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Optimal design of bioretention cells using multi-objective optimization technique

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ABSTRACT

The installation and maintenance costs, as well as non-point pollution reduction efficiency of LID facilities, should be reflected to design and apply LID facilities. In addition, when considering the characteristics of LID facilities installed in a spatially distributed way, efficiencies and costs associated with installation locations of LID facilities should also be reflected in the design. In this study, the optimal design method of multiple bioretention cells is proposed with a focus on considering both cost and non-point pollution (TP) reduction efficiency. EPA SWMM is applied to simulate bioretention cells in the target catchment, and an interaction module between MATLAB and EPA SWMM is constructed to optimize multiple objective functions. The target catchment is the Daeyeon Campus of Pukyong National University at Busan, South Korea, and a total of 140 bioretention cells design alternatives are searched to obtain optimal design solution. As a result of comparing the three design alternatives based on the cost, it is shown that the proposed method can find the optimal design layout for a total design capacity of bioretention cells and install locations in accordance with the given budget.

Keywords: Bioretention cells; EPA SWMM; Low impact development; Multi-objective optimization

1. Introduction

The rapid urbanization caused by the industrial development of South Korea has inevitably resulted in an increase in impervious area, and non-point pollutant sources in urban areas have received much public attention. Accordingly, the Ministry of Environment in Korea (KMOE) recently introduced the concept of low impact development (LID) and began efforts to manage stormwater. LID is an urban development concept with minimal impact on the natural system, and one of the purposes for MOE to introduce the LID concept is intended to manage non-point pollutant sources with spatially distributed small LID facilities [1].

Some domestic studies introducing the LID concept are as follows. Including Park et al. [2] who investigated the optimal design capacity of a bioretention facility which is one of popular non-point pollutant sources reduction facilities in South Korea, many studies have been conducted to design facilities [3,4]. These studies can be summarized as a study to estimate the optimal capacity for non-point pollution sources reduction facilities or explore their optimal installation locations. However, the above studies are difficult to apply to real policies since the cost for the construction and maintenance of facilities was not clearly considered [5].

In order to overcome this drawback, studies considering non-point pollutant sources reduction efficiency and economic feasibility of facilities are in progress. In the work done by Zhang et al. [6], genetic algorithm was used to find a cost-effective solution which gave the optimized design capacity and installation locations of a non-point pollutant sources reduction facility with the highest stormwater reduction rate. Similar studies have been done by Harrel and Ranjithan [7], and Maringanti et al. [8]. As a relevant domestic research, Lee et al. [5] used SUSTAIN to calculate the optimal size of LID facilities and their optimal installation locations and to draw up economic costs of the corresponding

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optimal design solutions. However, they reported that there were a lot of problems that should be solved before applying SUSTAIN to South Korea.

In this study, an LID facility design method which can give the cost-effective solution to reduce non-point pollutant sources is proposed for the purpose of direct practical applications. EPA SWMM which is the most popular LID facilities design computer software in South Korea is used to quantify non-point pollutant sources reduction efficiency of LID facilities installation. The LID facility in this study is limited to bioretention cells. The target catchment is the Daeyeon Campus of Pukyong National University located in Busan, South Korea, and the non-point pollutant sources reduction efficiency when a number of bioretention cells installed within various budget scenarios are investigated. The genetic algorithm of the Pareto method is applied to find the optimal solution of the various installation alternatives within the budget. Since it requires a large number of EPA SWMM runs to select the best alternative of various alternatives, the automatic interaction operating module between SWMM and MATLAB is built.

2. Materials and methods

2.1. Target catchment

Daeyeon Campus of Pukyong National University which is the target catchment in this study with an area of 34.95 ha can be divided into the impervious and pervious area. Approximately 60% of the total area occupied by impervious area can be divided into six land use conditions, such as residential, commercial, culture–sports–recreation facilities, transportation, public facilities, and playground area. Pervious area (approximately 40%) is composed of agricultural plantations section, coniferous trees section, and artificial grass section (Fig. 1).

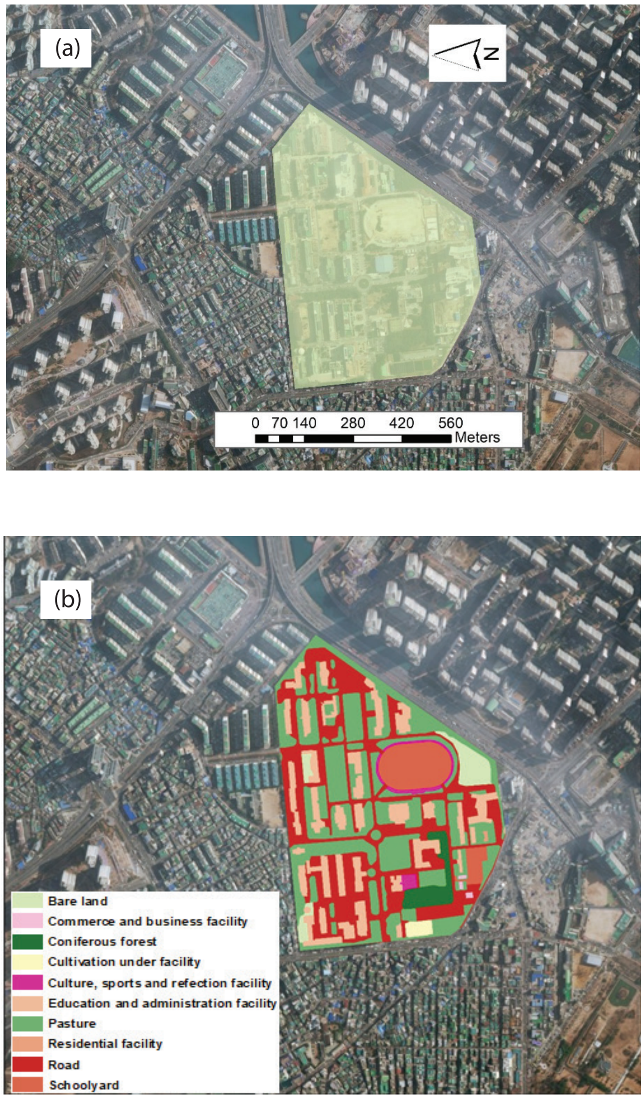

Fig. 1. Study area. (a) Aerial image and (b) land use.

2.2. Model development

2.2.1. EPA SWMM

Based on the stormwater pipe network of Daeyeon Campus, the model was developed using SWMM with a total of 62 sub-catchments and 2 outlet points (Fig. 2), and Table 1 presents the total area and impervious rate of each sub-basin.

Catchment characteristics which are necessary to construct SWMM were obtained from the digital elevation model with spatial resolution of 30 m, detailed land use map was provided by KMOE, detailed soil map was provided by Korea Rural Agency, and so on. Hourly precipitation data (2004–2014) and monthly evaporation data in Busan station operated by Korea Meteorological Administration [9] were used.

2.2.2. Model parameters estimation

After the model is developed, it is necessary to estimate model parameters to simulate the actual rainfall runoff phenomena. Ideally, model parameters should be estimated by using the actual measurement data, but there is no observed data on the stormwater quantity and quality in the target catchment. In fact, the absence of observations is the same situation in most of the urban drainage catchments in Korea. Therefore after separating impervious and pervious area, daily stormwater reference time series are constructed for each area to be used for model parameters estimation. The daily stormwater reference time series is produced by using the soil moisture index method based on NRCS-CN method [10]. After making monthly stormwater reference time series from daily stormwater reference time series, model parameters minimizing the objective function of Eq. (1) are estimated.

$$f = \sqrt{\frac{\sum_{n=1}^{N}\left(S_{\text{runoff},n} - O_{\text{runoff},n}\right)^2}{N}} \tag{1}$$

where O_{runoff} is the monthly reference stormwater (mm/month), and S_{runoff} is the corresponding simulated stormwater (mm/month). N is the number of data. In this study, the interaction module for estimating SWMM parameters developed by Choe et al. [11] is used, and the estimated stormwater parameters are shown in Table 2.

The monthly water quality (total phosphorus, referred as TP) reference time series are the monthly land-based emission loads which can be calculated in the manner specified by the Korean total maximum daily load technical guidance [12]. Water quality parameters are estimated with the objective function of Eq. (2):

$$f = \sqrt{\frac{\sum_{n=1}^{N}\left(S_{\mathrm{TP},n} - O_{\mathrm{TP},n}\right)^2}{N}} \tag{2}$$

where O_{TP} is the monthly reference water quality (kg/month), and S_{TP} is the corresponding simulated water quality (kg/month). Non-point pollutant loading in SWMM is simulated by the build-up and wash-off processes. The exponential function is used for the build-up process, and EMC (Event Mean Concentration) proposed by Park [13] is applied for the wash-off process in this study. Therefore, the number of water quality parameters which should be estimated is two which are related to the build-up process. One is the maximum possible build-up parameter (mass per area), and the other is the build-up rate constant (L/d). Land use is further considered in estimating each parameter value. As with stormwater parameters estimation, the interaction module for estimating SWMM parameters is used. Simulation period for the estimation of parameters is 11 years (2004–2014), and the first year (2004) is used in order to stabilize the model.

Fig. 2. EPA SWMM model of the sub-catchments.

Table 2
Description of estimated stormwater parameters [16]

Parameter	Description
% Slope	Average surface slope (%)
N-Imperv	Manning's N for impervious area
N-Perv	Manning's N for pervious area
Dstore-imperv	Depth of depression storage on impervious area (mm)
Dstore-perv	Depth of depression storage on pervious area (mm)
Curve number	NRCS curve number

Table 1
Percentage of impervious area in each sub-catchment

Sub-catchment	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11
Area (ha)	0.41	0.33	0.15	0.16	0.22	0.50	0.36	0.31	0.33	0.29	0.23
Impervious rate (%)	83.54	35.04	1.86	31.02	64.99	81.95	85.16	63.96	93.26	88.89	100.00
Sub-catchment	A12	A13	A14	A15	A16	A17	A18	A19	B01	B02	B03
Area (ha)	0.13	0.51	0.22	0.33	0.64	0.17	0.43	0.31	0.72	0.83	0.49
Impervious rate (%)	86.04	93.59	0.00	100.00	92.55	8.36	35.53	32.66	95.12	39.76	42.07
Sub-catchment	B04	B05	B06	B07	B08	C01	C02	C03	C04	C05	C06
Area (ha)	0.88	0.45	0.88	0.55	0.52	0.49	1.02	0.73	0.27	0.46	0.87
Impervious rate (%)	13.35	50.89	53.55	98.52	100.00	50.06	59.28	40.06	69.64	69.28	62.23
Sub-catchment	C07	C08	C09	C10	C11	D01	D02	D03	D04	D05	D06
Area (ha)	0.80	0.63	1.00	0.48	0.53	1.13	0.52	0.21	0.33	0.71	0.19
Impervious rate (%)	29.58	78.62	43.52	73.28	7.03	13.80	87.17	89.19	88.95	8.32	94.08
Sub-catchment	D07	D08	D09	D10	D11	D12	F01	F02	F03	F04	F05
Area (ha)	1.11	0.89	0.30	0.49	0.46	0.28	0.77	1.64	0.85	2.70	1.90
Impervious rate (%)	9.04	67.03	92.03	51.12	96.62	19.17	62.40	77.51	49.05	80.44	60.95
Sub-catchment	F06	G01	G02	G03	G04	G05	G06				
Area (ha)	0.30	0.33	0.19	0.20	0.18	0.23	0.41				
Impervious rate (%)	76.95	72.07	87.83	62.87	99.69	81.07	74.47				

2.3. Design storm event

In order to derive the optimal design of bioretention cells in the target catchment, it is appropriate to use successive rainfall data obtained over a long period of time (e.g., 10 years). However, it takes a lot of time searching the optimal design solution for long-term simulation. Zhang et al. [6] reported that using a 24-h 10-year design storm event takes approximately 23 h to explore the best design solution for non-point pollutant sources facilities. In order to save the time of the optimization, a design rainfall event is set. Since LID facilities such as bioretention cells are designed to mainly intercept stormwater due to average rainfall events and not for extreme events, the average rainfall event was used as the design storm. Fig. 3 illustrates the procedure used to develop the design storm event applied in this study. First, hourly precipitation time series are separated into individual events using IETD (inter-event time definition) [14]. Since the hydraulic detention time of bioretention cells is recommended to be 24 h [15], IETD is set to be 24 h. For each separated storm event, the corresponding stormwater depth is calculated by using the NRCS-CN method. The value of 2.5 mm for the incipient loss of impervious surface in the NRCS-CN method is used. After the stormwater depth for each land use and soil patch is calculated, the event stormwater depth for the target catchment is computed by using area-weighted averaging. The mean of all non-zero event stormwater depth is defined as the design stormwater depth. The design rainfall depth can be obtained by using the inverse NRCS-CN method. The temporal distribution of the design rainfall depth is determined as follows. All rainfall events are classified into four levels with respect to rainfall depth; less than 10 mm, 10–30 mm, 30–50 mm, and more than 50 mm. All events in the level including the design rainfall depth are used to find the averaged dimensionless duration – dimensionless cumulative rainfall depth curve. The duration and inter-event time of the design storm event are defined as the mean value of all event durations and inter-event times in the level, respectively.

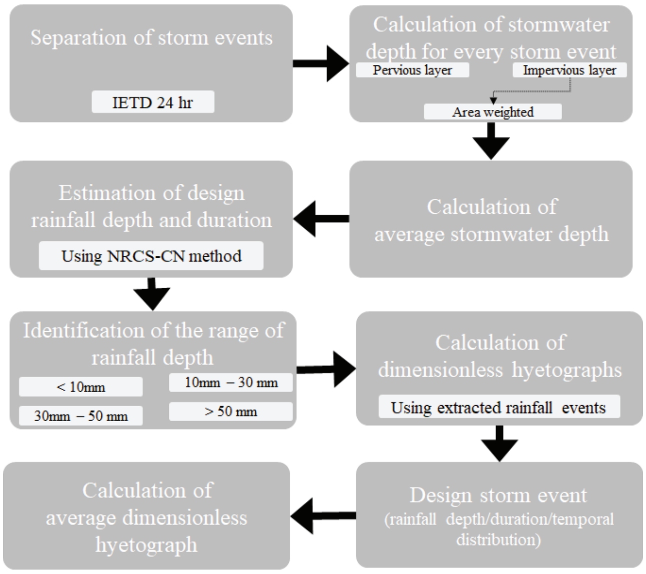

Fig. 3. Procedure for design storm hyetograph estimation.

2.4. Bioretention cells

In SWMM, the bioretention cell consists of three conceptual vertical layers: surface layer, pavement layer, and the storage layer. The surface layer is a layer into which rainfall or stormwater is directly introduced, and is a place where rainfall or stormwater can overflow, evaporate, infiltrate, get transpired, and be retained for a while. The pavement layer consists of porous concrete and asphalt, or porous block, and the infiltrated rainwater or stormwater from the upper surface layer is stored in the pavement layer and then infiltrated again into the lower storage layer. The storage layer consists of gravels with a relatively large porosity, which is the space where the infiltrated water is stored. SWMM parameters associated with bioretention cells are shown in Table 3.

Fig. 4 shows sub-catchments where bioretention cells can be installed, and Table 4 shows the size of the area of sub-catchments available for the possible installation of bioretention cells. The area in Table 5 shows the area where bioretention cells can be installed at the maximum.

2.5. Multi-objective optimization

The reduction efficiency of non-point pollutant sources (TP) and the cost for construction and management should be considered in the optimization process for designing bioretention cells. Given the standard layout of a bioretention cell, the increase of the total facilities installation surface area resulted in the reduction of TP loading and the increase in the cost. That is, TP loading and cost have an inverse relation. In this case, it is impossible to use a single objective function in the optimization process. Therefore, multi-objective optimization which is a multiple criterion decision-making processes and has more than one objective function to be optimized simultaneously is performed to design spatially distributed bioretention cells. In this study, a constrained

Table 3
Model parameters for bioretention cell [16]

Layer name	Parameter	Value
Surface layer	Berm height (mm)	300
	Vegetation volume	0
	Surface roughness	0
	Surface slope (%)	0
Soil layer	Thickness (mm)	600
	Porosity	0.45
	Field capacity	0.3
	Wilting point	0.15
	Conductivity (mm/h)	4.16
	Conductivity slope	10
	Suction head (mm)	3.5
Storage layer	Thickness (mm)	300
	Void ratio (voids/solids)	0.75
	Seepage rage (mm/h)	0
	Clogging factor	0

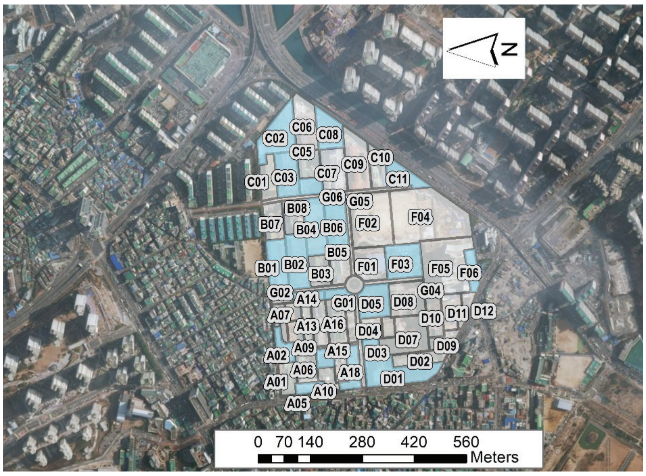

Fig. 4. Available sites for bioretention cells.

Table 4
Area available for installation of bioretention cells

Sub-catchment	Available area of bioretention cells (ha)	Sub-catchment	Available area of bioretention cells (ha)
A02	0.0328	C02	0.0035
A05	0.0218	C03	0.0364
A11	0.0231	C04	0.0272
A14	0.0443	C08	0.0630
A17	0.0345	C11	0.2665
A18	0.0428	D01	0.0565
B01	0.0720	D03	0.0320
B02	0.1665	D05	0.1411
B04	0.2000	F03	0.0425
B06	0.1060	F06	0.0303
Total area (ha)	1.4428		

Table 5
Bioretention cell cost (A: facility area, m^2)

Type	Equation
Construction cost (US Dollar)	147.7×A
Annual operation and maintenance cost (US Dollar)	13.64×A

multi-objective optimization technique by incorporating a Pareto genetic algorithm is applied. The surface area of bioretention cells served as decision variable, and the possible maximum area where bioretention cells can be installed is considered as constraints. Eqs. (3) and (4) are objective functions applied in this study.

$$f_{\text{op},1} = \sum_{i=1}^{N} C_i A_i \tag{3}$$

$$f_{\text{op},2} = T_{\text{total}} \tag{4}$$

where N is the number of bioretention cells, C is the cost per unit surface area of a bioretention cell, and A is the installed surface area of a bioretention cell. Eq. (3) means the cost for construction and management of installed bioretention cells. Environmental Management Corporation [17] presents costs for installing a bioretention cell and maintenance costs for 25 years. Using this reference, Table 5 shows the installation and maintenance costs per unit area (m^2) of a bioretention cell.

Eq. (4) is the TP loading from the target catchment after installing bioretention cells. If one focuses only on reducing TP loading which means to minimize the single objective function $f_{\text{op},2}$, the function $f_{\text{op},1}$ becomes increased since the surface area of installed bioretention cells are increased. Contrary, if one focuses only on reducing the cost, the reduction efficiency of non-point pollutant sources becomes decreased.

3. Results and discussion

3.1. Stormwater and TP loading simulations

Model parameters of SWMM for the target catchment are estimated through the procedure presented in section 2.2.2. Fig. 5(a) shows the reference stormwater time series which are produced by using the soil moisture index method combined with NRCS-CN method and the simulated stormwater time series. It can be seen that the stormwater is excellently simulated. Fig. 5(b) shows the reference TP loading time series which are produced by using the method recommended by National Institute of Environmental Research [12] and the simulated TP loading time series. It can be seen that the TP loading is also excellently simulated. For reference, the Nash-Sutcliffe model efficiency coefficients resulted from stormwater and TP loading simulation are 0.98 and 0.82, respectively.

3.2. Design storm event

The computed design stormwater depth is 25.95 mm and the corresponding design rainfall depth is 42.30 mm which is calculated by the inverse NRCS-CN method. The level including the design rainfall depth is 30–50 mm,

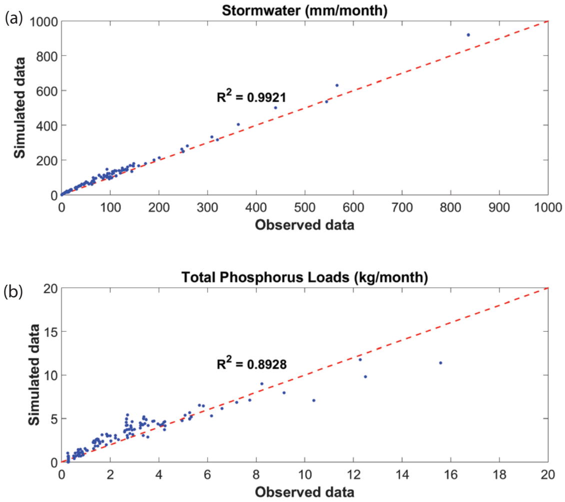

Fig. 5. Model calibration results: (a) stormwater, (b) total phosphorus loads.

and the number of events in this level over the past 10 years (2005–2014) is 46.

Fig. 6(a) shows all of the dimensionless duration–cumulative rainfall depth curves (thin lines) and the averaged curve (thick line). The duration and inter-event time of the design storm event are estimated to be 48 and 145 h, respectively. Fig. 6(b) shows the resulting design storm event hyetograph, which is the input storm event in the optimization process for designing bioretention cells.

3.3. Multi-optimization results for installing bioretention cells

Using the design storm event which represents the average storm event, the interaction module between EPA SWMM and MATLAB is constructed to obtain the optimal design solution. The Pareto method is applied to search the solution satisfying two objective functions (minimized cost and maximized TP reduction efficiency).

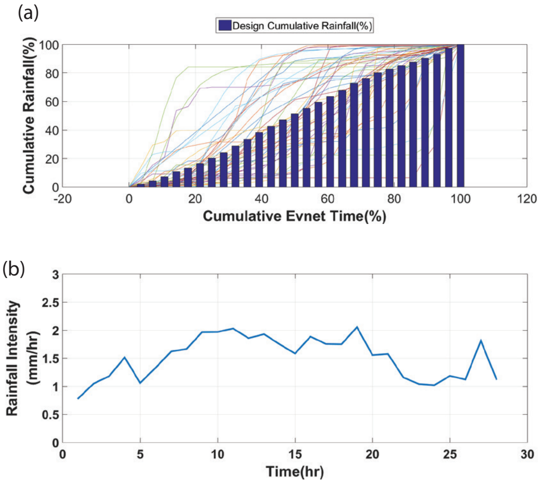

Fig. 6. Design storm event. (a) Cumulative rainfall curves and (b) design storm event hyetograph.

The black circles (●) in Fig. 7 show the results derived from all the alternatives analyzed to explore the optimal installation layout of bioretention cells. Of these alternatives, the red solid stars (✶) correspond to the optimal bioretention cells installation design in a given budget, and a total of 140 design alternatives are presented. As the installation area of bioretention cells increases, the necessary cost is increased, but the TP load is reduced. In addition, if the required cost is over about $900,000, the reduction effect of TP load is reduced even though the installation area of bioretention cells is increased. To illustrate this in more detail, three scenarios are selected, and the corresponding area and cost are shown (A, B, and C in Fig. 7, and Table 6). Scenario A assumes that bioretention cells are installed in 17.1% of the maximum installable area, which is the lowest cost of bioretention cell installation alternatives. The required cost is about $400,000, and the TP load is 1.35 kg. Scenario B was projected to increase costs by approximately 3.5 times compared with scenarios A and to reduce the TP load by 0.1 kg. Scenario C costs about 1.47 times more than scenario B, but TP load is reduced by only 0.008 kg. This is similar to the results of the study by Lee et al. [5], which reported that excessive cost is required to reduce non-point pollutants above a certain level.

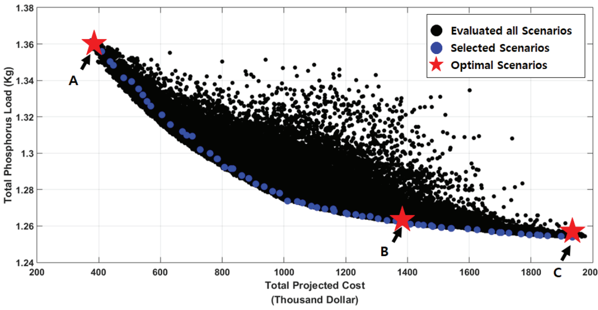

Fig. 7. TP loadings vs. total costs of all alternatives.

Table 6
LID facility surface area and total costs

Scenario A				Scenario B				Scenario C			
Sub-catchment	LID size (m^2)	Sub-catchment	LID size (m^2)	Sub-catchment	LID size (m^2)	Sub-catchment	LID size (m^2)	Sub-catchment	LID size (m^2)	Sub-catchment	LID size (m^2)
A02	56.3	C02	6.7	A02	282.0	C02	28.2	A02	285.4	C02	30.6
A05	24.8	C03	240.1	A05	144.8	C03	360.5	A05	188.0	C03	362.3
A11	86.7	C04	32.3	A11	182.2	C04	258.6	A11	167.2	C04	271.7
A14	176.6	C08	250.7	A14	184.3	C08	619.0	A14	269.7	C08	629.9
A17	14.1	C11	37.0	A17	135.9	C11	691.2	A17	189.4	C11	1,766.8
A18	281.2	D01	341.4	A18	368.8	D01	496.9	A18	378.8	D01	537.5
B01	57.0	D03	100.5	B01	719.4	D03	319.2	B01	719.2	D03	319.7
B02	302.6	D05	45.6	B02	827.0	D05	544.7	B02	1,648.5	D05	1,208.9
B04	77.8	F03	22.2	B04	1,310.3	F03	135.7	B04	1,685.1	F03	182.5
B06	373.3	F06	7.9	B06	1,059.8	F06	70.7	B06	1,059.6	F06	86.8
∑	2,534.75			∑	8,739.10			∑	11,987.5		
Cost (1,000 US Dollars)		4.09		Cost (1,000 US Dollars)		14.10		Cost (1,000 US Dollars)	19.34		

4. Conclusion

Several LID facilities evaluation has been previously conducted focusing on the non-point pollutant sources reduction efficiency. However, design methods for considering economic feasibility as well as the non-point pollutant sources reduction efficiency should be studied since ongoing maintenances are required.

In this study, the optimal design method for bioretention cells incorporating the non-point pollutant sources reduction efficiency and economic feasibility was proposed by using the multi-objective optimization technique. The Pareto method is applied to maximize the non-point pollutant sources reduction efficiency and to minimize the cost for facilities construction and maintenance, and the interaction module between SWMM and MATLAB are built up to ensure practical applicability.

In addition, the design storm events are presented to save the optimization time to search the optimal design layout for bioretention cells. The design storm event for installing LID facilities is proposed to represent normal storm events since extreme storm events are appropriate to design a flood-control facility. The design rainfall depth in Busan station is 42.30 mm, and its duration and inter-event time are 28 h and 145 h, respectively.

A total of 140 installation alternatives were identified for 20 sub-catchments where bioretention cells could be installed. While it was confirmed that the cost increases (that is, the increase of the installation surface area of bioretention cells) with reducing TP loadings, the investment in facilities over a certain amount was shown to be unable to secure the corresponding reduction of TP loadings expected by the investment.

Since the optimal bioretention cells design method proposed in this study can consider the non-point sources pollutant sources reduction efficiency and the corresponding cost, the proposed method is expected to be applicable in a more realistic design facilities LID scheme. However, since the proposed design approach is dealing with only one LID facility (bioretention cell) although bioretention cells are installed at multiple sites, there is a need for further research. In future studies, it will be needed to develop an optimal design method for various types of LID facilities.

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