


The applicability of LID facilities as an adaptation strategy of urban CSOs management for climate change

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ABSTRACT

The magnitude and frequency of extreme rainfall due to climate change is increasing. Increasing rainfall causes serious hydrological problems in cities. Rainfall does not infiltrate the soil, but mostly flows through the sewer pipes into the stream. Most old urban watersheds have combined sewer pipes. When rainfall exceeds the capacity of the combined sewer pipes, sewage mixed with stormwater overflows the sewer pipes and flows directly into the stream. This is called Combined Sewer Overflows (CSOs). CSOs enter the stream with non-point source pollutants accumulated on the surface and pollute the stream. CSOs are one of the major water quality problems in older urban watersheds. This can be solved by replacing the combined sewer pipes with separated sewer pipes, but in reality it requires astronomical costs. As an alternative, the Low Impact Development (LID) technique has recently been introduced. In this study, we analyzed the effects of climate change on CSOs in urban watersheds and applied LID techniques to offset the effects. The LID facility was applied with the most commonly used Bio-Retention cells.

Key words: bio-retention cells, climate change, CSOs, EPA SWMM, low impact development

HIGHLIGHTS

- Applicability of bio-retention to offset the negative effects of climate change on urban streams are investigated using EPA SWMM.
- Run-off, TP load, and CSOs in urban watershed show high potential for increases by climate change.
- The bio-retention cell is useful for offsetting the negative effects of climate change.

1. INTRODUCTION

Recent studies on climate change emphasize the severity of changes in future rainfall patterns (Christensen *et al.* 2007; Sagarika *et al.* 2016; Pathak *et al.* 2017). Increased rainfall causes serious hydrological problems in urban areas (Tamaddun *et al.* 2016). When looking at rainfall data from various regions, rainfall in most regions is increasing (Easterling *et al.* 2000). In some areas, rainfall intensity is likely to increase even though rainfall due to climate change has decreased (Solmon & Coauthors 2007).

When rainfall occurred in natural watersheds, rainfall infiltrated into the soil smoothly and did not generate much stormwater. Because of the good infiltration, most of the rainfall is stored in the soil, and evapotranspiration naturally occurs. However, urbanization has caused many problems (Hewitt & Rashed 1992; Perdikaki & Mason 1999; Maniquiz *et al.* 2012). Increasing impermeable area due to urbanization reduces rainfall infiltration and results in increased stormwater (Semadeni-Davies *et al.* 2008). In addition, the peak flow increases and the time of concentration decreases, resulting in much stormwater in a short time (Anderson 1970). In addition, the magnitude and frequency of rainfall due to climate change are very likely to cause greater problems (Kharin *et al.* 2007; Loo *et al.* 2015; Burt *et al.* 2016).

Most old urban watersheds have combined sewer pipes. Combined sewer pipes are a system for transporting rainwater and sewage together, and have the advantages of low cost and convenient construction. However, combined sewer pipes have a disadvantage in that a large amount of pollutants enter the stream when it rains a lot. In Korea, it is the principle to install separated sewer pipes in urban areas that have been recently developed. However, combined sewer pipes have been installed

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in most old towns. During rainfall in these areas, non-point source pollutants accumulated on the surface during the dry season are swept away with stormwater, and contaminated stormwater enters combined sewer pipes and merges with sewage. Increasing impermeable areas and increasing frequency and intensity of rainfall due to climate change often exceed the capacity of combined sewer pipes, and sewage and stormwater flowing through the combined sewer pipes overflows directly into the stream.

Various climate change adaptation measures can be applied to solve these problems, one of which is the introduction of Low Impact Development (LID) techniques (Pyke *et al.* 2011). LID facilities that can be applied to various urban watersheds include bio-retention cells, green roofs, infiltration trenches, and permeable pavements. The principles for reducing stormwater and water pollution are similar. The main purpose of LID is to maintain natural hydrological functions while developing cities (Coffman & France 2002; U.S. Department of Housing, and Urban Development 2003). The effects of LID techniques on stormwater reduction and water quality improvement in urban watersheds have already been validated in various literature (Hunt *et al.* 2006; Bedan & Clausen 2009; Hurley & Forman 2011).

In this study, we investigated the effect of reducing combined sewer overflows (CSOs) by applying Bio-Retention (BR) among LID facilities in Oncheon stream basin located in Busan, Korea. First, climate change scenarios were applied to the EPA SWMM constructed for the Oncheon stream basin to analyze the impact of climate change. Then, when BR was installed in the Oncheon stream basin, it was revealed how much the adverse effects of climate change were offset.

2. MATERIALS AND METHODS

2.1. Study area

Korea is geographically located in the mid-latitudes of the northern hemisphere, with annual average precipitation varying by region but about 1,500 mm. Seasonally, between 60 and 70 percent of annual precipitation is concentrated in summer, and the spatial variability of precipitation is very high due to topographical and meteorological factors (Kang 2000). The study basin is the Oncheon stream basin, a city stream in Busan, located southeast of the Korean Peninsula (see Figure 1). The Oncheon stream basin consists of a typical old town area with combined sewer pipes. Therefore, it is appropriate to investigate the change of CSOs in urban areas due to climate change. Oncheon stream basin area is 56.28 km² and river length is 14.85 km (BETCE 2007).

2.2. Climate change scenarios

Future climate change scenario data are mainly generated using Global climate models (GCMs) and Regional climate models (RCMs). The low spatial resolution of GCMs makes it difficult to apply to the small area of the Korean peninsula, which is heavily influenced by the ocean. Therefore, it is desirable to use RCMs to investigate the impact of future climate change. In

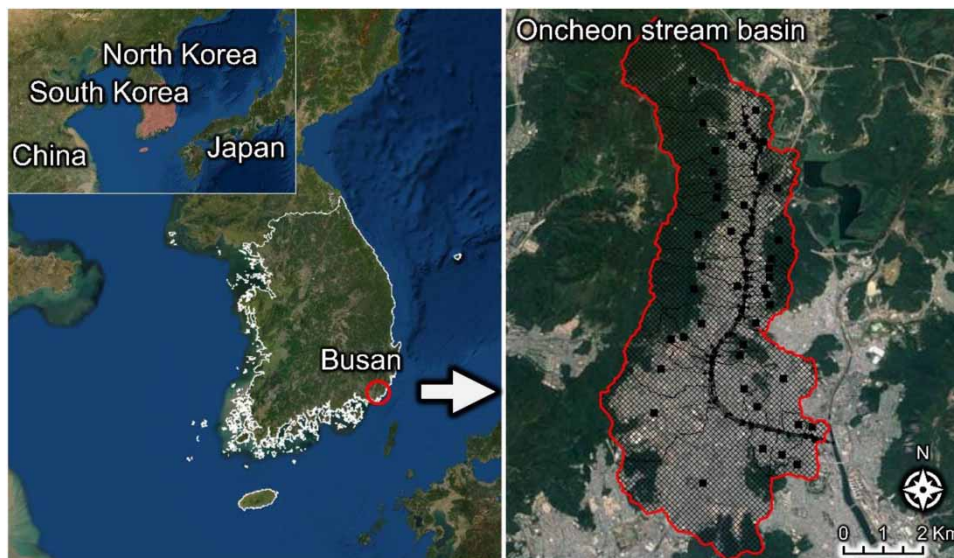


Figure 1 | Study area.

this study, we used the future data of the Busan site, which dynamically downscaled the MPI-ESM-LR data using the Weather Research and Forecasting model (WRF).

MPI-ESM-LR is a model developed by the Max Plank Institute in Germany and consists of representable models the interactions between the atmosphere (ECHAM6) and the ocean (MPIOM), the effects of the ground and vegetation (JSBACH), and the biogeochemical processes in the ocean (HAMOCC5). WRF is a mid-scale forecasting system for weather forecasting and research. WRF features a multidisciplinary core that includes a three-dimensional variant data assimilation system (3DVAR data assimilation), a parallel computer platform, and a software architecture that follows system expandability. CORDEX-East Asia uses WRF3.2 with spectral nudging for long-term climate simulations (von Storch *et al.* 2000). For more information on WRF, please visit web-site (www.wrf-model.org).

The spatial resolution of the generated future precipitation time series is 12.5-km and the temporal resolution is 3-hour. The present period of the simulated data is from 1981 to 2010, and the future period is from 2021 to 2050. RCP 8.5 climate change scenarios were applied. In this study, the data belonging to the grid corresponding to the Busan site of the Korean Peninsula were extracted from the spatial resolution 12.5-km grid data. This data was regarded as the future precipitation time series of the Busan site and a climate change impact assessment was conducted.

2.3. Construction of EPA SWMM

2.3.1. Subcatchment topographic data

In this study, most subcatchment input data were composed by referring to Busan City Master Plan for Sewage and Drainage and Busan City Urban Information System (UIS). The basin was divided into 43 subcatchments using the drainage system and contour maps of the Oncheon stream basin. The area of subcatchment was calculated by GIS. The slope of the subcatchment was calculated using the highest altitude of the subcatchment, the length of the sewer pipe, and its slope.

The impervious area of the terrain data has a big impact on stormwater. The concept of impervious area in SWMM applies the effective impervious area (EIA). EIA is the area directly connected to the body of water in the Total Impervious Area (TIA). TIA was calculated from land use of 1: 25000. The portion of TIA by land use is provided in the SWMM manual (U.S.EPA 2015). However, these figures are based mainly on data from the United States and are unlikely to match Korea. Therefore, in this study, the portion of EIA by land use proposed by NIER (2014) was applied (see Table 1).

Infiltration process was applied to CN method. The necessary parameter, CN, was estimated using land use and soil map. The subcatchment width was estimated as a function of the area of the subcatchment. In the case of the subcatchment roughness coefficient, the pervious area was applied to 0.13 of the natural area, and the impervious area was applied to 0.011, which is equivalent to smooth asphalt. In the case of initial depression storage depth, the pervious area was 5.0 mm and the impervious area was 1.85 mm. Of these, the CN, subcatchment width, and initial surface storage depth are later modified during parameter tuning.

2.3.2. Pipe network data and CSOs simulation method

Using UIS, the stream consisted of 64 pipes and the sewer pipe networks consisted of 169 pipes. In order to simulate CSOs, the Flow Divider function built into SWMM is included in sewer pipe networks (Jang *et al.* 2007).

2.3.3. Pollutants input data

The average amount of daily sewage planned for each subcatchment was entered into that subcatchment. The water quality applied in this study is T-P. Sewage water quality was equally applied to all subcatchments at 6.4 mg/L, the concentration entering the sewage treatment plant.

Table 1 | Percent of impervious area of EIA for urban land use in Korea (NIER 2014)

Urban land use	Average percent impervious area of EIA	Range in percent impervious area of EIA
Residential	0.44	0.32–0.60
Commercial	0.62	0.44–0.92
Industrial	0.79	0.59–0.93
Transportation	0.95	0.85–1.00
Education	0.47	0.30–0.77

Stormwater quality in the EPA SWMM is simulated through a build-up process that simulates the buildup of contaminants during the dry season and a wash-off process that simulates the removal of contaminants during rainfall. In this study, an exponential function was used as a build-up process and EMC was used as a wash-off process.

Finally, 30,000 tons per day are taken from the nearby Nakdong River and supplied to the Oncheon stream as maintenance water. The maintenance water of the Oncheon stream is input to the starting node of the stream, and it is set so that the maintenance water is not supplied in case of rainfall.

2.4. Calibration and verification

After the model is built, the parameters of the model must be tuned so that the model reproduces the observations well. In this study, we used a module that links SWMM and Matlab (Choi *et al.* 2018). The parameters were estimated based on the Pattern-Search optimization technique built into Matlab. The objective function for the optimization technique is Kling-Gupta Efficiency (KGE) as follows (Gupta *et al.* 2009):

$$KGE = 1 - \sqrt{(\gamma - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (1)$$

where γ is the correlation coefficient between the observed and simulated data, α is the ratio of the mean of the observed data to the mean of the simulated data, and β is the ratio of the standard deviation of the observed data to the standard deviation of the simulated data. Figure 2 shows the schematic diagram of the Matlab-SWMM linkage module.

River flow and precipitation data were provided by Pusan National University (<http://pnuhydro.pusan.ac.kr/>). For T-P concentration, data from SeByeong Bridge site observed at Clean Water Lab in Pukyong National University were used. Figure 3 shows the locations of precipitation and stream flow and water quality locations.

2.5. Application of bio-retention cells

In SWMM, BR serves as a generalized facility for all LID facilities. That is, other LID facilities are considered to be modified facilities based on BR. BR is used all over the world and is one of the best performing LID facilities (Davis *et al.* 2009; Ahiablame *et al.* 2012). BR also provides other effects such as aesthetic effects and ecological restoration (Houdeshel *et al.* 2012; Demuzere *et al.* 2014; Liu *et al.* 2014). BRs are installed in various ways (different configurations or sizes) depending on the purpose of adoption (Yang & Chui 2018). On the other hand, the parameters constituting BR in SWMM consist of a total of 18 parameters including surface layer height, soil layer thickness and porosity, storage layer thickness and porosity, and drainage related parameters. The implementation of various BRs in SWMM can be reflected by adjusting the numerical values of these parameters. In this study, we tried to understand the general performance of BR by setting BR of standard configuration. Choi *et al.* (2018) investigated the parameters of the BR-related SWMM presented in a number of documents

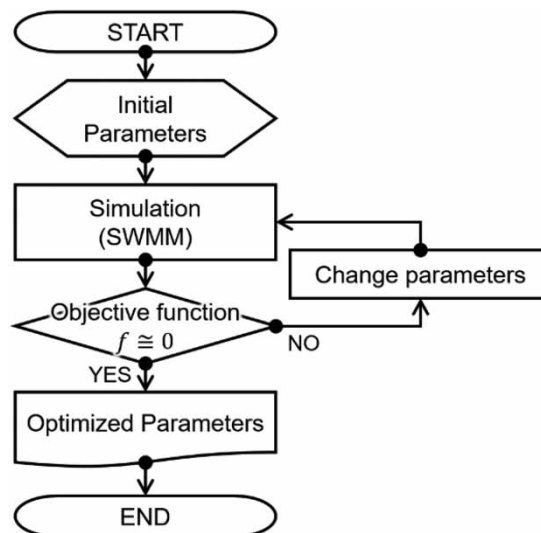


Figure 2 | Schematic diagram for SWMM-Matlab linking module.

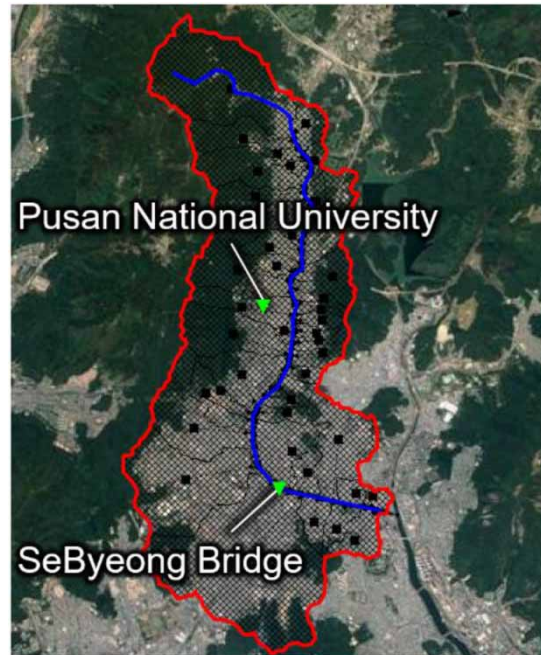


Figure 3 | Location of SeByeong Bridge and Pusan National University.

(U. S. EPA 1999; KECO 2009; Palhegyi 2010; DER 2002; CVC 2012; DOEE 2013; VWRRC 2013; U. S. EPA 2015), and from these investigations, the parameters of the standard configuration for SWMM were presented (see Table 2 and Figure 4).

Among the parameters presented in Table 2, the seepage rate, which means the ability to penetrate into existing soil, is the most conservative soil infiltration rate of Type B of the NRCS hydrological soil group. The reason is that in case of Type C and D which have poor drainage characteristics, it is difficult to expect the effect of the facility, so the principle was not to install the LID facility on such soil.

Table 2 | General parameters of standard bio-retention cell (Choi *et al.* 2018)

LID type	Parameter	Value	Unit	
Bio retention cell	Area	Contributing area	2,000	m ²
		Percent of facility area	4	%
	Surface	Berm height	300	mm
		Vegetation volume fraction	0	–
		Surface roughness	0	–
		Surface slope	0	%
	Soil	Thickness	600	mm
		Porosity	0.45	–
		Field capacity	0.30	–
		Wilting point	0.15	–
		Conductivity	50	mm/hr
		Conductivity slope	46.9	–
		Suction head	61.3	mm
		Storage	Thickness	300
	Void ratio (voids/solids)		0.625	–
	Seepage rate		4	mm/hr
	Clogging factor		0	–
	Drain	Coefficient	0.23094	–
		Exponent	0.5	–
		Offset height	300	mm

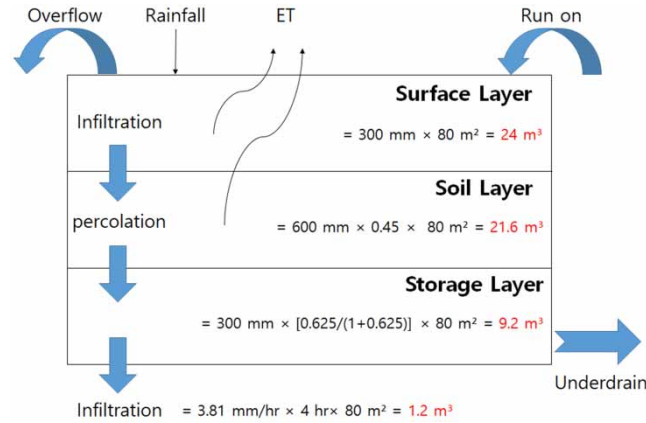


Figure 4 | Capacity of bio-retention by each layer.

In this study, the BR with a facility area of 80 m² was defined as a standard BR (ie, 1 unit of BR), and the interception capacity of the standard BR was calculated. From the parameters in Table 2, we can calculate the interception capacity of the standard BR. The interception capacity of BR is calculated by adding storage capacity and infiltration capacity. In the case of storage capacity, the surface layer capacity + soil layer porosity + storage layer porosity can be calculated as follows:

- (1) Capacity of surface layer = 300 mm × 80 m² = 24 m³
- (2) Porosity of soil layer = 600 mm × 0.45 × 80 m² = 21.6 m³
- (3) Porosity of storage layer = 300 mm × [0.625/(1 + 0.625)] × 80 m² = 9.2 m³
- (4) Total storage capacity = 24 m³ + 21.6 m³ + 9.2 m³ = 54.8 m³

Infiltration capacity can be estimated by multiplying soil infiltration capacity by average rainfall duration. For infiltration into existing soils, 4.0 mm/hr applied to BR’s standard specifications were applied. Since the average rainfall duration of Busan site was 6-hour and median 4-hour, the conservative 4-hour was applied. Therefore, the infiltration capacity was estimated to be 4 mm/hr × 4 hr × 80 m² = 1.28 m³. Finally, the interception capacity of BR was calculated as 56.8 m³, which is the sum of storage capacity 54.8 m³ and infiltration capacity 1.28 m³. The interception capacity corresponding to each layer is shown in Figure 4.

The cost of the standard BR was estimated using the method proposed in CWRA (2010). CRWA (2010) proposed the cost of interception capacity of LID facilities as follows:

$$C_A = V \times C_B \times F \tag{2}$$

where, C_A is the cost of LID facility by unit area (\$), V is the LID capacity (ft³), C_B is the unit cost estimate (\$/ ft³), and F is the adjustment factor (see Tables 3 and 4).

In Equation (2), V used 54.8 m², the estimated interception capacity, C_B used 15.46 \$/ft³, which corresponds to bio-retention in Table 3, and F applies 2.0, which is the newly installed BMP in the area developed in Table 4. Therefore, the cost of installing the calculated standard BR was estimated to be 59,836 \$.

Table 3 | Proposed BMP cost estimates (CRWA 2010)

BMP	Cost (\$/ft ³)
Bioretention (includes rain garden)	15.46
Dry pond or detention basin	6.80
Infiltration trench	12.49
Porous pavement – porous asphalt pavement	5.32

Table 4 | Example of cost adjustment factors (CRWA 2010)

BMP type	Cost adjustment factor
New BMP in underdeveloped area	1
New BMP in partially developed area	1.5
New BMP in developed area	2
Difficult installation in highly urban settings	3

2.6. Scenarios

Projects implemented to mitigate the effects of climate change will involve manpower and costs. Therefore, it is important to understand how much of the impact of climate change can be offset by limited resources. This study benchmarked the case of New York City, USA. New York City, USA, has been implementing a long-term Green Infrastructure Plan since 2002. The project aims to capture 1 inch of stormwater by LID facilities that occurs in an area of 10% of urban land use patches. It is planned to install LID facilities in all subcatchments by 2030 (NYC-DEP 2017). This study examined the extent to which the adverse effects of future climate change were offset when the project was applied to the Oncheon stream basin.

The total area of the Oncheon stream basin is 56,280,000 m² and urban land use is 27,575,847 m². Urban land use area is composed of residential area, commercial area, industrial area, public facility area, transportation area and amusement facility area. The target stormwater capture is 70,043 m³. By dividing this value by 56 m³, the interception capacity of standard bio-retention cells, the number of standard BRs to be installed in the Oncheon stream basin can be estimated. A total of 1,251 units should be installed and the cost is about 74.8 million \$. In terms of cost, installing BR in every subcatchment is practically impossible.

In order to apply BR effectively, it is necessary to determine the subcatchment that should be installed first. In this study, it is considered effective to preferentially install a subcatchment with a high proportion of urban land use area, and the subcatchments where the ratio of land use land area exceeds 70% are summarized (see Table 5).

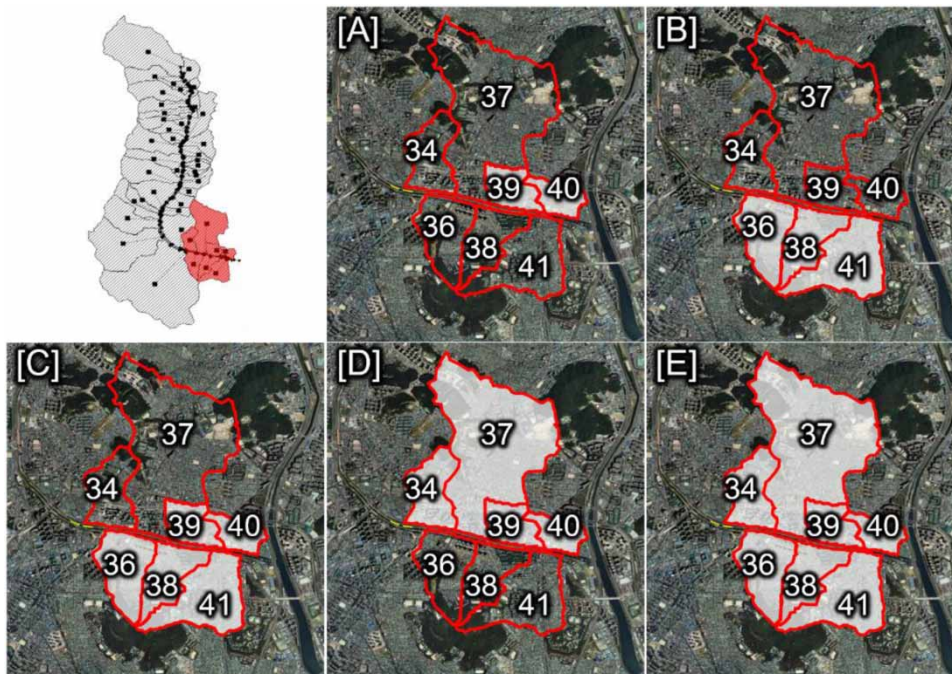
Most of the subcatchments, which have a high proportion of urban land use, are densely populated with residential and commercial areas, and are also located downstream. In this study, seven subcatchments located downstream were used to construct a BR installation scenario. Five scenarios for installing BR in seven subcatchments and one scenario for installing all subcatchments were constructed (see Table 6). Figure 5 shows the subcatchments where BR is installed in each scenario.

Table 5 | Subcatchments with high urban land use area rate

Subcatchment No.	Area (m ²)	Urban land use area (%)	The number of bio-retention cells
4	178,656	90.50	7.3
11	213,561	77.27	7.5
22	283,765	95.15	12.2
27	669,198	84.20	25.6
33	1,703,575	84.88	65.6
34	532,625	91.81	22.2
36	670,477	79.87	24.3
37	2,244,853	80.93	82.4
38	556,518	93.58	23.6
39	634,490	91.15	26.2
40	269,705	77.42	9.5
41	922,286	83.21	34.8

Table 6 | Bio-retention installation scenario in Oncheon stream basin

Scenarios	Subcatchment No.	The number of bio-retention cells (unit)	Cost (million \$)
[A]	39, 40	35.7	2.50
[B]	36, 38, 41	82.7	5.79
[C]	36, 38, 39, 40, 41	118.4	8.29
[D]	34, 37, 39, 40	140.1	9.53
[E]	34, 36, 37, 38, 39, 40, 41	222.8	15.16
[F]	Full installation	1249	84.97

**Figure 5** | Selected subcatchments for study scenarios.

3. RESULT AND DISCUSSION

3.1. Calibration and verification results

Parameters were calibrated using flow rates and TP loads observed at the SeByeong Bridge site in the Oncheon stream basin. From 2014 to 2015, 22 rainfall events were extracted and used for flow calibration, and from 2016 to 2018, 14 rainfall events were extracted and used for verification. The parameters used for correction are the width of the subcatchment (W), CN , the initial depression storage depth (d_{s_perv}) of the permeable zone, and the initial depression storage depth (d_{s_imperv}) of the impervious zone. Table 7 shows the parameter initial estimates and the corrected parameter estimates.

Width W inputs initial values for each subcatchment assuming the subcatchment as a square, and CN inputs initial values for each subcatchment using land use and soil map. If the initial W (or CN) of one subcatchment is greater than the initial W (or CN) of another subcatchment, it is undesirable to change this order of magnitude during parameter estimation. Therefore, a method of correcting by multiplying the initial input value by the coefficient was taken. In other words, W and CN were estimated using Equations (3) and (4), respectively.

$$W_c = f_W \times W_o \quad (3)$$

$$CN_c = CN_o + f_{CN}(100 - CN_o) \quad (4)$$

Table 7 | Stormwater depth calibration parameters

Parameter	f_w (coefficient)	f_{CN} (coefficient)	d_{s_perv} (mm)	d_{s_imperv} (mm)
Original value	1.0	0	5.0	1.875
Optimized value	2.0	0.450	4.0	1.5

where W_c is the calibrated width of the subcatchment, W_o is the initial width, f_w is the calibration coefficient of the width, CN_c is the calibrated CN of the subcatchment, CN_o is the initial CN, and f_{CN} is the calibration coefficient of CN. In the case of CN, the reason for the configuration as shown in Equation (4) is that the calibration was not smooth due to insufficient stream flow. In other words, the large initial CN value is smally corrected, and the small initial value is largely corrected. The depression storage depths d_{s_perv} and d_{s_imperv} were applied equally to all subcatchments.

Figure 6 shows the simulated stormwater depth (SIM run-off depth) and observed stormwater depth (OBS run-off-depth) for rainfall events. Figure 6(a) is the calibration result. Figure 6(b) is the verification result. As a result of calibration, the determinant coefficient (R^2) was 0.9989 and the model efficiency coefficient (NSC) was 0.9746. In verification, $R^2 = 0.95471$ and $NSC = 0.93639$. Therefore, it can be seen that the simulated stormwater depth reproduces the observation data well.

The data observed at Pukyong National University was used to reproduce the T-P loads. T-P loads observed for 15 rainfall events from August 2013 to August 2017 were used to calibrate the water quality parameters. The calibrated water quality parameters are the B_{max} and K_b of the build-up process and the EMC of the wash-off process. Table 8 shows the initial and final corrected values of the parameters.

Since parameter B_{max} is the mass of pollutant per unit area, it is conceptually similar to land-based unit load in Korea. Therefore, B_{max} uses 5 times land-based unit load as the initial value. Parameter EMC used EMC for land use provided by the Korea Institute of Environmental Research as the initial value. As in the stream flow calibration, B_{max} and EMC were also calibrated by applying the initial value to the coefficient.

$$B_{max,c} = f_B \times B_{max,o} \quad (5)$$

$$EMC_c = f_E \times EMC_o \quad (6)$$

where $B_{max,c}$ is the calibrated B_{max} of each land-use patch, $B_{max,o}$ is the initial B_{max} , f_B is the calibration coefficient of B_{max} , EMC_c is the calibrated EMC of each land-use patch, EMC_o is the initial EMC , and f_E is the calibration coefficient of EMC . The parameter K_b was applied equally to all subcatchments.

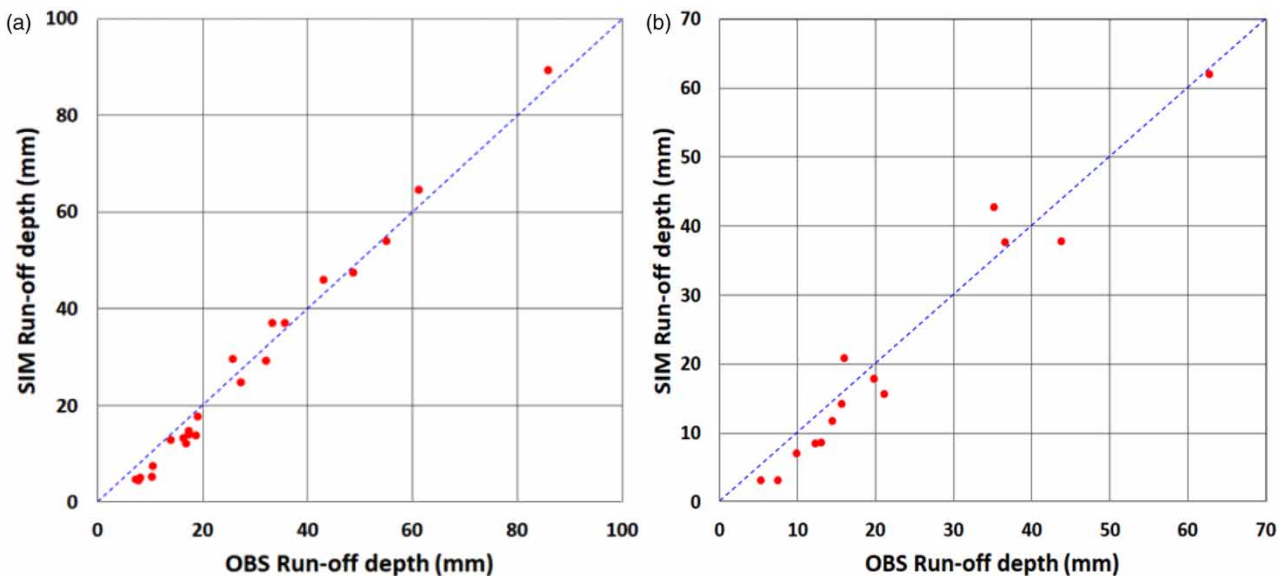
**Figure 6** | (a) Flowrate calibration result, (b) flowrate verification result.

Table 8 | T-P loading calibration parameter

Parameter	f_B (coefficient)	K_D (/day)	f_E (coefficient)
Original value	1.0	0.2	1.0
Optimized value	4.7578	0.98135	1.25

Figure 7 shows the simulated T-P loads (SIM T-P Loading) and the observed T-P loads (OBS T-P Loading). As a result of the calibration, $R^2 = 0.70283$ and $NSC = 0.65922$. Loads are generally not as easy to calibrate parameters as stream flows. This is because, firstly, the observation error occurs easily compared to the flow rate, and secondly, the load is calculated as the product of the flow rate and the concentration, and the error occurs twice.

3.2. Analysis of the effects of climate change

There are biases between climate change scenario data and observational data (Boe *et al.* 2007). In general, when applying climate change scenarios, priority is given to correcting these biases. The input climate data needed to simulate the SWMM are precipitation and evapotranspiration, and both data were bias-corrected using the quantile mapping method. However, the results of SWMM simulations using present climate simulations and SWMM simulations using observational climate data may be different even if the present climate simulations with bias-correction are applied. By comparing these, the applicability of the climate change scenario data was examined. Observational data consists of 30 years of data from 1981 to 2010, corresponding to the Busan site, among the data provided by the Korea Meteorological Administration (KMA). Present climate simulations were obtained from the same period of MPI-ESM-LR/WRF/RCP 8.5 combinations.

Table 9 shows the water quality items (NPS pollutants, CSOs) and hydrologic components (precipitation, run-off depth, evaporation) simulated from observational data to present climate simulations. Precipitation, run-off depth, and evaporation showed very similar observation data to present climate simulations. In terms of water quality, NPS pollutants differed by about 850 kg per year and CSOs by about 2,000 kg per year. There seems to be a big difference, but the error is about 5% for NPS pollutants and about 7% for CSOs. Water quality can vary greatly due to the complex and varied factors involved. In addition, CSOs are not calculated directly in the subcatchment but rather by adding routing processes. This leads to greater uncertainty. In view of this, it is unlikely that the results from observational data and current climate simulations will vary significantly. Through this verification, the applicability of the relevant climate change scenario data can be judged as sufficiently verified.

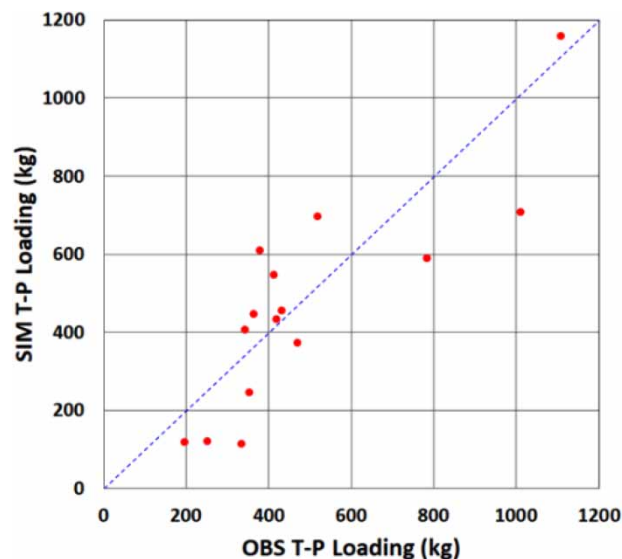
**Figure 7** | Water quality calibration results.

Table 9 | Comparison of observed with present (ref. Obs is a simulated result using the observed data, Pre is a simulated result using the present data)

Major category	Sub category	Obs	Pre
Hydrological quantity	Precipitation (mm/yr)	1519.06	1464.91
	Run-off depth (mm/yr)	1076.30	1027.13
	Evaporation (mm/yr)	119.74	109.90
Water quality	NPS pollutants loading (kg/yr)	14894.94	14052.26
	CSOs loading (kg/yr)	28109.05	26155.39

Next, current and future data were compared to identify the effects of climate change. The hydrologic components and water quality items compared in Table 10 were configured in Table 9. Change rate (%) was added to identify changes in the future compared to the present. In the case of hydrologic components, all components increased, but the change in run-off depth was relatively higher than that in precipitation. This means that more runoff occurs and relatively less evaporation occurs than rainfall. For water quality items, NPS pollutants and CSOs were similarly increased by about 10%. In summary, these results suggest that future climate change may deteriorate hydrologic systems in urban watersheds and contribute to increased loads of water pollutants.

3.3. Off-set effect of BR for climate change

Table 10 uncovers the effects of climate change on the hydrologic components and water quality in the future. This section looks at how BR offsets the effects of climate change. The effect of BR is quantified as follows:

$$E = \frac{Fut - Fut_{BR}}{Fut - Pre} \times 100 \quad (7)$$

where, *Pre* is the result in the present climate, *Fut* is the result in the future climate, and *Fut_{BR}* is the result when the BR is installed in the future climate. Thus, *E* means the extent to which BR offsets the effects of climate change. Table 11 shows the effects of BR on climate change offsetting stormwater depths. BRs, on average, have reduced the stormwater depth increased by climate change by 13.5%. However, scenario F did not show a good offsetting effect compared to other scenarios. This is because all the subcatchments that do not expect BR efficiency are included.

Table 10 | Comparison of present with future (ref. Pre is a simulated result using the present data, Fut is a simulated result using the future data)

Major category	Sub category	Pre	Fut	Change (%)
Hydrological quantity	Precipitation (mm/yr)	1464.91	1738.95	+18.7
	Run-off depth (mm/yr)	1027.13	1285.50	+25.15
Water quality	NPS pollutants Loading (kg/yr)	14052.26	15571.38	+10.81
	CSOs loading (kg/yr)	26155.39	28949.48	+10.68

Table 11 | Stormwater depth by scenario (mm/yr)

Scenarios	A	B	C	D	E	F
<i>Pre</i>	1350.80	1247.86	1278.34	1248.20	1248.08	1027.14
<i>Fut</i>	1620.08	1513.76	1545.24	1513.76	1513.76	1303.72
<i>Fut_{BR}</i>	1583.32	1477.73	1509.00	1478.21	1478.04	1280.69
<i>E (%)</i>	13.65	13.55	13.58	13.39	13.44	8.33

Tables 12 and 13 show the effect of BR's climate change offset on NPS pollutants and CSOs. The effect of BR on NPS pollutants was found to offset, on average, 40% of the adverse effects of climate change. This offset is more than three times the stormwater depth. BR's climate change offset effects on CSOs average 70%. It can be seen that the effect of BR on CSOs is very high. This can be understood by looking at the mechanism by which LID is applied in the EPA SWMM. NPS pollutants are directly reduced by BR in subcatchments. CSOs are generated by both stormwater and NPS pollutants from subcatchments. Thus, stormwater and NPS pollutants reduced by BR drive changes in CSOs. This overlapping effect makes BR's climate change offset effects on CSOs larger than those for stormwater depth and NPS pollutants.

4. CONCLUSION

Oncheon stream catchment is a typical urban area and generates a lot of stormwater due to the large number of impervious areas caused by urbanization. Rainfall does not infiltrate into the soil layer, so stormwater flows into the stream with large amounts of pollutants without natural purification through soil and vegetation, and groundwater is depleted, reducing the base flow of the stream. Climate change is increasing the frequency and intensity of rainfall. This disturbance of hydrological systems continues to occur. Most of the Oncheon stream watershed consists of a combined sewer pipe network, which results in frequent CSOs. Therefore, this study analyzed the effects of climate change on the hydrologic systems and CSOs in urban watersheds, and investigated the effects of bio-retention cells among LID facilities to mitigate the adverse effects of climate change.

The results of applying various climate change scenario data to SWMM revealed that the increase in stormwater depth is greater than the increase in precipitation. Future NPS pollutants and CSOs are projected to grow by about 10% over present ones. In other words, water pollution loads in urban watersheds are likely to increase due to climate change.

To reduce the impact of climate change, bio-retention cells were applied among LID facilities. Bio-retention cells were assumed to be installed in subcatchments, referring to the Green Infrastructure Plan in New York City, USA. In the high impermeability subcatchments, the stormwater depth offsets the adverse effects of climate change by 13.5%. The offset effects on NPS pollutants and CSOs were 40 and 70%, respectively. In particular, bio-retention cells have been shown to be a useful means of countering the increase in CSOs caused by climate change.

However, there are various types of BRs (e.g., rain gardens), and its size, composition, and cost can change depending on the conditions of the installation site. The key purpose of this study is to derive and examine the average effect of the standard BR, with no specific BR method. Hence, in this study, the standard BR was constructed using general BR parameters obtained through literature research for standard BR, without a selection of certain kinds of vegetation, material, and so on. However, when designed with specific BRs suitable for certain sites, the effects may differ from the results of this study, so a sensitivity

Table 12 | NPS pollutants loading by scenario (kg/yr)

Scenario	A	B	C	D	E	F
<i>Pre</i>	436.62	806.78	1243.40	1471.37	2278.15	14052.26
<i>Fut</i>	488.55	895.85	1384.4	1634.63	2530.48	15571.38
<i>Fut_BR</i>	469.26	856.7	1325.96	1564.87	2421.57	15061.58
E (%)	37.15	43.95	41.45	42.73	43.16	33.55

Table 13 | CSOs by scenario (kg/yr)

Scenario	A	B	C	D	E	F
<i>Pre</i>	675.89	1475.67	2151.56	2452.22	3927.89	26155.39
<i>Fut</i>	737.95	1609.33	2347.28	2657.95	4627.28	28949.48
<i>Fut_BR</i>	696.48	1507.67	2204.14	2510.3	4017.96	27919.47
E (%)	66.82	76.06	73.13	71.77	87.12	36.86

analysis to reflect various BR methods is one of the good topics of further research. In addition, many of the literature examined ignores some characteristics such as the vegetation volume fraction, the roughness of surface, and so on, thus this study also intactly reflected the values investigated without considering the characteristics (i.e., set to zero; see Table 2). However, note that these parameters may largely affect the effectiveness of the facility in certain cases.

This study is a pilot application of climate change scenarios. In other words, urban hydrological and water quality responses to one type of climate change scenario data were investigated through the SWMM. In the future, various climate change scenario data need to be applied and analyzed. In addition, since more than nine LID facilities can be simulated in the SWMM, it is possible to investigate the effects of various LID facilities. The application of various climate change scenarios and various facilities could contribute to the search for the optimal urban drainage design to adapt to climate change.

ACKNOWLEDGEMENTS

This work was supported by Korea Environment Industry & Technology Institute(KEITI) through Smart Water City Research Program, funded by Korea Ministry of Environment(MOE)(2019002950004).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 27 May 2020; accepted in revised form 16 August 2021. Available online 30 August 2021