Analysis of Treatment performance of constructed stormwater wetland with utilising a simplified conceptual model

by Isri Ronald Mangangka

ANALYSIS OF TREATMENT PERFORMANCE OF CONSTRUCTED STORMWATER WETLANDS WITH UTILISING A SIMPLIFIED CONCEPTUAL MODEL

Isri Ronald Mangangka[1], Ashantha Goonetilleke[2], Prasanna Egodawatta[3], Sukarno[4] and Cindy Jeane Supit[5]

[1,4,5] Sam Ratulangi University, Dept. of Civil Engineering, Indonesia
[2,3] Queensland University of Technology, Science and Engineering Faculty, Australia
e-mail: isri_mangangka@unsrat.ac.id

ABSTRACT

Constructed wetlands are used to treat stormwater pollutants and reduce impacts no downstream environment by attenuating peak discharge and reducing runoff volume. They can also treat stormwater quality by removing pollutants through processes such as settling, filtration, adsorption, and biological uptake. The hydrologic and hydraulic characteristics such as rainfall depth and intensity, wetland area and bathymetry, inflow discharge, hydraulic retention time and outlet structure are the most important parameters influencing treatment performance. A simplified conceptual model to replicate hydraulic processes of a constructed wetland has been developed. The model is based on conceptual approaches using empirical mathematical equations to represent water movement through interlinked storage of wetland inlet pond and its cells via inlet/outlet structures, and estimation loss rates due to percolation and evapotranspiration. The model has been calibrated and validated using recorded data from a monitored constructed wetland. The model enables to evaluate the fluctuation of stormwater in the wetland during the storm event and predict the retention time.

Water quality treatment process in a wetland has also been evaluated in this study. The evaluation involved water quality analysis to a number of water samples from a monitored constructed stormwater wetland, univariate, bivariate and multivariate statistical analysis including Principal Component Analysis (PCA) and development of Partial Least Square (PLS) model. The water quality parameters which have been evaluated in this study were Total Suspended Solid (TSS), Total Nitrogen (TN) and Total Phosphorus (TP). The analysis results show that rainfall intensity does not influence the treatment performance. The results also show that more rainfall depth and runoff volume decrease the treatment performance.

Prior to develop the PLS models the dataset was normalized and transformed using principal component analysis (PCA) in order to increase the efficiency of the model. The developed PLS models have been calibrated and validated using cross validation procedure. The calibration plots show that the developed PLS models are adequate to be used for prediction.

KEYWORDS: Conceptual model, constructed stormwater wetland, wetland treatment, wetland hydraulic model

1 INTRODUCTION

Constructed stormwater wetland is one of the most used Water Sensitive Urban Design (WSUD) measure in Australian context (Lloyd 2001; Wong et al. 1999; Wong et al. 2000). Constructed wetland is primarily used for stormwater quality treatment however; it serves as a hydraulic device that reduces peak flows and runoff volumes diminishing the quantitative impacts of urbanisation. Stormwater quality treatment in a constructed wetland is primarily achieved by processes such as settling, filtration, adsorption and biological uptake (Kadlec & Knight 1996; Wong et al. 1999; Melbourne Water 2005).

Treatment processes in a constructed wetland are complex and show significant variability in underlying characteristics and performances with a range of hydraulic, chemical and biological conditions. Among all, hydraulic conditions within a constructed wetland gained specific attention in design scenarios as well as in performance monitoring as the most influential (Guardo 1999; Ronkanen & Kløve 2008). Two hydrologic parameters, retention time and hydraulic loading are typically considered as the most important in constructed wetland design. However, a range of other parameters that have indirect influence on these two main parameters were also considered as significant. For example Holland et al. (2004) considered water depth and flow rate as influential parameters for water quality treatment in constructed wetlands.

However, the understanding developed on the influence of hydraulic parameters on contrasted wetland treatment performance is inconclusive. This is due to the use of lumped hydraulic and water quality parameters for treatment performance analysis. It is commonly used predictive models for performance evaluation of wetlands (for example: Bautista & Geiger (1993), Duncan (1998), Lawrence (1999) and Livingston (1988)), however, many of which evaluated long term performances rather than the event performances (Carleton et al. 2001; Reinelt & Horner 1995; Ronkanen & Kløve 2009). In order to understand the influence of hydraulic parameters on treatment performance, it is necessary to focus on event performances evaluation. In this regard, generation of hydraulic parameters using a detailed hydraulic model which operate in fine time steps is important. Furthermore, the focus should be given to the primary pollutants such as suspended solids and nutrients in constructed wetland performance assessments. Studies such as Tomenko et al. (2007) that evaluated the constructed wetland treatment performance for biochemical oxygen demand (BOD) does not provide comprehensive outcomes.

This study aims to evaluate hydraulic and hydrologic factors which influence the treatment performance of a constructed stormwater wetland. For this, influential hydrologic and hydraulic parameters were derived by using a detailed hydraulic conceptual model. Multivariate analytical techniques such as Principal Component Analysis (PCA) and Partial Least Square (PLS) were used for pattern recognition between water quality parameters and for the development of relationship between parameters and treatment performances.

2 METHOD

Constructed wetland located in 'Coomera Waters' residential estate, Gold Coast, Australia was selected for investigation. This is due to the presence of in-depth monitoring system and availability of historical data. The wetland consisted of an inlet pond at the upstream of the system and two cells of macrophyte zones as the main treatment area. The sizes of the wetland are 149 m2 of inlet pond, 465 m^2 of cell 1(upstream macrophyte zone) and 653 m^2 of cell 2 (downstream macrophyte zone). The total area is equivalent to 2.06% of the contributing catchment area of 6.15 ha. The constructed wetland is receiving runoff from two sub-catchments. The areas of the two sub-catchments are 5.10 ha (sub-catchment A) and 1.05 ha (sub-catchment B) respectively.

The two wetland inlets, the wetland outlet and the bypass outlet have been monitored since April 2008. This is by installing automatic monitoring stations to record the rainfall and runoff data and to capture stormwater samples for water quality testing. Monitoring systems established in each location consisted of a set of instrumentation as shown in Figure 1. Details of the instrumentation are as follows:

- Two automatic tipping bucket rainfall gauges were installed within the vicinity of the wetland.

- Stormwater flow rates were measured using calibrated V-notch weirs with pressure transducer probes to measures the water depth at the weir.

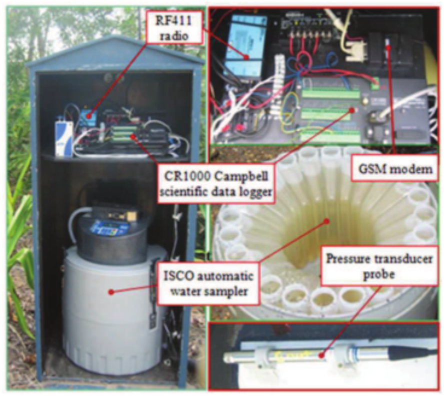

Figure 1: Station apparatus set up

Water samples were collected using ISCO automatic sampler. Only stormwater samples from rainfall events with more than five antecedent dry days were considered for this study. This is to allow appreciable amounts of pollutants to be built-up on catchment impervious surfaces. Based on the build-up equations developed by Egodawatta et al. (2006), a minimum of five days can result more than 50% of the maximum possible build-up on road surfaces. Collected water samples were stored under 4°C during and transport and storage. Samples were analysed for a set of selected water quality parameters as shown in Table 1. The test methods used for the analysis are also presented in Table 1.

Table 1: Title of the table

Parameter	Test Method	Comments
TSS	APHA No. 2540D	Filtered using o.45µm glass fiber 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

2.1 Analytical Methods

A number of statistical analysis methods were used for the evaluation of water quality treatment performance of the wetland. The method included univariate and bivariate statistical techniques, Principal Component Analysis (PCA) and Partial Least Square (PLS) regression. Univariate analysis was used to explore the variance of each variable in the dataset separately and to understand their attributes, while bivariate analysis was performed to analyse two variables simultaneously. These two techniques were used prior to multivariate techniques, so that the variability and distribution of each variable is understood.

PCA was used for pattern recognition and correlation analysis. PCA is a multivariate statistical technique that reduces a large raw dataset into a few numbers of principal components based on associated variances. PCA is the most popular method that has been used in water quality research (Bengraïne & Marhaba 2003; Wunderlin et al. 2001; Mendiguchía et al. 2004; Goonetilleke & Thomas 2004). Details of PCS can be found elsewhere.

PLS is a popular analytical technique which has been used for multivariate predictions. PLS model bears some relation to principal components regression (PCR). However, instead of finding maximum variance between the response and independent variables in PCR, it finds a linear model by predicting the dependent variables and the observed variables to a new space (Adams 2004; Kramer 1998). PLS has been widely used in water quality research such as by Goonetilleke & Thomas (2004), Einax (1998).

3 DEVELOPMENT OF WETLAND'S HYDRAULIC CONCEPTUAL MODEL

A conceptual model was developed to replicate the hydraulic scenarios and hence develop hydraulic parameters essential for constructed wetland performance evaluation. In this approach, the hydraulic response of the wetland system from inflow to sedimentation tank, conveyance through to cell 1 and cell 2 and outflow from the outlet device was modelled using conceptual approaches and empirical mathematical equations. Model was developed such a way that the essential hydraulic parameters such as flow velocity, flow path, hydraulic loading and retention time can be derived from simulations. The basic concept used in modelling is the water balance. This considered the wetland components that are inlet pond and its cells as interlink storages. The change in storage volume in the form of Equation 1 was used.

$$\Delta S = S_{t+\Delta t} - S_t = I_{\Delta t} - O_{\Delta t} \qquad (1)$$

Where: ΔS is the change in storage volume, S_t and $S_{t+\Delta t}$ are the storage volume at the beginning and end of a time interval Δt respectively, and $I_{\Delta t}$ and $O_{\Delta t}$ denote the inflow and outflow volumes of the reservoir during the period of time interval Δt.

The inflow components to the wetland were considered as the inflow from inlet structure and the direct precipitation to the wetland area. The outflow components considered were outflow through the outlet structure, bypass flow, percolation and evapotranspiration. Direct precipitation was calculated from rainfall depth and wetland area. Simplified equations which available else ware were used to predict wetland percolation and evapotranspiration.

Flow between wetland components from inlet to outlet is illustrated using Figure 2. Based on the nature of the hydraulic structures used to convey water through wetland system, surface elevation becomes the primary parameter influencing conveyance between wetland elements. Water elevation was obtained using volume-depth curve developed for each element.

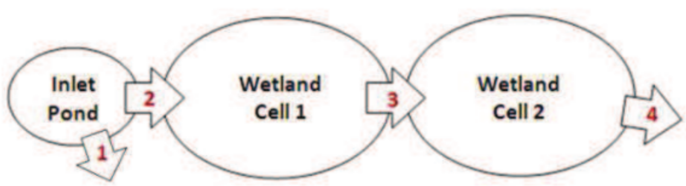

Figure 2: The diagram of water flow

The characteristics of the model are explained as follow:

1) The excessive amount of water entering the inlet pond is bypassed when the water level rises above the bypass weir. Flow through bypass weir was modelled using broad-crested weir formula
2) Flow from Inlet pond to wetland cell1 is through a 350 mm diameter concrete pipe. Water entering to this pipe was control by a rectangular control pit (1.90m x 1.00m). Flow through pipe utilised submerged flow formula, while flow through pit was assumed as flow through a broad-crested weir. Both flows were calculated and the lesser value was considered as the flow into cell 2. The discharge coefficient Cd was obtained from calibration process.
3) Flow from cell 1 to cell 2 was considered as the flow through a broad-crested weir. Width of the weir was obtained from field measurements.
4) A PVC riser with a number of 20 mm diameter holes is used to control the outlet discharge. When a hole is completely submerged, the flow was assumed as flow through a small orifice. When the hole is only partially submerged, flow was assumed to be equals to flow through a circular sharp-crested weir. Weir formula was obtained from Greve (1932) and Stevens (1957).

Recorded flow data at the wetland outlet for 11 storm events were used for model calibration. The calibration was performed by adjusting discharge coefficients of all the flow control devices used. Calibration was done in trial and error approach and an example calibration is shown in Figure 3.

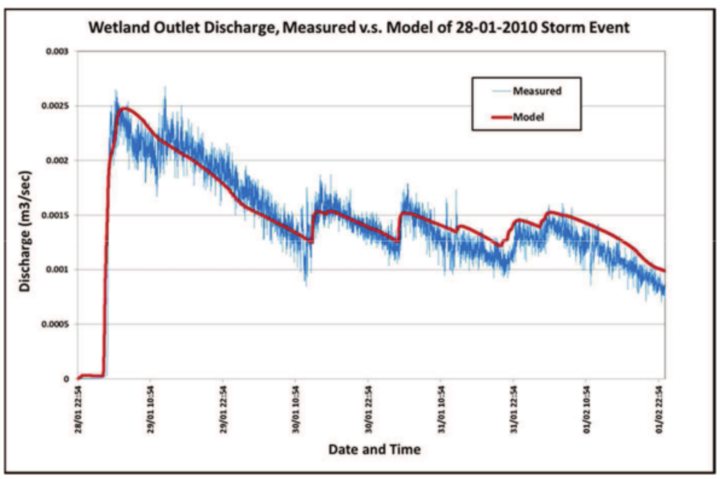

Figure 3: Typical calibration hydrograph of wetland conceptual model

4 RESULTS AND DISCUSSION

Dataset for the analysis was obtained from the measurement from automatic stations and outcomes from laboratory testing. A total of 11 events occurred from 5 May 2008 to 19 July 2010 was used for the analysis. Hydraulic parameters correspond to each event was obtained by simulating conceptual model. In the final dataset, the storm events were arranged as objects and water quality and hydraulic parameters were arranged as variables. The water quality parameters considered were measured pollutant loads of TSS, TN and TP at the inlet of the monitored constructed wetland represented by TSS-I, TN-I and TP-I variables respectively. For evaluation of the water quality treatment performances, percentage reductions of the pollutant loads were calculated and added to the data set as additional variables, represented by TSS-R, TN-R and TP-R respectively.

Rainfall data were obtained from the rainfall records. Two rainfall variables; rainfall depth (RD) and rainfall effective intensity (REI) were used for data analysis. Rainfall effective intensity was calculated as the intensity of the rainfall bursts when an event is occurred as a combination of bursts.

The hydrologic and hydraulic variables used in the dataset were inflow peak discharge (InPD), volume of stormwater treated (VTt), and the average retention time (RT). Volume of stormwater treated and inflow peak discharge were obtained from the recorded flow data, while the average retention time was resulted from the wetland hydraulic conceptual model. The objects and variables of the dataset are presented in Table 2.

4.1 Univariate and Bivariate Statistical Analysis

The univariate statistical analysis was first performed by calculating mean, standard error, standard deviation and variance are shown in Table 2

Table 2: Monitored constructed stormwater wetland data matrix

Variable	Percent Reduction			Pollutant Load In			Rainfall Burst		Inflow Peak Discharge	Volume Treated	Retention Time
	TSS	TN	TP	TSS	TN	TP	Depth	Intensity			
Unit	(%)	(%)	(%)	(kg)	(kg)	(g)	(mm)	(mm/hr)	(m3/sec)	(m3)	(day)
Object & Variable ID	TSS-R	TN-R	TP-R	TSS-I	TN-I	TP-I	RD	REI	InPD	VTt	RT
Rain-1	83.902	61.058	65.267	3.072	0.090	8.619	6.4	4.000	0.06511	98.095	2.544
Rain-2	86.950	18.163	73.332	34.546	0.299	50.714	18.4	3.915	0.12882	493.055	2.557
Rain-3	27.428	15.204	13.174	61.358	1.888	184.675	41.8	6.333	0.76735	985.646	1.408
Rain-4	27.649	26.515	85.109	5.550	0.208	167.524	6.8	11.333	0.25603	167.524	3.966
Rain-5	75.181	38.011	45.016	3.161	0.056	5.734	3	3.750	0.07113	44.188	4.313
Rain-6	3.394	16.338	27.115	33.800	1.535	140.162	25.8	4.691	0.25356	594.011	2.482
Rain-7	14.373	17.022	-7.397	21.172	0.509	99.858	19.4	8.083	0.46152	383.086	3.148
Rain-8	81.175	38.324	8.060	1.350	0.074	20.850	4.8	2.526	0.02690	93.142	4.241
Rain-9	60.862	51.308	6.464	17.035	0.278	61.589	9.6	8.727	0.51064	227.769	2.965
Mean	51.213	31.327	35.127	20.116	0.549	82.192	15.11	5.929	0.28200	342.946	3.069
Std. err. of mean	3.659	1.869	3.700	2.239	0.076	7.647	1.41	0.323	0.02800	34.154	0.107
Variance	1084.48	282.81	1109.08	406.16	0.46	4736.74	160.5	8.434	0.06300	94486.234	0.923
Std. deviation	32.931	16.817	33.303	20.153	0.680	68.824	12.67	2.904	0.25000	307.386	0.961
Skewness	-0.287	0.744	0.338	1.103	1.516	0.386	1.27	0.806	0.93900	1.222	-0.148
Kurtosis	-1.926	-0.768	-1.539	0.799	0.871	-1.545	1.30	-0.335	0.07000	1.18	-0.545

The statistical analysis result in Table 2 shows that the data are not distributed as normal distribution but with a variety of skewness and kurtosis. The analysis result also shows that the data set contains high variability of the available data. Particularly, water quality data indicate scattering by the high variance and standard deviation, for example the ratio of the standard deviations to means of TSS-R and TP-R reach 64% and 95% respectively, and the variance of these two variables reach more than 20 times their mean. This underlies the complexity of wetland treatment due to variability with a range of influential parameters. This could also be due to less number of data sets. All these suggest the necessity of PCA pattern recognition.

4.2 Principal Component Analysis (PCA)

The PCA was undertaken to the dataset (Table 2) which is consisted of all 9 objects and all 11 variables. The variables of the percentage reduction of pollutant (TSS-R, TN-R and TP-R) were become the dependent variables to represent the water quality treatment performance, while the other variables; the pollutant load in (TSS-I, TN-I and TP-I), rainfall depth (RD) and effective Intensity (REI), inflow peak discharge (InPD), volume treated (VTt) and retention time (RT) were become the independent variables. PCA biplot resulted from the analysis is shown in Figure 4.

From the Biplot as shown in Figure 4, it was found that the variance accounted by the first two PCs was 79.6% of the overall variance. This suggests that the first two PCs represent majority of the variance associated to original data set. In interpretation of outcomes from biplot, the eigen vectors make an acute angle were considered as correlated, perpendicular vectors were considered have no correlation, whilst vectors making obtuse angle were considered negatively correlating. As seen in Figure 4, TSS-R, TN-R and TP-R are very closely correlated to each other. This suggests similar treatment performances for all three major pollutant types. It is also found that the retention time is an important variable which can increase the performance of constructed stormwater wetland in treating water quality. This is based on the strong correlation between TSS-R, TN-R, TP-R and RT. This agrees with other research findings that residence time increases the treatment performance (Wong et al. 1999; Carleton et al. 2001).

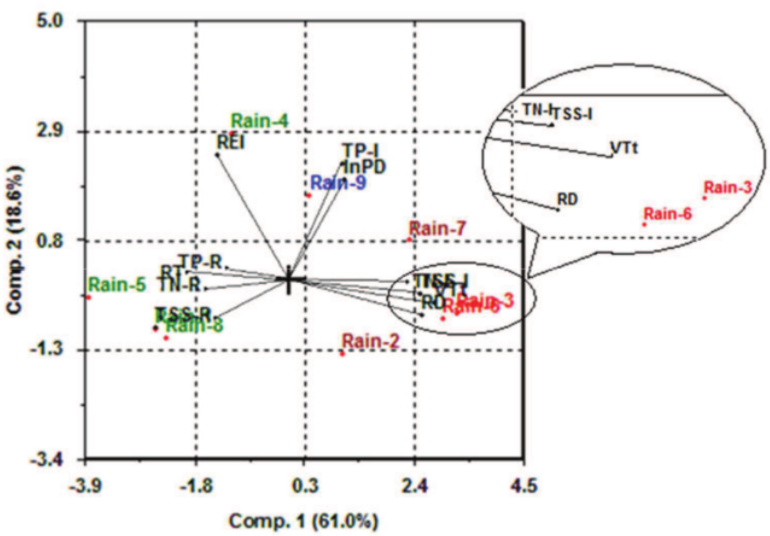

Figure 4: Biplot

Figure 4 also shows that the increase of rainfall depth and stormwater volume decreases the performance, indicating by the negative correlation of the wetland performance variables with RD and Vtt. High correlation between RD and VTt means more rainfall depth results in more runoff volume entering the wetland. This increases the velocity and reduces retention time, thereby reduces the treatment performance. This agrees with the finding of Holland et al. (2004) who claimed that high water depth decreases the retention time and reduces the treatment performance. However, the high inflow peak discharge reduces the treatment performance, shown by the negative correlation of TSS-R, TN-R and TP-R, with InPD in Figure 4. This differs with their finding that flow rates did not have a significant effect of retention time.

The Biplot shows that the pollutant reduction variables are not correlated with the rainfall intensity. Moreover, since no correlation between REI and three important parameters; RD, VTt and RT which have significant influence to the treatment performance, the REI does not affect the performance. All these suggest that for further analysis, rainfall effective intensity (REI) variable should be excluded from the dataset.

4.3 Partial Least Square (PLS) Regression Model

As all measured hydrology, hydraulic and water quality data and recorded rainfalls were not from a complete range of possible rainfalls, it was necessary to develop a PLS model. The model was created to be used for prediction of pollutant load reductions (TSS-R, TN -R and TP-R) as the dependant variables from rainfall, hydrologic and hydraulic parameters (RD, InPD, VTt and RT) as the independent variables. Therefore, pollutant load reduction of three major pollutants (solid, nitrogen and phosphorus) from any form of rainfall might be predicted. In order to increase the efficiency of the modelling, the dataset was normalized and transformed using PCA. The dataset was extracted first into five components and then analysed how many components should be used in the model. A component is not significant when (i) the Standard Error of Cross Validation (SECV) plot no longer shows a significant decreases, (ii) explained variance does not increase significantly, and (iii) cross validation (CsvSD) ratio exceeds 1.0. Based on these criteria, the PLS model for TSS used 3 principal components, PLS model for TN used 4 principal components while PLS model for TP utilized only two principal components.

Having 3 principal components for TSS, 4 principal components for TN, and 2 principal components for TP, three PLS models were developed. The PLS model for TSS was used to predict TSS-R as the dependent variable while PLS models for TN and TP were used to predict TN-R and TP-R respectively. Resulted PLS models are shown in Figure 5.

Due to the limited number of objects, all of nine objects were used for calibration and cross validation procedure was used for validation. The accuracy of the developed model can be evaluated from the calibration plot which presents the predicted vs. measured values of the dependant variable (Figure 5). The calibration plot shows that the developed PLS models are well calibrated regression models which are adequate to be used for prediction of wetland treatment performance.

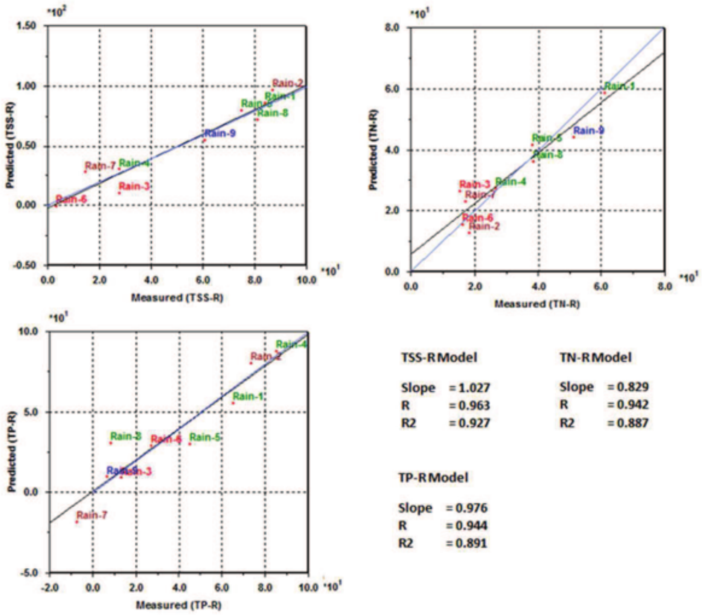

Figure 5: Calibration plot of the developed PLS model

5 CONCLUSION

A simplified wetland hydraulic conceptual model based on conceptual approaches using empirical mathematical equation has been developed. The model simulates the water movement through interlinked storage of wetland inlet pond and its cells based on rainfall, hydrologic and hydraulic parameters. The model has been well calibrated using monitored stormwater wetland data. Therefore, it enables to determine the influential rainfall, hydrologic and hydraulic parameters to the treatment performance of wetlands.

The analytical results using univariate statistical analysis show that the dataset contains high variability of the available data with high in variance and standard deviation. Therefore, prior to developed the PLS model, PCA is necessary to increase the efficiency of the model. The analysis results show that retention time is an important parameter which increases the treatment performance of the wetland. On the other hand, rainfall intensity does not influence the treatment performance. The results also show that rainfall depth, inflow peak discharge and runoff volume affect the treatment performance. The developed PLS models were well calibrated and therefore are adequate to be used for prediction.

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