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Water-Cycle Efficiency Analysis of a Multi-Zone LID Facility Using K-LIDM

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Abstract: This study evaluated water-cycle efficiency at the Korea Green Infrastructure and Low Impact Development Center using the Korean Low Impact Development Model (K-LIDM). The outdoor demonstration area comprises five land-use-based LID zones: architectural, road, parking lot, rain garden, and bioretention. Event simulations used 5-, 30-, and 100-year design rainfall with a 60-min duration, while continuous simulation used hourly rainfall and potential evapotranspiration data for 2004-2013. Relative to the impervious-pavement scenario, the full LID configuration reduced peak discharge by 86.90%, 83.97%, and 81.49% for the 5-, 30-, and 100-year events, respectively. The corresponding runoff-volume reductions were 84.76%, 82.44%, and 81.33%, and annual average runoff was reduced by 65.18%. In the individual-zone scenarios, average peak-discharge reductions were 23.08% for the architectural zone, 30.16% for the road zone, 23.52% for the parking-lot zone, 21.63% for the rain-garden zone, and 47.33% for the bioretention zone. The corresponding annual-runoff reductions were 21.50%, 31.28%, 23.52%, 21.65%, and 34.48%, respectively. The results provide a comparative assessment of whole-site and zone-level water-cycle performance under the evaluated K-LIDM scenarios.

Keywords: K-LIDM, Low Impact Development, Urban Runoff, Water-Cycle Efficiency, Runoff Reduction

I. Introduction

Urbanization replaces natural soil and vegetation with roofs, roads, and parking surfaces, thereby reducing infiltration and increasing runoff volume and peak discharge. Climate variability and more intense rainfall further increase the hydraulic burden on conventional drainage systems and the risk of urban flooding [1,2]. Low-impact development (LID) manages rainfall near its source through infiltration, storage, evapotranspiration, and delayed drainage. Typical practices include green roofs, planter boxes, permeable pavement, rain gardens, and bioretention facilities [3,4].

K-LIDM was developed as a Korean LID analysis tool capable of representing linked LID facilities and performing event-based and continuous hydrologic simulations [5]. Previous applications have used K-LIDM to examine green-roof hydrology, permeable-area requirements, and bioretention performance at the Korea GI&LID Center [6-8]. These studies establish the methodological background for applying K-LIDM to field-scale LID systems.

The objective of this study was to evaluate water-cycle efficiency at the Korea GI&LID Center using K-LIDM. The analysis was conducted at two scales. At the whole-site scale, the full LID configuration was compared with an impervious-pavement scenario. At the zone scale, the architectural, road, parking-lot, raingarden and bioretention scenarios were compared using the same evaluation indicators. Peak discharge and runoff volume were evaluated under design-storm conditions, and annual average runoff was evaluated under continuous-rainfall conditions.

II. Experimental Section

The Korea GI&LID Center is located on the Yangsan Campus of Pusan National University. The site covers 4,895 m², including 4,065.4 m² of outdoor LID demonstration area. The outdoor area comprises five LID zones: architectural, road, parking lot, rain garden, and bioretention. Table 1 presents the facility composition, area ratio, and calculated area of each zone.

Korea GI&LID Center

Architectural LID zone

Road LID zone

Parking-lot zone

Rain-garden LID zone

Bioretention LID zone

Figure 1: Field photographs of the Korea GI&LID Center and the five LID zones.

Table 1: LID zones, area ratios, and calculated areas at the study site

Zone	LID facilities	Area ratio (%)	Calculated area (m^2)
Architectural	Green roof, planter box, rain barrel, impervious rooftop	26.77	1,088.31
Road	Permeable concrete, permeable asphalt, impervious concrete, impervious asphalt	24.93	1,013.50
Parking lot	Permeable concrete, permeable asphalt, impervious concrete, impervious asphalt, permeable block, vegetated swale	8.79	357.35
Rain garden	Rain garden, sand filter, impervious pavement, rainwater storage block	6.90	280.51
Bioretention	Bioretention basin, impervious pavement, permeable block	32.61	1,325.73
Total		**100.00**	**4,065.40**

Based on the 4,065.4 m² outdoor demonstration area, the calculated zone areas are shown in Table 1. The five area ratios sum to 100.00%, corresponding to the full 4,065.40 m² outdoor demonstration area. The zone configuration includes rooftop, pavement, storage, filtration, swale, rain garden and bioretention elements as listed in Table 1.

K-LIDM can represent multiple hydrologically linked LID elements and evaluate both runoff reduction and water-cycle response [5]. For the center model, subcatchments were delineated for the individual LID facilities and model parameters were assigned from topographic and design information. The storm-sewer network and runoff pathways were constructed from the design drawings. Total site runoff was evaluated by combining discharge from the road-zone outlets and the bioretention-zone outlet. The configured K-LIDM network and the five LID-zone groups are shown in Figure 2.

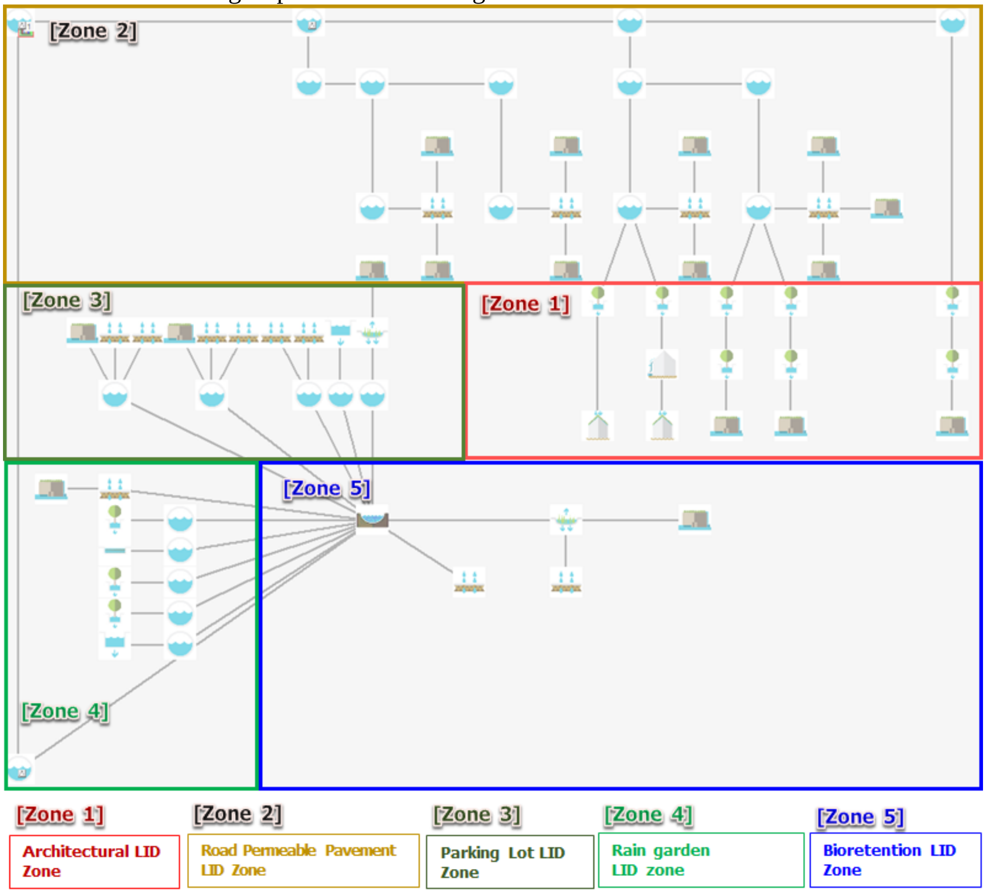

Figure 2: K-LIDM model configuration of the Korea GI&LID Center and the five LID zones.

The facility-specific dimensions and hydraulic parameters used to configure the K-LIDM representation of the Korea GI&LID Center are summarized in Table 2.

Table 2: Main K-LIDM facility and soil parameters used for the Korea GI&LID Center model

Component	Model unit(s)	Parameter	Value
Green roof	GRT-1, GRT-2	Soil depth; roof slope; vegetation cover; green-roof length	101.6 mm; 0.001 m/m; Ground Cover; 15.24 m
Planter box	BPB-1–3, SPB-1–5	Layer 1; layer 2; underdrain diameter; standpipe height and diameter	Sandy loam, 0.40 m; Gravel, 0.25 m; 0.10 m; 0.30 m and 100 mm
Rain garden	RGLID-S1–S4	Plan dimensions; effective depth; freeboard; soil layers	3.60 × 3.60 m; 1.20 m; 0.10 m; Sandy loam, 0.40 m + Sand, 0.30 m
Bioretention basin	BR-DP	Length; bottom width; effective depth; freeboard	31.96 m; 9.659 m; 0.60 m; 0.20 m

Component	Model unit(s)	Parameter	Value
Permeable concrete—road	PCPR-S1, PCPR-S2	Pavement; upper layer; lower layer (thickness/porosity)	0.20 m/0.20; 0.20 m/0.30; 0.06 m/0.30
Permeable asphalt—road	PAPR-S1, PAPR-S2	Pavement; upper layer; lower layer (thickness/porosity)	0.10 m/0.20; 0.30 m/0.30; 0.06 m/0.30
Permeable asphalt—parking	PAPP-S1, PAPP-S2	Pavement; upper layer; lower layer (thickness/porosity)	0.25 m/0.20; 0.08 m/0.30; 0.57 m/0.25
Permeable concrete—parking	PCPP-S1, PCPP-S2	Pavement; upper layer; lower layer (thickness/porosity)	0.20 m/0.20; 0.06 m/0.30; 0.64 m/0.25
Permeable block—parking	PBPP-S1, PBPP-S2	Pavement; upper layer; lower layer (thickness/porosity)	0.10 m/0.20; 0.30 m/0.30; 0.40 m/0.25
Gravel	Soil hydraulic set	Wilting point; Kmin; VG n; Ksat; A; L; BPH	0.005; 0.42 cm/h; 10.00; 1260.00 cm/h; 0.50; 1.190; 0.20
Sand	Soil hydraulic set	Wilting point; Kmin; VG n; Ksat; A; L; BPH	0.020; 0.42 cm/h; 3.00; 23.56 cm/h; 6.00; 0.694; 7.26
Sandy loam	Soil hydraulic set	Wilting point; Kmin; VG n; Ksat; A; L; BPH	0.035; 0.44 cm/h; 1.45; 5.98 cm/h; 7.69; 0.553; 8.69

The event-simulation inputs were based on Busan design rainfall data published by the Ministry of Land, Transport and Maritime Affairs [9]. For a 60-min duration, the rainfall depths for the 5-, 30-, and 100-year return periods were 60.40, 89.50, and 108.11 mm, respectively. The design storms were temporally distributed using the third-quartile Huff method. Continuous simulation used hourly rainfall and potential evapotranspiration data for the Busan weather station from 2004 to 2013. The mean annual rainfall during this period was 1,465.08 mm.

Peak-discharge and runoff-volume reduction rates were calculated for the design-storm simulations, and annual-runoff reduction was calculated for the continuous simulation. The reduction rate was calculated as $R = (B - S) / B \times 100$, where B is the baseline value and S is the scenario value. Table 3 presents the whole-site comparison, and Table 4 presents the individual-zone comparison.

The evaluated conditions were the impervious-pavement scenario, the full Korea GI&LID Center configuration, and the individual architectural, road, parking-lot, raingarden and bioretention zone scenarios. Peak discharge and runoff volume were evaluated for the design-storm simulations, while annual average runoff was evaluated for the continuous simulation. The individual-zone values are scenario-level results; they were not normalized by zone area, facility count, construction volume, or cost.

III. Results

The model outputs showed lower runoff for the full LID configuration under all three design-storm conditions. Peak discharge decreased from 0.0893 to 0.0117 m^3/s for the 5-year event, from 0.1341 to 0.0215 m^3/s for the 30-year event, and from 0.1777 to 0.0329 m^3/s for the 100-year event. The corresponding peak-discharge reductions were 86.90%, 83.97%, and 81.49%. The runoff-volume reductions were 84.76%, 82.44%, and 81.33%, respectively. In the continuous simulation, annual average runoff decreased from 1,259.97 to 438.74 mm, corresponding to a reduction of 65.18%.

Table 3: Runoff reduction of the full LID configuration relative to the impervious-pavement scenario

Return period	Baseline Qp (m^3/s)	LID Qp (m^3/s)	Qp reduction (%)	Baseline volume (m^3)	LID volume (m^3)	Volume reduction (%)
5 yr	0.0893	0.0117	86.90	170.31	25.96	84.76
30 yr	0.1341	0.0215	83.97	256.00	44.95	82.44
100 yr	0.1777	0.0329	81.49	310.78	58.03	81.33

Direct comparison of the three design-storm events shows that peak-discharge reduction decreased from 86.90% for the 5-year event to 81.49% for the 100-year event, while runoff-volume reduction decreased from 84.76% to 81.33%. Both reduction indicators remained above 80% for all three design storms.

The design-rainfall depth increased from 60.40 mm for the 5-year event to 89.50 mm for the 30-year event and 108.11 mm for the 100-year event. Over the same sequence, the impervious-pavement baseline peak discharge increased from 0.0893 to 0.1341 and 0.1777 m^3/s, while the corresponding full-LID values were 0.0117, 0.0215, and 0.0329 m^3/s.

Event runoff volume increased with return period. Baseline volumes were 170.31, 256.00, and 310.78 m^3 for the 5-, 30-, and 100-year events, respectively, and the corresponding full-LID volumes were 25.96, 44.95, and 58.03 m^3. The baseline and full-LID event responses are summarized graphically in Figure 3.

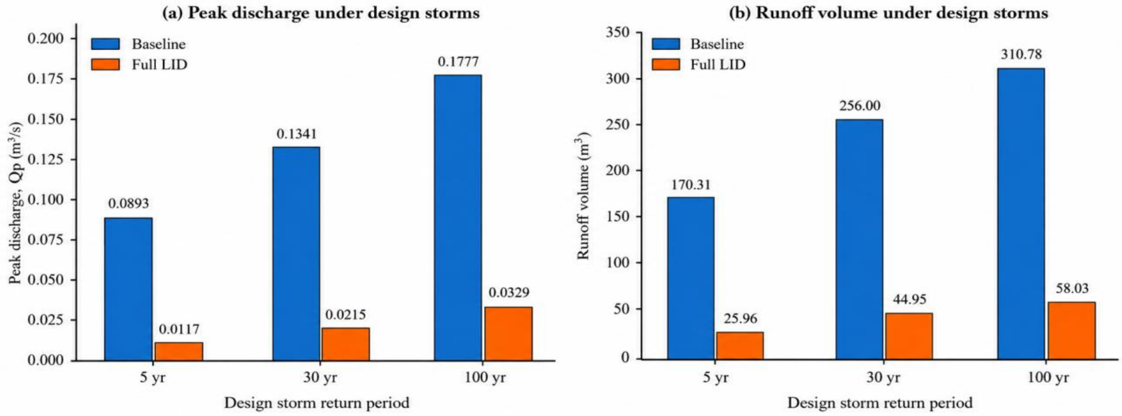

Figure 3: Comparison of baseline and full-LID hydrologic response under the design storms listed in Table 3.

Among the individual-zone scenarios, the bioretention zone showed the highest average peak-discharge reduction of 47.33% and an annual-runoff reduction of 34.48%. The road zone showed reductions of 30.16% and 31.28%, respectively. The architectural zone showed reductions of 23.08% and 21.50%, the parking-lot zone showed reductions of 23.52% and 23.52%, and the rain-garden zone showed reductions of 21.63% and 21.65%.

Table 4: Area-normalized peak-discharge efficiency results for the individual LID-zone scenarios

LID zone	Average peak-discharge reduction (%)	Annual-runoff reduction (%)	Site area ratio (%)	Area-normalized calculation (peak reduction / area ratio)	Rank
Architectural	23.08	21.50	26.77	23.08 / 26.77 = 0.862	5
Road	30.16	31.28	24.93	30.16 / 24.93 = 1.210	4
Parking lot	23.52	23.52	8.79	23.52 / 8.79 = 2.676	2
Rain garden	21.63	21.65	6.90	21.63 / 6.90 = 3.135	1
Bioretention	47.33	34.48	32.61	47.33 / 32.61 = 1.451	3

For an equal-area comparison, the average peak-discharge reduction was divided by the corresponding site area ratio, as shown directly in Table 4. Because all zone areas are referenced to the same total outdoor area, dividing by the site-area ratio is proportional to dividing by the corresponding zone area and therefore provides a relative equal-area ranking. The resulting value is an area-normalized efficiency index, not a simulated 1 m^2 performance value.

The center model was configured using design drawings and design-based parameters; calibration and validation using measured site data were not performed.The analysis also did not evaluate parameter uncertainty, water-quality performance, construction cost, maintenance demand, or optimal LID sizing. The findings should therefore be interpreted as comparative results for the evaluated K-LIDM scenarios.

IV. Conclusion

This study evaluated the water-cycle efficiency of LID facilities at the Korea GI&LID Center using K-LIDM under design-storm and continuous-rainfall conditions. Compared with the impervious-pavement scenario, the full LID configuration reduced peak discharge by 81.49-86.90%, runoff volume by 81.33-84.76%, and annual average runoff by 65.18%. These results confirmed that, under the rainfall conditions established in this study, the full LID configuration substantially reduced runoff volume and peak discharge compared with the impervious-pavement scenario.

Analysis of the individual LID zones showed that average peak-discharge reduction ranged from 21.63% to 47.33%, while annual-runoff reduction ranged from 21.50% to 34.48%. In terms of absolute scenario-level reduction rates, the bioretention zone showed the highest reductions in both average peak discharge and annual runoff, followed by the road zone. Specifically, the average peak-discharge and annual-runoff reductions were 47.33% and 34.48% for the bioretention zone, and 30.16% and 31.28% for the road zone, respectively.

When the average peak-discharge reduction of each zone was normalized by the site area ratio, the efficiency ranking was rain garden > parking lot > bioretention > road > architectural. The area-normalized value is not the result of separately simulating an actual 1 m² area; rather, it is a relative equal-area comparison index calculated using each zone's area ratio based on the same total outdoor area. Accordingly, this study compared both the absolute runoff-reduction rates of the individual zones and their relative efficiency considering area.

In addition, the whole-site LID configuration showed greater runoff reduction than the individual LID-zone scenarios under the conditions evaluated in this study. Accordingly, this study compared and evaluated the water-cycle performance of LID at both the whole-site and individual-zone scales. However, the K-LIDM model used in this study was constructed using design drawings and design-based parameters, and calibration and validation using actual field measurement data were not performed. Therefore, the results of this study should be interpreted as comparative results among the configured K-LIDM scenarios.

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