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Cost-effectiveness analysis of stormwater best management practices (BMPs) in urban watersheds

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ABSTRACT

This study demonstrates a cost-effectiveness analysis of stormwater BMPs to answer questions, such as what type to place and how large it should be. Cost-effective analysis showed that for the basin considered, a porous pavement was the most effective means of controling runoff, which was able to bring the peak runoff down to the predevelopment level with the least budget. A storage basin was the second best, which was able to bring the peak runoff down to the predeveloped conditions, but with a higher budget. The effectiveness of a green roof in reducing the peak runoff plateaued beyond a certain budget, and was unable to bring the peak runoff down to the predeveloped level, regardless of cost. It is thought that a porous pavement would be a cost-effective BMP in a severely urbanized setting.

Keywords: Cost-effectiveness; Stormwater BMP; SWMM 5.0

1. Introduction

Due to continued urbanization and development around rivers, impervious areas have increased, reducing the infiltration capacity and; thus, increasing the amount of runoff into watersheds. Such human activities inevitably result in a change in the hydrological characteristics, such as an increase in peak flow and a decrease in the time to peak. Stormwater runoff from urbanized watersheds increases the potential for floods and the associated pollutant loads, which impairs the receiving water bodies [1].

To resolve this problem, interest in facilities capable of storage and infiltration has rapidly increased [2–6]. In fact, the introduction of the facilities has gradually spread throughout certain local governments. Devices, such as storage basins, green roofs and porous pavements, serve to control runoff at the source by retaining water before it can enter the draining network; thereby, preventing an increase in the frequency and intensity of flood events.

Although the utility of the above mentioned devices has become well known, in practice, the question of what type of BMP should be chosen, how large it should be and where to put them has to be addressed for particular sets of BMP alternatives. Modeling is a useful tool when such decisions are required to decide on the particular type of BMP to use [7].

There are some models that can be utilized to mimic the stormwater BMPs; however, but the modeling technique is still at the initial stage. Also, only a few studies have investigated the cost-effectiveness analysis to help make the decisions as to which type, and its placement

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and size. This study is a follow- up of the earlier work in which a methodology for simulating stormwater BMPs was developed using the established urban hydrology model, SWMM. In this study, a cost-effectiveness analysis of stormwater BMPs has been demonstrated to answer such questions in the context of reducing the peak runoff to that under predevelopment conditions.

2. Methods

2.1. Study site

The Goonja drainage in metropolitan Seoul, Korea, was chosen as the test site [8]. It is located downstream of the Joong-Rang River, draining to its left bank, and has an area of 96.4 ha and an impervious ratio of 83.4%. The main drainage length is 3910.6 m, with a 1.4% slope. Water quantity and quality observatories are located approximately 50 m downstream of the Goonja Bridge. This site consists mainly of residential and commercial areas, roads and public facilities. Figure 1 presents the land use in the watershed. The classification of the soil according to the SCS hydrologic soil group was mainly type B; the average curve number (CN) for the study site was 89.7.

2.2. Stormwater runoff modeling

Runoff modeling was performed using the EPA SWMM 5.0 [9]. Flow routing methods included none, steady, kinematic and dynamic wave options. Infiltration losses were estimated using either the Horton, Green-Ampt or SCS-CN formulae. For this study, the dynamic wave option was used for flow routing. The Green-Ampt and SCS-CN methods were used for simulating the rainfall excess when porous pavements [10] and green roofs [11, 12] were installed at the study site, respectively. To simulate the storage basin, the storage module within SWMM was utilized. Detailed discussion on simulating stormwater BMPs using SWMM for the Goonja Drainage is found in Lee et al. [13].

Various design storms, with frequencies of 2-, 10-, 50- and 100-year [14, 15], were used to analyze the effectiveness of the stormwater BMPs; storage basin, green roofs and porous pavement, depending on the size of the storms. The first quartile of the Huff method was used for the temporal distribution of the design storm. Existing and predevelopment peaks were also calculated to find the base conditions without BMPs for later comparison, with the target value for the reduction in runoff used to determine the size of a BMP using the current land use conditions and those from 1975, which is the earliest available information.

For each designed storm, the effectiveness of the BMPs was tested by increasing the budget to obtain the most effective BMP for a given budget. The size of a BMP for a given budget is determined from the construction cost information available in the literature. Seoul Development Institute [16] provided the storage volume-cost relationship (Fig. 1). English Nature [17] compared the costs of green roofs for several countries; this study used a figure of \$134.5/m^2 (\$12.5/ft^2) found in Paladino [18]. For a porous pavement, a cost of \$16.1/m^2 (\$65,000/acre) was used, as found in Heaney and Lee [19]. The consideration of the operation and maintenance costs was beyond the scope of this research; however, such a life-cycle-analysis can be performed via a continuous simulation [20].

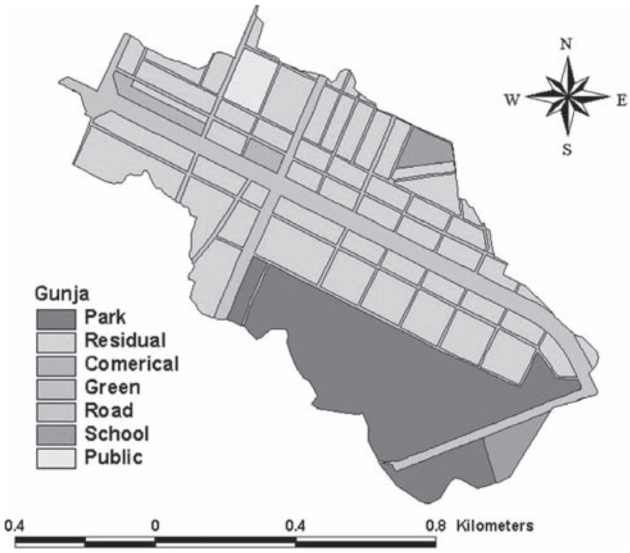

Fig. 1. Land use of Goonja.

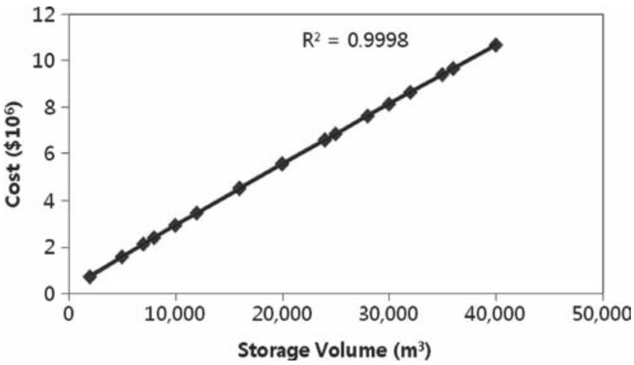

Fig. 2. Storage cost by volume.

3. Results and discussion

3.1. Comparison of peak flow reduction by budget

The runoff analysis of BMPs with frequencies of 2-, 10-, 50- and 100-year rainfalls revealed a reduction in peak flow according to budget (Fig. 3).

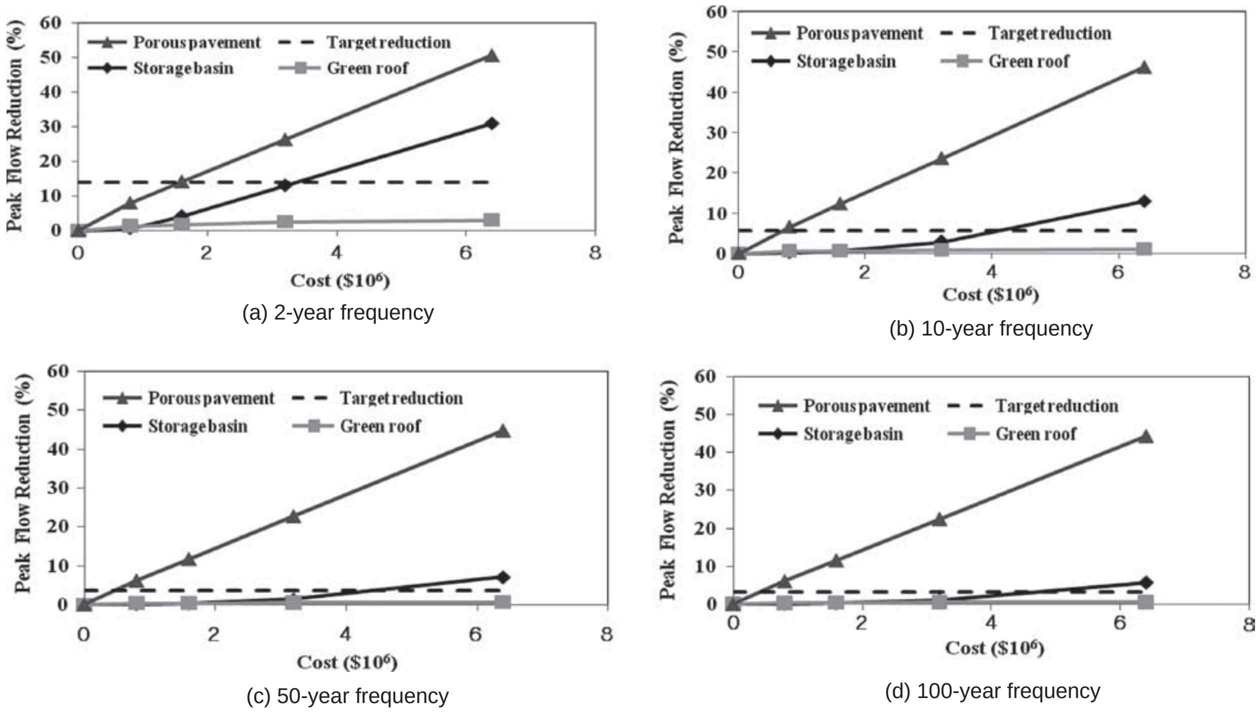

Fig. 3. Comparison of peak flow reduction by BMPs for the various budget ranges.

The reduction in peak flow of the storage basin tends to increase nonlinearly for all return periods. This was thought to be due, from the depth-outflow relationship, to the more rapid changes in the flow rate as the depth becomes shallower. As the capacity of the storage basin increases with increasing budget, the depth will decrease and; thus, the outflow will also decrease rapidly, resulting in an increased reduction in peak flow.

In the case of green roofs, the reduction in peak flow for a given return period increased up to budget of 0.8 million dollars; however, it became constant thereafter. This may be explained by the increase in the average CN value for a permeable area on the installation of a green roof, which has a higher CN value than the existing permeable area. The reduction in peak flow due to the decrease in impervious areas is offset by the increased runoff from permeable areas as a result of the increased average CN value for a permeable area; this was similar to the findings of Perez-Pedini et al. [3].

In the case of a porous pavement, the reduction in peak flow for a given return period increased linearly with increasing budget. This may be explained by the high hydraulic conductivity of a porous pavement. The rainfall considered in this study was all found to infiltrate the porous pavement area as the absorbing characteristic of a porous pavement was sufficiently high compared to these designed storms. As a result, the reduction in peak flow increased linearly with increasing budget.

3.2. Comparison of peak flow reduction by return period

The reduction in peak flow due to the installation of a BMP for various return periods is given in Fig. 4.

As shown in Fig. 4, the peak flow was reduced by the installation of BMPs, and for a given budget, the reduction in peak flow tended to decrease with increasing return period. In the case of a storage basin, when the budget was relatively small, the reduction in peak flow was very low. For large storms, if the capacity was low, the reduction in peak flow was minimal, as the area of the orifice should be increased in order to avoid flooding. However, as the storage volume increased with budget, the reduction in peak flow was superior to that of a green roof.

In the case of an infiltration facility, such as a green roof and porous pavement, the reduction in peak flow was larger for small storms because of the effective infiltration of the pervious area. However, infiltration tends to sharply decrease in pervious area with increases in the return period. This is due to the decrease in the moisture retention ability of soil being nonlinear with rainfall depth and duration. For large storms, soil becomes saturated and runoff increases; therefore, the reduction in peak flow decreases.

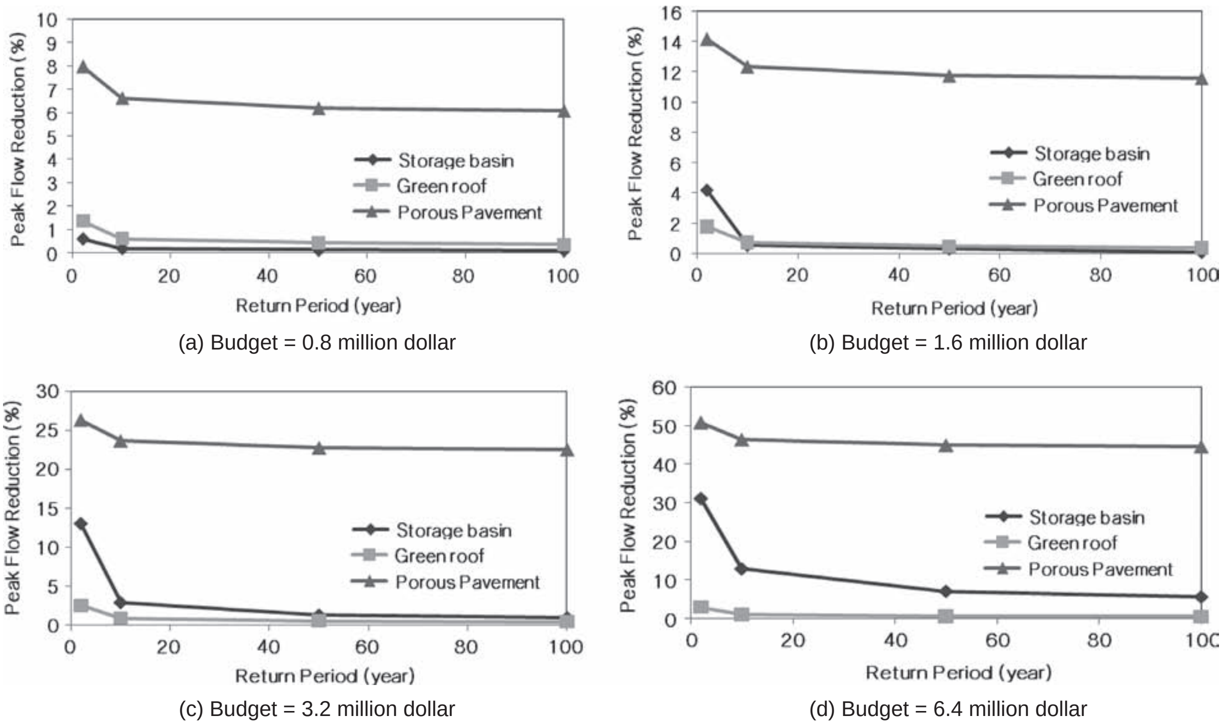

Fig. 4. Comparison of peak flow reduction by BMPs.

4. Conclusions

In this study, the reduction in peak flow due to stormwater BMPs was simulated using SWMM, developed by the US EPA. The reduction in peak flow for the study area was then analyzed to evaluate the performance of the storage and infiltration devices, as well as their cost-effectiveness. In order to compare the cost-effectiveness of each BMP, the reduction in peak flow due to each BMP was compared for a given budget. The unit cost for each BMP was estimated from the literature. The following conclusions were drawn from this study.

1. The results of the runoff analysis on the storage basin with 2-year frequency rainfall revealed that the peak flow decreased by a maximum of 31%. The peak flow reduction of storage showed a endency to increase nonlinearly for a given return period, which was thought to be due to the nonlinear decrease in the outflow with increasing budget.
2. In the case of a green roof, the peak flow reduction was less than for the other BMPs. The peak flow reduction was almost constant, regardless of the budget, because the average CN value increases for a permeable area due to the inclusion of the higher CN value of a green roof. This increases the runoff from a permeable area; thus, offsetting the peak flow reduction effect due to the decreased impervious area.
3. A porous pavement showed a maximum peak flow reduction of 50.7%, and about 43% even for a higher return period. The peak flow reduction tends to increase linearly with increasing budget. This was thought to be due to the fact that the total rainfall onto a porous pavement area infiltrates due to its high hydraulic conductivity and did not contribute to the generation of runoff.
4. A porous pavement was found to be the most cost-effective for the basin considered in this study for the given designed storms and budget range. It was assumed that the performance of the porous pavement would be maintained, but in reality, the clogging phenomenon of infiltration facilities can occur. The SWMM cannot simulate such a phenomenon and it would be expected that the actual peak discharge could be higher than the simulated peak discharge in the long run.
5. It is also thought that this study can be used more effectively for a cost-effectiveness analysis of storage and infiltration facilities if the predicted reduction in peak flow from the hydrology model can be further verified by monitoring of drainage areas installed with BMPs.

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