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Lifecycle cost assessment of best management practices for diffuse pollution control in Han River Basin

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한강수계 비점오염원 저감시설의 생애주기비용 평가

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Abstract

Diffuse pollution management in Korea initiated by the Ministry of Environment (MOE) resulted to the construction of pilot facilities termed Best Management Practices (BMPs). Twelve BMPs installed for the diffuse pollution management in the Kyung-An Stream were monitored since 2006. Data on the mass loading, removal efficiency, maintenance activities, etc. were gathered and utilized to conduct the evaluation of long-term performance of BMPs. The financial data such as actual construction, design and maintenance cost were also collected to evaluate the lifecycle cost (LCC) of BMPs. In this study, most of the maintenance activity was focused in the aesthetic maintenance that resulted to the annual maintenance cost of the four BMP types was closely similar ranging from 8,483 $/yr for retention pond to 8,888 $/yr infiltration system. The highest LCC were observed in constructed wetland ($418,324) while vegetated system had the lowest LCC ($210,418). LCC of BMPs was not so high as compared with the conventional treatment facility and sewage treatment plant. On the other hand, the relationship of removal efficiency on unit cost for TSS and TN was significant. This study will be used to design the cost effective BMP for diffuse pollution management and become models for LCC analysis.

Key words : Annual maintenance cost, Best management practices, Diffuse pollution, Lifecycle cost, Removal efficiency, Stormwater

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요 약

환경부는 비점오염원 관리를 위해 시범사업으로 12개의 비점오염 저감시설을 경안천 유역에 설치하였으며, 2006년부터 모니터링이 시작되었다. 본 연구는 비점오염 저감시설의 오염부하량, 저감효율, 유지관리 활동 등의 장기간 수행된 모니터링 결과를 바탕으로 각 시설의 경제성을 평가하기 위해 수행되었으며, 생애주기비용(Lifecycle cost, LCC)을 분석하였다. 비점오염 저감시설의 유지관리는 시설경관을 향상시키기 위한 심미적 관리가 중점적으로 수행된 것으로 나타났으며, 저류형 시설(Retention Pond, RP)이 년간 8,483$, 침투형 시설(Infiltration System, IS)이 8,888$로 대부분 비슷한 비용이 발생한 것으로 분석되었다. LCC는 인공습지(Constructed Wetland, CW)가 가장 높은 것($418,324)으로 나타났으며, 반면에 식생형 시설(Vegetated System, VS)이 가장 낮은 것($210,418)으로 분석되었다. 본 연구에서 조사된 비점오염 저감시설의 LCC와 하수처리장 등 수질처리시설의 LCC를 비교한 결과 비점오염 저감시설이 낮은 것으로 나타났다. 한편, 처리용량 대비 생애주기비용이 높아질수록 TSS와 TN의 저감효율은 높아지는 것으로 나타났다. 이러한 연구결과는 비용효율적인 비점오염 저감시설을 설계하는데 유용하게 활용될 것으로 기대되며, 향후 LCC 모델의 기초자료에도 활용될 수 있을 것으로 판단된다.

핵심용어 : 년간 유지관리비용, 비점오염 저감시설, 비점오염원, 생애주기비용, 저감효율, 강우유출수

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1. Introduction

The Ministry of Environment (MOE) in Korea established the Comprehensive Measures for Diffuse Pollution Management in 2004. The major policies include the implementation of total maximum daily load (TMDL), land acquisition, riparian zone, and a water use change to support the program's efforts. The effective control of diffuse pollution is believed to be the key method for successfully meeting the TMDL (Jung et al., 2008). Changes in management policies have resulted in the introduction of pilot projects, termed 'best management practices' (BMP). As a part of carrying out policies on diffuse pollution management, various types of pilot BMP facilities were constructed in the Han River basin since 2005 and were continuously constructed in other the major rivers. Long-term monitoring is being conducted since 2006 to provide detailed insight in the performance of the BMPs. The experience and performance data collected will be used to better understand and implement similar BMPs in the future as well as to assist the MOE in developing and improving the design and maintenance guidelines of BMPs (Maniquiz et al., 2010).

In general, implementing integrated BMPs can result in enhanced environmental performance while at the same time reducing development costs when compared to conventional stormwater management approaches. Cost savings are typically seen in reduced infrastructure because the total volume of runoff to be managed is minimized through infiltration and evapotranspiration. The cost of actually treating the stormwater should be included as well. The BMP design should ensure that the overall goals of the stormwater system are not generated specifically on cost, but functionality as well (Huber et. al., 2006). Other possible factors to consider in design evaluation include existing infrastructure property ownership, health and safety, and volume reduction. Cost control in construction, operation and maintenance is one of the main concerns in the process of promoting BMPs (Lee et al., 2010; Panagopoulos et al., 2011).

Lifecycle cost (LCC) analysis for cost estimate is often adopted to characterize the complicated and varied BMP strategies in terms of initial cost, maintenance cost, and particularly, the lifespans of BMPs (Montalto et al., 2007). The purpose of an LCC analysis is to estimate the overall costs of project alternative and to select the design that ensures the facility will provide the lowest overall cost of ownership consistent with its quality and function. The LCC analysis should be performed early in the design process while there is still a chance to refine the design to ensure a reduction in LCC. Many projects were considered only the initial costs of projects without considering long-term operations and maintenance. Focusing only on initial costs makes it less likely that project will adopt stormwater controls that may have higher initial costs, but are less expensive to operate and maintain in the long term.

Overall initial and maintenance costs are not the only costs that should be involved in the LCC assessment. Each project is unique based on the site's soil conditions, topography, existing vegetation, land availability etc. The actual costs vary greatly based on the character of the individual site and the creativity of the designer. Therefore, this study was performed to evaluate the LCC of BMPs over a 30-year time frame based on actual construction, design and maintenance cost. The specific purpose was to provide a reference on the methods and parameters for cost analysis of BMPs. The final results of this study could serve as models for LCC analysis and cost control of BMPs for diffuse pollution management.

2. Materials and Methods

2.1 Site description

The Han River has 26,018 km^2 of total watershed area with 481.7 km of total water course length. It provides raw water for drinking water treatment plants that serve over 20 million people in the Seoul metropolitan area (Jung et al., 2008). The Kyung-An Stream is a tributary of the Han River. It has a total watershed area of 768.4 km^2 with 76.1 km of total water course length and passes through major cities, including Gwangju, Yongin and Icheon. Fig. 1 shows the location of constructed BMP pilot facilities in the Kyungan Stream. Eight BMPs including constructed wetlands, infiltration systems, and vegetated systems (CW-1~2, IS-1~2, VS-1~4) were installed by the end of 2005 and four BMPs including a retention pond and infiltration systems (RP-1, IS-3~5) were completed by the end of 2006. Table 1 shows the characteristics of the sites such as location, catchment area (CA), storage volume (STV) and landuse

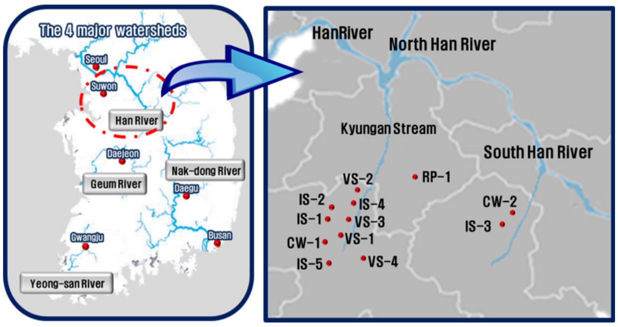


Fig. 1. Location of twelve BMP pilot facilities in the Kyungan Stream watershed

Table 1. Characteristics of site and BMP facilities

BMP Type		Location	CA (ha)	STV (m^3)	Landuse
Retention pond (RP)	RP-1	Gwangju	1.6	170	Road, Residential
Constructed wetland (CW)	CW-1	Yongin	10.4	893	Agricultural
	CW-2	Icheon	7.4	1,741	Road, Agricultural
	Average		8.9	1,317	
Infiltration system (IS)	IS-1	Yongin	0.3	39	Road
	IS-2	Yongin	0.5	55	Road
	IS-3	Icheon	1.6	135	Road, Residential
	IS-4	Yongin	9.6	500	Road, Agricultural
	IS-5	Yongin	9.1	517	Road
	Average		4.2	249	
Vegetated system (VS)	VS-1	Yongin	0.8	41	Road
	VS-2	Yongin	27.7	420	Road, Agricultural
	VS-3	Yongin	7.0	98	Agricultural
	VS-4	Yongin	2.5	84	Agricultural, Forest
	Average		9.5	161	

of the four treatment types of BMP facilities that include a retention pond (RP), constructed wetland (CW), infiltration system (IS), and vegetated system (VS). The CA for different landuse such as road, agricultural, residential and forest range from 0.3 to 27.7 ha and STV range from 39 to 1,741 m^3.

2.2 Monitoring and data collection

The treatment performance of the BMPs was monitored during wet seasons to evaluate the pollutant mass loading. The removal efficiency in treating stormwater runoff and maintenance activities were also conducted during wet and dry seasons since 2006. At least twelve samples were manually collected at both the inflow and the outflow of the BMP (Maniquiz et al., 2010). The first six samples were collected during the first hour at zero minute (initial sampling time) and after 5, 10, 15, 30, and 60 minutes followed by another six samples collected at an hourly interval. Short time of intervals were selected at the beginning if the runoff to determine the existence of a first flush. Grab sampling was also employed to collect the outflow samples following the same scheme of collecting inflow samples. Continuous flow measurements were performed and recorded using 10-min interval. Water quality parameters and constituents typically analyzed for total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved organic carbon (DOC), total nitrogen (TN), total Kjeldahl nitrogen (TKN), total phosphorus (TP), oil and grease (O&G) and total heavy metals (Cd, Cr, Cu, Ni, Fe, Pb, and Zn), and will be selected based on specific landuses. In addition, pH, electrical conductivity and turbidity were analyzed. Analyses were conducted in accordance with standard methods for the examination of water and wastewater. Meteorological data for study site were collected from Korea Meteorological Administration. The pollutant removal efficiency was calculated as the percent removal R for each parameter, which was calculated by $R = (1 - C_e)/C_i \times 100$, where C_i and C_e are the influent and effluent concentration in mg/L.

2.3 LCC calculation

LCC assessment is a technique-based analysis on several selectable long-term economic benefits. It is widely used for industrial analysis such as water supply design, water treatment, and also for the assessment of rainwater control measures (Racoviceanu et al., 2007; Stokes and Horvath, 2009; Santos and Ferreira, 2013; Liao et al., 2014). The LCC calculation for BMP was generally the summation of initial and maintenance costs as figure up from the whole life cycle. The initial cost includes the investment costs for land acquisition, construction, design and planning cost etc. The maintenance cost which includes manpower, material, energy, and equipment investment is usually calculated in terms of the time unit "year". Real costs were used for LCC analysis in this study, and the base year was set at 2005. The financial data such as actual construction, design and maintenance cost were also collected to evaluate the LCC of BMPs.

Before starting the LCC analysis, all of the future and annual costs associated with the system were converted into the present worth value. Present worth value of costs approach is used for the calculation of LCC of BMP and LID engineering measures, which means that all the input of occurred costs in different times of life cycle or analysis cycle should be converted the as present value, in accordance with the scheduled discount rate (Liao et al., 2014). The choice of discount rate influences the conversion of future costs to an equivalent present value. Eq. (1) can be used to determine a real discount rate (*d*) according the major economic indicators of bank of Korea.

$$d=\frac{1+D}{1+i}-1 \qquad \text{Eq. (1)}$$

Where, *d*: 'real' discount rate (%); i: assumed rate of general inflation (%); *D*: assumed 'nominal' discount rate. The assumed 'nominal' discount rate (*D*) is the minimum rate of return on an alternative investment for borrowed capital. Maintenance cost was converted into the present value using Eq. (2) (Ehlen and Marshall, 1996).

$$P=A\frac{(1+d)^{n}-1}{d(1+d)^{n}} \qquad \text{Eq. (2)}$$

Where, *P*: present worth value ($); A: annual maintenance cost ($); *d*: discount rate (%); *n*: design life (years).

3. Results and Discussion

3.1 Maintenance activities

BMP operation and maintenance were primarily based on BMP Design Management Manual (MOE, 2008) prepared by the MOE in Korea. The manual includes design, construction, operation, maintenance, management inspection checklists, and monitoring method for several BMPs. The recent maintenance activities conducted in BMPs are shown in Table 2. Only the maintenance costs of the stormwater management practices were considered in this study, the costs covered the renovation and rebuild were not included.

The maintenance of BMP can be broken down into two primary categories: aesthetic and functional maintenance. Aesthetic maintenance is important primarily for public acceptance of BMPs such as ponds, while functional maintenance is important for performance and safety reasons. In this study, most of the maintenance activities were focused in the aesthetic maintenance such as cleaning and removal of debris, litters and accumulated solid in the inflow channel and cover with a frequency of 20 times/year. The rearrangement of the soil at the retention zone and the cleaning of the sedimentation zone and surroundings have contributed to the improvement of pollutant removal efficiency of the system. Moreover, harvesting of the aboveground plants and dormant plants were performed during the highest biomass season (August or September) and winter season (December or January). In all of the sites, routine maintenance was increasingly performed every year. The BMPs were able to perform well if regularly maintained. The increasing maintenance activities suggest

Table 2. Maintenance activities at the BMP facilities

Site	Procedure/details	Frequency/year	Photos
Routine (all sites)	Checking of the BMP during non-storm event	20	
	Checking of the BMP after storm event	12	
	Cleaning and removal of litters and accumulated solid in the inflow channel	20	
	Determination of the accumulated sediment amount in the sedimentation tank	10	
	Removal of accumulated sediment at the sedimentation tank	1	
	Management of plant and grass outside the boundary of the BMP	10	
RP	Checking of the clogging in the RP after storm event	12	
	Removal of the accumulated solid and litters at the retention basin	1	
	Rearrangement of the soil for improving the infiltration rate at the retention basin	1	
IS	Checking the clogging or blockage of in the infiltration layer	12	
	Removal of the debris and litters at the infiltration layer and cover	20	
CW and VS	Harvesting of the aboveground plants	1	
	Harvesting of dormant plants	1	

that as the facility gets older, it requires a more frequent maintenance. It is also highly recommended that renovation/ replacements should be made at least biannually so as to maintain the efficiency of the system.

3.2 Annual maintenance cost

Maintenance costs are a substantial portion of the LCC of BMPs. Operation and maintenance costs have been estimated as a percentage of base construction costs. While some BMPs require infrequent, costly maintenance, others need more frequent but less costly maintenance. Accordingly, the selection of appropriate structural BMPs must factor in maintenance cost to ensure the necessary long-term performance.

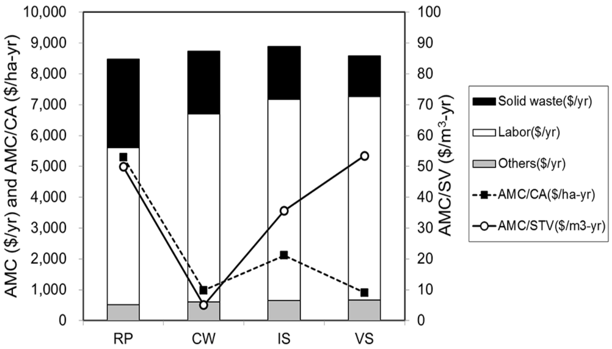


Fig. 2. Comparison of annual maintenance cost (AMC) per year, AMC to catchment area (AMC/CA) and AMC to storage volume (AMC/STV) ratios of BMPs

Fig. 2 shows the annual maintenance cost and cost of maintenance activities (i.e., solid waste, labor, and others) associated with annual maintenance cost per CA (AMC/CA) and STV (AMC/STV) ratios. The annual maintenance cost of the four BMP types was closely similar ranging from 8,483 $/yr for RP to 8,888 $/yr for IS while the cost of maintenance activities vary significantly among BMP types. Routine maintenance for IS required more tasks and included more reactive activities such as inlet cleaning which tend to be more complex and incur higher costs. The labor and solid waste costs included all of the staff activities cost and treating cost of accumulated sediment, harvesting plant, debris and litters etc., respectively. The labor cost constituted the majority cost of the maintenance activities between 60 and 77%. VS, IS and CW had high labor cost (VS: 77%, IS: 73%, CW: 70%) because many staff were frequently involved to remove the plant and grass outside the boundary of BMPs. RP was found to require the most solid waste cost, followed in declining sequence by the CW, IS, and finally the VS facility. On the other hand, the unit cost of AMC/CA and AMC/STV ratios for RP were higher as compared to the other BMPs. In contrast, CW had higher annual maintenance cost and lower unit cost of AMC/CA and AMC/STV ratios.

3.3 LCC evaluation and pollutant removal efficiency

LCC analysis is recognized to reliably identify cost optimal in building design solution. It was utilized for the economic analysis of the four BMP types that include the calculation of initial cost and annual maintenance cost to obtain the present unit LCC of each BMP as shown in Table 3. Before starting the LCC analysis, the design life and discount rate were set up and the annual maintenance cost was converted into the present value. Based on the results, the highest annual maintenance cost expressed as a percentage of initial

Table 3. Summary of LCC analysis and treatment performance for BMPs

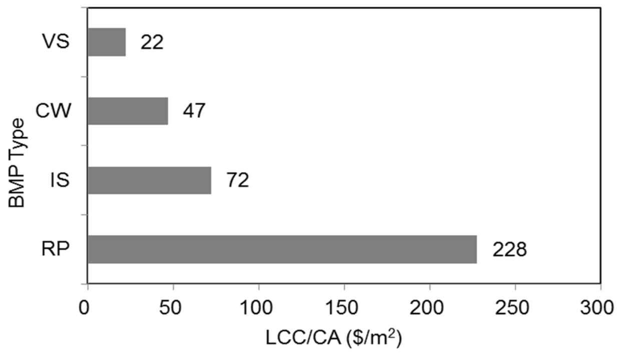
Characterization	RP	CW	IS	VS
Design life (years)	30	30	30	30
Discount rate (%)	3	3	3	3
Initial cost ($)	198,190	247,059	131,222	42,081
Annual maintenance cost ($/yr)	8,483	8,738	8,888	8,588
LCC ($)	364,458	418,324	305,425	210,418
LCC/STV ($/m^3)	2,144	318	1,226	1,309
LCC/CA ($/m^2)	228	47	72	22
Annual maintenance cost / Initial cost (%)	4	4	16	39
Maintenance-Initial cost comparison (yr)*	23	28	15	5
Monitoring period	2007-2008	2006-2008	2006-2011	2006-2013
TSS (%)**	67	73	78	84
BOD (%)**	59	67	76	60
TN (%)**	42	41	64	68
TP (%)**	58	68	70	64

* Number of year at which amortized maintenance costs equal capital construction costs

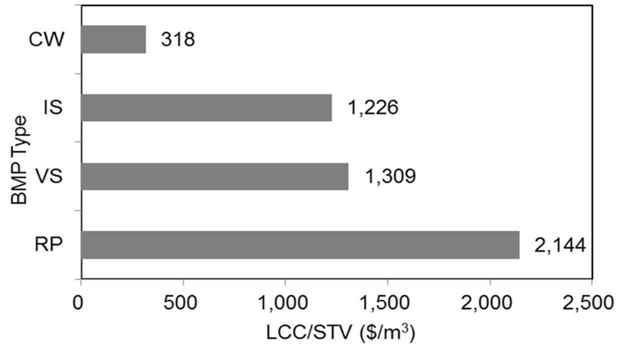
** Mean removal efficiency last years

cost were 39% for VS followed by the 16% for IS, and 4% for CW and RP. At these rates, the annual maintenance expenditures will be equivalent to the total upfront initial cost after 5, 15, 23 and 28 years for VS, IS, RP and CW, respectively. The highest LCC and initial cost were observed in CW ($418,324 and $247,059, respectively) while VS had the lowest LCC and initial cost ($210,418 and $42,081, respectively). LCC and initial cost of CW were not so high as compared with the conventional treatment facility and sewage treatment plant (Kloss and Crystal 2006; EPA 2005, 2007; Lim et al., 2014). Lim et al., (2014) reported that initial cost of BMP was 10% of the sewage treatment plant' initial cost. According to EPA (2005, 2007), BMP and LID design were resulted in a savings of over $600,000 compared to conventional design and projects of LID estimate suggest can be completed at a cost reduction of 25-30% over conventionally developed projects. In most cases, significant initial costs were reduced by avoiding grading, stormwater infrastructure, additional paving and vegetation. Savings ranged from 15-80% with the few exceptions mentioned (EPA, 2007).

Fig. 3 shows the comparison of unit cost of LCC/CA and LCC/STV for BMPs. The lowest unit cost was determined for CW (LCC/STV: 318 $/m^3) and VS (LCC/CA: 22 $/m^2) which had high treatment storage and widely catchment area. While the highest unit cost were determined for RP (LCC/CA: 228 $/m^2, LCC/STV: 2,144 $/m^3).



(a) LCC/CA



(b) LCC/STV

Fig. 3. Comparison of LCC/CA and LCC/STV ratios of BMPs

Fig. 4 shows the estimated mean removal efficiency for BMPs. The mean removal efficiency was calculated from the relevant influent and effluent pollutant loadings. The TSS was achieved highest removal efficiency from 67 for RP to 84% for VS. Once they were trapped, soluble organic constituents were reduced to carbon dioxide and become buried through sediment accretion (US EPA, 1999). There is an effective particulate removal of suspended solids and particulates since settleable incoming particulate matter usually has ample time to settle and become trapped in litter and dead zones of the plants due to the subsequent low velocity in BMP. Meanwhile, of all the parameters, the TN merely attained less than 50% removal efficiencies; especially CW had lowest (41%). Seasonal temperature changes greatly affect the pollutant retention in the CW. One factor that has proved highly influential in nearly all biological treatment processes is temperature. It can be observed that generally for all pollutants, lower removal efficiencies correspond to lower temperatures and the opposite (Hill and Payton, 2000). Moreover, TN removal via plant uptake accounts for a small fraction of the overall nitrogen removal as denitrification through anaerobic respiration remains the most effective procedure for nitrogen removal (Gersberg et al., 1983).

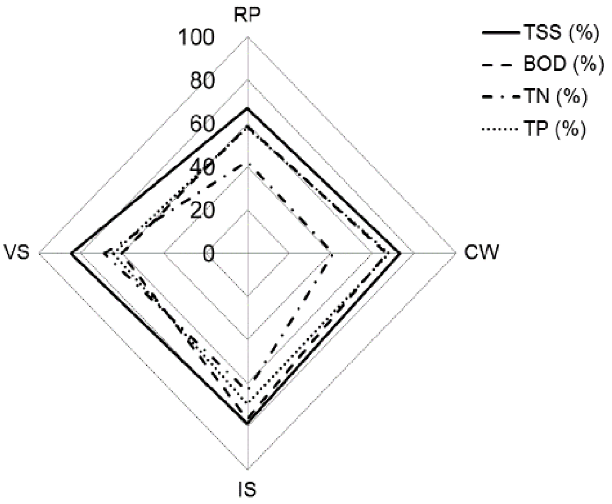


Fig. 4. Mean removal efficiency of BMPs

3.4 Relationship between pollutant removal efficiency and LCC

Fig. 5 illustrates the changes in the average removal efficiency during wet seasons with respect to the unit cost in BMP. The LCC/STV ratio of each BMP type was plotted against their removal efficiency for a better insight into the cost efficiency of different management measures for the studied sites relative to their treatment performance since

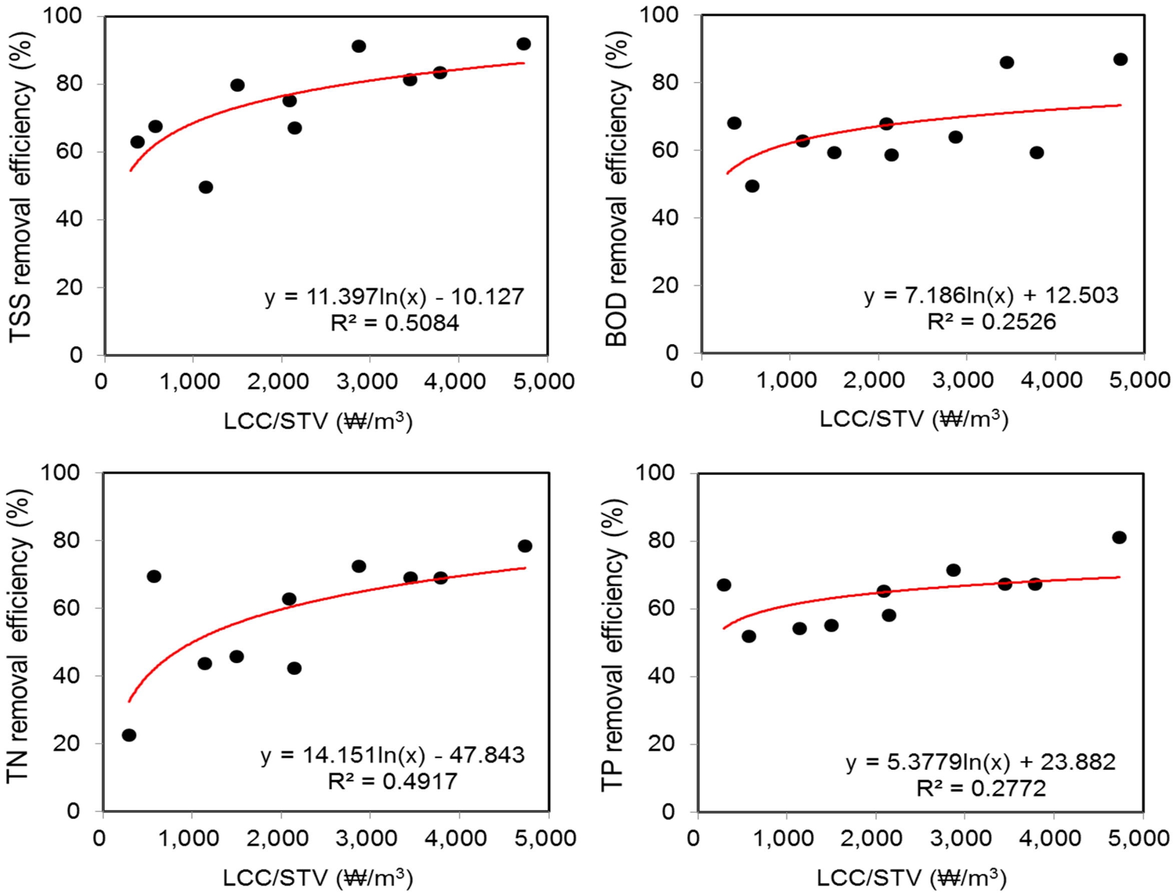


Fig. 5. Relationship between pollutant removal efficiency and LCC/STV ratio in BMPs

BMPs were particularly selected for their water quality treatment potential. For TSS and TN, the relationship of removal efficiency on unit cost was significant (R2≈0.5). The findings showed that the high unit cost of LCC/STV resulted in good efficiency. If the desired removal efficiency is in the 70% range, LCC or STV options can be easily decided. The plots shown in Fig. 5 therefore provide a useful summary if cost efficiency of BMP options that can be effectively guide the decision making design.

4. Conclusion

Case studies of twelve BMP installations for stormwater flow control and quality management were performed by the MOE in Korea since 2005. Results of this study showed that applying BMP techniques usually reduced project costs and had the added benefit of improved environmental performance for water quality of discharge. Most of the maintenance activities were focused in the routine aesthetic maintenance that resulted to the annual maintenance cost ranging from 8,483 to 8,888 $/yr closely similar for the four BMP types. The highest LCC were observed in CW ($418,324) while VS had the lowest LCC ($210,418). LCC of BMPs was less than the conventional treatment facility and sewage treatment plant. Among the pollutant parameters, TSS was the highly reduced with 67 and 84% efficiency for RP and VS, respectively. The results showed that the main mechanism of pollutant removal in the BMPs was sedimentation. Indeed, the physical process of sedimentation played an important role in terms of the performance of a natural type of treatment system. The relationship of removal efficiency on unit cost (LCC/STV ratio) for TSS and TN was significant. Evaluating the BMPs using the LCC analysis as well as for water quality analysis can be an effective method for design evaluation of BMPs.

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