Water balance: case study of a constructed wetland as part of the bio-ecological drainage system (BIOECODS)

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ABSTRACT

The Bio-ecological Drainage System, or BIOECODS, is an urban drainage system located at the Engineering Campus, Universiti Sains Malaysia. It consists of a constructed wetland as a part of the urban drainage system to carry storm water in a closed system. In this closed system, the constructed wetland was designed particularly for further treatment of storm water. For the purpose of studying the water balance of the constructed wetland, data collection was carried out for two years (2007 and 2009). The results show that the constructed wetland has a consistent volume of water storage compared to the outflow for both years with correlation coefficients (R^2) of 0.99 in 2007 and 0.86 in 2009.

Key words | BIOECODS, constructed wetland, evaporation, water balance, water resources

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INTRODUCTION

Water balance has become a tool for managing water resources, operations and decision making, especially in agricultural areas, in order to ensure that crops receive a sufficient amount of water even in extreme conditions. Water balance is also a tool for protecting and maintaining the ecosystem of an environment, especially in swampy and wet areas. Managing accurate water balance assessment is necessary for short and long term water resource management. In order to do so, hydrological and meteorological data or components are most important for developing an accurate water balance. Recently, water balance for constructed wetlands has become a concern for researchers, as discussed by Huebner *et al.* (2009), Mogavero *et al.* (2009) and Shen & Chen (2009).

Impacts from climate change appear to interfere with water balances as well, such as in Lake Balaton (Nováky (2008) and Honti & Somlyódy (2009)). It is believed that environmental problems such as global warming, water scarcity, in addition to urbanization and population growth, are contributing to the hydrological changes, increasing water needs or use, water unbalances and unstable wetland ecosystems. Notably, the two main functions of the constructed wetland are to reduce peak flows and to improve the water quality of stormwater runoff. The constructed wetland is an important facility in urban drainage systems for the control of both parameters mentioned above.

The hydrology of a constructed wetland depends on the soils, nutrients and chosen species, which consequently influence the character of the ecosystem developed. In the constructed wetland, water comes from precipitation, overland flow, overbank flow and groundwater discharge. The water will flow out or be lost from the constructed wetland through evaporation, plant transpiration, channels, overland flow and groundwater recharge (Ramsar 2005). Constructed wetlands are commonly studied to check their capabilities for removing pollutants and reducing peak flow,

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but the water balance study of constructed wetlands is rare due to the long-term period of data needed.

Because the development of water balance involves long term monitoring and difficulty in estimating certain hydrologic components (e.g. groundwater-surface water exchange), its study has been hindered. A few studies have been conducted regarding the water balance of constructed wetlands for humid tropic climates, and thus this paper focuses on short term monitoring data as the beginning of a later detailed study. The objective of the present study is to obtain water balance data of a constructed wetland under a humid tropic climate over the short-term.

STUDY AREA AND DATA COLLECTION

Based on the Urban Stormwater Management Manual for Malaysia (MSMA), the Bio-ecological Drainage System (BIOECODS) was constructed to become a national pilot project for Malaysia. The drainage system was constructed at a newly developed university campus, the Engineering Campus of the Universiti Sains Malaysia, in 2000. The campus is made up of school buildings, hostels and a sport center, and the remaining areas are made up of parking spaces and landscaped areas. Most of these landscaped areas were utilized as dry ponds for BIOECODS. The total catchment area is 121 hectares, and the campus was opened in April 2001. BIOECODS (Figure 1) integrates a combination of best management practices (BMP) techniques for sustainable new developments, with the conveyance provided by ecological swales Type A, Type B and Type C, which differ depending on the numbers of subsurface modules available underneath the swale. Dry ponds with subsurface storage, acting as temporary detention storage, were constructed on several landscaped areas in the campus as the second component of BIOECODS. Swale and dry ponds are located upstream from the system (Figure 2).

The third component of the BIOECODS system, known as an ecological pond (which consists of a wet pond, detention pond and constructed wetland), is located at the downstream part of the catchment (Figure 3). The wet pond, detention pond and wetland, with surface areas of 4,500 m^2, 10,000 m^2 and 9,100 m^2, respectively, were constructed for further treatment of stormwater runoff (Ayub *et al.* 2005). Several wetland species such as *Typha augustifolia, Lepironia articulata, Hanguana malayana* and *Eleocharis dulcis* were planted in order to improve storm runoff by using their capability to provide oxygen and tolerance for organic matter in storm runoff (Mohd Sidek *et al.* 2004).

Details of the constructed wetland in the BIOECODS system are summarized in Table 1. All flows generated in

Figure 1 | Areal view of USM Engineering Campus, Nibong Tebal.

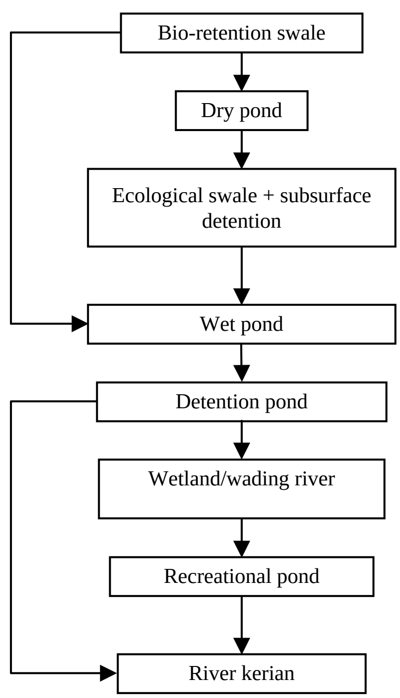

Figure 2 | Schematic diagram of BIOECODS.

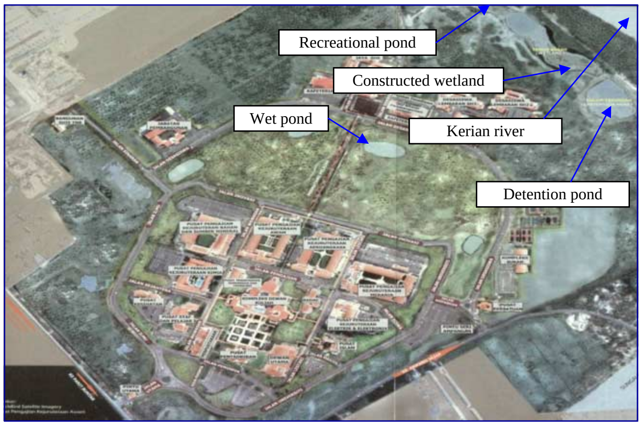

Figure 3 | View from the Quickbird satellite showing the location of the study area.

the catchment area enter BIOECODS before flowing into the Kerian River at the downstream end. There is no flow coming into the catchment area from surrounding areas. Details of the concept, design and construction of BIOECODS are given in Zakaria *et al.* (2003).

Data collection was carried out from January 2007 until December 2007 and April 2009 until November 2009. Data used in the analyses were those from March 2007 until October 2007 and April 2009 until November 2009. There were two monitoring flow stations, which were located at the inlet and outlet of the constructed wetland, respectively, both using the American Sigma AV Flowmeter 950. Evaporation data were recorded from an evaporation pan, which was located near the study area, using a Global Water Ultrasonic Water Level Indicator. Precipitation data were obtained from an ISCO Model 674 Triggering Rain Gauge located in the study area. All locations of the data logger equipment are shown in Figure 4.

Table 1 | Wetland design criteria in the study area

Design parameter	Criteria
Catchment area	1.214 km^2
Design Rainfall (3 month ARI)	22.5 mm/hr
Longitudinal	155 m
Width	60 m
Surface area of wetland	9,100 m^2
Volume	9,100 m^3
Percent of area	0.7
Inflow	0.25 m^3/s
Average of resident time	3 days
Depth	0.6 m
Media	Pea gravel and soil mixture

DATA ANALYSES

The hydrologic budget equation of the study area based on the changes in the surface-water volume for a given time period is equal to the difference between the water inflows and outflows, as shown in Equation (1). The daily climate and hydrology data are the best representation of a detailed process in a water balance analysis.

$$\Delta S = (P_{gross} + GW_{in} + SW_{in}) - (I + ET + GW_{out} + SW_{out}) \quad (1)$$

where ΔS is the change in storage (delta storage), P_{gross} is the gross precipitation, GW_{in} is the groundwater flow into the system, SW_{in} is the surface water flow into the system, I is the interception, ET is the evapotranspiration, GW_{out} is the groundwater flow out of the system and SW_{out} is the surface water flow out of the system. All values were determined on a daily basis (Kirk *et al.* 2004).

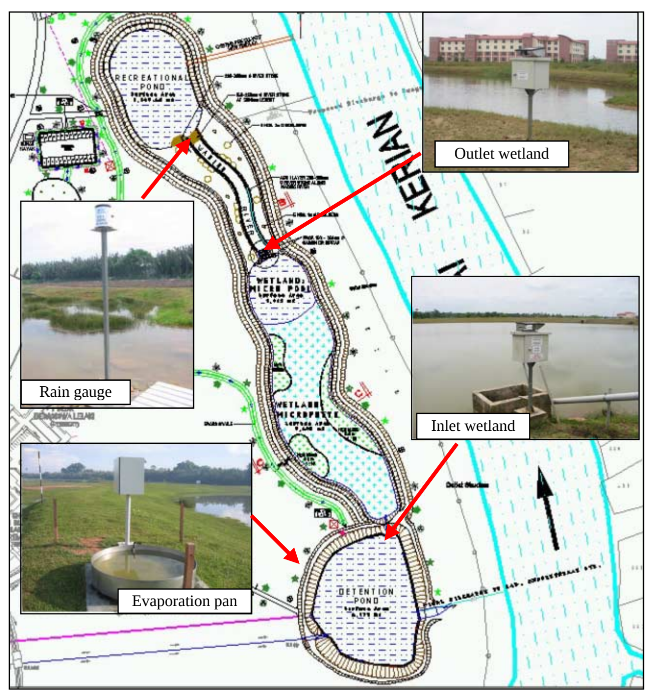

Figure 4 | Location of equipment installed in the study area.

However, in this study, the monthly water balance of the constructed wetland was a priority. Only historical data recorded for the period of March to October 2007 and April to November 2009 were analyzed. In this study, water losses due to evapotranspiration and infiltration of the water from the wetland to the groundwater were not encountered due to the wetland design, where the assumption was made that there was no infiltration of water from the wetland to the subsurface area (groundwater). The water balance in the constructed wetland or change in storage (delta storage) calculated by using the basic water balance equation is as follows:

$$\text{Delta Storage (volume)} = P + R - E - O \qquad (2)$$

where P is the precipitation over the constructed wetland surface (m^3/month) in a month, R is the inflow for the constructed wetland (m^3/month), where the flow comes from the outlet of the detention pond located before the wetland and is considered as the inflow for the wetland. E is the evaporation of the constructed wetland ($m^{3/}$month), and O is the outflow (m^3/month) of the constructed wetland.

RESULTS AND DISCUSSION

All elements that contribute to the water balance determination in the constructed wetland were studied. High precipitation was recorded in the range of 81 mm to 545 mm for the year 2007, whereas for the year 2009 the range of rainfall depth was 7 mm to 739 mm in the study area (Figure 5). In 2009, greater precipitation was recorded compared to 2007. Although more precipitation occurred in 2009, the delta storage volume of the wetland area shows that the volume decreased in comparison to 2007, as summarized in Figure 6.

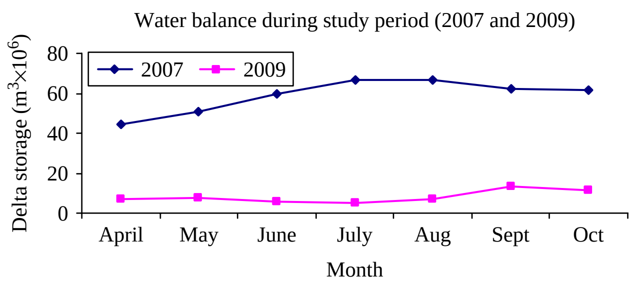

Figure 6 | Volume of delta storage.

Because the study area is located in a tropical climate area, low levels of evaporation occurred compared to those in dry areas. The highest evaporation recorded during the dry season was in October 2007 (24,206 m^3), and the lowest was in March 2007 (5,642 m^3). However, in 2009, evaporation recorded was higher than in 2007, except in October 2009 (12,922 m^3) (Figure 7). Although the study area received a greater amount of precipitation in 2009 compared to 2007, it also had a higher evaporation rate in 2009, which could be the reason for the lower volume of delta storage in 2009. This might be a result of climate change, which reflects the microclimate of the study area.

A high volume of surface runoff also occurred in the wetland area, and it was calculated in the range of 33.4 × 104 cubic meters (m^3) to 21.1 × 105 m^3 (Table 2). The volume runoff-precipitation ratio also varied depending on the volume of runoff and precipitation each month. Shen & Chen (2009) showed that the ratio of evaporation-precipitation and runoff-precipitation vary for different

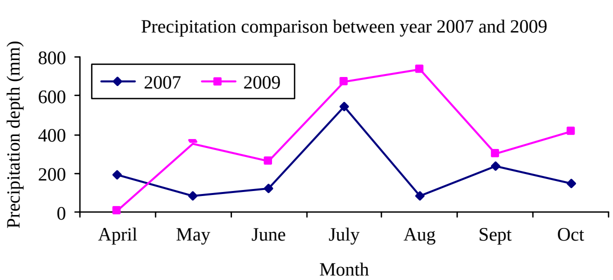

Figure 5 | Monthly precipitation in study area.

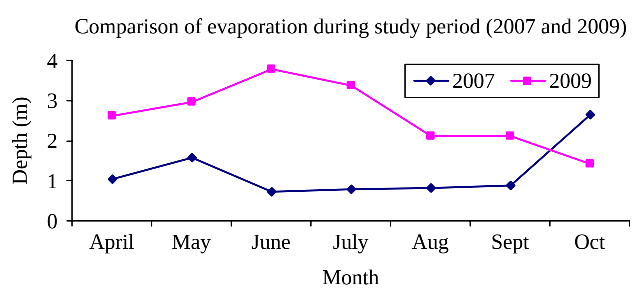

Figure 7 | Evaporation in the study area.

Table 2 | Monthly water balance in constructed wetland for 2007

Months of 2007	Precipitation (mm)	Evaporation, *E* (m^3)	Precipitation, *P* (m^3)	Inflow runoff, *R* (m^3)	*E/P*	*R/P*
March	109	5,642	994	2,099,040	5.68	2,112.3
April	192	9,489	1,745	1,701,900	5.44	975.09
May	83	14,196	753	1,300,219	18.84	1,725.62
June	122	6,643	1,113	333,631	5.97	299.78
July	545	7,280	4,960	1,045,128	1.47	210.73
August	81	7,423	737	416,996	10.07	565.73
September	238	8,008	2,163	1,531,072	3.7	707.82
October	148	24,206	1,344	1,253,671	18.01	932.74

Table 3 | Monthly water balance in the constructed wetland for 2009

Months of 2009	Precipitation (mm)	Evaporation, *E* (m^3)	Precipitation, *P* (m^3)	Inflow runoff, *R* (m^3)	*E/P*	*R/P*
April	7	23,751	65	726,636	367.61	11,246.50
May	355	26,936	3,227	140,169	8.35	43.44
June	263	34,307	2,394	96,418	14.33	40.27
July	673	30,667	6,126	1,282,924	5.01	209.42
August	739	19,110	6,722	1,162,420	2.84	172.92
September	300	19,201	2,734	722,828	7.02	264.42
October	416	12,922	3,787	1,082,116	3.41	285.71
November	541	13,559	4,927	3,706,291	2.75	752.28

climate regions. For the tropical region, they are about 0.43 mm per year and 0.57 mm per year, respectively. The high evaporation rate in 2009 also decreased the volume of inflow runoff (*R*) compared to that in 2007 (Table 3). It is believed that the runoff volume strongly depends on the evaporation rate and precipitation that the study area received. Yao *et al.* (2009) showed that high rates of evaporation occurred in their study area (Harp Lake, Ontario Canada), where the lake area was about 0.714 km^2. The highest rate of evaporation they recorded was about 434 × 103 (m^3).

This study also found that the regression relationship between the water balance and outflow of the constructed wetland had a correlation coefficient value (R^2) of 0.99 for 2007, as illustrated in Figure 8. For 2009, a correlation coefficient of 0.87 was obtained (Figure 9).

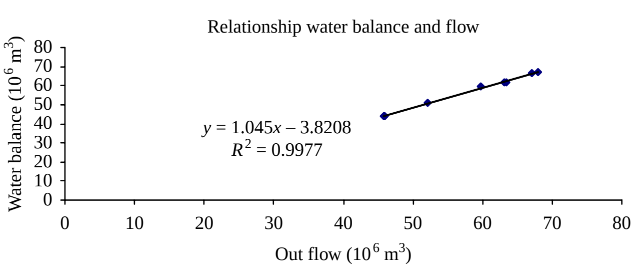

Figure 8 | Relationship between water balance and outflow for 2007.

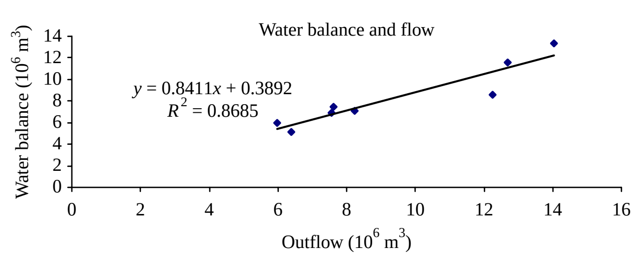

Figure 9 | Relationship between water balance and outflow for 2009.

CONCLUSIONS

A constructed wetland functions not only to treat stormwater runoff but also to control the quantity of stormwater that flows downstream. As a component of BIOECODS, the performance of the constructed wetland for water storage (quantity control) was studied. Although the study area received a high amount of rainfall and also had a high evaporation rate, particularly in 2009, the constructed wetland was found to be capable of storing water according to design.

Further studies are needed for long term data monitoring and for determining what other scenarios and parameters contribute to the water balance in constructed wetland. Developing the model for water balance in the study area will give a reliable indicator for future water resource management and planning.

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