Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.781104

51 (2013) 4081–4087
May

Taylor & Francis
Taylor & Francis Group

Performance comparison of two hybrid stormwater treatment systems having different filter media configuration

Franz Kevin F. Geronimo, Marla C. Maniquiz-Redillas, Lee-Hyung Kim*

Department of Civil and Environmental Engineering, Kongju National University, 275 Budaedong Cheonan, Chungnamdo 330-717, South Korea
Email: leehyung@kongju.ac.kr

Received 15 May 2012; Accepted 31 December 2012

ABSTRACT

Stormwater best management practices (BMPs) commonly employ only one function that is sometimes insufficient to achieve its necessary efficiency. The method of integrating several functions of BMP technologies and incorporating them in one treatment system is referred to as hybrid BMP. This study developed, investigated, and compared the efficiency of two laboratory-scale hybrid BMP in reducing stormwater pollutants and runoff volume. The laboratory-scale hybrid BMPs developed were composed of treatment tanks arranged in series referred to as infiltration, storage or retention and final tanks that have different media configuration. Based on the results, both hybrid types were effectual in pollutant removal and flow volume reduction since both hybrid types significantly reduced the inflow volume and all pollutants including total suspended solids, chemical oxygen demand and total metals ($p < 0.05$). Hybrid type A was more advantageous for designs considering greater volume for groundwater recharge, less pollutant discharged to sewer systems and good removal efficiency for shorter hydraulic retention time. Meanwhile, hybrid type B was more appropriate for designs considering greater volume for stormwater reuse and less cost in terms of filter media usage. Depending on the design consideration, either one of the hybrid BMP types may be applicable.

Keywords: Hybrid BMP; Infiltration; NPS pollution control; Reuse; Runoff reduction

1. Introduction

Nonpoint source (NPS) pollutants are complex urban pollutant mixtures which originated from equally complex array of sources [1]. Stormwater runoff from highly urbanized areas related to transportation land uses carries NPS pollution to surface water bodies in the form of organics, nutrients, particulates, and solids [2,3]. One study identified that the water quality in reservoirs is significantly impacted by NPS pollution [4]. Thus, increasing urban water quality issues and its impact on the receiving water bodies resulted to much interest in the use of

*Corresponding author.

Presented at the Nonpoint Source (NPS) Workshops
at the Third International Conference on Rainwater Harvesting & Management, Goseong, Korea, 20–24 May 2012
and the Korea-China World Expo Exhibition Plan, Beijing Normal University, Beijing, China, 4–7 July 2012

stormwater best management practices (BMPs) compared with the conventional drainage approach [5,6]. BMPs are advantageous urban stormwater management, since it provides broad range of benefits in controlling the negative impacts of NPS pollution including several treatment mechanisms such as sedimentation, infiltration, filtration, and plant uptake.

BMPs are commonly used as cost-effective mechanisms that mitigate both the water quality and quantity problems occurring during storm events [7,8]. Many types of BMPs are currently utilized in different parts of the world such as constructed wetlands, permeable pavements, retention, detention, bioretention, filtration, and infiltration systems [9,10]. Usually, the stormwater was captured, filtered, stored, used for groundwater recharging and sometimes collected for other purposes by BMPs [11]. Different approaches and guidelines for the selection and design of appropriate BMP for a particular site are available in several BMP design manuals. However, pollutant reduction efficiencies of BMPs vary due to differences in design methods, implementation, and maintenance frequency resulting to high uncertainties in BMP effectiveness [12]. Also, many BMP technologies use only one treatment mechanism or function. The method of integrating several functions of BMP technologies and incorporating them in one treatment system is referred to as hybrid BMP. Hybrid BMPs are incorporating basic elements of several types of BMP which is one of the complicating factors in analyzing its efficiency [13].

This study developed, investigated, and compared the efficiency of two laboratory-scale hybrid BMPs having different media configuration in reducing stormwater pollutants and runoff volume. This study also determined the most efficient configuration between the two hybrid types considering several design factors such as volume for groundwater recharge or reuse and pollutant removal efficiency. Specifically, the pollutant mass and water balance of the systems were analyzed to illustrate the process of pollutant reduction that each system undertakes. In addition, both laboratory-scale hybrid BMPs were evaluated based on its volume and pollutant load ratio with respect to hydraulic retention time (HRT).

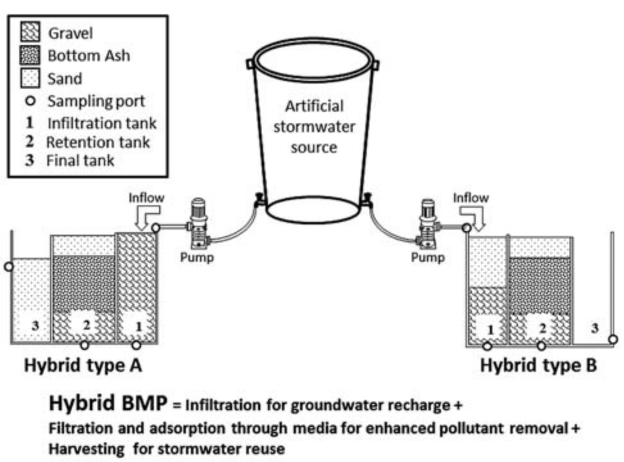

Fig. 1. Schematic of laboratory-scale hybrid BMPs.

2. Materials and methods

2.1. Design of laboratory-scale hybrid BMPs

The laboratory-scale hybrid BMPs developed were composed of three main tanks in series referred to as the infiltration, storage or retention and final tanks as shown in Fig. 1. The three tanks corresponded to the functions that each one performed. The hybrid BMP types were identical in size but have different media configurations. Table 1 presents the detailed physical characteristics of each tank employed in the two hybrid types developed. The infiltration tank occupied 30% of each hybrid BMP's total volume which served as the initial runoff treatment tank during the test runs. Treatment functions such as infiltration, filtration, and adsorption were incorporated in the infiltra-

Table 1
Design specifications of the laboratory-scale hybrid BMPs

Parameters	Hybrid type					
	A			B		
Tank	Infiltration	Retention	Final	Infiltration	Retention	Final
L:W:H[a]	0.5:1:1.5	0.8:1:1.5	0.8:1:1.5	0.5:1:1.5	0.8:1:1.5	0.8:1:1.5
SV/TV[b]	0.69	0.61	0.75	0.69	0.61	1.00

[a]Aspect ratio of length, width, and height.

[b]Ratio of facility storage volume to total volume.

tion tank before discharging the treated runoff for groundwater recharge. The media used in the infiltration tank of hybrid type A was gravel (38 cm depth), while top sand layer (17 cm depth) and bottom gravel layer (20 cm depth) were used in hybrid type B. The runoff in excess of the storage capacity of infiltration tank overflows to the retention tank. The retention tank covered 41% of each hybrid BMP's total volume and incorporated BMPs' treatment functions such as filtration, adsorption, harvesting, and reuse. Top sand layer (10 cm depth), middle bottom ash layer (20 cm depth), and bottom gravel layer (10 cm depth) were used as filter media in the retention tanks of both hybrid types. Lastly, the runoff was treated in the final tank before discharging to the sewer systems. Sand (29 cm depth) was used in the final tank of hybrid type A incorporating treatment functions such as filtration and adsorption, while no media were used in the final tank of hybrid type B. The permeability of the sand, gravel, and bottom ash media used in this study were 1.32, 1.52, and 1.03 cm/s, respectively.

2.2. Operating conditions, data collection and analyses

The artificial stormwater runoff used for the experimental test run of this study was prepared by wetting a 520 m^2 impervious road during dry days. Seven experimental test runs for each hybrid BMP type were performed. Each test run was conducted during 240 min. The artificial stormwater runoff was applied to the system with an initial inflow rate of 0.17 L/min during the first 30 min of the test run. After 30 and 120 min, the inflow rate was increased to 0.67 and 1.3 L/min, respectively. The samples were collected after the initial application of artificial stormwater runoff and after 15, 30, 60, 120, 180, and 240 min. Consequently, manual flow checking was conducted every 5 min to ensure that there will be no changes in flow rate. Similarly, samples were also collected and flow rates were also checked from the discharge of infiltration, retention, and final tank. Analytic analyses of the artificial stormwater including total suspended solids (TSS), chemical oxygen demand (COD), and total metals such as chromium (Cr), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb) conducted in accordance with the standard methods for the examination of water and wastewater [14].

Results were statistically analyzed using SYSTAT 12 and OriginPro 8 package software including Pearson-r correlation and analysis of variance using one-way ANOVA. Significant correlations and difference between parameters were accepted at 95% confidence level, signifying that probability (p) value was less than 0.05. In addition, pollutant mass and water balance of the system were analyzed using Eqs. (1) and (2).

$$\text{Mass}_{\text{inflow}} - \text{Mass}_{\text{outflow}} = \text{Mass}_{\text{infiltrated}} + \text{Mass}_{\text{retained}} + \text{Mass}_{\text{reduced}} \quad (1)$$

$$\text{Volume}_{\text{inflow}} - \text{Volume}_{\text{outflow}} = \text{Volume}_{\text{infiltrated}} + \text{Volume}_{\text{retained}} + \text{Volume}_{\text{reduced}} \quad (2)$$

3. Results and discussion

3.1. Flow and pollutant characterization

The changes in the average flow rate and concentration of the representative constituents for each hybrid BMP type are presented in Fig. 2. During the first 30 min of test run, the difference (mean ± standard deviation) between the inflow rate and infiltration flow rate were 0.02 ± 0.14 and 0.03 ± 0.18 L/min for hybrid type A and B, respectively. After increasing the inflow rate at 30 min, the infiltration flow rate of hybrid type A stabilized at 0.42 ± 0.01 L/min. On the other hand, the infiltration flow rate of hybrid type B stabilized after 150 min at 0.38 ± 0.01 L/min. The differences between infiltration flow rates were associated with different media configuration employed in the infiltration tanks of both hybrid types. During the initial 70 min of discharge in the retention tank of hybrid type A, the infiltration flow rate was greater than retention flow rate by 0.19 ± 0.04 L/min which probably caused by the prompt stabilization of infiltration flow rate. Similarly, the infiltration flow rate was greater than the flow rate of hybrid type B by 0.004 ± 0.04 L/min during the initial 30 min of discharge in the retention tank. The outflow rate of hybrid type B is 40% greater than hybrid type A. The use of sand filter media in hybrid type A and the difference of 29 cm between the discharge flow ports of the final tanks in both hybrid types were considered as affecting factors for this occurrence. High variation was observed in the inflow rates with coefficient of variation (CV) ranging from 0.50 to 0.51 for both hybrid types; however, low variation was observed in the inflow concentrations (CV = 0.09–0.28) of both hybrid types in terms of the representative constituents. These findings suggested that the variation in the influent concentration was not highly dependent on the inflow rate ($r < 0.5$; $p > 0.05$). The inflow

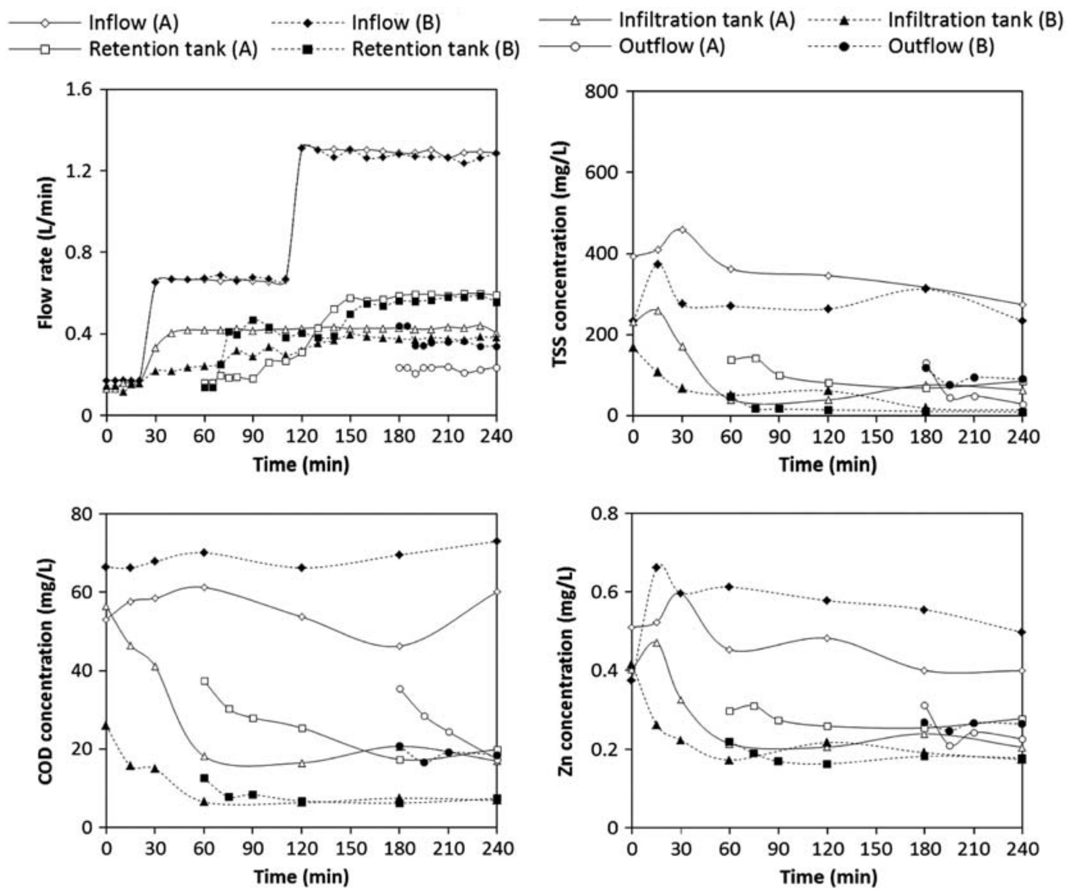

Fig. 2. Mean flow rate and concentration changes from seven test runs with respect to time in each hybrid BMP type.

concentration used in hybrid type A and B were not significantly different for all constituents with *p* value ranging from 0.43 to 0.89. The TSS, COD, and Zn inflow concentrations (mean ± standard deviation) for hybrid type A were 366 ± 323, 55.8 ± 64.9 and 0.48 ± 0.45 mg/L, respectively. Meanwhile, the TSS, COD, and Zn inflow concentrations for hybrid type B were 280 ± 117, 68.5 ± 28, and 0.55 ± 0.17 mg/L, respectively. For hybrid type A, it was identified that the concentration decreases with respect to flow length of the system. This finding was evident in the discharged TSS concentration of infiltration, retention and final tank which were 126 ± 185, 103 ± 169, and 65.3 ± 88.3 mg/L, respectively. Similar trend was identified for the discharged Zn concentration of infiltration, retention, and final tank which were 0.29 ± 0.28, 0.28 ± 0.30, and 0.25 ± 0.18 mg/L, respectively, for hybrid type A. On the other hand, the discharged TSS, COD, and Zn concentration in the final tank for hybrid type B were greater than the infiltration and retention tank. The discharged TSS concentration from infiltration, retention, and final tank were 69.3 ± 120, 19.4 ± 28, and 94.9 ± 54 mg/L, respectively, while the discharged COD concentration of the three tanks were 12 ± 9.2, 8.2 ± 3.2, and 19.2 ± 5.6 mg/L, respectively, for hybrid type B. Hybrid type B discharged 0.24 ± 0.14, 0.18 ± 0.07, and 0.27 ± 0.09 mg/L of Zn through the infiltration, retention and final tank, respectively. The absence of filter media in hybrid type B was considered as an affecting factor for greater pollutant discharge in the final tank of hybrid type B compared with hybrid type A.

3.2. Water and pollutant mass balance

Fig. 3 exhibits the pollutant mass and water balance of the two hybrid BMPs developed. Hybrid type A discharged 46% of the inflow volume from the infiltration tank, while only 34% was discharged by hybrid type B. Since the discharged volume by the infiltration tank in hybrid type A was 8% greater than the retention tank, only less than 34% of the inflow volume was available for reuse compared to type B which has almost 40%. Based on the statistical

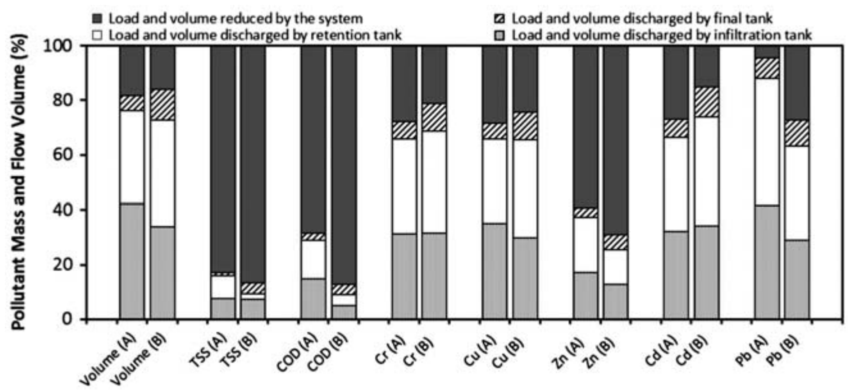

Fig. 3. Mean pollutant mass and water balance of seven test runs for each hybrid BMP type.

analysis, the discharged volume of hybrid type A was significantly greater than hybrid type B ($p = 0.02$). These occurrences resulted from the use of gravel filter media in the infiltration tank of hybrid type A and top sand layer and bottom gravel layer in hybrid type B. On the contrary, no significant difference was identified between the discharged volumes of the retention tanks in both hybrid types ($p > 0.05$) due to same media configuration. Hybrid type A discharged approximately 6% of the inflow volume through the final tank, while hybrid type B discharged 11%. The discharged volume in hybrid type B was significantly greater than hybrid type A ($p = 0.002$) which showed the important role of filter media configuration and location of discharge flow ports in flow reduction. Meanwhile, the volume reduction efficiency of hybrid type A and B were not significantly different ($p = 0.37$).

Among all the constituents analyzed, TSS, COD, and Zn discharged the least pollutant load from the infiltration, retention, and final tanks in both hybrid BMP types developed. Hybrid type A discharged 8, 15, and 17% of the inflow TSS, COD, and Zn, respectively, from the infiltration tank. While hybrid type B discharged only 7, 5, and 13% of the inflow TSS, COD, and Zn, respectively from the infiltration tank. The percentage of inflow Cu and Pb discharged by hybrid type A through the infiltration tank were greater than hybrid type B by 5 and 13%, respectively. Conversely, the percentage of inflow Cr and Cd discharged by hybrid type A through the infiltration tank were less than hybrid type B by 1 and 2%, respectively. These findings were associated with the combination of sand and gravel media layers for the infiltration tank in hybrid type B resulting to better pollutant removal efficiency compared with gravel media in hybrid type A. However, the discharged percentages of inflow load in the infiltration tanks of both hybrid types were not significantly different except for COD ($p = 0.04$). Although similar media configuration were used in the retention tanks of both hybrid types, the percentage of inflow load discharged through retention tanks were different. The discharged percentage of inflow through the retention tank of hybrid type A for TSS, COD, Zn, and Pb were greater than hybrid type B by 6, 10, 8, and 12%, respectively. Meanwhile, the percentage of the discharged inflow of Cr, Cu, and Cd through retention tank of hybrid type B were 3, 5 and 5% greater than hybrid type A, respectively. The pollutant reduction of the hybrid BMPs was affected by the discharged pollutant mass in the infiltration, retention, and final tanks. The load and volume reduced and stored by the hybrid BMPs included losses, evaporation, and media absorption during the test run. The overall pollutant removal efficiency of hybrid type A was significantly greater than hybrid type B for TSS ($p < 0.001$), Cr ($p = 0.008$), Cu ($p = 0.01$), and Cd ($p = 0.01$) due to the media configuration of hybrid type A in final tank. Reduction of pollutant mass was identified to be highly correlated with the inflow pollutant load except Cr, Cu, Cd and Pb for hybrid type A (TSS, COD and Zn: $r = 0.86$–0.99; $p < 0.01$), and Pb for hybrid type B (All pollutants except Pb: $r = 0.76$–0.99; $p < 0.05$). The pollutant mass reduction of the hybrid BMPs was highly dependent on the inflow pollutant load implying that greater pollutant mass reduction can be expected from the system for higher inflow pollutant load.

3.3. Volume and pollutant load ratio with respect to HRT

Fig. 4 demonstrates the changes in the load ($Load_{outflow}/Load_{inflow}$) and volume ($Volume_{outflow}/Volume_{inflow}$) ratio with respect to HRT. Hybrid type B retained higher volume until approximately 1.8 h,

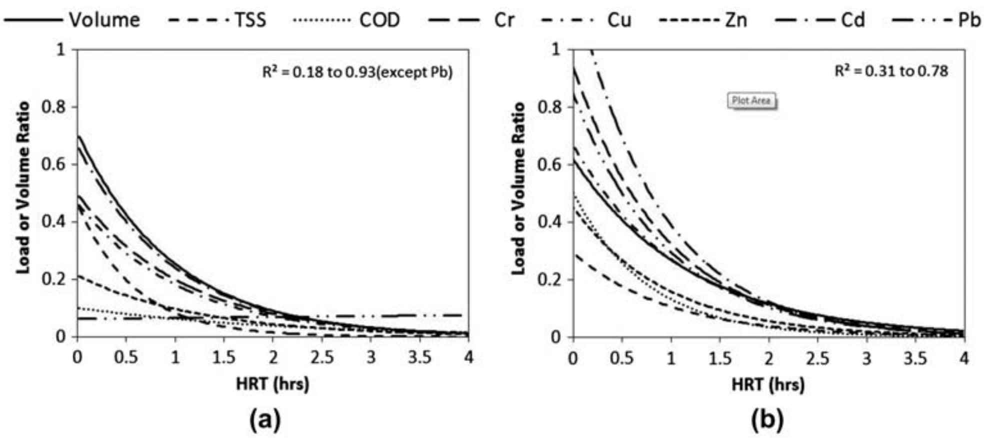

Fig. 4. Changes in load and volume ratio with respect to HRT for (a) hybrid type A and (b) hybrid type B.

beyond this time, hybrid type A retained higher volume of runoff. The media configuration and location of discharge flow ports in both hybrid BMPs resulted to the difference in volume ratio and HRT. This finding was important especially in peak flow management during storm events. Increased HRT corresponded to decreased discharge load ratio for both BMP. Initially, hybrid type A discharged 0.1–0.7 load and volume ratio except Pb which was decreased to 0.08 to 0.43 after 30 min of HRT. On the other hand, hybrid type B discharged higher load and volume ratio during the initial time of test run ranging from 0.29 to 1 which was decreased to 0.18–0.72 after 30 min of HRT. After increasing the inflow rate during the second hour of the test run, hybrid type B discharged 0.03–0.13 load ratio, while hybrid type A discharged only 0.01–0.09. Hybrid type A achieved the stable load ratio less than 0.1 or greater than 90% removal efficiency at approximately 1.9 h HRT, while hybrid type B achieved the stable load ratio less than 0.1 at approximately 2.18 h HRT probably due to the sand filter media used in the final tank of hybrid type A.

4. Conclusions and recommendations

BMPs were commonly utilized to effectively control the NPS pollution in stormwater runoff. However, due to a need to improve the efficiency of these BMPs, basic elements of several types were combined and integrated into one treatment system referred to as hybrid BMP. In this study, two- laboratory scale hybrid BMPs having different media configurations were developed, investigated and compared to know the efficiency in reducing stormwater pollutants and runoff volume. Based on the findings presented in the study, the following conclusions were summarized as follows:

(1) Both hybrid types significantly reduced the inflow volume and all pollutants including TSS, COD, Cr, Cu, Zn, and Pb ($p < 0.05$) signifying that both hybrid types were effectual in pollutant removal and flow volume reduction. In addition, greater pollutant mass reduction can be attained by the system for higher inflow pollutant load.
(2) The combination of top sand layer and bottom gravel layer resulted to greater pollutant mass reduction in the discharge of infiltration tank of hybrid type B compared with type A which only has gravel layer. Meanwhile, the application of sand as filter media in the final tank of hybrid type A yielded to less discharged pollutant mass compared with hybrid type B. The discharge from infiltration, retention, and final tanks of hybrid type A were not significantly different with the discharge from each tank of hybrid type B ($p < 0.05$).
(3) The discharged load ratio for both BMP types ranged from 0.1 to 1 for HRT less than 1 h, while the increased HRT corresponded to decreased discharge load ratio. Among the two BMPs developed, hybrid type A achieved the stable load ratio less than 0.1 at a shorter HRT of 1.9 h compared with hybrid type B.

The configuration of hybrid type A was more advantageous and suggested for design considering greater volume for groundwater recharge compared wih reuse and for design requiring less pollutant discharged to sewer systems. On the other hand, the configuration of hybrid type B was more appropriate for design considering greater volume for stormwater reuse and less cost in terms of filter media usage. The findings and factors considered in this study may be used to design and improve the performance of a similar hybrid BMP in the future.

Acknowledgments

This research was funded by the Construction Technology Renovation Research Project (10CCTI-C056937-01) from the Korea Ministry of Land, Transportation and Maritime Affairs. The authors are grateful for their support.

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