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Evaluation of capacity adequacy in LID according to LID structure

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ABSTRACT

The interest in low impact development (LID) facilities for recovering natural water cycle systems degraded by urbanization is increasing worldwide. However, problems occur when installing LID facilities due to the incomplete and incomprehensive analysis of their design capacity adequacy. In this study, the removal efficiency and design volume adequacy of LID facilities were analyzed based on rainfall monitoring data in four LID facilities (grassed swale, vegetative filter strip, bio-retention, and permeable pavement). The group of LID facilities designed on WQV showed a higher flow (37%) and pollutant (total suspended solids, biochemical oxygen demand, total nitrogen, and total phosphorus) removal efficiencies (20%~37%) than the group of LID facilities designed on WQF. A surface area/catchment area (SA/CA) graph was developed for the evaluation of design volume adequacy based on rainfall monitoring data. The graph's coefficient of determination showed over 0.5 in all parameters. In particular, flow and TP were more than 0.95. The SA/CA and L/CA graph considered the difference of structure mechanisms in LID facilities and confirmed an improved coefficient of determination in flow, TSS, and TP compared to the SA/CA graph. These results confirm the feasibility of applying a SA/CA and L/CA graph for the evaluation of design volume adequacy in LID facilities. Further research for generalization and normalization is necessary.

Keywords: Non-point pollution source; Green infrastructure; LID; Design volume criteria

1. Introduction

Green infrastructure (GI) for urban water circulation is the main policy of Korea's central and local government. A significant amount of research and support falls under the concept of a healthy water cycle city, rain city, moist city, and HWC2 [1]. This research aims to restore natural water purification systems to solve the problems of dry weather, urban flooding, urban drought, and aquatic pollution caused by the increase of impermeable area due to rapid urbanization [4,5]. Other countries are also interested in building such urban water circulation systems, including low impact development and green infrastructure (LID and GI) in the United States, decentralized urban design (DUD) in Germany, water sensitive urban design (WSUD) in Australia, well-balanced hydrological system (WBHS) in Japan, and sponge city for flood control (SC) in China [8–10]. Although the titles differ in each country, it is a common aim to attempt to return the urban water circulation system to its pre-development state using LID as a core technology. Among them, the application of zero liquid discharge (ZLD) to the city at the University of Humboldt, Germany, achieved an outstanding result by reducing 99% of rainfall discharge. However, the technologies of each

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country were built considering each country's particular situation, and reckless domestic introduction is likely to cause confusion in the domestic water circulation system. It is timely to develop a green infrastructure suitable for domestic situations [10–12]. Representative LID facilities for GI construction include grassed swale, vegetative filter strip, bioretention, permeable block, and artificial wetland [14–16]. Common to all these LID facilities is the prevention of runoff through infiltration, sinking, and storage of rainfall runoff, and reducing contaminants (non-point pollutants) contained in rainfall runoff by precipitation, filtration, and vegetation [17,18]. In addition, many studies have been conducted on factors and ranges for the design and maintenance of each LID technology, and various LID technology design manuals have been published [14–16,19]. In particular, in the 2016 design and maintenance manual for non-point pollution reduction facilities published by the Ministry of Environment, design capacity estimation criteria are classified into water quality volume (WQV) and water quality flow (WQF) in consideration of the basic structure of non-point pollution reduction facilities and LID facilities. As such, design manuals for domestic nonpoint pollution abatement facilities (including LID) have been revised and supplemented, and research on appropriate design factors and ranges for optimal design has been ongoing [20]. Among them, research has recently been proposed using the surface area/catchment area (SA/CA) to select the appropriate area of LID facilities [21,22]. Existing studies commonly use area ratios of facilities and watersheds, regardless of the type of LID facility, which does not consider the basic structure of the facility. Facilities using WQF as a design factor have a basic flow structure, whereas facilities using WQV as a design factor are clearly different due to the basic structure of storage. However, if the analysis is based on the area ratio of the facilities, there is a high possibility that the characteristics of the facilities designed by the WQF will not be reflected clearly. It is necessary to prepare a supplementary solution. In this study, on-site efficiency assessment monitoring was conducted on the representative LID facilities introduced in Korea such as the grassed swale (GS), the vegetative filter strip (VFS), the bio-retention (BR), and the permeable block (PB). Based on the monitoring results, the difference in flow rate and nonpoint pollutant reduction efficiency of the facilities designed by WQF and WQV was analyzed. It will be considered the method of calculating the appropriate area considering the characteristics of each design criteria.

2. Materials and methods

2.1. Monitoring location and LID technology for research

The LID technologies selected for this study were GS, VFS, BR, and PB. The technologies were selected by applying the water treatment flow rate to the GS, the VFS, and the water treatment capacity to the vegetation lodge and the permeate block as the capacity design criteria [16]. In order to select the facilities to be monitored, those that can clearly understand the characteristics of each technology and are managed by the central government were selected. These facilities are the GS and VFS located in Y city, Gyeonggi-do, and the vegetation detention center and pitcher block located in J city, Jeollabuk-do. The flow and pollutant reduction mechanisms common to each technology are infiltration and filtration, and vegetation effects can be expected for the rest of the facility with the exception of PB. Fig. 1 and Table 1 show location of monitoring sites and characteristics of LID facilities.

2.2. Monitoring of rainfall events

In Table 2, the monitoring rainfall events conducted at each study facility for this study are shown. GS and VFS were monitored for real rainfall, and BR and PB were monitored through artificial rainfall and real rainfall + artificial rainfall. The difference between these rainfall monitoring methods is that the watershed area of the BR and the PB is relatively small, so the rainfall runoff cannot be secured and the monitoring was conducted with artificial rainfall. Rainfall monitoring was performed eight times for the GS, eight times for the VFS, 12 times for the infiltration reservoir, and 12 times for the permeate block, total 30 monitoring times. The rainfall for monitoring rainfall events ranged from 2 to 90 mm in the GS, 2 to 120 mm in the VFS, 1.8 to 150 mm in the BR, and 47.5 to 227.7 mm in the PB. The average rainfall intensity ranged from 1.0 to 7.5 mm/h in GS, 0.7 to 23.5 mm/h in VFS, 2.0 to 32.9 mm/h in BR, and 2.9 to 77.6 mm/h in PB. The monitoring was conducted to represent various rainfall conditions.

2.3. Monitoring method

The four monitoring facilities (GS, VFS, BR, and PB) in this study were chosen considering the watershed characteristics, installation, and site conditions. GS was monitored at the 30 m point after the inflow, and the watershed covered 100% of the road. Samples were taken at 5 min intervals at the commencement of the outflow. After 1 h, samples were taken based on rainfall intensity, influent flow rate, and turbidity. VFS was monitored at the inlet and outlet of the facility and as most land uses consisted of forests and paddy fields, the sampling time was determined based on rainfall intensity, inflow, and turbidity. BR were sampled with surface runoff and permeate blocks runoff through perforated pipes installed at the bottom of the facility. GS and VFS were monitored for real rainfall, and BR and PB were monitored for artificial rainfall. The reason for experimenting with artificial rainfall was because the basin area is a human-occupied 100% permeate block, so no rainfall runoff flows from the basin area. In the case of PB, experiments were conducted using artificial rainfall because the basin area was the same as the area of the facility. The efficiency analysis through artificial rainfall was carried out in the facility where it was impossible to inflow sufficient rainfall effluent for evaluating the efficiency of the facility due to the difference in basin area.

3. Results and discussion

3.1. LID facility inflow and outflow pollution load

In Fig. 2, the inflow and outflow pollutant loads (TSS, BOD, TN, and TP) of the rainfall monitoring results of the

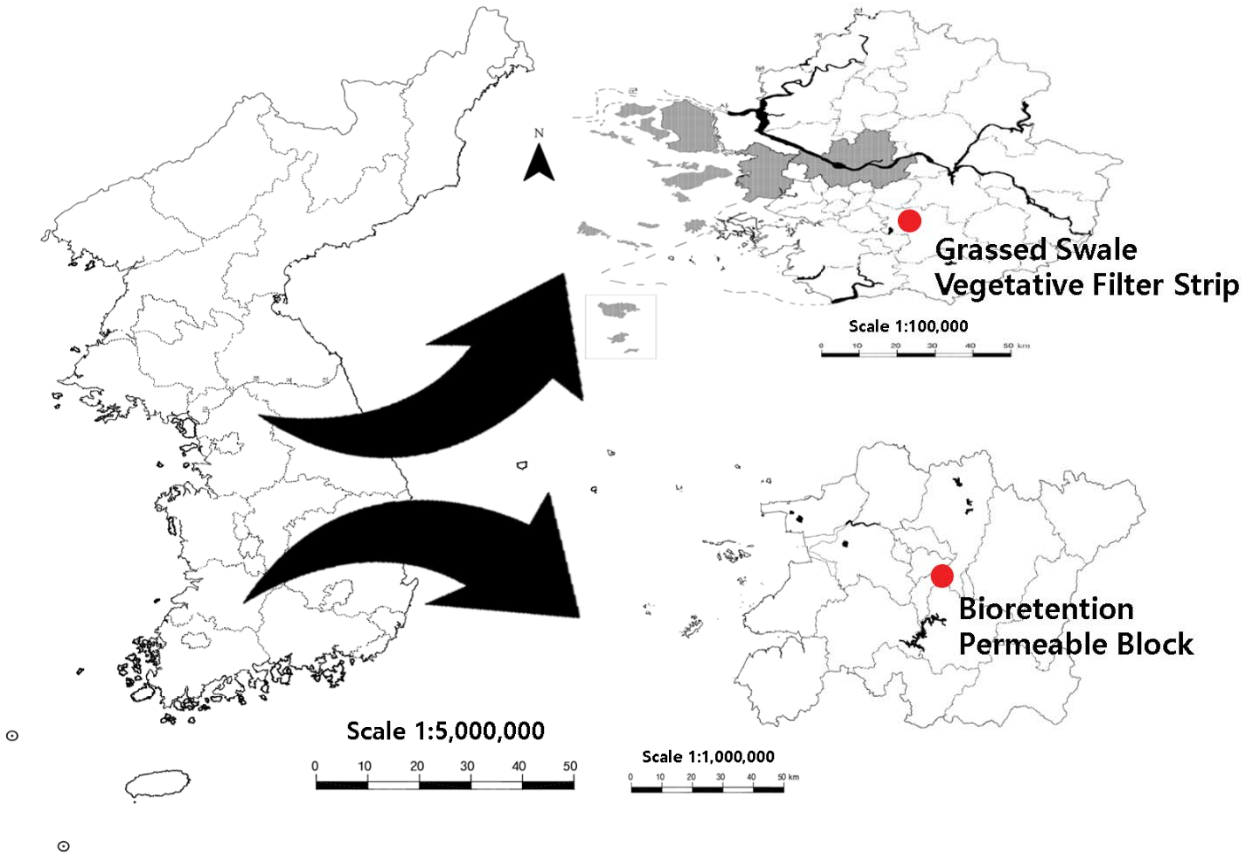

Fig. 1. Location of monitored LID facility.

Table 1
Characteristics of LID facility

Contents	GS	VFS	BR	PP
Runoff source	Road	Forest land	Park	Park
Catchment area (m^2)	7,700	25,300	220	16
Surface area (m^2)	40	84	109	16
Length (m)	30	75	19	4
CA/SA	0.005	0.003	0.495	1.0
Mechanism	Infiltration Sedimentation Vegetation Filtration	Infiltration Sedimentation Vegetation Filtration	Infiltration Sedimentation Vegetation Filtration	Infiltration Sedimentation Filtration
Design volume criteria	WQF	WQF	WQV	WQV

LID facility are summarized. The GS, TSS, TN, BOD, and TP were found to have high inflow loads (Fig. 2a). The GS watershed's land use status is road, with high levels of dust of dust from road traffic that accumulates during the dry season. For VFS, the BOD contamination load was analyzed to be the highest. This is because the VFS basin is composed of rice paddy, fields, and mountainous areas that are likely to generate large amounts of organic matter during rainfall (Fig. 2b). For BR (Fig. 2c) and PB (Fig. 2d), artificial rainfall experiments were conducted after artificially spraying 2 and 0.5 kg (It is calculated by surface area) of road dredged soil before the test, and the BOD load was analyzed to be the highest, with the exception of TSS. The inflow loads of each facility differed, which may have been influenced by the land use status of each watershed. This analysis can predict that large amounts of nonpoint pollutants will be released during rainfall in areas affected by anthropogenic conditions such as roads. However, in order to generalize this result, it is necessary to analyze it through additional data.

Table 2
Statistical summary of monitored rainfall

Contents		Antecedent dry day (d)	Rainfall (mm)	Rainfall duration (h)	Rainfall intensity (mm/h)
	Median ± SD	30.5 ± 26.1	7.5 ± 7.3	3.26 ± 2.2	5.0 ± 1.7
GS	Minimum	2	2	1	2
	Maximum	90	25	7.5	7
	Median ± SD	30.5 ± 30.4	8 ± 5.5	3.7 ± 5.0	5 ± 8.9
VFS	Minimum	2	0.17	0.7	1.2
	Maximum	120	25	23.53	45
	Median ± SD	91.9 ± 42.8	9.7 ± 13.5	8.4 ± 8.2	4.5 ± 4.5
BR	Minimum	1.8	0.92	2	2
	Maximum	150	46	32.9	19
	Median ± SD	191.3 ± 71.5	12.1 ± 13.2	8.9 ± 32.1	4.5 ± 5.5
PP	Minimum	47.5	2.6	2.9	2
	Maximum	227.7	40.9	77.6	19

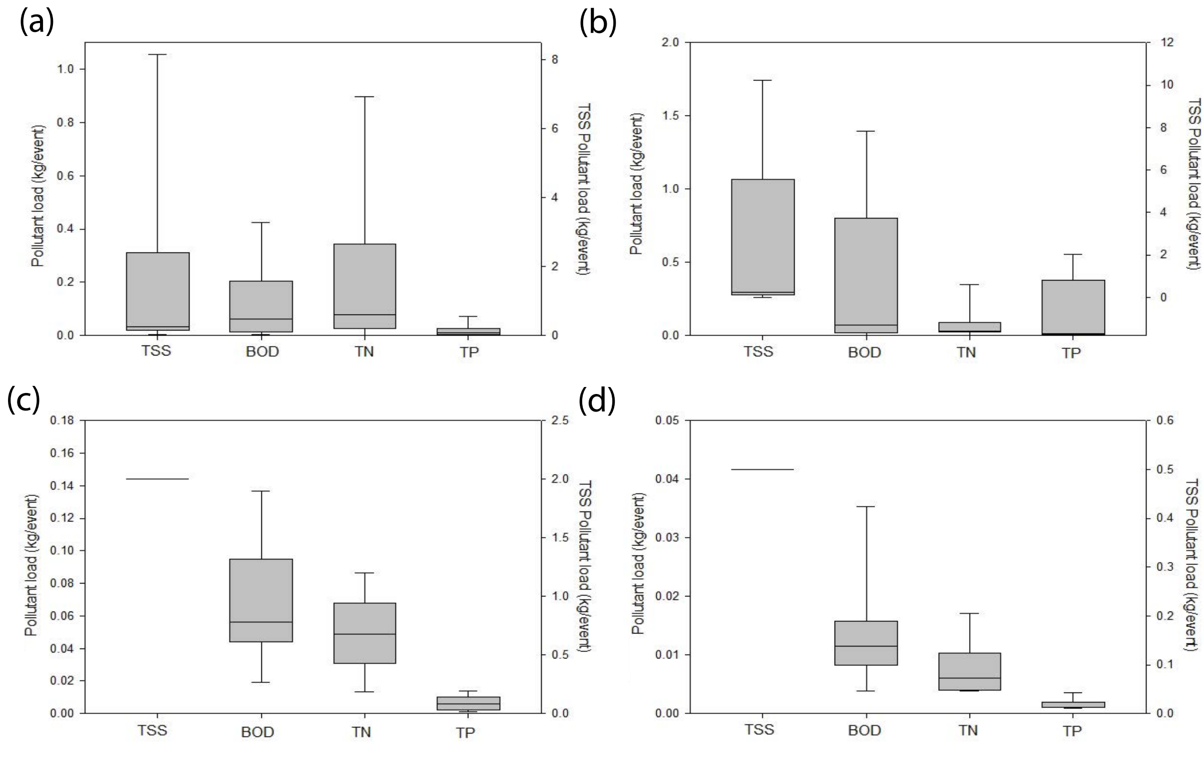

Fig. 2. Inflow pollutants load of monitored LID facilities: (a) GS, (b) VFS, (c) BR, and (d) PP-B.

3.2. Reduction efficiency by LID facility

Fig. 3 indicates the LID study facility and the flow rate and the reduction efficiency of the GS, VFS, BR, and PB. For runoff reduction effect, BR (94.6%) > PB (86.1%) > GS (59.7%) > VFS (51.6%) (Fig. 3a), the difference between the maximum and minimum efficiencies of the GS and VFS was approximately 43%. For pollutant reduction effect (Figs. 3b–e), summation of load (SOL) was used, and showed a tendency similar to the emission reduction efficiency because it was substantially affected by the emission reduction efficiency. From on-site monitoring, the median values of the monitoring targets showed reductions of more than 70% of TSS, more than 60% of BOD, more than 60% of TN, and more than 60% of TP. For BR and PB, the median value of the reduction efficiency of pollutants was shown to be over 90%. In addition, the GS and VFS have a relatively wide range of flow rate and pollutant reduction efficiency compared to BR and PB. The main reasons for this difference in reduction efficiency are firstly, the effect of SA/CA (LID facility surface area/catchment area). The SA/CA of the GS and VFS with relatively low reduction efficiency

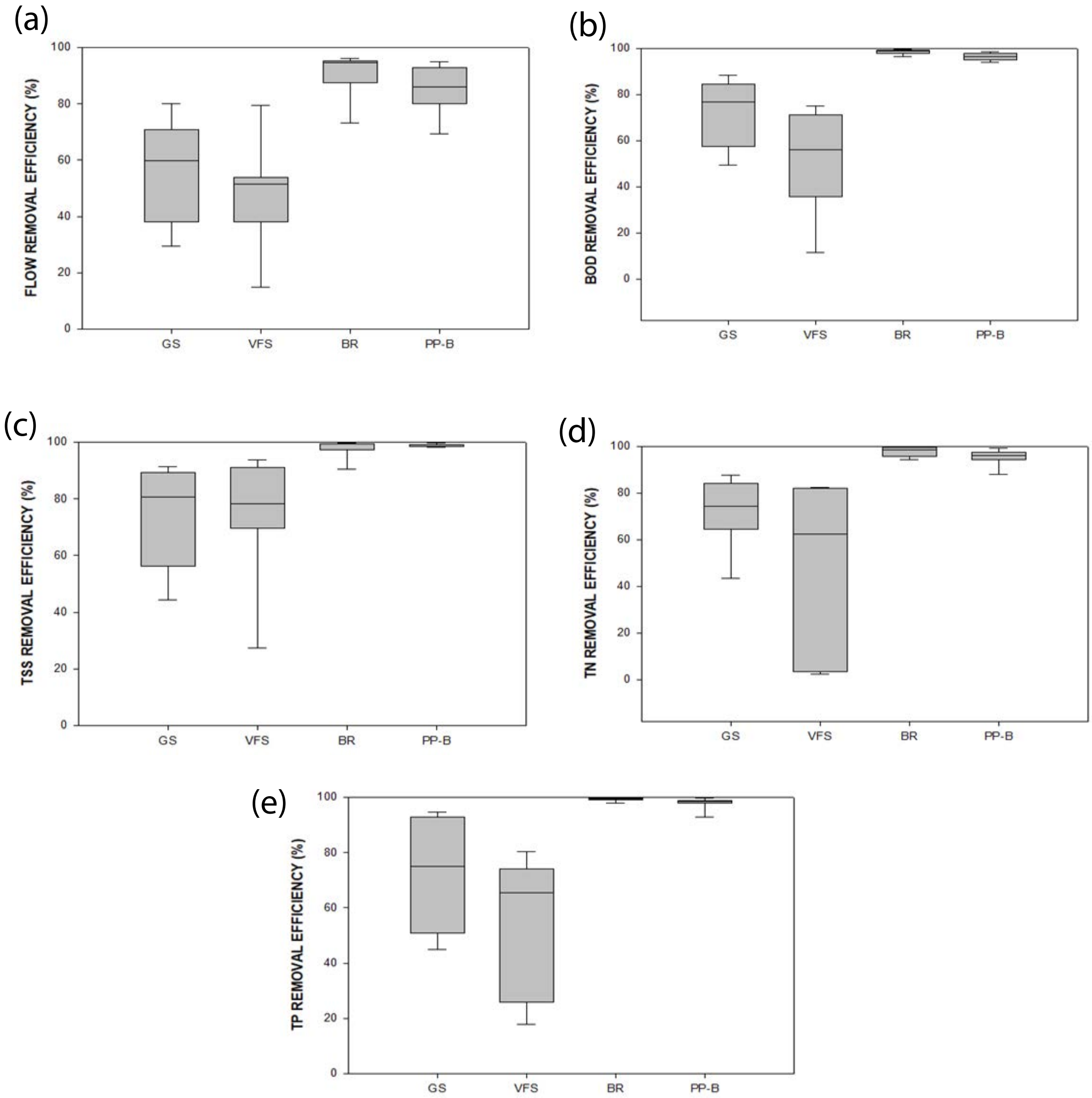

Fig. 3. Flow and pollutants reduction efficiency of monitored LID facilities: (a) flow, (b) TSS, (c) BOD, (d) TN, and (e) TP.

are 0.006 and 0.003, which is lower than 0.495 and 1.0 for the SA/CA of the BR and the PB. Translated into facility area and basin area, the watershed area to be reduced per unit area of the LID facility is 188.7 and 301.2 m^2/m^2, respectively. As the BR and the PB are small (5.4 and 1 m^2/m^2, respectively), the reduction efficiency is considered large. Secondly, structural differences in facilities can be examined. GS and VFS reduce rainfall runoff based on flow, while infiltration reservoirs and permeation blocks are LID facilities based on storage. As shown in Table 1, the capacity estimation criteria used in designing LID facilities also apply different values of WQF and WQV [16]. In addition, the difference in monitoring rainfall conditions and land use patterns can be considered. A large amount of monitoring has been carried out under various rainfall conditions, and therefore the impact is relatively insignificant compared to the two mentioned above.

3.3. Comparison of reduction efficiency between WQF *and* WQV *infrastructure*

Fig. 4 demonstrates the result of comparing and analyzing the flow rate and pollutant reduction efficiency by grouping the facilities to be studied based on the capacity estimation criteria (F and V for each item's mean WQF and WQV, respectively). As shown, the overall efficiency of the group based on the WQV capacity estimation was high for all items. The median rainfall effluent reduction efficiency showed a difference of 37.4%, and pollutant reduction efficiency showed a difference of 20%–37.1% for each item. In addition, the range of reduction efficiency of field monitoring was analysed to be low in LID facilities based on WQV. It can be interpreted that, based on WQV, a more stable reduction efficiency can be expected in LID facilities.

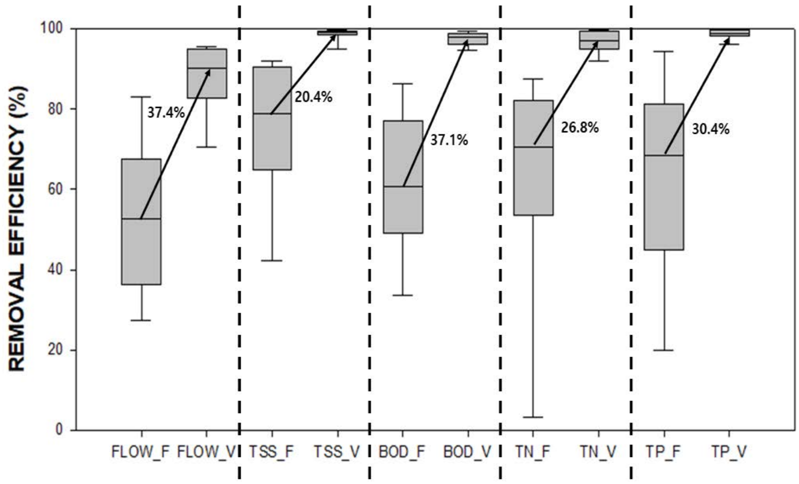

Fig. 4. Comparison of flow and pollutants removal efficiency according to design criteria of LID.

There may be various reasons for such efficiency differences such as monitoring sites for rainfall conditions, dry season days, and land use patterns as well as the structural differences between LID facilities based on WQF and WQV capacity estimation criteria. In general, LID facilities, based on estimations of WQF capacity, have rainfall and runoff flows along the surface of the GS and VFS and has the basic structure of filtration and partial infiltration. Conversely, in the LID facilities based on the WQV capacity estimation such as reservoirs, infiltration ditches, plant cultivation pots, BR, and PB, the basic structure was to temporarily store rainfall runoff and infiltrate the lower soil [16] As such, LID facilities based on WQF and WQV capacity estimations show clear differences in their basic structural aspects [16]. Therefore, the basic structure of the LID facility appears to be the main cause of the difference in flow rate and pollution reduction efficiency. However, due to the lack of analytical monitoring facilities, the amount of monitoring data, and the difference in experimental conditions, it is unreasonable to generalize the results of this analysis as LID facilities based on WQV capacity. Estimation criteria are more effective in suppressing rainfall and pollutant outflow than LID facilities based on WQF capacity estimation criteria. However, the results of this study confirm the possibility that there may be a slight difference in the efficiency of LID facilities applying WQF and WQV as the capacity estimation criteria. Further investigation and research is needed to verify this.

3.4. Proper area calculation plan for LID facilities

It was analyzed the correlation between reduction efficiency and facility area/watershed area (SA/CA) for the estimation of capacity and area of appropriate LID facilities, using the monitoring-based reduction efficiency of this study facility. For SA/CA, the design factors of the study facilities presented in section 2 (materials and methods) were used. For each LID facility, SA/CA was applied as GS 0.0053, VFS 0.0033, BR 0.4955, and PP 1.0. The purpose of this analysis was to correlate two continuous data sets of LID facility SA/CA and reduction efficiency. A simple regression analysis using linear and nonlinear regression models was applied (Fig. 5). As the SA/CA value increased, the reduction efficiency showed a positive linear relationship in all the items analyzed. As a result of examining the coefficients of determination between each item in Table 3, the linear regression model showed a strong correlation of more than 0.7 in the flow rate reduction efficiency (0.7146) and the TP reduction efficiency (0.8192). Conversely, the nonlinear regression model showed a tendency to increase the coefficient of determination for each item. In particular, it exhibited a high coefficient of determination on the flow rate reduction efficiency (0.9471), BOD reduction efficiency (0.8348) TP and the reduction efficiency (0.9628). In other items, the coefficients of nonlinear regression model were higher than those of the linear regression model. This suggests that the relationship between SA/CA and LID facility reduction efficiency can be more strongly identified through the nonlinear regression model.

3.5. Changes in LID facility efficiency according to SA/CA and L/CA

As a result of the analysis in section 3.2, the reduction efficiency of the LID facilities differs according to the design capacity estimation criteria due to the basic structure. However, SA/CA in section 3.3 (comparison of reduction efficiency between WQF and WQV infrastructure) is an analysis that does not take into account the structural differences of LID facilities although the facility area is commonly used as a variable. Therefore, this section intends to apply the structural differences of LID facilities to the SA/CA analysis. To analyze correlations with the reduction efficiency, facilities based on a WQV design capacity calculation (botanical habitat and permeation block) apply SA/CA, and facilities based on WQF design capacity calculation (GS and VFS apply L/CA. The SA/CA of BR and PB are the same as in section 3.3 (comparison of reduction efficiency between WQF and WQV infrastructure). The L/CA of GS and VFS was applied to 0.0039 and 0.0027, respectively. Fig. 6 shows the linear and nonlinear regression curves of SA/CA and L/CA and reduction efficiency. Table 4 summarizes the correlation coefficients for each regression curve. As a result

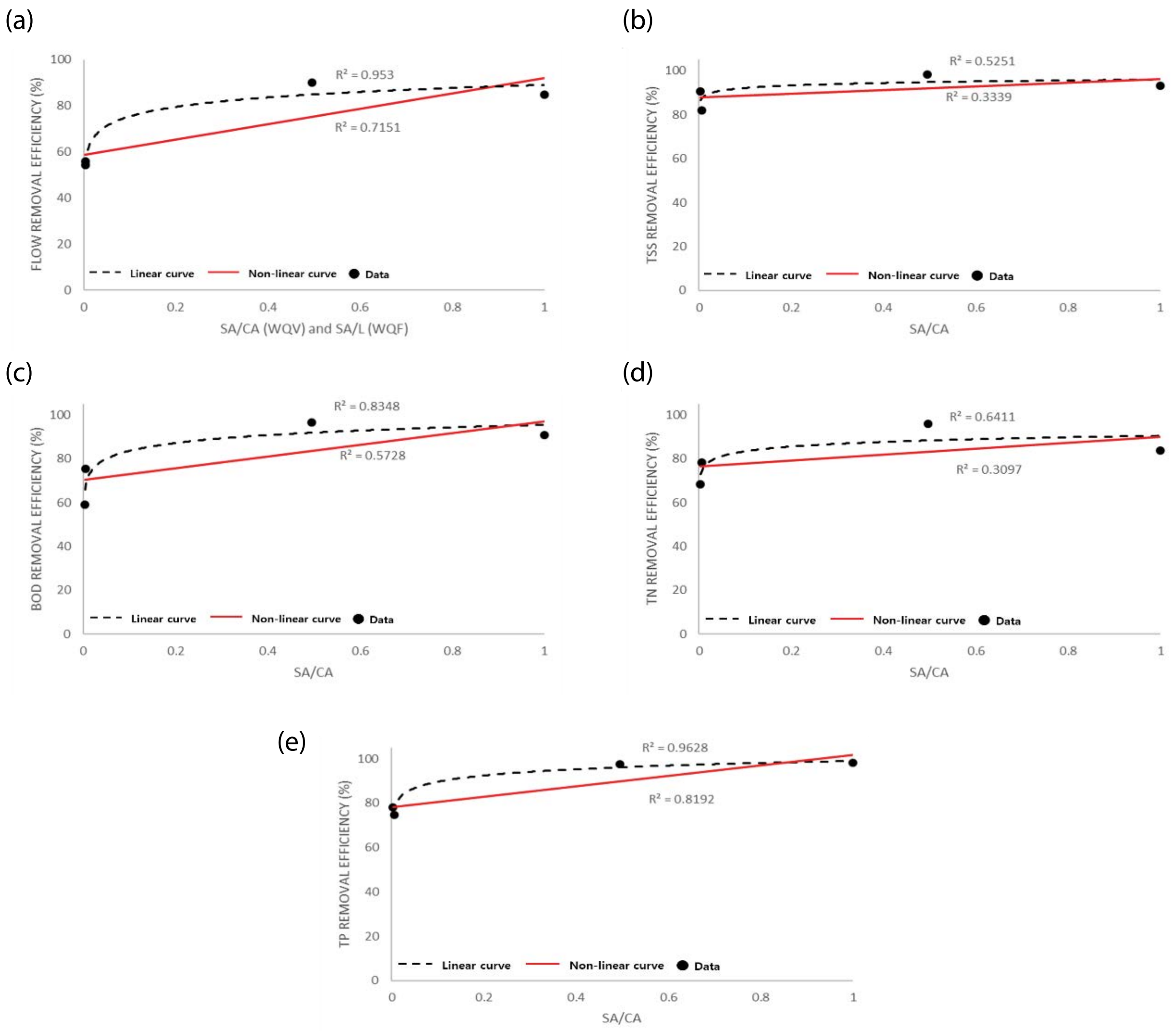

Fig. 5. Regression curve between SA/CA and removal efficiency: (a) flow, (b) TSS, (c) BOD, (d) TN, and (e) TP.

Table 3
Coefficient of determination between SA/CA and removal efficiency

Parameters	Coefficient of determination	
	Linear	Non-linear
Flow	0.7146	0.9471
TSS	0.3339	0.5251
BOD	0.5728	0.8348
TN	0.3097	0.6411
TP	0.8192	0.9628

Table 4
Coefficient of determination between "SA/CA and L/CA" and removal efficiency

Parameters	Coefficient of determination	
	Linear	Non-linear
Flow	0.7151	0.953
TSS	0.3347	0.5502
BOD	0.5727	0.8187
TN	0.3097	0.6297
TP	0.8197	0.9724

of the analysis, similar to SA/CA in section 3.3 (comparison of reduction efficiency between WQF and WQV infrastructure), SA/CA and L/CA and reduction efficiency showed a positive linear relationship, and the coefficient of determination of nonlinear regression curve was higher than that of the linear regression curve. The linear regression model showed a strong correlation in the flow reduction efficiency (0.7151) and the TP reduction efficiency (0.8197), and the nonlinear regression model showed a strong correlation in the flow reduction efficiency (0.953), BOD reduction

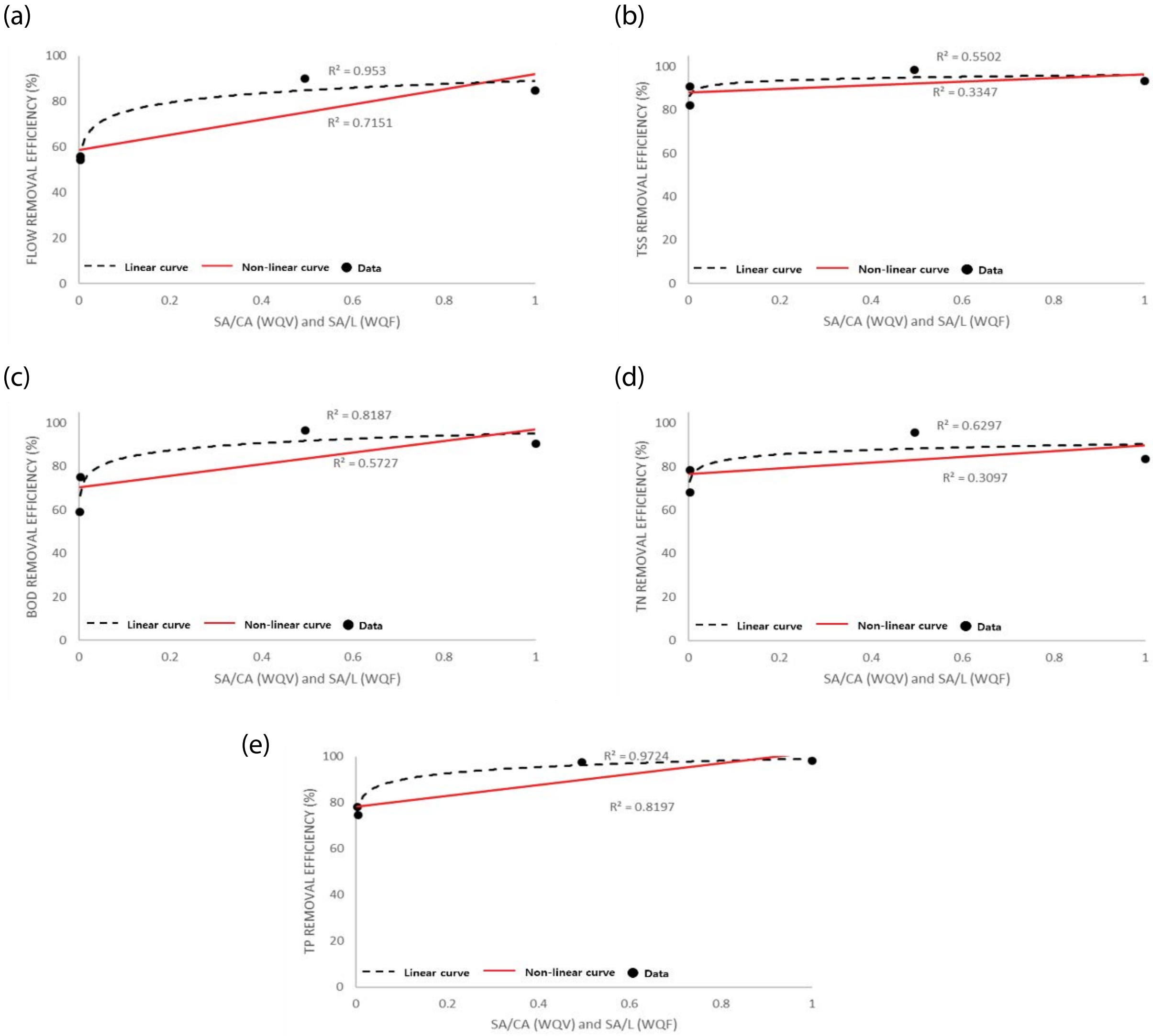

Fig. 6. Regression curve between "SA/CA and L/CA" and removal efficiency: (a) flow, (b) TSS, (c) BOD, (d) TN, and (e) TP.

efficiency (0.8187), and TP reduction efficiency (0.9724). Therefore, it would be appropriate to apply a nonlinear regression curve when applying SA/CA and L/CA.

In order to reflect the correlation of reduction efficiency with "SA/CA" and structural differences of LID facilities, Table 5 compares the coefficients of regression curves for each item to analyze the improvement effect of the SA/CA and L/CA presented in this paper. In the case of the linear regression model, the coefficient of difference was in the range of 0.0 to 0.0008 and in the case of the nonlinear regression model, the range was –0.0161–0.051. Applying SA/CA and L/CA instead of SA/CA did not show a clear increase in the coefficient of determination, but showed the largest increase in the coefficient of determination in the TSS (0.0251), and the highest coefficient of determination (0.9724) in TP. For this analysis, the number of data used is relatively small, so it is not easily generalized and applied. However, based on the increase in the coefficient of determination in Flow, TSS, and TP, and no significant decrease in the coefficient of determination, WQF-based facilities using L/CA instead of the conventional SA/CA to determine the proper area is necessary to fully review the use of the system.

Table 5
Gap of coefficient of determination between SA/CA and "SA.CA and L/CA"

Parameters	Gap of coefficient of determination	
	Linear	Non-linear
Flow	0.0005	0.0059
TSS	0.0008	0.0251
BOD	0.0001	–0.0161
TN	–	–0.0114
TP	0.0005	0.0096

The 42 rainfall monitoring results were investigated from articles and reports [17,22]. Thus, total 45 rainfall

Table 6
Review of the possibility of adequacy evaluation of “SA/CA and L/CA”

Parameters	G_1	G_2	G_3	G_4	G_5	G_6	G_7
TSS	0.0025	0.0151	0.2749	0.0293	0.0406	0.0038	0.2137
COD	0.1029	0.2353	0.1029	0.2353	0.1580	0.4870	0.4939
TN	0.0001	0.0246	0.0805	0.0542	0.1536	0.1181	0.0741
TP	0.0063	0.0664	0.1209	0.0393	0.1726	0.0451	0.0099

G_1. ALL (SA/CA): all resources SA/CA.
G_2. ALL (SA/CA and SA/CA and L/CA): WQV applies SA/CA, WQF applies L/CA.
G_3. EXCEPT 1 (SA/CA): ALL (SA/CA): SA/CA data except SA/CA 1 value.
G_4. EXCEPT 1 (SA/CA and SA/CA and L/CA): data except SA/CA is 1 WQV applies SA/CA, WQF applies L/CA.
G_5. EXCEPT 1 (WQV): SA/CA data for WQV only.
G_6. EXCEPT 1 (WQF): L/CA for WQF only.
G_7. EXCEPT 1 (L): L for WQF only.

monitoring results were used in this research. Table 6 shows the correlation coefficient (R^2) between pollutant removal efficiency and characteristics of LID structure (surface area and length). According to various grouping of basic management mechanism of LID facility. Overall R^2 was calculated under 0.3, except TN (using SA/CA) and (using L/CA). Especially, group of SA/CA (total) calculated lower R^2 than other groups. According to this result, capacity assessment of LID based on SA/CA is expected to show low accuracy result than other cases. Thus, it is deemed suitable to separate and consider in the design of LID facility according to design criteria.

4. Conclusions

In this study, the inflow/outflow EMC and pollutant removal efficiencies were analyzed. Based on the results of the analysis, a study was conducted on the necessity of estimating the appropriate design volume according to the characteristics of the permeable pavement. The results are as follows.

- The difference in rainfall runoff and reduction efficiency for each LID facility was determined by the SA/CA and structural differences.
- The LID facilities in this study were grouped into WQV and WQF, which are capacity design criteria, and the results showed that the efficiency of rainfall effluent and pollutant load reduction for the facilities designed based on WQV were relatively high.
- According to the SA/CA analysis for estimating the appropriate LID facility capacity and area based on the resources of the researched LID facilities, the rainfall runoff, TSS, BOD, TN, and TP items all had a coefficient of determination of 0.5 or more. In TP, the coefficient of determination was approximately 0.95. In contrast, the SA/CA and L/CA analysis, which considered the structural differences between the WQV and WQF facilities, suggests an improvement in the coefficient of determination, TSS and TP. Although the number of data used in the analysis was too small for generalization, it is prudent to consider applying the SA/CA and L/CA analysis method that reflects the structural differences to estimate the proper capacity and area of the LID facility.

The management mechanism of LID could be considering for the analyzed of optimal LID capacity. Thus, it is necessary to research about method of improved accuracy for evaluation of LID capacity.

Acknowledgments

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