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An Effectiveness Study on the Use of Different Types of LID for Water Cycle Recovery in a Small Catchment

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Abstract: Low-Impact Development (LID) is alleviating the water cycle problems that arise from an increasing impervious surface area caused by urbanization. However, there is insufficient research on the application and analyses of LID techniques that are used for studying the management goals for water cycle restoration. The present study applied various LID techniques, utilizing the stormwater management model (SWMM) in the Naju-Noan Waterfront Zone Construction Project and studying its effects, aiming to restore the runoff that had increased due to urbanization to its pre-development state. The five LID techniques used in the analysis were permeable pavements, bioswales, rainwater gardens, green roofs, and planter boxes, which took up 36.2% of the total area. Our analysis showed that development increased the runoff rate from 39.4% to 62.4%, and LID reduced it to 34.7%. Furthermore, development increased the peak flow from 0.77 m^3/s to 1.08 m^3/s, and the application of LID reduced it to 0.78 m^3/s. An effective reduction in the runoff and peak flow was shown in every recurrence period that was tested, and the bioretention cell type of LID showed the best effectiveness per unit area compared with permeable pavements and green roofs.

Keywords: low-impact development; LID; SWMM; stormwater management; runoff; infiltration

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1. Introduction

Urbanization is a worldwide trend [1,2]. In 2018, 55% of the world population resided in urban areas, and by 2050, it is projected to be 68% [3]. Construction of roads and structures [4] on natural landscapes has rendered these surfaces impervious to vegetation and water, which means that along with climate change, urbanization is a major factor causing urban hydrological change [5,6]. In South Korea, the total percentage of impervious surface increased by a factor of 2.63 from 3.0% in the 1970s to 7.9% in 2012, indicating an accelerating trend [7]. Urban drainage systems, which have drastically increased, exert pressure on water circulation [5] due to increasing runoff, shorter times of concentration, decreased baseflow, and infiltration [1,8,9], and they cause the deterioration of water quality [1]. Conventional urban areas aim for the most rapid rainwater runoff [7], which generally entails high construction costs and excessive draining to downstream regions [10]. Because drainage-based control measures and end-control methods fail to achieve proper rainwater management, it is critical to search for a novel method to control the source of the runoff [10].

Managing rainwater in cities is an essential component of development and has ecological, economic, and social significance [6]. The recent trend of paying attention to climate change, urbanization, and ecology has promoted the need for new rainwater management systems to alleviate hydrologic impact and water quality problems due to urbanization [1,6]. Low-Impact Development (LID) is a new approach to stormwater management [11] which proposes weakening the influence of impervious surfaces on the amount of rainfall runoff and water quality [12]. The basic mechanism of LID, Sustainable Urban Drainage Systems (SUDS), and Water-Sensitive Urban Design (WSUD) are source-reduction approaches that utilize soil, vegetation, and bioengineering to reduce and process rainfall runoff [8].

LID solutions mimic hydrologic conditions that existed before the advent of urban development and thus promote storage, infiltration, and evapotranspiration processes [11]. LIDs include storm water infiltration systems, rain gardens, storm water wetlands, green roofs, and permeable pavements [8,11,13,14]. The use of LID and its spatial pattern can play a key role in reducing the directly connected impervious areas (DCIA) and effective impervious areas (EIA) [8,9], reducing water runoff and peak flow and solving the water quality issue [11]. In addition, it can reduce surface runoff and stream erosion while increasing the recharge of underground streams, which results in urban development that promotes biodiversity and improves river quality [8].

As computational tools are necessary to quantitatively assess the hydrological benefits of LID techniques [14], the development of an integrated model that evaluates the effectiveness of alternative approaches for managing rainwater—LID, for example—is gaining attention [1]. Several models, which include conceptual models such as MUSIC and the SWMM, are being developed to investigate the impact of urban development on rainwater and hydrology and better understand the efficacy of rainfall runoff management strategies [1]. To evaluate the performance of several LID techniques, the Storm Water Management Model (SWMM) of the United States Environmental Protection Agency (USEPA) is being widely used [11]. Released in 1971, the SWMM was developed to include dynamic continuous simulation and water quality and is being extensively used [1]. Fanhua et al. [9] used the SWMM to study the hydrologic response to changes in land use. Anna et al. [11] used continuous simulation to research the role of vegetation LID in alleviating rainfall runoff in urban basins. Sara et al. [15] utilized the LID controls module of the SWMM along with the long-term precipitation and temperature data to simulate the hydrological performance of green roofs. Jiake et al. [16] explored the relationship between the effectiveness of a rain garden and its area percentage using the SWMM. Palla et al. [8] used the SWMM to study the hydrological performance of green roofs. Xie et al. [17] used the SWMM to study the effect of LID with respect to the placement of bioswales and permeable asphalt. These references show that the SWMM is actively being used in a lot of research to verify the efficacy of LID.

Past research centered on the runoff before and after LID application, peak flow, times of concentration, and hydrological analysis of certain LID techniques but failed to propose water management objectives using LID techniques. This research uses several locations in which urban development is underway to compare the runoff before and after the development with a goal of runoff management using LID based on the difference. Scenarios were written and simulated to achieve this goal, and the effect of LID on rainfall runoff management was analyzed under different precipitation conditions to provide guidance for implementing LID in small-scale urban developments in watershed areas.

2. Materials and Methods

2.1. Research Location

For this research, we selected the Naju-Noan Waterfront Zone Construction Project in Naju-si in Jeollanam-do [18], where a waterside village construction project is being constructed under the Special Act on the Utilization of Water Fronts. The southern portion of the site, with an area of 105,494 m^2, features the Yeongsan River, which is one of the four major rivers of Korea. The annual average precipitation of the area is 1374 mm, with the highest being 2020 mm in 1989 and the lowest being 764 mm in 1995. Figure 1 shows the location of the research site, and Figure 2 shows the annual and monthly average precipitation over the last 49 years.

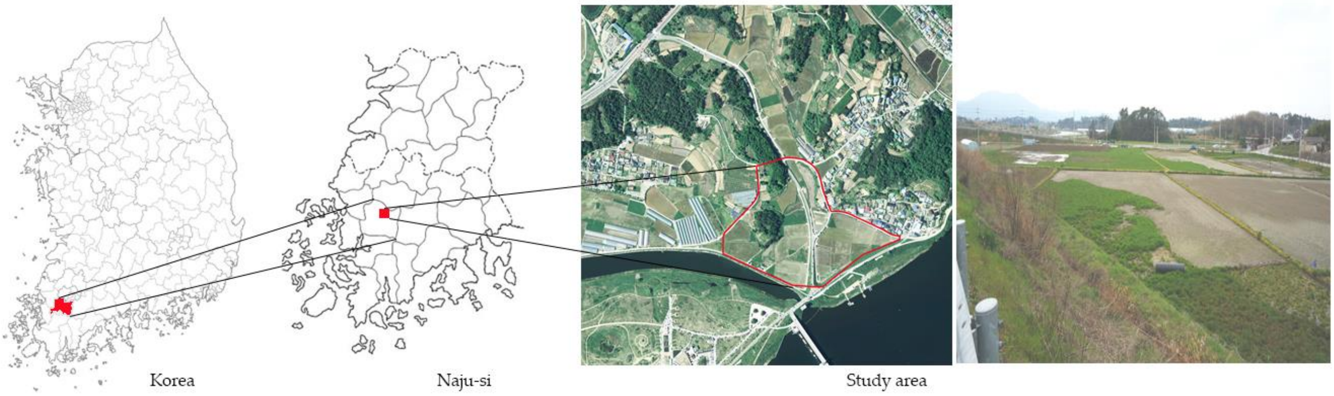
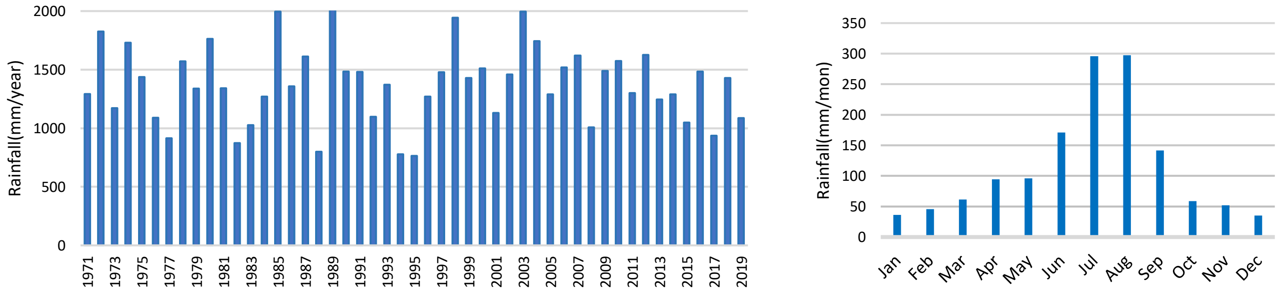


Figure 1. Research site location and landscape.



(a) (b)

Figure 2. (**a**) Annual average precipitation. (**b**) Monthly average precipitation.

As 83% of the research site is used for agriculture and 13% is forest [18], it exhibits a land use that is typical of the Korean waterside region. The development will install residential and commercial districts and is projected to increase the impervious area percentage by more than a factor of 2 from 24% to 59%. The change in land use before and after the development is shown in Table 1.

Table 1. Land use before and after the development.

Before Development (m^2, %)	**Rice Paddy Field**	**Crop Field**	**Coniferous Forest**	**Traffic Area**	**Residential Area**				
	60,618 (57.4)	27,358 (25.9)	13,463 (12.8)	3552 (3.4)	503 (0.5)				
After Development (m^2, %)	**Houses**	**Roads**	**Green**	**Accommodations**	**Cultural District**	**Parks**	**Malls in Residential Complex**	**Parking Lot**	**Other**
	37,835 (35.9)	22,248 (21.1)	10,700 (10.1)	10,554 (10.0)	8403 (8.0)	7285 (6.9)	6140 (5.8)	1296 (1.2)	1033 (1.0)

The research site is an undeveloped rural region which is likely to experience drastic water cycle disturbance due to development. This increases the significance of rainfall runoff management using LID. In particular, the Yeongsan—one of the four major rivers of Korea—being in the vicinity indicates that urban development imparts a direct and significant influence on the water cycle, with increased flooding and runoff resulting from the formation of larger impervious areas. These factors contributed to its selection as the research site.

2.2. SWMM

To study the hydrological effect of LID implementation, this research utilized the SWMM, whose utility and efficacy have been confirmed for application to rural and urban waterside areas with various LID simulations.

The SWMM was developed by USEPA in 1971 and is currently the most widely used program to simulate rainfall runoff with its hydrology, hydraulic, and water quality modules [17,19]. The SWMM is capable of simulating the rainfall runoff process, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and migration and diffusion of TN, TP, and 6 other pollutants [17]. The SWMM has served various purposes, including assessing the performance of the rainfall green infrastructure [20]. The 2010 version of SWMM5 supports LID modeling, which enables several forms of LID factors using the LID controls [17,21]. The LID controls express the LID factors as a combination of vertical layers, where each layer defines the LID characteristics based on the unit area, and the SWMM tracks the amount of water moving from one layer to another. Figure 3 illustrates a typical bioretention cell, which can be used to model various LID techniques [22].

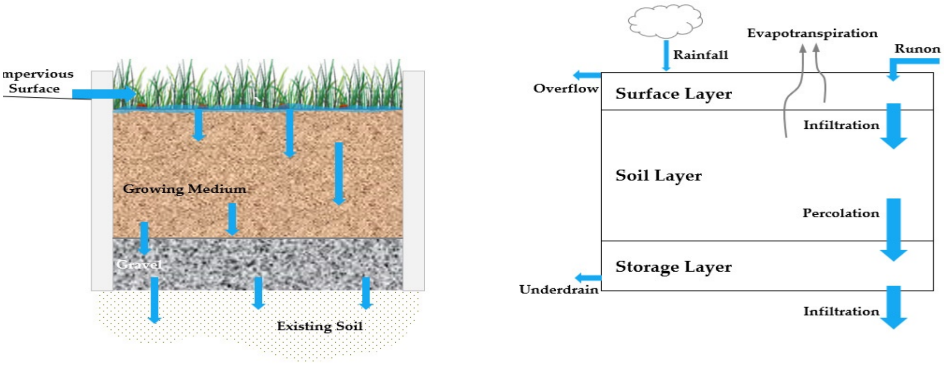
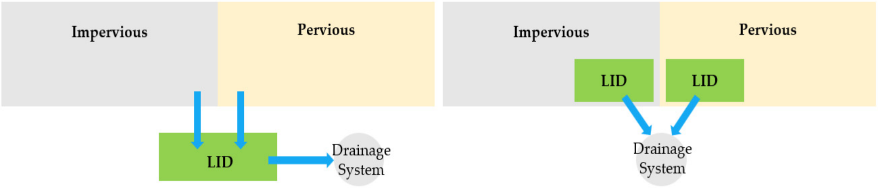


Figure 3. A typical bioretention cell [21].

There exist two methods for placing LID controls into the subcatchment of the SWMM. The first method (Figure 4a) creates a new subcatchment dedicated exclusively to a single LID practice. Under this method, the LID controls may only act in series and not in parallel, because each subcatchment may have only one outlet, whereas the second method (Figure 4b) places one or more LID controls within an existing subcatchment, and the LID controls can only act in parallel [23,24]. In this research, the second method was used.



(a) (b)

Figure 4. LID modeling method 1 schematic (**a**). LID modeling method 2 schematic (**b**) [23,24].

2.3. Precipitation Analysis

The precipitation data for this research, shown in Table 2, were taken from the 1971–2019 clock hour rainfall data of the Gwangju observing station of the Korea Meteorological Administration, which is located closest to the research site and retains the most credible long-term observation data. A portion of the detailed precipitation analysis is given in Table 3.

Table 2. The location of the observing station.

Name of Station	Method of Observation	Address	North Latitude	East Longitude	Elevation (EL. m)	Date of Observation
Gwangju	T/M	Unam-dong, Buk-gu, Gwangju	126-53-29	35-10-22	0.6	1 May 1939

Table 3. Design rainfalls by return periods and rainfall durations.

Return Periods (Year)	Duration (h) and Design Rainfalls (mm)									
	1 h	2 h	3 h	5 h	6 h	9 h	12 h	15 h	20 h	24 h
2	44.3	60.2	69.2	84.1	90.5	104.6	114.2	121.1	130.8	139.6
3	50.1	68.7	79.7	97.4	105.0	122.3	133.6	142.3	153.9	164.5
5	56.5	78.3	91.4	112.1	121.1	142.0	155.3	165.9	179.7	192.2
10	64.7	90.2	106.1	130.7	141.5	166.8	182.4	195.5	212.0	226.9
20	72.5	101.7	120.2	148.5	160.9	190.6	208.5	224.0	243.1	260.3
30	77.0	108.3	128.3	158.7	172.1	204.3	223.5	240.3	260.9	279.5
50	82.6	116.5	138.5	171.5	186.1	221.4	242.3	260.8	283.2	303.5
100	90.1	127.6	152.2	188.8	205.0	244.4	267.6	288.4	313.3	335.8

The design rainfall is the total amount of precipitation for a specific duration. A temporal distribution of precipitation is necessary to examine runoff, where the distribution is an important factor that affects the design flood hydrograph and the peak discharge [25,26]. This research used 3-quantile analysis of the Huff method, as suggested in [25,27,28].

2.4. Model Construction

Parameters like the area, width, and average slope of each subcatchment for constructing the SWMM model were derived by the Digital Elevation Model (DEM), which was created using ArcGis Desktop ver.10.1 with digital maps provided by the National Geographic Information Institute (NGII). To simulate rainfall infiltration, the Soil Conservation Service Curve Number Method (SCS-CN) was selected, where necessary data were provided by the Ministry of Environment [28] based on the Korean land use status. The 30-year (1981–2010) monthly evaporation data provided by the Korea Meteorological Administration were used as input values, as shown in Table 4.

Table 4. Monthly evaporation.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation (mm/mon)	39.6	47.4	84.0	121.8	146.8	143.7	130.4	143.6	107.0	92.7	54.1	41.3

The pipe network and the descriptive data were constructed using the district blueprint. As a result, the research site was subdivided into subcatchments with 71 junction nodes, 70 conduits, and 1 outfall as shown in Figure 5.

Considering the fact that there has been ongoing construction in the research site, the comprehensive runoff coefficient (CRC) method of Table 5 was used for the calibration and validation of the SWMM model [29]. The runoff coefficient of the research site before development was 0.39, which met the CRC requirement of a sparsely populated area (0.3–0.5). The runoff coefficient after development was 0.62, which met the CRC requirement of a densely built residential area (0.5–0.7).

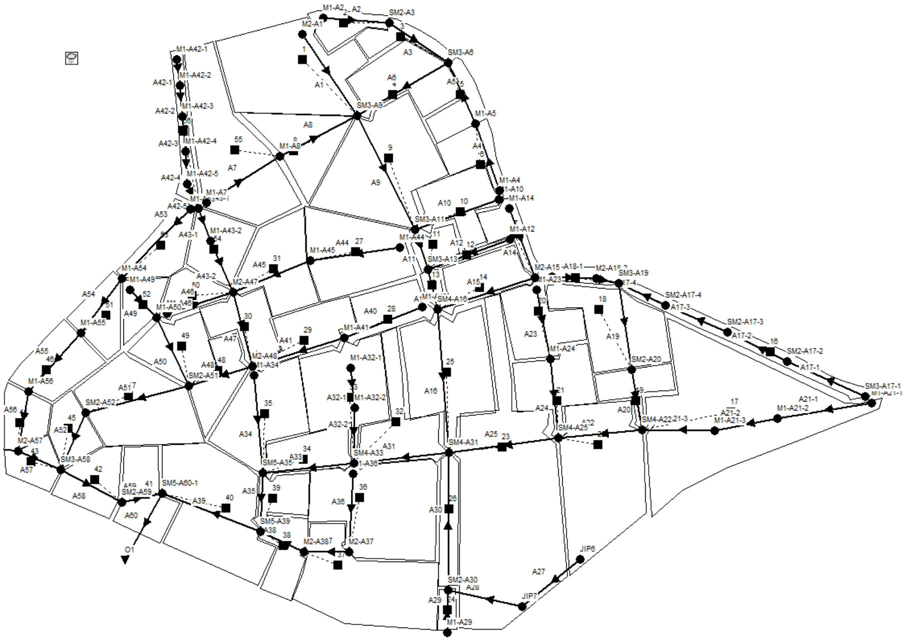


Figure 5. Layout of the drainage system.

Table 5. Empirical values of the regional comprehensive runoff coefficient [29].

Land Use	Type	Comprehensive Runoff Coefficient
built central area	Densely	0.6–0.8
built residential area		0.5–0.7
	Sparsely	0.4–0.6
populated area		0.3–0.5

The five most commonly used LID techniques [8] were deployed based on the land use data and construction guidelines [30], and the deployed LID techniques—permeable pavements, bioswales, rainwater gardens, planter boxes, and green roofs, as listed in Table 6—took up 36.2% of the total area. Bioswales, rainwater gardens, and planter boxes were reported by use of the bioretention cell of the LID control type to enhance infiltration. Figure 6 shows an overview of the deployment of LID techniques.

Table 6. Area of LID techniques.

Constituent	Total	Permeable Pavement	Bioswale	Rainwater Garden	Planter Box	Green Roof
Area (m^2)	38,189	22,946	3589	1634	543	9459
Area percentage (%)	36.2	21.8	3.4	1.5	0.5	9.0
SWMM-LID method	-	Permeable pavement	Bioretention cell	Bioretention cell	Bioretention cell	Green roof

In addition, the LID parameters were selected by referring to the typical values listed in the SWMM user manual [21,22], drawings, specifications, and relevant documents [28,30]. The values of some important parameters are given in Table 7. When specifying the LIDs to subcatchments, the LIDs were assumed to be dry at the beginning of the rain events. In the LID usage editor, the bioswales, planter boxes, and rainwater gardens had their impervious portions treated by LID, and the permeable pavement and green roofs were only treated for direct rainfall.

Figure 6. Overview of the deployment of LID techniques.

Table 7. Parameter values of the LID design.

Layer	Parameter	Unit	Permeable Pavement	Bioswale	Rainwater Garden	Planter Box	Green Roof
Surface	Berm Height	mm		200	300	300	0
	Vegetation Volume Fraction	-		0.1	0.2	0.1	0.2
	Surface Roughness (Manning's n)	-	0.014	0.15	0.24	0.15	0.41
	Surface Slope	%	1.5	1.0	1.0	1.0	0.5
Pavement	Thickness	mm	60	-	-	-	-
	Void Ratio	-	0.2	-	-	-	-
	Permeability	mm/hr	3600	-	-	-	-
Soil	Thickness	mm	40	500	500	500	300
	Porosity	-	0.35	0.52	0.8	0.52	0.6
Storage	Thickness	mm	300	500	500	1000	-
	Void Ratio	-	0.4	0.4	0.4	0.4	-
Drain	Flow Coefficient	-	-	0	0	0	-
	Flow Exponent	-	-	0.5	0.5	0.5	-
	Offset	mm	-	6	6	6	-
Drainage Mat	Thickness	mm	-	-	-	-	50
	Void Fraction	-	-	-	-	-	0.5
	Roughness	-	-	-	-	-	0.3

2.5. Management Goal

Because LID is a technique introduced to restore distorted water circulation systems, it is critical to set a management target through hydrological analysis before and after urban development is carried out [30]. The fundamental direction of setting management targets is comparing the runoff characteristics before or after development to enable the water circulation closest to the pre-development situation. There exist various methods to select targets, which include selecting precipitation such that the cumulative runoff depth is no less than 5 mm, using precipitation percentile analysis, reducing the runoff increase after development, and so on [30]. This research compares and analyzes the runoff before and after development to set the magnitude of the increase as the management target to be reduced via the application of LID techniques. The precipitation data used for the comparison were taken from 1993 (1372 mm), which was closest to the annual average precipitation of the research site (1374 mm).

Furthermore, six recurrence periods were selected in order to perform LID runoff analysis with respect to various precipitation scales. The 2-year, 3-year, and 5-year periods were selected, referring to [26], along with the 10-year, 20-year, and 30-year periods, which were used for the pipe design. As the critical rainfall duration that induces the maximum load on the drainage system has been analyzed [26] and found to be 2 h, the rainfall duration was set to 2 h. The precipitation distribution for the recurrence periods that were used for the simulation is given in Table 8, and the rainfall distribution is shown in Figure 7.

Table 8. Temporal distribution of precipitation for different recurrence periods.

Time Step (min)	2-Year	3-Year	5-Year	10-Year	20-Year	30-Year
0	0.00	0.00	0.00	0.00	0.00	0.00
10	1.62	1.85	2.11	2.43	2.74	2.93
20	3.37	3.84	4.38	5.05	5.69	6.06
30	2.91	3.32	3.79	4.37	4.92	5.25
40	3.54	4.05	4.61	5.31	5.99	6.38
50	5.86	6.68	7.62	8.77	9.89	10.53
60	8.67	9.89	11.27	12.99	14.64	15.59
70	10.40	11.86	13.53	15.57	17.57	18.70
80	10.01	11.42	13.01	14.99	16.90	17.98
90	7.49	8.55	9.73	11.22	12.64	13.45
100	3.95	4.52	5.14	5.92	6.68	7.11
110	1.25	1.43	1.64	1.88	2.12	2.27
120	1.13	1.29	1.47	1.70	1.92	2.05

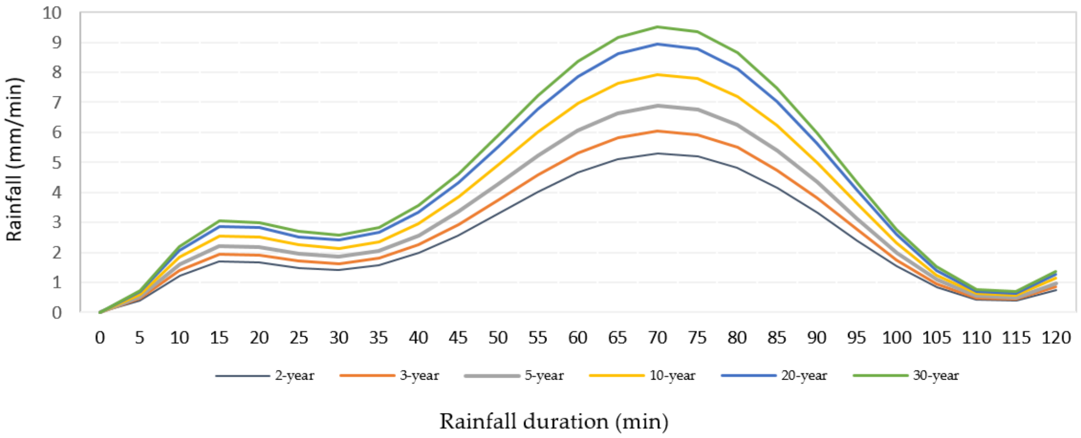


Figure 7. Hyetographs of different recurrence periods with a 2-hour duration.

3. Results

3.1. Hydrological Change

The research site before development mostly consisted of farmlands or forest, which implied that the impervious area would double after it had undergone development into residential or commercial districts. The simulated result of the hydrological changes of the site is given in Table 9, and the rainfall and runoff are shown in Figure 8.

Table 9. Hydrological analysis of the pre- and post-development research site.

Pre or Post	Rainfall (m^3)	Evaporation (m^3, %)	Infiltration (m^3, %)	Runoff (m^3, %)	Peak Runoff (m^3/s)
(1) Pre-Development	144,748 (100.0 %)	20,459 (14.1%)	67,342 (46.5%)	56,947 (39.4%)	0.77
(2) Post-Development		23,354 (16.1%)	31,162 (21.5%)	90,232 (62.4%)	1.08
Difference (2) − (1)	-	2895 (1.9%)	36,180 (25.0%)	33,285 (23.1%)	0.31

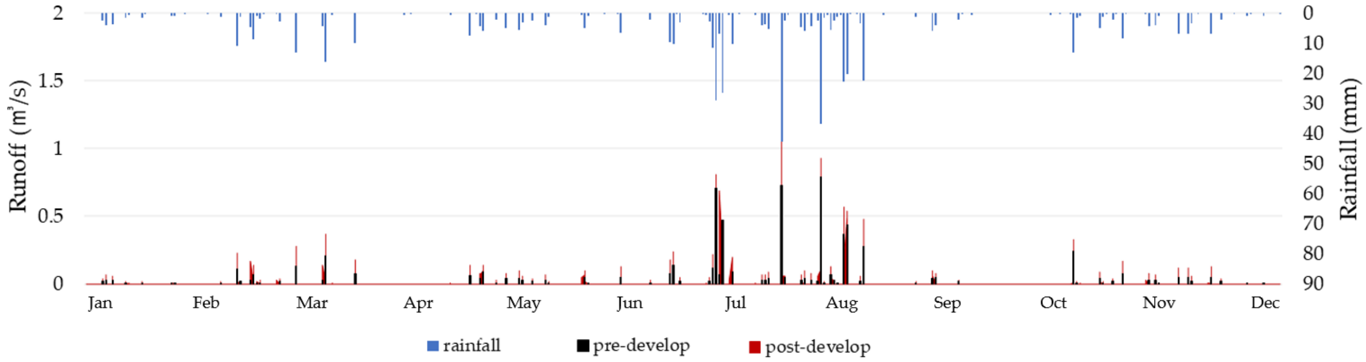


Figure 8. Rainfall and runoff of pre- and post-development research site.

According to the simulation, before development, evaporation took up 14.1% of the result, while infiltration and runoff were at 46.5% and 39.4%, respectively, whereas after development, the evaporation was 16.1%, infiltration was 21.5%, and runoff was 62.4%. The infiltration decreased by 25.0%, and the runoff increased by 23.1%. The peak runoff increased by 40.3% from 0.77 m^3/s before development to 1.08 m^3/s after development, which proved that a negative impact was caused by the increasing impervious surface area due to urbanization.

The management goal that is to be reduced using the LID techniques is 33,285 m^3, which is the difference between the pre- and post-development runoff (pre: 56,947 m^3; post: 90,232 m^3), which amounts to 23.1% of the total precipitation of 144,748 m^3.

3.2. Application of LID and Effect Analysis with Respect to the Management Goals

In this research, as it was judged that LID application is relatively challenging for privately used lands, LID was deployed separately for public-use and private-use lands. The public-use lands are a part of the infrastructure, which amounts to 40% of the total area, whereas the private-use lands are residential or commercial districts, which take up 60% of the total area. This indirectly suggests that, in order to suppress the increasing runoff, it is necessary to apply LID to privately used lands.

To apply LID to public-use lands, permeable pavement was laid on sidewalks, pedestrian roads, and parking lots, and bioswales were used for park irrigation, greens, and parking lots, where rainwater gardens were also applied to parks and greens. In privately used lands, 60% exclude that the site occupied by the building (50–60% of the site) was laid with permeable pavements, the planter boxes were installed on the public open space between commercial buildings and roads, and green roofs were planted on 50% of the roof areas of houses. Rainwater gardens were not applied in privately used lands in consideration of private property, yard utilization, and maintenance.

As a result, LID was implemented on 9.8% of the total area, or the equivalent of 24.5% of public-use lands (12.1% permeable pavements, 8.5% bioswales, and 3.9% rainwater gardens).

For private-use lands, 26.4% of the total area, or 44.0% of the private-use lands (permeable pavements 28.2%, planter boxes 0.9%, and green roofs 14.9%), was treated with LID.

The LID-applied area of Table 10 is a result of simulating the percentages of different LID methods to achieve the management goals. Table 11 shows the effect of LID application and the simulation results. Figure 9 shows the ratio of the evapotranspiration, infiltration and storage, and runoff with respect to each constituent.

Table 10. LID deployment status.

Public Land Use **Roads, Greens, Parks, Parking Lot, etc.**			**Private Land Use** **Houses, Accommodations, Malls in Residential Complexes, etc.**		
Total area: 42,062 m^2			Total area: 63,432 m^2		
LID-applied area (10,294 m^2, 24.5%)			LID-applied area (27,895 m^2, 44.0%)		
Permeable pavement	Bioswale	Rainwater garden	Permeable pavement	Planter box	Green roof
5071 m^2 (12.1%)	3589 m^2 (8.5%)	1634 m^2 (3.9%)	17,893 m^2 (28.2%)	543 m^2 (0.9%)	9459 m^2 (14.9%)

Table 11. Summary of simulation results.

Constituent	**Rainfall (m^3)**	**Evaporation (m^3, %)**	**Infiltration + Storage (m^3, %)**	**Runoff (m^3, %)**	**Peak Runoff (m^3/s)**
Pre-development	144,748	20,459 (14.1%)	67,342 (46.5%)	56,947 (39.4%)	0.77
Post-development		23,354 (16.1%)	31,162 (21.5%)	90,232 (62.4%)	1.08
LID(1) (public)		27,968 (19.3%)	49,748 (34.4%)	67,032 (46.3%)	0.88
LID(2) (private)		31,313 (21.6%)	51,407 (35.5%)	62,028 (42.9%)	0.91
LID(1,2) (public, private)		35,292 (24.4%)	59,249 (40.9%)	50,207 (34.7%)	0.78

LID(1) = LID applied to public-use lands; LID(2) = LID applied to private-use lands; LID(1,2) = LID applied to public-use and private-use lands.

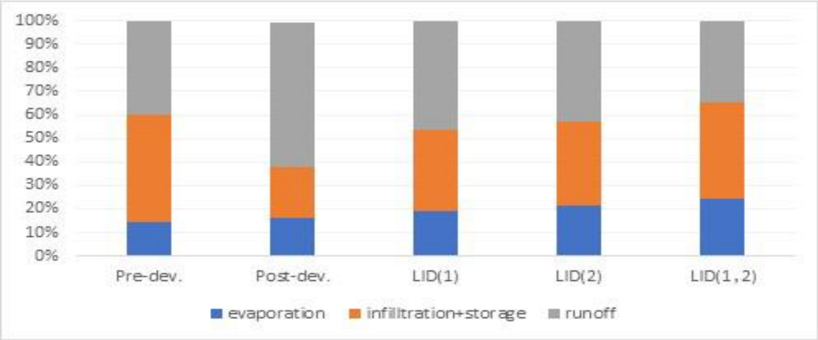


Figure 9. Evaporation, infiltration and storage, and runoff rates.

For LID(1), the evaporation was 19.3%, infiltration and storage was 34.4%, and runoff was 46.3%. In contrast to the post-development results, the infiltration and storage increased by 12.9%, and the runoff decreased by 16.1%, where the difference in runoff between pre- and post-development decreased from 23.0% to 6.9% after the application of LID. For LID(2), the simulation results showed 21.6% evaporation, 35.5% evaporation and storage, and 42.9% runoff. In contrast to post-development, the infiltration increased by 14.0%, and the runoff decreased by 19.5%, where the runoff difference between pre- and post-development decreased from 23.0% to 3.5% after LID application. The peak runoff decreased from 1.08 m^3/s to 0.88 m^3/s for LID(1), to 0.91 m^3/s for LID(2), and to 0.78 m^3/s for LID(1,2), which verified the efficacy of LID. This is consistent with the simulation results of Bae et al. [26], which showed that the peak flow decreased by 33.79% after the application of LID, which took up 34% of the total area.

The results of the LID(1,2) simulation showed 24.4% evaporation, 40.9% infiltration, and 34.7% runoff. In contrast to post-development, the infiltration and storage increased by 19.4%, and the runoff decreased by 27.7%. The infiltration and storage showed a difference of 5.6% compared with pre-development, but the runoff decreased from 39.3% to 34.7%, which showed the restoration of the runoff percentage to the pre-development state. This confirmed that in order for the research site to be restored to a pre-development state, it is necessary to construct the LID techniques over 36.2% of the total area, which is only possible if the LID application is performed on both public-use and private-use lands as shown in the simulation results. Therefore, it is necessary to search for ways to induce LID installation on private-use lands by raising awareness about LID, proposing LID application in district unit planning, and financially supporting the installation of green roofs and permeable pavements, among other methods.

To study the short-term effect of LID application on flooding reduction, the precipitation data was analyzed with 30-year recurrence periods, since the conduits were constructed for rainfall over a 30-year long period. For the critical duration, 2 h (which corresponded to 108.33 mm) was used. The precipitation and hydrograph are shown in Figure 10.

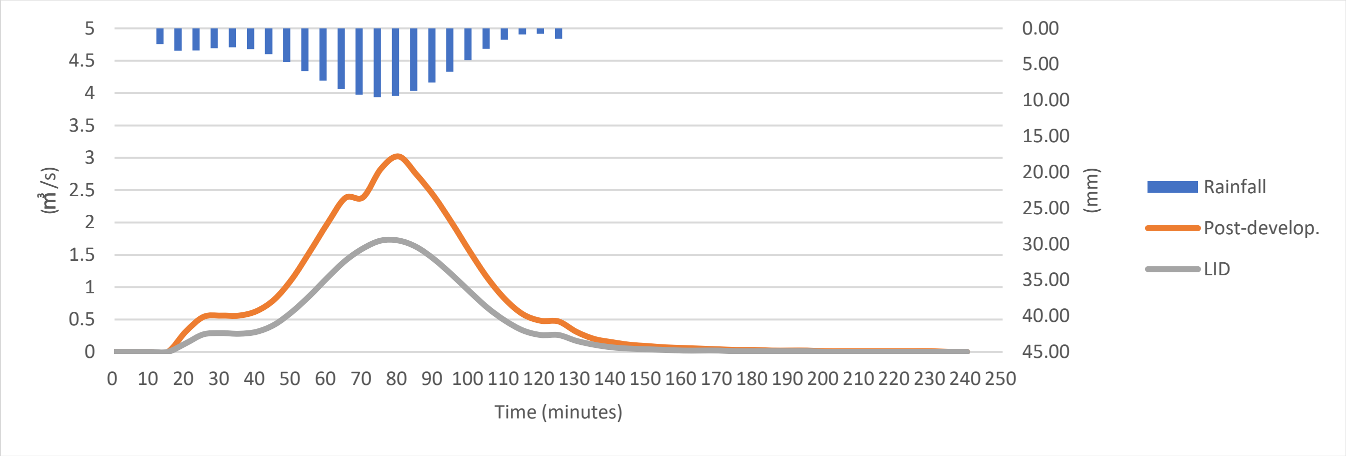


Figure 10. Hydrograph (2 h duration, 30-year design precipitation).

Although the peak flow occurrence time did not significantly change from the post-development state after the application of LID, the amount of the peak flow decreased by 43.4% from 3.07 m^3/s after development to 1.74 m^3/s after the application of LID. The total runoff decreased by 42.3% after the application of LID, from 9600 m^3 after development to 5540 m^3 after applying LID.

3.3. The Efficacy of LID under Various Precipitation Conditions

To analyze the efficacy of LID under various precipitation conditions, the LID techniques were classified into three types as shown in Table 12—permeable pavement (PP), bioretention (BR), and green roof (GR)—and were simulated with a duration of 2 h of rainfall over 2-year, 3-year, 5-year, 10-year, 20-year, and 30-year periods. The results are collated in Table 13.

Table 12. LID types and applied areas.

Constituent	Total	Permeable Pavement (PP)	Bioretention (BR)	Green Roofs (GR)
Area (m^2)	38,189	22,964	5766	9459
Area percentage (%)	36.2	21.8	5.4	9.0

Table 13. Precipitation simulation results with various periods.

Simulation Item	2-Year Period				3-Year Period				5-Year Period			
	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)
Post-development	6351	4810 (-)	1.42	83	7247	5640 (-)	1.67	82	8260	6580 (-)	1.97	82
LID(PP)		3770 (21.6)	1.13 (20.3)	83		4420 (21.6)	1.33 (20.4)	82		5160 (21.6)	1.56 (20.6)	82
LID(BR)		3930 (18.3)	1.18 (16.8)	87		4650 (17.6)	1.41 (15.9)	87		5490 (16.6)	1.67 (15.2)	83
LID(GR)		4400 (8.5)	1.31 (7.8)	83		5160 (8.5)	1.54 (7.9)	82		6020 (8.5)	1.81 (8.1)	82
LID (PP+BR+GR)		2690 (44.1)	0.83 (41.3)	87		3180 (43.6)	0.99 (41.0)	87		3740 (43.2)	1.16 (40.9)	83

Simulation Item	10-Year Period				20-Year Period				30-Year Period			
	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)	Rainfall (m^3)	Runoff (m^3, %)	Peak Flow (m^3/s, %)	Peak Flow Occurrence Time (min)
Post-development	9516	7780 (-)	2.33	82	10,729	8940 (-)	2.69	82	11,425	9600 (-)	3.07	82
LID(PP)		6090 (21.7)	1.85 (20.7)	82		6990 (21.8)	2.13 (20.7)	82		7520 (21.7)	2.29 (25.3)	82
LID(BR)		6530 (16.1)	2.00 (14.4)	82		7560 (15.4)	2.32 (13.8)	82		8150 (15.1)	2.50 (18.4)	82
LID(GR)		7100 (8.7)	2.14 (8.1)	82		8160 (8.7)	2.47 (8.3)	82		8770 (8.7)	2.65 (13.5)	82
LID (PP+BR+GR)		4440 (42.9)	1.39 (40.6)	82		5140 (42.5)	1.61 (40.1)	82		5540 (42.3)	1.74 (43.4)	82

Quantities within parentheses denote the reduction rate from the post-development state.

As is shown in Table 13, the total amounts of rainfall for the 2-year, 3-year, 5-year, 10-year, 20-year, and 30-year periods were 6351 m^3, 7247 m^3, 8260 m^3, 9516 m^3, 10,729 m^3, and 11,425 m^3, respectively. For all the periods and LID types, the runoff and the peak flow decreased, where the runoff decrease rates for the 2-year, 3-year, 5-year, 10-year, 20-year, and 30-year periods were 44.1%, 43.6%, 43.2%, 42.9%, 42.5%, and 42.3%, respectively, when all the LID types were applied; similarly, the decrease rates for the peak flow were 41.3%, 41.0%, 40.9%, 40.6%, 40.1% and 43.4%, respectively. Although the amount of runoff reduction increased along with the recurrence periods, the percentage of the decrease declined. Furthermore, although the difference was not significant, while LID(PP) and LID(GR) showed increasing efficiency in runoff reduction with increasing return periods, LID(BR) showed a decreasing trend in efficiency, and the same trend was shown for the peak flow efficiency.

Furthermore, the peak flow occurrence time showed a slight difference between various recurrence periods and LID types. The peak runoff occurred over recurrence periods of more than 10 years, mainly 82 minutes after the start of rainfall. The LID(BR) and LID(PP+BR+GR) of the 2-year, 3-year, and 5-year recurrence periods showed the latest start of the peak runoff, which occurred 83–87 minutes after the start of rainfall. Figure 11 shows the hydrographs and the rainfall patterns for various recurrence periods.

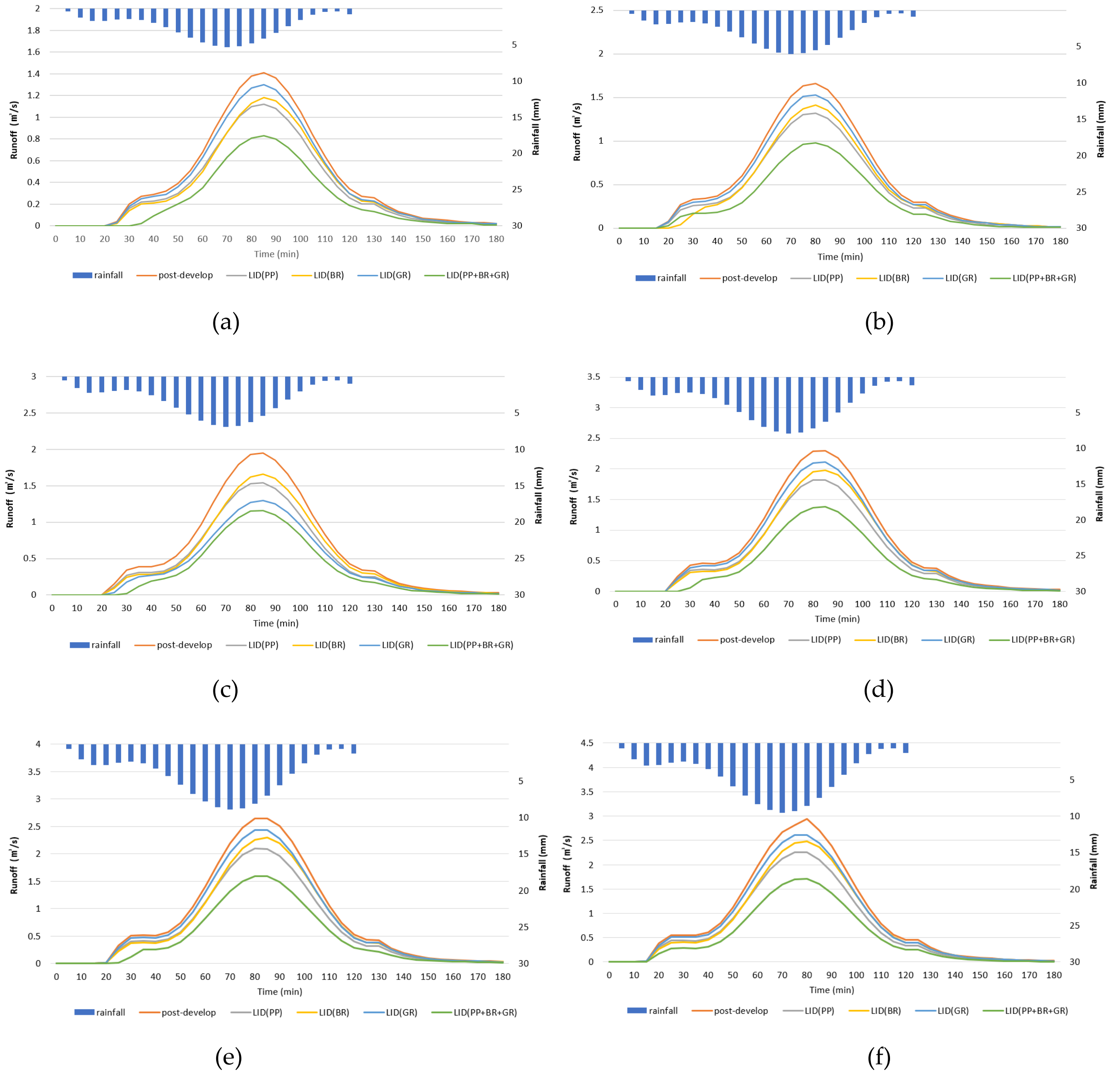


Figure 11. Rainfall and runoff under various precipitation conditions: (**a**) 2-year period, (**b**) 3-year period, (**c**) 5-year period, (**d**) 10-year period, (**e**) 20-year period, and (**f**) 30-year period.

If the LID-applied areas for different LID types are different, it is challenging to perform an objective comparison [31]. Therefore, in order to examine the LID efficacy per unit area, the amount of the runoff decrease was divided by the LID area for both the post-development scenario and all the LID types applied. For both the runoff and peak flow reduction efficiency, the efficiency order was LID(BR) > LID(PP) > LID(GR). For green roofs, a drainage mat and impermeable layers are formed under the surface or soil layers. In contrast, soil or storage layers exist under permeable pavements, which induces continuous infiltration onto the lower soil layers. For bioretention, it was judged that its relatively large capacity could be attributed to its relatively high berm height compared with those of permeable pavements, the high Manning roughness coefficient, and the soil and storage layers. This confirms that it is necessary to implement LID techniques while taking the upper vegetation, sufficient soil and storage layers, and permeability into account, rather than using LID with a simple structure. Additionally, LID techniques that utilize upper vegetation can provide several ecosystem services, including rainwater control.

4. Discussion

LID is a technique proposed to restore water cycle systems distorted by urbanization to their pre-development state, for which the setting of appropriate rainwater management goals and LID implementation methods are vital. Previous research has been centered on the effects of single-type LID installation, which lacks quantitative analysis on the amount of necessary LID techniques. There have been limits on setting LID goals on a business site. This research utilized the SWMM program to compare the pre- and post-development rainwater runoff at an actual business site to set a goal of reducing the rainwater runoff, amounting to 23% of the total precipitation. In addition, it was proposed that it is possible to achieve the management goal if 36% of the total area is treated with LID. Furthermore, the analysis with various recurrence periods presented the positive effects that LID has on water cycles, which include runoff reduction, a smaller peak flow, and a shorter time of concentration. Most of this research site is flat plains below 20 m above sea level and slopes less than 10% [18], and the soil belongs to group-C of the NRCS hydrological soil group [32]. The LID area to be applied may vary depending on the topographical and soil conditions.

It was shown through analysis that the implementation of LID for both public-use and private-use lands is necessary to achieve the management goals. It is necessary to reflect the LID implementation in district unit planning to provide incentives or financial support for LID installation or to raise awareness of LID [33].

The Special Act on the Utilization of Water Fronts [34] aims to prevent the excessive development of waterfronts on the four major rivers of Korea and to promote sustainable development, which places the limit of the minimum area of development at 100,000 m^2. As it is believed that the needs for the small-scale development of watersides will continue due to the regional advantages (e.g., landscapes, flatness of the area, low land price, and the desire for a country life), the methodologies presented in this research (e.g., hydrological analysis given the pre- and post-development land uses, setting appropriate water cycle management goals, and planning water cycle restoration with LID) will be helpful in making the concept of the water cycle get considered during the planning of new development projects.

5. Conclusions

In this research, the land for the Naju-Noan Waterfront Zone Construction Project was taken to simulate hydrological change using a rainfall runoff model, the SWMM, and the amount of increase in the runoff after development was set as the rainwater management goal. To reduce the increased runoff, the five LID techniques—permeable pavement, green roof, and bioretention (bioswale, rainwater garden, and planter box)—were used and simulated with the SWMM to analyze their effects. The major results are the following:

(1) As the impervious area rate increased from 24% to 59% after urbanization, the infiltration decreased by 25.0%, the runoff increased by 23.1%, and the peak flow increased by 40.3%. The rainwater management goals with LID were 33,285 m^3, 23% of the total precipitation, and 144,748 m^3.

(2) The land use after development consisted of 40% of the public-use sector and 60% of the private-use sector. The LID-applied area was 36.2% of the total area, where 24.5% of the public-use lands and 44.0% of the private-use lands were implemented with LID. As a result of LID application to the public-use lands, the runoff difference between the pre- and post-development states decreased from 23.0% to 6.9%. Application of LID to the private-use lands reduced the runoff difference from 23.0% to 3.5%. Aside from that, when LID was applied to both the public- and private-use lands, the runoff was restored to the pre-development state, and the peak flow showed a 98.7% restoration result compared with the pre-development state.

(3) To analyze the efficacy of LID of different types, the simulation was performed with 2 h of rainfall and 2-year, 3-year, 5-year, 10-year, 20-year, and 30-year periods. As a result, the runoff and peak flow decreased in all recurrence periods and LID types, and

better efficiency was shown when multiple types of LID were applied together. As the recurrence period increased, the amount of runoff reduction increased, but the percentage of the runoff reduction decreased.

(4) When the LID effect was analyzed per unit area for objectivity, the efficiency for reducing the runoff and peak flow was BR > PP > GR from highest to lowest. This indicates that when applying LID, it is beneficial to use LID of multiple layers such as vegetation, soil, or storage for reducing the runoff rather than using single-layer LID.

As shown in this research, LID techniques have been confirmed to have beneficial effects for solving the distortion of urban water cycle systems by increasing the infiltration and reducing the total runoff, peak flow, and time of concentration. However, it is likely for the rainwater management target and LID application areas to vary for different research sites, used LID practices, and arrangements. In the future, if LID installations are planned in the beginning of city development projects and monitoring is conducted for the LID-installed areas for comparative analysis, it is speculated that more accurate evidence for LID will be provided.

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