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Evaluation of a small HSSF constructed wetland in treating parking lot stormwater runoff using SWMM

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ABSTRACT

Stormwater management modelling (SWMM) is a dynamic hydrologic simulation model developed by the Environmental Protection Agency for urban areas. In this study, the objective was to evaluate and simulate the performance of an HSSF (horizontal subsurface flow) constructed wetland (HW) with long-term monitored data in treating urban runoff utilizing SWMM. HW was constructed beside a 424 m^2 combined road and parking lot land uses in 2009 with a design rainfall of 5 mm. The facility was manually monitored with a total of 20 storm events from May 2010 until September 2016 to obtain hydrologic, hydraulic and water quality data. Monitored data were used for calibrating and verifying hydraulic parameters such as sub-catchment area, sub-catchment width, and depression storage and water quality parameters such as build-up and wash-off coefficients. Based on the results, the calculated relative errors between the uncalibrated and calibrated parameters were within the accepted ranges (<30%). 0.68–0.98 Nash–Sutcliffe model efficiency coefficient values were computed inciting that the observed and simulated results have a good fit. The volume and TSS loads reduction were also better performed in SWMM (55%–92%) than the observed values. Generally, the simulated results had higher reduction efficiency which suggests that the SWMM model maximized the capability of the facility.

Keywords: Calibration; Horizontal subsurface flow wetland; Low impact development; Simulation; Stormwater management modelling; Total suspended solids

1. Introduction

The increase of impervious development in urban cities (e.g., buildings, rooftops, roads, highways, and parking lots) leads to higher volume, peak flow, stream temperature, and even decreases base flow. These result in flooding, habitat loss, soil erosion, channel widening, and stream alteration [1,2]. According to Hinman [3], as development advances and impervious surfaces replace rural or native vegetation, water depths can increase rapidly in response to individual storm events. Pollutants are also generated and transported without being treated to the receiving water bodies due to impervious areas [4]. Most pollutants recognized in conventional stormwater management practices were found to be total suspended solids (TSS), organics, bacteria, nutrients, and heavy metals which are also collectively known as non-point source (NPS) pollution [5].

Several technologies have been applied to control the effects of urbanization and NPS pollution receiving waters and to prevent ineffective designs, excessive budget costs and severe maintenance requirements. Low Impact Development (LID) technology was introduced and has

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sustainable approaches that allow full development simultaneously maintaining the hydrologic function providing social and ecosystem services [6]. LID has a variety of techniques (e.g., bioretentions, rain gardens, infiltration trenches, and constructed wetlands) aimed to treat stormwater runoff as close to its source having small-scale physical properties but maximize the storage and treatment mechanisms.

Specifically, constructed wetlands are small-scaled engineered systems utilizing wetland vegetation, and microbial activities to treat contaminants in surface water, streams, and groundwater [7]. Free water surface (FWS), horizontal subsurface flow (HSSF), vertical subsurface flow (VF), and hybrid wetlands are different constructed wetland types which vary in flow directions and operations. In this study, a HSSF wetland was utilized wherein it is filled with filter media within which water flows horizontally.

Quantifying the effectiveness of the HSSF wetland has led to problems pertaining to personnel or instrument availability, repetitive or laborious monitoring scheme, and monetary budget for water analysis [8]. Moreover, data collection through manual monitoring was found to be prone to errors due to complex nature (e.g., anthropogenic activities, road cracks, uneven areas, vehicular activities, etc.). Thus, computer models have been developed and enhanced to address impractical problems from field measurements and better predict the movement of stormwater runoff and its characteristics. Quantity and quality of data obtained from field sampling of each event were the basis of stormwater prediction models [9]. Stormwater management modelling (SWMM) is a comprehensive rainfall-runoff-routing simulation model used for single event or long-term simulation of runoff quantity and quality from urban areas [1,2,10,11]. SWMM can also mimic the hydrologic and water quality circulation for designing LID techniques to an extent of accurateness that is based on selected model parameters (i.e., hydrologic and hydraulic parameters, build-up rates, wash-off coefficients, etc.). Therefore, SWMM was conducted in this study to evaluate and simulate the performance of a small HSSF constructed wetland with long-term monitored events in treating stormwater runoff through runoff and TSS reduction. The study also determines the appropriateness of the selected model parameters in designing a cost-effective constructed wetland.

2. Material and methods

2.1. Physical characteristics of the HSSF constructed wetland

The small HSSF constructed wetland (HW) was utilized in the study which is located at Kongju National University, Cheonan campus, South Chungcheong, South Korea. The wetland was installed adjacent to an impervious parking lot with a surface area of 424 m^2. HW has an aspect ratio of 1:0.1:0.1 (L:W:H) and designed for a 5 mm rainfall. Moreover, Table 1 summarizes the physical characteristics of the HSSF wetland in campus including the design components and types of media.

Fig. 1 describes the different mechanisms of the constructed wetland. The wetland consists of pre-treatment, plants, and filter bed zone. HW pre-treats the runoff through

Table 1
Physical design characteristics of the LID facilities

Characterization	LID types
	Hybrid wetland (HW)
Year constructed	2010
Actual dimensions (L × W × H), m	7 × 1 × 0.7
Infiltration capability	No
Design rainfall, mm	5
Surface area, m^2	5.94
Storage volume, m^3	2.94
Total volume, m^3	4.9
Runoff source	Road and parking lot
Catchment area, m^2	424
Media	Sand, gravel, bioceramic

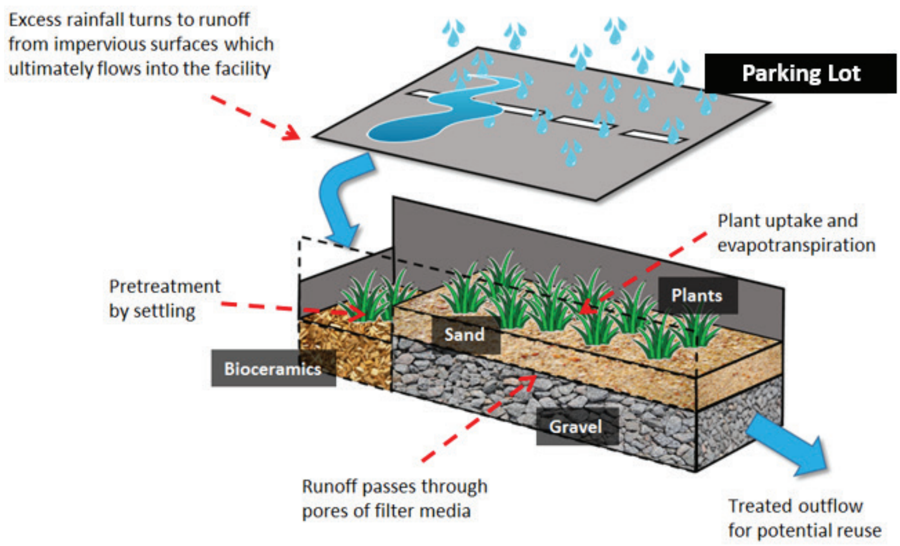


Fig. 1. Schematic diagram and design strategy of the HSSF wetland.

a 0.67 m^2 sedimentation tank with bioceramics as filter media. The filter bed was composed of compacted sand, gravel bedding, and plants. *Acorus calamus* (Russian iris) was planted on the bed because it was identified as a hyperaccumulator of some metals [12].

2.2. Monitoring and analysis of samples

Sampling was manually done at the inflow and outflow ports of the constructed wetland to obtain the water quality and quantity of the stormwater runoff for every storm event. The sampling scheme was based on the typical sampling method used in Korea [13–15]. There were six samples collected in the first hour of the monitoring wherein collection of samples has a time interval of 0, 5, 10, 15, 30, and 60 min. More samples were collected every 1 h until runoff has stopped. The facility was manually monitored from July 2010 until September 2016 with a total of 20 storm events. TSS content in the runoff was analyzed in accordance with the Standard Method for the Examination of Water and Wastewater. Event mean concentration (EMC) was used to quantify the pollutant concentration. The determination of the pollutant loads was also a means of water quality analysis in the study.

2.3. Model application, calibration, verification, and data handling

SWMM was utilized in the study to simulate the hydrologic and water quality effects of the HW. The HSSF wetland was represented as a storage node. Using the storage node, designers can input the surface area and volume of a facility using either functional or tabular curve. Runoff generated by the simulation in the catchment areas (sub-catchment areas in SWMM) was collected or routed to junction nodes which serve as the inlet of the HW. On the other hand, the outlet was represented as an outfall node. Link conduits were used to connect the nodes to relay the runoff through the whole model. The parameters considered for the hydraulic calibration were the sub-catchment area, sub-catchment width, and depression storage. Build-up and wash-off values were parameters that were calibrated for water quality. Iterative adjustments of the parameters by trial and error were conducted in the study to match the simulated and observed data. Moreover, the first half of the total events was subjected to calibration and the latter half for verification of the simulated results. Calibrated parameter values should be in the range of the allowed relative errors (5%–30%) [8,16]. Nash–Sutcliffe model efficiency coefficient (NSEC) was calculated in the study to express the satisfaction between the observed and simulated results. Accepted values of NSEC values should be closer or equal to 1 and must be more than 0.5 [17]. NSEC can be computed as follows:

$$\text{NSEC} = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \quad (1)$$

where Q_o is the observed flow, Q_m is the simulated or modelled flow, $\overline{Q_o}$ is the average observed flow, Q_o^t and Q_m^t are the observed and simulated flow at time t, respectively.

3. Results and discussion

3.1. Data generation and urban runoff characteristics

The urban runoff characteristics were collected and utilized for data generation for the modelling process. Tables 2 and 3 summarize the hydrologic, hydraulic, and TSS characteristics of the HSSF wetland. Most of the hydrologic parameters have high standard deviations along the 6-year monitoring period inciting that there were varied values in each storm event. Furthermore, the mean values of the EMCs and pollutant mass loadings from the wetland were higher than the median which indicates that the pollutant concentration was generally lower in most of the storm events [18]. TSS was the only water quality component considered in the study since it was found to be important in the partitioning of heavy metals between soluble and particulate form during a storm event [19]. The average rainfall duration of storm events for calibration and verification were 3.29 ± 3 and 2.04 ± 1.31 h, respectively.

3.2. Calibration and verification of the simulated model

The sub-catchment area, width, and depression storage were calibrated to get a good fit correlation with the hydraulic observed data. On the other hand, the water quality

Table 3
TSS content statistical summary of monitored events of the HW

TSS water quality characteristics	Mean	Standard deviation	Median
EMC_{in} (mg/L)	124.98	87.16	117.35
EMC_{out} (mg/L)	44.90	31.20	33.33
$Load_{in}$ (kg)	0.2074	0.3134	0.0648
$Load_{out}$ (kg)	0.0864	0.1652	0.0171

Table 2
Hydrologic and hydraulic statistical summary of monitored events of the LID facilities

Hydrologic and hydraulic characteristics	Minimum	Maximum	Mean	Standard deviation	Median
Antecedent dry days, d	0.2	20.7	6.1	5.0	4.9
Total rainfall, mm	1.0	33.0	7.9	9.0	4.8
Rainfall duration, h	0.53	10.0	2.7	2.3	1.8
Average rainfall intensity, mm/h	0.28	27.4	4.8	6.7	1.6
Runoff volume, m^3	0.03	11.8	2.0	3.3	0.4

parameters for calibration were the build-up mass per unit area, build-up rate constant, and the wash-off coefficient. The calibrated values of each parameter are shown in Table 4. The selected parameters for calibration were found to be sensitive by repetitive substitution of values of the other sub-catchment and water quality properties. The water quality parameters (i.e., build-up rates and wash-off coefficients) have higher relative errors than the water quantity parameters which mean that water quality calibration was more complicated to match with the observed data.

Table 4
Parameter values and relative error between initial and calibrated values

Parameters	Unit	Initial	Calibrated	Relative error
Subcatchment area	m^2	424	401.4	5.2
Subcatchment width	m	65	56.7	14.9
Depression storage	mm	2.5	4.2	20
Build-up mass per unit area, bu_{max}	kg/m^2	20	14.7	30
Build-up rate constant, b_1	1/d	0.5	0.35	20
Wash-off coefficient, w_1	n/a	0.20	0.15	25

The correlation between the observed and calibrated runoff volumes and TSS mass loads are presented in Fig. 2(a). NSEC values computed for the runoff volumes were 0.98 (inflow) and 0.88 (outflow). Moreover, 0.86 and 0.91 NSEC values were calculated for the TSS influent and effluent mass loads, respectively. The volume and TSS loads reduction were also better performed in SWMM (55%–92%) than the observed values. Although the simulated runoff and TSS mass loads had similar values with the manually monitored data, SWMM generated more runoff and TSS loads. Moreover, the calibrated results overestimated the observed data since the simulation was modelled to have 100% routing in the whole catchment area. Nevertheless, the calibrated parameters were accepted in the study since the NSEC values were at least more than 0.5. However, TSS NSEC values were considerably lower than the hydraulic calibration. Likewise the inevitable in situ condition during monitoring, it was more evident the build-up and wash-off processes of particulates will be more complicated. Moreover, the input of the respective antecedent dry days (ADD) of each monitored event mattered in the simulation process. Using the ADD

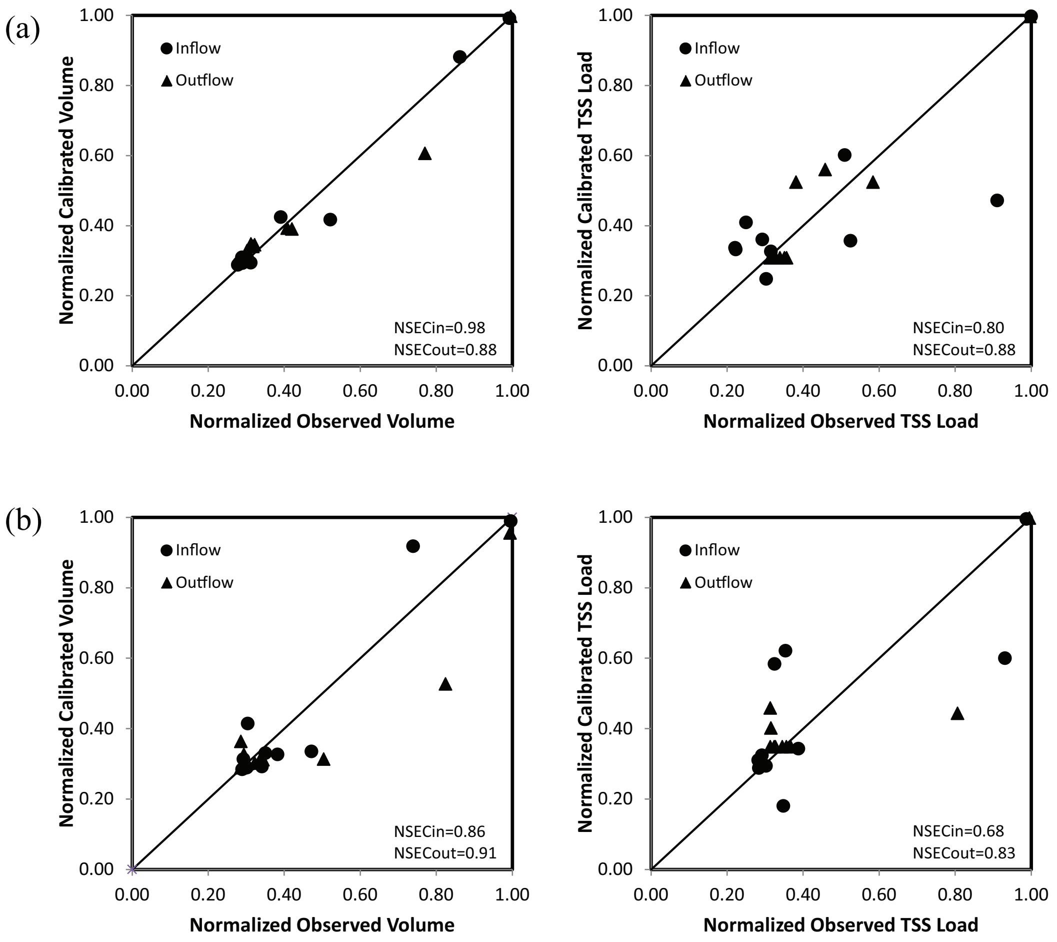


Fig. 2. Normalized observed and calibrated (a) and verified (b) results comparison of runoff volumes and TSS loads.

recorded from the observed data, the simulated TSS loads were approximately similar although uncertainties remain apparent.

The verified values had particularly overestimated the observed results. Shown in Fig. 2(b) were the verified results using the calibrated parameters on the latter half of the storm events considered in the study. Same as the calibrated results, the verified results had particularly overestimated the observed results.

3.3. Comparison of observed and calibrated results

The hydrographs presented in Fig. 3 show the observed and calibrated flows of the representative storm event (2 April 2015). During the first part of the storm event, the inflow was already evident in the simulation model. Although the observed inflow had a delay, it was found out that this was due to the several cracks and depressed areas present in the actual catchment area. The outflow readings from the simulation were continuous until the rain stops compared with the observed inflow and outflows, the monitoring has stopped which can lead to flow imbalance. The model had lower outflow readings suggesting that HW as storage node had lessened the intensity of the storm event.

Fig. 4 shows a representative water quality calibration model in terms of a polluto-graph. The representative model demonstrated overestimation of the inflow TSS loads during the first flush. The calibrated TSS loads had a 14% decrease

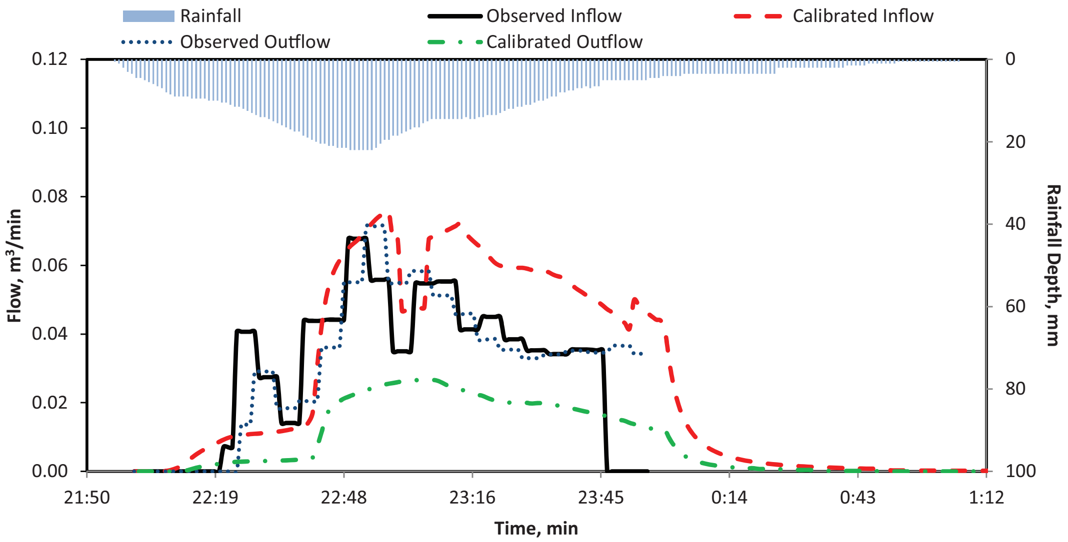


Fig. 3. Representative hydrograph for hydraulic calibration model of the HSSF wetland.

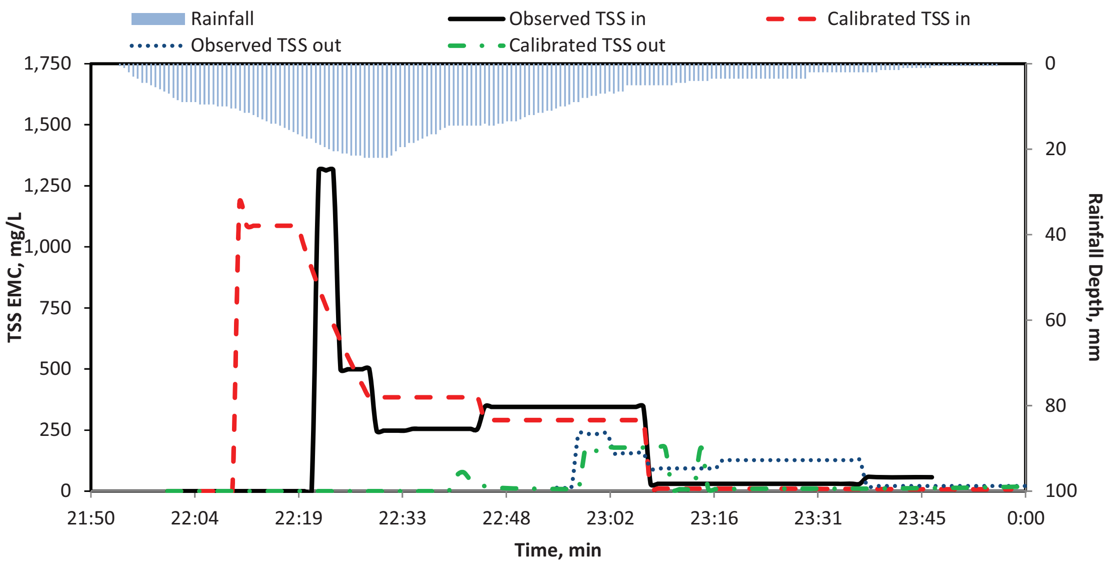


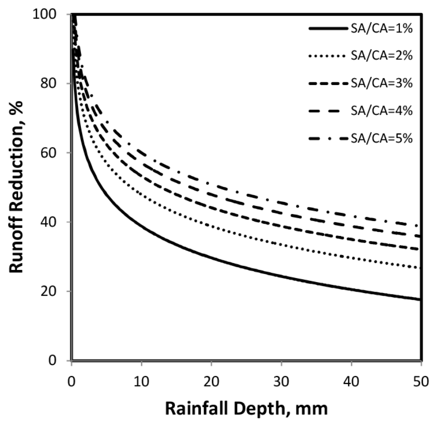
Fig. 4. Representative TSS polluto-graph for water quality calibration model of the HSSF wetland.

from the observed TSS loads. The peak flow readings between the calibrated and observed results had extensive similarities. Moreover, the model had approximately mimicked the first flush phenomenon and the successive outflow TSS readings were much lower. Physical mechanisms such as filtration which cannot be considered in SWMM were considered as constraints on why outflow TSS concentrations were not following the trend of the observed TSS outflow concentrations.

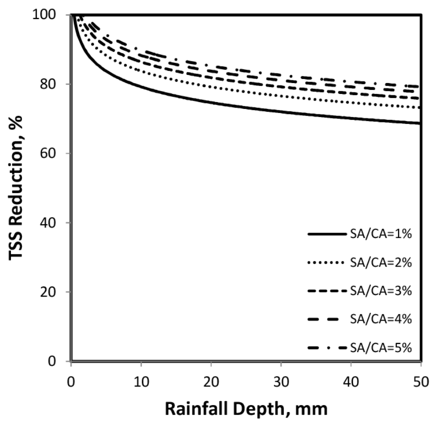
3.4. Cost-effective design and pollutant loadings reduction of the HSSF wetland

The cost-effectiveness of a design can be loosely based on the surface area–catchment area (SA/CA) ratio of a treatment system to the corresponding catchment area. Based on the data collected after simulation and calibration of models, regression plots were constructed to show the respective rainfall depths and reduction efficiency for every SA/CA which can be used as guidelines in designing LID facilities. The results in Fig. 5 had shown that even with a smaller SA/CA ratio has better treatment performance than the actual SA/CA (1.4%) of the HW. The calibrated 1% SA/CA ratio shows that there is a 59.96% runoff reduction from a 14.5 mm rainfall compared with the 38.6% observed runoff reduction. Regardless of the SA/CA ratios, TSS reduction efficiencies for the HW calculated have similar values because of the high reduction efficiency from the calibrated values. Considering a 15 mm rainfall in the HW, TSS reduction ranges from 76.57% to 87.12% suggesting HW as an efficient facility for treating stormwater runoff.

The TSS loading delta values are shown in Fig. 6(a). The area enclosed by the trend lines represents the range of the expected values of retained pollutant loads. Each delta of a pollutant loading in a certain event was computed by obtaining the difference between the inflow and outflow loadings

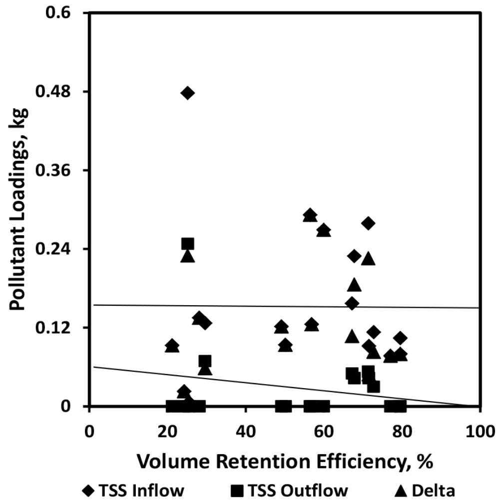


(a)

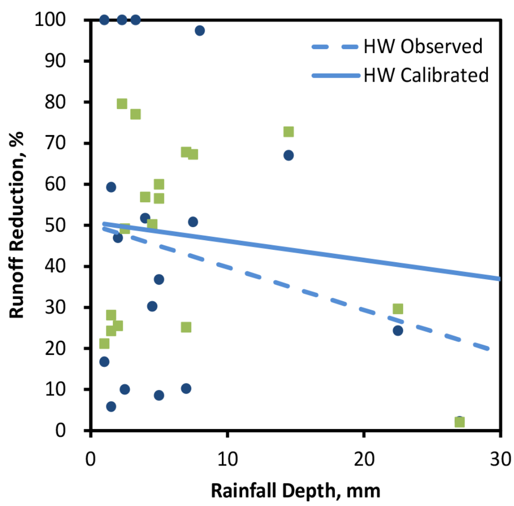


(b)

Fig. 5. SA/CA ratio of the HSSF wetland according to varying rainfall depths and corresponding (a) runoff reduction and (b) TSS reduction.



(a)



(b)

Fig. 6. TSS loadings with respect to volume reduction efficiency (a) and rainfall depth-runoff reduction relationship (b) of the HSSF wetland.

of pollutants. The percentage of flow retentions was arranged from lowest to highest values to consolidate and demonstrate the trend of deltas [20]. TSS reduction in HW exhibited increasing delta ranges as volume retention also increases. Fig. 6(b) shows the rainfall depth-runoff reduction relationship for the HSSF wetlands. In addition, the calibrated results surpassed the reduction efficiencies of the actual facility. The figures can be used to predict both the runoff reduction and TSS loads using various rainfall depths.

4. Conclusions and recommendations

The study evaluated the performance of a small HSSF constructed wetland in a highly urbanized campus in treating stormwater runoff using SWMM. Manual monitoring which spanned more than 5 years was utilized in SWMM for simulation, calibration, and verification. Based on the results, the calibrated values presented a 'good fit' with the observed values which are based on NSEC values and hydrographs. NSEC values calculated for both hydraulic and water quality calibration were particularly high (0.68–0.98) inciting that the model effectively mimic the overall runoff process in the catchment area through the HSSF wetland. Moreover, the simulated HW model generated more runoff and TSS loads from the catchment area both by approximately 12% and generated lower outflow readings by 28% (runoff) and 14% (TSS loads) which suggests that the model optimized the performance of the HSSF wetland. Through the calibrated SA/CA ratios based on the calibrated values, HW could have been designed smaller than its actual SA/CA ratio. Even with the use of long-term monitoring event data, SWMM was successful in mimicking the hydrologic and pollutant regime of a small catchment area with an LID facility. However, inevitable obstructions from the actual parking lot which cannot be declared in SWMM have caused the subtle differences between the results. Therefore, HW is capable of treating urban runoff more than it was originally designed. The study can be used as guidelines for designing cost-effective LID facilities.

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