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Assessment of porous pavement effectiveness on runoff reduction under climate change scenarios

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ABSTRACT

Climate change has affected both water quantity and quality by increased rainfall, runoff, and associated pollutant loading in urban areas. Stormwater Best Management Practices (BMPs) are now being popularly considered for the reduction of increased runoff due to urbanization. Most research has been conducted on the analysis of BMP effectiveness under current conditions. However, there is no extensive literature on BMP effectiveness studies considering climate change. In this study, the effectiveness of BMP, porous pavement in particular, has been assessed under climate change scenarios. Climate change scenarios were generated by trend analysis of the historical rainfall data. The 2-year and 100-year design storms having 24-h durations were determined for three scenarios: current conditions, 2020, and 2050 using frequency analysis. Storm Water Management Model was then calibrated and used to evaluate the impact of climate change and the effect of incorporating porous pavement on runoff. Geographic information system analysis showed that 33.4% of the basin was suitable for the installation of porous pavement. Hydrologic modeling demonstrated that climate change can increase peak flows by as much as 26.9% relative to current condition. Further analysis showed that porous pavement can be effective in reducing the runoff volume and peak flow below current conditions for all scenarios, offsetting negative impact of climate change.

Keywords: Climate change; Porous pavement; Runoff; Stormwater modeling; SWMM

1. Introduction

Due to continued urbanization and development around rivers, the impervious areas have been on the rise, reducing infiltration capacity and thus, increasing the amount of runoff in watersheds. Such human activities inevitably result in the change of hydrological characteristics such as the increase in peak flow and decrease in the time-to-peak. In addition, the newly emerging climate change issue and associated rainfall pattern change further exacerbate the negative impact due to development. It is reported that the number of

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recorded disasters related to climatological events, such as cyclones and flood, has increased more than that of the disasters related to geological events [1].

With the abnormal changes in the weather pattern, rivers have frequently flooded and design capacities of sewers have been exceeded causing major damages especially on urban areas. For this reason, typical centralized flood reduction approaches such as detention basin have reached their limits and are not as efficient as in the past in reducing runoff. Therefore, stormwater Best Management Practices (BMPs) are now being considered for the reduction of increasing runoff due to urbanization. These include practices such as infiltration basin, porous pavement, and green roof which encourage natural water cycle and recharge. This reflects the paradigm shift in stormwater management from centralized to distributed approaches [2].

BMP modeling simulates the hydrologic performance of BMPs. In early days, such modeling technique was developed to focus on the scale of an individual BMP. However, their performance at the watershed scale became ultimately more important, and it had become the subsequent research interest [3].

Various researches that estimate the effectiveness of BMP installation have been conducted using rainfall-runoff models such as Storm Water Management Model (SWMM) and Model for Urban Stormwater Improvement Conceptualisation [4–7]. Newly emerging climate change issues also have significant implication on urban stormwater and spawned many research [8]. However, there is no extensive literature to date to investigate the improvement on water cycle by BMPs under climate change scenarios. Accordingly, watershed-scale modeling of stormwater BMP under climate change scenarios would be necessary for the sustainable development considering external factors of climate change.

In this study, such research gap is to be filled by developing the framework on the modeling of a stormwater BMP, porous pavement, under climate change scenarios as a climate change adaptation measure for sustainable development.

2. Materials and methods

2.1. Stormwater modeling

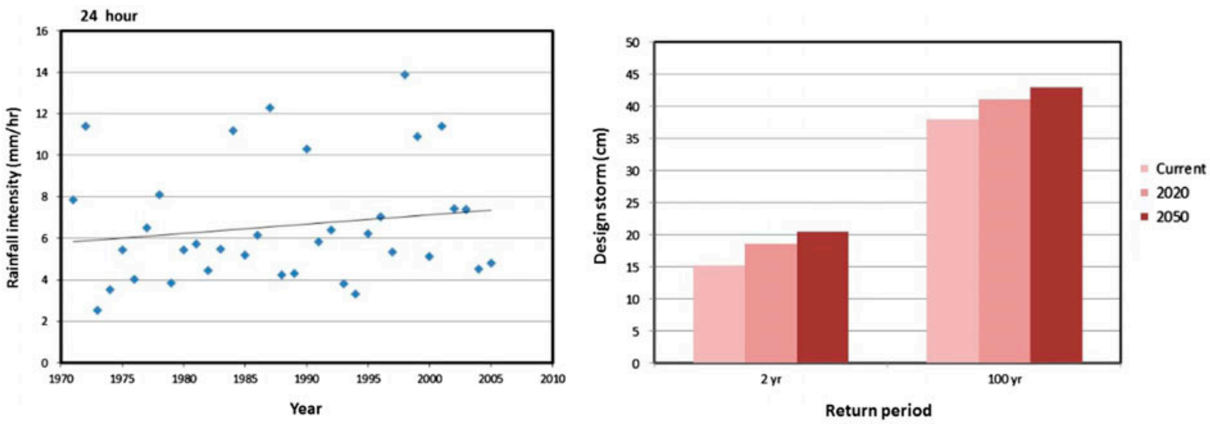
BMP modeling helps the design of stormwater BMPs and can make quantitative predictions on its performance. Conventional urban hydrology model was designed to be used for storm sewer design and the detention basin for efficient drainage and storage to be used for detention. In many models, BMPs are not explicitly conceptualized and thus it is more difficult to evaluate their effectiveness [9].

SWMM is one of several advanced computer-assisted models designed to simulate urban storm water runoff. SWMM was first developed by the US Environmental Protection Agency in 1971 and has undergone several major upgrades since then. It continues to be used throughout the world for planning, analysis, and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with applications in non-urban areas as well. The current edition, Version 5 provides an integrated environment for editing study area input data, running hydrologic, hydraulic, and water quality simulations, and viewing the results in a variety of formats. The flow routing methods consist of steady flow, kinematic wave, and dynamic wave methods. Runoff hydrographs are predicted based on the input hyetograph and the physical characteristics of the subcatchment including area, average slope, degree of imperviousness, overland flow resistance factor, surface storage, and overland flow distance. The infiltration losses are estimated by using the Horton equation, Green-Ampt equation, or Soil Conservation Service-Curve Number (SCS-CN) method. Especially, SWMM 5.0 provides LID module that can simulate stormwater BMPs. Therefore, SWMM was used for analysis of runoff reduction by porous pavement.

2.2. Climate change scenario

Trend analysis using linear regression model [10–12] was used for the generation of climate change scenario. This method tests the statistical significance of linear trend in annual maximum rainfall series of a given rainfall duration and tries to extrapolate future rainfall scenarios. This method is known to be able to quantify the characteristics of nonstationary time series in a simpler fashion and more advantageous over GCM data where spatio-temporal resolution tends to be insufficient and sensitivity analysis where future condition is arbitrarily assumed, e.g. ±10%, ±20%, etc.

In this study, annual maximum rainfalls with 24-h duration were analyzed for their frequencies for target future years (2020 and 2050). The data for trend analysis were collected at Seoul Station operated by Korea Meteorological Administration (KMA) which is close to the study basin, Goonja Drainage, and data with the duration desired in this study are available for the period that spans from 1961 through 2011. Then, for the duration that is found to have a linear trend by trend analysis, the trend line is extrapolated to estimate future rainfall scenarios (Fig. 1). The design rainfall is estimated by using probability rainfall and



(a) Trend analysis (b) Design storm for the future

Fig. 1. Rainfall intensity trend of 24-h duration at KMA's Seoul Station and future design storm.

Huff's quartile distribution [13]. Probability rainfall was determined using type I extreme value distribution. The result of investigation on rainfall time distribution revealed that peak intensity occurred 39.3% in the 1st quartile, 25.0% in the 2nd quartile, 16.2% in the 3rd quartile, and 19.5% in the 4th quartile. Therefore, the 1st quartile distribution was taken for the time distribution of rainfall.

2.3. Study area

The study area is Goonja Drainage in metropolitan Seoul of Korea. It is located at the downstream of Joong-Rang River draining to its left bank. Subcatchment input data were estimated by a commonly used geographic information system software package ArcView 3.2 (Table 1) using digital elevation model, land use map, and from available literature. For the modeling of infiltration, commonly used SCS-CN method option was chosen, which is a new feature in SWMM 5.0. The analysis of soil map revealed that SCS hydrologic soil group is type B. Average CN of the watershed was estimated using land uses and corresponding areas in the drainage (Table 2). Fig. 2 presents the land use in the watershed. Table 3 shows infiltration parameters estimated for existing basin condition. Water quantity and quality observatories are located approximately 50 m downstream of Goonja Bridge.

Table 1
Subcatchment input data

Area (ha)	Impervious ratio (%)	Slope (m/m)	Width (m)	Impervious Manning's n	Pervious Manning's n	Impervious initial loss (mm)	Pervious initial loss (mm)
96.4	83.4	0.014	3910.6	0.02	0.04	2.54	5.08

Table 2
Land use and CN of Goonja Drainage basin

Land use	Area (m^2)	Ratio of area (%)	CN
Main road	126,137	13.1	98
Parking lot and street	322,240	33.4	89
Building roof	353,733	36.7	98
Green zone	161,820	16.8	69
Total and average CN	963,930	100.0	88.04

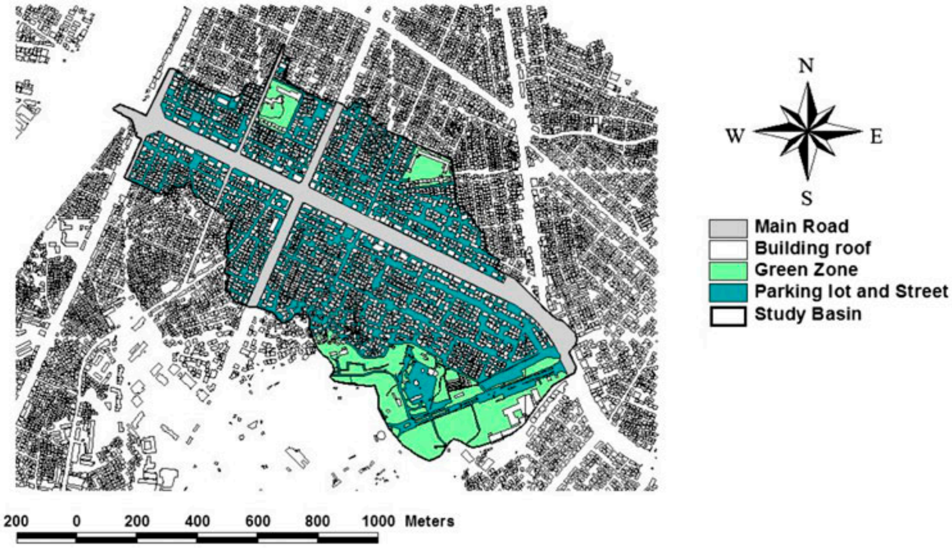


Fig. 2. Land use of Goonja Drainage.

Table 3
Subcatchment infiltration data

Curve number	Conductivity (mm/h)	Drying time (d)
88.04	6.25	4

3. Results

3.1. Calibration and verification

Simulated hydrograph was characterized by the following parameters: (1) the peak discharge; (2) the time-to-peak; and (3) the volume under the hydrograph [14]. For calibration run, width and impervious ratio were adjusted to match simulated hydrograph with the observed one (6 April 2005). The parameters estimated from the calibration were used to simulate an independent storm event (16 May 2005) with the purpose of validating the model. The results of calibration and validation could be seen in Fig. 3.

The errors for peak discharge and runoff volume were within 1.5 and 5%, respectively, and time-to-peaks were captured quite accurately within 7.4% of the observed. Overall, both calibration and validation runs were found to be satisfactory in terms of runoff volume, peak flow, and time-to-peak.

3.2. Analysis of porous pavement effectiveness

From a geographic information analysis, 33.4% of the Goonja Drainage was found to be suitable for the

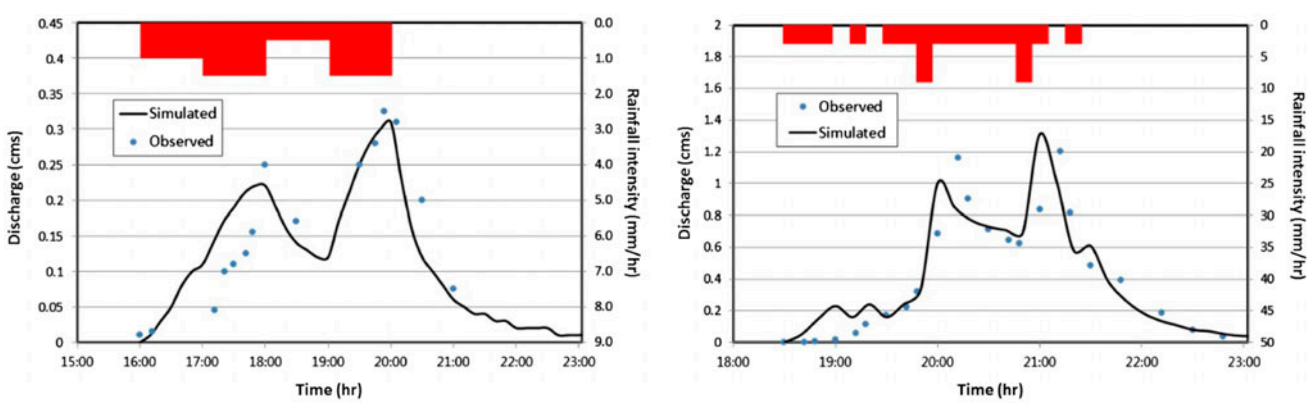


Fig. 3. Model calibration and verification for storm events recorded on 6 April 2005 (left) and 16 May 2005 (right).

Table 4
Parameter for porous pavement

Process layer	Parameter	Value
Surface	Surface storage depth (mm)	2.54[a]
	Vegetation volume fraction	0.0
	Surface roughness	0.15[a]
	Surface slope (%)	2.296
Pavement	Thickness (mm)	150[a]
	Void ratio	0.21[a]
	Impervious surface fraction	0
	Permeability (mm/h)	2,540[a]
	Clogging factor	0
Storage	Height (mm)	450[a]
	Void ratio	0.5[a]
	Conductivity (mm/h)	750[a]
	Clogging factor	0

[a]SWMM 5 User's Manual.

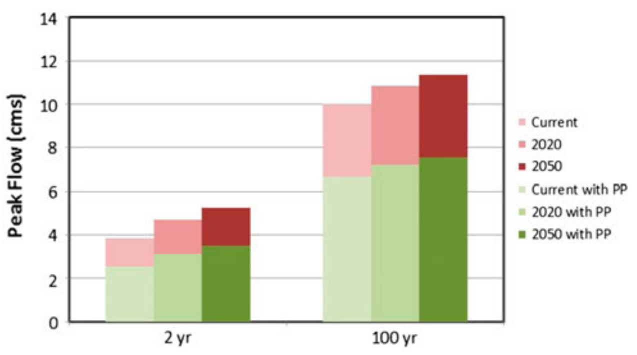


Fig. 4. Changes in peak flow due to the porous pavement installation under climate change scenarios.

installation of porous pavement including roads and parking lots. In addition, associated parameters for stormwater BMPs found in the literature are presented [15]. Table 4 presents the corresponding input parameter values for the SWMM-LID module. In order to get highest reduction in runoff, maximum value was selected for the installation area of porous pavement, and other parameters were estimated to meet the same goal.

The simulated results of installing porous pavement show that peak flow was reduced in all cases by around 33.4% (Fig. 4). Similar reduction rate found for small (2-year) and large (100-year) design storms is attributed to the higher infiltration capacity of porous pavement than both design storms. Further analysis showed that porous pavement can be effective in reducing the runoff volume and peak flow below current conditions without porous pavement and for future scenarios, offsetting negative impact of climate change.

4. Conclusions

This study combines SWMM and trend analysis being tried as a new tool for the evaluation of BMP effectiveness on improving water cycle under climate change scenarios. Once the future runoff condition is determined by SWMM based on future rainfall scenarios, questions regarding the decision-making can then be addressed by modeling BMPs, such as how much runoff reduction can be made by BMP, what is the required size of BMP to mitigate the effect of climate change, and which BMP will be more effective given the same monetary resources.

In this study, the effects on the reduction of peak flow by installing porous pavement in urban drainage area were simulated by using SWMM, and the effects are compared between the current condition and climate change scenarios. Peak flow reduction rates from the study area, obtained using SWMM 5.0, were analyzed to evaluate the performance of the porous pavement. It was found that the peak flow under future scenarios with porous pavement can be reduced below the peak flow of the current existing condition suggesting the BMP's ability to adapt to the negative impact of climate change on runoff.

Recently, there is a rising interest in the assessment of impact by climate change and utilizing BMPs as mitigation measures. However, until now there is no extensive study on BMP modeling for its improvement on water cycle under the context of climate change, and, as such, methodological framework established in this study and a case study done to an urban watershed, are thought to be useful in providing a means to assess climate change impact on stormwater runoff and establishing disaster prevention measures for the future.

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