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Modelling the Hydraulic Processes on Constructed Stormwater Wetland

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Abstract: Constructed stormwater wetlands are manmade, shallow, and extensively vegetated water bodies which promote runoff volume and peak flow reduction, and also treat stormwater runoff quality. Researchers have noted that treatment processes of runoff in a constructed wetland are influenced by a range of hydraulic factors, which can vary during a rainfall event, and their influence on treatment can also vary as the event progresses. Variation in hydraulic factors during an event can only be generated using a detailed modelling approach, which was adopted in this research by developing a hydraulic conceptual model. The developed model was calibrated using trial and error procedures by comparing the model outflow with the measured field outflow data. The accuracy of the developed model was analyzed using a well-known statistical analysis method developed based on the regression analysis technique. The analysis results show that the developed model is satisfactory.

Keywords: Stormwater wetland; wetland modeling; wetland hydraulic.

Introduction

Constructed stormwater wetlands are artificial, shallow, and extensively vegetated water bodies. Constructed wetlands are primarily created for stormwater pollutant removal, to improve landscape amenity and to ensure the availability of water for re-use. A constructed wetland generally consists of an inlet zone, a macrophyte zone (wetland cells) as the main area of the wetland, and a high flow bypass channel.

Constructed stormwater wetlands are stormwater quantity and quality treatment measures which promote runoff volume and peak flow reduction through infiltration, evaporation, and retention, and also efficiently treat stormwater runoff quality [1-3]. A diverse range of processes are involved in stormwater treatment in constructed wetlands including settling of particulates under gravity, filtration, adsorption, vegetation uptake, and biological decomposition [4-6]. These processes are affected by a range of hydraulic factors such as hydraulic loading, retention time, water depth, and inflow rate. A range of studies, for example by Carleton et al. [7], Chang et al. [8], and Holland et al. [9], have been conducted to evaluate the hydraulic factors that influence wetland treatment performance.

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However, most of these studies only used computer simulations to predict the hydraulic characteristics based on empirical formulae with simplifying assumptions of the related hydrologic and hydraulic conditions without any comparison with the real field conditions. Most of the studies have also focused on long term or event based assessment where hydraulic factors were generated on a lumped basis. There are limited information available to understand the hydraulic processes that occur during the treatment of stormwater. Therefore, a model which can predict changes in hydraulic factors during the occurrence of a rainfall event is necessary to be developed in order to replicate constructed wetland hydraulic conditions.

This paper discusses the development of constructed wetland conceptual model which enabled the generation of influential hydraulic factors essential for water quality treatment performance analysis. The assumptions made and their mathematical formulae which are capable to replicate the hydraulic processes within the wetland sub-systems, the calibration process, and evaluation of the accuracy of the developed model are further discussed.

Research Method

This study required rainfall data and quantity data of flow entering and leaving a constructed stormwater wetland collected from an in-depth field investigation of stormwater wetland. For this, data obtained from a previous research conducted from April 2008 until March 2011 in Coomera Waters residential estate, Gold Coast - Australia were used [10]. The research conducted a comprehensive monitoring of a constructed stormwater wetland, built in compliance with accepted standards and guidelines. The monitoring constructed wetland consisted of some instruments installed at the inlet and outlet including two rain gauges, V-notch weir with pressure sensor probe for flow measurement, data logger for recording rainfall and flow data, and spread spectrum Radio Frequency (RF) modem and Global System for Mobile communication (GSM) modem to support telemetry system. The configuration of the monitoring constructed stormwater is shown in Figure 1.

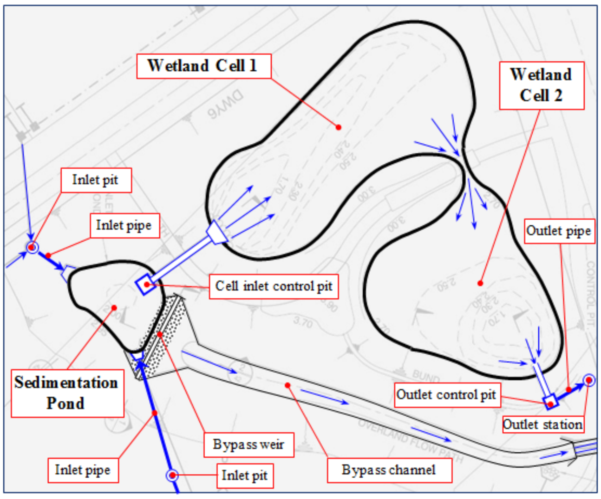

Figure 1. The Constructed Wetland Configuration

Data sets recorded by each station were precipitation to produce rainfall hyetographs and water depth which were converted to flow rate to produce runoff hydrographs at the inlet and outlet of the monitoring constructed wetland for the storm events investigated. Precipitation which was measured using rain gauges and water depth which was measured by pressure sensor probe were recorded in the data logger installed at the inlet and outlet of the constructed wetland. All data recorded in the data logger could be accessed and periodically downloaded by either direct connection on site or using the telemetry system through the monitoring computer. To minimise the loss of data in the data loggers, the telemetry system was set to automatically download the data periodically.

For analysing the treatment performance of constructed stormwater wetland, data relating to hydraulic conditions of constructed wetland were essential. Since field investigations can only provide inflow and outflow data, a modelling approach was needed to generate other hydraulic factors such as average retention time and average depth of water. The model should be able to replicate the fluctuation of the hydraulic factors in the simulated wetland in response to the input data from recorded inflow runoff hydrographs. The model was conceptually designed as a collection of hydraulic devices based on available equations to replicate each device.

The developed hydraulic model of constructed wetland is subjected to evaluate its accuracy. Statistical analysis available which supports this evaluation by comparing the developed model with measured field data was used to justify the precision of the developed model.

Development of the Hydraulic Conceptual Model

The hydraulic conceptual model of constructed stormwater wetland was necessarily developed to represent water movement through the wetland. The basic concept incorporated in the model is the water balance approach. This considers the wetland components, the inlet pond and its cells, as storage interlinked via inlet/outlet structures. Water balance in each of the interlinked storages was replicated using a standard water balance equation (Equation (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 (sec)
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/sec)
O = outflow discharge rate (m^3/sec)

The inflow to the wetland system comprises of inflow from inlet structures and direct precipitation to the wetland area and seepage from groundwater. Outflow from the wetland system comprises of outflow through the outlet structure, percolation and evapotranspiration. All inflow and outflow components mentioned 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 system was replicated using the schematic shown in Figure 2, and can be explained as follows:

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

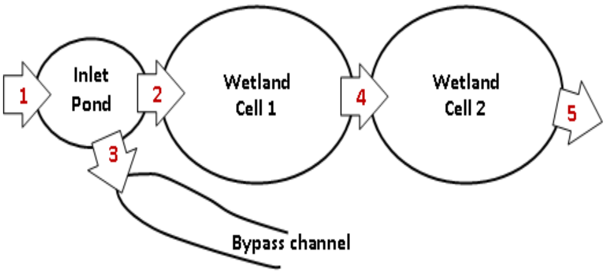

Figure 2. The Schematic of Stormwater Flows in the Wetland System

Generating the Volume versus Depth Curve

Accurate estimation of storage volume played a pivotal part in the constructed wetland conceptual model. Due to the potential changes in bathymetry from its design configuration over time, outcomes from a specially conducted field bathymetry survey were used for the development of the three-dimensional topography of all the wetland cells. The wetland bathymetry contour map resulting from this survey is presented in Figure 3.

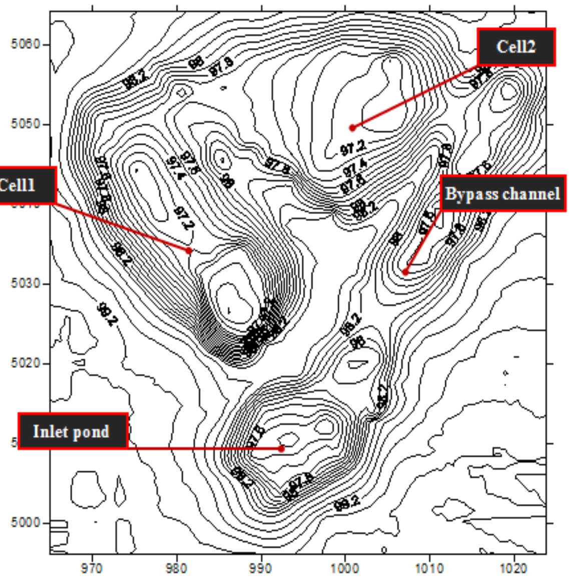

Figure 3. The Wetland Contour Map

Based on this 3D topography, volume versus depth curves were developed for each wetland cell and inlet pond. The curves are presented in Figure 4.

Water flows from inlet pond to cell 1 and from cell 1 to cell 2 was calculated based on the difference in free surface elevations. Free surface elevation in each storage device therefore, acts as the control parameter in the model. Free surface elevation was obtained based on the volume versus depth relationships developed for each storage component. For this, volume versus depth relationship in the form of regression equations was used.

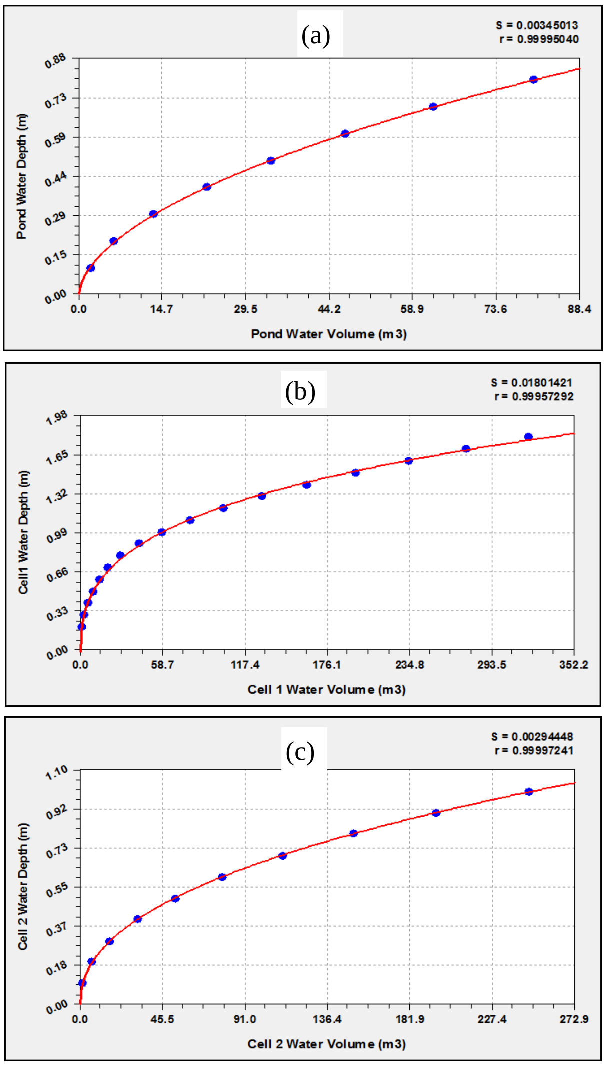

Figure 4. Volume versus Depth Curves for (a) Pond, (b) Cell 1, and (c) Cell 2

CurveExpert software Version 1.40 was used to develop the regression formulae for each wetland component. Volume versus depth relationship for all wetland components were developed using Morgan-Mercer-Flodin (MMF) regression model [11]. The model is widely known as a sigmoidal or S-shaped growth model. It is expressed by the following equation:

$$y = \frac{ab+cx^d}{b+x^d} \qquad (2)$$

Where:
y = water volume (m^3)
x = water depth (m)
a, b, c and d = model coefficients

This model was selected primarily due to its best-fit to the volume versus depth relationship based on the bathymetry. CurveExpert calculated the coefficient of determination and standard error among 33 common trends/models available and found that The MMF regression models for all wetland components provided satisfactory accuracy with highest coefficients of determination (R^2) and lowest standard error (S). The model coefficients, R^2 and S values are presented in Table 1.

Table 1. Model Coefficient, R^2 and S values of Predicted Model

Wetland Component	Model Coefficient	Coefficient of Determination	Standard Error
Pond	a = -8.55055 x 10^{-4} b = 222.310 c = 15.7368 d = 0.565020	0.999901	0.00345
Cell 1	a = -1.59261 x 10^{-2} b = 38.8680 c = 8.91392 d = 0.394738	0.999146	0.01801
Cell 2	a = 3.35185 x 10^{-3} b = 386.642 c = = 32.2859 d = 0.454851	0.999945	0.00294

Flow through Wetland Cells and Bypass

Water Flow from Inlet Pond to Cell 1

Stormwater flow from inlet pond to wetland cell 1 is through a pit and pipe arrangement as shown in Figure 5. The concrete pipe discharging water from pit to cell 1 has a diameter of 350 mm. This pipe is typically submerged, below the free surface level of the pit and wetland cell 1. In such a scenario, stormwater flowing through this pipe is dependent on the flow through the rectangular control pit. The pit has 15 cm thick concrete walls with length and width of 1.90 m and 1.00 m, respectively.

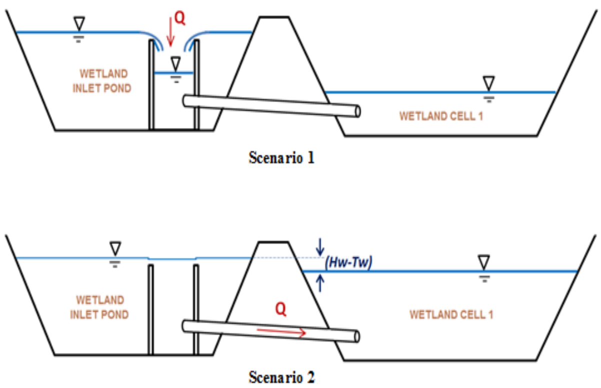

Figure 5. Flow from Wetland Inlet Pond to Wetland Cell 1

Based on this configuration, the flow from inlet pond to the wetland cell 1 was modelled for two different scenarios (see Figure 5) and the governing scenario was taken into account. The first scenario was when the free surface elevation in the wetland cell 1 is relatively low and the flow from inlet pond to cell 1 is controlled by the flow entering the pit. In this scenario, the pipe is assumed to have adequate capacity to convey the flow indicated by the water flow from inlet pond to the pit is free fall. The second scenario was when the water free surface elevation in wetland cell 1 is above a threshold and the resulting backwater influences the water level in the inlet pond. This is indicated by the pit was already submerged due to the backwater obstructed the flow of water in the pipe. In this scenario, flow from inlet pond to cell 1 was modelled by estimating discharge capacity through the pipe.

For scenario 1, water entering the pit was assumed as flow through a broad-crested weir. The weir width was very wide of about 5.4 m as it was taken as the inner perimeter of the pit. This resulted in the thickness of the flow entering the pit above the pit wall was only a few centimetres. With the thickness of the pit of about 15 cm and the upstream head over crest of only a few centimetres, the flow is classified as flow through a broad-crested weir since the ratio of the crest length to the upstream head is greater than 1.5 [12]. According to Gerhart and Gross [13], the discharge through a broad-crested weir can be written as in Equation (3).

$$Q = Cd\left(\frac{2}{3}\right)\sqrt{2g}\;L\,H^{3/2} \tag{3}$$

Where:
Q = Discharge
Cd = Discharge coefficient
g = Acceleration due to gravity
L = Weir width
H = Head above the weir crest

The theoretical value of Cd which is $\frac{1}{\sqrt{3}}$ was used as an initial estimate. Final value used for Cd during simulations was obtained using a calibration process. It was 1.71.

Since the flow velocity was relatively low in the second scenario, the entry loss and frictional head loss was not considered to be significant. Therefore, the simplified flow equation as shown in Equation (4) was used to replicate the second flow scenario. In this equation, discharge coefficient (Cd) was used to compensate other minor losses.

$$Q = Cd\,A\sqrt{2g\,(Hw - Tw)} \tag{4}$$

Where:
Q = Discharge (m^3/sec)
Cd = Discharge coefficient
A = Cross section area of the inner pipe (m^2)
g = Acceleration due to gravity (m/sec^2)
Hw = Head water (water elevation in the pond) (m)
Tw = Tail water (water elevation in the wetland cell 1) (m)

The initial discharge coefficient of 0.6 was used in the model and the actual discharge coefficient of 0.63 was obtained during model calibration.

Water Flow from Cell 1 to Cell 2

The flow of water from cell 1 to cell 2 was considered as the flow through a broad-crested weir, equivalent to the flow described in Equation (3). The weir width *(L)* was about 1.05 m, estimated based on the opening shown in the bathymetric survey and the head *(H)* was the height of free water surface elevation in cell 1 from the crest. However, when the water level in cell 2 rose above the weir crest, then the difference in the surface water elevation between cell 1 and cell 2 was assumed as the head *(H)*.

Water Bypass

Bypass from detention pond is over a 7 m wide broad-crested weir. It was designed to bypass excess water above the crest of the weir to flow across to the bypass channel. The model adopted an equation similar to Equation (2) to replicate the bypass flow.

Modelling the Outlet

Retention time in a wetland is significantly influenced by the outlet structure. For example, Konyha et al. [14] in their study found that an orifice outlet structure would provide longer retention time than a weir outlet structure. In their study involving simulation of 100 years of rainfall events, Wong et al. [6] reported different performances of outlet structures and suggested that a riser outlet gives the best performance. The monitored wetland in this study utilises a PVC riser outlet, which consists of a number of 20 mm diameter slots with 10 cm distance as shown in Figure 6.

Two scenarios were used to model this outlet using the conceptual model. In the first scenario, when a slot is fully submerged, the flow was assumed as flow through a small orifice as shown in Figure 7.

Flow through a fully submerged orifice was calculated using Equation (5).

$$Q = Cd\,A\,\sqrt{2g\,H} \tag{5}$$

Where:
Q = Discharge (m³/sec)
Cd = Discharge coefficient
A = Cross section area of the slot (m²)
g = Acceleration due to gravity(m/sec²)
H = Head from the centre of the slot (m)

In the second scenario, when a slot is partially filled, flow was calculated considering it operates as a circular sharp-crested weir (Figure 8).

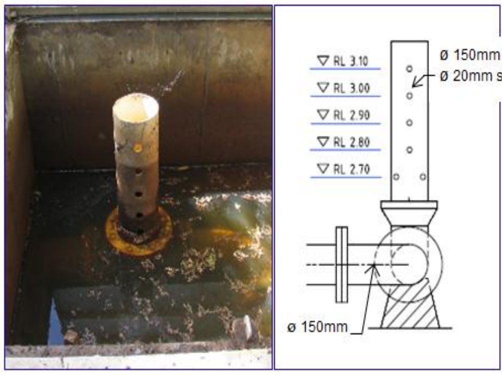

Figure 6. The Configuration of the PVC Riser

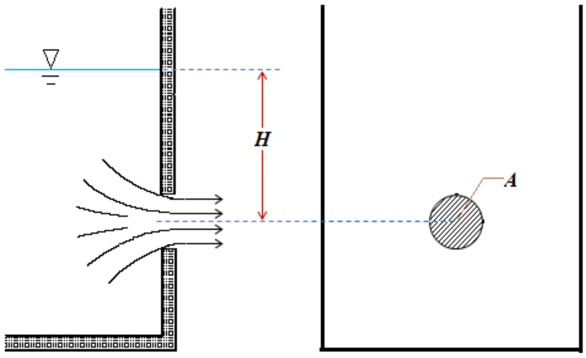

Figure 7. Flow through a Small Orifice

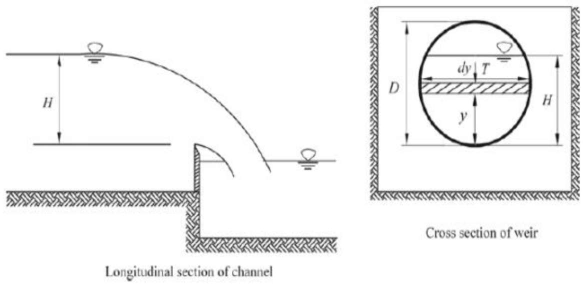

Figure 8. Flow through a Circular Sharp-crested Weir (Adapted from Vatankhah [15])

Assuming that the approach velocity is negligible, theoretical discharge *Qt* through circular sharp-crested weir was derived from first principles as shown in Equation (6).

$$Qt = \int_0^H \sqrt{2g\,(H-y)}\,T\,dy \tag{6}$$

Where:
g = The acceleration due to gravity (m/sec²)
H = Flow depth above the weir crest (m)
y = Vertical distance from an element strip of thickness dy to the weir crest (m)
T = Width of the weir cross section at y (m)

Integration of the theoretical discharge as given in Equation (5) is not easy to be solved since the water surface width and wetted cross section area are variable according to the circular shape. In this regard, the equation form developed by researchers such as Greve [16] and Stevens [17] was used for this model. They have expressed discharge through a circular sharp crested weir as shown in Equation (7).

$$Q = 0.3926Cd\sqrt{2g}H^{3/2}D\eta^{1/2}\,(\sqrt{1-0.2200\eta} + \sqrt{1-0.7730\eta} \qquad (7)$$

Where:

Cd = The discharge coefficient
g = The acceleration due to gravity (m/sec^2)
H = Flow depth above the weir crest(m)
D = The diameter of circular weir (m)
η = The filling ratio (=H/D)

Researchers have noted a diverse range of experimental values for discharge coefficient (Cd) in Equation (6). For this study, the equation presented by Vatankhah as shown in Equation (8) was used to estimate Cd [15].

$$Cd = \frac{0.728+0.240\eta}{1+0.668\sqrt{\eta}} \qquad (8)$$

However, the value obtained using Equation (8) was only used as an initial value. The actual Cd value obtained during the calibration process was 0.696.

Percolation, Evapotranspiration, and Direct Precipitation

Percolation and evapotranspiration are two important factors influencing the wetland water balance. Percolation refers to the downward movement of water through the soil. Evapotranspiration is the sum of evaporation and plant transpiration from the wetland surface and vegetation [18,19].

A range of methods are available to estimate percolation rates. However, in the developed model a constant percolation rate was used to ensure simplicity of the model. Initial percolation rate was selected based on the bed soil characteristics. The monitored wetland bed consisted of silty clay soil and approximate percolation rate was estimated as 5 x 10^{-4} m/h [20]. The actual percolation rate obtained during the model calibration was 1.8 x 10^{-6} m/h. A range of methods are available to estimate evapotranspiration. Estimation of evapotranspiration requires a range of meteorological parameters such as temperature, wind speed, relative humidity and solar radiation to be considered [21,22]. For the developed wetland conceptual model, a constant daily evapotranspiration rate obtained from the Bureau of Meteorology Australia [23] was used to ensure simplicity.

Direct precipitation into the wetland perimeter is also an input to the wetland. Direct precipitation considered in the conceptual model consisted of two parts. Firstly, rainfall falls directly into wetland surface water area, which was considered as equivalent to the rainfall depth. Secondly, rainfall falls into the wetland perimeter with no contribution to the piped flow network. Direct precipitation is not significant to the developed model since the contributed area of the direct precipitation is only 1.828 m^2 from the total catchment area of 61.500 m^2 or only less than 3%. Therefore the direct precipitation was only estimated by multiplying rainfall depth with a runoff coefficient, and runoff coefficient of 0.7 was considered acceptable to compensate for the loss of water due to interception and infiltration.

Model Calibration

Calibration was undertaken to obtain model parameters ensuring that the model was performing as close as possible to the constructed wetland system. A trial and error method was used in the calibration procedure. In this procedure, simulation results were visually compared with measured data. Simulation results were obtained using various combinations of the parameter set and the best performing parameter set based on visual comparison was selected for further simulation [24].

In order to obtain a good comparison during the calibration process, a noise suppression technique was required to reduce the data noise due to the sensitivity of the pressure sensor reading the fluctuating water depth in the V-notch weir boxes. In this study, the average method was used for noise suppression, by averaging several data points before and after each data point as a corrected data point. The typical hydrographs before and after reducing noise using the averaging method are shown in Figure 9.

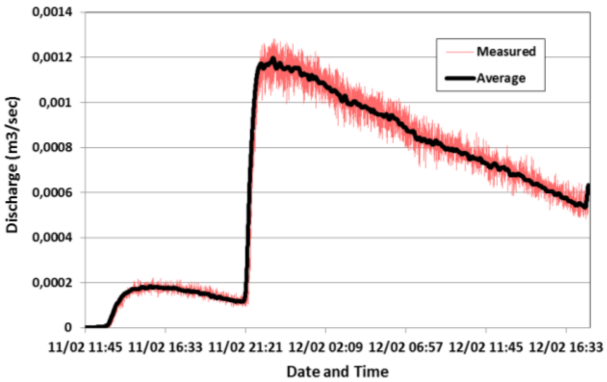

Figure 9. Hydrograph before and after Noise Suppression

The model calibration was done using flow data from eleven storm events during April 2008 to March 2011 period, and the calibration results were found to be satisfactory. To assess the accuracy of the calibrated model, the study adopted a well-known statistical analysis method developed based on the regression analysis technique [25,26]. In this method, coefficient of determination (R^2) which can be used to measure the 'goodness-of-fit' of the estimated model is calculated based on regression residual by taking time as the independent variable (x) and measured and model values as dependent variables. The residual ($\hat{u}_i$) associated with each paired data values (measured and model) is the vertical distance between the measured value (y_i) and model value ($\hat{y}_i$) which can be written as $\hat{u}_i = y_i - \hat{y}_i$ (see Figure 10) [27].

The R^2 value is calculated using Equation (9) [21].

$$R^2 = 1 - \frac{SSR}{SST} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{9}$$

Where:
R^2 = Coefficient of determination
SSR = The sum of the squared residuals
SST = Total sum of squares
y_i = Measured value of dependent variable
$\hat{y}$ = Model value of dependent variable
$\bar{y}$ = Mean value of dependent variable

The sum of squared residuals (SSR) represents the residuals/errors of the model to the measured data while the total sum of squares (SST) represents the variation of the dependent variable around its mean, therefore, SSR/SST can be defined as the proportion of the residual to the variation in the dependent variables. R^2 can be written as 1 minus the proportion of the residual to the variation in the dependent variable and must be bounded by 0 and 1 ($0 \leq R^2 \leq 1$). The closer the value of R^2 to 1, the closer the model to the data points [27].

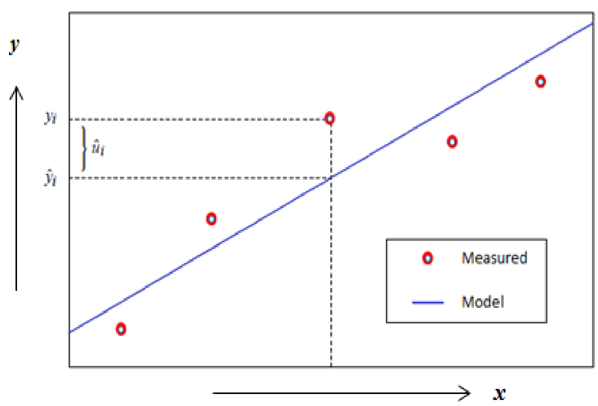

Figure 10. Regression Residual (Adapted from Rawlings et al. [27])

An example of a typical analytical result showing the goodness-of-fit of the developed wetland conceptual model hydrograph for the measured data is presented in Figure 11.

The coefficient of determination R^2 for all wetland measured-model hydrographs is presented in Table 2. It shows that the R^2 values for the eleven storm events range from 0.80 to 0.97. This is considered satisfactory suggesting that the approach used to develop the model is satisfactory.

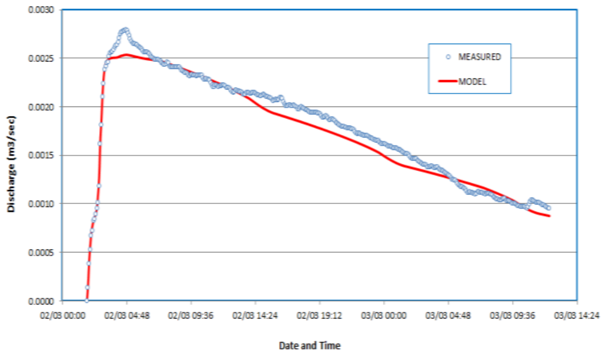

Figure 11. Measured and Model Discharge Hydrograph

Table 2. The Goodness-of-fit, Coefficient of Determination R^2

No.	Rainfall Event	R^2
1	05-04-2008	**0.80**
2	18-04-2008	0.93
3	29-05-2008	0.89
4	11-02-2009	0.95
5	04-03-2009	0.85
6	29-01-2010	0.90
7	18-04-2010	0.96
8	23-06-2010	0.89
9	19-07-2010	0.89
10	02-03-2011	**0.97**
11	29-03-2011	0.86
	Average	**0.90**

Conclusion

The treatment processes of stormwater in a constructed wetland are influenced by a range of hydraulic factors. However, these influential hydraulic factors can vary during an event and the variation can be generated using a detailed modelling approach. Therefore, in this study a hydraulic conceptual model of constructed stormwater wetland which is capable to replicate the hydraulic conditions within the wetland was developed. The basic concept incorporated in the model is the water balance approach which considers the wetland components, i.e. the inlet pond and its cells as interlinked storages via inlet/outlet structures.

The model was calibrated using trial and error procedure which is the most robust procedures available. The approaches used in this study to develop the wetland hydraulic conceptual model are appropriate. Evaluation using regression analysis demonstrated the accuracy of the calibrated model with resulting average coefficient of determination (R^2) is 0.90 for measured outflow discharge. This suggests that the performance of the model in simulating hydraulic conditions is satisfactory.

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