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Assessment and development of design criteria for a hybrid stormwater treatment system

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ABSTRACT

Continuous monitoring of stormwater best management practices (BMPs) is essential to fully understand their efficiency and capacity. In this study, a hybrid mobile stormwater BMP system was assessed, and the design implications to remove and reduce pollutant loads and large volumes were observed by conducting a series of storm event monitoring. The water balance attributed by a variety of rainfall depth affected the pollutant removal capacity of the system. Treatment units of the hybrid system showed effectiveness in reducing particulates. However, only appreciable pollutant reductions for TN and heavy metal constituents were observed. Results from the water balance in the system aided the development of design criteria for further improvement in the design of the system.

Keywords: Best management practices; Design; Hybrid; Monitoring

1. Introduction

Stormwater runoff best management practice (BMP) is a method or combination of methods found to be the cost effective and feasible means of moderating the amount of pollution accumulated by nonpoint sources (NPS) to a level compatible with water quality goal [1]. They effectively remove, reduce, retard and prevent targeted stormwater runoff quantity and quality from reaching receiving water bodies [2]. It has been identified that physical-chemical treatments can be effective in reducing pollutant loads in stormwater runoff [3]. Treatment removal processes occurring in BMPs include sedimentation, adsorption, filtration and biological uptake and degradation [4]. Nominal design removal efficiency of typical pollutants such as suspended solids, nitrogen, phosphorus, pathogens and metals ranges from 15% to 100% for structural BMPs like detention and infiltration basins, constructed wetlands, infiltration trenches, grassed swales and so on [5]. However, it is highly unlikely to remove all pollutants in urban stormwater runoff through BMPs. Also, many BMP technologies usually make use of a singular 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 [6]. Hybrid BMPs are incorporating basic elements of several types of BMP, which is one of the complicating factors in analyzing its efficiency [7].

In the Swedish suburbs, stormwater runoff is controlled using a combination of BMPs, and on the process of its implementation, complications arise, such as spatial constraints in finding a space to logistically change the urban landscape [8]. Moreover, some BMPs insufficiently retain pollutants that make it necessary to develop new centralized treatment facilities with consideration of low space requirements and necessary effectiveness in retaining pollutant constituents in urban stormwater runoff [9–13]. Hence, adaptation of mobile BMP system can possibly resolve such shortcomings. The term mobile is a distinct characteristic that allows the treatment system to be "movable" or to "move freely", which inhibits compromising the original conditions of landscape when BMPs are constructed.

The objective of this research was to investigate the performance of a newly developed hybrid mobile BMP system

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in treating urban stormwater runoff. Specifically, the system's water balance was identified in this research as well as its capacity to remove pollutants induced by the urban stormwater runoff. With the aid of the results from actual monitoring, a design criterion will be developed to attain further targeted treatment goals of the mobile hybrid BMP system.

2. Materials and methods

2.1. Design of hybrid BMP system

2.1.1. Physical design characteristics

The design characteristics of the mobile hybrid BMP system are shown in Table 1. The system is 200 cm long, 75 cm wide and 40 cm deep. The depth is divided into two segments: filter bed and storage tank depth. The facility has a 1.5% slope along its length to comply with the recommended slopes for BMPs. The two sedimentation tanks and storage tanks constitute almost 40%–60% of the storage volume while the small fraction consists of the filter media bed. Pretreatment is required to both minimize groundwater contamination and prolong the life of BMP [14].

2.1.2. Flow scheme within the system

The flow scheme within the hybrid BMP system is quite complex. During actual conditions, the stormwater runoff from an elevated 100% impervious roadway as shown in Fig. 1(a) initially passes through the first sedimentation tank prior to its entrance to the infiltration tank. As for the secondary flow, if the water level in the first sedimentation tank rises up to 15 cm, the runoff enters the retention tank and is transferred through a 5-cm hole at the division of the sedimentation tank as shown in Section B-B′ in Fig. 1(b). Similar to the infiltration tank but with no woodchip filter, the runoff was treated by filtration and adsorption prior to entrance in the retention unit. Finally, if the infiltration and retention functions fail to accommodate all input stormwater runoff, the water is directed to the overflow tank where runoff is being discharged out of the system.

Table 1
Design specification of the hybrid BMP system

Parameters	Treatment function			
	Infiltration	Retention	Overflow	Storage
Aspect ratio[a]	6:1:1	7.5:1.25:1	8:1:1.2	20:2.5:10
SV/TV[b]	1:7	1:7.74	–	1:3.56

[a]Ratio of length, width and height.
[b]Ratio of the facility storage volume to total volume.

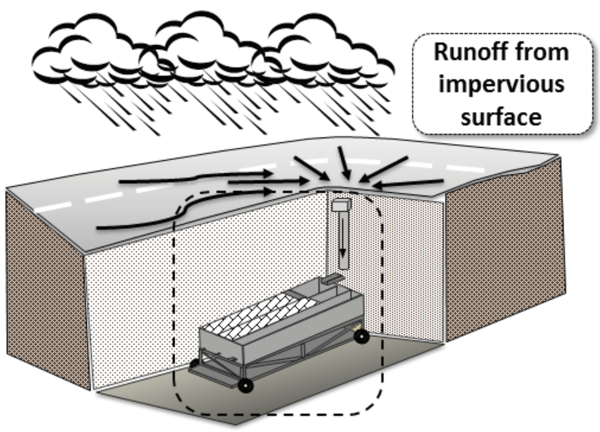
2.1.3. Filter media

Different media compositions are expected to demonstrate different removal efficiencies because of the effects on pollutant capture mechanisms [15]. The filter media utilized in the system was sand, gravel and bottom ash. Specifically, sand and gravel media was utilized for the infiltration tank while an additional bottom ash layer was inserted between the sand and gravel layer. Sand filter has shown high removal efficiency, but in some cases it has not received widespread usage since it requires frequent maintenance to ensure hydraulic performance and thought to be ineffective in treating soluble and particulate fractions [16]. The applicability of bottom ash as a filter media was investigated and proven [17]. According to this study, bottom ash has a higher capacity to adsorb metals constituents because of the surface phenomenon where high adsorption rate is achieved by smaller particles.

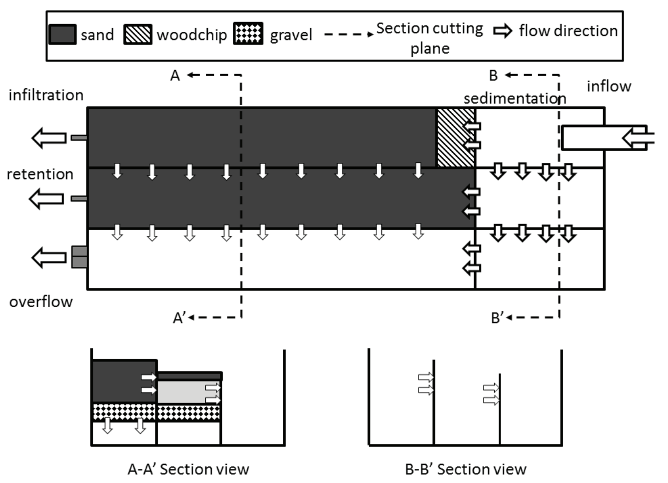
2.2. Data collection and analysis

2.2.1. Monitoring scheme

The pilot scale mobile hybrid BMP system was situated at the campus grounds of Kongju National University in Cheonan City, northeast of South Chungcheong Province, Korea (36°51′1.11″N, 127°9′0.23″E). Monitoring of the mobile hybrid BMP was conducted from May to October 2013 with a total of nine monitored storm events. The sampling scheme follows the typical sample collection method practiced



(a)



(b)

Fig. 1. (a) Site setup and (b) schematic of the hybrid BMP system showing the cross-section and flow directions.

similarly in most NPS studies domestically and globally [14,18]. The sampling frequency was matched to the hydrograph, with more intensive sampling during the first part on an event. Six samples were collected during the first hour with a time interval of 5, 10, 15, 30 and 60 min and another six samples every 1-h interval, which totals to a maximum of twelve samples during sampling. Similarly, grab samples were also taken at the outflow units originally intended to be used to compute flow and mass balance efficiencies of the system.

2.2.2. Analytical analysis

The stormwater runoff samples obtained from the entire storm events were brought in the laboratory for analytical tests to obtain concentration data of typical water quality constituents in stormwater runoff. All stormwater runoff samples were analyzed based on the standard test methods for the examination of water and wastewater [19].

3. Results and discussion

3.1. Monitored storm events

The summary of the monitored storm events characteristics is presented in Table 2. The monitored storm events generated a total rainfall depth ranging from 0.5 to 39 mm with a mean of 10.125 mm. During the first monitoring, it was observed that no overflow occurred despite 6.5 mm accumulated rainfall depth due to low rainfall intensity about 1.05 mm/hr. Moreover, lesser rainfall intensity was observed on September 6, 2013 storm event with a rainfall intensity of 0.29 mm/hr wherein no water was transferred to either the retention or the overflow unit. Aside from the storm event previously mentioned, runoff conveyed from the retention and overflow units was observed from the other storm events. It was also observed that if the storm event is too strong and if such rainfall is to occur, stormwater treatment cannot be maximized in the infiltration and retention units due to the runoff will only tend to bypass into the system.

3.2. Water balance

Fig. 2 shows the water balance in the mobile hybrid BMP in actual storm events. It can be observed that the percentage of water allocated to the infiltration unit was decreasing with the increase in rainfall depth. Same observation was apparent for the runoff coming for the retention. On the other hand, the amount of overflowed water showed the contrary. However, this is not consistent with the rainfall depth since the amount of overflow relies more on the rainfall intensity. This implies that a large amount of stormwater runoff will be left untreated at bigger storm events. From the storm events monitored, it was quite evident that the mobile hybrid BMP system is more capable of treating stormwater runoff at rainfall depths up to 10 mm. Nevertheless, continuous rainfall monitoring is needed to determine the maximum rainfall intensity or rainfall depth that the system can effectively operate.

3.3. Event mean concentration

Similar to the water balance, the Event mean concentration (EMC) of pollutant constituents was categorized according only to less than 5 mm, 5 to 10 mm, and 10 to 15 mm rainfall depth ranges as shown in Fig. 3. Inflow EMC for the TSS, COD_{cr}, TN, TP and heavy metal parameters was found to be higher for rainfall events ranging from 5 to 10 mm, and for the rainfall event ranging from 10 to 15 mm, inflow EMC was observed to be lower compared with previously mentioned rainfall events, which was probably due to the dilution effect

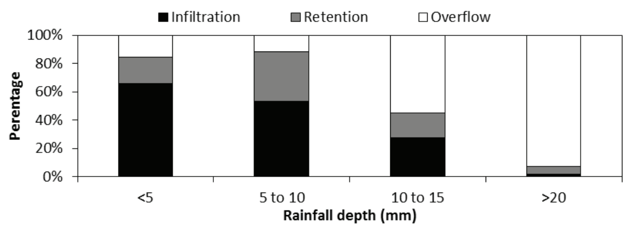


Fig. 2. Water balance with respect to rainfall depth.

Table 2
Summary of the monitored events characteristics

Parameter	Units	Mean	SD[a]	Median	CV[b]	p-value
Total rainfall	mm	10.125	12.631	5.75	1.248	0.009
Total rainfall duration	h	4.711	2.461	4.27	0.522	0.317
Total runoff duration	h	2.796	1.197	2.915	0.428	0.343
Time before inflow starts	h	1.91	2.467	1.025	1.292	0.01
Time before infiltration starts	h	0.308	0.358	0.155	1.165	0.001
Time before retention starts	h	0.818	0.788	0.435	0.963	0.026
Time before overflow starts	h	1.047	0.839	0.89	0.801	0.381
Total runoff	m^3	1.739	3.029	0.529	1.741	0
Total infiltration	m^3	0.189	0.153	0.151	0.813	0.545
Total retention	m^3	0.184	0.14	0.189	0.762	0.173
Total overflow	m^3	1.509	3.044	0.061	2.018	0
Runoff coefficient		0.512	0.287	0.459	0.559	0.617

[a]Standard deviation.
[b]Coefficient of variation.

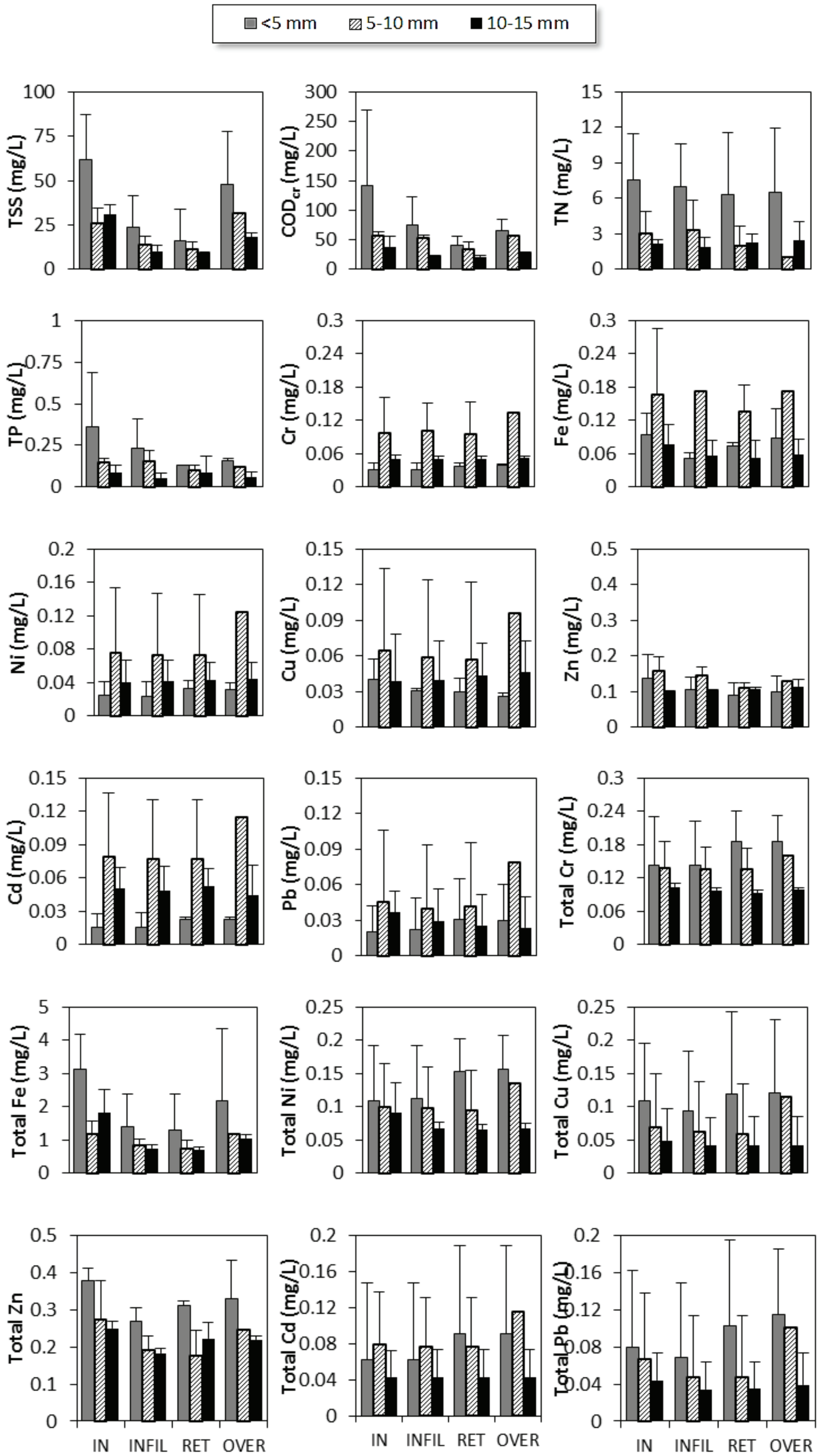


Fig. 3. Event mean concentration at the sampling ports of each treatment unit.

on the pollutants. It can also be observed that the EMC was significantly reduced from the inflow going to the infiltration and retention outputs and the EMC in the overflow tank was expected to be at minimum to no reduction observed. Nonetheless, there is still reduction in the outflow EMCs. Among the pollutant EMCs, TSS and COD_{cr} were effectively reduced in the system.

3.4. Load ratio with respect to rainfall depth

Load ratios at the infiltration, retention and overflow with respect to the rainfall depth were presented in Fig. 4. The 1:1 slope suggests neutrality on treatment after passing through the mobile hybrid system. As can be seen, trend in load ratio was decreasing with the increase in rainfall depth for infiltration and retention unit. The trend in the overflow showed otherwise. This suggests that on larger rainfall depths, pollutant loads from the infiltration and retention units were found to be lower compared with the inflow loads, which may have been attributed by the water balance in the system. As discussed previously, most of the water was directed to the overflow unit as a bypass for large storm events that is why the pollutant load ratio at the overflow unit increases with the increase in rainfall depth.

3.5. Pollutant removal efficiency

Through the transfer of runoff from the infiltration unit to the retention unit, it was observed that the pollutant removal efficiency of pollutants was enhanced. The mean removal efficiency of TSS, COD, BOD, TN and TP for the infiltration unit was 86%, 75%, 44%, 70% and 77%, respectively. For the retention unit, TSS, COD, BOD, TN and TP removal efficiency was increased by 10%, 17%, 31%, 18% and 13%, respectively. In addition, the pollutant removal efficiency of dissolved and particulate heavy metals was increased by 9%–24% due to the runoff transfer from the infiltration to the retention unit.

3.6. Design criteria

The results from the actual storm event monitoring of the pilot scale hybrid mobile BMP rendered essential information in developing a design criteria and guidelines of field or

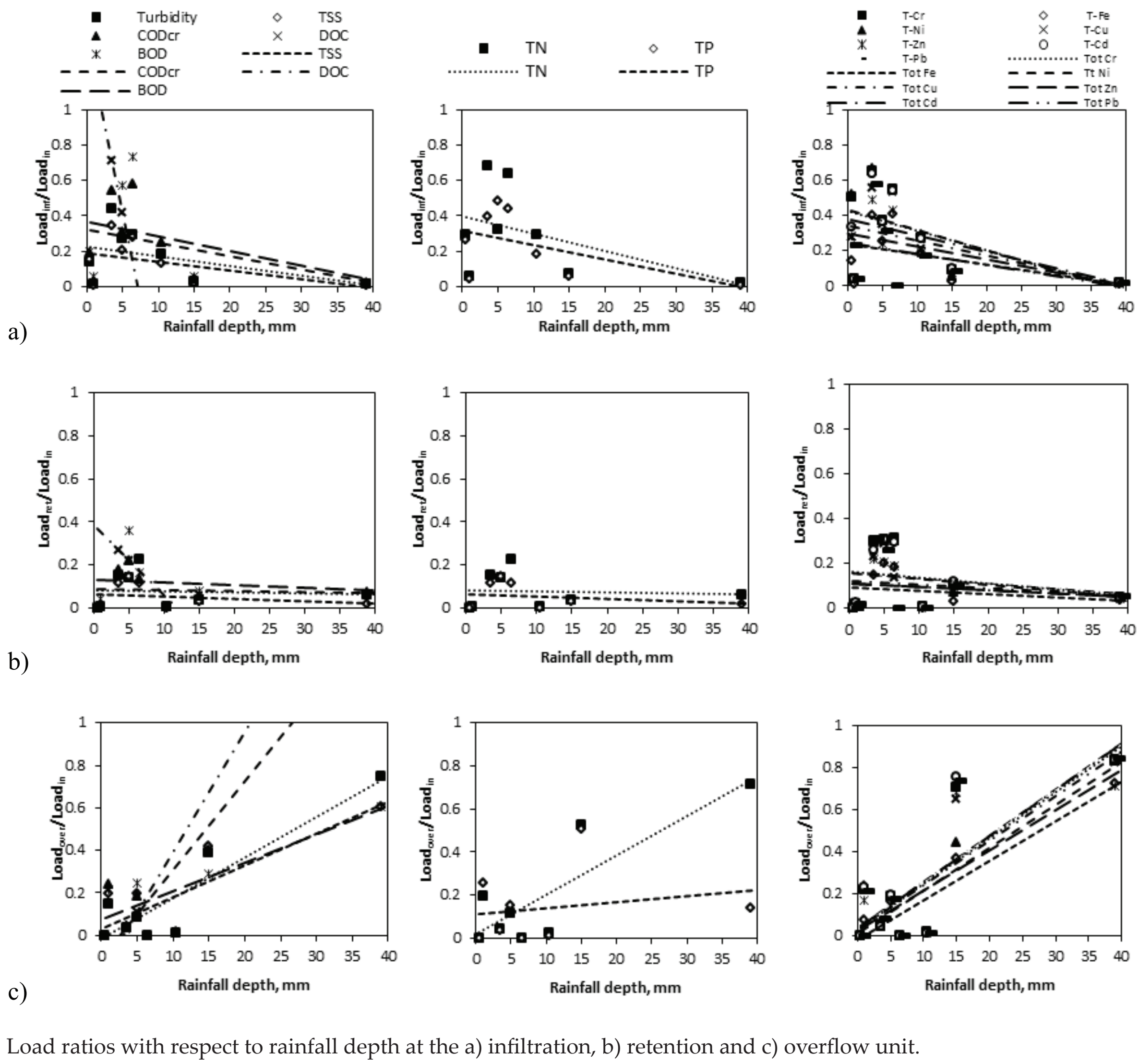
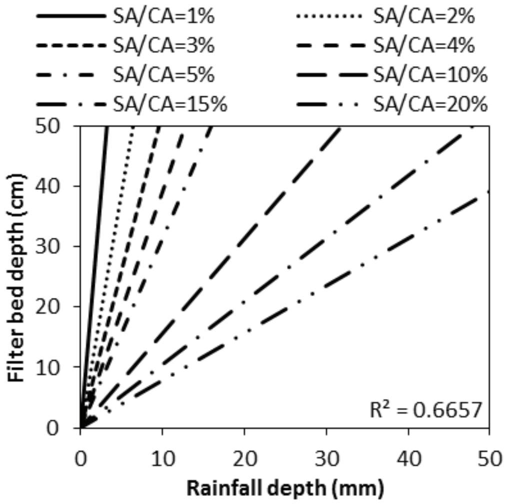
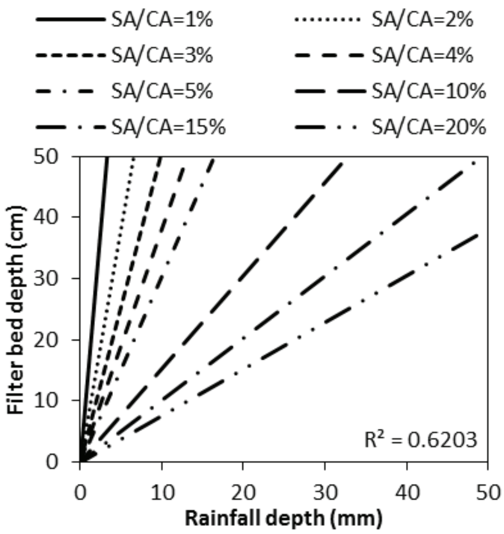


Fig. 4. Load ratios with respect to rainfall depth at the a) infiltration, b) retention and c) overflow unit.



(a)



(b)

Fig. 5. Regression plots for filter bed depth at the a) infiltration and b) retention unit to rainfall depth at varying surface area to catchment area ratio for infiltration unit.

location scale hybrid BMP system. It was vitally important to determine the water balance or the amount of water entering and leaving each treatment unit of the hybrid BMP system. It has been previously identified that with increasing rainfall depth, stormwater runoff for bypass increases while treated runoff for infiltration and retention decreases. For design criteria that are independent on the discharge allocation, sizing of treatment unit based in the filter bed depth at varying surface area (SA) and catchment area (CA) ratio and rainfall depths is presented in Fig. 5. Filter bed depth, which is directly associated with the (storage) volume of the BMP, is an essential consideration in dealing with a more cost-effective design (e.g., lower construction costs and still efficient BMP). As shown in the figure for both the infiltration and retention units, the design of the filter depth could be decided based on the SA/CA ratio and rainfall depth to be treated. It indicates that bigger filter bed depth is required for the treatment of runoff from a smaller SA and CA ratio as well as high rainfall depth.

4. Conclusions and recommendations

In this study, the development of innovative system, such as the hybrid mobile BMP system, will be of great contribution for stormwater management. Continuous monitoring and design improvement has to be done in order to allow the system to perform at its optimum. Based on the results on the storm event monitoring, it was found that as rainfall depth increases, bypassed runoff also increases that exhibited more untreated runoff was discharged as compared with treated runoff. To overcome this shortcoming, it is suggested to alter the design of the sedimentation tanks. Reduction of bypassed runoff can be done by increasing the height of sedimentation tanks prior to the entry of runoff into the infiltration and retention unit. The uneven height between the retention and overflow can also be adjusted such that extreme downpour of rainfall will only allow stormwater runoff to be bypassed. The filter bed depth can also be increased to provide larger storage volume and maximize the filtering capacity of the treatment units. The developed design criteria in this study can be used as a guide in adjusting the depth and storage volume of the system.

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