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A Multi-Criteria Decision Analysis System for Prioritizing Sites and Types of Low Impact Development Practices: Case of Korea

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Abstract: This study developed a multi-criteria decision analysis (MCDA) framework to prioritize sites and types of low impact development (LID) practices. This framework was systemized as a web-based system coupled with the Storm Water Management Model (SWMM). Using TOPSIS method, which is a type of MCDA method, multiple types and sites of designated LID practices are prioritized. This system is named the Water Management Prioritization Module (WMPM). WMPM can simultaneously determine the priority of multiple LID types and sites. In this study, an infiltration trench and permeable pavement were considered for multiple sub-catchments in South Korea to demonstrate the WMPM procedures. The TOPSIS method was manually incorporated to select the vulnerable target sub-catchments and to prioritize the LID planning scenarios for multiple types and sites considering social, hydrologic and physical-geometric factors. In this application, the Delphi method and entropy theory were used to determine the subjective and objective weights, respectively.

Keywords: low impact development; multi-criteria decision analysis; Storm Water Management Model; Water Management Prioritization Module

1. Introduction

Urbanization alters the hydrologic cycle by increasing impervious surfaces [1,2], compacting pervious surfaces [3], replacing indigenous vegetation with irrigated ornamental vegetation [4], withdrawing water for urban uses [5], and discharging treated wastewater collected from municipal and industrial users [6]. Low impact development (LID), which is similar to best management practice (BMP), has become important in the preparation for and prevention of natural disasters [7,8]. Especially LID practices has been regarded as one of the climate change adaptation or mitigation strategies because they can mitigate the negative impact of climate change on urban hydrology [9–11]. Therefore, hydrological simulation models and decision support systems (DSSs) that use powerful engines to perform LID and BMP calculations have been used to simulate and analyze the hydrological effectiveness of the planned LID practices [12–15]. Several DSSs for LID design and planning have been developed based on different engines. The Best Management Practice Decision Support System (BMPDSS) [16] is the most notable planning and analysis tool and is based on ArcGIS. The BMPs SELECTion expert system (BMPSELEC) was developed to facilitate the ranking system and multi-criteria index system processes of BMPs [17].

However, the design and planning specifications of LID practices must be determined carefully [18–20]. The selection of LID types, installation location, size and number of LID facilities, and costs of construction, operation and maintenance are all important factors that affect the hydrological effectiveness and economic efficiency [21,22]. Even within a single LID type, determining the optimal or near optimal design and planning includes more than a dozen parameters. Meanwhile, many studies using multi-criteria decision analysis (MCDA) methods have been performed to determine the best specifications for water resource planning and management when considering various evaluation criteria [23,24]. MCDA can logically structure complicated problems and concretize various uncertainties. Therefore, all specifications for LID design and planning, locations and LID types can be systematically determined through the MCDA process, which considers both anthropogenic status and hydrological results [25,26].

There have been some popular DSSs such as Personal Computer Storm Water Management Model (PCSWMM) [27], System for Urban Stormwaer Treatment and Analysis IntegratioN (SUSTAIN) [28], Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) [29], BMPSELEC [17], BMPDSS [16], and Water Management Analysis Module (WMAM) [30] which have been further developed with powerful Geographic Information System (GIS) engines, high performance sensitivity tools, and cost-benefit optimization. However, they are not able to develop the priority of all feasible locations and types for the LID design and planning for a study area. In addition, priority for sustainable development should be objectively determined with the consideration of various social aspects as well as hydrologic effectiveness [31–33].

Therefore, a framework for analyzing multiple LID practices in multiple sites was developed in this study to prioritize all feasible scenarios defined by the user considering hydrological simulation results and additive social conditions. The result is a web-based DSS coupled with SWMM5.1, named the Water Management Prioritization Module (WMPM), which uses an MCDA framework for the systematic prioritization of multiple LID types and sites. This study also shows an example application of WMPM to South Korea.

This article consists of five sections. Section 2 describes the theoretical backgrounds for TOPSIS and subjective and objective weight derivation. Section 3 includes the description of WMPM software including functions and systematic framework. Section 4 presents the applications and results based on the eight-step framework of this study. Section 5 contains the discussions and conclusions of this study.

2. Background Theory

2.1. Description of the SWMM LID Function

Storm Water Management Model (SWMM) is highly recommended for runoff quantity and quality simulations in highly urbanized areas, and its most recent version has extended to cover the simulation of LID techniques. SWMM has editing tools called "LID control editor" and "LID usage editor". The "LID control editor" is used to define a LID practice that can be deployed throughout a study area to store, infiltrate, and evaporate sub-catchment runoff. The design of the control is made on a per-unit-area basis so that it can be placed in any number of sub-catchments at different sizes or numbers of replicates. Users are able to select the type of LID and enter the design parameter values to designate LID practices. The "LID usage editor" is used to specify how a particular "LID control" will be deployed within the sub-catchment. Note that the planning area of LID practices cannot be larger than the sub-catchment area [34].

LID design parameters are factors that define the physical properties of a unit surface that represents the LID practice. Parameters are grouped into several vertical layers that are applied to each LID type. The layered group consists of surface, pavement, soil, storage, drain, and drainage mats components. All layers can describe how much water moves and is stored as rainfall impacts the ground and flows to an outlet (Table 1). Each LID type has a minimum of five to a maximum of 23 parameters. The details are shown in [35]. For instance, an infiltration trench includes a surface layer, storage layer, and drain layer, and thus eleven design parameters (berm height, vegetation volume fraction, surface roughness, surface slope, thickness, void ratio, seepage rate, clogging factor, flow coefficient, flow exponent, and offset height) must be defined. Each parameter must be feasibly assumed while the value of some parameters can be ignored when there are physical constraints.

Table 1. Layers used to model different types of low impact development (LID) units.

LID Type	Surface	Pavement	Soil	Storage	Drain	Drainage Mat
Bio-retention cell	O		O	O	*	
Rain garden	O		O			
Green roof	O		O			O
Infiltration trench	O			O	*	
Permeable pavement	O	O	*	O	*	
Rain barrel				O	O	

Notes: O means required, * means optional.

LID planning parameters that are shown in Section 4.2 are factors that define the number, capacity and scale of designed LID practices. The values for the planning parameters will proportionally affect the final hydrological results. That is, the increase in area for each unit and the number of each unit will absolutely increase the degree of infiltration, storage, and runoff delay, while the percentage of the initially saturated area treated may increase direct runoff levels. Instead, the cost will increase. Therefore, using feasible planning parameter values that suit the given field circumstances is important.

2.2. TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is an MCDA method that considers the best alternative as the one with the shortest geometric distance from the positive ideal solution (PIS) and the farthest geometric distance from the negative ideal solution (NIS) [36]. The detailed procedures for TOPSIS are presented in [37]. After the closeness coefficients are calculated, all of the alternatives can be ranked. The separation measures between each alternative and the PIS and the NIS are defined as shown in Equations (1) and (2); then, the closeness coefficient of each alternative i can be defined as shown in Equation (3):

$$d_i^+ = \left\{ \sum_{j=1}^{m} \left(a_{ij} - a_j^+ \right)^2 \right\}^{\frac{1}{2}}, \quad (1)$$

$$d_i^- = \left\{ \sum_{j=1}^{m} \left(a_{ij} - a_j^- \right)^2 \right\}^{\frac{1}{2}}, \quad (2)$$

$$C_i^* = \frac{d_i^-}{d_i^+ + d_i^-}, \quad (3)$$

where d_i^+ is the geometric distance between alternative i and the PIS, d_i^- is the geometric distance between alternative i and the NIS, a_{ij} is the performance value of the jth criterion of alternative i, a_j^+ and a_j^- are the maximum and minimum values of a_{ij}, respectively, and C_i^* is the closeness coefficient of alternative i.

Therefore, TOPSIS among many MCDM methods was selected in this study due to the simple calculation process. In particular, the number of steps remains the same regardless of the number of attributes. Because this study included three sub-criteria consisting of eight indicators, TOPSIS was applied to two different steps in a flexible way.

2.3. Subjective and Objective Weight Derivation

In general, the weights for criteria can be derived in either a subjective or objective way. Delphi and entropy methods are frequently used to quantify all subjective and objective weights for criteria, respectively [38].

Delphi is a technique used to derive weighting values subjectively [39]. It is defined as a method for solving complex problems by collecting information through a series of questionnaires and feedback from a group of experts who remain anonymous to one another [40]. The Delphi method is a structured process for collecting and distilling knowledge from a group of experts using a series of questionnaires with controlled opinion feedback [41]. The Delphi technique uses a series of iterative questionnaires that are sent to a group of intentionally selected experts who remain anonymous to one another [42]. The results of the previous questionnaires are returned to the respondents, who are then allowed to modify their responses. By the second or third round of this process, it is hoped that the experts will arrive at a consensus on the estimation problem. If a judge happens to overlook some aspects of the problem, he will likely be apprised thereof through the feedback of others' opinions. Delphi is generally regarded as a very objective and rational method because no member of the panel can exert undue influence over the other members. When experts live some distance apart and it is prohibitive to bring them together for a committee meeting, Delphi can be very effective. Accordingly, the selection of panels is an important field to implement the Delphi technique [43].

Shannon's entropy is a method for determining criteria weights objectively [34–46]. The original procedure can be expressed as a series of steps [47]. The following steps were used to derive the objective weights in this study:

Step 1: Normalization of the raw data

$$P_{ij} = \frac{a_{ij} - a_i^-}{a_i^+ - a_i^-}\ (i = 1, 2, \ldots, m,\ j = 1, 2, \ldots, n), \tag{4}$$

where a_i^+ and a_i^- are the maximum and minimum values of x_{ij} in criteria i, respectively.

Step 2: Calculation of the entropy constant h_0 and entropy h_i

$$h_0 = (\ln n)^{-1},\ h_i = -h_0 \sum_{j=1}^{n} p_{ij} \cdot \ln p_{ij}, \tag{5}$$

Step 3: Calculation of the degree of diversification d_i

$$d_i = 1 - h_i, \tag{6}$$

Step 4: Calculation of the weight of criteria i, w_i

$$w_i = \frac{d_i}{\sum_{s=1}^{m} d_s}, \tag{7}$$

where i is the number of criteria, j is the number of alternatives, and p_{ij} is the normalized data.

3. Description of Water Management Prioritization Module (WMPM)

3.1. Functions of WMPM

WMPM is a DSS used to prioritize all the combined scenarios of multiple types and multiple sites of LID practices based on SWMM5.1. The specific information of WMPM availability is shown in Appendix A. Using the TOPSIS method, WMPM guides users to select the more vulnerable target sub-watersheds that can be easily affected by extreme rainfall intensity and long droughts in a hydrologic and social way. That is, WMPM uses the existing hydrologic conditions (e.g., peak flow and total flow) obtained from SWMM simulations and the social factors manually inputted by the user. Then, WMPM analyzes the simulated results of all feasible LID scenarios defined by the users and prioritizes them by the degree of their hydrological effectiveness (e.g., the total runoff and peak peal flow) and social vulnerability. WMPM also supports users by providing figures and tables to clarify and complete all outputs and by providing all the generated SWMM input and output files so that they can be used for SWMM.

3.2. Systematic Framework

The systematic procedure of WMPM is illustrated in Figure 1. WMPM has three systematic parts: (1) inputs for WMPM; (2) automatic generation, simulation, and calculation of WMPM; and (3) outputs of WMPM. The procedure of WMPM describes the eight steps that users should follow for the developed DSS, whereas the systematic algorithm describes the logic of how WMPM functions to determine the best LID planning and location.

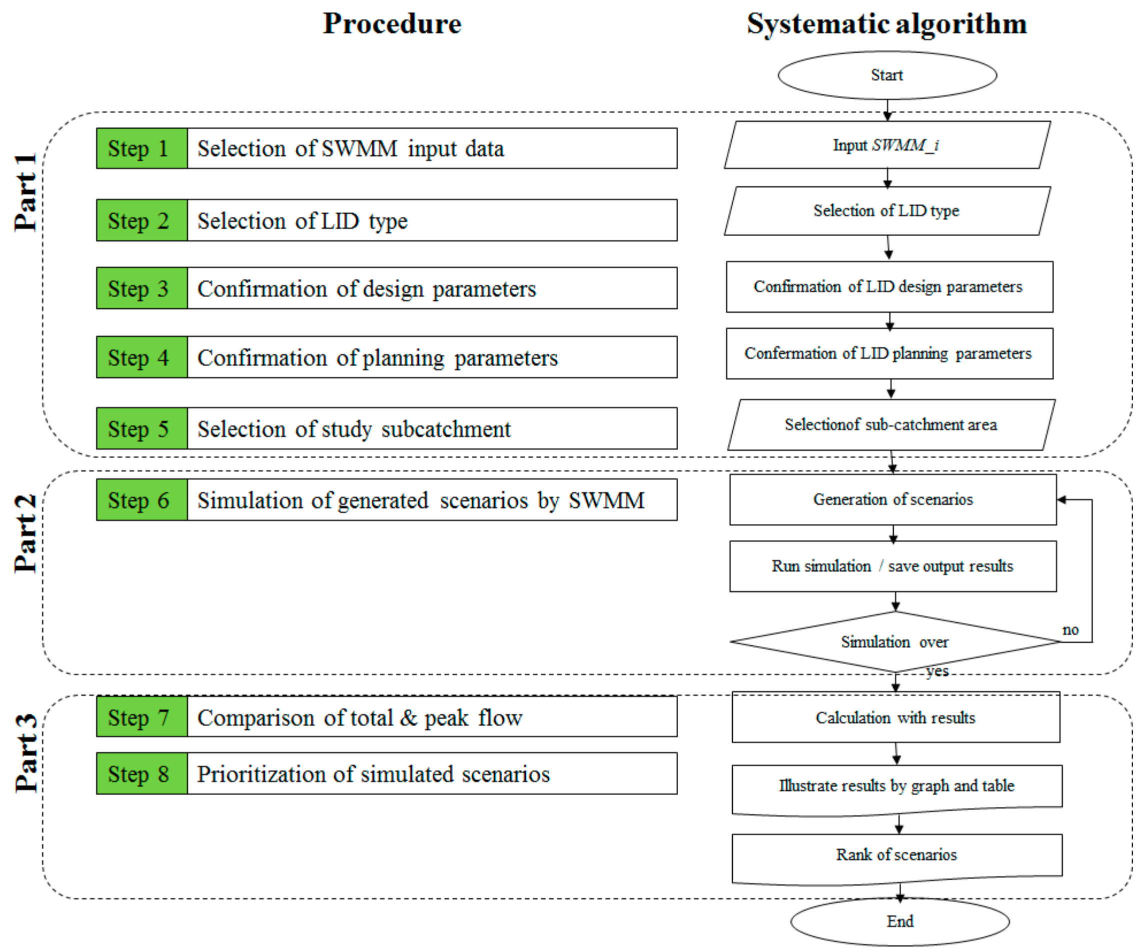

Figure 1. Detail procedure of Water Management Prioritization Module (WMPM).

Part 1 includes five steps. An original background SWMM input file (S_i) that includes all the basic information of the study region such as sub-catchments, channels and junctions should be loaded for Step 1. In Step 2, users can upload multiple SWMM input files corresponding to different target LID types ($m = 1, 2, \ldots, k$); these can be obtained from the particular LID product and plan. In Steps 3 and 4, users can individually check all the values of the physical design and planning specifications for multiple LID types. In Step 5, based on the SWMM simulation of the original background SWMM input file loaded in Step 1, users should select multiple target sub-catchments ($1, 2, \ldots, n$), combining the hydrologic conditions from the SWMM simulation with anthropogenic factors proposed by the user. Through Part 1, different SWMM input files are generated for all the user-defined LID scenarios to describe the LID types and locations.

In Part 2 and Step 6, WMPM automatically performs the SWMM simulations of all the generated SWMM input files (concluding $S_{m,n}$) corresponding to the selected LID types (m) and the sub-catchments (n) developed in Part 1. The total number of scenarios is ($n \times k + 1$).

In Part 3, the priority for all feasible scenarios is finalized considering the hydrological efficiency and anthropogenic conditions. All the peak flow and total runoff values for the feasible scenarios are analyzed and compared in Step 7, and the comparative results are illustrated using tables and graphs. Additionally, the scenario rankings are determined by the variation ratio of the peak and total runoff, as shown in Equation (8):

$$R = \frac{1 - \frac{Q_{sub}}{Q_{sub_i}}}{1 - \frac{O}{O_i}}, \quad (8)$$

where R is the variation ratio of the peak and total runoff, $Qsub$ is the runoff of the generated scenario of the selected sub-catchment, $Qsub_i$ is the runoff of S_i of the selected sub-catchment, and O_i and O are the total outflow of S_i and of the generated SWMM scenario, respectively. The rank is higher when the variation ratio of the runoff (R) is higher.

In Step 8, to finalize the priorities of all feasible scenarios, WMPM considers both the hydrological effectiveness and the physical and anthropogenic criteria and then uses TOPSIS with both subjective and objective weights. In this study, population, population density and usage area, which are the social factors, are selected manually, and the total runoff, peak runoff, and total infiltration, which are the hydrologic effectiveness parameters, are automatically extracted from the SWMM simulation results of S_i. In addition, slope and imperviousness, which are the physical-geometric factors, are automatically extracted from the SWMM input file S_i. Therefore, eight factors and the selected sub-catchments from Part 1 are considered as the criteria and alternatives, respectively. The subjective weights are obtained from two rounds of expert surveys using the Delphi method, and the objective weights are calculated using entropy theory. Then, the final priority is derived using TOPSIS.

4. Application and Results

The application of WMPM was presented as follows. Section 4.1 describes the study region and the formulated SWMM input file. Section 4.2 describes the physical specifications of two LID types that were previously derived from various studies or were predefined from LID products. Section 4.3 presents the procedure for deriving all target sub-watersheds. In Section 4.4, the hydrological effectiveness values from the SWMM simulations are analyzed and compared. In Section 4.5, the priority of all the selected scenarios for the LID types and locations are calculated using TOPSIS.

4.1. Descriptions of the Study Region and SWMM Input Files (Steps 1 and 2)

In this study, WMPM was applied to a university campus in Seoul, South Korea, as shown in Figure 2; this figure also includes a study area map of the SWMM model. Seoul is the capital of South Korea with a population exceeding about ten million. The annual precipitation in Seoul is around 1300 mm with 80% for summer. The study area is located at (37° N, 127° E) and has a total area of 508,690 m^2, 92.7% of which is covered by buildings, roads and green spaces. A stream passes through the campus, but there is no water during the dry period, which is usually longer than 150 days every year. In addition, the university is undergoing various expansion projects including two dormitories, one research center and one mixed building. However, they aren't considering the incorporation of a number of LID practices for stormwater management. Therefore, the LID practices for sustainable hydrologic cycle should be urgently planned and constructed considering various hydrologic and social factors.

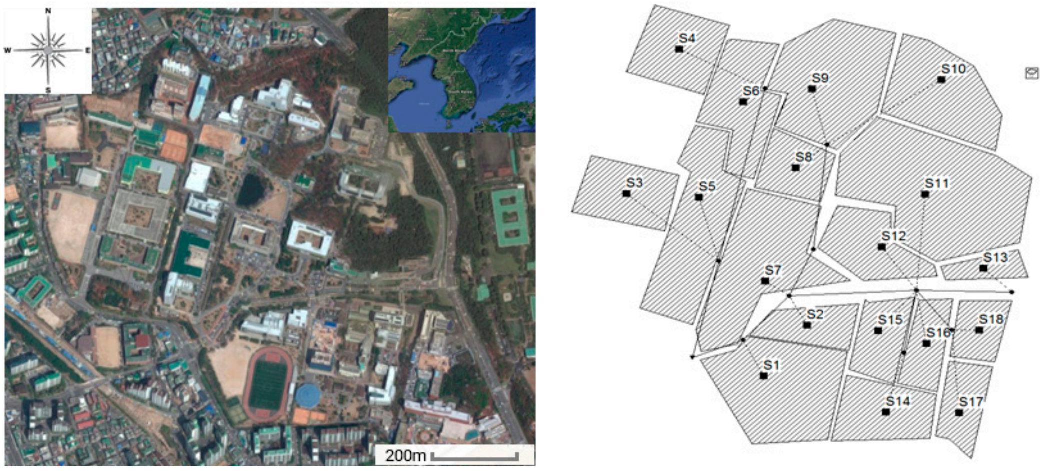

Figure 2. Model map of study region using the EPA's SWMM.

The study area was divided into 18 sub-catchments based on the drainage system. Each sub-catchment has values of total slope, imperviousness and usage rate that range from 1% to 10%, 15% to 90%, and 230 to 3450 m^2, respectively. Table 2 shows the specific properties commonly used in all sub-catchments. Manning's *Ns* for impervious and pervious areas of 0.013 and 0.24, which were proposed from [35,48], respectively, are frequently used for the urban areas of South Korea and thus are used in this study. The depth of depression storage for impervious and pervious areas is assumed to be 2.338 mm. A daily rainfall event from 17 August 2014 to 26 August 2014 recorded by the Seoul observatory, with a total rainfall of 110 mm and a maximum rainfall of 1.6 mm/h, was used in this analysis. A small rainfall event was used because these are more effective for LID performance analysis [49].

Table 2. Properties of sub-catchment in the Storm Water Management Model (SWMM) input file S_i.

Property	Unit	Value
Width of overland flow path	m	50
Manning's N for impervious area	Manning's n	0.013
Manning's N for pervious area	Manning's n	0.24
Depth of depression storage on impervious area	mm	2.338
Depth of depression storage on pervious area	mm	6.381
Percent of impervious area with no depression storage	%	18.282
Infiltration method	Type	Horton
Maximum rate on the Horton infiltration curve	mm/h	3
Minimum rate on the Horton infiltration curve	mm/h	0.5
Decay constant for the Horton infiltration curve	1/h	4
Time for a fully saturated soil to completely dry	days	7
Maximum infiltration volume possible	mm	0

In the first step of WMPM, the background SWMM input file (S_i), consisting of 18 sub-catchments, was loaded. In the second step, two different SWMM input files, including the design and planning specifications for infiltration trench and porous pavement, were loaded using the previous research result [49].

4.2. Descriptions of the LID Design and Planning Parameters (Steps 3 and 4)

In Steps 3 and 4, the users confirm that the details of the physical values used for the design and planning parameters corresponding to the selected LID types loaded in Step 2 are correct. In this study, the design and planning parameters of the infiltration trench were determined based on the previous results of [49]. All of the design parameters of porous pavement were obtained from the experimental results [50], and its planning parameters were determined by the field circumstances, as shown in Table 3. The berm height, vegetative volume fraction, surface roughness, and surface slope for the surface layer of infiltration trench were set to 150 mm, 0, 0.013, and 5%, respectively, whereas the values for porous pavement were 0 mm, 0, 0.1, and 1% individually. The thickness, void ratio, impervious surface fraction, and permeability for the pavement layer of porous pavement were set to 1200 mm, 0.21, 0, and 390.74 mm/h, respectively. The thickness, void ratio, seepage rate, and clogging factor for the storage layer of infiltration trench were set to 750 mm, 0.4, 210 mm/h, and 0, respectively, whereas those for porous pavement were set to 305 mm, 0.75, 254 mm/h, and 0 individually. The flow coefficient, flow exponent, and offset height for the drain layer of infiltration trench were set to 0, 0.5, and 0 mm, respectively, whereas those for the drain layer of porous pavement were set to 0, 0.5, and 152.5 mm individually.

Table 3. Design and planning parameters of infiltration trench and porous pavement used in this study.

Category	Layer	Parameter	Unit	Infiltration Trench	Permeable Pavement
Design parameters	Surface	Berm height	mm	150	0
		Vegetation volume fraction		0.0	0
		Surface roughness	Manning's *n*	0.013	0.1
		Surface slope	%	5	1
	Pavement	Thickness	mm	-	1200
		Void ratio		-	0.21
		Impervious surface fraction		-	0
		Permeability	mm/h	-	390.74
		Clogging factor		-	0
	Storage	Thickness	mm	750	305
		Void ratio		0.4	0.75
		Seepage rate	mm/h	210	254
		Clogging factor		0	0
	Drain	Flow coefficient		0	0
		Flow exponent		0.5	0.5
		Offset height	mm	0	152.5
Planning parameters		Area of each unit	m^2	460	700
		Number of units	EA	10	2
		Surface width per unit	m	1	10
		% initially saturated	%	0	10
		% of impervious area treated	%	0	0

4.3. Selection of Target Sub-Catchments Using TOPSIS (Step 5)

In Step 5, all the sub-catchments are prioritized by TOPSIS, considering social, hydrologic, and physical-geometric criteria. In this study, the weights of all the criteria were determined using the Delphi method and entropy theory, as shown in Table 4. All the data for the hydrologic and physical-geometric factors were automatically extracted from the SWMM inputs and outputs. The population, which is a social factor, was estimated from the 2015 statistical data based on students, faculty, teaching staff, and educational personnel. The population density was calculated by dividing the population by the sub-catchment area. The usage area was defined by multiplying the floor area by the number of floors of the buildings located in each sub-catchment.

Table 4. Data used and derived ranks using TOPSIS for the selection of sub-catchments to the 5th step of Water Management Prioritization Module (WMPM).

Criterion	Social			Hydrologic			Physical-Geometric		Ranking	
Sub-Catchment	Population (Person)	Population Density (Person/m^2)	Usage Area (m^2)	Total Runoff (mm)	Peak Runoff (LPS)	Total Infiltration (mm)	Slope (%)	Imperviousness (%)		
Sub. Weight		0.367			0.498		0.135			
	0.328	0.322	0.350	0.230	0.315	0.455	0.425	0.575		
Obj. Weight		0.518			0.302		0.180		Subjective	Objective
	0.320	0.417	0.263	0.459	0.202	0.339	0.680	0.320		
S1	82	0.022	360	43.09	5.93	66.82	1	25	18	17
S2	82	0.043	660	97.25	7.71	12.59	7	80	10	13
S3	41	0.017	230	89.94	8.82	19.89	6	70	13	18
S4	1266	0.550	1720	96.69	9.27	13.02	4	80	2	2
S5	345	0.093	1850	95.56	14.58	13.84	3	80	4	5
S6	386	0.142	810	99.45	11.03	9.96	2	85	6	8
S7	603	0.154	1170	91.97	14.88	17.57	4	75	3	3
S8	579	0.289	1000	53.13	4.69	56.84	3	25	16	15
S9	620	0.167	1480	55.97	8.87	53.99	7	30	12	9
S10	1522	0.475	1600	45.63	6.66	64.36	10	15	15	10
S11	2157	0.431	1000	88.35	18.45	21.30	8	70	1	1
S12	932	0.388	720	90.01	9.22	19.83	7	70	7	6
S13	932	0.517	900	82.71	6.47	27.17	4	60	9	11
S14	270	0.112	360	74.34	7.79	35.56	5	50	14	12
S15	300	0.125	240	64.70	6.66	45.22	3	40	17	14
S16	1266	0.538	1175	85.25	8.50	24.53	3	65	8	7
S17	41	0.017	3450	81.92	8.10	27.93	4	60	11	16
S18	562	0.244	1380	97.23	9.34	12.60	10	80	5	4

The subjective weights for all the criteria and factors were determined by a series of surveys from eight experts, and the objective weights were calculated using Equations (4) and (7). The social criterion (0.518) was found to be the strongest weight for the objective weights determined using entropy theory, while the hydrologic criterion (0.498) had the highest subjective weight. Using the TOPSIS process, the priority of all the sub-catchments was calculated for LID installation. The sub-catchment of S11 was ranked 1st for both subjective and objective weights. The sub-catchments of S7, S5, S4, and S6 followed for the subjective weights and the sub-catchments of S4, S7, S18, and S5 were the next for the objective weights. However, the pre-assessment of TOPSIS was performed without considering the LID design and planning; thus, the sub-catchment of S11 can be considered a suitable location for planning an LID practice, but the following sub-catchments should not be disregarded. Therefore, sub-catchments of S4, S5, S6, S7, S11, S12, S16, and S18, which all have a one-digit ranking after averaging the two subjective and objective ranks, were chosen to be further studied in the WMPM procedure as target areas for the construction of infiltration trench and porous pavement.

4.4. Hydrological Analysis (Steps 6 and 7)

In Step 6, infiltration trench and porous pavement were combined with eight sub-catchments. Then, sixteen scenarios were generated, and seventeen scenarios were simulated using SWMM through WMPM (Figure 3). In Step 7, the hydrological components of all the sub-catchment areas were compared according to the peak and total runoffs of the S_i and their variation ratios with the selected LID in the selected sub-catchment area.

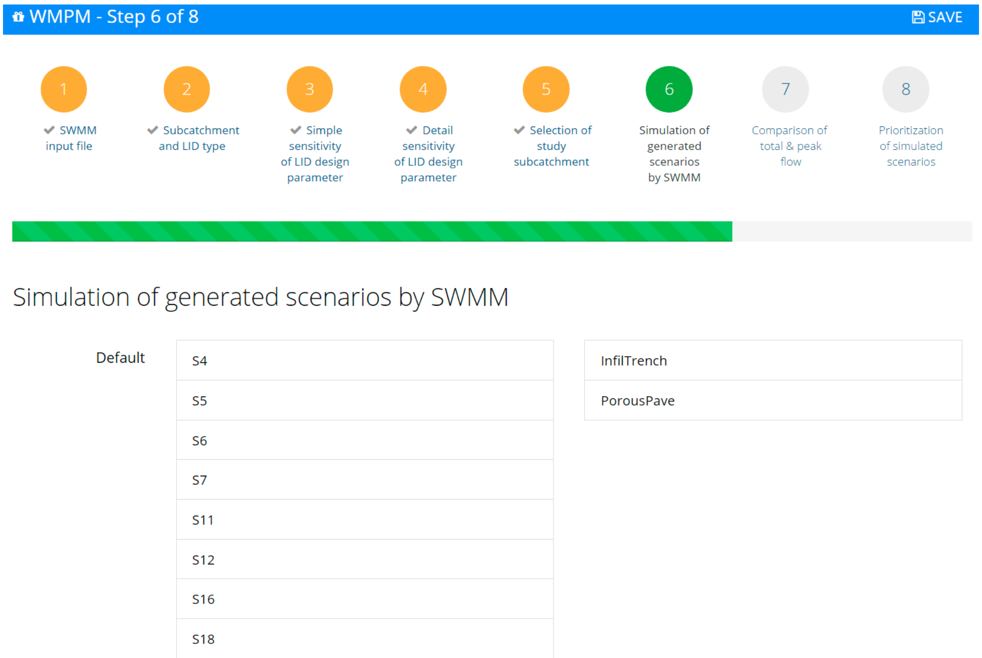

Figure 3. Screenshot of the 6th step of WMPM: generation and simulation of scenarios.

Figure 4 compares the peak and total runoffs of S_i and $S_{m,n}$. The details of the changed runoffs and the ranking of all the scenarios as calculated by Equation (8) are shown in Tables 5 and 6. According to the peak runoff results, the sub-catchment of S11 showed the greatest discharge of 18.45 LPS (liters per second) when LIDs were not applied. Applying infiltration trench and porous pavement to the sub-catchment of S11 decreased the peak runoff to 16.87 and 17.97 LPS, respectively. In S11, the infiltration trench was more effective than porous pavement from the hydrological aspect as the infiltration trench decreased the peak runoff 1.10 LPS more than porous pavement. Throughout all the scenarios, infiltration trench in the sub-catchment of S18 showed the greatest decrease in peak runoff by −1.85 LPS. However, using Equation (8), infiltration trench in the sub-catchment of S18 ranked 6th; this result is due to the difference in the initial peak runoff before the LID was applied in each sub-catchment and because the total surface runoff was not considered. In terms of Equation (8), the infiltration trench in S16 was ranked first for its effectiveness since the variation ratio of the runoff had the highest value of 18.87.

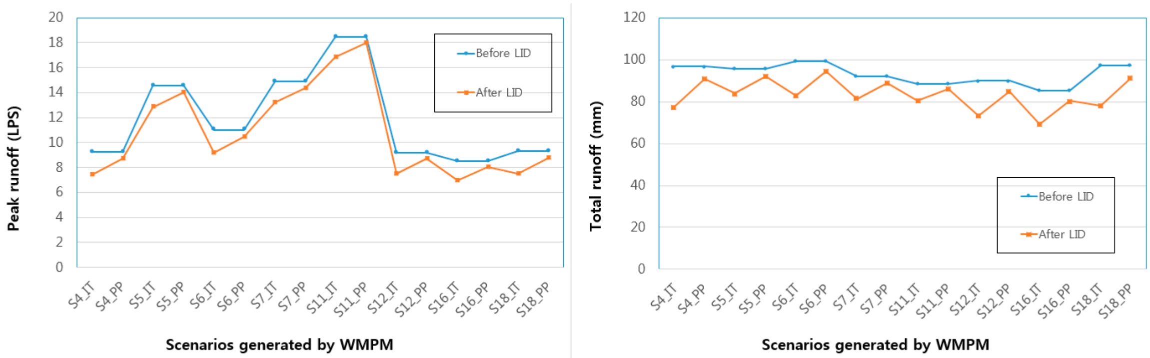

Figure 4. Comparison of peak and total runoff using WMPM.

Table 5. Comparison of peak runoff by WMPM.

Sub-Catchment	LID Type	Total Outflow (O_i) (mm)	Total Outflow (O) (mm)	Peak Runoff (S_i) (LPS)	Peak Runoff ($S_{m,n}$) (LPS)	R	Rank
S4	*IT*	78.84	77.97	9.27	7.45	17.69	5
	PP		78.58		8.72	17.58	7
S5	*IT*		77.99	14.58	12.85	10.91	11
	PP		78.58		14.06	10.77	13
S6	*IT*		77.95	11.03	9.2	14.56	9
	PP		78.57		10.48	14.40	10
S7	*IT*		78.02	14.88	13.22	10.71	14
	PP		78.59		14.37	10.85	12
S11	*IT*		78.06	18.45	16.87	8.61	16
	PP		78.61		17.97	8.62	15
S12	*IT*		78.03	9.22	7.52	17.97	3
	PP		78.60		8.71	17.72	4
S16	*IT*		78.09	8.50	6.96	18.87	1
	PP		78.61		8.04	18.55	2
S18	*IT*		77.96	9.34	7.49	17.66	6
	PP		78.57		8.78	17.57	8

For total runoff, the sub-catchment of S6 had the highest initial runoff of 99.45 mm when neither infiltration trench nor porous pavement was applied. When infiltration trench or porous pavement was applied to the sub-catchment of S6, the total runoff decreased to 82.74 and 94.37 mm, respectively. Infiltration trench was also more effective for S5, as infiltration trench decreased the total runoff, 8.10 mm, more than porous pavement. Among the sixteen scenarios, infiltration trench in the sub-catchment of S18 showed the greatest reduction in total runoff, 19.29 mm. Although the total runoff of S18 decreased the most due to infiltration trench, its ranking from Equation (8) was 7th. Infiltration trench in the sub-catchment of S16 ranked 1st because the variation ratio of the runoff had the highest value of 19.74.

Table 6. Comparison of total runoff by WMPM.

Sub-Catchment	LID Type	Total Outflow (O_i) (mm)	Total Outflow (O) (mm)	Total Runoff (S_i) (mm)	Total Runoff ($S_{m,n}$) (mm)	*R*	Rank
S4	*IT*	78.84	77.97	96.69	77.58	17.80	5
	PP		78.58		90.89	17.78	6
S5	*IT*		77.99	95.56	83.93	11.19	11
	PP		78.58		92.03	11.15	12
S6	*IT*		77.95	99.45	82.74	14.75	10
	PP		78.57		94.37	14.75	9
S7	*IT*		78.02	91.97	81.39	11.04	14
	PP		78.59		88.76	11.05	13
S11	*IT*		78.06	88.35	80.47	8.97	16
	PP		78.61		85.95	8.99	15
S12	*IT*		78.03	90.01	73.08	18.33	3
	PP		78.60		84.87	18.30	4
S16	*IT*		78.09	85.25	69.09	19.74	1
	PP		78.61		80.36	19.66	2
S18	*IT*		77.96	97.23	77.94	17.69	7
	PP		78.57		91.37	17.66	8

Although most of the rankings were similar, minor differences remained between the rankings when different LID types were applied to the sub-catchment area. For example, the infiltration trench in sub-catchment S6 ranked higher for peak runoff, and porous pavement in S6 ranked higher for total runoff. Moreover, some sub-catchments, such as S4, S5, S12, S16, and S18, had higher ranks in terms of total runoff when infiltration trench was applied. These results show that different LID practices can be more effective for different hydrological components and that a single LID type can perform differently when applied to different locations. Therefore, LID types, including various combinations of LID design and planning parameters, and various locations should be carefully examined for sustainable planning. Using WMPM to compare the peak and total runoff among generated scenarios can help users quantify the hydrological differences of different types and sites of installed LID practices.

The results showed that the peak and total runoff attained the best efficiency when the infiltration trench and porous pavement were constructed in the sub-catchment of S16. Specifically, the infiltration trench was better for decreasing both the peak and total runoffs. However, compared to the previous study [25], the sub-catchment of S5, which was randomly chosen, was ranked 11th (infiltration trench) and 12th and 13th (porous pavement) in this study. Therefore, by applying the designated LID in multiple sub-catchments, WMPM can determine a better region for the designated LID. Moreover, installing an infiltration trench in the sub-catchment of S16 can be the best scenario for mitigating flood damage, reducing drought severity and rehabilitating the hydrological cycle, as these practices can reduce the peak discharge and increase the storage in the sub-catchment.

4.5. Final Prioritization Using the MCDA Method (Step 8)

Using Equation (8), WMPM calculates the hydrological ranking of all the scenarios to conduct the most effective planning. However, in Step 8, the social and physical-geometric factors are included to finalize the most sustainable decision for LID types and sites.

The values for all eight evaluation criteria were derived for the sixteen scenarios of LID types and sites, as shown in Table 7. Because the social and physical-geometric factors were the same for five of the sub-catchments, the data of the four selected sub-catchments were used in this step. The hydrological effectiveness resulting from installing LIDs includes the variation ratios of the total runoff, peak runoff and infiltration obtained from Step 7. Thus, Table 7 represents the decision matrix used for this evaluation.

Table 7. Data used and derived final ranks for the best LID planning using TOPSIS considering social, hydrologic, physical-geometric factors.

Criterion	Social			Hydrologic			Physical-Geometric		Ranking	
Scenario	**Population (Person)**	**Population Density (Person/m^2)**	**Usage Area (m^2)**	**Total Runoff**	**Peak Runoff**	**Total Infiltration**	**Slope (%)**	**Imperviousness (%)**		
Sub. Weight		**0.367**			**0.498**		**0.135**			
	0.328	**0.322**	**0.350**	**0.230**	**0.315**	**0.455**	**0.425**	**0.575**		
Obj. Weight		**0.337**			**0.329**		**0.334**		**Subjective**	**Objective**
	0.317	**0.372**	**0.311**	**0.337**	**0.361**	**0.302**	**0.494**	**0.506**		
S4_*IT*	1266	0.550	1720	17.80	17.69	51.90	4	80	3	1
S4_*PP*	1266	0.550	1720	17.78	17.58	51.88	4	80	4	2
S5_*IT*	345	0.093	1850	11.19	10.91	30.35	3	80	15	13
S5_*PP*	345	0.093	1850	11.15	10.77	30.44	3	80	16	14
S6_*IT*	386	0.142	810	14.75	14.56	57.76	2	85	11	15
S6_*PP*	386	0.142	810	14.75	14.40	57.74	2	85	12	16
S7_*IT*	603	0.154	1170	11.04	10.71	22.70	4	75	14	12
S7_*PP*	603	0.154	1170	11.05	10.85	22.75	4	75	13	11
S11_*IT*	2157	0.431	1000	8.98	8.61	14.59	8	70	10	10
S11_*PP*	2157	0.431	1000	8.99	8.62	14.64	8	70	9	9
S12_*IT*	932	0.388	720	18.33	17.97	32.63	7	70	5	5
S12_*PP*	932	0.388	720	18.30	17.72	32.64	7	70	6	6
S16_*IT*	1266	0.538	1175	19.74	18.87	26.96	3	65	1	7
S16_*PP*	1266	0.538	1175	19.66	18.55	26.90	3	65	2	8
S18_*IT*	562	0.244	1380	17.69	17.66	53.63	10	80	7	3
S18_*PP*	562	0.244	1380	17.66	17.57	53.61	10	80	8	4

TOPSIS with subjective and objective weights was used to quantify the performance values for the sixteen scenarios. A Delphi survey of eight experts was conducted to determine the subjective weights, whereas the objective weights were re-calculated based on the change data shown in Table 7. In addition, Figure 5 shows the derived ranking of each alternative relating to Table 7. Sub-catchments S4, S5, S7, and S18 had higher ranks when objective weighting values were used, while sub-catchments S6 and S16 were ranked higher when subjective weighting values were used.

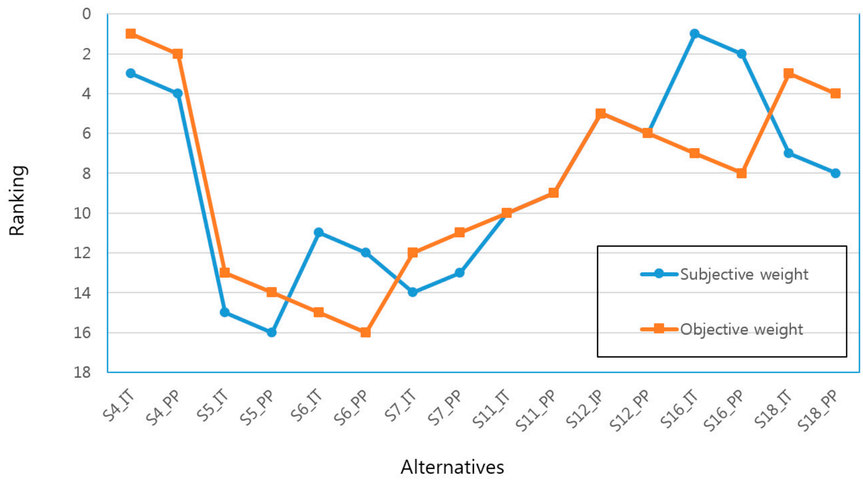

Figure 5. Derived rankings of each alternative.

According to the subjective TOPSIS results, among the eight selected sub-catchments from WMPM, S16 was the most suitable location for the LID because it ranked in 1st and 2nd place when the infiltration trench and porous pavement were applied, respectively. S4 ranked in 3rd and 4th place when subjective weights were applied to the infiltration trench and porous pavement and in 1st and 2nd when objective weights were applied to the infiltration trench and porous pavement; therefore, the sub-catchment of S4 was concluded to be the best location for constructing the infiltration trench when considering the objective weights. The subjective and objective rankings were not the same; therefore, both objective and subjective weights must be considered in making important decisions.

5. Conclusions

This study proposed the MCDA system to prioritize the types and sites of LID practices considering various criteria. It was systemized as a web-based tool for SWMM to guide users through automatic scenario generation and simulations for many combinations of LID types and sites. This system, namely WMPM, can simulate multiple cases of SWMM models with multiple LID types and multiple sub-catchments and can rank the candidate scenarios based on hydrological aspects as well as social and physical-geometric factors. WMPM uses TOPSIS, which is a type of MCDA method, to quantify all the performance values for the scenarios. This study applied WMPM to a region in South Korea. Two LID types, i.e., an infiltration trench and permeable pavement, were considered to compare the total and peak runoff of eight selected sub-catchments.

As a result, this study found several important results. First, MCDA framework was incorporated to derive the priorities among sixteen plausible scenarios for two LID types and eight locations. TOPSIS was used to quantify the performances of all LID scenarios. Second, it can consider eight evaluation criteria including three hydrological and two physical geometric as well as three social factors. Third, the weights for eight decision criteria can be determined through subjective and objective ways. The subjective and objective weights were quantified by Delphi and entropy methods, respectively. Fourth, WMPM developed by this study can be used to automatically simulate all plausible scenarios for LID practices types and locations. Furthermore, it supports the comparative hydrological results for all considered scenarios.

Thus, WMPM can carefully select the best LID types and sites based on SWMM simulations for many plausible scenarios and various social evaluation criteria. Determining superior scenarios of LID types and sites is very helpful for water resource engineers in evaluating different strategies. Furthermore, policy-makers can better decide on urban water plans for sustainable development. However, the framework of LID practice design and planning should be incorporated into this study in order to make the perfect decision because the design and planning specifications of LID practices are closely related to the site selection of LID practices. In addition, the economic criteria should be included in this system for the priority of LID practice scenarios because the construction and operation costs of the same LID practice may differ according to regional conditions. Therefore, the economic efficiency will be added and the DSS for the design and planning of LID practice can be developed.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Software availability.

Name of Software	Water Management Prioritization Module (WMPM)
Description	Decision support system that guides the prioritization of types and locations of low impact development (LID) practices based on the EPA's SWMM5.1.
Developers	Eun-Sung Chung and Jae Yeol Song
Source Language	Python 2.7
Software Requirements	Chrome browser (web-based tool, not available through Internet Explorer)
Software Availability	WMPM and useful guidelines can be found at the following link: http://dev.cedar.kr:5001

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