Physical design optimization of an urban runoff treatment system using Stormwater Management Model (SWMM)

J. A. S. Tobio, M. C. Maniquiz-Redillas and L. H. Kim

ABSTRACT

The study presented the application of Stormwater Management Model (SWMM) in determining the optimal physical design properties of an established low impact development (LID) system treating road runoff. The calibration of the model was based on monitored storm events occurring from May 2010 to July 2013. It was found that the total suspended solids was highly correlated with stormwater runoff volume and dominant heavy metal constituents in stormwater runoff, such lead, zinc and copper, with a Pearson correlation coefficient ranging from 0.88 to 0.95 ($P < 0.05$). Reducing the original ratio of the storage volume to surface area (SV/SA) of the facility and depth by 25% could match the satisfactory performance efficiency achieved in the original design. The smaller SV/SA and depth would mean a less costly system, signifying the importance of optimization in designing LID systems.

Key words | design optimization, heavy metals, SWMM, treatment system, urban runoff

J. A. S. Tobio
M. C. Maniquiz-Redillas
L. H. Kim (corresponding author)
Department of Civil and Environmental Engineering,
Kongju National University,
275 Budaedong, Seobukgu,
Cheonan city,
Chungnamdo,
331-717,
Korea
E-mail: *leehyung@kongju.ac.kr*

INTRODUCTION

Urban impervious surfaces cause alteration of the natural hydrological regime and contribute to the intolerable pollutant discharge in receiving waters. These surfaces generate a larger amount of stormwater runoff volume and faster peak flows during a storm event compared to other land uses (e.g. agricultural, residential) (House *et al.* 1993). Moreover, the runoff generated from paved roads was commonly regarded as the primary pollutant source of particulates, inorganics and heavy metals (Ball *et al.* 1998). Low impact development (LID) was developed to preserve the pre-development hydrologic regime, reduce the increased runoff volume and abate the diffuse pollution at the downstream area through natural treatment processes (e.g. filtration, bioremediation and soil microbial activities) (Urbonas 1994). Infiltration trenches and basins are depression areas designed to capture and retain the stormwater runoff while simultaneously treating it before it infiltrates to the subsoil (Davis 2005; Dietz 2007). Direct monitoring of these treatment systems can effectively quantify the runoff volume and contaminants involved; however, it is costly, onerous and time consuming. In order to efficiently design these LIDs based on the typical hydrologic and pollutant processes, the application of computer modelling was recommended (Egodawatta & Goonetilleke 2008).

Several simulation models were developed for evaluating these treatment facilities and the common programs used were Stormwater Management Model (SWMM) (Huber & Dickinson 1988), Model for Urban Sewers (MOUSE) (Danish Hydraulic Institute (DHI) Inc. 1999) and Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (Gold Coast City Council 2006). A stormwater quality model is a combination of mathematical procedures which are used to describe the water quality response of a catchment area to a particular storm event (Zoppou 2001; Akan & Houghtalen 2003). Stormwater simulation models also incorporate the complex pollutant processes (i.e. build-up, transport and wash-off) occurring in a storm event. The US Environmental Protection Agency's SWMM is a comprehensive hydrologic and water quality simulation model primarily developed for urban areas (Huber & Dickinson 1988). The mentioned model simulates different aspects of urban hydrologic and water quality cycles such as conversion of rainfall into surface runoff, transport through the sewer system, retention and treatment. In this study, SWMM was utilized to simulate and evaluate the performance efficiency of stormwater runoff treatment employed as LID based on the monitored storm events with varying physical design characteristics.

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The evaluation aims to determine the most effective physical design properties of the LID.

MATERIALS AND METHODS

Experimental site and sampling description

The urban runoff treatment system used was a storage–infiltration system treating the runoff from a 371 m^2 paved road. The storage–infiltration system was a combination of infiltration trench and basin which consisted of three basic components (i.e. pre-treatment, media zone and effluent storage tank). Based on Figure 1, the pre-treatment tank filters the runoff and captures the first flush; the media zone implements filtration and adsorption mechanisms; the final effluent tank stores the filtered runoff and discharges to the sewer system. The hydrologic, hydraulic and water quality data used in the modelling were gathered from 16 storm events monitored from May 2010 to July 2013.

The water samples gathered in each monitored event were obtained through manual sampling. Six grab samples were collected during the first hour of runoff having a 0, 5, 10, 15, 30 and 60 minute time interval. Another six grab samples were collected with a 1 hour time interval or until the end of runoff. The mentioned sampling scheme was performed on both inflow and outflow of the facility and was based on the typical sampling scheme in Korea (Jung *et al.* 2008). Several water quality parameters (e.g. particulates, inorganics, organics and heavy metals) were analysed based on *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 1992). However, among the measured water quality parameters only the total suspended solids (TSS) and its correlation with the common heavy metal constituents (e.g. lead, zinc, copper) was considered in this study.

Calibration and limitations of the SWMM

The storage–infiltration system has a complex media arrangement (i.e. combination of several vertical and horizontal media layers) and was modelled as a *storage node*. The essential input parameter for the simulation was specified based on the accumulated monitored events. Operation of prediction models in evaluating certain treatment system should be calibrated based on the observed data, to assure its reliability. A calibrated model should have satisfied the following three specified hydraulic and water quality conditions. First, the simulated hydrograph should be similar to the observed data with close

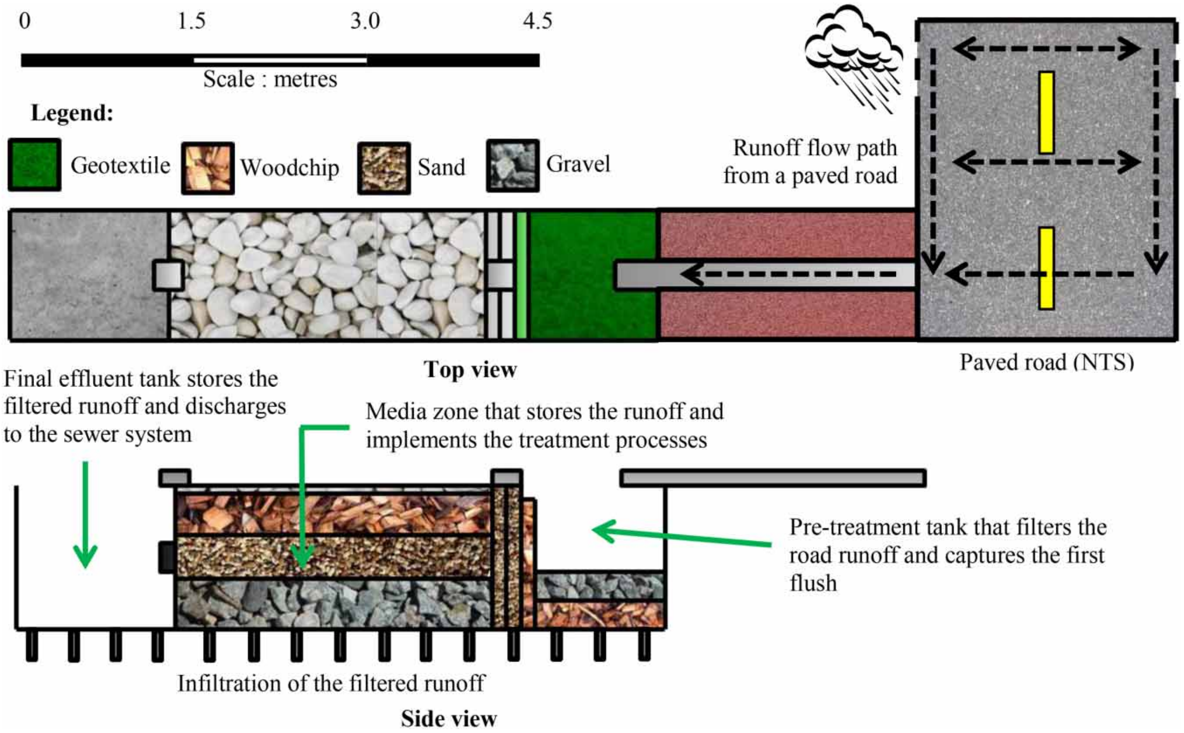

Figure 1 | Schematic diagram of the storage–infiltration system (NTS: not to scale).

examination of the base and peak flow, shape and time. The same investigation should be applied to the pollutographs of all monitored events. In the SWMM model, both pollutant build-up and wash-off were simulated using exponential method equations as shown in Equations (1) and (2), respectively (US Environmental Protection Agency 2010).

$$BU = bu_{\max}(1 - e^{-b_1 t}) \tag{1}$$

$$WO = w_1 q^{w_2}(BM) \tag{2}$$

where BU = build-up mass per unit area (kg/m^2), $bu_{\max}$ = maximum build-up possible in mass per unit area (kg/m^2), b_1 = build-up rate constant (1/days), t = antecedent dry days (ADD) (in days), WO = wash-off load rate per unit area (kg/hr), w_1 = wash-off coefficient, w_2 = wash-off exponent, q = runoff rate per unit area (mm/hr), and BM = build-up mass in the catchment (kg). Three parameters were used for the quality calibration: bu_{max}, b_1 and w_1. According to Wicke *et al.* (2010), w_2 could be assumed as 1, and in the estimates of Hossain *et al.* (2010) it ranges from 0.608 to 1.27. Second, the value of the Nash–Sutcliffe model efficiency coefficient (NSEC) as shown in Equation (3) should be near 1.0 for both hydraulic and water quality. The NSEC was used to assess the prediction reliability of the simulation model (Nash & Sutcliffe 1970).

$$NSEC = 1 - \frac{\sum_{t=1}^{T}(N_o^t - N_m^t)^2}{\sum_{t=1}^{T}(N_o^t - \overline{N_o})^2} \tag{3}$$

where N_o is observed discharge or load, N_m is modelled discharge or load, $\overline{N}_o$ is the mean observed discharge or load, N_o^t and N_m^t are the observed discharge and measured discharge or load at time t, respectively. The simulated results are more accurate and reliable than the observed values if the NSEC = 0. However, an opposite evaluation can be concluded if the NSEC < 0. The target value for the NSEC was close to or equal to 1, which means that the simulated and observed values were matched, justifying that the model values were calibrated. Lastly, because of the complexity and singularity of an actual storm event, a stormwater model could have constraints in the simulated results. Certain limitations and restrictions in the modelling approach are inevitable, listed as follows and in Table 1.

Table 1 | Hydraulic calibration limits utilized in the research

Parameter	Unit	Calibration limit
Average impermeable area	m^2	±10%**
Average width	m	±30%**
Average slope	%	±30%**
Impermeable surface storage area	mm	0.3–2.5*

*Huber & Dickinson (1988).
**Temperano *et al.* (2006).

- The media layer content of each LID site will be presented as the initial storage value of the *storage node* prior to any simulation. Thus, the media properties such as porosity will be disregarded in the model; however, the overall treatment performance of the site will be provided as an equation.
- It is assumed that there will be no residual pollution after a total rainfall of ≥5 mm for a minimum of 1 hour rainfall duration for it would affect the pollutant build-up simulation of each model. This assumption was based on the monitoring data gathered on the site; the ‘dilution’ effect was observed after the ‘first flush’ (highly concentrated) runoff occurred during the initial hour of storm.
- The time lag difference between the simulated and observed base and peak flow or concentrations should not be longer than 10 minutes (Temperano *et al.* 2006).

Data handling and relative error

In order to efficiently design a LID, the relationship of each physical characteristic (i.e. dimensions, storage volume and surface area) should be evaluated. The ratio of storage volume to surface area (SV/SA) was analysed with respect to the system volume and pollutant reduction capabilities. Furthermore, the depth of the existing LID was analysed with the SV/SA ratio. The observed water quantity and quality were statistically analysed 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. Moreover, calculating the inflow and outflow pollutant load was an essential component to properly evaluate the treatment performance of a facility. In order to quantify the accuracy of each parameter, the relative error was calculated for each calibrated variable as shown in Equation (4), wherein, RE = relative error; x_S = simulated variable; x_O = observed or true variable value.

$$\mathrm{RE} = \left|1 - \frac{x_S}{x_O}\right| \times 100 \tag{4}$$

RESULTS AND DISCUSSION

Characteristics of the monitored storm events and road runoff

The water quantity characteristics of the storage–infiltration system are shown in Table 2. The average total rainfall in this study was 7.5 mm, which represents at least 60% of the total number of storm events occurring in Korea per year (Maniquiz *et al.* 2012). It was found that the influent pollutant mass load of TSS for the mentioned LID site was positively correlated with the total runoff volume for having a Pearson coefficient of 0.88 and $P < 0.05$. Among the several parameters being analysed, the TSS was regarded as the main pollutant target. Primarily, TSS was found to be responsible for the partitioning of heavy metals between soluble and particulate form during a stormwater runoff transport (Sansalone & Buchberger 1997). Thus, the removal efficiency of the treatment facilities in treating the heavy metals could be possibly predicted based on the behaviour of TSS.

Shown in Figure 2 are the statistical pollutant load characteristics of the storage–infiltration system. Based on the figure, all of the pollutants have higher mean load compared to the median load, which implies that the concentration was generally lower during most of the storm events. The Pearson correlation coefficients of TSS inflow mass loads with total lead (TotPb), total zinc (TotZn) and total copper (TotCu) were 0.89, 0.95 and 0.90 respectively and have a probability value of less than 0.05. However, the Pearson coefficients for the TSS outflow mass loads and the heavy metal outflow load were lower compared to the inflow pollutant loads, being less than 0.60, and probability values were higher than 0.01. Based on the significant correlations, the TSS simulations of each monitored event would be represented by the mass loadings since the mass loadings would be more reliable (Maniquiz 2012).

Table 2 | Statistical summary of the water quantity of the 16 monitored storm events

		Basic statistics			
Parameter	**Unit**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**
ADD	days	0.30	16.15	5.69	4.74
Total rainfall	mm	1.50	29.00	7.50	7.63
Total rainfall duration	hours	0.88	6.20	3.08	1.47
Total runoff volume	m^3	0.30	12.78	2.99	3.57
Total discharge	m^3	0.13	6.21	1.95	2.05

Hydraulic and water quality calibration using SWMM

Using Box's complex optimization algorithm, the calibrated values for each hydraulic and water quality parameter were obtained (shown in Table 3). The respective values were considered as calibrated by minimizing the error between the observed and simulated runoff volume. The calibrated value for the depression storage of the storage–infiltration system was found to be above the specified range limit. The reason was the uneven depression areas of the catchment area due to the frequent pavement degradation caused by vehicular activities. The values shown in Table 3 were obtained by measuring the actual depression storage of each catchment area during a rainfall event. Even though the measured values were not within the range limit, using Box's complex method it was found to lessen the error between the observed and simulated runoff volume. Thus, the values were retained and considered to be calibrated.

For the storage–infiltration system, the NSEC values were 0.86 to 0.93 for the inflow and outflow respectively (shown in Figure 3(a)). However, shown in Figure 3(b) are

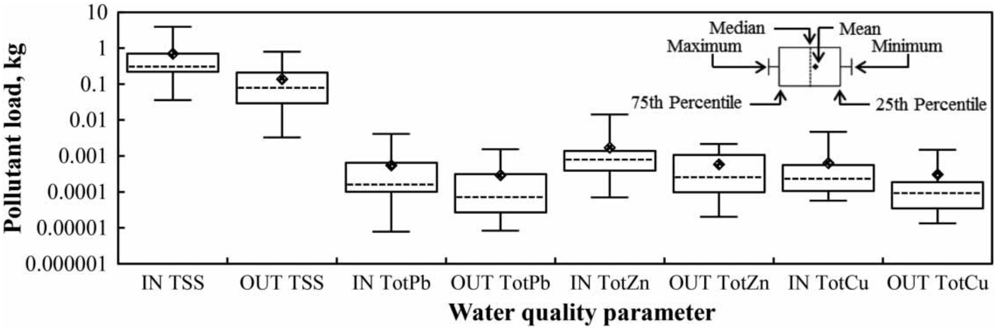

Figure 2 | Statistical pollutant loads of the particulates and heavy metal constituents.

Table 3 | Calibrated values of the hydraulic and water quality simulation of the LID

Parameter	Unit	Storage–infiltration system	Relative error (%)
Subcatchment area	m^2	344	7.28
Subcatchment width	m	68	16.18
Depression storage	mm	5.0	N/A*
Build-up mass per unit area	kg/m^2	23	21.30
Build-up rate constant	1/days	0.37	N/A*
Wash-off coefficient	N/A	0.15	N/A*

*Has no relative RE since the limit for the respective parameter was presented in range of values.

the NSEC values of the water quality, which were relatively lower compared to the hydraulic calibration results. The complexity of the build-up and wash-off processes caused the higher relative error (ranging from 20 to 22%) compared to the hydraulic calibration. In addition, the land use parameters (i.e. subcatchment area, subcatchment width and depression storage) considered on the hydraulic calibration of each LID site were stable in nature unlike the build-up and wash-off parameters. According to Alley (1981), the wash-off equation used in SWMM and its variants are a function of the runoff volume during the time increment and could predict the same pollutant discharge loads for any two storm events having the same runoff volume. Alley also claimed that the wash-off coefficient (c_2) has limitations because it could not consider the effects of runoff duration and temporal variation of the parameter. Moreover, the simulation of build-up and wash-off loads was initially complex due to the heterogeneity of the urban surfaces, which could not be considered in SWMM.

As shown in Figure 4(a), the heavy metal constituents (i.e. TotPb, TotZn and TotCu) have high correlations with the particulates, having R^2 value of 0.77 to 0.87. These results suggested that the metal transport and behaviour was relatively comparatively related to the partitioning between the soluble and particulate form, in which the TSS was an important limiting factor (Maniquiz-Redillas & Kim 2014). However, the R^2 values for the simulated results were reduced by a maximum of 40% compare to the monitored results (shown in Figure 4(b)). The lower values attest to the difficulty and limitations of the pollutant simulation compared to the hydraulic component. The lower relationship of Zn in the simulated results was attributed to the higher variability of Zn compared to the other metals, Cu and Pb.

Physical design optimization of the storage–infiltration system

Shown in Figure 5 are the TSS load and volume reduction of each LID site as a function of varying SV/SA and depth. The SV/SA ratio and depth were increased and decreased by increments of 25% to evaluate the reduction capabilities of each facility. It was found that decreasing the original SV/SA (0.77) and depth (1.5 m) of the infiltration/filtration system by 25% correspondingly reduced the TSS load by 80 to 90% even when only 50% of volume was reduced. However, the improved reduction capabilities of the storage–infiltration system by adjusting the respective physical parameters were somehow similar with the initial removal

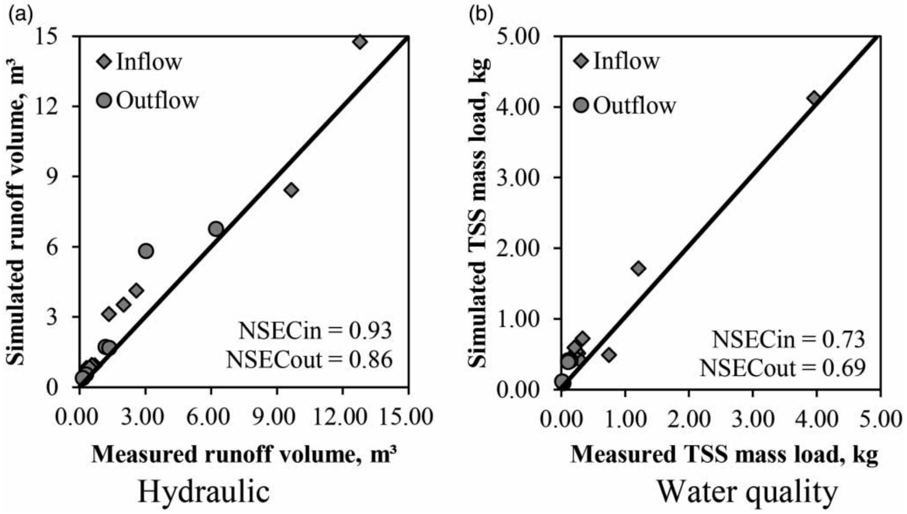

Figure 3 | The (a) hydraulic and (b) water quality calibration results of the storage–infiltration system presented through NSEC.

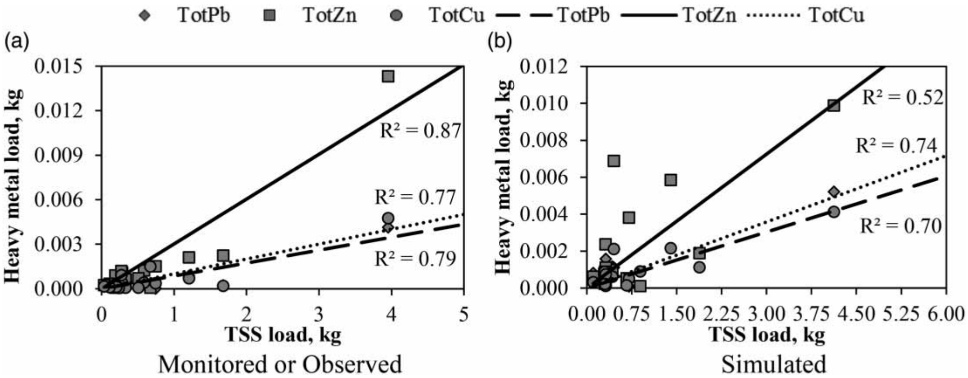

Figure 4 | Relationship between the particulate and heavy metal constituents' inflow mass loads of the (a) monitored events and (b) simulated results.

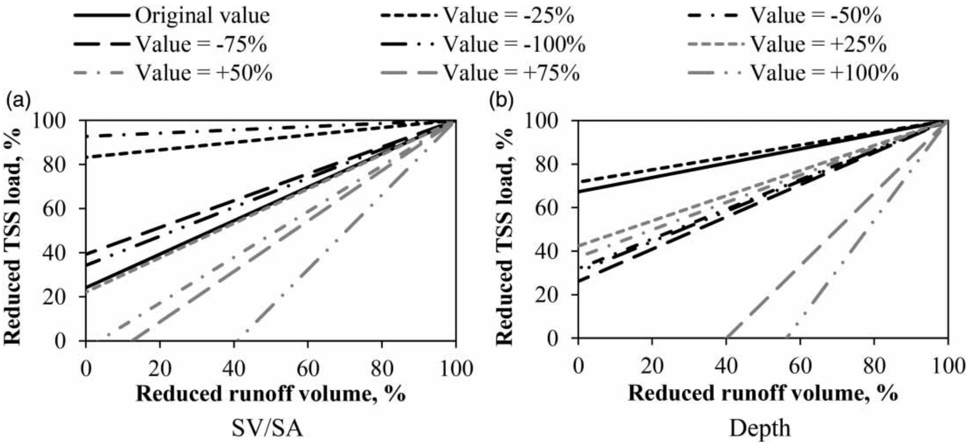

Figure 5 | TSS load and volume reduction of an adjusted storage–infiltration system as a function of varying (a) storage volume and SV/SA and (b) depth of the facility.

performance. Nevertheless, the storage–infiltration system could significantly reduce the volume and pollutant concentration of the runoff for any given adjustment.

CONCLUSION

This study attempted to determine the most effective physical design properties of an existing LID by simulating and evaluating the respective volume and pollutant reduction capabilities using SWMM. The SV/SA ratio and depth of the storage–infiltration system were adjusted by increments of 25% in both directions. The results implied that the TSS has high correlation to the total runoff volume and common heavy metal constituents (i.e. TotPb, TotZn and TotCu) for having r values of 0.88 and 0.89 to 0.95 (all P values < 0.05), respectively. Moreover, the calibrated hydraulic values have high NSEC values compared to the water quality calibration, indicating the complexity of the pollutant build-up and wash-off process. Lastly, it was found that reducing the original SV/SA and depth by 25% could match the satisfactory performance efficiency achieved in the original design. The smaller SV/SA and depth would mean a less costly system, signifying the importance of optimization in designing LID systems.

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