Understanding Treatment Characteristics of Constructed Stormwater Wetlands

Isri R. Mangangka
Postgraduate student, Queensland University of Technology, Brisbane, Australia
Email: isri.mangangka@student.qut.edu.au

Prasanna Egodawatta
Lecturer, Queensland University of Technology, Brisbane, Australia
Email: p.egodawatta@qut.edu.au

Jay Rajapakse
Lecturer, Queensland University of Technology, Brisbane, Australia
Email: jay.rajapakse@qut.edu.au

Ashantha Goonetilleke
Professor, Queensland University of Technology, Brisbane, Australia
Email: a.goonetilleke@qut.edu.au

Abstract

Constructed wetlands are a common structural treatment measure employed to remove stormwater pollutants and forms an important part of the Water Sensitive Urban Design (WSUD) treatment suite. In a constructed wetland, a range of processes such as settling, filtration, adsorption, and biological uptake play a role in stormwater treatment. Occurrence and effectiveness of these processes are variable and influenced by hydraulic, chemical and biological factors. The influence of hydraulic factors on treatment processes are of particular concern. This paper presents outcomes of a comprehensive study undertaken to define the treatment performance of a constructed wetland highlighting the influence of hydraulic factors. The study included field monitoring of a well established constructed wetland for quantity and quality factors, development of a conceptual hydraulic model to simulate water movement within the wetland and multivariate analysis of quantity and quality data to investigate correlations and to define linkages between treatment performance and influential hydraulic factors. Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorus (TP) concentrations formed the primary pollutant parameters investigated in the data analysis. The outcomes of the analysis revealed significant reduction in event mean concentrations of all three pollutants species. Treatment performance of the wetland was significantly different for storm events above and below the prescribed design event. For events below design event, TSS and TN load reduction was comparatively high and strongly influenced by high retention time. For events above design event, TP load reduction was comparatively high and was found to be influenced by the characteristics of TP wash-off from catchment surfaces.

1. INTRODUCTION

Constructed wetlands are one of the commonly used water sensitive urban design (WSUD) measures in Australia for stormwater quality treatment (Lloyd, 2001; Wong et al., 1999). However, its ability as a hydraulic device to reduce peak flows and runoff volumes is also considered important. Stormwater quality treatment in a constructed wetland is primarily achieved by processes such as settling, filtration, adsorption and biological uptake (Wong et al., 1999). These processes are complex and significantly influenced by hydraulic, chemical and biological factors. The influence of hydraulic factors on treatment processes are of particular concern as they indirectly link to the chemical and biological factors (Guardo, 1999, Ronkanen and Kløve, 2008). As noted in research literature, two hydraulic parameters, namely, retention time and hydraulic loading are typically considered as the most critical in constructed wetland design. However, a range of other parameters that have an indirect influence on these two main parameters are also considered as important. For example, Holland et al. (2004) considered water depth and flow rate as influential parameters for water quality treatment in constructed wetlands.

The knowledge relating to the influence of hydraulic parameters on constructed wetland treatment performance is inconclusive. This is due to the common use of lumped hydraulic and water quality parameters for treatment performance analysis. Predictive models are commonly used for performance evaluation of wetlands (for example: Bautista and Geiger, 1993; Lawrence, 1999; Livingston, 1988). However, many of these studies have focused on evaluating long term performance rather than event based performance (Carleton et al., 2001; Ronkanen and Kløve, 2009). In order to understand the influence of hydraulic parameters on treatment performance, it is necessary to focus on the evaluation of event based performance.

This paper presents the outcomes of a detailed study of a constructed wetland using event based analysis to understand the role of influential hydraulic parameters on treatment performance. For this study, influential hydrologic and hydraulic parameters were derived by using a detailed hydraulic conceptual model.

2. MATERIALS AND METHODS

2.1. Study site

The constructed wetland selected for the study is located at 'Coomera Waters' residential estate, Gold Coast, Australia. This wetland was selected due to the availability of historical rainfall, runoff and water quality data. The wetland consists of an inlet pond at the upstream end of the system and two cells of macrophyte zones as the main treatment area. The sizes of the wetland components were; inlet pond area of $149m^2$, Cell 1(upstream macrophyte zone) area of $465m^2$ and Cell 2 (downstream macrophyte zone) area of $653m^2$. The total area is equivalent to 2.06% of the contributing catchment area of 6.15 ha. The constructed wetland receives runoff from two sub-catchments (see Figure 1). The areas of the two sub-catchments are 5.10ha (sub-catchment A) and 1.05ha (sub-catchment B) respectively.

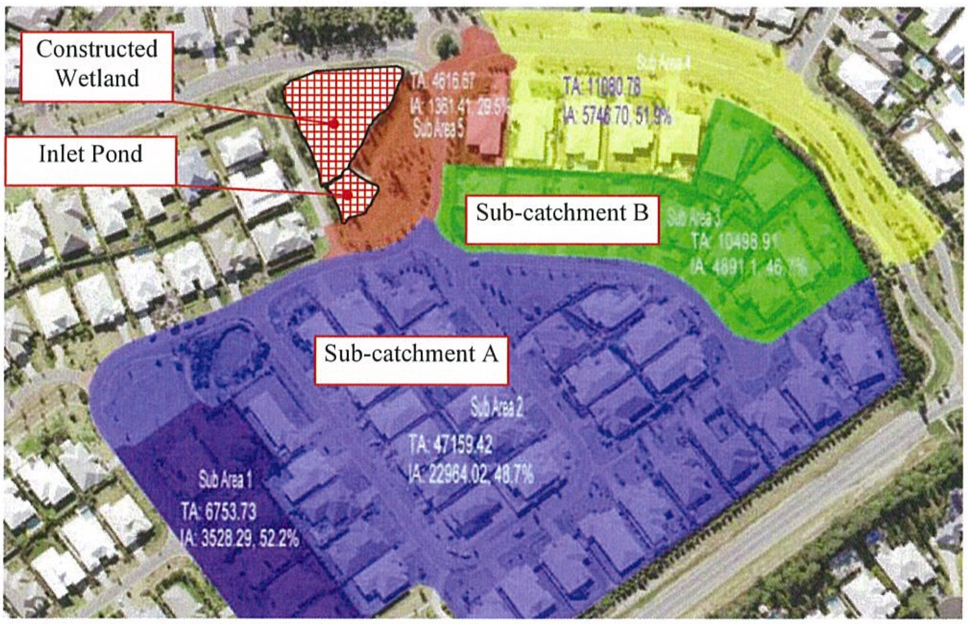

Figure 1: Study site: Constructed wetland and contributing catchments (adapted from Parker et al. 2009)

The two inlets to the wetland and the wetland outlet and the bypass 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 monitoring. Refer to Parker et al. (2009) for further details regarding the automatic monitoring stations.

2.2. Sampling and testing

Only stormwater 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. Based on the empirical build-up equations developed by Egodawatta et al. (2006), a minimum of five antecedent dry days can result in more than 75% of the maximum possible build-up on road surfaces. Collected water samples were stored under 4°C before testing. Samples were analysed for the suite of water quality parameters as shown in Table 1. The test methods used for the analysis are also presented in Table 1.

Table 1: Test parameters and methods

Parameter	Test Method	Comments
TSS	APHA No. 2540D	Filtered using o.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

3. DEVELOPMENT OF WETLAND'S HYDRAULIC CONCEPTUAL MODEL

3.1. Description of conceptual model

A conceptual model was developed to replicate the hydraulic behaviour of the wetland in order to obtain hydraulic parameters essential for performance evaluation of the wetland. The conceptual model was a collection of conventional hydraulic equations representing typical hydraulic devices, storages and channels, which was arranged in such a way that they collectively mimicked the hydraulic response of the wetland system. The model was designed so that the essential hydraulic parameters can be obtained from simulations. Schematic diagram of the wetland is shown in Figure 2 and the following discussion provides a brief outline of the conceptual approach used in developing the model.

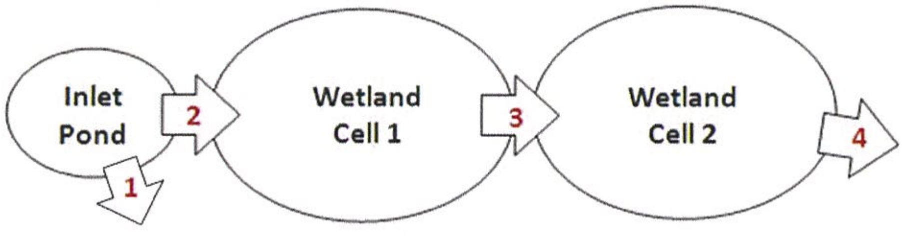

Figure 2: Conceptual representation of water flow through the constructed wetland

- The three basic elements of the wetland, inlet pond, Cell 1 and Cell 2, were replicated using water balance equations typically used for storage devices (see Figure 2).
- Inflow from the contributing catchment and direct precipitation were considered as inputs. Measured inflows were considered as the inflow from the contributing catchment. Measured rainfall was used to estimate direct precipitation.
- Outflow through the designated outlet structure (4 in Figure 2), bypass flow (1 in Figure 2), percolation and evaporation were considered as outflows from the model.

- Outlet structure (4 in Figure 2) was modelled as a collection of standard orifices based on its geometric properties. The outlet structure is a PVC riser with a number of 20 mm diameter orifices. This arrangement was modelled as standard orifices when the holes are completely submerged. When a hole is only partially submerged, flow was assumed to be similar to flow over a circular sharp-crested weir. Weir formula was obtained from Greve (1932) and Stevens (1957).
- Bypass flow (1 in Figure 2) was considered as a flow over a standard broad crested weir. Infiltration was modelled using Green-Ampt equation and standard pan-evaporation data was used to replicate evaporation.
- Flow transfer within the wetland components were modelled as illustrated in Figure 3. Geometric characteristics of each component were represented using data obtained from a hydrographic survey.
- Flow from the inlet pond to wetland Cell 1 (2 in Figure 2) is through a rectangular control pit (1.90mx1.00m) and a 350mm diameter concrete pipe. Flow through the pipe was determined using the submerged flow formula, while flow through the pit was assumed as flow over a broad-crested weir. Both flows were calculated and the lesser value was considered as the flow into Cell 2.
- Flow from Cell 1 to Cell 2 (3 in Figure 2) was considered as the flow over a broad-crested weir. Width of the weir was obtained from a hydrographic survey.

3.2. Model calibration

The conceptual model developed to replicate the constructed wetland was calibrated using measured flow data from inlet, outlet and bypass. For this purpose data from eleven storm events, which occurred from 5 May 2008 to 19 July 2010 were used. The calibration was performed by adjusting coefficients in all the standard flow control equations. An example of the model performance is shown in Figure 3.

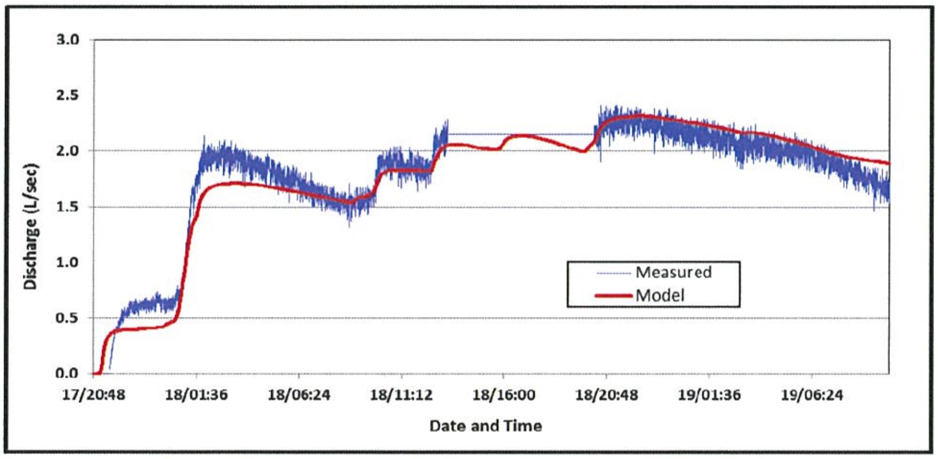

Figure 3: Example of performance of the wetland conceptual model

4. RESULTS AND DISCUSSION

4.1. Analysis of concentrations

Dataset obtained from the sampling and laboratory testing was used for the analysis. For the analysis, principal component analysis (PCA) was used as the primary analytical technique. PCA is an analytical technique commonly used for pattern recognition. The technique is popularly used in water quality data analysis (Bengraïne and Marhaba, 2003). PCA reduces a large raw dataset to a number of principal components (PCs) based on the associated variance. Details of PCA can be found elsewhere (Adams, 2004).

PCA was initially undertaken to understand the pollutant removal performance of the constructed wetland using the event mean concentrations (EMC) of inlet and outlet water quality. Variables used were; TSS, TN as a summation of TKN + NO_2 + NO3, PO_4 and TP. Data from eleven storm events were used and the formed a matrix with 33 objects due to the presence of three sampling locations. The resulting PCA biplot is shown in Figure 4.

As shown in Figure 4, EMC for the two inlets are clustered into two distinct regions and indicated as Cluster A and Cluster B. This suggests different inflow quality characteristics from sub-catchment A and sub-catchment B. Sub-catchment A is a typical urban development with a combination of roads, roofs and grassed areas where TSS and TP concentrations are comparatively high. Sub-catchment B is primarily a roof catchment with a minor fraction of grassed surfaces where concentrations of nitrogen species are comparatively high. Objects representing outflow are clustered separately (Cluster C). Clustering of objects as shown in Figure 4 clearly indicate the proper functioning of the constructed wetland as a stormwater pollutant treatment device. Orientation of variables (vectors) is in the direction of inlet water quality objects indicating the high pollutant concentrations in the inflow water. Outlet water quality objects are clustered opposite to the direction of most variables indicating lowered concentration due to treatment action of the wetland. Furthermore, outflow objects are clustered closely, indicating no significant variation in water quality irrespective of the inflow quality.

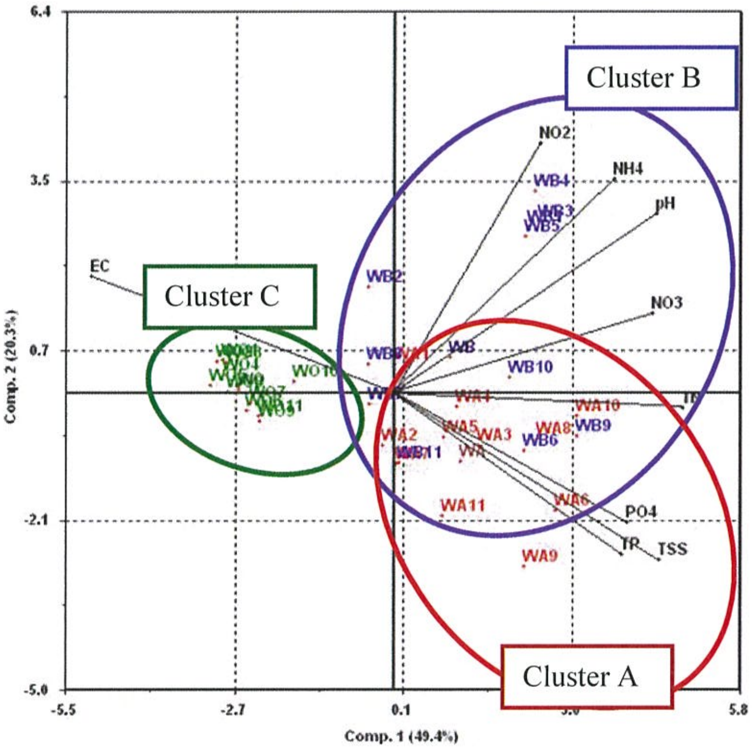

Figure 4: Comparison of event mean concentrations for two inlets and outlet using PCA

4.2. Analysis of pollutant loads

The observation of consistent outflow quality from the constructed wetland irrespective of its inflow quality and quantity led to the undertaking of detailed investigations into the factors influencing treatment under variable inflow conditions. These detailed investigations utilised pollutant load reduction as a measure of treatment performance rather than the change in EMC. In stormwater treatment, changes in concentration can be misleading due to storage action and the significant volume losses within the system.

It was hypothesised that the hydraulic factors of the constructed wetland specific to each storm is influencing treatment. Accordingly, influential hydraulic factors such as outflow peak, volume treated, average water depth in the wetland during the event and average retention time was used for the analysis. The resulting data matrix used is shown in Table 2 and the biplot resulting from PCA is shown in Figure 5.

As evident in Table 2, TSS load reduction varies from 7% to 92% with an average of 57% for the monitored eleven storm events. Average load reduction for TN and TP are 29% and 30% respectively. Additionally, load reduction for all three pollutant species show significant scatter for different storm events indicating the significant influence exerted by the hydraulic factors on treatment performance.

Table 2: Pollutant load reduction and influential hydraulic parameters

Object ID	Pollutant Reduction (%)			Average Retention Time (RT)	Outflow Peak (OQ)	Volume Treated (VT)	Average Depth (AD)
	TSS-R	TN-R	TP-R	(day)	(L/sec)	(m^3)	(m)
W1	81	62	61	3.17	1.2	98	0.35
W2	92	11	71	2.93	2.3	493	0.46
W3	86	42	89	2.70	2.7	524	0.54
W4	64	3	42	6.29	1.1	168	0.25
W5	67	22	-4	6.73	0.8	44	0.27
W6	19	16	10	2.65	2.5	594	0.45
W7	59	23	-3	3.33	1.8	383	0.40
W8	79	32	-1	4.52	1.0	93	0.28
W9	62	51	4	3.87	1.5	228	0.33
W10	7	40	18	2.18	2.5	251	0.50
W11	13	14	50	2.42	2.2	255	0.44

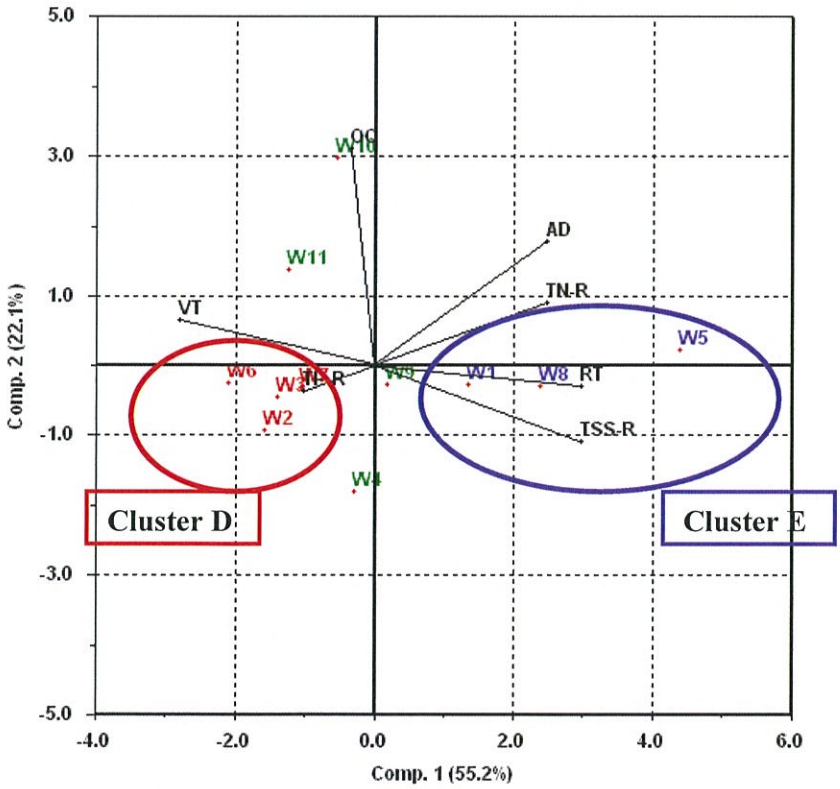

Figure 5: Biplot of the pollutant reduction and the wetland hydraulic parameters

Figure 5 shows the correlations between the load reductions of the three pollutant types with the influential hydraulic parameters. For convenience of interpretation, two object clusters can be identified in Figure 5. Cluster D represents events above the adopted design event that used for the design of this wetland system and cluster E represents events below the design event. These two clusters are located a distant apart along the PC1 axis. This suggests that the treatment characteristics of the constructed wetland are significantly different for storm events above and below the adopted design event.

As shown in Figure 5, TSS-R and TN-R correlate with AD (average depth) and RT (retention time) as the vectors form an acute angle. The vectors also point towards the objects in Cluster E. This suggests that TSS and TN load reduction is high for events that create longer retention time. Such a hydraulic scenario is possible for relatively smaller rainfall events. It can also be concluded that processes such as settling and nitrification are dominant treatment processes for such events.

On the other hand, TP-R correlates with VT (volume treated) and negatively correlates with RT (as the vectors form an obtuse angle). This suggests that high load reduction of TP occurs when the volume of stormwater flowing into the constructed wetland is high. This can be due to continuous wash-off of TP from the contributing catchment during larger and longer storm events (Miguntanna 2009). The negative correlation of TP-R with RT also suggests that a high fraction of TP retained is associated with particles with high settling potential where relatively long retention is not required. The fact that there is no correlation of OQ (outflow peak) with load reduction for all three pollutant types (indicated by the fact that these vectors do not form an acute angle) suggests that this is not an influential factor.

5. CONCLUSIONS

The primary outcomes from the study are:

- Average TSS, TN and TP load reductions can be appreciable, but below the treatment performances reported in past research literature. Load reduction of these three pollutant species showed significant scatter for different storm events confirming the significant influence exerted by hydraulic factors on treatment performance.
- Treatment performance of the constructed wetland was significantly different for events above and below the adopted design event. TSS and TN load reduction is strongly influenced by hydraulic retention time where performance is relatively higher for rainfall events below the design event. Settling and nitrification are the dominant treatment processes for such events.
- TP load retention is strongly influenced by the characteristics of TP wash-off from catchment surfaces. TP was found to be associated with particles with high settling ability where longer retention time is not required for removal.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Adams, M. J. (2004), Chemometrics in analytical spectroscopy, Cambridge, Royal Society of Chemistry.

Bautista, M. F. and Geiger, N. S. (1993), Wetlands for Stormwater Treatment. Water Environment and Technology 5(7), 50-55

Bengraïne, K. and Marhaba, T. F. (2003), Using principal component analysis to monitor spatial and temporal changes in water quality, Journal of Hazardous Materials, 100, 179-195.

Carleton, J. N., Grizzard, T. J., Godrej, A. N. and Post, H. E. (2001), Factors affecting the performance of stormwater treatment wetlands, Water Research, 35, 1552-1562.

Egodawatta, P., Goonetilleke, A., Ayoko, G. A. and Thomas, E. (2006). Understanding the interrelationship between stormwater quality and rainfall and runoff factors in residential catchments, In:

7th International Conference on Urban Drainage Modelling and the 4th International Conference on Water Sensitive Urban Design, 2006 Melbourne, Australia. 43 - 50.

Goonetilleke, A. and Thomas, E. (2004), Water quality impacts of urbanisation: Relating water quality to urban form. Centre for Built Environment and Engineering Research, Queensland University of Technology.

Greve, F. V. (1932), Flow of water through circular, parabolic and triangular vertical notch weirs. Engineering Bulletin, Purdue University, 40, 37-60.

Guardo, M. (1999), Hydrologic balance for a subtropical treatment wetland constructed for nutrient removal, Ecological Engineering, 12, 315-337.

Holland, J. F., Martin, J. F., Granata, T., Bouchard, V., Quigley, M. and Brown, L. (2004), Effects of wetland depth and flow rate on residence time distribution characteristics, Ecological Engineering, 23, 189-203.

Lawrence, A. I. (1999), Stormwater Pollution Control Pond and Wetland Models. In: Eighth International Conference on Urban Storm Drainage, Sydney, Australia, 1058-1065.

Livingston, E. H. (1988), The Use of Wetlands for Urban Stormwater Management. In: Engineering Foundation Conference on Design of Urban Runoff Quality Control, 1988 Potosi, Missouri. ASCE, 467-490.

Lloyd, S. D. (2001), Water Sensitive Urban Design in the Australian Context, Cooperative Research Centre for Catchment Hydrology.

Miguntanna, N. P. (2009), Nutrient build-up and wash-off processes in urban land uses, Queensland University of Technology, Brisbane, PhD Thesis.

Parker, N., Gardner, T., Goonetilleke, A., Egodawatta, P. and Giglio, D. (2009), Effectiveness of WSUD in the 'real world'. In Proceedings of the 6th International Water Sensitive Urban Design Conference and the 3rd Hydropolis: Towards Water Sensitive Cities and Citizens, Parmelia Hilton, Perth, Western Australia.

Ronkanen, A.K. and Kløve, B. (2008), Hydraulics and flow modelling of water treatment wetlands constructed on peatlands in Northern Finland, Water Research, 42, 3826-3836.

Ronkanen, A.K. and Kløve, B. (2009), Long-term phosphorus and nitrogen removal processes and preferential flow paths in Northern constructed peatlands. Ecological Engineering, 35, 843-855.

Stevens, J. C. (1957), Flow through circular weirs, Journal of Hydraulic Engineering, 83, 1455.

Tomenko, V., Ahmed, S. and Popov, V. (2007), Modelling constructed wetland treatment system performance, Ecological Modelling, 205, 355-364.

Wong, T. H. F., Breen, P. F., Somes, N. L. G. and Lloyd, S. D. (1999). Managing Urban Stormwater Using Constructed Wetlands, Cooperative Research Centre (CRC) for Catchment Hydrology and Department of Civil Engineering, Monash University.