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RESEARCH ARTICLE

Performance evaluation of various stormwater best management practices

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Abstract Many best management practices have been developed and implemented to treat the nonpoint source pollution of the aquatic environment in Korea's four major river basins. The performance and cost of these facilities were evaluated and compared using broad categories, including grassed swales, constructed wetlands, vegetated filter strips, hydrodynamic separators, media filters, and infiltration trenches, based on the monitoring and maintenance work undertaken between 2005 and 2012. Constructed wetlands, media filters, and infiltration trenches generally performed better in removing pollutants than other types of facilities, while media filters were the most expensive factor in terms of construction and operational costs. In addition, constructed wetlands incurred the least operational cost, as well as helping to control the quantity of runoff. This illustrates that a high cost facility does not necessarily give a better performance. A slightly more expensive facility, such as wetland, could prove to be a reasonably effective treatment. The selection of the most appropriate treatment for stormwater runoff should be based on an overall analysis of performance and cost.

Keywords Best management practices · Cost comparison · Nonpoint source pollution · Performance evaluation · Pollutants removal · Selection criteria

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Introduction

Historically, best management practices (BMPs) were designed and implemented to reduce soil erosion, and attempts were made to use those BMPs to reduce the sediment load entering waterways at the beginning of the 1970s (Rao et al. 2009). Various infield and off-site best management practices have currently been proposed and applied to treat diverse levels of pollution worldwide (Otto et al. 2008). Since stormwater runoff from impervious or pervious surfaces contributes significant quantities of pollutants to the surrounding surface water bodies (Smith et al. 2000; Datry et al. 2003; Boving and Neary 2007), increasing environmental concerns regarding the spread of such pollutants have led to the construction and installation of various kinds of treatment. However, it is considered that better information about the performance of different BMPs can improve their application and development.

In some cases, greater pollutant removal or a better environmental performance is needed to fully protect aquatic resources and/or human health and safety within a particular watershed or receiving water. Thus, when planning the construction of BMPs, developers/contractors must answer a key question with respect to storm water quality control, i.e., what kind of water quality controls are needed? The BMPs selected for a site should fulfill many goals and objectives; for example, they should be appropriate for the given site constraints, possess a moderate capability to remove pollutants, and be cost effective. In order to achieve these goals, BMPs should be selected by using appropriate selection criteria that serve to identify the capabilities and limitations of each BMP.

The performance of BMPs has been documented in a large number of studies, and this enables the evaluation and selection of BMPs. Grassed swales are closely related to the timing and magnitude of inflows, coupled with available storage, and the channel length of the swales (Davis et al. 2011). Vegetative filter strips are a potential low-input technique to reduce the transportation of pollutants in water runoffs. They can improve water quality and produce additional environmental benefits when used with other best management practices (Rankins and Shaw 2001; Borin et al. 2004; Otto et al. 2008). Filtration systems comprised of a media layer with an adsorption capacity are a relatively recent innovation through which the runoff passes and is filtered before being collected by an under drain (Fuerhacker et al. 2011). Infiltration trenches reduce the amount of land space required by enabling the stormwater to be retained below the ground. They effectively control the pollutants in the surface runoff. Hydrodynamic separators are usually used to remove litter, debris, and sediment from the runoff using the centrifugal force inside the device.

All stormwater BMPs can potentially be affected by many factors. These include antecedent dry days, hydraulic conditions (hydraulic loading rate and hydraulic retention time), and influent pollutants (source and state) (Reinelt and Horner 1995; Fink and Mitsch 2004). However, each type of BMP is inherently endowed with some superiority in terms of pollution removal, no matter how it is influenced by affecting factors, e.g., constructed wetlands can removal total nitrogen more effectively, media filters are extremely efficient at totally removing phosphorus, and hydrodynamic separators can effectively remove coarse solids. Furthermore, operation and maintenance practices can also significantly influence the actual effectiveness of structural BMPs.

BMPs have been used for stormwater treatment in Korea for more than 10 years. A series of initiatives, led by the Prime Minister's Office with the cooperation of related ministries, have been established for stormwater quality management (Jung et al. 2008). The most commonly used facilities have been grassed swales (GS), constructed wetlands (CW), vegetated filter strips (VFS), hydrodynamic separators (HS), media filters (MF), infiltration trenches (IT), and so on. Although the performance of different BMPs has been widely documented, few reports have been sufficiently comprehensive to enable a detailed assessment and comparison of different types of BMPs. Information of performance evaluation and comparison using broad categories is rarely available. As the focus of stormwater design transitions from simple conveyance to quantitative treatment and management, it is becoming increasingly important to identify the performance of BMPs and link them to their design and selection. The objectives of this work are (1) to evaluate the ability of BMPs widely used in the treatment of runoff in Korea to remove pollutants, (2) to compare the construction/operational costs and other performance characteristics of these BMPs, and (3) to provide some BMP selection criteria in the treatment of nonpoint source pollution based on the results of a performance and cost comparison.

Materials and method

Data source

The data used in this study was taken from the project entitled “Monitoring and maintenance study of test pilot BMP facilities on nonpoint source pollution in four major-river system”. This river system includes Korea's Han River, Geum River, Yeongsan River, and Nakdong River, and this project involved the establishment of many different BMPs along the four major rivers with the support of Korea's Ministry of Environment (Jung et al. 2008) (Fig. 1). Most of the facilities included in this study were installed along the Han River. The comprehensive work of monitoring and maintenance can be used to evaluate the performance of the installed facilities, and the results of the analysis of the performance will contribute to developing BMP construction and management techniques.

Table 1 lists the locations and land use of the BMPs examined in this study, while Table 2 summarizes the characteristics of the BMPs and the rainfall conditions of the monitored events. Six types of BMPs were examined, including grassed swales, constructed wetlands, vegetated filter strips, hydrodynamic separators, media filters, and infiltration trenches, and a total of 19 individual systems were included in the study (see Table 2). The total number of monitored events for these six types of BMPs was 19, 46, 35, 40, 96, and 35 respectively.

According to the requirement of the project, 12 samples from both the inlet and outlet were selected for laboratory analysis in all the monitored events for each site. Six samples were collected within 1 h at the beginning of rainfall at durations of 0, 5, 10, 15, 30, and 60 min, and another six samples were respectively collected at the end of the rainfall event. The duration of the sampling depended on the rainfall patterns (rainfall intensity, rainfall duration, and rainfall depth). The sampling process normally included the increases and decreases of the hydrograph during the rainfall events. The number of antecedent dry days for each event was required to be no less than two. The parameters of analysis included total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) which were measured according to the standard method for the examination of water and wastewater, 19th edition (APHA 1995). The flow rate was measured automatically during the monitoring period using a flowmeter for both inflow and outflow.

Data of construction and operational costs was also provided by the project, and the operational costs included an annual inspection and maintenance cost. Two approaches

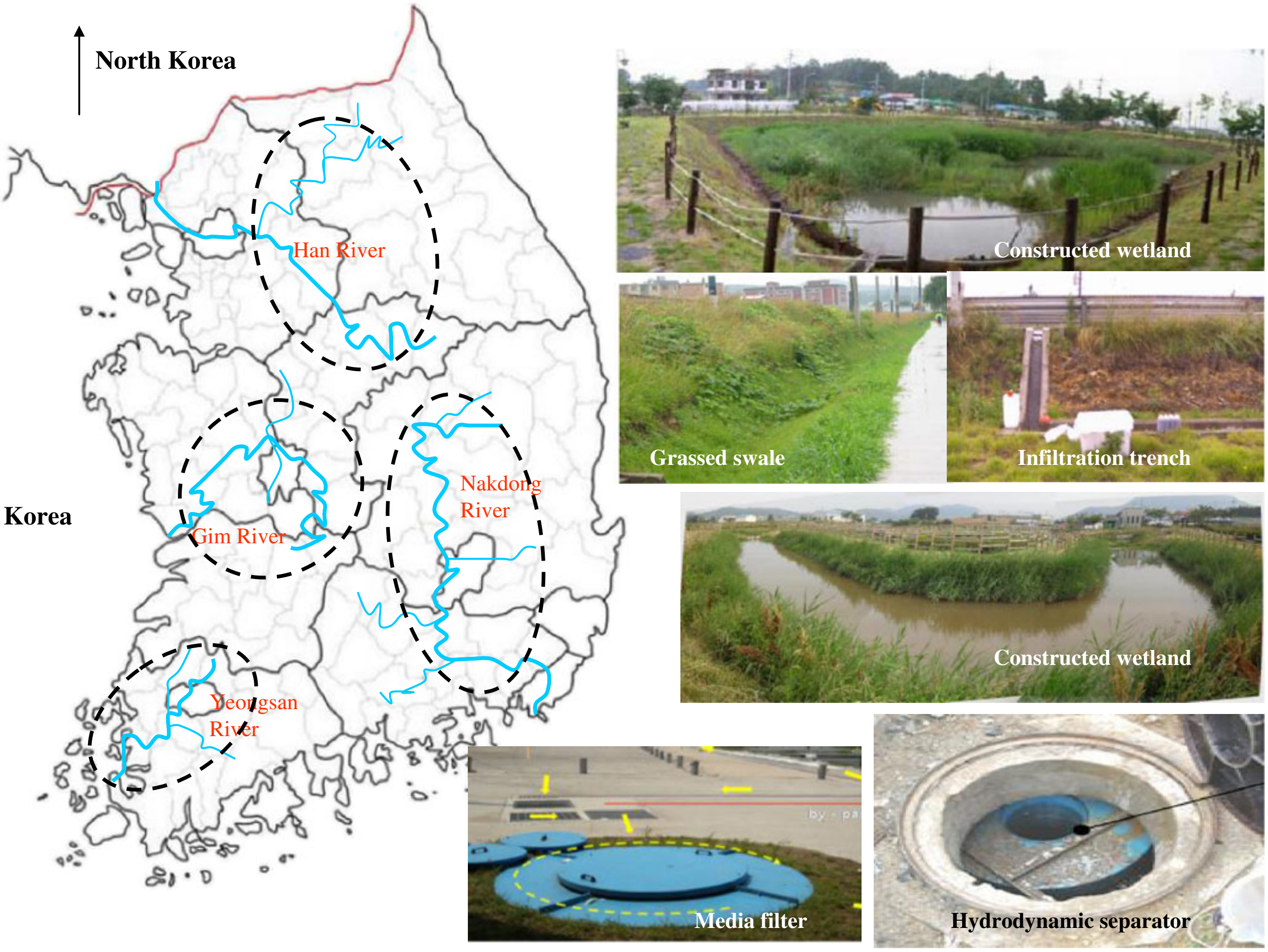


Fig. 1 The four major rivers and sample photos of BMPs in Korea

were used to compare the operational costs of various BMPs. One was the annual unit cost based on the served watershed area, while the other was the annual unit cost based on the pollutants removed.

Annual precipitation and temperature

The annual precipitation is around 1,000～1,300, 1,200～1,500, and 1,000～1,800 mm for the northern part, middle part, and southern part, respectively. Generally, the precipitation in the Nakdong River area is relatively lower than that in other areas. Most storm events are concentrated from May to September, which coincides with the time of agricultural cultivation. The precipitation is so concentrated that the interval between storm events is rather short (Yi et al. 2010). The weather is hot and humid during this rainy period. The daily average temperature is in the range of 23～26 °C in summer and around −6～3 °C in winter. The annual humidity is in the range of 60～75 %; specifically, it is around 70～85 % in July and August and around 50～70 % in March and April.

Data analysis

BMPs have been grouped into broad categories in this study, and these categories may mask the distinctive differences in design and performance in subcategories for multiple BMP types (BMP database 2008). Also the effect of hydraulics (flow rate, hydraulic retention time) and rainfall patterns (rainfall depth, rainfall intensity, and antecedent dry days) is not included. Being based on a broad category approach, this paper only focuses on the evaluation of pollutants removal and the economic situation from a rough perspective. The most cost effective and feasible means of moderating diffuse pollution are found to be stormwater-runoff BMPs or a combination of methods. It is essential to understand the performance and economic feasibility of BMPs before implementing them, and the main factor to demonstrate performance is the capacity to remove pollutants. The

Table 1 Location and land use of BMPs

Item	Site	Location	Land use of watershed
Grassed swale	1	37.2411 N, 127.1776 E	Road: 100 %
	2	37.3313 N, 127.2629 E	Agricultural: 58 %; urban: 19 %; mountain: 23 %
Constructed wetland	3	37.2411 N, 127.1776 E	Rice paddy: 67 %; road: 7 %; others: 26 %
	4	37.3029 N, 127.4893 E	Agricultural: 45 %; urban: 3 %; mountain: 39 %; others: 13 %
	5	37.4769 N, 127.0857 E	Agricultural: 100 %
	6	36.2948 N, 127.0315 E	Forest:72 %; agricultural: 28 %
Vegetated Filter Strips	7	37.1924 N, 127.2747 E	Agricultural: 30 %; urban: 70 %
	8	37.3093 N, 127.2536 E	Agricultural: 65 %; urban:35 %
Hydrodynamic separator	9	37.3891 N, 127.2298 E	Urban: 100 %
	10	37.4489 N, 127.2673 E	Urban: 100 %
	11	35.9677 N, 126.7366 E	Urban: 100 %
Media filter	12	37.2881 N, 127.2364 E	Road: 100 %
	13	37.4164 N, 127.2507 E	Urban: 100 %
	14	37.3330 N, 127.2630 E	Road: 100 %
	15	37.3627 N, 127.2230 E	Road: 100 %
	16	37.4008 N, 127.2364 E	Road: 100 %
	17	37.4028 N, 127.2678 E	Road and parking lot: 100 %
Infiltration trench	18	37.2656 N, 127.4623 E	Urban: 49 %; road: 4 %; others: 47 %
	19	37.2869 N, 127.2155 E	Road: 100 %

efficiency in removing pollutants was calculated using event mean concentrations, and the cost data was converted to unit construction or operational costs based on watershed areas and pollutant reduction.

Table 2 Summary of BMPs used in this study

Item	Site	Event number	Watershed area (ha)	Surface area (m^2)	Capacity (m^3)	Rainfall (mm)			Rainfall intensity (mm/hr)		
						Max	Min	SD	Max	Min	SD
Grassed swale	1	2	1.9	300	98.4	77.0	33.5	–	4.81	2.39	–
	2	17	27.7	630	210	83.0	2.0	25.7	5.2	0.3	1.5
Constructed wetland	3	17	10.38	3,400	893.2	94.5	4.0	26.0	6.7	0.9	1.9
	4	17	22.02	2,230	1,740	80.5	1.5	18.2	7.9	0.1	1.9
	5	6	221	12,705	11,235	44.0	18.0	9.0	7.1	1.5	2.1
	6	6	465	3,282	2,957	32.5	13.5	7.1	7.1	0.6	2.2
Vegetated filter strips	7	17	2.53	3,320	84.3	120.0	4.0	31.9	23.5	0.7	5.7
	8	18	7.03	3,840	97.5	62.0	2.5	22.8	10.6	0.5	2.9
Hydrodynamic separator	9	17	7.31	–	–	77.8	1.5	23.9	8.8	0.5	2.9
	10	17	2.47	–	–	80.5	1.5	23.4	10.8	0.5	3.0
	11	6	2.6	–	–	34.5	4.0	11.7	7.0	0.8	2.4
Media filter	12	18	1.9	15	–	50.5	2.0	13.5	11.4	0.9	2.5
	13	17	1.24	15	–	62.0	4.0	19.4	8.9	0.8	2.4
	14	17	1.61	–	–	58.0	2.0	19.2	14.5	0.5	3.6
	15	17	1.28	–	–	58.0	1.0	20.4	14.5	0.3	3.7
	16	11	0.79	–	–	57.0	1.0	21.2	57.0	1.0	22.6
	17	16	3.51	–	–	35.0	2.5	9.0	22.2	1.0	5.3
Infiltration trench	18	12	1.60	110	135	33.0	3.0	8.5	15.9	2.3	4.4
	19	23	0.50	280	55	65.0	2.0	20.8	15.2	1.0	3.1

The efficiency in pollutant removal was based on event mean concentration, which was calculated using the following formula:

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i}$$

where V is the runoff volume during the monitored period i; C is the average concentration associated with period i; n is the total number of measurements taken during each event.

Results and discussion

Efficiency in removing pollutants of different BMPs

TSS removal

Figure 2 shows the efficiency of pollutant removal of different BMPs. Overall, these six types of BMPs can effectively remove total suspended solids (average efficiency was around 60 %), except hydrodynamic separators (average efficiency around 25 %).

It was evident that the TSS efficiency in removing hydrodynamic separators was lower and varied in a narrower range than the other five types of BMPs (Fig 2 (a)). The removal efficiency was in the range of 0.8~66.5 % with an average value of 25.7 %. The low efficiency is supported by the data presented in Fig 3 (a), which indicates that the TSS concentrations were comparable between inflow and outflow, and the outflow TSS concentration of hydrodynamic separators was higher than that of other BMPs. This low and stable efficiency was because the hydrodynamic separators could effectively separate coarser particles, while they were ineffective for removing finer particles. The relatively high effectiveness of separating the coarse particles contributed to relatively stable TSS removal, and the ineffectiveness of removing fine particles resulted in relatively lower efficiency (around 25 %) (EPA 1999; Andoh and Saul 2003). Therefore, considering the high pollutants adsorbed in fine particles (Malcolm and Kennedy 1970; Braskerud 2003), it can be concluded that hydrodynamic separators are not appropriate for the removal of TSS when other facilities are available, although they can be used as a pretreatment device prior to other vegetative systems. However, they are an appropriate choice in conditions of limited space, especially in highly developed urban areas (EPA 1999). It should be noted that the inflow TSS concentrations varied in a larger range for grassed swales, but the outflow concentrations were relatively constant (Fig. 3(a)). This indicates that grassed swales are an effective treatment for TSS. The suspended solids can be removed in a grassed swale by two mechanisms, (1) filtration by vegetation and (2) sedimentation and capture on the bottom of the swale (Backstrom 2002). Stagge et al. (2012) reviewed TSS removal by grassed swales, and found that the efficiency was also higher than the designed values. The documented TSS removal ranged from 48 to 98 % based on the average event values.

As shown in Fig. 3 (a), the average TSS concentration GS, CW, VFS, HDS, MF, and IT was around 29.2, 23.6, 41.3, 89.8, 42.5, and 20.7 mg/L, respectively. The New Jersey Administrative Code suggests that the TSS concentration of surface runoff should not exceed 40 mg/L (NJAC 2011). Thus, it can be concluded that these BMPs, except hydrodynamic separators, indicated effective treatment for TSS removal.

Removal of organic matters

In terms of the removal of BOD and COD, grassed swales, constructed wetland, media filters, and infiltration trenches showed a better performance than other types of BMPs (Fig 2. (b) and (c)). The average removal efficiency of these four types was comparable at more than 40 %. However, the outflow concentration of COD and BOD in media filters was higher than in other types of BMPs (Fig. 3 (b) and (c)). The relatively high efficiency of media filters in the removal of organic materials was mainly due to higher inflow concentration.

Similar to the removal of TSS, the hydrodynamic separator showed the poorest performance in the removal of organic matter with an average efficiency of no more than 20 % (Table 3). Hydrodynamic separators can divide the inflow into dense and light phases due to the different density of solids and water; thus, they are effective for removing pollutants that are denser than water (Yu et al. 2010). However, because of the low density of organics, they generally pass through hydrodynamic separators as a light phase, which is considered to be the separators' outflow, and this is why hydrodynamic separators are inefficient in removing organic materials. It is reported that removing organics in wetland mainly depends on bacterial metabolism and decomposition (Kadlec and Wallace 2009). In terms of media filters and infiltration trenches, the removal of organics is mainly the result of a filtration process. The mechanisms include a physical process (interception, adsorption) and a biochemical process (such as biodegradation) (Dechesne et al. 2004); Goss and Gorczyca 2011).

Nitrogen removal

Grassed swales, constructed wetlands, and hydrodynamic separators showed a poor performance when attempting to remove TN with an average efficiency of no more than 20 %. Vegetated filter strips, media filters, and infiltration

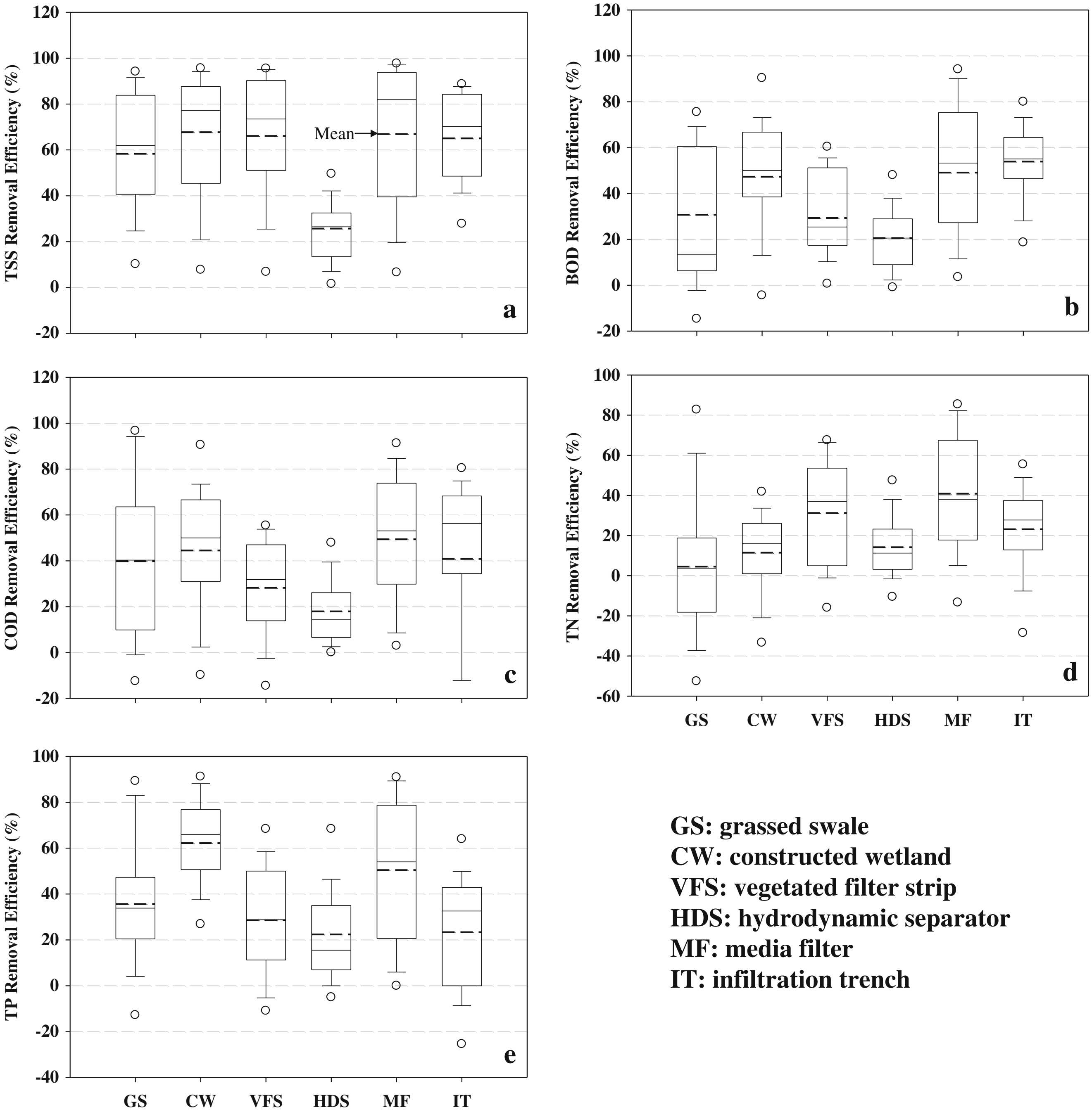
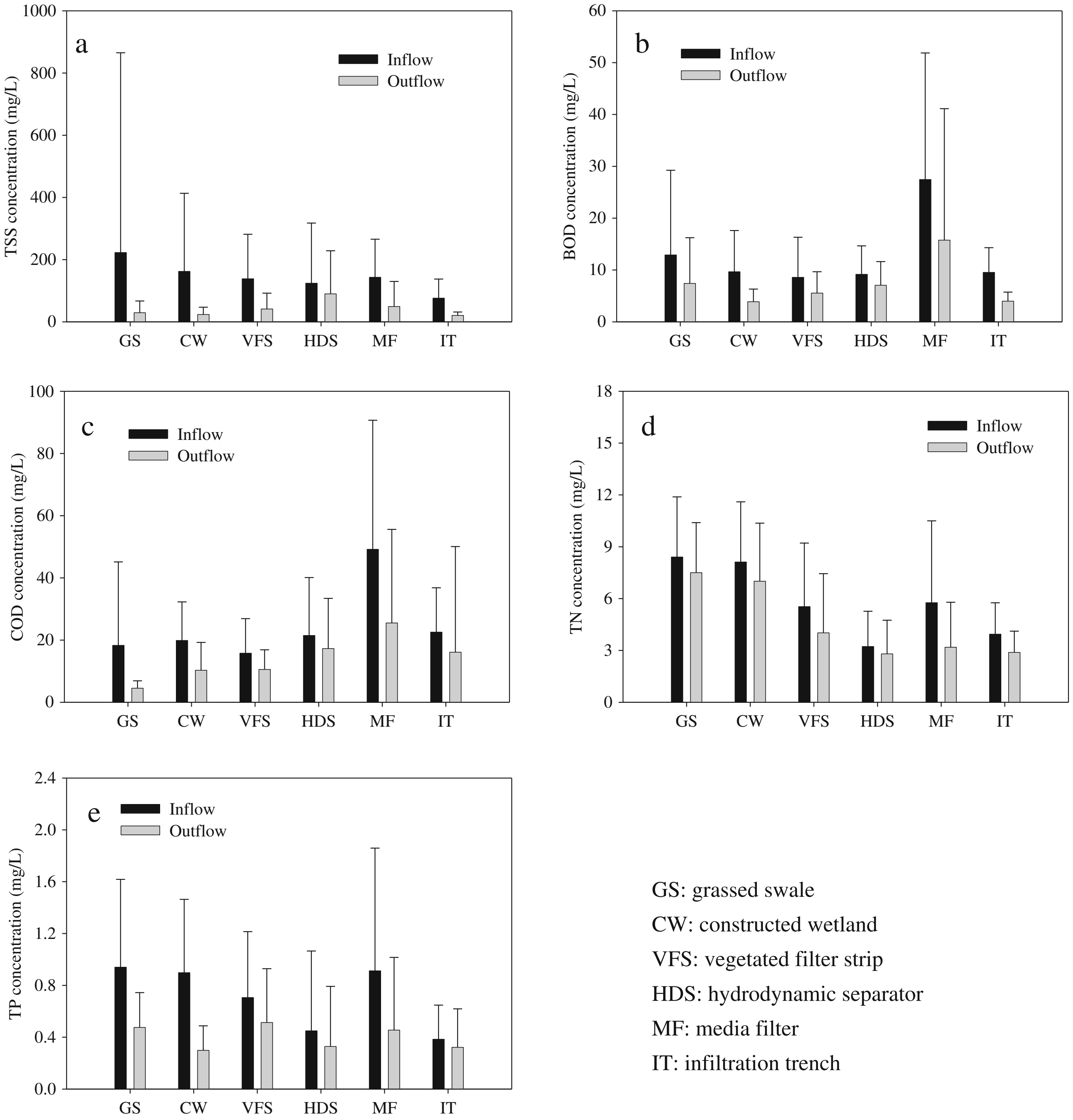


Fig. 2 Efficiency of pollutant removal of BMPs. **a** Total suspended solids. **b** Biological oxygen demand. **c** Chemical oxygen demand. **d** Total nitrogen. **e** Total phosphorus

trenches performed better, with average levels of efficiency of 31.2, 40.9, and 23.1 %, respectively (Fig 2 (d) and Table 3).

The average levels of efficiency of grassed swales and constructed wetland in removing TN were only 4.5 and 11.5 %, respectively (Table 3). This was less than the designed values of 20 % for grassed swales and 40 % for constructed wetlands. In addition, the inflow TN concentrations were generally higher in grassed swales and constructed wetland (Fig. 3 (d)), and no significant correlation was found between the concentration of inflow and the efficiency of the removal. Thus, it can be said that the treatment of TN in these two types of facilities was independent of the inflow concentration. The removal of nitrogen in grassed swales and wetland mainly depends on biological activities, such as the uptake of plants and microorganisms and the degree of nitrification and dentrification. Most of the monitoring work for this study was done outside the rainy season, when the antecedent dry



GS: grassed swale
CW: constructed wetland
VFS: vegetated filter strip
HDS: hydrodynamic separator
MF: media filter
IT: infiltration trench

Fig. 3 Pollutant concentrations of different BMPs. **a** Total suspended solids. **b** Biological oxygen demand. **c** Chemical oxygen demand. **d** Total nitrogen. **e** Total phosphorus

days were normally short, and the hydraulic retention time was short. Thus, there was inadequate biological activity, which was why the level of TN removal was lower than the designed criteria. A low level of TN removal in stormwater-constructed wetlands was also reported by another study. Yi et al. (2010) investigated a constructed wetland treating stormwater runoff in a forest and agricultural area and only obtained an average level of TN removal of 6.1 % based on 17 sampling trips. As for TN removal in grassed swales, many studies have reported similar results as those found in this paper. The average removal efficiency of TN was 11 and −7 %, respectively, at Maitland EPCOT (Deletic and Fletcher 2006), and another grassed swale was investigated and showed a similar result in Melbourne, Australia when no effective removal of TN was found (Lloyd et al. 2001).

Table 3 Efficiency of pollutant removal of different BMPs

Item	TSS			BOD			COD			TN			TP		
	Range	Average	SD	Range	Average	SD	Range	Average	SD	Range	Average	SD	Range	Average	SD
Grassed swales	1.3~94.2	58.3	26.1	−23.5~78.7	30.7	31.4	−20.0~97.3	39.8	36.2	−62.1~85.9	4.5	36.5	3.1~78.4	35.6	28.8
Constructed wetlands	4.9~97.3	67.7	27.4	−50.0~96.6	47.3	28.4	−47.6~96.5	44.5	30.4	−39.6~47.9	11.5	21.3	0.0~93.2	62.2	21.1
Vegetated filter strips	5.2~96.0	66.1	27.8	−34.5~62.0	29.3	21.6	−45.8~59.2	28.2	23.6	−18.5~67.6	31.2	27.0	−19.4~75.0	28.5	25.0
Hydrodynamic separators	0.8~66.5	25.7	14.3	−2.7~72.7	20.5	15.5	−3.3~64.5	17.9	15.1	−18.6~59.2	14.2	16.7	−10.5~89.1	22.4	21.7
Media filters	2.6–99.8	66.9	31.9	−102~97.2	49.1	34.2	−39.5~95.6	49.4	29.0	−59.4~98.9	40.9	30.8	−8.2~91.0	50.4	31.3
Infiltration trenches	26.7~89.0	65.0	19.3	9.8~84.4	53.9	17.8	−116~86.4	40.8	46.8	−53.8~58.9	23.1	25.2	−29.4~74.1	23.3	26.4

In terms of the hydrodynamic separator, the low level of TN removal was due to the fact that most of the nitrogen in stormwater is dissolved (Yi et al. 2010), and the separator is ineffective for the removal of dissolved pollutants.

In terms of the outflow concentration of TN, it was found to be normally greater than 3.0 mg/L for all six types of BMPs. This level of concentration significantly exceeded the surface water quality limitation. The US EPA proposes that the total nitrogen concentration criteria for streams and rivers should be less than 1.0 mg/L (WDEQ 2008), while the New Jersey Administrative Code suggests that the TN concentration should be less than 1.5 mg/L for surface water (NJAC 2011).

Removal of phosphorus

Overall, the removal of TP was better than that of TN in the six types of BMPs. Based on average values, grassed swales, constructed wetlands, and media filters can remove more than 30 % of TP, especially constructed wetlands; the average removal efficiency of which was more than 60 %. On the other hand, the removal of TP was relatively lower for vegetated filter strips, hydrodynamic separators, and infiltration trenches with a respective average efficiency of 28.5, 22.4 and 23.3 % (Table 3). Except for the infiltration trench, a significant difference ($P<0.01$) was found between the inflow and outflow pollutant concentrations of the other five types of BMPs. This result corresponded with the data presented in Fig. 3 (e), which shows that the removal of TP varied in a large range in all six types of BMPs. TP is mainly sediment-bound, and the major TP removal mechanisms are adsorption and precipitation in various BMPs; in other words, it can be reduced while passing through them (Richardson 1985; Borin et al. 2005; Li et al. 2007; Vymazal 2010). Unstable TP removal has also been reported in other studies; for example, the level of TP removal has been documented to be from 7.5 % to more than 80 % in a swale (Mazer et al. 2001).

On the other hand, outflow TP concentration was normally greater than 0.2 mg/L in all these BMPs (see Fig. 3). This exceeds the TP water quality criteria required in the USA, which generally ranges from 0.01 to 0.1 mg/L (Moore and Hicks 2004).

Comparison with BMPs in the USA

As shown in Fig 4, the performance of BMPs in the USA and Korea was compared. For constructed wetlands, the average removal efficiency of TSS was found to be at the same level between the national databases of Korea and the USA, but the minimum value of the USA was evidently lower than that of Korea. The average removal efficiency of TN was lower in Korea than shown in the USA national

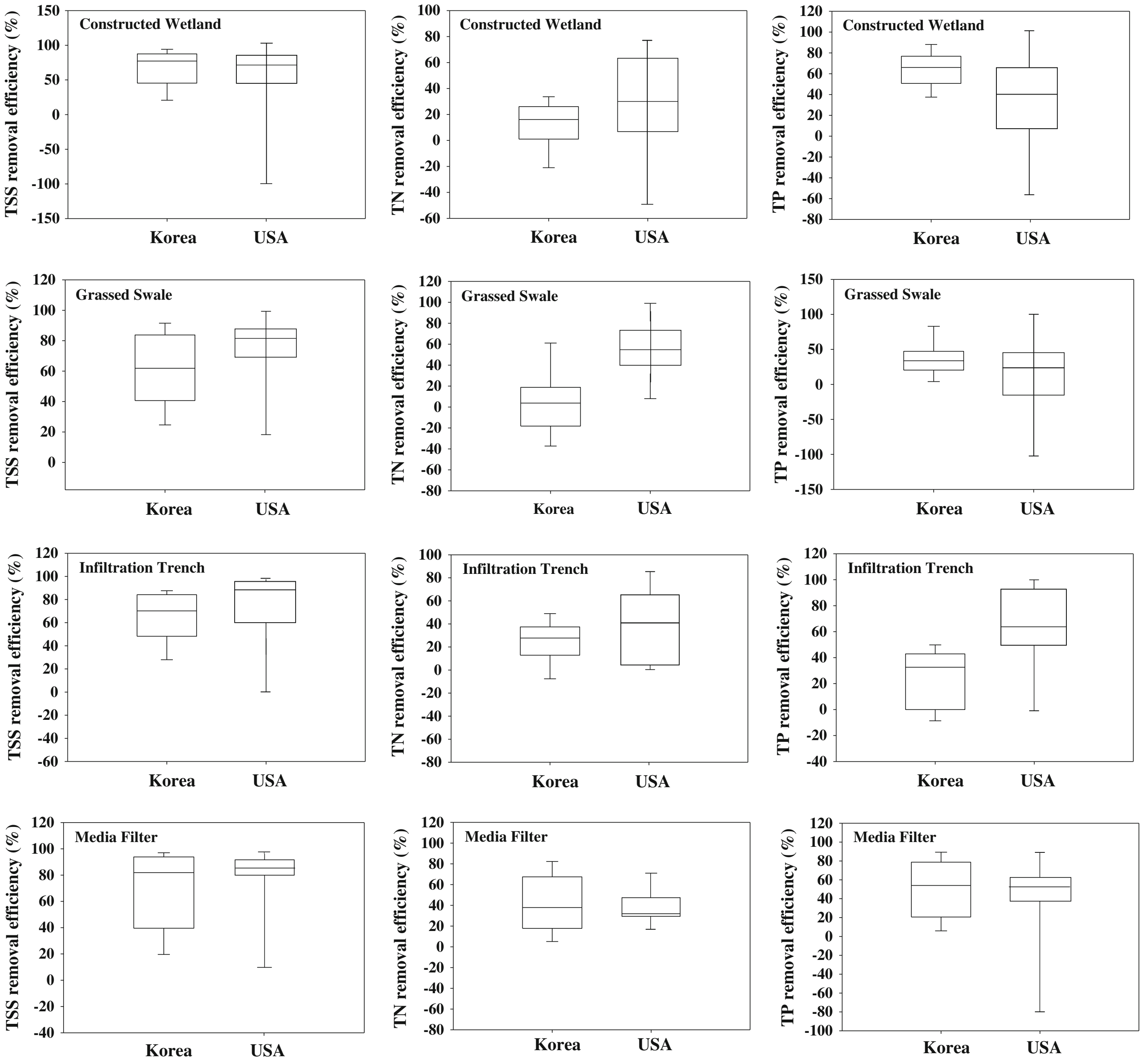


Fig. 4 Comparison of the performance of various BMPs in Korea and the USA (data source: ASCEBMP database, http://www.bmpdatabase.org/)

database, whereas the efficiency of removing TP shows a contrary behavior. In terms of media filter systems, the average removal efficiency of TSS, TN, and TP were at the same level between the Korea and USA national databases, although the pollutant removal efficiency was generally comparatively centralized in the USA. The TSS removal efficiency typically ranged from 40 to 96 % in Korea, while it ranged from 80 to 95 % in the USA. The corresponding value of TN was 20~70 % in Korea and 30~50 % in the USA, while the corresponding value of TP was 20~80 % in Korea and 30~60 % in the USA. The average removal efficiency of TSS, TN, and TP of infiltration trenches was evidently lower in Korea than in the USA. The TSS removal efficiency typically ranged from 50 to 85 % in Korea, while it ranged from 60 to 95 % in the USA, and the corresponding value of TN was 30~40 % in Korea and 0~7 % in the USA, and the corresponding value of TP was 0~45 % in Korea and 40~60 % in USA. In terms of grassed swales, the average removal efficiency of TSS and TN was lower in Korea than the USA, while the removal efficiency of TSS was comparatively centralized (69~87 %) with a lower minimum (18 %) value in the USA. The average removal efficiency of TP was slightly higher in Korea (30 % average) than the USA (24 %), and the minimum efficiency was evidently lower in the USA.

Comparison of other parameters

The construction cost was converted to unit construction costs in this study, which were defined as being the total construction cost per hectare of watershed areas. Considering the economic differences in the world, and the uncertainty of construction costs caused by several factors, such as design parameters, soil condition, site specifics, regulation requirements, etc., the construction cost was evaluated and compared using a high–low concept without giving specific cost values. The comparison analysis indicated that the construction cost for media filters was much higher than for other BMPs. Wetlands and hydrodynamic separators indicated high construction costs, while grassed swales and vegetated filter strips ranked in the middle, and infiltration trenches required lower construction. The higher construction cost of media filters could probably be accounted for by the expensive media used in these BMPs. Synthetic fibers or woodchips were normally employed in the media filters; the high cost of these media resulted in the high construction cost of media filters. In addition, media filters were generally constructed underground; some supporting facilities also increased the construction cost. The relatively high cost of HDS could be attributed to the fact that a served watershed area is normally smaller than other types of facilities. These results are supported by the situation presented in the Stormwater Best Management Practice Manual prepared by the North Carolina Division of Water Quality (NCDWQ 2007). Furthermore, the operational costs of the BMPs were analyzed using the unit cost of removed TSS. As listed in Table 4, the operational cost of media filters was higher than the others, while constructed wetlands and vegetated filter strips required low operation. Since operational costs can be extremely expensive throughout the lifetime of BMPs, it is vital that they are considered when selecting a treatment method.

Constructed wetland appears to have a significant advantage in terms of controlling the volume of runoff, since it can store runoff for several days or more. Grassed seals, vegetated filter strips, and media filters show a low capacity of runoff volume control due to their infiltration function. While hydrodynamic separators can divide the runoff into a pollutant-concentrated underflow and a pollutant-diluted overflow, they have no capacity to store it.

The six types of BMPs were compared based on other parameters. Normally, constructed wetlands, vegetated filter strips, and infiltration trenches show high social adaptability. Constructed wetlands and infiltration trenches can effectively prevent erosion, and infiltration trenches can be easily maintained and managed. The limiting factor of constructed wetlands is the need for a high level of construction area.

It can be observed from the above discussion that high-cost BMPs, such as media filters, have the greatest ability to remove pollutants. However, low/medium-cost BMPs, such as the constructed wetlands, do not necessarily have a poor performance. Constructed wetlands are shown to be a reasonable treatment method which only requires low operational costs. Furthermore, the great strength of wetlands is the ability to control the quantity of runoff, and they are also advantageous in preventing erosion, as well as being socially adaptable. Therefore, it can be concluded that the selection of BMPs for the treatment of stormwater runoff should be based on an overall analysis of performance and costs.

Conclusion

The ability of various BMPs to remove pollutants was compared by using broad categories, including grassed swales, constructed wetlands, vegetated filter strips, hydrodynamic separators, media filters, and infiltration trenches.

All these BMPs, with the exception of hydrodynamic separators, showed a good performance for the removal of TSS with an average efficiency of around 60 %. Constructed wetland, media filters, and infiltration trenches showed a better performance than other BMPs for the removal of BOD and COD, while grassed swales, constructed wetlands, and hydrodynamic separators showed a poor performance for the removal of TN, and grassed swales, constructed wetlands, and media filters were shown to more effectively remove TP. The average efficiency was more than 30 %,

Table 4 Comparison of characteristics of BMPs referred to in this study

Item	Construction cost	Operation cost	Volume reduction	Area requirement	Social adaptability	Erosion prevention
Grassed swale	Median	Median	Low	Small	Median	Normal
Constructed wetland	High	Low	High	Big	High	High
Vegetated filter strip	Median	Low	Low	Small	High	Low
Hydrodynamic separator	High	Median	Low	Small	Low	Low
Media filter	Very high	High	Low	Small	Low	Low
Infiltration trench	Low	Median	Low	Small	High	High

especially for constructed wetlands, and the average removal efficiency was more than 60 %.

In terms of cost, media filters were the most expensive BMP due to the high level of construction and operational costs; whereas infiltration trenches exhibited the lowest construction and median maintenance costs. Hydrodynamic separators required a high level of construction costs and median maintenance costs, while constructed wetlands showed the lowest cost, although their construction costs were a little higher. Grassed swales and vegetated filter strips generally require a medium level of cost; in addition, constructed wetlands showed more advantage in terms of runoff volume control, but required a greater area than the other BMPs.

Overall, it can be concluded that a slightly more expensive BMP may often be a better choice for overall site design. When selecting and applying a BMP, constructed wetlands can be recommended to achieve reasonable treatment when sufficient space is available and runoff volume control is required. However, grassed swales are a better choice for saving space and better pollutant removal.

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