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Evaluation of a hydrology and run-off BMP model in SUSTAIN on a commercial area and a public park in South Korea

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ABSTRACT

Adapting best management practices (BMPs) is influenced by target reduction efficiency BMP size, and BMP type. The System for Urban Storm water Treatment and Analysis INtegration (SUSTAIN) model was evaluated to determine optimal size and type of BMP with monitoring results from a commercial area and a public park in Korea. The hydrology model in SUSTAIN was tested in a commercial area (impervious area: 85%) and a public park (impervious area: 36%) in South Korea. A sensitivity analysis revealed that the significant parameters for total flow were impervious area Manning's roughness (IMPN) and saturated hydraulic conductivity (HYDCON); and those for peak flow were IMPN, Manning's roughness of conduit (ROUGH) and HYDCON. The observed average run-off ratios of the two study sites were 0.59 and 0.30 for the commercial area and the public park, respectively. In contrast, the simulated average run-off ratios were 0.53 and 0.22, respectively. The SUSTAIN hydrology model was also evaluated statistically by comparing observed and simulated run-off. In a commercial area, R^2, root mean square error, and Nash–Sutcliffe efficiency were 0.68, 10.98, and 0.46, respectively, whereas the public park yielded 0.74, 1.97, and 0.62, respectively. After calibrating the model, the BMP options of SUSTAIN (i.e. bioretention, dry pond, and wet pond) were utilized to test run-off reduction capability with 11 mm of retaining run-off depth from the commercial area and 3 mm from the public park. Monitoring data showed that 11 and 3 mm run-off storage ensured about a 50% reduction of run-off from the commercial area and the public park, respectively. In the commercial area, average reduction rates were identically all 43.0% for bioretention, dry pond, and wet pond, respectively, and those for the public park were 49.6, 57.6, and 53.5%, respectively. Overall, the BMP function of SUSTAIN seemed to be reasonable for reducing run-off and could be used to design BMP to meet a target reduction goal where monitoring data does not exist.

Keywords: SUSTAIN; Run-off; Run-off ratio; Public park; Commercial area; BMP; Rainfall-run-off depth; Dry pond; Wet pond; Bioretention

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1. Introduction

Continued urbanization and development result in an increase of impervious area, thereby increasing surface run-off to receiving water bodies. This also increases the potential for floods and associated pollutant loads, which impair the receiving water bodies [1,2]. Therefore, control of urban run-off quantity has emerged as a key concern for municipal officials [3,4] and effective management is needed throughout watersheds to achieve the desired flow mitigation effects [5].

A number of monitoring studies [6–10] have been conducted to characterize the non-point source (NPS) pollution run-off from various pollution source types (e.g. roofs, highways, urban watersheds, and different land-use types) during rainfall. However, these studies were mostly conducted in fully impervious areas, and only a few focused on run-off from pervious areas. Mathematic modeling can be used to determine best management practice (BMP) type and placement with limited stormwater management funds [11]. A number of mathematic modeling studies have been conducted to characterize urban run-off. The Storm Water Management Model (SWMM) is a widely used model for urban watersheds such as researching stormwater BMP treatment performance for sediment and heavy metals [12], modeling an industrial area [13], analyzing run-off changed by the impervious ratio [14], modeling considering CSO [15], and a study on a transportation area [16]. Similarly, the system for urban stormwater treatment and analysis integration (SUSTAIN) can be used to analyze rainfall-runoff and load transportation, flow and load reduction for green infrastructure BMP (e.g. dry ponds, wet ponds, infiltration trenches, retention, and green roofs). However, the SUSTAIN model has been rarely applied to Korean urban conditions.

In this study, the SUSTAIN model was applied to a commercial area and a public park in Gwangju, South Korea, which have different impervious ratios. We conducted a sensitivity analysis, simulated stormwater-run-off characteristics, and evaluated the BMP module in SUSTAIN to suggest the optimal type of BMP and run-off depth.

2. Materials and methods

2.1. Site description

This study was performed in a commercial area (35˚09´33.12´´N, 126˚50´49.63´´E) (Fig. 1(a)) and a public park (35˚10´58.11´´N, 126˚53´13.94´´E) (Fig. 1(b)) in Gwangju, South Korea. The commercial area covered 0.0125 km^2 and had imperviousness of 85%. The area has offices and restaurants as well as a municipal sewer and rainwater drainage network, which were separated. The public park had an area of 0.0158 km^2 with imperviousness of 36%, and the municipal sewer and rain water drainage network were separated. Office buildings were found inside the park.

2.2. Sampling design and acquisition of data

To measure the flow rate of the rainwater drainage conduit, an automated flowmeter (Flo-Tote 3, Hach, Loveland, CO, USA) was installed at the outlet of the drainage network. Sampling was conducted at 15 min intervals for the first 120 min of a storm event and then at 60 min intervals during receding flow. Storm events were monitored in the commercial area and public park during 2009 and 2012.

Meteorological and geographic data were required for implementing the SUSTAIN model at the two different sites. Meteorological data included rainfall, maximum temperature, minimum temperature, evaporation, and wind velocity, whereas the geographical data included the digital elevation model (DEM) and land-use and soil maps. The meteorological data were acquired from a nearby Gwangju weather station (Gwangju, South Korea). The DEM and the land-use map were obtained from the National Geographic Information Institute in South Korea. The soil map was acquired from the Rural Development Administration, South Korea.

2.3. Model description

The SUSTAIN model consists of a framework manager, land module, BMP module, conveyance module, optimization module, and post-processor. The framework manager manages data for system functions, links between system modules, and creates a simulation network to guide the modeling and optimization activities. The land module generates run-off and pollutant loads from the land through land process simulation. The BMP module simulates flow and water quality throughout the BMP implementation and the conveyance module performs flow and water quality in a channel. The optimization module evaluates cost-effective BMP placement and selection strategies for applicable BMP types and ranges of BMP size. The post-processor analyzes model results [17]. The hydrology component of SUSTAIN is adapted from the SWMM land surface and groundwater compartment. The run-off, snowmelt, evapotranspiration, infiltration, overland flow, and street cleaning processes were derived from EPA SWMM5 [17].

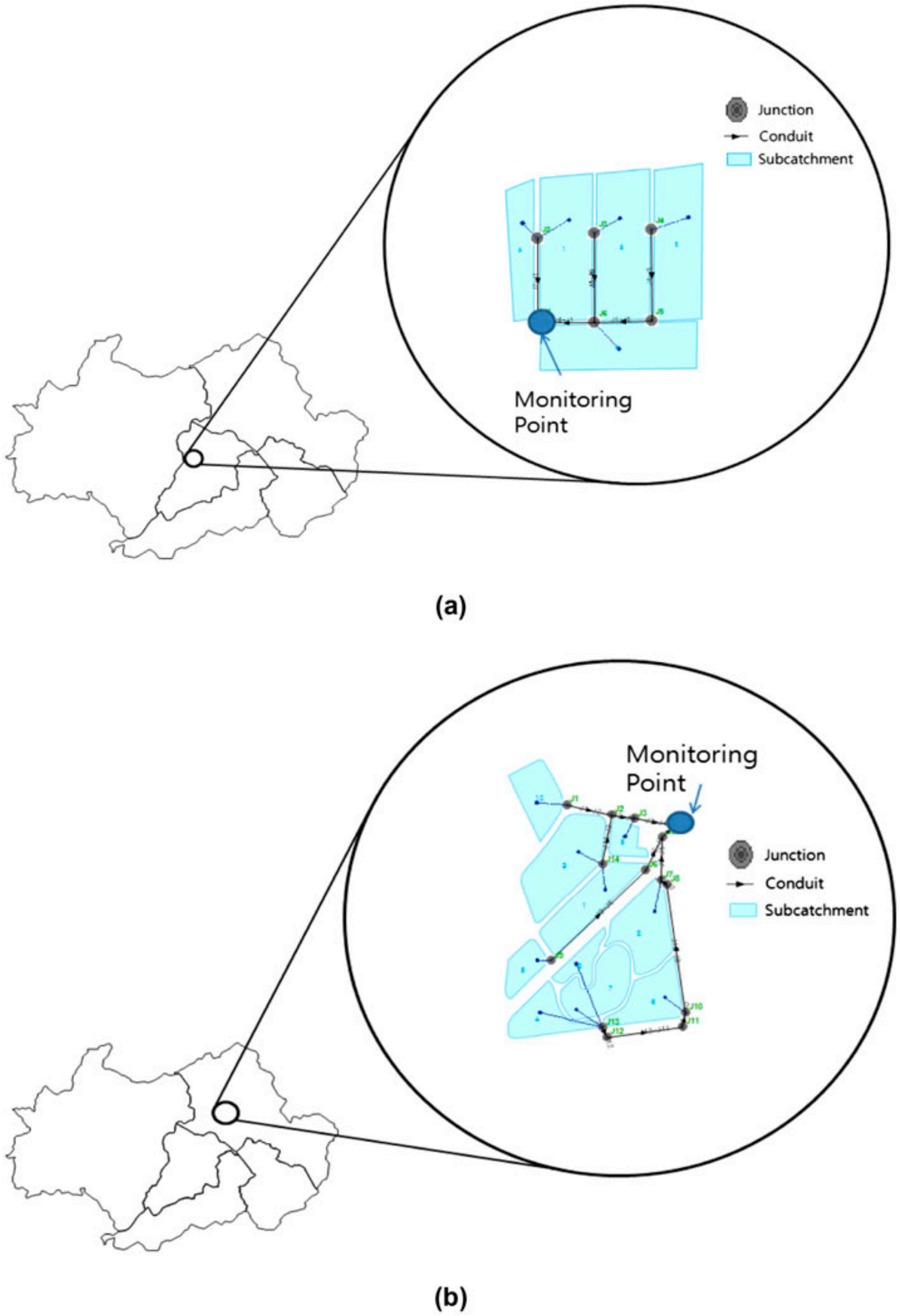


Fig. 1. Location of (a) commercial area and (b) public park and schematic map of study site in Gwangju city.

2.3.1. Hydrology module

The infiltration model of the SUSTAIN model employed the Green–Ampt model, which computes the amount of infiltration of rainfall into the unsaturated upper soil zone on a pervious land area, whereas surface run-off is computed by Manning's equation [17]. The Green–Ampt infiltration method assumes that a distinct and precisely definable wetting front exists in the soil column in which the soil separated the unwetted zone of soil with saturated soil above and initial moisture content below [18]. Eq. (1) was used to calculate infiltration as a function of soil moisture, average wetting front suction head, and saturated hydraulic conductivity (HYDCON) based on Dracy's law and the principle of mass conservation [19].

$$f = \frac{\mathrm{dF}}{\mathrm{d}t} = K\left[1 + \frac{(\theta_s - \theta_i)}{F}\right] \tag{1}$$

where f is infiltration rate (in/h), K is saturated HYDCON (in/h), Ψ is average wetting front suction head, θ_s is saturated moisture content, θ_i is initial moisture content, and F is the amount of infiltration (in).

The surface of the subwatershed was treated as a nonlinear reservoir. Inflow comes from precipitation of subwatersheds, whereas outflows were treated as infiltration, evaporation, and surface run-off in the downstream area. Eq. (2) was used to calculate surface run-off per unit area, Q, which only occurs when the surface water depth exceeds the maximum surface storage depth, and d_p, which is calculated by Manning's equation [17].

$$Q = W1.\frac{49}{n}(d - d_p)^{\frac{5}{3}}S^{\frac{1}{2}} \tag{2}$$

where W is subwatershed width (ft), n is Manning's roughness coefficient, d_p is depth of depression storage (ft), and S is the subwatershed slope (ft/ft).

Subwatershed width (W) was calculated by dividing the subwatershed area by the length of the flow path. The run-off depth from the subwatershed was calculated with a time series by solving water balance Eq. (3) for the subwatershed.

$$\frac{\mathrm{d}d}{\mathrm{d}t} = i_e - \frac{k.W}{A.n}(d - d_p)^{\frac{5}{3}}S^{\frac{1}{2}} \tag{3}$$

where d is water depth (m, ft); t is time (sec); k is a unit constant (1.0 for meter, 1.486 for feet); W is subwatershed width (m, ft); A is surface area of the subwatershed (m_2, ft_2); n is Manning's roughness coefficient; i_e is rainfall excess (m/s, ft/s); d_p is depth of depression storage (m, ft); and S is subwatershed slope (m/m, ft/ft).

2.3.2. BMP module

The BMP module in SUSTAIN calculates a process-based simulation of flow transport for structural BMPs. It is designed so that new BMPs and alternative solutions can be added over time, and the BMP module calculates the following hydrologic processes to reduce run-off volume and peak flows through evaporation of surface water, infiltration of pond water into the soil media, deep percolation of infiltration water into groundwater, and outflow through a weir or orifice [5]. Water balance storage routing was calculated by methods associated with flow routing in ponds and impoundments.

$$\frac{\Delta V}{\Delta t} = l - O \tag{4}$$

where ΔV is the change in storage (volume), Δt is the time interval (time), I is inflow (volume per unit time), and O is outflow (volume per unit time).

2.4. Model evaluation

The performance of the model for simulating discharge was evaluated graphically and statistically using Nash–Sutcliffe Efficiency (NSE), root mean square error (RMSE), and the coefficient of determination (R^2). The R^2 is explained by fitting a regression line and is a measure of the linear relationship between observed and simulated data. R^2 ranges between 0 and 1 (Eq. (5)) [20]. The RMSE was employed as a goodness of fit method to select the optimal parameter value (Eq. (6)) [21]. NSE uses the model prediction between the predicted and observed data [22]. This method has been widely used to identify the best model in various fields (Eq. (7)) [23,24].

$$\frac{\sum_{i=1}^{n}(O_i - \bar{O})(I_i - \bar{I})}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{5}$$

$$\sqrt{\frac{1}{n\sum_{i=1}^{n}(O_i - I_i)^2}} \tag{6}$$

$$1 - \frac{\sum_{i=1}^{n}(O_i - I_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{7}$$

where I_i is the predicted value by the SUSTAIN model, O_i is the measurement, n is the number of data, $\bar{O}_i$ is the average of measurement, and $\bar{I}$ is the average of predicted value.

2.5. Sensitivity analysis

A sensitivity analysis was applied to identify sensitive parameters for effective model calibrations [25]. From this analysis, we evaluated model performance under various parameters sets [26]. The hydrology component of SUSTAIN was adapted from the SWMM land surface model. James and Huber [27] applied sensitivity analysis to the following hydrological parameters such as impervious area Manning's roughness (IMPN), pervious area Manning's roughness (PERVN), Manning's roughness of conduit (ROUGH), impervious area depression storage (IDS), pervious area depression storage (PDS), average capillary suction (SUCT), saturated HYDCON, and initial moisture deficit for soil (SMDMAX). Here, we tested these parameters by changing values from −50 to 50%.

2.6. Estimating BMP size and evaluating the SUSTAIN BMP modules

Before performing the BMP simulation, we explored BMP size using monitoring data. The target reduction of run-off was about 50% and BMP size was determined based on the target goal. We tested the reduction rate of a dry pond, a wet pond, and bioretention under given rainfall, and if the BMPs satisfied the target reduction rate or not.

3. Results and discussion

3.1. Results of the sensitivity analysis

Fig. 2 presents the sensitivity graph for hydrological parameters (IMPN, PERVN, ROUGH, IDS, PDS, SUCT, HYDCON, and SMDMAX). The significant parameters of SUSTAIN in total flow were IMPN (−1.91–5.31%) and HYDCON (−1.58–4.49%). The most significant parameters of SUSTAIN in peak flow were IMPN (−9.38–24.39%) and ROUGH (−3.18–3.53%) followed by HYDCON (−4.39–2.39%) (Fig. 2). These parameters were associated with the major SUSTAIN equation (run-off or infiltration). Sharifan et al. [28] suggested that influential parameters of SWMM were IMPN, ROUGH, and their results were similar to those in this study.

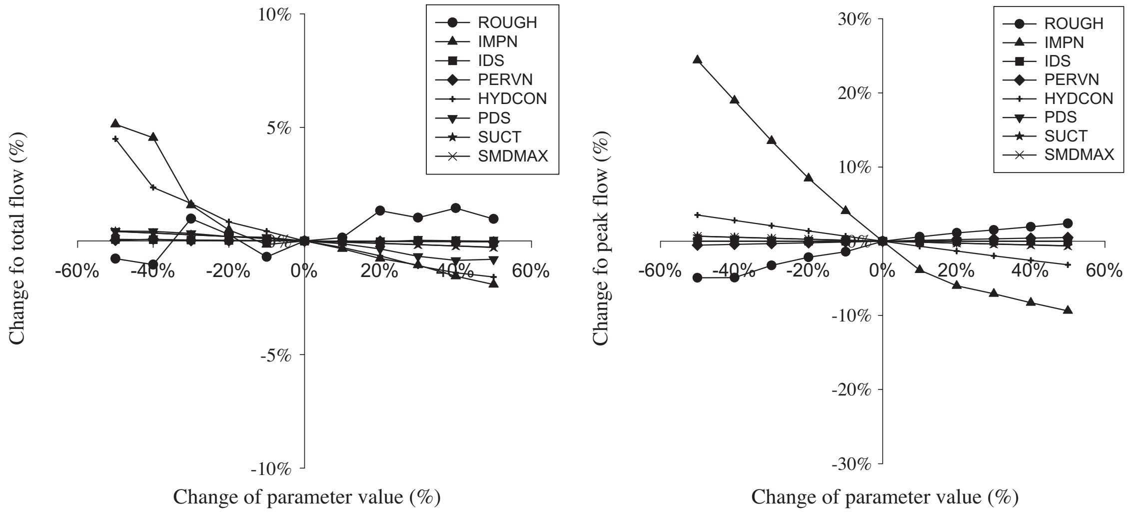
3.2. Hydrology simulation

Table 1 shows the hydrological parameters that served as input for the SUSTAIN model in the commercial area and the public park. Slope, HYDCON, SUCT, and SMDMAX were estimated by DEM and the soil map, whereas the other parameters were manually calibrated. Lee et al. [5] used 0.02 for IMPN and 0.13 in/h for HYDCON for SUSTAIN, whereas we used 0.012 for IMPN and 0.13 in/h for HYDCON.

Figs. 3 and 4 show the simulated run-off of the commercial area and the public park. The simulated run-off was in good agreement with the observed discharge. As shown in Fig. 3, although rainfall depth on 9 June 2009 was quite small (approximately 1 mm), the SUSTAIN model reproduced the temporal variation in surface run-off well. Although rainfall amounts for two different events (29 June 2009 and 22 June 2011) were identical, the run-off depth on 29 June 2009 (36.7 mm) for the commercial area was much higher than that of 22 June 2011 (10.8 mm) for the public park. This is because the commercial area has more impervious surface than that of the public park.

Tables 2 and 3 show the antecedent dry days, rainfall, observed run-off and run-off ratio, and the run-off and run-off ratio. The observed run-off data in the commercial area were 0.2–158.4 mm and the run-off ratio was 0.21–0.86. Simulated run-off was 0.2–149.7 mm and run-off ratios were 0.11–0.78.

In the public park, run-offs of the observed data were 0.6–84.1 mm, and their run-off ratios were 0.08–0.71. Simulated run-off was 0.3–65.2 mm and the run-off ratios were 0.06–0.55.



(a) Total flow (b) Peak flow

Fig. 2. Results of sensitivity analysis.

Table 1
Parameter of SUSTAIN on commercial area and public park after calibration

Parameter	Commercial area	Recreation park
PERVN	0.001	0.09
IMPN	0.012	0.012
Slope (%)	0.3	0.8
HYDCON (in/h)	0.13	0.13
SUCT (in)	3.5	3.5
SMDMAX (in/in)	0.116	0.116
PDS (in)	0.05	0.05
IDS (in)	0.07	0.07

The average run-off ratio of the observed data was 0.59 and the average run-off ratio of the SUSTAIN model was 0.53 for the commercial area. The average run-off ratio of observed data was 0.30 and the average run-off ratio for the SUSTAIN model was 0.22 in the public park. These results show that SUSTAIN can reproduce the run-off characteristics of a commercial area and a public park.

3.3. Model evaluation

Ramanarayanan et al. [29] suggested that when the R^2 and NSE values are close to zero, a model's simulation is unacceptable, whereas when R^2 and NSE values are >0.5 and 0.4, respectively, the model's performance is satisfactory. Model performance was evaluated using R^2, RMSE (L/s), and NSE. In the commercial area, NSE was 0.20–0.80. NSE of the public park was 0.24–0.82 (Table 4). In the commercial area, the average R^2 and NSE were 0.68 and 0.62, respectively, whereas the public park yield was 0.74 and 0.62, respectively. Lee et al. [5] applied SUSTAIN to model flow in a Kansas City watershed. Their R^2 value of flow was 0.7, which was similar to the value in our study. Based on the values suggested by Ramanarayanan et al. [29], the SUSTAIN model simulations for rainfall-run-off processes in the commercial area and public park in Korea were satisfactory.

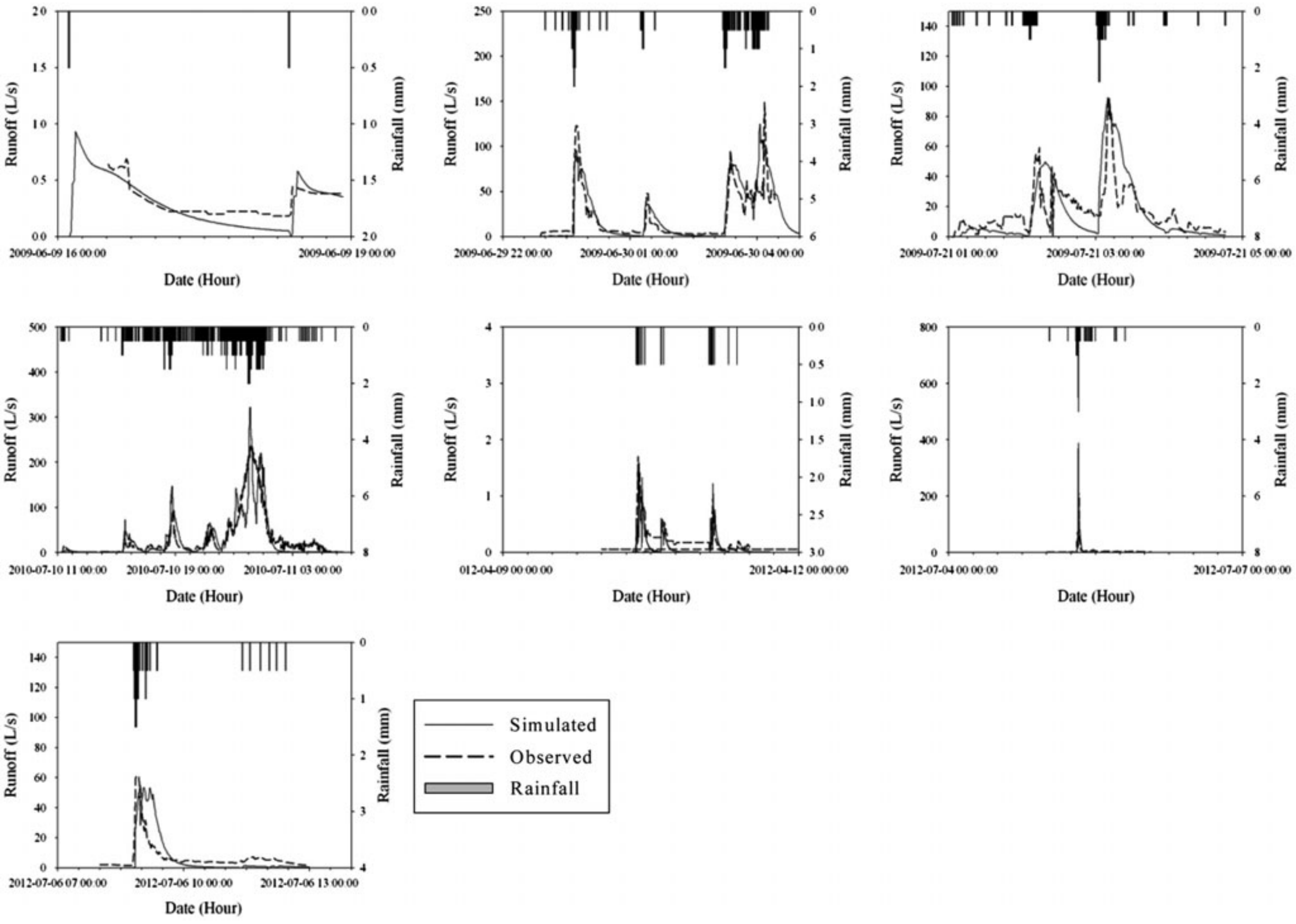


Fig. 3. Observed and simulated run-off of commercial area.

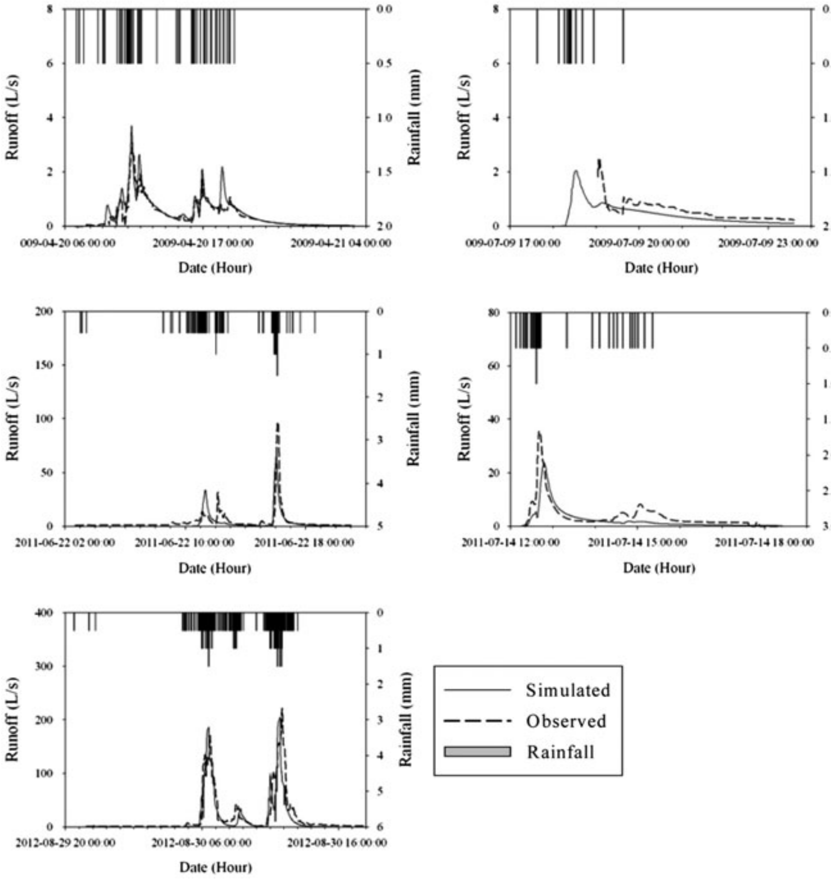


Fig. 4. Observed and simulated run-off of public park.

Table 2

Observed and simulated run-off depth and run-off ratio for commercial area

EVENT	ADD (d)	Rainfall (mm)	Run-off Simulated (mm)	Run-off Observed (mm)	Run-off ratio Simulated	Run-off ratio Observed
2009-06-09	1	1.0	0.2	0.2	0.17	0.21
2009-06-29	0	47.0	36.7	33.8	0.78	0.72
2009-07-21	0	24.5	16.9	17.6	0.69	0.72
2010-07-10	5	217.0	149.7	158.4	0.69	0.73
2012-04-09	6	9.0	1.0	2.3	0.11	0.26
2012-07-04	0	43.0	29.2	37.0	0.68	0.86
2012-07-06	0	14.5	9.0	10.0	0.62	0.69
Min	0	1.0	0.2	0.2	0.11	0.21
Max	6	217.0	149.7	158.4	0.78	0.86
Average	1.7	50.9	34.7	37.04	0.53	0.59

3.4. Estimate of BMP size using monitoring data

The Korean MOE [30] recommends the size of LID facilities to hold 5 mm rainfall-run-off from watershed to treat urban NPS. In this study, run-off reduction rates were analyzed using monitoring data, assuming storage facility holding rainfall-run-off depths of 1–15 mm in the commercial area and public park. Reduction rates were calculated based on monitored rainfall and run-off volume relationship of the commercial area and the public park. Fig. 5 shows

Table 3
Observed and simulated run-off depth and run-off ratio for public park

			Run-off		Run-off ratio	
EVENT	ADD (d)	Rainfall (mm)	Simulated (mm)	Observed (mm)	Simulated	Observed
2009-04-20	4	23	2.3	1.8	0.1	0.08
2009-07-09	0	5.5	0.3	0.6	0.06	0.1
2011-04-30	3	13	2.1	3.3	0.16	0.25
2011-06-22	10	47	10.8	17.9	0.23	0.38
2011-07-14	1	15.5	3.1	5.1	0.2	0.33
2012-03-29	4	29.5	6.8	8.8	0.23	0.3
2012-08-29	0	118.5	65.2	84.1	0.55	0.71
Min	0	5.5	0.3	0.6	0.06	0.08
Max	10	118.5	65.2	84.1	0.55	0.71
Average	3.1	36.0	12.9	17.3	0.22	0.30

Table 4
Statistical evaluation of SUSTAIN for commercial area

Commercial area				Public park			
EVENT	R^2	RMSE (L/s)	NSE	EVENT	R^2	RMSE (L/s)	NSE
2009-06-09	0.77	0.33	0.44	2009-04-20	0.83	0.19	0.67
2009-06-29	0.8	12.79	0.78	2009-07-09	0.63	0.31	0.24
2009-07-21	0.58	14.16	0.43	2011-04-30	0.88	1.01	0.71
2010-07-10	0.76	24.9	0.8	2011-06-22	0.59	6.72	0.59
2012-04-09	0.62	0.16	0.38	2011-07-14	0.55	3.81	0.48
2012-07-04	0.67	15.19	0.2	2012-03-29	0.90	0.69	0.82
2012-07-06	0.54	9.36	0.3	2012-08-29	0.78	1.10	0.81
Minimum	0.54	0.16	0.20	Min	0.55	0.19	0.24
Maximum	0.80	24.90	0.80	Max	0.9	6.72	0.82
Average	0.68	10.98	0.46	Average	0.74	1.97	0.62

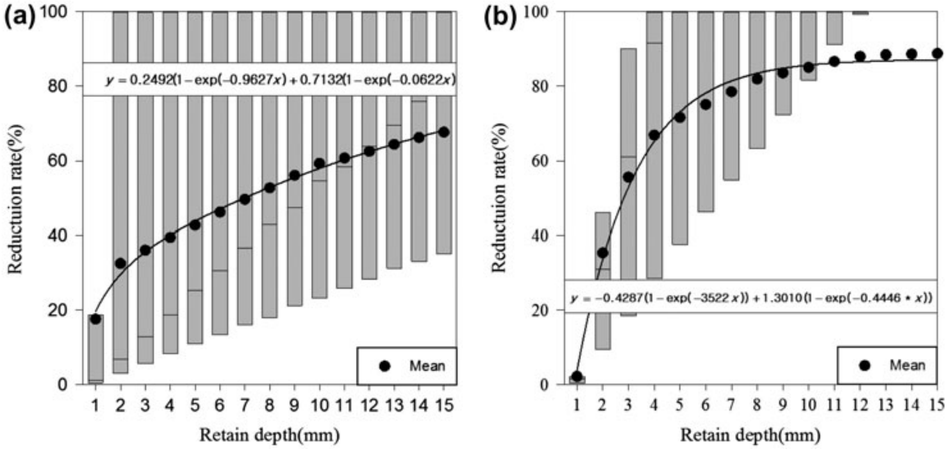


Fig. 5. Water volume removal ratio of depth of retained run-off at commercial area (a) and public park (b).

Table 5
Parameter value of BMPs(bioretention, dry pond, wet pond) in commercial area and public park

Parameter	Commercial area		Public park		Unit
Rainfall-run-off depth	11	5	3	5	mm
Width	48	34	21	38	ft
Length	48	34	21	38	ft
Soil depth	2	2	2	2	ft
Porosity	0.3	0.3	0.3	0.3	–
Soil capacity	0.25	0.25	0.25	0.25	–
Witling point	0.15	0.15	0.15	0.15	–
Suction head(in)	3	3	3	3	in
Initial deficit	0.3	0.3	0.3	0.3	–

the mean and box plot of reduction rates by changing rainfall-run-off storage depths from 1 to 15 mm in the commercial area and public park, respectively. The figure shows that as rainfall-run-off storage depth increase, the reduction ratio also increases, but cost effectiveness decreased. The results of the analysis show that storage facilities require at least 11 and 3 mm rainfall-run-off depths from the commercial

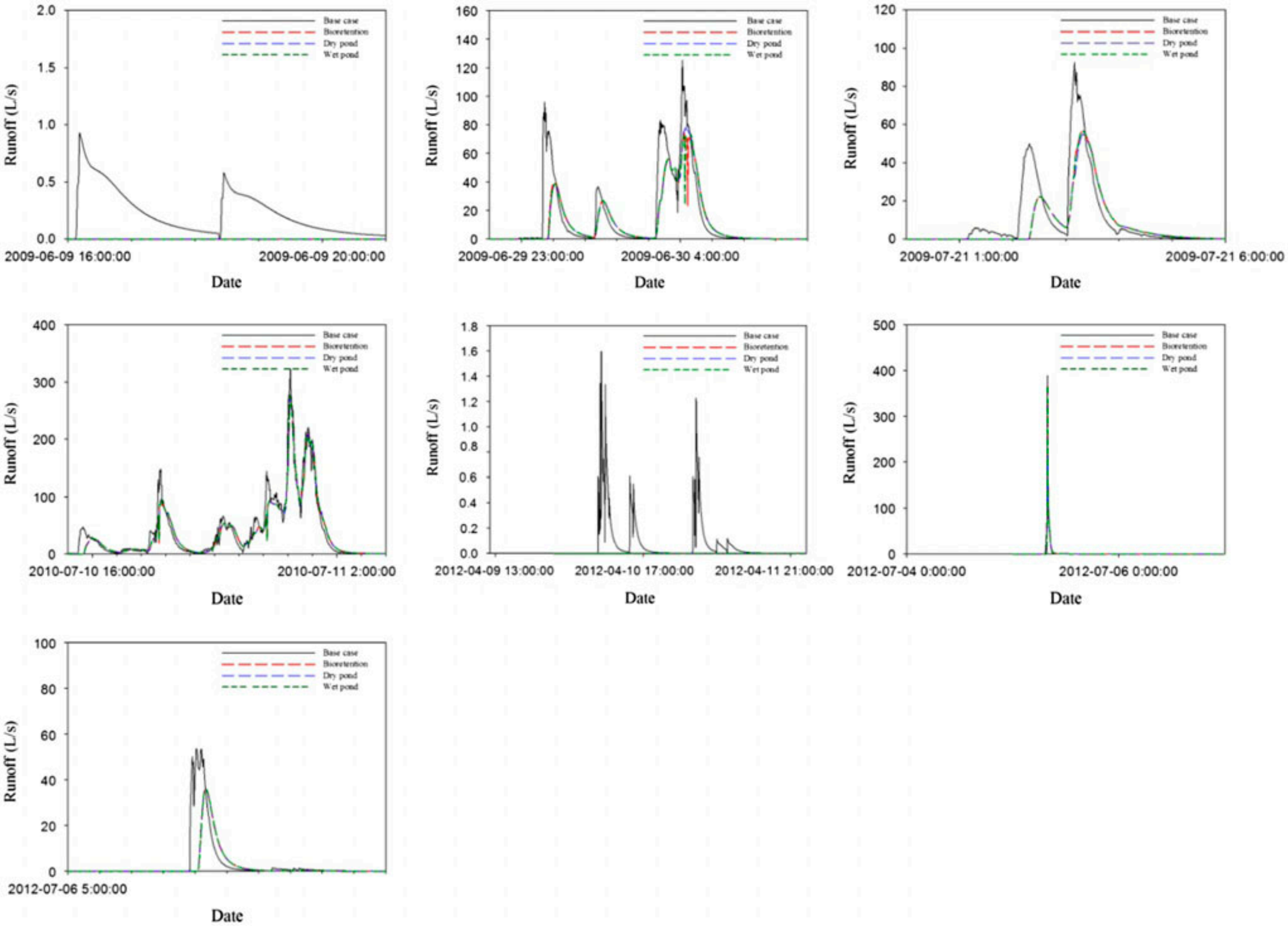


Fig. 6. Comparison result of application to BMPs(bioretention, dry pond, wet pond) for commercial area.

area and public park to achieve run-off reduction of about 50%, respectively.

3.5. BMP simulation

Table 5 lists the BMP parameters involved in the commercial area and public park to apply SUSTAIN. A run-off depth of 11 mm was used for the BMP volume determination for the commercial area and 3 mm was used for the public park. We also tested 5 mm, which was recommended by MOE [30], as rainfall-run-off storage depth of an urban BMP. The other BMP parameters were identical for the commercial area and public park.

Figs. 6 and 7 show the result of BMP implementation in both the commercial area and public park in terms of run-off reduction. Simulated run-off reductions of bioretention, dry pond, and wet pond in both the commercial area and public park were 6–100%.

Fig. 8 shows the mean and standard deviation of run-off reduction rates by BMPs. In the commercial area, the average reduction rates of bioretention, dry pond, and wet pond were 43.0, 43.1, and 43.1% respectively, when the BMPs were designed to hold 11 mm run-off depth. In contrast, if BMP size were determined by the MOE [30] criterion, which is a 5 mm rainfall-run-off storage depth, the reduction rates of bioretention, dry pond, and wet pond were 36.4, 37.2, and 38%, respectively.

In the public park, average reduction rates were 49.6, 57.6, and 53.5% for bioretention, dry pond, and wet pond with a 3 mm rainfall-run-off storage depth. If BMP size was 5 mm of rainfall-run-off storage depth, as recommend by the MOE [30], reduction rates of bioretention, dry pond, and wet pond would be 73, 85.9, and 74%, respectively.

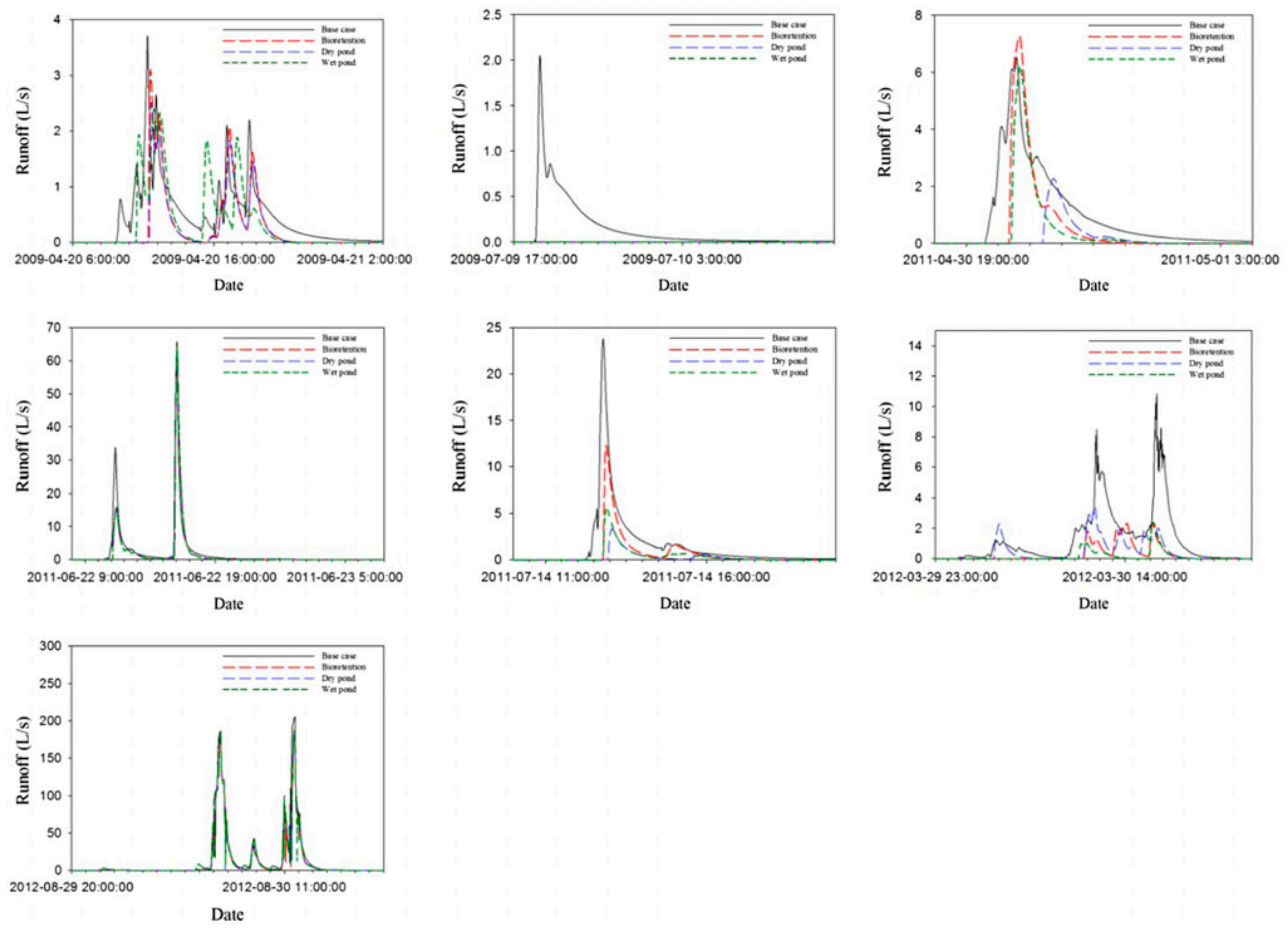


Fig. 7. Comparison result of application to BMPs(bioretention, dry pond, wet pond) for public park.

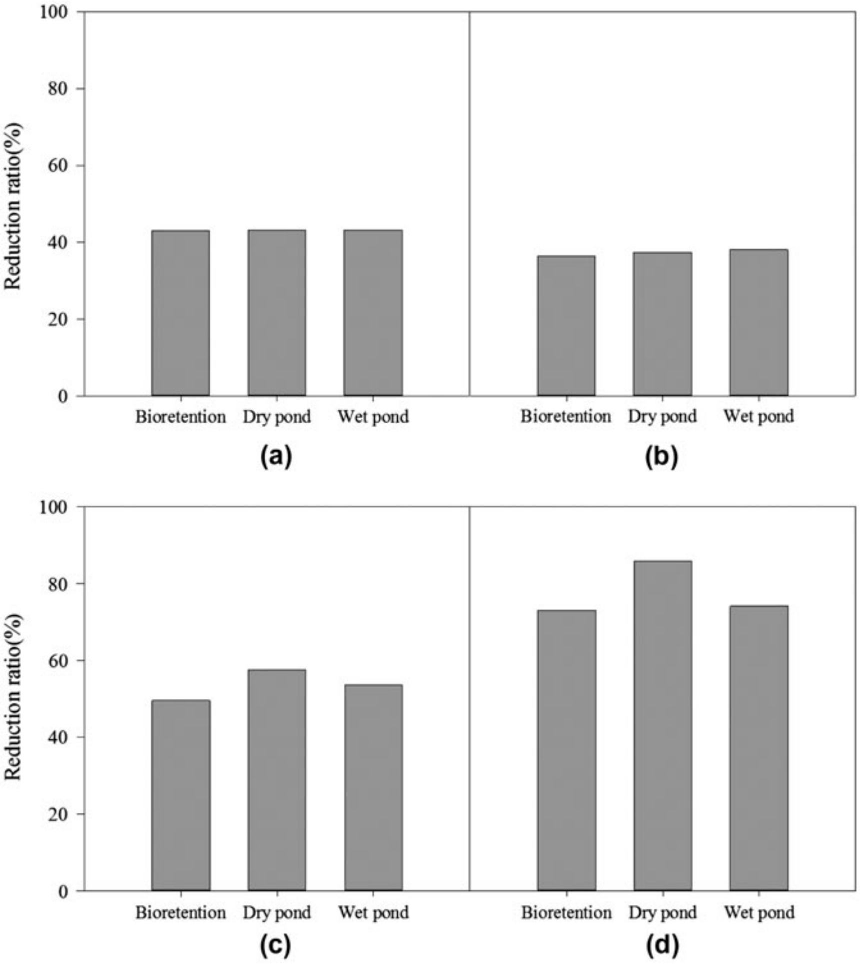


Fig. 8. Mean value of using comparison result of application to BMPs(Bioretention, Dry pond, Wet pond) for criteria of in this study (11 mm) (a) and MOE (5 mm) (b) for commercial area and, BMPs for criteria of in this study (3 mm) (c) and MOE (5 mm) (d) for public park.

4. Conclusions

The hydrology and run-off BMP models in SUSTAIN were evaluated for a commercial area (impervious area: 85%) and a public park (impervious area: 36%) in South Korea. Major results and conclusions are as follows:

(1) The most significant parameters for total flow were IMPN and HYDCON, whereas those for peak flow were IMPN, ROUGH, and HYDCON.

(2) The observed average run-off ratios of the two study sites were 0.59 and 0.30 for a commercial area and public park, respectively. In contrast, the simulated average run-off ratios were 0.53 and 0.22, respectively.

(3) The hydrology model of SUSTAIN was evaluated statistically by comparing observed and simulated run-off. In the commercial area, the averages of R^2, RMSE (L/s), and NSE were 0.68, 10.98, and 0.46, respectively, whereas the public park yielded 0.74, 1.97, and 0.62, respectively. The SUSTAIN model demonstrated the capability of simulating rainfall-run-off from the commercial area and public park in Korea.

(4) Monitoring data were analyzed to determine BMP size. The results of the analysis showed that storage facilities would be required to hold about 11 and 3 mm rainfall-run-off depths from the commercial area and the public park to achieve run-off reduction of about 50%.

(5) To evaluate BMP assessment of SUSTAIN, bioretention, dry pond, and wet pond were tested with size retaining run-off depth of 11 mm

from the commercial area and 3 mm from the public park, which could result in a 50% run-off reduction. In the commercial area, average reduction rates were 43.0, 43.1, and 43.1% for bioretention, dry pond, and wet pond, respectively, whereas those for the public park were 49.6, 57.6, and 53.5%, respectively.

Overall, the BMP assessment function of SUSTAIN seemed to be reasonable for run-off reduction and could be used to design BMP meet target reduction goal where monitoring data does not exist.

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