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Assessing the efficiency of aggregate low impact development (LID) at a small urbanized sub-catchment under different storm scenarios

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ABSTRACT

While the size of single low impact development (LID) unit determines the performance in attenuating water quantity and quality from storm runoff, the performance of multiple LID units is sensitive to both their size and arrangement order. This study describes a methodology to obtain the best performance for multiple LID units under varying by time-to-peak of storm with the same intensity and duration using storm water management model (SWMM), a popular model for rainfall–runoff and water quality simulation. The hypothetical temporal distributions were designated by Huff curves, which provided characterizing storm mass curves, along with the relationship of intensity–duration–frequency to determine storm intensity for 1-h in 2-year return period. Three types of LID units (rain barrel, infiltration trench, and vegetative swale) were selected to develop aggregate LID scenarios using the SWMM. The results indicated that, when compared with other field experiments, the SWMM successfully estimated change in flow discharge and suspended solid (SS) loss reflecting different storm patterns at the final outlet of and urbanized sub-catchment as well as the effects of LID practices. The performances of aggregate LID scenarios including lag time of peak runoff, peak runoff reduction, volume reduction, and SS loss reduction were sensitive to arrangement order and time-of-storm peak-to-storm duration. Scenario 5, which had the order of vegetative swale, rain barrel, and infiltration trench, showed the most effective serial arrangement, as it exhibited the more consistent results across the storm patters. This study thus provides insights into the effective design of aggregate LID scenarios considering different storm characteristics.

Keywords: Low impact development; Design storm; Storm water management model; Aggregate LID; Urban runoff

1. Introduction

The increasing imperviousness of ground condition caused by urbanization brings a serious change to the nature of the water cycle on undeveloped lands through increased surface runoff, raised peak flow rate, and decreased infiltration during storms [1–3]. Moreover, it degrades water quality in downstream waters by increasing non-point source (NPS) pollutants through urban catchment [4]. Low impact development (LID) practices have been recommended as a viable solution to mitigate these impacts of urbanization [5–7]. Essentially, LID practices are designed to return hydrologic conditions in an urbanizing environment to the pre-development state by promoting storage, infiltration, and evaporation operations [8,9]. However, LID may be achieved with a wide variety of structural

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and non-structural techniques, while it is difficult to maintain consistent reduction performances of runoff quantity and quality, which vary according to storm characteristics and size.

Consequently, urban storm water models are useful to understand the characteristics of runoff from various catchments and to verify the performances of LIDs prior to implementing them in the field. During the last three decades, approximately 40 models for urban storm water have been developed; of these, 10 (MOUSE, MUSIC, P8-UCM, PURRS, RUNQAL, SLAMM, StormTac, SWMM, UVQ, and Water Balance) have been used around the world, and three (MOUSE, MUSIC, and SWMM) have been considered as suitable tools in terms of range of uses, temporal and spatial resolution, runoff generation and routing, contaminants, and LID practices by Elliott and Trowsdale [10]. Overall, the storm water management model (SWMM) appears to be the most appropriate to develop an urban catchment model and estimate the effects of LID practices because it is capable of handling various runoff generation methods (i.e., SCS curve number, Green-Ampt method, and groundwater/baseflow) and routing methods (i.e., steady flow, kinematic wave, and dynamic wave) and it best enables the employment of LID practices.

In previous studies, the effectiveness of LID in controlling surface runoff and NPS pollution has been evaluated using SWMM. For example, Chui et al. [2] identified the optimal design of green roofs, bio-retention cells, and porous pavement in terms of hydrological performance and cost-effectiveness at household and business scale using the SWMM. Baek et al. [11] proposed the optimal size of bio-retention cell, green roof, infiltration trench, porous pavement, rain barrel, and vegetative swale to minimize mass first flush with the SWMM. Most studies, however, including those mentioned (above), have focused on the effectiveness of single LIDs and optimization of their size. A few studies have also considered multiple LIDs for mitigating hydrological performance. Palla and Gnecco [9] assessed the impact of LID scenarios consisting of different green roof area ratios for roof runoff and permeable pavements for surface runoff from parking lots in terms of hydrologic response. Guan et al. [12] compared runoff volume and peak discharge of combinations of non-structural LIDs, including green roof, porous pavement, and structural LIDs with a rain barrel and storage unit. However, the LID combinations in these two studies did not consider the serial arrangement of structural LID units.

Here, we examined the aggregate LID scenarios consisting only of a structural LID (rain barrel, infiltration trench, and vegetative swale), considering variations in time-to-peak storm with the same intensity and duration. The specific aims of this study were to: (1) assess the hydrologic response of the study catchment according to different storm patterns, (2) examine the performance of individual LID controls, and (3) investigate effective aggregate LID scenarios according to different storm patterns. It is our hope that this study will take us one step further toward solving the environmental issues involved in urbanization.

2. Methodology

2.1. Study area

A relatively small area of the Sangmu District, which is close to an urban stream of the Gwangju Tributary, was selected to assess the performance of six aggregate LID scenarios (Fig. 1). With a total drainage area of 12,500 m^2 and impervious surface coverage reaching 85% of the entire region, the sub-catchment mainly consisted of commercial and residential areas. Most of the impervious area in the Sangmu District was urbanized in the mid-1990s with the construction of many complex buildings as well as low- and high-story apartments in a previously undeveloped area to meet the increasing population needs.

The selected sub-catchment was divided into five subdrain areas, six junctions (to collect surface runoff from individual sub-sections), and eight conduits (to deliver the collected water to subsequent junctions) for simulation of water quality and quantity at the final outlet using the SWMM. In our study, the final effluent was specifically designed to be discharged to the aggregate LID that integrated the unit treatment systems (i.e., rain barrel, infiltration trench, and vegetative swale) in different orders through additional conduits in which no reaction was assumed to take place. Note that we neglected to consider any fate and transport processes in the conduit routing involved in the aggregate LID scenarios, unlike in the case of the sub-catchment routes, aiming to focus on the effect of LID arrangement order on the reduction efficiency of peak runoff, volume, and pollutant loss.

The study area followed the Asian monsoon climate system, in which approximately 65%–70% of the annual precipitation occurs from June to September. Over the last three decades, the mean annual temperature and precipitation recorded for the Gwangju City, including the study area was 13.8°C and 1,391 mm, respectively.

2.2. Storm water management model

We used the SWMM not only to describe the hydrologic and water quality behavior of the selected sub-catchment, but also to evaluate the efficiency of the integrated LID with different arrangement orders in attenuating the runoff volume and pollutant concentration discharged from the sub-catchment during simulation [5]. Released by United States Environmental Protection Agency (US EPA) since 1969, the SWMM was developed to specialize in continuous and single-event simulations of storm water runoff quantity and quality from urban areas. In particular, the model is known for its adoption of various modules for different natural attenuation processes that were not embedded in other equivalent rainfall–runoff models such as rain garden, bio-retention cell, green roof, infiltration trench, permeable pavement, rain barrel, and vegetative swale [13–15].

In principle, the SWMM consists of a hydrologic, hydraulic, and water quality module [5]. Focusing on the hydrologic module aspect, this model uses a non-linear reservoir approach including infiltration, depression storage, evaporation, and surface runoff [9,16]. In the present study, the Green-Ampt method was used to solve infiltration of rainfall into the unsaturated upper soil zone with initial water content. The Manning's equation was used to compute surface runoff. In respect of the hydraulic module, kinematic wave routing is used to calculate flow in conduits and the hydraulic head at junctions. The water quality module is developed by build-up and wash-off processes to estimate the suspended solid (SS) loss discharged from the sub-catchment area.

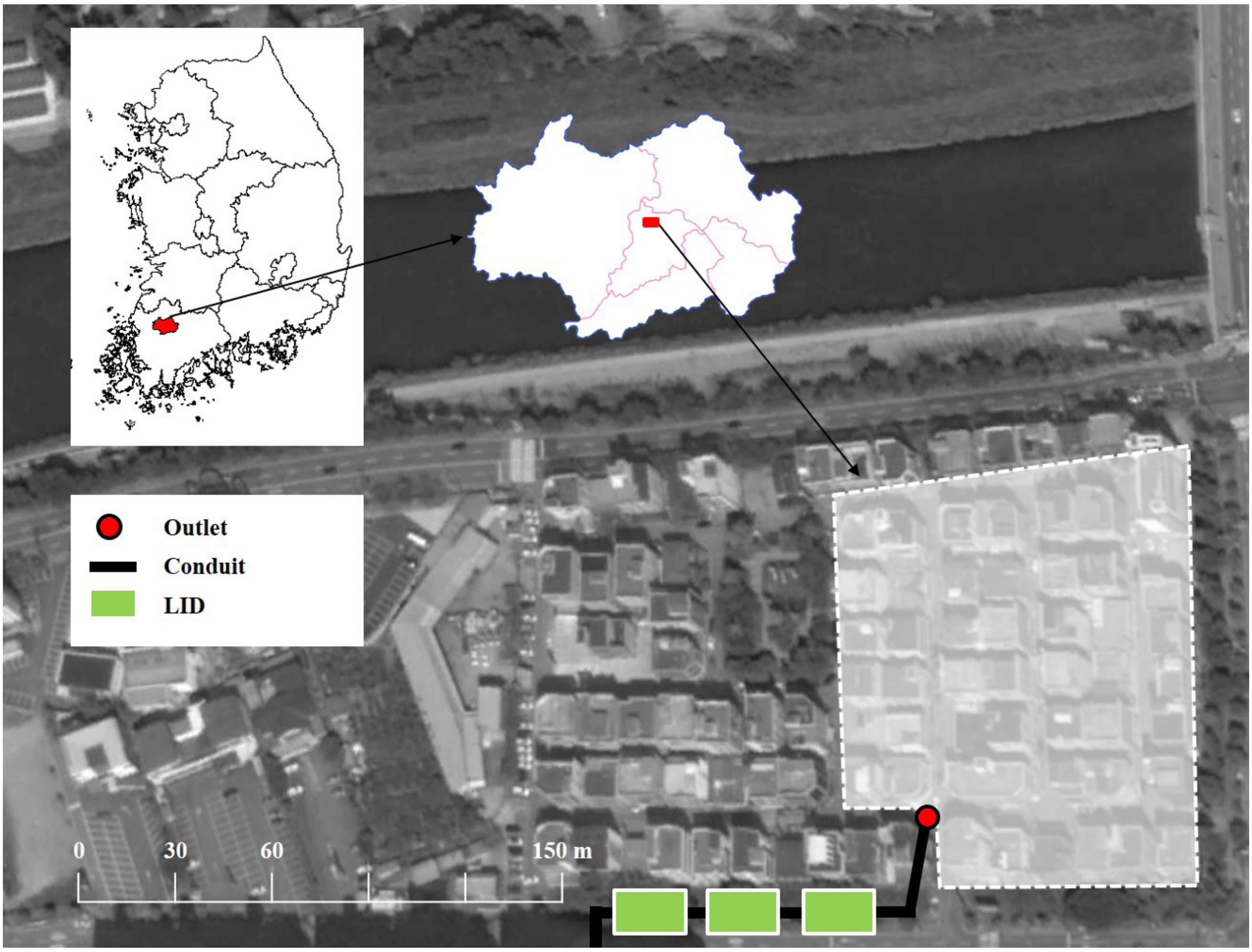

Fig. 1. Urban sub-catchment Sangmu District at Gwangju City in Korea selected for performance evaluation of aggregate LID.

This sub-catchment model was calibrated and validated to reproduce variations of discharge and SS loss that, at the final, outlet measured four storm events observed in the study area; the storm events on 7/6/2010 and 7/10/2010 were used for the calibration process, and the storm events on 6/29/2009 and 7/5/2012 were used for the validation process [11]. The water quantity and quality, which was simulated from the calibrated SWMM, were both in good agreement with the observed discharge and SS load during the calibration and the validation events. The Nash–Sutcliffe efficiency (NSE) values of runoff prediction were 0.80 and 0.54, and the NSE values of SS load prediction were 0.52 and 0.67 for the calibration events and validation events, respectively. More detailed information about the storm water monitoring and development of this sub-catchment model is available in our previous study [11].

2.3. Design of aggregate LID scenarios

LID controls are an effective way to attenuate the storm water quantity and quality through the detention, infiltration, and evaporation of surface runoff discharged from urban catchment [5]. The fundamental goal of LID controls is to mimic the pre-development conditions of hydrologic and pollutant loss by designing the size and arrangement of LID controls [17]. In this study, we focused on trying to find an effective LID arrangement order of aggregate LID scenarios in terms of lag time of peak runoff and the reduction efficiency of peak runoff, runoff volume, and SS loss using calibrated SWMM.

We selected three LID controls (rain barrel, infiltration trench, and vegetative swale) to develop aggregate LID scenarios. The rain barrel was a storage container that gathers runoff during storm events; we used this control as a storage unit to detain runoff volume [5]. The infiltration trench was a long, narrow, and rock-filled channel that intercepts surface runoff from upslope impervious areas [5,18]. It consisted of a surface and a storage layer, which enabled it to provide storage volume and additional time for captured runoff to infiltrate the native soil below. The vegetative swale was a shallow open channel with sloping sides covered with vegetation [5]. This was mainly used to slow the conveyance of collected surface runoff and infiltrate the native soil beneath it [8]. The parameter values of the LID design were set according to the recommendations by references [5,11,19]. The vales of the parameters employed in applying the three LID controls are given in Table 1.

Table 1
Parameter values for LID practices in SWMM

Layers	Parameters	Rain barrel	Infiltration trench	Vegetative swale
Surface	Berm height, mm	–	150	50
	Vegetation volume	–	0	0
	Surface roughness	–	0.1	0.24
	Surface slope	–	1.0	1.0
Storage	Thickness, mm	800	500	–
	Void ratio	–	0.5	–
	Seepage rate, mm/h	–	12.7	–
	Clogging factor	–	0	–
Drain	Flow coefficient	0	0	–
	Flow exponent, mm/h	0.5	0	–
	Offset height, mm	0	0	–
	Drain delay, h	0	–	–

Six aggregate LID scenarios were proposed according to the arrangement order of the rain barrel, infiltration trench, and vegetative swale (Table 2). We assumed that 2% (250 m^2) of the total sub-catchment would be set as the size of each LID controls to cope with rainfall intensity with 1-h storm in a 2-year return period.

2.4. Design storm

The concept of a design storm has been widely used to assess the hydrologic impacts of land development and to design the LID system. In this study, we used the relationship of intensity–duration–frequency (IDF) to estimate a representative rainfall amount for Gwangju City, taking into consideration rainfall duration and return period. IDF is one of the commonly used methods in water resources engineering [20]. The IDF curve table for this study area was obtained from the Korea precipitation frequency data server operated by the Ministry of Land, Infrastructure and Transport (MOLIT). This table was created with long-term (1939–2011) rainfall records collected at a weather station in Gwangju City. Assuming the rainfall duration and return period to be 1 h and 2 years, respectively, the rainfall amount was calculated at 39.6 mm.

After calculating the IDF relationship, the temporal rainfall distribution was produced by Huff curves. This method was employed to generate the probability isopleths of dimensionless storm mass curves for given elapsed times, and it provided four quartile Huff distributions (thus, the peak rainfall intensity occurred in the first, second, third, or fourth quarter of the storm) [11,21]. In this study, the four quartile Huff distributions were generated from sextic regression equations developed from the Gwangju City rainfall observations during the 72 years period (1939–2011).

Huff curves of 50% probability across a four quartile Huff distribution were adopted as the temporal rainfall distribution as representing their central tendency; but this is also commonly done in Korea [22]. Fig. 2 shows four storm water distributions in 1 min during 1 h as designed by the IDF relationship and Huff curves. These four design storms were used to investigate the performance of the aggregate LID scenarios in terms of time-to-peak, peak runoff, total runoff volume, and SS loss seeking what is effective for these considering location of peak rainfall intensity.

Table 2
Arrangement of LID treatment train scenarios

Treatment train scenarios	Rain barrel	Infiltration trench	Vegetative swale
S1	1	2	3
S2	1	3	2
S3	2	1	3
S4	3	1	2
S5	2	3	1
S6	3	2	1

3. Results and discussion

3.1. Runoff characteristics of base case

Fig. 3 presents the simulation results of flow and SS loss over time at storm outfall according to four different design storms in the base case, namely, that to which the LID controls were not applied in the study catchment. Fig. 3(a) shows distinct differences in flow in the first, second, third, and fourth quartile storms during runoff, even if the individual storms have the same intensity and duration. In terms of total flow, the duration time of runoff for the first and third quartiles was slightly longer, and in the fourth quartile it was the longest (first quartile: 178 min, second quartile: 181 min, third quartile: 182 min, and fourth quartile: 194 min).

The total runoff volume increased with each quartile (first quartile: 471.0 m^3, second quartile: 481.6 m^3, third quartile: 497.7 m^3, and fourth quartile: 548.2 m^3). In terms of peak flow, the lag time between peak rainfall and peak flow was 23, 20, 17, and 15 min for the first, second, third, and fourth quartile storms, respectively. The lag time was generally shortened with the time-to-peak of storm delay during a storm event. The peak flow was 183.7 L/s in the first quartile, 208.0 L/s in the second quartile, 228.9 L/s in the third quartile, and 243.1 L/s in the fourth quartile. With each quartile (increasing from the first through fourth), the surface runoff had a higher peak flow and a shorter time interval between peak rainfall and peak flow because the peak runoff traveled more quickly to the sub-catchment.

Fig. 3(b) shows the variation in runoff losses of SS in response to the four different rainfalls. The total mass of SS was calculated as 5.17 kg in the first quartile, 5.12 kg in the second quartile, 5.22 kg in the third quartile, and 5.85 kg in the fourth quartile. The fourth quartile showed the biggest total mass of SS; this was closely related with total runoff volume. Focusing on the variation in runoff losses of SS with elapsed time, this exhibited a different pattern in the fourth quartile compared with the others. The reason for this was that a part of the SS loss was already discharged with the mid-point of surface runoff before coming to the time-to-peak of surface runoff.

3.2. Performance of single LID control

Table 3 shows the time interval of peak flow between the base case and LID applications including single LID and aggregate LID scenarios. Focusing on single LID, a delay in peak timing appeared in the order of rain barrel followed by infiltration trench, and this was reduced as time-to-peak of storm delay. Vegetative swale was then applied, but with little or no effect because the size of the vegetative swale for study catchment was undersized in the case of a single application [23]. Therefore, the high flow was by-passed rapidly vegetative swale compared with the base case.

Fig. 4 illustrates the peak runoff, volume, and SS loss reductions of individual LIDs in the four quartile storms. Fig. 4(a) shows that the peak runoff reduction in the first quartile storm was higher than in the other quartile storms, whereas the three LID controls (rain barrel, infiltration trench, and vegetative swale) each showed a negative effect in the fourth quartile. The reason for this was that the individual LID units were saturated by surface runoff that had entered them before the coming peak storm, so the surface runoff rapidly passed the units [23]. From the results shown in Fig. 4(b), the volume reduction rates were highest for the rain barrel followed by the infiltration trench and then the vegetative swale. Also, these rates decreased slightly with each succeeding quartile. As Fig. 4(c) shows the SS loss reduction performances in order from best to worst were

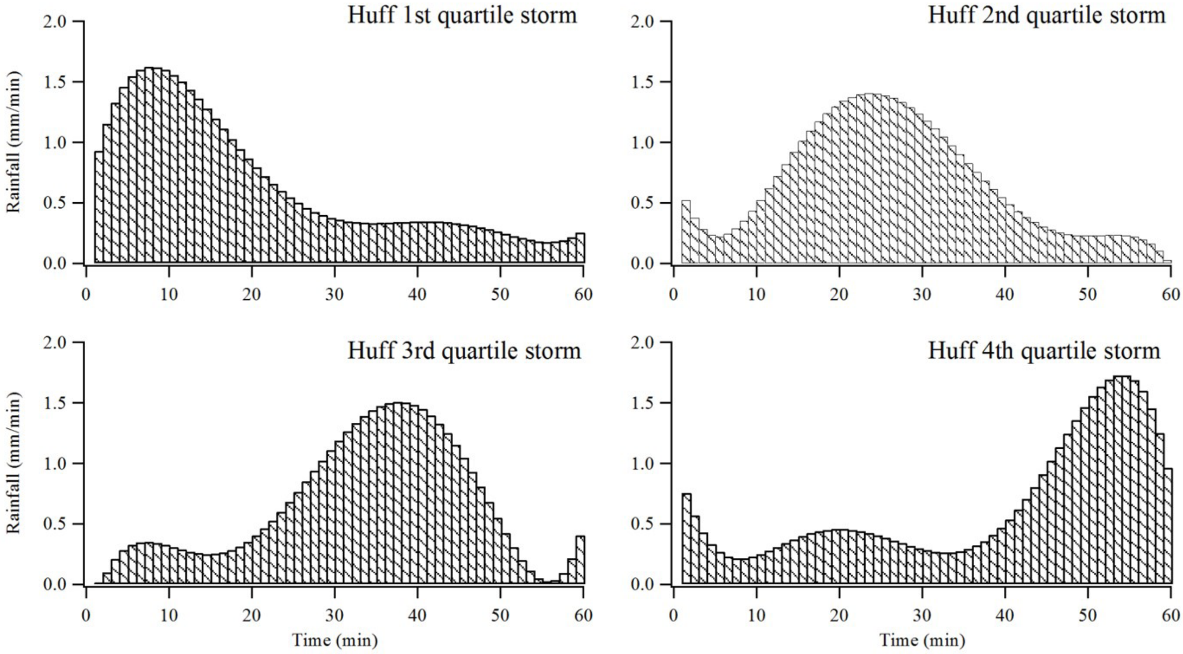

Fig. 2. Four different (synthetic) rainfall time series generated from the Huff quartile distributions (which represent the quarters of the peak rainfall intensity) for 1-h storm duration in a two-year return period in Gwangju City.

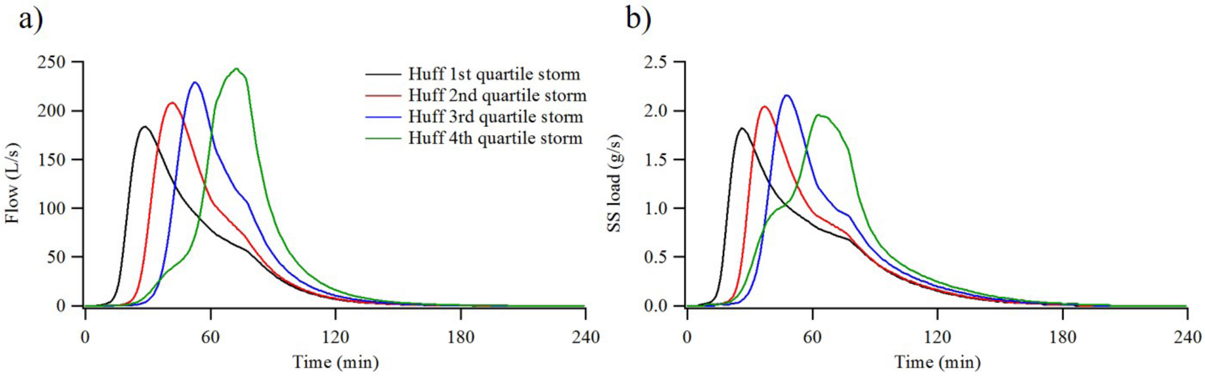

Fig. 3. Characteristics of (a) influent flow rate and (b) SS load provided from the sub-catchment outlet to aggregate LID according to the four rainfall time series generated.

rain barrel, infiltration trench, and vegetative swale. These patterns can be explained by the fact that SS concentration was usually high at the beginning of surface runoff irrespective of the timing of peak runoff [24].

Table 3
Period of time interval (min) between base case and various LID applications (single and aggregate LID scenarios)

Types		First quartile	Second quartile	Third quartile	Fourth quartile
Single	Rain barrel	12	6	4	1
	Infiltration trench	6	3	2	1
	Vegetative swale	1	0	0	0
Aggregate LID scenarios	S1	23	16	15	12
	S2	27	17	20	11
	S3	25	14	15	12
	S4	25	15	19	11
	S5	28	18	20	12
	S6	25	16	25	11

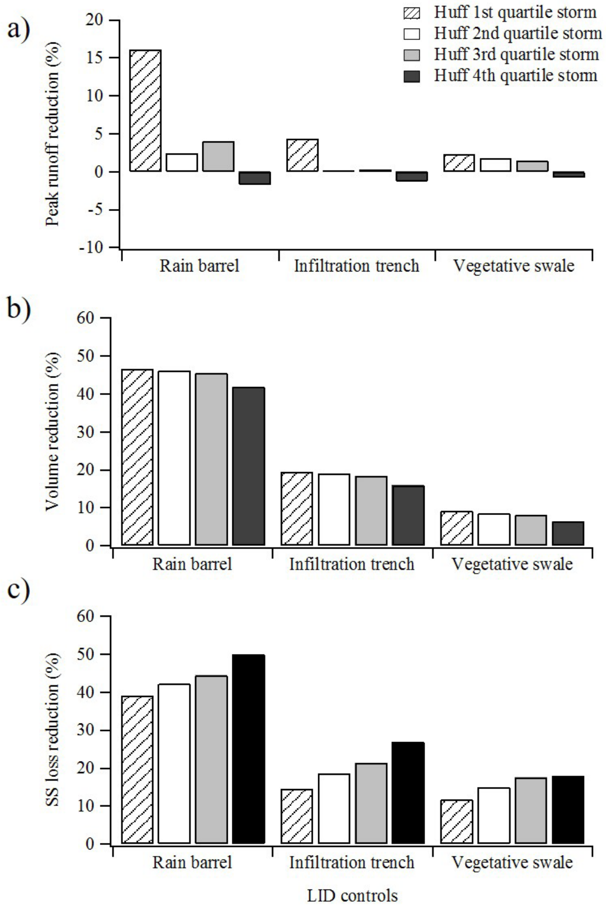

Fig. 4. Performance comparison of individual LID (i.e., rain barrel, infiltration trench, and vegetative swale) for four different rainfall time series in terms of (a) peak runoff reduction, (b) volume reduction, and (c) SS loss reduction.

3.3. Effective LID treatment train

Table 3 shows the difference of delay in peak timing of runoff between the base case and the aggregate LID scenarios. All the aggregate LID scenarios had the effect of a delay in peak timing, regardless of storm pattern. This effect was prominently featured in the first quartile, in which the time-to-peak of storm occurred earlier than in the other quartiles for all the aggregate LID scenarios. Also, the delay in peak timing shortened with each successive quartile, except for the third quartile. When we compared this effect among the different aggregate LID scenarios, we found that the scenario arranged in order of infiltration trench-vegetative swale, rain barrel (S5) appeared as the most effective aggregate LID for all the storm patterns.

Fig. 5 presents the reduction effects of peak runoff, runoff volume, and SS loss of LID treatment train scenarios for the four quartile storms. As can be seen in Fig. 5(a), the peak runoff reduction rates of the six scenarios vary by storm pattern. The peak runoff reduction rates of scenario S1, S2, S3, and S5 decreased with the time-to-peak of storm delay. Also, the reduction rates dropped drastically in the fourth quartile for all scenarios. The aggregate LID scenarios did not fully

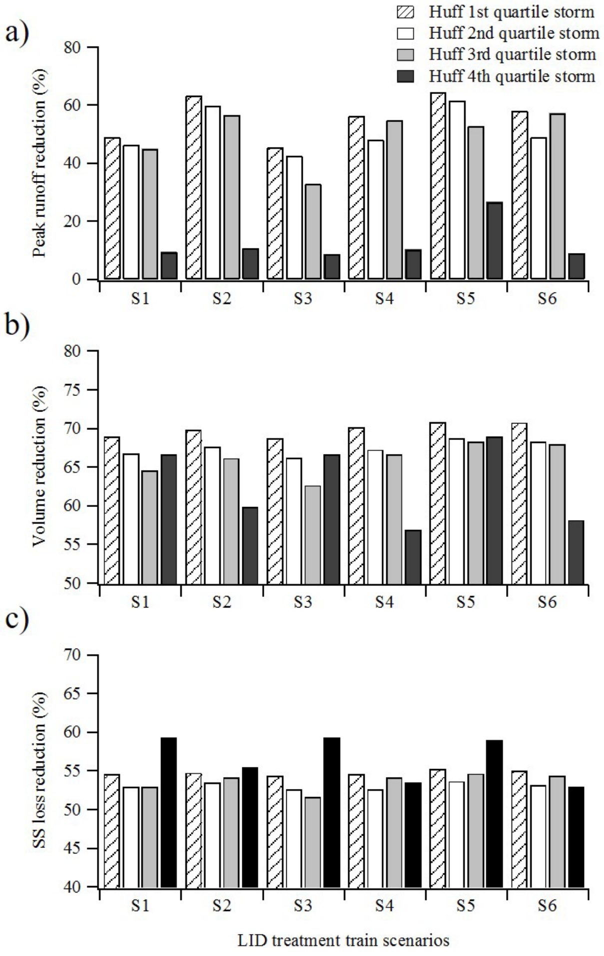

Fig. 5. Performance comparison of various treatment train scenarios of six aggregate LIDs (S1–S6) for four different rainfall time series in terms of (a) peak runoff reduction, (b) volume reduction, and (c) SS loss reduction.

catch peak runoff in the fourth quartile because they were already saturated by the surface runoff that had entered the LID treatment train system before the receiving peak storm. For S5, however, the peak runoff reduction rate for the fourth quartile was more than double that of the other scenarios. As a result, S5 was verified as the most effective LID treatment train in terms of peak runoff reduction.

Fig. 5(b) presents the volume reduction rates of the aggregate LID scenarios for the four quartile storms. These were over 58% regardless of scenario or storm pattern. These simulation results were included in the range of volume reduction based on field monitoring of an aggregate LID system in China [25]; the vegetative swale and bio-retention cell in their study showed the reductions by 9%–74% and 47%–80%, respectively, for 10 storm events. In our study, volume reduction showed similar features that declined slightly in all aggregate LID scenarios as time-to-peak of storm occurred later from the first to third quartiles. In the case of the fourth quartile, the volume reduction rates were distinctly different among the scenario. Considering the simulation results for all the quartile storms, S5 showed higher and more consistent volume reduction rates than did the others, for all storm patterns.

Fig. 5(c) shows the SS loss reduction rates according to aggregate LID scenarios in the different storm patterns. The SS loss reduction rates for all scenarios were 52%–60% regardless of storm pattern. This type of SS loss reduction was similarly observed by previous field studies [25–28]. Focusing on the differences of rates according to storm pattern, these decreased in the order of first, third, and then second quartile in all the scenarios except for S3. Regarding the fourth quartile, two groups could be identified: those with more than 59% (S1, S3, and S5) and those with less than 56% (S2, S4, and S6). Among all quartile storms, S5 showed a relatively high performance for reducing the SS loss from urban catchment. As a result, S5 is recommended as the most effective serial arrangement for urbanized sub-catchment, because it showed relatively consistent performances in peak runoff reduction, volume reduction, and SS loss reduction in the various storm patterns.

4. Conclusion

Using the SWMM, this study analyzed the impacts of LID treatment train design on time-to-peak, peak flow, total runoff volume, and SS loss in an urbanizing catchment with different storm patterns. From this study, we obtained the following results.

- In the base case of no LID controls on study catchment, the duration time of runoff, total runoff volume, and peak flow increased with time-to-peak of storm delay even if individual storms had the same intensity and duration. Whereas, time interval between peak rainfall and peak flow was shorted as time-to-peak of storm delay.
- Among individual LIDs, rain barrel showed the most effective performances for peak runoff reduction, volume reduction, and SS loss reduction across four quartile storms.
- Of the six aggregate LID scenarios, S5 (in the order vegetative swale–rain barrel–infiltration trench) appeared as the most effective serial arrangement with regard to peak runoff reduction, volume reduction, and SS loss reduction considering the four quartile storm patterns.

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