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Optimization of the design of an urban runoff treatment system using stormwater management model (SWMM)

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ABSTRACT

This study presents an application of stormwater management model in predicting the optimal physical characteristics and rainfall design criteria of an established low impact development (LID) treating urban stormwater runoff. The optimization of this LID was performed for the purpose of enhancing the treatment performance and serve as future guidelines in designing treatment systems. The values of different calibration parameters used in the model were obtained from the 10 monitored storm events conducted from July 2010 to July 2013. Based on the findings, the runoff volume reduction of the system was found out to be directly proportional with storage volume/surface area (SV/SA) ratio. However, it was also dependent on the amount of rainfall during a storm event. For the total suspended solids load reduction of the system, it has no significant relationship with the rainfall but found to be directly proportional with SV/SA ratio as well. Lastly, the physical dimensions of the system were also analyzed with respect to the SA/SV ratio.

Keywords: Calibration; Optimization; Prediction; Stormwater management model

1. Introduction

Continuous urbanization has led to increased impervious surfaces that have negative effects on the local water quantity and quality balance. The alteration of natural hydrological regime resulted to increase of stormwater runoff volume, faster peak flow rates, and flushing of dissolved and particulate matter to the receiving waters during a storm event [1]. A best management practice (BMP) concept called "low impact development" (LID) was developed to preserve the pre-development hydrologic regime and to abate the runoff volumes and diffuse pollution at the downstream area [2]. One of the LIDs that being potentially utilized are the tree box filters, wherein it incorporates street trees with stormwater runoff collection and pollutant reduction through physical, chemical, and biological processes. Tree box filters are commonly situated alongside of paved roads or adjacent to impervious parking lots [3]. However, due to sudden change in weather and variation of human activities (e.g. improvement of city, increase of traffic density, etc.) the severity of the impacts transferred to the catchment escalates. Thus, estimates of stormwater runoff volume and pollutant loads are required to

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assess the level of impacts of the pollution on receiving water bodies.

To understand the cause–effect relationships and assessing the impacts of pollution and inundation, the operation of modeling techniques for the prediction of storm event impacts are recommended. Several computer simulation models were developed for this purpose and the mostly used programs were; stormwater management model (SWMM) [4], System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN) [5], and MIKE21 [6]. In this study, the Environmental Protection Agency's (EPA) SWMM was utilized. SWMM was selected due to the dynamic rainfall-runoff properties of the model which was adequate for the simulation of water quantity and quality related with urban run-off [4]. Furthermore, it presents several options to simulate the buildup and washoff of the pollutants under different conditions.

Most existing studies only includes the monitoring approach of assessing the performance of LIDs since modeling applications relied on extensive calibration for accurate outputs. However, model simulations could predict and assess the future performance of LIDs which requires considerable amount of time and effort in manual sampling. Several studies were conducted for the improvement of model calibration parameters. Among these were the enhancement of automatic calibration of runoff flow [7], formulation of innovative approach in quantification of contaminant buildup [8], and improvement of washoff model [9]. In order to design the LIDs sufficiently in terms of efficiency basis, the determination of the appropriate runoff volume it should accumulate and treat is highly necessary. Thus, in this research, optimizing an existing LID using SWMM based on its respective monitored data would indicate the most suitable design with regards to rainfall and physical characteristics criteria.

2. Materials and methods

2.1. Study site description

The urban runoff treatment system used was a tree box filter located in a university campus. The catchment area of this LID was a 300 m^2 rough asphalt parking lot having a 0.33% slope and 98% impervious. In Fig. 1, the specific location, schematic diagram, and arrangement of the media of the tree box filter were shown. The aspect ratio of the length, width, and depth of the LID was 1:0.67:0.87. There were three layers of media present in the treatment system namely, top layer woodchip, middle layer sand, and bottom layer gravel with a corresponding depths of 400, 400, and 500 mm, respectively.

2.2. Water quantity and quality sampling

The monitoring of storm events was conducted from July 2010 to July 2013 having a total of 10 monitored storm events. For each of the monitored storm event, water samples were obtained by manual sampling. In accordance to the typical sampling scheme in Korea, six grab samples were collected at the first hour of the stormwater runoff and another six grab samples with a 1-h time interval or until the end of the runoff [10]. Flow rates of inflow and outflow were consistently measured and recorded in a 5-min interval. Several water quality parameters such as particulates, organics, nutrients, and heavy metals were analyzed based on the standard methods for the examination of water and wastewater [11]. However, among the measured water quality parameters only the total suspended solids (TSS) was analyzed in this study.

2.3. SWMM calibration procedure

2.3.1. Water quantity calibration setup

The catchment was considered as a 98% impervious area wherein the 2% compromised to the several cracks on the area which eventually leads to the infiltration of the runoff to the ground. In SWMM, the tree box filter was simulated as a "storage node." Approximately 36 months of monitoring were conducted, and the simulated runoff volumes corresponding to the monitored 10 storm events were compared with the obtained measured runoff volumes. The simulation was repeated by adjusting the physical characteristics of subcatchment until the best Nash–Sutcliffe model efficiency coefficient (*NSEC*) was obtained between the simulated and measured values. The mentioned coefficient has the following equation:

$$NSEC = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \bar{Q}_o\right)^2} \tag{1}$$

where Q_o is observed discharge, Q_m is modeled discharge, $\bar{Q}_o$ is the mean observed discharge, and Q_o^t and Q_m^t are the observed discharge and measured discharge at time t, respectively. If $NSEC = 0$, it shows that the model is accurate just like the obtained measured value. However, if the $NSEC < 0$, it shows that the observed value is better than the simulated results. In order to show, if the simulation was properly

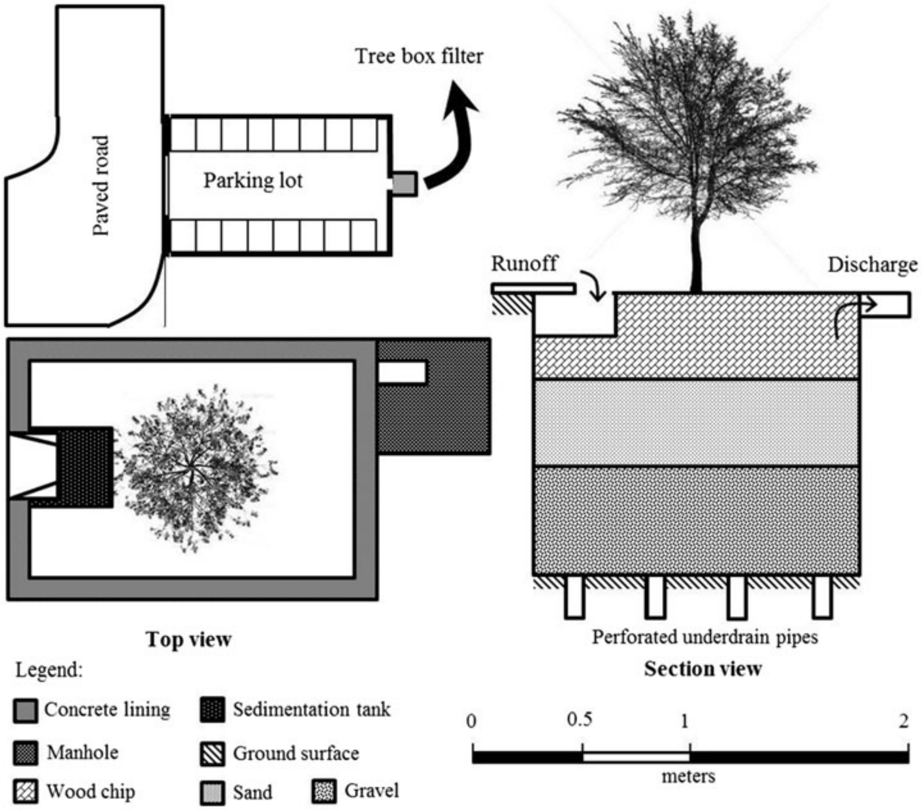

Fig. 1. Specific location and schematic diagram of the tree box filter.

calibrated, the *NSEC* should be close to value of 1, which means that the observed and modeled results were matched.

The calibration was made by means of iterative process of trial and error by adjusting the mentioned parameters in Table 1 and comparing (numerically and graphically) the hydrograph obtained in each monitored event simulation. The simulation would be presumed to be calibrated when a good fit was obtained from both values and with respect to the pre-determined calibration limits.

2.3.2. Water quality calibration setup

In SWMM, both buildup and washoff were simulated using exponential method equations as shown in Eqs. (2) and (3), respectively [12]:

Table 1
Parameter used for water quantity calibration

Parameter	Unit	Calibration limit	Initial value taken
Average impermeable area	m^2	±10%**	300
Average width	m	±30%**	35
Average slope	%	±30%**	0.33
Impermeable surface storage area	mm	0.3–2.5*	2.5
Maximum infiltration (Horton equation), f_o	mm	25–75*	25
Minimum infiltration (Horton equation), f_c	mm	0.0–10*	1.0
Decay coefficient, k	s^{-1}	0.00056–0.00139*	0.00115

*[4].
**[16].

$$BU = b_{max}(1 - e^{-c_1 t}) \tag{2}$$

$$WO = c_2 q^{c_3}(BM) \tag{3}$$

where BU = buildup mass per unit area (kg/m^2), b_{max} = maximum buildup possible in mass per unit area (kg/m^2), c_1 = buildup rate constant (1/d), t = antecedent dry days (ADD) (in days), WO = washoff load rate per unit area (kg/h), c_2 = washoff coefficient, c_3 = washoff exponent, q = runoff rate per unit area (mm/h), and BM = buildup mass in the catchment (kg). According to [10], the washoff exponent could be assumed as 1 which is also subsumed in the estimates of Hossain et al. [13] wherein it ranges from 0.608 to 1.27. Four parameters were used for the quality calibration: b_{max}, c_1, c_2, and BM. These parameters were varied individually, hence, in order to obtain a good concurrence between the simulated outputs application of different combinations were performed. Furthermore, to presume that the water quality was calibrated properly the simulated value should comply with the total pollutant load and peak concentrations.

2.4. Data handling

In order to design a LID properly, the relativity of each corresponding physical characteristics should be evaluated. The ratio of storage volume and surface area (SV/SA) was analyzed with respect to the system volume and pollutant reduction capabilities. Furthermore, the physical dimension of the existing LID was also analyzed with the surface area and storage volume ratio. The observed water quantity and quality were statistically analyzed using SYSTAT 12 which includes correlation analysis. Pearson correlation coefficient (r) was used to determine the dependence between each parameter, wherein the significant correlations were accepted at 95% confidence level, signifying that the probability value (p) was less than 0.05.

3. Results and discussion

3.1. Urban runoff characteristics

Table 2 shows the water quantity and quality characteristics of the 10 monitored storm events. The total runoff volumes recorded were ranged from approximately 0.1 to 5.0 m^3 with a corresponding ADD approximately ranging from 0.5 to 12 d. The monitored events showed high variation in terms of the hydraulic data which were necessary to obtain a good calibration of SWMM. Among the parameters being analyzed in this facility, only the TSS were being considered as the main pollutant target of the tree box filter. The event mean concentration (EMC) of TSS was found out to be positively correlated with chemical oxygen demand (COD) having a Pearson coefficients of 0.650 ($p < 0.05$) and 0.492 ($p < 0.10$) for the influent and effluent concentration, respectively. Also, TSS were found out to be responsible in the partitioning of heavy metals between soluble and particulate form during a stormwater runoff transport [14]. Thus, the removal efficiency of the tree box filter in treating the inorganics (especially COD) and heavy metals could be possibly predicted based on the behavior of TSS. The mass loads of TSS were positively correlated with the total runoff volume having a Pearson coefficients of 0.854 ($p < 0.05$) and 0.774 ($p < 0.05$) for the influent and effluent, respectively. Based on the high correlation, the simulation regarding the TSS concentrations of each monitored event would be presented by the mass loadings. Since in terms of pollutant reduction, the mass loadings would be more reliable than the concentration [15].

3.2. Hydraulic and water quality simulation

The final values obtained to the hydraulic calibration of the model were shown in Table 3. The impermeable surface area was found out to be the most sensitive parameter in affecting the total runoff volume and the peak flows. Subcatchment width, slope, and the impermeable surface storage had a time influence on the base time of the runoff and the peak flows. In order to obtain a good adjustment of the hydrograph, the initial value for the impermeable area and slope was reduced by 5 and 15%, respectively, wherein the width was increased by approximately 8%. These adjustments were deemed reasonable when taking into account the possible error margin can be obtained in estimating these parameters [16]. Ovbiebo and She [17] once used a module of automatic calibration for SWMM and adjustments of the parameters were inevitable in acquiring good calibration of the models. The obtained value for the impermeable surface storage area was 6 mm, wherein it was above the specified limits. The catchment area considered was made of rough asphalt with several cracks that causes some area elevation to be more depressed than the rest of subcatchment. The used value was based from the mean of several measure points performed during different storm events.

The adjusted values in Table 3 with other fixed parameters were used in calibration of monitored storm event dated on 12 March 2013 (Fig. 2). The simulated average peak flows were approximately 25%

Table 2
Statistical summary of water quantity and quality data of the 10 monitored storm events

		Basic statistics			
Parameter	Unit	Minimum	Maximum	Mean	Standard deviation
Antecedent dry day (ADD)	day	0.5	11.7	5.24	3.584
Total rainfall	mm	3.0	22.5	10.40	6.847
Total runoff volume	m^3	0.096	5.071	1.866	1.430
Influent TSS EMC	mg/L	5.91	96.66	44.88	33.63
Effluent TSS EMC	mg/L	2.19	39.06	15.25	11.74
Influent TSS load	kg	0.006	0.452	0.091	0.137
Effluent TSS load	kg	0.001	0.062	0.020	0.022
Removal efficiency	%	40.0	86.3	71.31	14.18

Table 3
Obtained values from the hydraulic calibration of SWMM

Parameter	Unit	Obtained values in calibration
Average impermeable area	m^2	285
Average width	m	38
Average slope	%	0.28
Impermeable surface storage area	mm	6
Maximum infiltration (Horton equation), f_o	mm	25
Minimum infiltration (Horton equation), f_c	mm	2.0
Decay coefficient, k	s^{-1}	0.00115

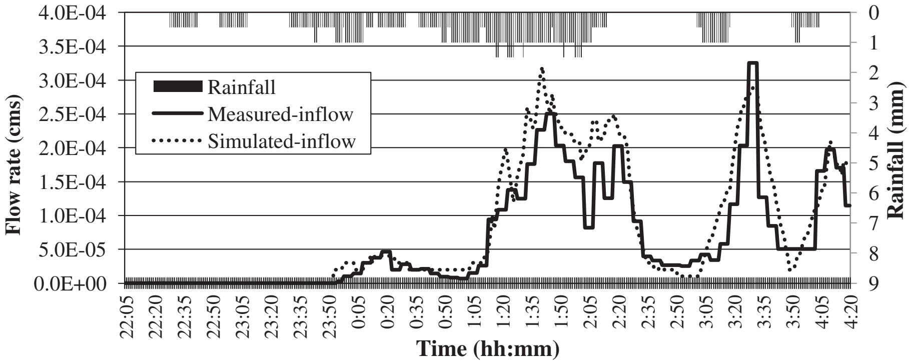

Fig. 2. Simulation of the monitored storm event (12 March 2013).

greater than the measured value. The simulated time of base flow and peak flows was quite accurate for having a difference of approximately 10 min than the measured time. Based on Maksimovic [18] there was estimated uncertainty level of between 5 and 25% in the measurement of flows depending on the method used. In addition, calibration of hydrographs should only have at least 30% of difference in terms of peak and minimal flows and difference of 10 min in presentation of base time and peak flows [16].

Shown in Fig. 3 was the comparison between measured runoff volume and TSS run-off mass load with the simulated values. As shown in Fig. 3(a), the simulated run-off volume was well matched with the measured runoff volume for having a *NSEC* value of 0.825. As for the monitored events having a rainfall more than 10 mm, the simulated runoff was less than the obtained runoff volume data. The greater value of the measured runoff volume could be possible due to the fast runoff rate that caused an inaccurate

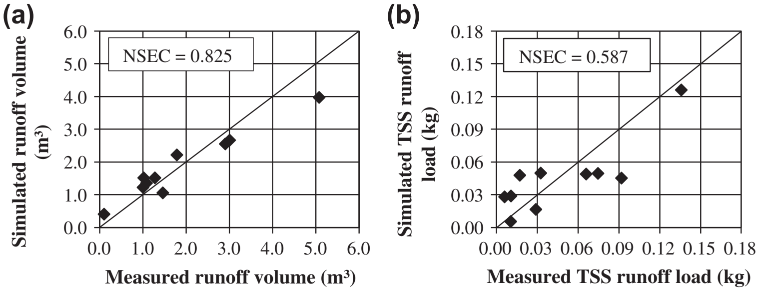

Fig. 3. Simulation results of the calibrated model presented through *NSEC*. (a) Measured vs. Simulated runoff volume (b) Measured vs. Simulated TSS runoff load.

measurement. The peak flow rates of these events ranged from 0.02 to 0.13 m^3/min, which was approximately 40% higher than the other monitored storm events (less than 10 mm rainfall). Nevertheless, based on the *NSEC* coefficient, the calibration of SWMM in terms of water quantity was reliable. The optimized values for b_{max}, c_1, and c_2 which minimized the error between measured and simulated values were 29 kg/m^2, 0.38/d, and 0.18, respectively. As for the value of *BM*, it was calculated using the calibrated value of *BU*. As shown in Fig. 3(b), the simulated data points were more scattered compared to the runoff volume. The discrepancies in the TSS load prediction were being evaluated by different researchers. According to Alley [19], the washoff coefficient (c_2) has limitations because it cannot consider the effects of runoff duration and variation in washoff loads. Huber [20] also claimed that as a rainfall-runoff model, the distinction between dry and wet weather process is not clear and thus the input of ADD as a basis in predicting pollutant load could be uncertain. In general, the discrepancy in predicting pollutant loads can be inevitable due to the limitations in buildup–washoff mechanisms and infliction of nature uncertainties (e.g. wind, human activities, and traffic) [21]. Furthermore, the total TSS runoff loads obtained from the 10 monitored storm events were found to be 23% underestimated compared to the simulated results. Wherein the measured total load has approximately 11 kg/year while simulated has 8.5 kg/year.

3.3. Performance and design parameters of tree box filter

The calibrated values in hydraulic and water quality were used to predict the volume and TSS reductions of the tree box filter in varying physical parameters. Shown in Fig. 4 were the predictions of volume and TSS reductions with respect to SV/SA. In Fig. 4(a), it was evident that the volume reduction capacity of the system has some limitations depends on the amount of rainfall. The original SV/SA ratio of the system was 0.45 which corresponds to approximately 52 and 21% volume reduction for rainfall lesser than 10 mm and greater than 10 mm, respectively. The rainfall lesser than 10 mm was found out to be direct proportional with varying SV/SA ratio wherein, if the SV/SA ratio increases from 0.5 to 0.8 the volume reduction of the system could increase from 50 to 80%. However, the rainfall greater than or equal to 10 mm could have lower volume reduction based on the simulation results whether the SV/SA ratio increased. Like for instance, if the SV/SA ratio was between 0.5 and 0.8, the corresponding volume reduction would be 18–20%. In terms of the TSS load

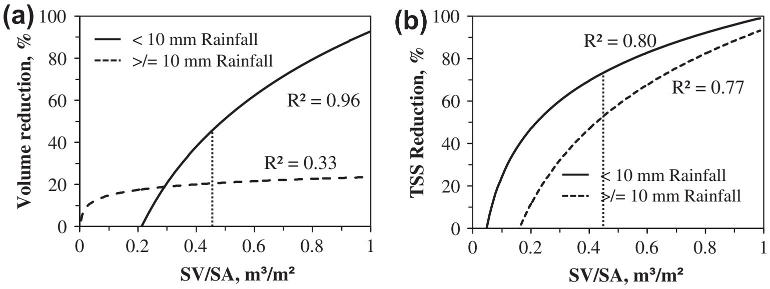

Fig. 4. Volume reduction and TSS removal as a function of SV/SA. (a) Volume reduction (b) TSS load reduction.

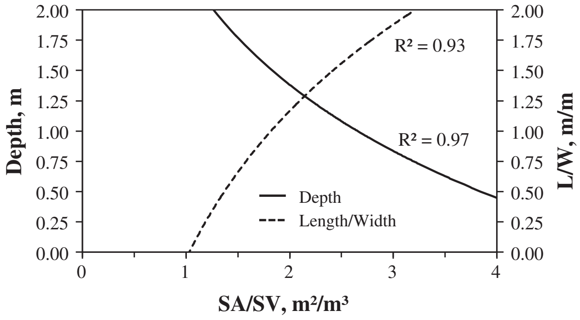

Fig. 5. Physical dimension parameters, depth, and length/width (L/W) as a function of SA/SV.

reduction of the system, the effect of rainfall showed minor impact (Fig. 4(b)). At least 50% of TSS reduction could be achieved in the original SV/SA ratio if the rainfall was less than 10 mm. As for the rainfall greater than or equal to 10 mm, the SV/SA ratio should be decreased by approximately to 0.2.

The predictions regarding the physical dimensions of the tree box filter were shown in Fig. 5. Only the depth and length/width (L/W) ratio with respect to the SA/SV ratio was analyzed. The current SA/SV ratio of the system was 2.21 which correspond to the current physical dimensions of the LID. As the SA/SV ratio increases, the predicted depth values for the system decreases. A depth of 1.5 m corresponds to approximately 0.8 of SA/SV. Increasing the SA/SV ratio by 50% could result to reduction of at least 0.3 m. In contrary with depth, the L/W ratio was directly proportional with SA/SV ratio. Increasing the SA/SV ratio by 50% could result to an increase of approximately 30% of L/W ratio.

4. Conclusion

An attempt to optimize the design of an urban runoff treatment system using SWMM was performed in this study. The LID or treatment system considered was a tree box filter with a catchment area composed of rough asphalt parking lot. The SWMM model was calibrated using the 10 monitored storm events of the mentioned LID. The monitored events considered were varying in rainfall and runoff volume accumulation giving the calibration process an accurate result. The calibration was made by means of iterative process of trial and error on both hydraulic and water quality components. In order to assure an accurate calibration of the model, various limitations were considered such as the computation of *NSEC* and specifying limit values in several parameters based on other studies. The obtained *NSEC* values for runoff volume and TSS reduction calibration were 0.825 and 0.587, respectively. As for the optimization of the design parameters of the tree box filter, the relationship of SV/SA ratio (and vice versa) with the volume and pollutant reduction capacity of the system was analyzed. It was found out that the volume reduction was dependent on the amount of rainfall and directly proportional with SV/SA ratio as long as the rainfall was less than 10 mm. In contrary, the TSS load reduction has no effect on the varying rainfall but directly proportional with the SV/SA ratio as well. As for the physical dimensions of the system, depth was found to be inversely proportional with SA/SV ratio. Wherein, as the SA/SV ratio increased by at least 50% a possible reduction of 0.3 m in depth could be obtained. Nevertheless, the L/W ratio of the system was directly proportional with SA/SV ratio.

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