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Sectional analysis of stormwater treatment performance of a constructed wetland

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ABSTRACT

Constructed wetlands are among the most common Water Sensitive Urban Design (WSUD) measures for stormwater treatment. These systems have been extensively studied to understand their performance and influential treatment processes. Unfortunately, most past studies have been undertaken considering a wetland system as a lumped system with a primary focus on the reduction of the event mean concentration (EMC) values of specific pollutant species or total pollutant load removal. This research study adopted an innovative approach by partitioning the inflow runoff hydrograph and then investigating treatment performance in each partition and their relationships with a range of hydraulic factors. The study outcomes confirmed that influenced by rainfall characteristics, the constructed wetland displays different treatment characteristics for the initial and later sectors of the runoff hydrograph. The treatment of small rainfall events (<15 mm) is comparatively better at the beginning of runoff events while the trends in pollutant load reductions for large rainfall events (>15 mm) are generally lower at the beginning and gradually increase towards the end of rainfall events. This highlights the importance of ensuring that the inflow into a constructed wetland has low turbulence in order to achieve consistent treatment performance for both, small and large rainfall events.

1. Introduction

Constructed wetlands are among the most common Water Sensitive Urban Design (WSUD) measures for stormwater treatment. It is typically a shallow, extensively vegetated water body with different zones that uses enhanced sedimentation, fine filtration and pollutant uptake processes to remove pollutants from stormwater. Water levels rise during rainfall events and outlets are configured to slowly release the stormwater and then maintain dry weather water levels. Since a constructed wetland serves as a structural measure to treat stormwater runoff, the treatment efficiency is of significant concern (Shutes et al., 1999).

Constructed wetlands have been extensively studied to understand their performance and influential treatment processes (for example Scholes et al., 1999; Terzakis et al., 2008; Pan et al., 2013). However, most past studies have been undertaken considering a wetland system as a lumped system with the primary focus on the reduction of the event mean concentration (EMC) values of specific pollutant species or total pollutant load removal (for example Carleton et al., 2001; Birch et al., 2004). Unfortunately, this type of approach does not permit the detailed investigation of treatment trends within the constructed wetland over the duration of the runoff process, which is critical for the effective design of these treatment systems.

It is hypothesised that the treatment performance of a constructed wetland differs during dry periods (when there is no stormwater inflow) and wet periods (during rainfall events) and also differs at different time periods (sectors) of a runoff event. This hypothesis needs to be viewed in the context of the occurrence of the first flush phenomenon, which refers to a relatively higher pollutant load at the initial part of a runoff event and hence relatively more polluted stormwater will enter the constructed wetland in the early sector of the runoff hydrograph (Deletic 1998; Lee et al., 2004; Alias et al., 2014). This could lead to differences in

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treatment performance between early and later parts of the runoff hydrograph. In-depth understanding of these differences in treatment performance will contribute to the design of more efficient constructed wetland systems. In this context, the research study discussed in this paper adopted an innovative approach by partitioning the inflow runoff hydrograph and then investigating the treatment performance of each runoff segment within a constructed wetland. The new knowledge created will help to enhance the design of constructed wetlands and thereby ensure more effective stormwater treatment systems.

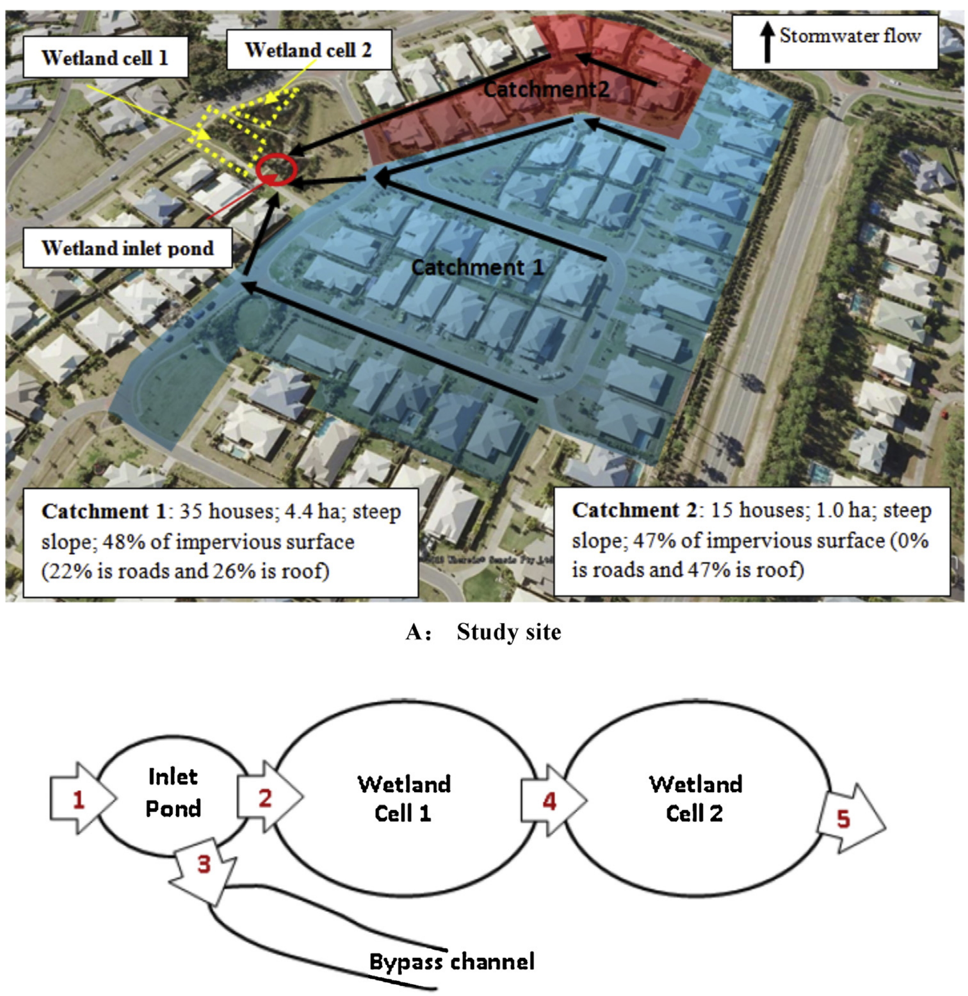
2. Materials and methods

2.1. Study sites

The constructed wetland selected for the study is located at 'Coomera Waters' residential estate, Gold Coast, Australia. The constructed wetland consisted of a sedimentation pond, two wetland cells and an overflow bypass system (see Fig. 1A). The wetland system receives runoff from two small urban catchments that were termed as Catchment 1 and Catchment 2. Stormwater monitoring stations were established to monitor inflows and outflows from Catchment 1 and 2. Stormwater entering the constructed wetland was pre-treated in the sedimentation pond prior to receiving further treatment in the wetland cells. Additionally, the maximum inflow rate which was allowed to enter the wetland cells was controlled by a bypass system. The bypass system is a 7 m wide broad crested weir placed 0.25 m above the crest of the flow transferring pit between the sedimentation pond and cell 1 of the constructed wetland. The weir was located to divert excess stormwater inflow into a bypass channel.

2.2. Sample collection and laboratory testing

The inlet and outlet of the constructed wetland have been monitored from 2008 to 2011 using automatic monitoring stations to record rainfall and runoff data and to capture stormwater



B: The schematic of stormwater flows in the wetland system

- Stormwater entering the wetland system is through the inlet structure to the inlet pond (1);
- The water then flows to wetland cell 1 through a concrete pipe controlled by an inlet pit (2);
- High inflow creates high free surface elevation in the inlet pond leading to part of the inflow to bypass through a channel (3);
- The water from wetland cell 1 flows into wetland cell 2 through a 1 meter wide channel (4) which was assumed as a broad crested weir;
- The water in wetland cell 2 leaves the wetland system through a PVC riser (outlet structure) (5).

Fig. 1. The wetland system.

samples for water quality testing. Flow measurements were undertaken using calibrated V-notch weirs and samples were collected by stage triggered, peristaltic pumping. Discrete stormwater runoff samples were collected during rainfall events to investigate the variation in inflow and outflow water quality.

The samples collected were tested for total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS), which are the primary stormwater pollutants of concern in Australia (Goonetilleke et al., 2005; Liu et al., 2012). Pollutant loads at the inlet and outlet were obtained for each monitored rainfall event. Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA 2005). The test methods were: TSS (Method 2540 C); TP (Method 4500-P-B); TN which is the summation of NO_2^--N (Method 4500-NO2-B), NO_3^--N (Method 4500-NO3-E) and TKN (Method 4500-Norg-B). Additionally, field blanks and laboratory blanks were used as part of the QA-QC procedure. Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS 1998).

2.3. Development of the hydraulic conceptual model

In order to investigate the relationship between treatment performance and hydraulic factors as the rainfall event progresses, a conceptual modelling approach was developed to replicate hydraulic conditions within the wetland. The model was developed to represent water movement through the wetland using a series of mathematical equations. The fundamental approach adopted for model development was to ensure water balance. The modelling approach considered the wetland components including the inlet pond and cells as storages interlinked via inlet/outlet structures. Water balance in each of these interlinked storages was replicated using a standard water balance equation as shown in Eq. (1).

$$\Delta S = S_{t+\Delta t} - S_t = I\Delta t - O\Delta t \quad (1)$$

where ΔS = change in storage volume (m^3), Δt = time interval (s), S_t = storage volume (m^3) at the beginning of the time interval Δt, $S_{t+\Delta t}$ = storage volume (m^3) at the end of the time interval Δt, I = inflow discharge rate (m^3/s), O = outflow discharge rate (m^3/s).

The inflow to the wetland system comprises of flow through the inlet structure direct precipitation to the wetland area and seepage from groundwater. Outflow from the wetland system comprises of flow through the outlet structure, percolation and evapotranspiration. All inflow and outflow components noted above were included in the model developed. In this regard, inflow as seepage from the surrounding soil was considered negligible. The water flow within the wetland was replicated using the schematic shown in Fig. 1B. Details of the conceptual model development and calibration are provided in the Supplementary information.

2.4. Rainfall event selection and determination of section parameters

The eleven rainfall events selected for analysis were less than 1 year average recurrence interval (ARI). The detailed information relevant to estimating ARI of these rainfall events are provided in the Supplementary Information. This ARI range is used for most urban stormwater treatment system design (Dunstone and Graham 2005) due to their relatively more frequent occurrence and being responsible for a high fraction of annual runoff volume from catchments (Liu et al., 2013). Furthermore, the research study required rainfall data, runoff flow data and detailed stormwater quality data during the runoff process at the inlet and outlet of the constructed wetland. Even though a large number of rainfall events were monitored, the eleven rainfall events were carefully selected because they met all of the data availability requirements.

Additionally, the eleven rainfall events accommodated the mid-range of the rainfall depth (3.0–44.6 mm) typical to the study area and an appropriate number of stormwater runoff samples were captured by the stormwater monitoring stations installed at the inlet and outlet. The overall hydrologic and hydraulic characteristics of selected rainfall events are given in Table 1.

In order to investigate the influence of hydraulic factors on wetland treatment as the rainfall event progresses, the inflow runoff hydrograph for each event was partitioned into 10 sectors with each sector representing 10% of the runoff volume and the pollutant load reduction was individually determined for every 10% increment in runoff volume. Selecting pollutant load reduction was due to the fact that it gives the actual pollutant amount removed by the wetland. Similarly, the hydraulic parameters, which were generated by the conceptual model were also determined based on the 10% increment in runoff volume. The calculation procedure can be found in the Supplementary information.

Accordingly, the resulting water quality section variables for each rainfall event included ten load reduction values for each pollutant species (TSS, TN and TP) giving a total of 30 load reduction values for each event while section hydraulic parameters consisted of outflow average discharge (OQ), average water depth in the wetland (AD), average retention time (RT) and outflow peak (OP). Section OQ values represented the outflow characteristics within each 10% increment in runoff volume while OP was the maximum outflow discharge recorded during each sector of the runoff volume. AD influences the wetland environment such as light penetration and dissolved oxygen concentration and hence could play an important role in treatment performance related to

Table 1
Selected rainfall events, their characteristics and pollutant load reductions.

Rainfall no.	Rainfall depth (mm)	Average retention time[a] (day)	Outflow peak[a] (L/s)	Average outflow discharge[a] (L/s)	Outflow volume[a] (m^3)	Average depth of water[a] (m)	Total pollutant load reduction (%) TSS	TN	TP
1	6.4	2.98	1.163	0.642	98	0.35	82	62	62
2	18.4	2.56	2.319	1.197	493	0.465	92.5	12	72
3	44.6	2.37	2.696	1.564	524	0.539	86	42.5	89
4	6.8	3.97	1.071	0.302	168	0.25	64.5	4	42
5	3	4.31	0.753	0.282	44	0.27	68	22.5	−4.5
6	25.8	2.48	2.477	1.255	594	0.452	19.5	16.5	9
7	19.4	3.15	1.768	0.883	383	0.403	59.5	23	−2
8	4.8	4.24	0.969	0.398	93	0.283	79	31.5	2.5
9	9.6	2.97	1.513	0.637	228	0.327	63.5	52.5	6.5
10	20.2	1.92	2.536	1.358	251	0.497	7	38.5	18
11	12.6	2.22	2.242	1.101	255	0.443	15.5	10	52

[a] Generated from the wetland conceptual model.

plants and microorganisms (Paudel et al., 2013). RT is a critical parameter as it represents the time period the stormwater receives treatment in the wetland system. The ten sectors of runoff volume for each event were represented as 1ST, 2ND, 3RD, 4TH, 5TH, 6TH, 7TH, 8TH, 9TH and 10TH.

3. Results and discussion

3.1. Factor analysis

Factor analysis (FA) was initially performed for deriving a general understanding of the treatment performance of the constructed wetland from the beginning and towards the end of the runoff events. For this analysis, the variables included the load reduction values for the ten sectors of the inflow runoff hydrograph while the objects were the three pollutant parameter values (TSS, TN and TP) for the eleven rainfall events. Accordingly, the data matrix was 33×10. Principal component extraction method with orthogonal VARIMAX rotation was adopted for the factor analysis. VARIMAX technique rotates the original factors such that the factors are strongly correlated with a specific set of variables, while weakly correlated with the others (Abdi 2003). After careful investigation of the rotated component matrix, two underlying factors were found sufficient. These factors were extracted based on the initial eigenvalue criteria $\geq$1. Detailed information in relation to factor analysis and eigenvalues are provided in the Supplementary information. Table 2 shows the factor analysis results.

As shown in Table 2, the section parameters representing initial sectors of the inflow runoff hydrograph (1ST, 2ND, 3RD, 4TH and 5TH) tend to correspond to Factor 2 while the later section parameters (6TH, 7TH, 8TH, 9TH and 10TH) tend to relate to Factor 1. This implies that the treatment behavior of the constructed wetland is different for the early and later sectors of the inflow runoff hydrograph. In other words, the treatment characteristics vary along with the runoff flow process. This highlights the need to understand the treatment characteristics of the constructed wetland based on different sectors of the inflow runoff hydrograph rather than using lumped parameters.

3.2. Comparison of treatment characteristics for different sectors of the inflow runoff hydrograph

The treatment characteristics of the constructed wetland during the runoff process were analysed using boxplots as shown in Fig. 2 while the total pollutant load reductions for the eleven rainfall events are given in Table 1. As shown in Table 1, the reduction percentages for TSS, TN and TP are in the ranges of 7 to 92.5%, 4 to 62% and −4.5 to 89%, respectively. These results are generally in agreement with previous research outcomes. For example, Fletcher et al. (2003) noted that constructed wetlands can achieve the pollutant load removal with annual efficiencies of up to 95% for TSS, up to 80% for TN and up to 85% for TP. However,

Table 2
Factor analysis.

Sector of runoff volume	Factor 1	Factor 2
1ST	0.266	−0.911
2ND	0.314	−0.927
3RD	0.475	−0.859
4TH	0.566	−0.798
5TH	0.678	−0.708
6TH	0.752	−0.64
7TH	0.841	−0.536
8TH	0.9	−0.434
9TH	0.932	−0.345
10TH	0.948	−0.26

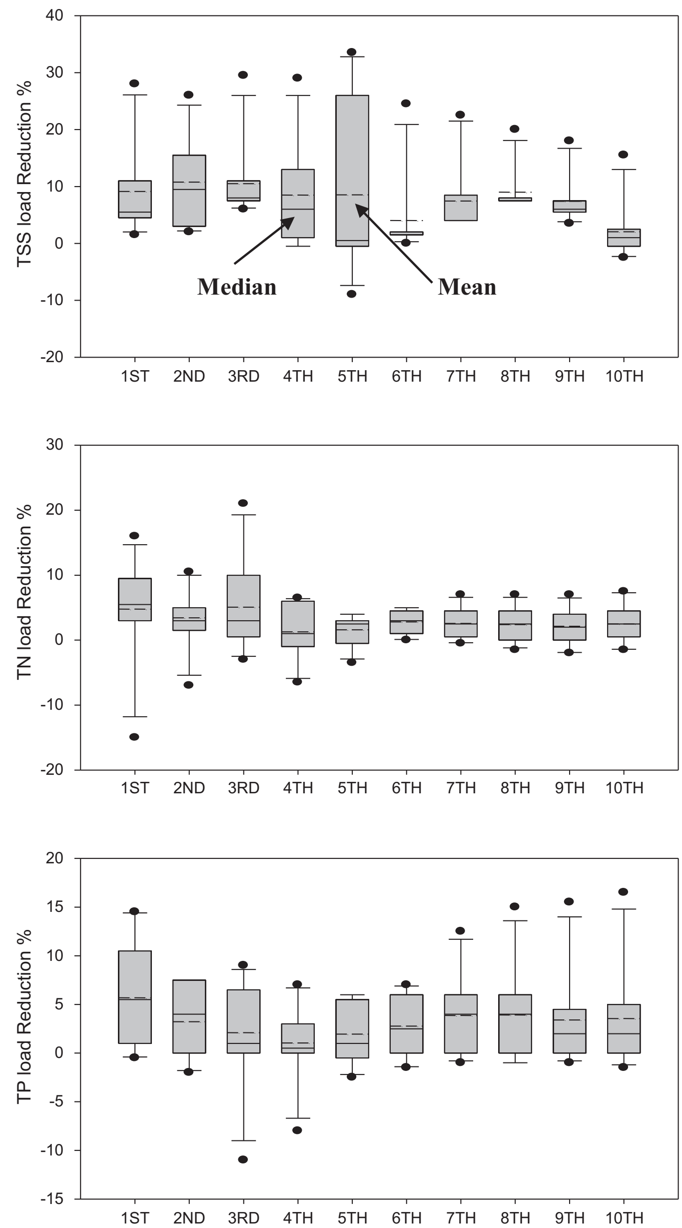


Fig. 2. Comparison of pollutant load reductions in different sectors of the runoff hydrograph.

Carleton et al. (2000) found inconsistency and high variability in the water quality improvement provided by constructed wetlands. This is due to the fact that the removal efficiencies were dependent on a number of factors such as system design, rainfall characteristics and hydraulic parameters. This further highlights the important influence of hydrologic and hydraulic characteristics on treatment performance of a constructed wetland.

In terms of Fig. 2, it is evident that although mean values of load reductions are not notably different among the ten sectors of the runoff hydrograph for the different pollutant species, the data ranges show differences in the early and later sectors. The first five sectors (the first 50% of runoff volume) generally have relatively wider data ranges than the later sectors, particularly in the case of TSS and TN. However, the data ranges for TP load reduction are relatively similar throughout the whole runoff flow process.

Since the data was collected from eleven events with different rainfall and hydraulic characteristics, these observations imply that the performance of the constructed wetland for TSS and TN removal vary comparatively highly with hydrologic and hydraulic characteristics in the initial sectors of the runoff hydrograph, while the TP load reduction varies all the way through the runoff flow process. This means that the pollutant load reduction percentage (particularly for solids and nitrogen) for the initial flow could vary highly based on the characteristics of each rainfall event such as ARI (rainfall frequency representing quantity) and antecedent dry days (representing pollutant load availability prior to rainfall). However, the corresponding percentages of the later flow would be relatively less variable although the characteristics of rainfall events producing runoff might be different. The relatively higher variability of TSS and TN load reductions in the initial sectors of the inflow runoff hydrograph is attributed to mixing with the stored water in the constructed wetland caused by the incoming stormwater flow generated by rainfall events with different characteristics. For example, relatively larger rainfall events would lead to stronger disturbance when the runoff enters the wetland while small runoff events would result in a relatively weaker mixing with the stored water.

In the case of TP, it could be attributed to the occurrence of both removal and release processes during the retention time. As noted by Lai and Lam (2009), phosphorus can be removed by adsorption while it can also re-enter the water column by desorption depending on the physico-chemical properties of soil and water in a constructed wetland. Therefore, TP load reductions could be variable within the runoff process.

Accordingly, it can be hypothesised that the hydraulic and hydrodynamic processes occurring in the wetland dominantly influence the treatment trends taking place. The hydraulic and hydrodynamic processes influence the treatment by mixing, outflow and replacement of the water retained in the wetland with incoming stormwater runoff. Additionally, the relatively higher variability of pollutant load reductions at the initial sectors of the runoff hydrograph (particularly for TSS and TN) caused by inflow mixing with the stored water means that controlling and stabilising the inflow prior to it entering the constructed wetland would be a feasible approach to improve treatment performance. This is due to the fact that lower variability in inflow characteristics commonly leads to an improvement in stormwater treatment.

3.3. Influence of hydrologic and hydraulic factors on treatment performance

The treatment performance of the constructed wetland indicates different pollutant load reduction characteristics in different sectors of the inflow runoff hydrograph. In this context, it was important to further investigate how the treatment performance varies with hydrologic and hydraulic factors. This investigation was conducted using PROMETHEE and GAIA analysis due to its ability to identify relationships between criteria and actions.

In PROMETHEE, a ranking order is developed according to the net ranking flow, the ϕ values, for a number of actions on the basis of a range of criteria. The ϕ values are computed for each action on the basis of the partial ranking out flow indices, $+\phi$ and $-\phi$. The actions 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 out flow values, ϕ, indicates that the two actions are dissimilar. The GAIA biplot is the result of principal component analysis of the data matrix constructed from the decomposition of the ϕ values.

The Pi axis in the GAIA biplot is the decision axis, which points to the top-ranked action/s. In the analysis, the Pi axis encompassed both, hydraulic factors and pollutant load reduction percentages rather than pollutant load reduction percentages only. Therefore, the Pi axis in effect points to the sector/s of rainfall events with both, relatively high values of investigated hydraulic factors as well as pollutant load reduction percentages. Since the objective of the analysis undertaken was to identify the treatment performances of different sectors of runoff volume, the Pi axis was not included in the interpretation of the analysis outcomes. The detailed explanation of the PROMETHEE method can be found in Keller et al. (1991) and Khalil et al. (2004) and the rules for the interpretation of the GAIA (principal component) biplot have been provided by Espinasse et al. (1997).

The criteria used for this analysis were TSS, TN and TP load reduction values, OP, OQ, AD and RT for each sector of the runoff hydrograph while the actions were the ten sectors of the runoff hydrograph for the eleven rainfall events. Accordingly, a matrix (110×7) was submitted to PROMETHEE analysis to form the GAIA biplot for all rainfall events (Fig. 3A). Additionally, two matrices for small (<15 mm, matrix 60×7) and large (>15 mm, matrix 50×7) rainfall events were also created for further analysis and the resulting GAIA biplots are given in Fig. 3B and C.

In terms of Fig. 3A, all the actions generally form two clusters primarily influenced by the rainfall depth. Most of the large rainfall events (>15 mm) are clustered on the positive PC1 axis, where OP, OQ and AD vectors are also projected while most of the small rainfall events (<15 mm) are clustered on the negative PC1 axis and are closely related to RT. This means that larger rainfall events lead to higher outflow peak, outflow discharge and water depth in the wetland and thereby suggesting greater displacement of the water stored in the wetland and higher outflow velocities, while longer retention time tends to occur during small rainfall events.

Additionally, Fig. 3A shows that actions which point in the direction of TSS, TN and TP load reduction vectors are primarily the initial sectors of the runoff hydrographs for small rainfall events (such as load reductions in the first 10% of the runoff hydrograph in Event 1, 1–1 and load reductions in the third 10% of the runoff hydrograph in Event 4, 4–3) and the end sectors of large rainfall events (such as load reductions in the ninth and tenth 10% of the runoff hydrograph in Event 3, 3–9 and 3–10). This can be also further supported by Fig. 3B and C. According to Fig. 3B (small rainfall events), it is evident that actions located close to pollutant load reduction vectors are primarily the initial sectors of the runoff hydrograph (such as load reductions in the first and second10% of the runoff hydrograph in Event 5, 5–1 and 5–2). In terms of Fig. 3C (large rainfall events), actions located close to pollutant load reduction vectors are primarily the later sectors of the runoff hydrograph (such as load reductions in the seventh, eighth, ninth and tenth 10% of the runoff hydrograph in Event 2, 2–7, 2–8, 2–9 and 2–10).

These results can be also supported by the original data. Fig. 4 shows the mean and standard deviation values of pollutant load reductions in each sector of the runoff hydrograph for small and large events. As evident in Fig. 4, in the initial sectors of the runoff hydrograph, small rainfall events generally have relatively higher pollutant load reductions compared to large rainfall events, while the opposite holds true for the later sectors of the runoff hydrograph.

These outcomes suggest that the treatment performance for small rainfall events and large rainfall events differ. In the case of small rainfall events, the relatively cleaner treated stormwater which was already stored in wetland cells flow out in the early stage of a runoff event. Later runoff from small rainfall events would mix with water stored in the wetland leading to the gradual increase in pollutant concentrations in the outflow. However, for large rainfall events, the trends in pollutant load reductions are generally lower at the beginning and gradually increase towards the end of a rainfall event. This is attributed to the rapid mixing of inflow runoff with the stored water in the wetland at the beginning, which typically carries high loads of pollutants termed as first flush (Amir and Ronald 2004; Lee et al., 2002). However, with time as there is a gradual decrease in velocity and the supply of particulate pollutants during the later part of runoff events, treatment performance increases. This is attributed to the increased settling of particulate pollutants in the wetland cells. These analysis outcomes highlight the importance of ensuring that the inflow into a constructed wetland is not turbulent in order to achieve consistent treatment performance for both, small and large rainfall events.

3.4. Implications for treatment design

As discussed above, large and small rainfall events are differently treated in a constructed wetland. The pollutant load reductions for the initial sector of runoff from large rainfall events are relatively low due to the rapid mixing. This means that it is critical to control the inflow to reduce turbulence before runoff enters a constructed wetland, particularly for the large events. Accordingly, it may be necessary to establish an inlet pond prior to

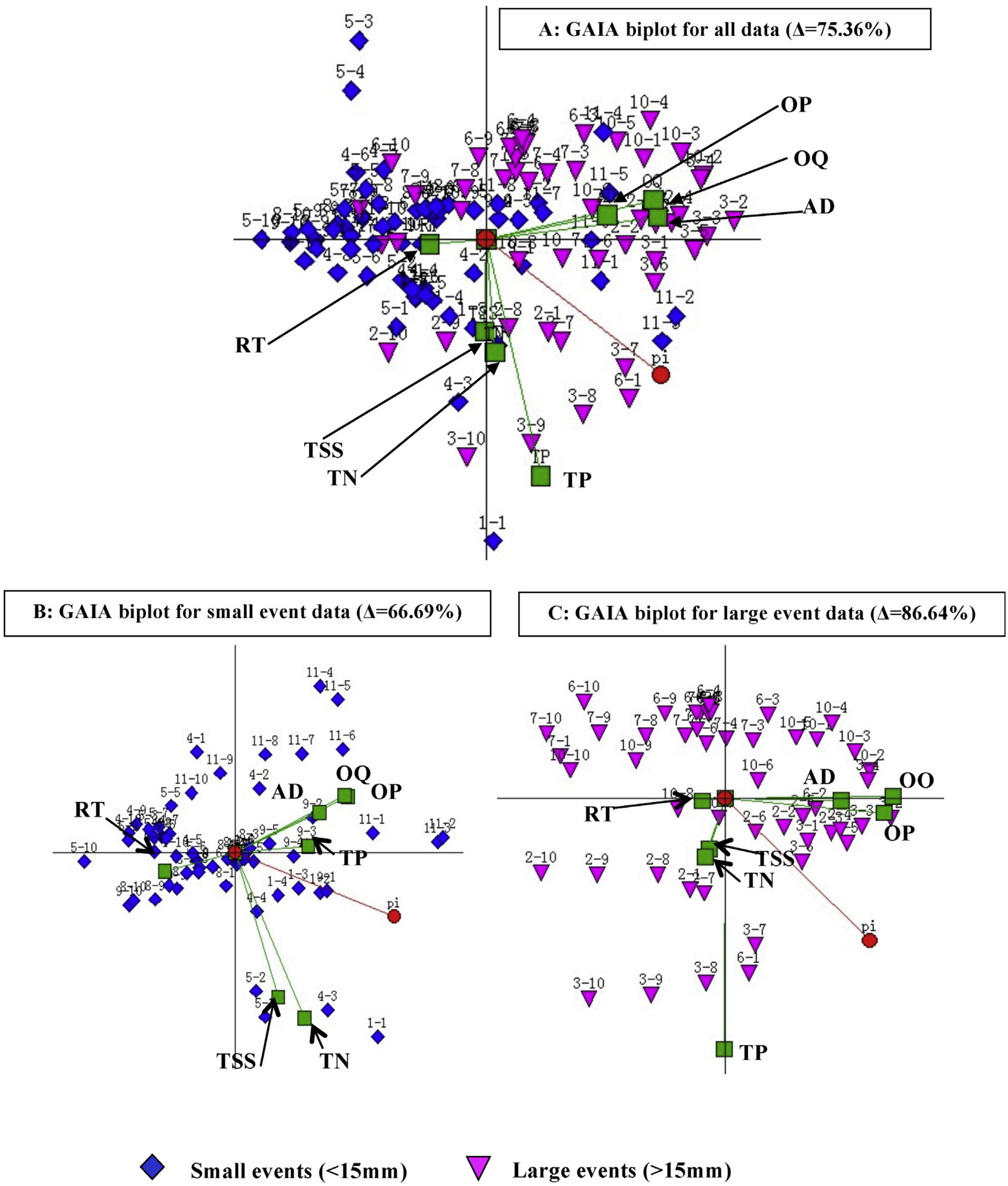


Fig. 3. GAIA biplots.
(The first digital is rainfall no. while the second digital represents the sector of runoff volume. For example, 5–6 represents the pollutant load reduction in the sixth 10% sector of runoff volume in Rainfall No. 5; RT = retention time in each sector of runoff volume, OP = outflow peak in each sector of runoff volume, OQ = average outflow discharge in each sector of runoff volume and AD = average water depth in each sector of runoff volume).

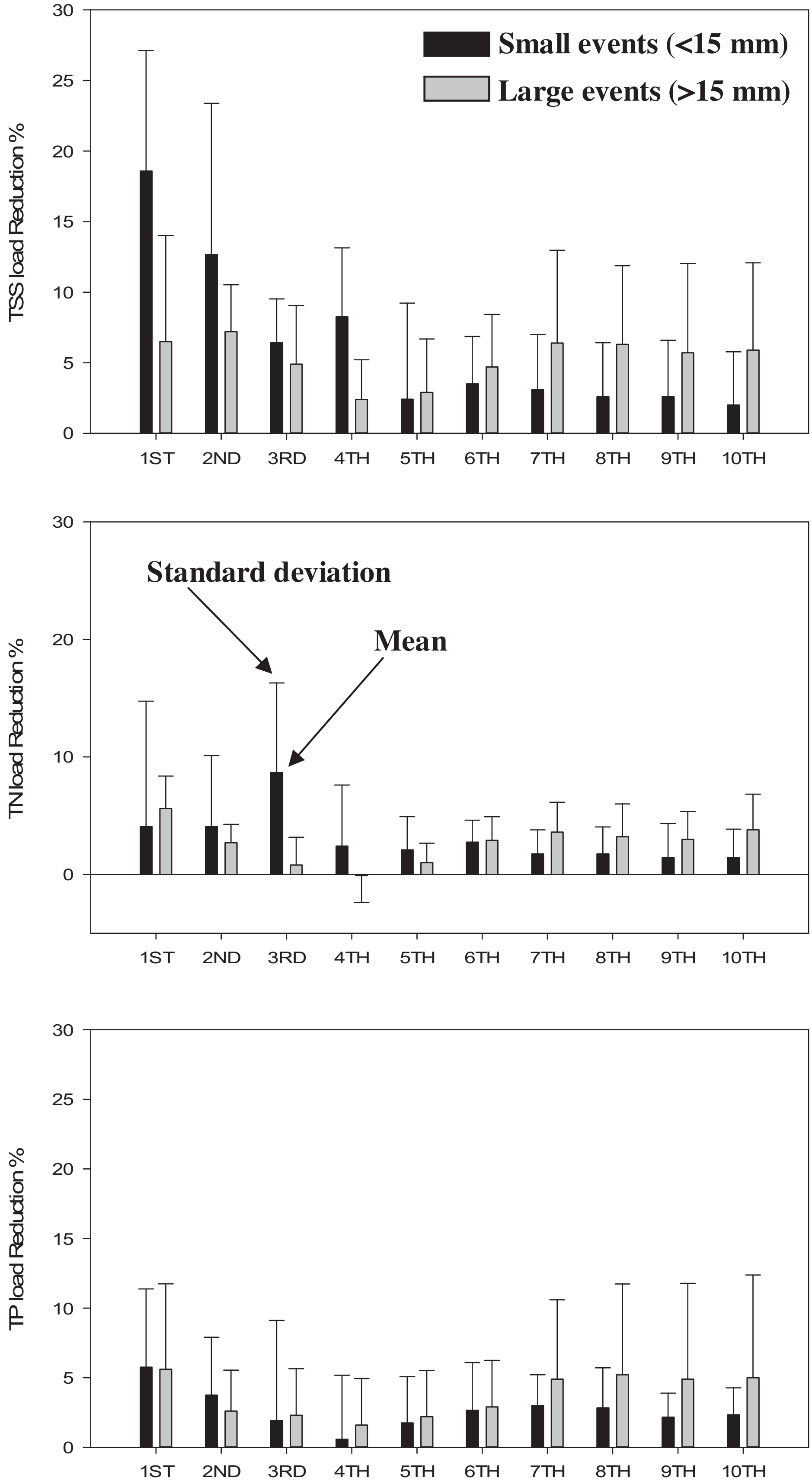


Fig. 4. Comparison of pollutant load reductions for small and large rainfall events.

the flow entering the constructed wetland so that the inflow will first stabilise. This is further supported by the occurrence of the first flush phenomenon where the initial sector of runoff generally carries higher pollutant loads. Therefore, enhancing the treatment of the initial sector of runoff could significantly contribute to the improvement of the overall treatment efficiency of a wetland. Additionally, the provision of a bypass system is recommended to control the runoff to the constructed wetland. This will protect the constructed wetland from erosion damage resulting from high runoff rates.

4. Conclusions

The research study investigated the treatment performance of a constructed wetland using innovative section parameters. The system was found to have different treatment characteristics for the initial and later sectors of the inflow runoff hydrograph based on the rainfall characteristics. A relatively higher variability in treatment performance in the initial sectors of the inflow runoff hydrograph was noted. This suggests that controlling and stabilising the inflow prior to entry into the wetland could be a feasible approach to improving treatment performance.

Additionally, it was found that the treatment of small rainfall events is comparatively better at the beginning of runoff events while the trend in pollutant load reductions for large rainfall events are generally lower at the beginning and gradually increase towards the end. This behaviour is influenced by the mixing, flow and the displacement of the water retained in the wetland with incoming stormwater runoff. This highlights the importance of ensuring that the inflow into the wetland has low turbulence in order to achieve consistent treatment performance for both, small and large rainfall events.

Supplementary information

A Supplementary Information section is provided which provides detailed information relating to the conceptual model development, conceptual model calibration, the stormwater bypass arrangement, the estimation of ARI of the investigated rainfall events, the division of pollutant load reduction for each sector of runoff volume and factor analysis.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.01.028.

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