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Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: Experimental and modeling approach

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A B S T R A C T

Currently, continued urbanization and development result in an increase of impervious areas and surface runoff including pollutants. Also one of the greatest issues in pollutant emissions is the first flush effect (FFE), which implies a greater discharge rate of pollutant mass in the early part in the storm. Low impact development (LID) practices have been mentioned as a promising strategy to control urban stormwater runoff and pollution in the urban ecosystem. However, this requires many experimental and modeling efforts to test LID characteristics and propose an adequate guideline for optimizing LID management. In this study, we propose a novel methodology to optimize the sizes of different types of LID by conducting intensive stormwater monitoring and numerical modeling in a commercial site in Korea. The methodology proposed optimizes LID size in an attempt to moderate FFE on a receiving waterbody. Thereby, the main objective of the optimization is to minimize mass first flush (MFF), which is an indicator for quantifying FFE. The optimal sizes of 6 different LIDs ranged from 1.2 mm to 3.0 mm in terms of runoff depths, which significantly moderate the FFE. We hope that the new proposed methodology can be instructive for establishing LID strategies to mitigate FFE.

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1. Introduction

Currently, continued urbanization and development result in an increase of impervious area and surface runoff. This also increases the potential for floods and can cause severe water quality degradation by increasing associated pollutants, including suspended solids, fine particles, heavy metals, nutrients, and organic chemicals (Kayhanian et al., 2012; Lee et al., 2010; Davis and McCuen, 2005; Barbosa et al., 2012). One of the greatest issues in pollutant emissions is the first flush effect (FFE), which implies a greater discharge rate of pollutant mass or concentration in the early part of the runoff volume as compared with later in the storm (Ma et al., 2002; Sansalone and Cristina, 2004). A number of monitoring studies and modeling studies have been conducted to characterize the stormwater runoff from various pollution types, including nutrient (Lee et al., 2002; Sollera et al., 2005; Huang et al., 2007; Lee et al., 2011; Beecham and Razzaghmanesh, 2015), heavy metal (Lee et al., 2002, 2004; Soller et al., 2005; Huang et al., 2007; Lee et al., 2011), oil and grease (Lee et al., 2011); and *E. coli* (Muirhead et al., 2011).

Recently, low impact development (LID) practices have been mentioned as a promising strategy for urban stormwater runoff control, pollution prevention and better urban ecosystems (Elliott and Trowsdale, 2007; Kayhanian et al., 2012; Ahiablame et al., 2012; Randhir and Raposa, 2014). LID is a green approach for managing stormwater that seeks to preserve the pre-development hydrology of a given site using decentralized micro-scale control measures (Coffman, 2002; HUD, 2003). However, it requires much experimental efforts to test LID characteristics and propose an adequate guideline for optimizing LID performance (Ahiablame et al., 2012). Mathematical modeling can be used to determine

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LID type and placement with limited stormwater management funds (Prez-Pedini et al., 2005) and can encourage the wider application of LID (Beecham, 2002). As well, it can be useful for implementation of LID in more efficient ways (Elliott and Trowsdale, 2007). Previously, stormwater management practices associated with LID have primarily focused on extreme event control for reducing the flood potential where a certain return period is an important criterion to design LID for given areas (Guo and Adams, 1998; Park et al., 2013). Water Quality Capture Volume (WQCV) was proposed to manage stormwater in urban areas in an attempt to prevent receiving water pollution from stormwater events (WEF and ASCE, 1998; Park et al., 2013; Guo and Urbonas, 2002). It has been applied to LID design in many places in the United States (WEF and ASCE, 1998; Park et al., 2013; Guo and Urbonas, 1996, 2002; Guo and Adams, 1998). Because WQCV is based on total volume, it does not consider the FFE on the receiving water quality. FFE provides an opportunity for Low Impact Development to be designed more effectively by optimizing removal efficiency for the early part of runoff (Kang et al., 2008). As well, Li et al. (2006) and Abrishamchi et al. (2010) emphasized first flush (FF) treatment for effective stormwater management, rather than just treating total water volume. In addition, different LIDs have their own hydrologic responses and water treatment characteristics; thereby the performance of each LID substantially varies. A few previous studies have focused on the sizing of different LIDs.

Here, we propose a novel methodology to design LID for minimizing FFE, incorporated with intensive monitoring programs and modeling efforts in a commercial area in Korea. The aims of this study are 1) to monitor/characterize stormwater runoffs from the study site, 2) to develop the stormwater model with observations, and 3) to optimize the sizing of different LIDs for mitigating FFE.

2. Material and methods

2.1. Site description

We selected a commercial area (35°09′33.12″N, 126°50′49.63″E) in Gwangju, Korea for characterizing stormwater runoff and FFE (Fig. 1). The area (0.0125 km^2), including the separated sewer system, can be characterized by high imperviousness (approximately 85%) and includes offices, restaurants, a parking lot, a car repair shop, and a residential area. The pervious area is located only at a parking lot and occupied small part of the study area (approximately 15%). Most of the restaurants and offices were situated on 1st and 2nd floors of the area, and the residential area occupied 3rd and 4th floors. The average annual rainfall at the study site is 1391 mm, and the average annual maximum and minimum temperatures are 29.3 °C and −1.9 °C, respectively.

2.2. Stormwater sampling and data acquisition

Stormwater runoff and suspended solids (SS) from the commercial area were monitored at the end of the drainage conduit using a flowmeter (Flo-Tote 3, Hach, Loveland, CO, USA) during the wet season. Flow rates were monitored every minute and samples for water quality analysis were manually collected at 15–30 min intervals for initial proportions of runoff and then at 1–2 h intervals for the receding flow. Monitoring was stopped after 12 h from the end of the rainfall event. We monitored four different rainfall events which were used to calibrate (7/6/2009 and 7/6/2012) and validate the model (6/29/2009 and 7/5/2012). The samples were stored in 4-L polyethylene bottles at the sites and transported to the laboratory at Chonnam National University for chemical analyses. SS were analyzed according to the APHA method (2001). The meteorological data were acquired from a nearby Gwangju weather station (Gwangju, Republic of Korea). The geographical data and the land-use and soil characteristics were obtained from the National Geographic Information Institute and Rural Development Administration in Korea.

2.3. Model description and LID modules

The EPA Storm Water Management Model (SWMM, version 5.1) has been applied to simulate stormwater runoff, combined sewers, sanitary sewers, open channels, irregular natural channels, and other drainage systems (Guitierrez, 2006). The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff model for continuous and single-event simulation of runoff quantity and quality (Rossman, 2005). In the hydrologic module of SWMM, the infiltration model employs the Green–Ampt model, which calculates the amount of infiltration of rainfall into the unsaturated upper soil zone on a pervious land area, whereas surface runoff is

Fig. 1. Location of the study area in Gwangju city (35°09′33.12″N, 126°50′49.63″E) (Google, 2014).

Table 1
Parameters for LID facilities.

Layer	Parameter	Bioretention	Green roof	Infiltration trench	Porous pavement	Rain barrel	Vegetative swale	Note
Surface layer	Storage depth (mm)	Below 151.8	12.4–24.8	0	0		1.97	Prince George's County Maryland (1999), ACCWP (2001)
	Vegetation volume fraction	0	0	0	0		0	
	Surface roughness	0.1	0.1	0.1	0.1		0.24	
	Surface slope (%)	1.0	1.0	1	1		0.5–4	
	Swale side slope						1–3	
Soil layer	Thickness (mm)	449.8 –899.9	74.9 –149.8					EPA (2010)
	Porosity	0.5	0.5					
	Field capacity	0.2	0.2					
	Wilting point	0.1	0.1					
	Conductivity	0.5	0.5					
	Conductivity slope	10	10					
	Suction head (%)	3.5	3.5					
Pavement layer	Thickness (mm)				0–3084.92	599.9 –899.9		EPA (2010), CRWA (2008)
	Void ratio (Voids/ Solids)				0.12			
	Impervious surface fraction				0			
	Permeability (mm/hr)				over 6.6			
	Clogging factor				9179			
Storage layer	Height (mm)	149.8 –449.8	149.8 –449.8	149.8–449.8	149.8–449.8			EPA (2010)
	Void ratio	0.5–0.75	0.5–0.75	0.5–0.75	0.5–0.75			
	Conductivity	10	10	10	10			
	Clogging factor	7042	7042	2817	7042			
Under drain	Drain coefficient (mm/ hr)	0	0	0	0	0		Use a Drain Coefficient if the LID unit has under drain
	Drain exponent	0.5	0.5	0.5	0.5	0.5		
	Drain offset height	0	0	0	0	0		
	Drain delay (hours)					6		

computed by Manning's equation (Rossman, 2005). The build-up and wash-off mechanism is the main model for the water quality simulation in SWMM (Rossman, 2010; Egodawatta, 2007). The amount of build-up is calculated as a function of the number of antecedent dry days as follows: (Rossman, 2010; Egodawatta, 2007)

$$B = \frac{B_1 t}{B_2 + t} \quad (1)$$

where B is the amount of pollutant (per unit area) (kg/ha), B_1 is the maximum buildup possible (mass per unit area or curb length) (kg/ha) and, B_2 is the half-saturation constant (days to reach half of the maximum buildup) (1/days).

Wash-off is significantly influenced by the pollutants on the catchment surface and wash-off from a given land use occurs during rainfall-runoff events (Rossman, 2010).

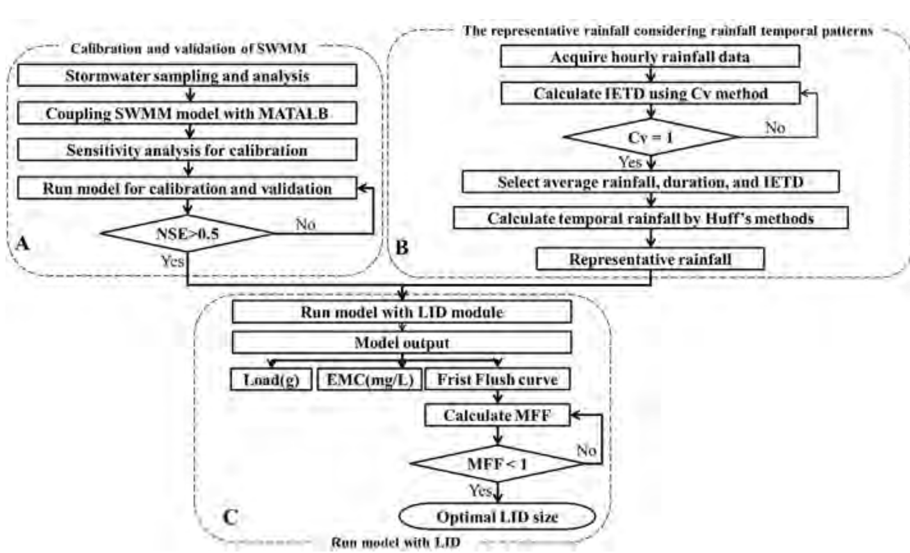

Fig. 2. Schematic overview for optimizing LID size.

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Table 2
Hydrologic parameters of SWMM.

Parameter	Description (James and Huber, 2003)	Calibration interval	Range of preceded researchers	Value	Sensitivity rank
PERVN	Pervious area Manning's roughness	0.005–0.5	0.02–0.8[a]	0.0172	1
IMPN	Impervious area Manning's roughness	0.001–0.02	0.011–0.033[a]	0.02	2
ROUGH	Manning's roughness of conduit	0.001–0.03	0.011–0.013[b]	0.0013	3
HYDCON (mm/hr)	Saturated hydraulic conductivity	7.62–127	8.58–899.92[c]	8.63	6
SUCT (mm)	Average capillary suction	7.62–228.6	9.65–243.8[c]	96.52	8
SMDMAX (mm/mm)	Initial moisture deficit for soil	0.01–0.1	0.014–0.020[c]	0.02	7
PDS (mm)	Pervious area depression storage	2.28–5.08	2.48–5.08[a]	2.54	4
IDS (mm)	Impervious area depression storage	0.25–2.54	0.25–2.48[a]	0.762	5

[a] Huber and Dickinson (1998).
[b] Wanielista and Yousef (1993).
[c] Chow et al. (1988).

$$W = C_1 q^{C_2} B \tag{2}$$

where W is the amount of load (per unit area) (kg/ha), C_1 is the wash-off coefficient, C_2 is the wash-off exponent, q is the runoff rate per unit area (inches/hour), and B is the pollutant buildup in mass units.

LID modules in SWMM are designed to capture surface runoff and are reflected in the overall runoff, infiltration, and evaporation calculated for the sub-watershed by SWMM (Rossman, 2010). Five different types are included: Bioretention, Infiltration, Porous pavement, Rain barrels, and Vegetative swale. Bio-retention cells, infiltration trenches, and porous pavement contain optional under drain to convey the captured runoff off. Infiltration trenches and porous pavement systems can consider the clogging effect which results in the decreased hydraulic conductivity. The SWMM model has been used to evaluate the effects of LID on conventional drainage (Zoppou, 2001). In this study, we used the parameters suggested by Cho et al. (2013) as shown in Table 1.

2.4. Model calibration and sensitivity analysis

In this study, SWMM was combined with MATLAB software to perform sensitivity analysis and to calibrate the hydrologic and

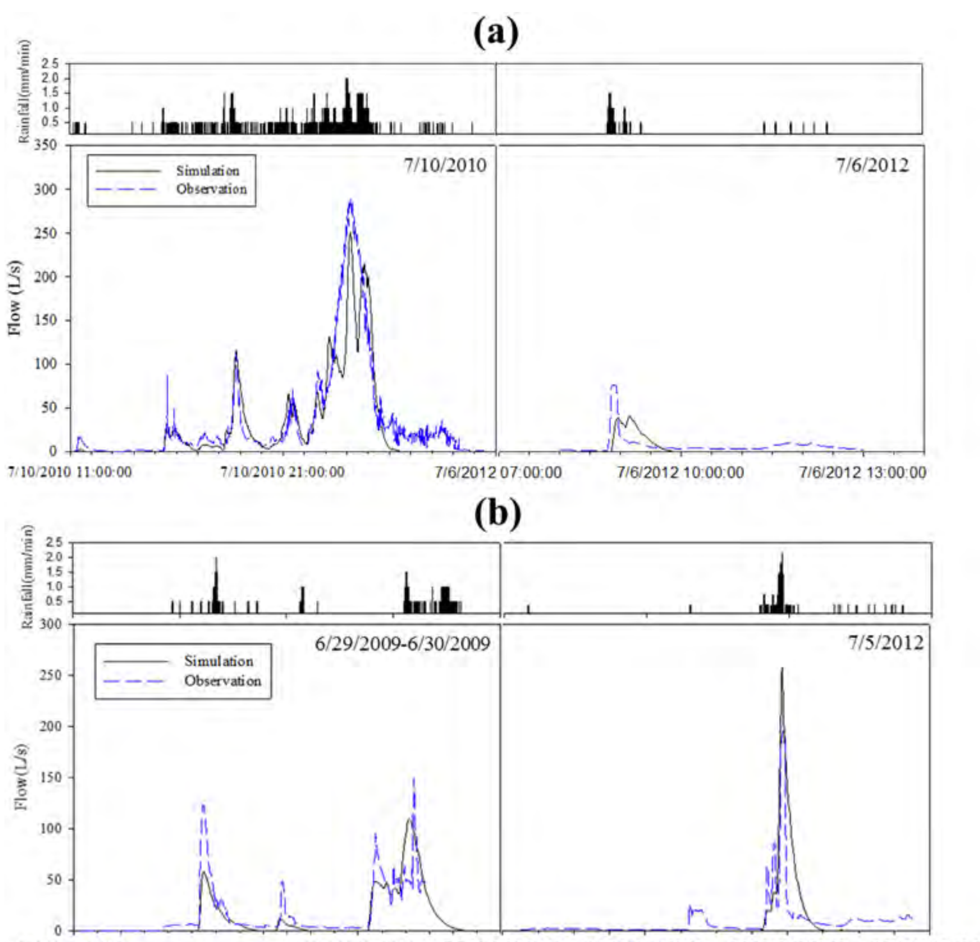

Fig. 3. Observed and simulated flow rates in calibration (a) and validation (b).

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Table 3
Suspend solids parameters of SWMM.

	Parameter	Description (James and Huber, 2003)	Calibration interval	Value	Sensitivity rank
Build-up	C_1	Maximum buildup possible	0–10	7.020	3
	C_2	Half saturation constant	0–0.1	0.001	4
Wash-off	C_1	Wash-off coefficient	0–10	0.27	2
	C_2	Wash-off exponent	0–5	0.41	1

water quality modules using a pattern searching tool (patternsearch.m). The pattern search algorithm is a global optimization method. This algorithm can determine an optimal point using a systematic direct search method based on a multidimensional search direction. The pattern search (PS) optimization is a derivative free evolutionary algorithm which can solve a variety of optimization problems (Sahu et al., 2015). This algorithm is useful for objective functions by minimizing errors (Findler et al., 1987; Maier and Dandy, 2000; Lewis and Virginia, 2002; Cho et al., 2011; Patuelli et al., 2011). We conducted sensitivity analysis using the Latin Hypercube-One-factor-At-a-Time method (LH-OAT) (Van Griensven et al., 2006). The objective function was set to be the sum of squared errors (SSE) by calculating the difference between the observation and simulation for flow rate and suspended solids. Then, we ranked parameters from the sensitivity analysis by efficiency to calibrate the model (Cho et al., 2012) (Fig. 2(A)). A sensitivity analysis was applied to identify sensitive parameters for effective model calibration (Park et al., 2014). The model performance was evaluated graphically and statistically using Nash–Sutcliffe Efficiency (NSE). NSE uses the model prediction between the predicted and observed data (Nash and Sutcliffe, 1970).

2.5. Optimizing LID size

2.5.1. The representative rainfall for simulation of optimizing LID size

In this study, we used the concept of Inter-Event Time Definition (IETD) for selecting appropriate rainfall for the simulation. To separate an individual rainfall event from continuous or discontinuous rainfall records, IETD, a minimum time interval for defining a dry period, is typically used (Restrepo-Posada and Eagleson, 1982; Guo and Adams, 1998; Palynchuk and Guo, 2008; Kim and Han, 2010). Methods of calculating IETD include autocorrelogram, coefficient of variation (Cv), and average annual number of rainfall events. In this study, we used the method of coefficient of variation (Cv) for calculating IETD from hourly rainfall data from 1981 to 2010 in Gwangju meteorological station because the method is a convenient way to calculate IETD.

After calculating IETD, Huff curves were applied to generate the temporal rainfall distribution. This method has been widely used to characterize temporal rainfall distribution (Huff, 1967, Azli and Rao, 2010). Huff curves are used to obtain probability isopleths. We used Huff curves of 50% probability which commonly are used in Korea (Ministry of Construction & Transportation in Korea, 2000; Lee, 2008) (Fig. 2(B)).

2.5.2. Objective of optimization: MFF_n

LID is designed to minimize FFE in the study area. For quantifying the FFE, Ma et al. (2002) suggested the concept of mass first flush (MFF) ratio. MFF can be calculated as follows:

$$\mathrm{MFF}_n = \frac{\dfrac{\int_0^{T_1} c(t)\times q(t)dt}{M}}{\dfrac{\int_0^{T_1} q(t)dt}{V}} \quad (3)$$

where, n is the point in the storm, and corresponds to the percentage of dimensionless cumulative runoff volume (0%–100%). M is the total mass of pollutant, V is the total runoff volume, c(t) and q(t) are the concentration of pollutant and volume as functions of time and T1 is the time of dimensionless cumulative runoff considering n. For example, if the value of MFF_{10} is 2, then 10% of the water volume has 20% of the load. If MFFn is greater than 1, it can be defined as FFE (Saget et al., 1996; Bertrand-Krajewski et al., 1998; Lee et al., 2002). Previous studies demonstrated that MFF_{30} is the most suitable index to characterize FFE (Li et al., 2007; Park et al., 2010). This is why MFF_{30} was selected as a performance

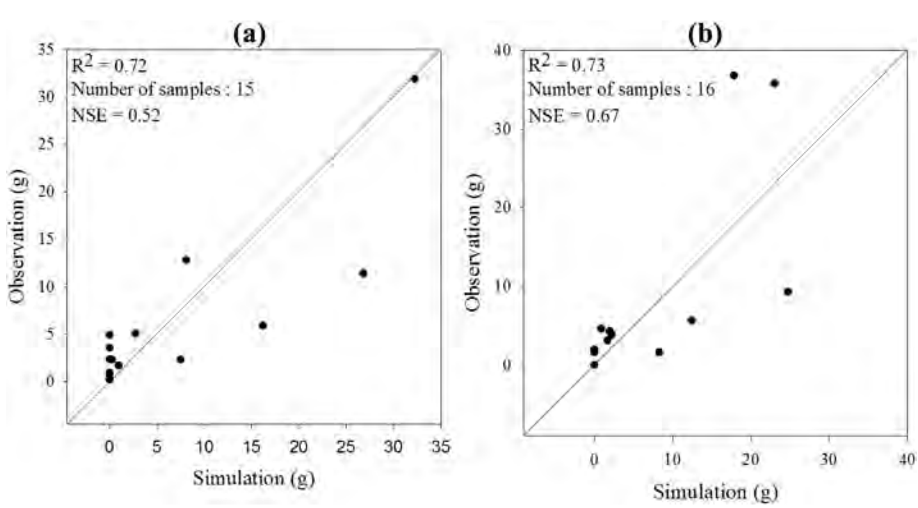

Fig. 4. Observed and simulated suspended solids in model calibration (a) and validation (b).

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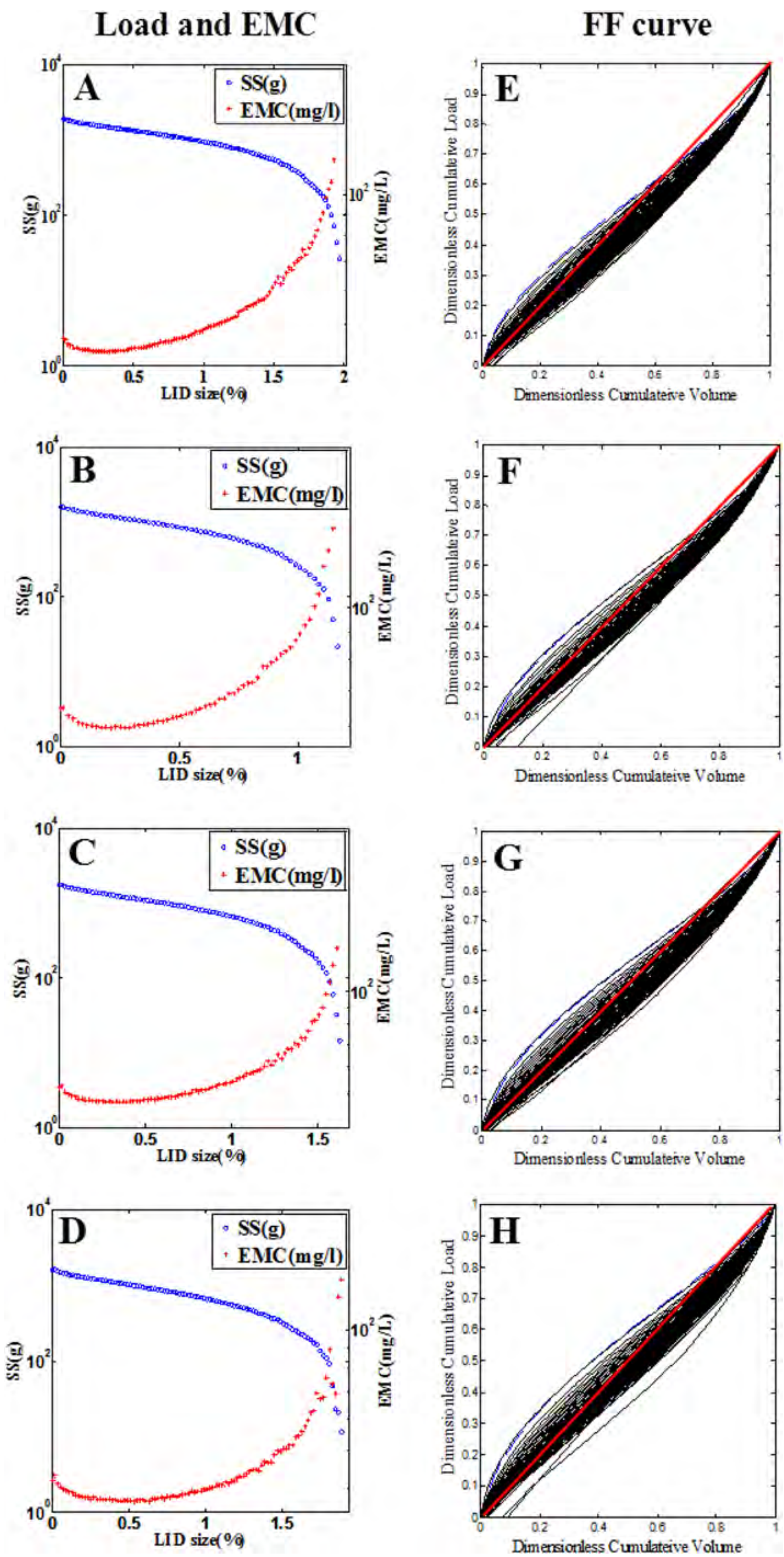
Load and EMC
FF curve
A
B
C
D
E
F
G
H
SS(g)
EMC(mg/l)
EMC(mg/L)
LID size(%)
Dimensionless Cumulateive Load
Dimensionless Cumulateive Volume

Table 4
Optimal LID size estimated from the SWMM.

LID	Optimal size (mm)
Bioretention	1.2
Green roof	3.0
Infiltration trench	2.6
Porous pavement	2.9
Rain barrel	1.5
Vegetative swale	3.0

index to determine the optimal LID size (Bertrand-Krajewski et al., 1998; Li et al., 2007; Lee and Lee, 2009; Park et al., 2010; Jung et al., 2013; Kwon et al., 2011). When the value of MFF_{30} is equal or less to 1 for a given LID size, we define it as an optimal LID size (Fig. 2(C)).

3. Results and discussion

3.1. Stormwater monitoring

Four different storm events were used to calibrate and validate the SWMM model; storm events on 7/10/2010 and 7/6/2010 for the calibration process, and storm events on 6/29/2009 and 7/5/2012 for the validation process. The total runoff volumes of the two calibration events were 2440.9 m^3 and 131 m^3, and rainfall depths were 217 mm and 14.5 mm. A calibration period covers maximum and minimum runoff volumes. Total runoff volumes of two events for validation were 427.6 m^3 and 397.5 m^3 and rainfall depths were 47 mm and 43 mm. The observed load of SS for calibration were 0.17–12.74 g and 1.69–31.88 g. Those for validation were 0.01–48.16 g and 1.61–9.34 g. The total numbers of samples in the calibration and validation processes were 15 and 16, respectively.

3.2. Calibration, validation, and sensitivity analysis

Before the calibration process, we performed sensitivity analysis for the efficient calibration process on hydrological and water quality modules in the SWMM. Table 2 shows hydrologic parameters for calibration using the pattern search tool in MATLAB software (Lewis and Virginia, 2002) and sensitivity analysis performed by LH-OAT. PERVN (i.e., Pervious area Manning's roughness), IMPN (i.e., Impervious area Manning's roughness), and ROUGH (i.e., Manning's roughness of conduit) were ranked the most sensitive parameters for calibrating the SWMM model. Baek et al. (2014) also suggested that IMPN, ROUGH, and HYDCON are significant parameters. Sharifan et al. (2010) suggested IMPN and ROUGH as influential parameters of SWMM. Their results were similar to those in this study, implying overland flow routing is the most influential process to calibrate the SWMM model.

Fig. 3 compares simulated flow with observed flow in both the calibration (events of 7/10/2010 and 7/6/2012) and validation steps (events of 6/29/2009 and 7/5/2012). The simulated runoff was in good agreement with the observed discharge. The Nash-Sutcliffe model efficiency coefficients (NSEs) were 0.80 and 0.54 for calibration and validation, respectively. These values are greater than 0.5 and can be regarded as acceptable performance (Moriasi et al., 2007). However the SWMM model underestimated the peak flow values and was unable to simulate runoff from small rainfall well (0.05 mm). Previous studies found that SWMM has a limitation in simulating the peak flow (Barco et al., 2008; Tsihrintzis and Hamid, 1998).

Table 3 shows pollutant (suspended solids) parameters and sensitivity analysis (LH-OAT) for calibration using the pattern search tool. Wash-off C2 (i.e., wash-off exponent) and wash-off C1 (i.e. wash-off coefficient) were ranked the most sensitive parameters for calibrating the SWMM model. We used a value of 7.020 for C1 (build-up), 0.001 for C2 (build-up), 0.27 for C1 (wash-off), and 0.41 for C2 (wash-off). Barco et al. (2004) set build-up C1, build-up C2, wash-off C1, and wash-off C2 to 18, 0.3, 0.13, and 1.2 respectively. Hood et al. (2007) used 25 for build-up C1, 1 for build-up C2, 4.9 for wash-off C1, and 1.57 for wash-off C2. Cambez et al. (2008) used 65–450 for build-up C1, 0.08 for build-up C2, 0.13 for wash-off C1, and 1.26 for wash-off C2. This significant discrepancy among researchers implies that pollutant parameters of SWMM are largely affected by geographical data, land-use, and soil characteristics. Fig. 4 compares the observed SS with the simulated SS, showing a good agreement with each other. The NSE values of calibration and validation were 0.52 and 0.67, which can be regarded as acceptable prediction accuracy (Moriasi et al., 2007).

3.3. Representative rainfall event

After calibration of the SWMM, we reproduced a representative rainfall event for further LID modeling and evaluation using observed rainfall patterns with the IETD concept. Fig. S1 illustrates the variation of coefficient of variation in response to different IETDs from 1 h to 30 h. By having 17 h, the coefficient of variation is equal to 1 (i.e., red line in Fig. S1). We chose 17 h as the value of IETD and estimated 32.4 mm of average rainfall and an average duration of 8.6 h. Finally, representative rainfall events for Gwangju were generated using the Huff curve using the regression equation made by the Ministry of Construction & Transportation (2000), as shown in Fig. S2.

3.4. Changing LID size, the reduction of SS for rainfall patterns

Before applying LID, SWMM was applied to estimate SS loadings in response to the representative rainfall patterns; 1944.96 (g) by the 1st quartile, 1605.01 (g) by the 2nd quartile, 1782.84 (g) by the 3rd quartile, and 1620.23 (g) by the 4th quartile. As well, the Event Mean Concentrations (EMC) of SS were calculated as 46.47 (mg/L) by the 1st quartile, 64.53 (mg/L) by the 2nd quartile, 52.17 (mg/L) by the 3rd quartile, and 42.11 (mg/L) by the 4th quartile. Fig. S3 shows that the first flush curves for rainfall variation are different each other. The 4th quartile showed the greatest FFE, since FFE is significantly influenced by the temporal variability of rainfall, even if individual storms have the same intensity and duration.

Fig. 5 (bioretention) and Figs. S4–S8 (green roof, infiltration trench, porous pavement, rain barrel, vegetative swale) present the reduction effect of each LID in terms of SS loadings, EMC, and FF-curves under the representative rainfall events. In all types of LID application, SS loadings are reduced by applying larger LID facilities. EMC initially decreased and bounced at a sudden point, and increased again, except for infiltration trench and porous pavement whose EMCs kept increasing by applying LID. This is because SS reduction is greater than surface runoff reduction by a smaller LID, but it is less than surface runoff reduction by applying a larger LID. It also implies that larger size of LID can result in an increase of EMC. The changes of SS loading and EMC in response to bioretention are very similar with those of green roof. In SWMM, the

Fig. 5. Applying bioretention for reducing suspend solids, A–D: SS loading (blue circles) and EMC (red makers) for 1st–4th quartile, E–H: FF-curves for 1st–4th quartile where red line (i.e., 45° line) indicates that pollutants are uniformly distributed (Verdaguer et al., 2014) and blue line is the FF curve before applying LID. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

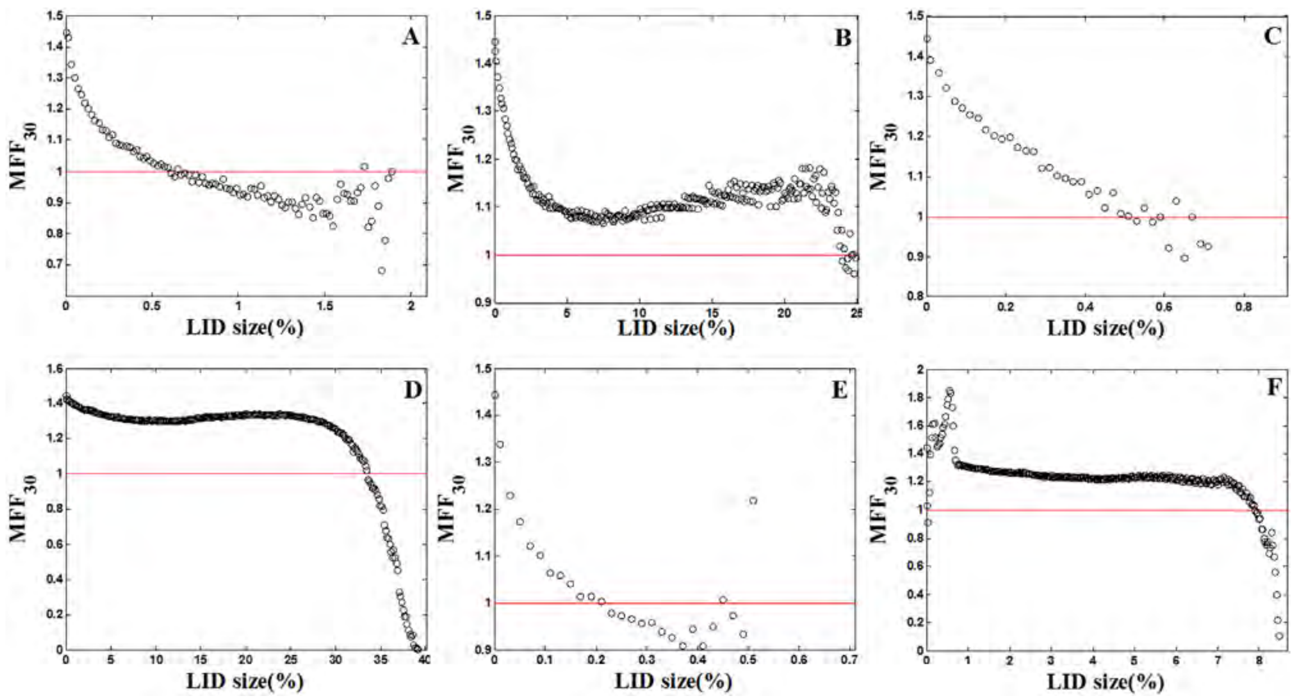

Fig. 6. Determination of the optimal LD size, A: bioretention, B: green roof, C: infiltration trench, D: porous pavement, E: rain barrel, F: vegetative swale.

calculation process of bioretention and green roof in SWMM were performed with the same parameters (surface layer, soil layer, storage layer, under drain) but this result shows that bioretention is reductive than green roof for treating suspended solids. This could be caused by the different depths of soil layers.

Porous pavement and vegetative swale demonstrated different responses from other types of LID. Porous pavement is characterized by a pavement layer which allows infiltration of stormwater (Nichols et al., 2015). As shown in Fig. S6, the EMC of porous pavement initially increased exponentially, and then decreased sharply. Also, porous pavement required the greatest LID size among the LIDs. Therefore, it needs enough space for implementing it to be effective. Compared to other LIDs, vegetative swale shows a different pattern of reduction for suspended solids depending on LID size. The EMC of vegetative swale initially decreased and then increased sharply (Fig. S8). This is because vegetative swale is used to reduce flow and pollutant and it is also used to convey stormwater runoff off (UNHSC, 2009). Here, we decided to use the rainfall pattern of the 4th quartile in determination of optimal LID size. This is because the 4th quartile results is the greatest FFE (Fig. S3).

3.5. Decision for optimal LID size considering MFF

Fig. 6 shows the change in MFF_{30} by implementing different sizes of bioretention. We found that MFF_{30} sharply decreased by increasing LID size, demonstrating that LID can be effective for reducing FFE. Except for porous pavement and vegetative swale, MFF_{30} initially decreased by increasing LID size, but bounced and increased after a certain LID size. Especially, rain barrel initially decreased MFF but sharply increased after 0.4% of LID size. This LID is most sensitive to size.

Many researchers proposed a variety of LID sizes that were calculated according to various rainfalls, duration, and intensity values and they suggested LID sizes which was unable to consider types of LIDs. Here, we proposed the optimal size for each LID from the SWMM-LID modeling for minimizing FFE in terms of runoff depths (mm) in the watershed (Table 4). As mentioned above, if MFF_{30} is equal to 1 for a given LID size, we determined it as an optimal LID size. We found that bioretention and rain barrel are most effective for reducing FFE of suspended solids (Table 4). Researchers have proposed a wide range of LID sizes (International Stormwater BMP Database, 2010; U.S. Dept. of Defense, 2004; Guo and Urbonas, 2002, 1996; Kim and Han, 2010). Previous studies recommended the WQCV method, which proposed runoff depth of 25.4 or 76 mm for LID size (International Stormwater BMP Database, 2010; U.S. Dept. of Defense, 2004). As well, some researchers recommended a runoff depth of 4.32–13 mm for LID size using the WQCV method (Guo and Urbonas, 1996, 4.32 mm; Guo and Urbonas, 2002, 13 mm; Kim and Han, 2010, 4.54 mm). Some suggested a runoff depth of 2.0–2.5 mm as incipient runoff (Guo and Urbonas, 1996; Driscoll et al., 1989; USEPA, 1986). Our results are similar to the incipient runoff depth suggested by Driscoll et al. (1989) and USEPA (1986), and also show different sizes according to different LID type for reducing FFE. Li et al. (2006) and Abrishamchi et al. (2010) recommend that the composition of conventional treatment systems divide into first flush treatment and the overall LID treatment. Most of the previous studies have determined LID size in terms of the overall LID treatment without deep consideration of hydrologic response and/or water quality dynamics by implementing different LIDs. The WQCV method is driven by the overall LID treatment. Here, this study simulated water quality dynamics using pollutant build-up and a wash-off module, coupled with a hydrologic response. The optimal size for each LID was estimated by considering the hydrological cycle and water quality dynamics, rather than the simple estimation of total water quality volume. We suggested LID sizes for each LID type in consideration of the objective function (i.e., MMF) for minimizing FFE, rather than the overall LID treatment. By applying the optimization process, bioretention was proposed as the most effective LID, showing the minimum size among 6 different LIDs. However, the performance of bioretention could be varied in how effluents are discharged from bioretention ponds. Effluent discharge from bioretention is dominantly influenced by orifice and weirs design, thereby practical engineers need to consider the influence of outlet structures to acquire sufficient and effective resident time for suspended solids to settle down. As well, outlet structuring should focus on replicating hydrologic responses from pre-development conditions (Coffman, 2001).

4. Conclusion

In this study, we explored a novel methodology to propose an optimal LID size, incorporated with intensive stormwater monitoring and numerical modeling. By considering MMF_n, LIDs were designed to mitigate FFE on the receiving waterbody. The methodology was tested to optimize the size of different LIDs in a commercial area in Korea. The major findings can be listed as follows:

1) SWMM combined with MATLAB performed sensitivity analysis and auto-calibration by using the pattern search tool, demonstrating the capability of simulating rainfall-runoff and suspended solids from the study area.
2) We produced a representative rainfall event for the given site, considering IETD, the observed rainfall pattern, and Huff curves. The value of the Inter-Event Time Definition (IETD) is 17 h, average rainfall is 32.4 mm, and average rainfall duration is 8.6 h.
3) The SWMM simulation demonstrated that EMC is highly variable in response to different sizes of LID, implying that there is a need to optimize the LID size.
4) The optimal LID sizes were proposed based on mass first flush (MFF) which is an indicator to quantify FFE, ranging from 1.2 mm to 3.0 mm in terms of runoff depths.

In this study, LID was designed by applying a modeling approach with stormwater monitoring in an attempt to improve water quality rather than flooding reduction. The optimization process incorporates the different hydrological responses and water quality dynamics of 6 different LIDs. We hope that our proposed methodology can be useful for effective LID strategies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.08.038.

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