.
- Even though nitrogen concentrations are more often elevated in the bioretention basin outlet, the overall loadings of all pollutants were reduced.

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