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Analysis on the integrated effects of stormwater management and economic benefits in an urban area using low impact development techniques

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ABSTRACT

The application of low impact development (LID) techniques preserves the predevelopment hydrologic environment and minimizes the effects of urbanization by reducing impervious areas and increasing green areas. The LID method also utilizes decentralized stormwater management approaches that attempt to manage stormwater at the location where rainfall occurs. The purpose of this study is to demonstrate the integrated effects of the LID technique for stormwater management such as flood control, improvement of water balance, and reduction of nonpoint source pollution by comparing it with conventional development methods. The economic efficiency of the LID method was also analyzed. These analyses were conducted for the Songsan Green City in the Republic of Korea, which is the construction site for a new urban area. The results show that flood peak flow and runoff volume were decreased by 4.81% and 8.37%, respectively, by applying the LID technique. Evapotranspiration and infiltration with the LID method were increased by 1.1% and 2.6%, respectively, compared with the conventional development method. The removal efficiency for nonpoint source pollution with the LID method was also 14.6% higher than with the conventional development method. Furthermore, the construction cost of the LID method was 9% lower than the cost of the conventional development method. These results show that the LID method is superior to the conventional development method in terms of stormwater management and can also reduce construction costs.

Keywords: Low impact development; Stormwater management; Construction cost; SWMM

1. Introduction

The increase in impervious areas due to watershed development distorts the hydrologic cycle of the watershed by increasing direct runoff and nonpoint source pollution loads, and reducing evapotranspiration and infiltration from the ground surface during rainfall. Low impact development (LID) is an alternative approach to improve stormwater management, which imitates the natural hydrology of a site by enhancing hydrologic controls such as infiltration, evaporation, and storage of runoff close to its source [1]. Use of these techniques can help reduce off-site runoff and ensure adequate groundwater recharge [2]. In fact, many countries are moving toward this type of decentralized stormwater management; typical examples include Sponge City in China [3] and water sensitive urban design (WSUD) in Australia [4].

LID strategies are structural stormwater best management practices (BMPs) and planning techniques that are intended

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to reproduce predevelopment hydrologic conditions by reducing impervious surfaces and infiltrating, evaporating, and storing stormwater runoff using native or improved soils, vegetation, and bioengineering [5]. In traditional stormwater management, water is typically moved off-site as quickly as possible to a centralized facility, such as a pond or a local tributary. LID, however, treats rainfall on-site by attempting to integrate control into site and building design to maintain hydrological function [6]. Therefore, the LID-BMPs planning process often needs to involve considerations of the relevant urban development planning schemes, such as urban master planning, land use planning, landscape planning, drainage system planning, and water pollution control planning [7].

Recently, various studies on LID methods have been carried out. These studies have analyzed the effect of LID on water quantity. Alfredo et al. [8] found that green roofs can delay and prolong roof discharge and reduce peak flow by 30%–78% compared with a standard roof. Chapman and Horner [9] analyzed the effect of a bio-retention facility located street-side, and found that runoff was reduced by 26%–52% in real weather conditions. Lee et al. [10] found that LID facilities in the Asan Tangjung New Town reduced the peak flow of floods with 50–100-year return periods by approximately 7%–15%. Qin et al. [11] showed that vegetated swales, green roofs, and permeable pavement are more effective for flood reduction than conventional drainage systems. Zahmatkesh et al. [12] found that LID methods had the potential to reduce increased watershed runoff due to climate change. A number of studies on the effectiveness of LID methods for pollutant removal have also been conducted [13–18].

However, most previous studies have focused only on the structural properties of LID techniques and have analyzed their effect on water quantity or quality by applying the LID method. In addition, the hydrological performance and benefits of green infrastructure (GI) practices have been demonstrated by numerous laboratory scale, in situ scale, and microscale studies [19]. In contrast, this study investigated not only the structural methods but also nonstructural methods including a large basin-scale distributed drainage system. Moreover, the stormwater management effect of the LID method was quantitatively analyzed in terms of flood control, water balance, and water quality, and compared with conventional development methods. Economic benefits of the LID method were also evaluated in comparison with conventional development methods. Many researchers have emphasized that it is important and necessary to determine the most cost-effective selection, size, and placement of LID facilities to accomplish the overall development goals and objectives [7,20–22].

In this study, the stormwater management model (SWMM) Ver. 5.1 [23] developed by the US Environmental Protection Agency (US EPA) was used to compare stormwater management for conventional development methods and LID techniques. SWMM has been widely used for studies and design of urban stormwater management because it can simulate watershed runoff events as well as perform continuous simulations and water quality simulations with LID facilities such as bio-retention, vegetative swales, infiltrative trenches, green roofs, and rain barrels. Examples of recent studies that have used SWMM to analyze the effects of LID can be found in Refs. [24–27].

Several sites in the Songsan Green City in the Republic of Korea were monitored and used to compare stormwater management with conventional development methods and LID techniques. The effects on flood control, the hydrologic cycle, and removal of nonpoint source pollution were quantitatively analyzed using SWMM for conventional development methods and LID techniques, and their economic efficiency was also evaluated by comparing construction costs.

2. Study method

2.1. Study area

The study area is a part of the Songsan Green City project site, which is being promoted as part of the Shihwa district development project in the Republic of Korea. The Songsan Green City Project aims to create a rational city that considers nature, the environment, and humanity by efficiently utilizing the large-scale tidelands created by the construction of the Shihwa Dike, while preserving the ecological environment around Shihwa Lake.

Fig. 1 shows a land use map for the eastern area of the Songsan Green City project site, which is the subject area for this study. The study area was planned to be a low-density ecological residential complex with a planned population of 20,000. The development area is 354.34 ha, in which 44% of the residential complexes and 38% of the parks and green areas are eco-residential complexes. Therefore, it is easy to apply LID techniques by utilizing these green areas.

2.2. Conventional development and low impact development

2.2.1. Drainage system

Originally, a centralized drainage system with four main channels was adopted as a conventional development method at the study site (Fig. 2(a)). In contrast, the LID concept pursues a distributed drainage system. Thus,

Fig. 1. Land use in the study area.

(a) (b)

Fig. 2. Comparison of stormwater drainage systems. (a) Conventional development and (b) low impact development.

two additional smaller drainages were considered for the distributed drainage system, and runoff from the areas immediately adjacent to Shihwa Lake and streams were designed to drain directly to the outfall. This scheme, which takes into account the various drainage directions of stormwater pipes, does not increase the size or length of the pipes (Fig. 2(b)).

2.2.2. Reduction in nonpoint source pollution

The Ministry of Environment in the Republic of Korea, in accordance with Article 53 of the Water Quality and Water Ecosystem Conservation Act, is implementing a nonpoint source pollution reporting system to enforce the establishment of nonpoint source pollution reduction facilities for development projects, which can discharge nonpoint source pollutants or wastewater [28].

Thus, there were originally 18 manufactured treatment devices (MTDs) for stormwater planned in the study area under the conventional development scheme. However, this study planned the construction of vegetative swales and artificial wetlands to apply LID techniques using the green space in the eastern area of the Songsan Green City. In addition, infiltration inlets were also planned for installation on the roadsides. Ultimately, 12 of the stormwater MTDs were replaced with natural stormwater treatment facilities in the LID scheme.

The total length of the vegetative swales installed in the study area was 7,000 m, and most of the rainfall runoff from the watershed flows into these vegetative swales. The outflows from the vegetative swales then enter 17 artificial wetlands. Initial rainfall of less than 5 mm is stored or infiltrated by these artificial wetlands. Meanwhile, 350 infiltration inlets were planned on the roadside.

2.3. SWMM simulation method

2.3.1. SWMM composition

The SWMM was used to simulate the water quantity, quality, and balance in the study area planned according to the conventional development method and the LID method. The SWMM was revised to analyze the hydrologic effects of applying LID stormwater management facilities [28].

Figs. 3(a) and 3(b) show the composition of the SWMM with the conventional development and LID methods,

(a) (b)

Fig. 3. SWMM compositions for the Songsan Green City. (a) Conventional development and (b) low impact development.

respectively. Table 1 lists the number of subcatchments, nodes, and conduits in the SWMM for each development method.

2.3.2. Simulation condition of the SWMM

The input data for the SWMM is classified into physical and hydrologic parameters. The physical parameters include the area and the slope of subcatchments, which were estimated using a digital map, and the dimensions of channels (pipes), which were determined from design reports. The width of the subcatchments is a hydrologic parameter and was also determined using a GIS program, as the width can be objectively estimated with recommended estimation processes [29]. Other hydrological parameters were estimated based on the SWMM manual and previous studies (Table 2).

Table 3 summarizes the meteorological data and simulation methods used for the SWMM. The meteorological data for the study area includes the hourly rainfall and average monthly evaporation data from the Suwon Regional Meteorological Office. A nonlinear storage equation and kinematic wave model were used for watershed routing and channel routing, respectively. The Green-Ampt equation was used for the infiltration method.

Watershed runoff event simulations and watershed runoff continuous simulations were performed with the SWMM to compare the stormwater management effects and efficiency in reduction of nonpoint source pollution between the conventional development method and LID technique. Table 4 summarizes the rainfall duration and time interval, as well as the time intervals for watershed routing and channel routing in each simulation method.

In general, models must be calibrated and verified o to derive accurate results. However, there was no monitoring data available for the study area, so calibration and verification of the model were not performed. This is, therefore, a limitation of this study. However, we aimed to analyze the relative differences rather than absolute indicators of the effects of stormwater management with LID and conventional methods. In addition, the physical parameters of the model (input data for the subcatchments and channels) were applied consistently, and the process parameters in the SWMM were estimated objectively from the manual and references to reduce errors in the model configuration. Although calibration and verification of the model were not performed in this study, it is still believed to be a valid method for producing the intended results.

Table 1
Number of SWMM subcatchments, nodes, and conduits for conventional and low impact development schemes

Classification	Conventional development	Low impact development
Subcatchments	362	513
Nodes	366	565
Conduits	362	576

3. Results

3.1. Watershed runoff event simulation

To consider the design flood of the target watershed, the rainfall depth used for flood analysis was the 30-year

Table 2
Major process parameters of the SWMM

	Classification	Value	Remark/Reference
Subcatchment	Roughness	Impervious: 0.015, pervious: 0.25	CDM Smith [30]
	Depression storage (mm)	Impervious: 2.54, pervious: 5.08	Rossman [29]
Infiltration equation	Hydraulic conductivity (mm/h)	3.30	Soil group: loam
	Suction head (mm)	88.90	Rossman [29]
Groundwater	Porosity	0.463	Soil group: loam
	Wilt point	0.116	Rossman [29]
	Field capacity	0.232	
Channel	Roughness	Pipe: 0.012 Swale or open channel: 0.04	Rossman [29]

Table 3
Meteorological information and simulation methods

Meteorological information		Simulation method	
Rainfall and evaporation station	Suwon Regional Meteorological Office	Watershed routing method	Nonlinear storage equation
Rainfall data	Hourly data	Channel routing method	Kinematic wave
Evaporation data	Monthly averages	Infiltration method	Green-Ampt equation

Table 4
Rainfall duration and time interval for the simulations

Classification of simulation		Rainfall duration	Time interval		
			Rainfall	Watershed routing	Channel routing
Continuous	Water balance	11 years	1 h	1 h	1 h
	Water quality	11 years	1 h	1 h	1 h
Event	Design flood	4 h	5 min	5 min	1 min

frequency probability rainfall for the Suwon Regional Meteorological Administration. The critical rainfall duration of the watershed was 240 min, and the probability rainfall depth for the duration was 171.5 mm.

Fig. 4 shows flood hydrographs at the outfalls for the conventional development method and LID method. The locations of the outfalls are shown in Fig. 3. Generally, the flood hydrographs obtained with the LID technique tended to be delayed by 4–5 min, depending on the outfall, compared with those obtained for the conventional development method. This observed lag with the LID technique is attributed to the increased water storage, infiltration, and roughness coefficient resulting from the artificial wetlands and vegetative swale. Fig. 4 also shows that the peak floods tended to decrease slightly with application of the LID technique.

Table 5 lists the results of a quantitative analysis of the design flood event. It was determined that the total peak flow and total runoff volume at outfalls (ⓐ–ⓓ) were reduced by 4.81% and 8.37%, respectively, with application of the LID technique. In particular, the peak flow rates at outfalls ⓑ, ⓒ, and ⓓ decreased by 3.10%, 4.35%, and 8.47%, respectively, with application of the LID method. However, the peak flow at outfall ⓐ was increased by 1.05% by applying the LID technique, which is due to the increased drainage area resulting from the change from the conventional method to the LID method. In addition, the runoff volume at outfalls ⓐ–ⓓ decreased by 0.25–18.36% with application of the LID

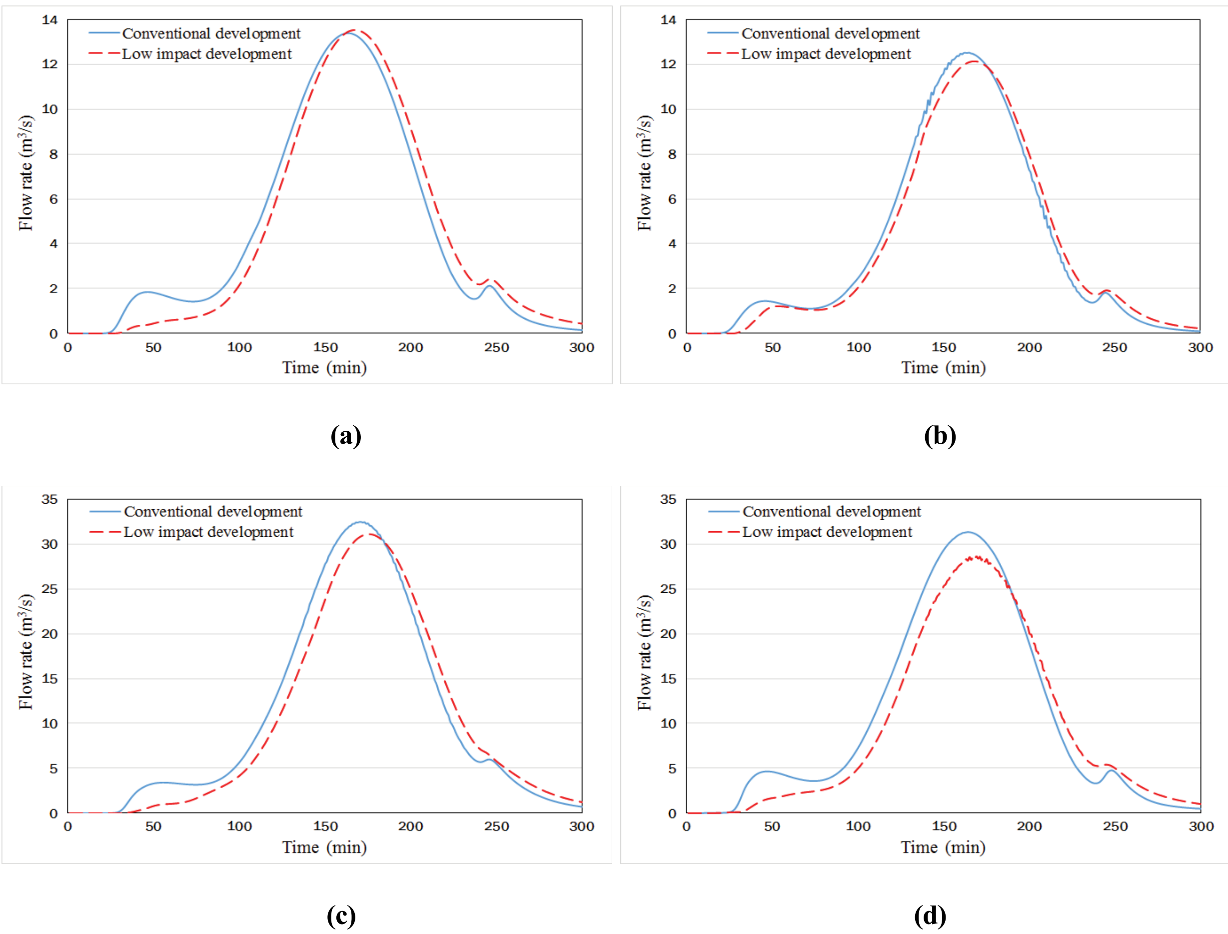

Fig. 4. Flood hydrographs for the different development methods. (a) Outfall ⓐ, (b) outfall ⓑ, (c) outfall ⓒ, and (d) outfall ⓓ.

Table 5
Analysis results for the watershed runoff event simulation

Outfall	Peak flow			Total volume		
	Conventional development (m^3/s)	Low impact development (m^3/s)	Reduction rate (%)	Conventional development (m^3)	Low impact development (m^3)	Reduction rate (%)
ⓐ	13.39	13.53	–1.05	80,009	79,812	0.25
ⓑ	12.52	12.14	3.10	71,834	70,598	1.72
ⓒ	32.52	31.11	4.35	195,255	188,966	3.22
ⓓ	31.35	28.70	8.47	213,458	174,259	18.36
Total	89.78	85.46	4.81	560,556	513,635	8.37

method. The higher runoff reduction rate at outfall ⓒ is due to the larger area of the planned artificial wetlands.

3.2. Watershed runoff continuous simulation

A watershed runoff continuous simulation was conducted for the water balance analysis and to evaluate the reduction efficiency of nonpoint source pollution. The simulation period was from 2002 to 2012. The meteorological data included hourly rainfall and average monthly evaporation from the Suwon Regional Meteorological Office.

3.2.1. Water balance analysis

Fig. 5 shows the relative proportions of surface runoff, infiltration to the watershed and channels, and evapotranspiration obtained from the results of the 11-year watershed runoff continuous simulation.

Evapotranspiration and infiltration were increased by 1.1% and 2.6%, respectively, with the LID method compared with the conventional development method. Therefore, surface runoff was decreased by approximately 4% with the LID method. In other words, the LID method improved the water balance somewhat compared with the conventional development method.

LID techniques include source control approaches and the use of microscale integrated management practices such as green roofs, porous pavement, and rain barrels (cisterns); however, these were not considered in this study. In the future, introduction of these LID techniques within the neighborhood site can be expected to produce better results for the water balance.

3.2.2. Efficiency analysis of nonpoint source pollution reduction

The SWMM uses conceptual formulas for the water quality simulation, which includes the buildup and wash off of pollution on the ground surface [31]. The event mean concentration (EMC) method, which includes only the wash off, was used to analyze the efficiency of nonpoint source pollution reduction in this study. The EMC was arbitrarily set at a suspended solids (SS) concentration of 100 mg/L because there was no measured data available for the study area. The purpose of this study is not a quantitative evaluation, but rather a relative comparison of the reduction in nonpoint source pollution between the conventional development method and the LID method. Thus, this assumption can be valid for obtaining the desired results of this study.

Table 6 summarizes the simulated total yield load of SS and the reduction amount obtained with the different development methods during 2002–2012. The conventional development method planned with MTDs reduced the total yield SS load by 51.1%, while the LID method with vegetative swales and artificial wetlands reduced the total yield SS

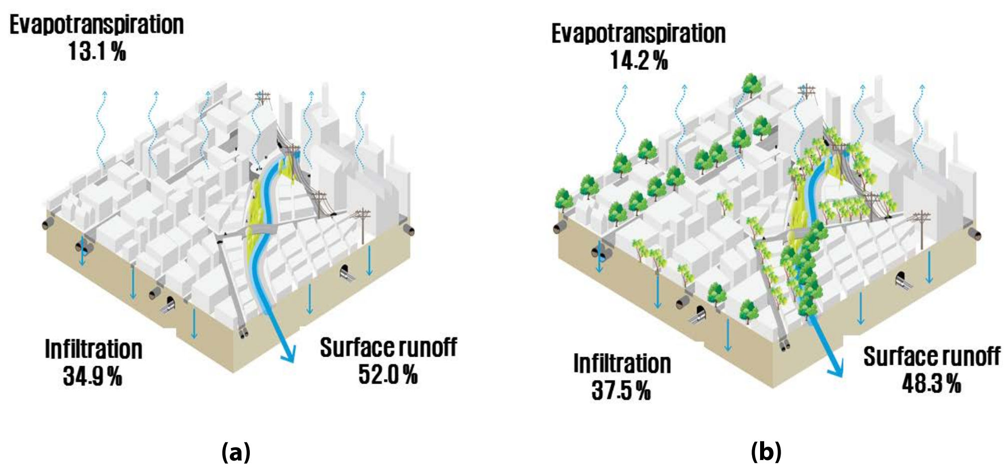

Fig. 5. Results of the hydrologic cycle analysis. (a) Conventional development and (b) Low impact development.

Table 6
Analysis of SS pollutant load and reduction amount

Classification		Conventional development (kg)	Low impact development (kg)
Total yield load of SS		7,349,840	
Reduction amount	Vegetative swale	–	3,121,163
	MTDs/Constructed wetland	3,756,624	1,707,368
	Sum	3,756,624	4,828,531
Final discharge load of SS		3,593,216	2,521,309

load by 65.7%. Fig. 6 shows the monthly average yield load of SS for the conventional development method and the LID method.

3.3. Analysis of economic benefit

The conventional development method has a centralized drainage system and MTDs, whereas the LID method has a distributed drainage system and natural stormwater treatment facilities. Thus, the construction cost for the two methods will differ, and rough costs were compared in this study (Table 7). The sketchy cost is not the total cost, but the direct (purity) construction cost that considers the cost of materials and labor expenses.

Twelve of the 18 MTDs were replaced with vegetative swale, artificial wetlands, and infiltration inlets for street drainage in the LID method. Thus, the cost of facilities for reduction of nonpoint source pollution with the LID method was increased by 63.6% compared with the conventional development method. This means that the natural facilities in the LID method are more expensive than the MTDs.

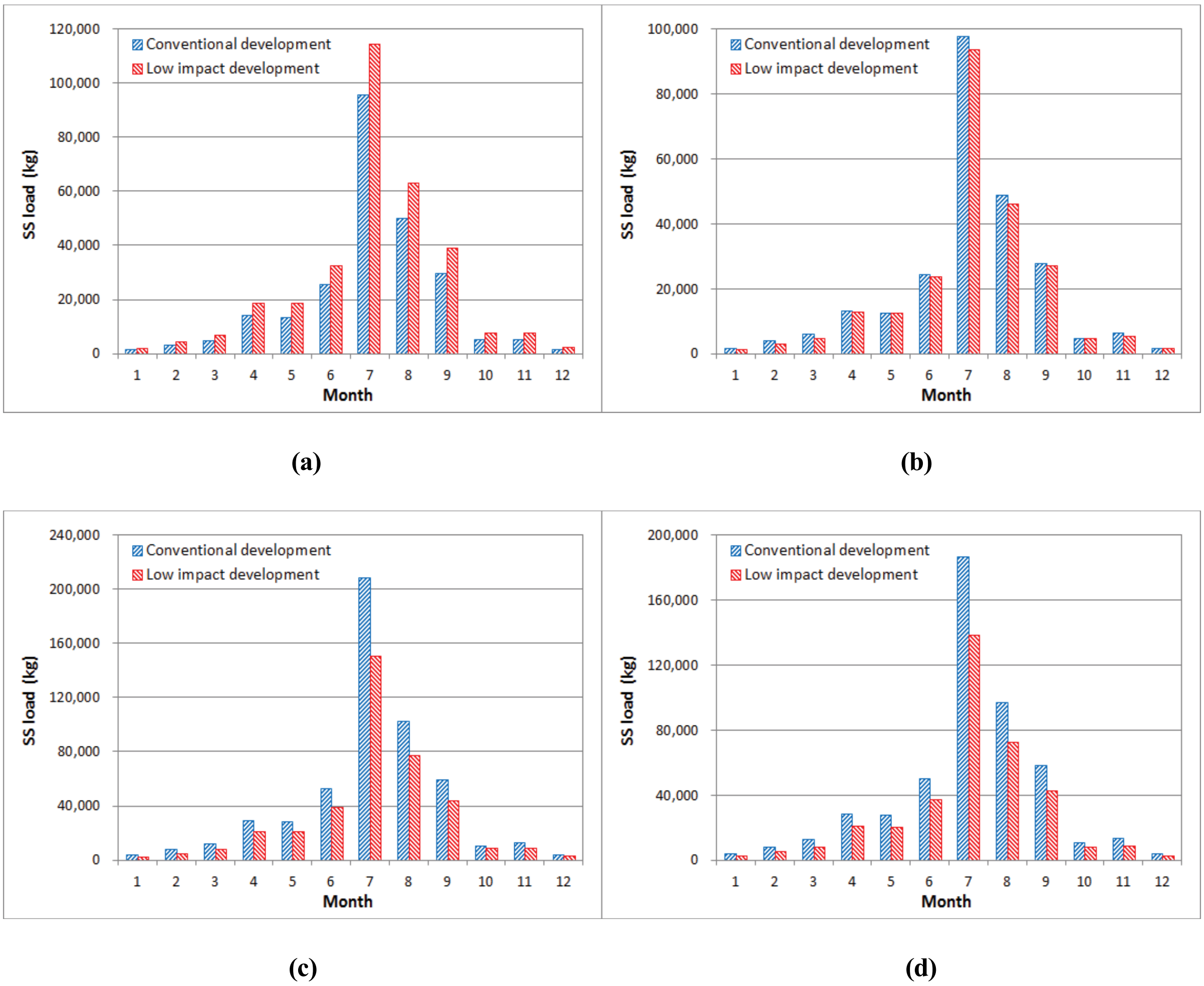

Fig. 6. Comparison of monthly SS pollutant load for the different development methods. (a) outfall ⓐ, (b) outfall ⓑ, (c) outfall ⓒ, and (d) outfall ⓓ.

Table 7
Comparison of cost between conventional and low impact development methods

Classification	Item	Conventional development (①)			Low impact development (②)			Difference (②–①)	
		Quantity	Unit	Cost (thousand won)	Quantity	Unit	Cost (thousand won)	Cost (thousand won)	Percent (%)
Reduction facility for nonpoint source pollution	Vegetative swale	–	m	–	7,000	m	752,000	752,000–	
	Constructed wetland	–	m^2	–	29,000	m^2	2,450,112	2,450,112	
	Infiltrative street inlet	–	Piece	–	350	Piece	210,000	210,000	
	Facilities type for nonpoint source reduction	18	Piece	2,832,000	6	Piece	1,220,000	–1,612,000	
	Sub total			2,832,000			4,632,112	1,800,112	+63.56
Pipe	Circular pipe	35,000	m	6,457,000	39,000	m	4,950,000	–1,507,000	
	Rectangular pipe	2,100	m	1,821,000	570	m	557,700	–1,263,000	
	Sub total			8,278,000			5,507,700	–2,770,300	–33.47
Total				11,110,000			10,139,812	–970,188	–8.73

However, because stormwater pipes were replaced with vegetative swale and a distributed drainage system was adopted in the LID method, the installation cost for stormwater pipe was decreased by 33.5%. Therefore, the integrated total cost was decreased by 8.7% by changing from the conventional development method to the LID method because the construction cost of stormwater pipe is a large portion of the integrated total cost.

These results are similar to a report published by the US EPA [32], which compared the economics of stormwater management for the two methods. In fact, the US EPA [32] determined that in most cases in their analysis, the LID method reduced construction costs by 15%–40% compared with traditional methods. Similar to this study, the US EPA [32] study demonstrated that LID techniques significantly reduced the installation costs for stormwater pipes compared with traditional methods.

4. Conclusion

This study focused on urban stormwater management with LID methods incorporating a distributed drainage system and natural stormwater treatment facilities. The LID method was compared with a conventional development method with a centralized drainage system and MTDs for the study area. In introducing the LID method, it was planned to reduce the length and size of stormwater pipes by adopting both structural and nonstructural techniques that have not been attempted in previous studies. The SWMM was used to compare the LID method and the conventional development method by simulating water quantity and quality.

The effects of the LID method on stormwater management were evaluated based on flood control, improvement of the hydrologic cycle, and reduction of nonpoint source pollution. The results showed that the LID method was superior in all aspects of stormwater management compared with the conventional development method. In particular, the flood peak flow and runoff volume were decreased by 4.81% and 8.37%, respectively, with the LID technique. Evapotranspiration and infiltration with the LID method were increased by 1.1% and 2.6%, respectively, compared with the conventional development method. The removal efficiency of nonpoint source pollution with the LID method was also 14.6% higher than with the conventional development method. Construction costs were compared for the two methods to determine whether the stormwater management effects observed with the LID method were due to excessive introduction of natural facilities. The results showed that the construction cost for the LID method was 9% lower than the cost of the conventional development method.

This study is distinguished from previous studies because it includes not only the structural LID techniques focused on facility installation but also the nonstructural LID techniques considering conceptual methods. The usefulness of the LID method was demonstrated with a quantitative evaluation of stormwater management effects and economic analysis in comparison with the conventional development method. As this study is a case study on application of the LID method, it may be used to guide various studies and design with the LID method in the future.

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