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Evaluation of a hybrid constructed wetland system for treating urban stormwater runoff

Jiyeon Choi[a], Franz Kevin F. Geronimo[a], Marla C. Maniquiz-Redillas[a], Min-Ji Kang[b], Lee-Hyung Kim[a,*]

[a]*Department of Civil and Environmental Engineering, Kongju National University, 275 Budaedong, Cheonan, Chungnamdo 330-717, Korea, email: leehyung@kongju.ac.kr (L.-H. Kim)*
[b]*Water Environmental Research Department, National Institute of Environmental Research, Incheon 404-708, Republic of Korea*

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ABSTRACT

This study developed hybrid constructed wetlands (CWs) for treatment of urban stormwater runoff pollutants. Hybrid CWs applied at narrow sections in urban areas are typically small and modular in type. Several treatment mechanisms were occurring in the hybrid system to treat high level of pollutant mass loading from urban stormwater runoff. A small scale hybrid CW comprised of a sedimentation tank, free water surface (FWS) CW, and horizontal sub-surface flow (HSSF) CW, was studied. A total of 10 test runs were simulated in the hybrid CW since July 2011–November 2012. Based on the results, almost 51–78% reduction in pollutants such as TSS, COD, TN, TP, and total heavy metals (Fe, Cu, and Zn) was achieved after passing the first and second units of the hybrid CW (i.e. sedimentation tank and FWS CW). Finally, additional 9–25% reduction of these pollutants was obtained as they went through the HSSF CW. Using normalized pollutant concentration with respect to the facility length, the appropriate size of hybrid CWs was determined to be at least 2 m. Comparing the removal efficiencies of the two types of hybrid CW system (i.e. reed and iris combination in Type A; and reed and cattail combination in Type B) similar results were obtained.

Keywords: Hybrid constructed wetland system; Stormwater runoff; Nonpoint source

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1. Introduction

Urban areas with high imperviousness rates are the sources of elevated levels of accumulated nonpoint source (NPS) pollutants due to vehicular activities. In particular, NPS pollutants in urban areas are usually concentrated on the road sections, directly affecting the quality of adjacent water systems and aqua-ecosystems through the conventional drainage system unless a proper measure of advanced treatment is applied [1–4].

Road NPS pollution may be managed by using best management practices (BMPs) and low impact development (LID) technologies. BMPs involve all

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*Corresponding author.

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types of treatment facilities while LID technologies include facilities with natural purification functions and water circulation mechanisms as well as road planning and soil erosion technology. In particular, LID includes urban planning, construction, and maintenance to minimize the impact of development to the ecosystem and water quality. LID includes variety of technologies that remove pollutants, restore natural water circulations, and improve ecological functions by means of natural purification, hydraulics, and hydrology [5]. LID includes technologies such as infiltration, vegetation, bioretention, rain gardens, and constructed wetlands (CWs). Among these, CWs have been applied for various purposes around the globe due to its multiple functions such as green space, ecosystem restoration, and pollution reduction.

CWs adopt environment-friendly technology that amplifies certain elements and functions of natural wetlands. CWs are known for high-pollutant removal efficiency and low-maintenance costs. Several types of CWs include free water surface (FWS) CWs, horizontal sub-surface flow (HSSF) CWs, vertical flow (VF) CWs, and hybrid CWs. FWS CWs have been applied to many regions in the United States for wastewater treatment particularly focusing on nutrient removal through wetland plants and microorganisms [6] HSSF CWs are effective in reducing organics and particulate matters regardless of seasonal changes [7,8]. VF CWs are effective considering aerobic degradation for oxidation of organics [9]. Lastly, hybrid CWs are combinations of different types of CWs. Hybrid CWs are effective for organics and nitrogen reduction compared to other types of CWs [10,11]. Hybrid CW may be connected to other CW types such as FWS, HSSF, and VF depending on the characteristics of influent water. Greater removal efficiency is expected in hybrid CW due to the physical removal mechanisms such as adsorption and filtration as well as the activity of plants and microorganisms [12]. Combined HSSF and VF CWs resulted to 71–87% TSS, COD, and TP removal efficiencies while the combined HSSF and FWS CWs yielded to 76–89% [13–18]. Although hybrid CWs may involve a higher level of pollutant removal efficiency compared to a single CW, actual application of hybrid CWs in urban areas are not yet fully utilized due to limited space. Therefore, this study developed a hybrid CW applicable to limited spaces for NPS pollution management and to provide ecological space in urban areas. This study aims to evaluate the treatment performance of each unit of hybrid CW system in terms of water quality and performance. Based on the findings, suggestions were provided on the design of hybrid CW system.

2. Materials and methods

2.1. Description of the hybrid CW system

Fig. 1 shows the schematic of the experimental hybrid CWs. The hybrid CW has a surface area of 2.41 m^2 and a total storage volume of 1.89 m^3. The hybrid CW was designed incorporating a sedimentation tank and two types of CWs, i.e. FWS CW and HSSF CWs connected in series. The detailed characteristics of the facility are presented in Table 1. The sedimentation tank served as a pretreatment chamber for large particles and first flush runoff volume thereby providing ease of maintenance in the succeeding parts of the hybrid CWs. The FWS CW was designed to reduce the particulate bound pollutants and nutrients in the synthetic stormwater runoff and prevent clogging in the filter media of the HSSF CW. The HSSF CW served as the final treatment unit in the hybrid CW which facilitates the removal of pollutants through adsorption and filtration in the filter media. The filter media used for FWS and HSSF CW were sand ranging from 2 to 5 mm in diameter and gravel between 10 and 20 mm in diameter. Three plant species such as reed (46 plants/m^2), iris (73 plants/m^2), and cattail (73 plants/m^2), which are all abundantly growing in South Korea, and were reported to achieve good nutrient removal efficiency, were planted in the hybrid CW. The HSSF CW units differently planted with iris and cattail, because to find on the effect of the treatment performance. The observed hydraulic retention time (HRT) in each unit of the hybrid CW ranges from 9.08 to 34.32 min.

2.2. Sampling and analyses

Synthetic stormwater runoff was prepared in the laboratory by diluting 1,000–2,000 g of sediment passing #100 sieve collected from a 450 m^2 highly impervious road. The synthetic stormwater runoff was applied to the hybrid CW using 138.8 and 278.3 cm^3/s flow rates which were selected to represent two rainfall depths of 5 and 10 mm, respectively in a 250 m^2 catchment area. A total of 10 test runs were performed between July 2011 and November 2012. Samples were collected after 0, 15, 30, 60, and 120 min at the influent and effluent collection units. Also, samples were collected at the middle port from 24 sampling ports shown in Fig. 1. Analytic analyses of typical water quality parameters such as total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total copper (Cu), total iron (Fe), and total zinc (Zn) were conducted in accordance with ASTM standard methods for the

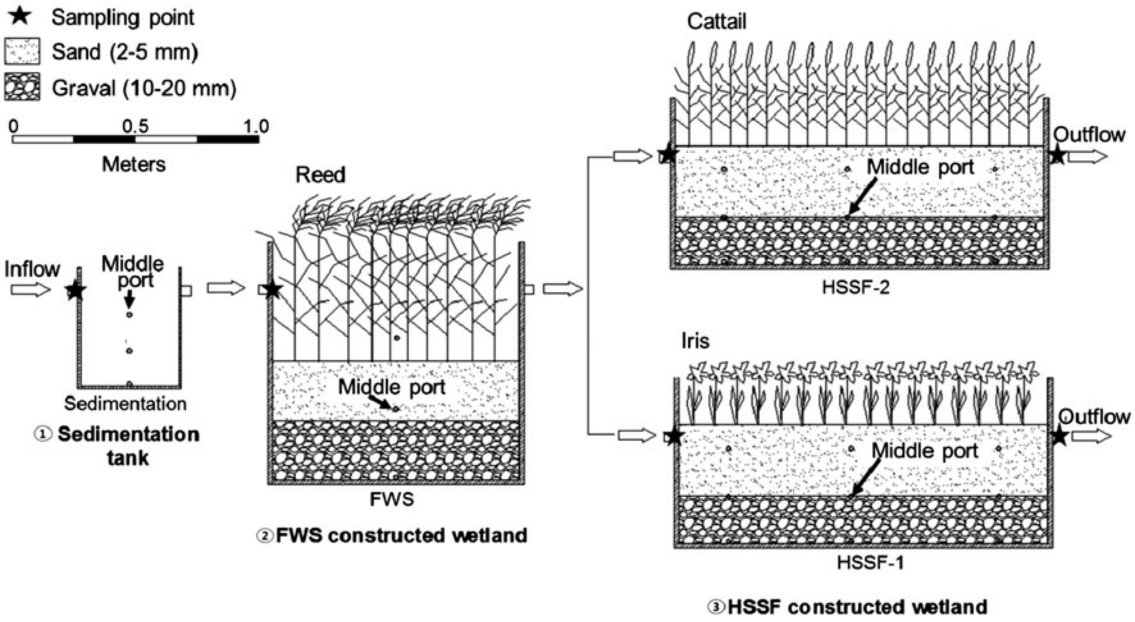


Fig. 1. Schematic of the hybrid CW system.

Table 1
Characteristics of the hybrid CW system

Type	Code	Facility aspect ratio	Surface area (m^2)	Plant	Porosity (%)	HRT (min)
Sedimentation tank	Sedimentation	0.4:1 (r:H)[a]	0.126	Unplanted	100	9.08
FWS CW	FWS	0.5:1 (r:H)	0.785	Reed (*Phragmites australis*)	36	32.63
HSSF CW	HSSF-1	0.7:2.1:1 (L:W:H)[b]	0.750	Iris (*Acorus calamus*)	24	31.27
	HSSF-2			Cattail (*Typha angustata*)	26	34.32

[a] radius:Height.
[b] Length:Width:Height.

examination of water and wastewater [19]. The flow-weighted mean concentration (FMC) was calculated for each test run as the average concentration considering the total input volume to the system (Eq. (1)). The removal efficiency was calculated as shown in Eq. (2) based on the "efficiency ratio (ER) method" defined in terms of average removal efficiency of pollutants for the time period [20]. The pollutant mass balance in the hybrid CW system can be expressed as Eq. (3):

$$\text{FMC} = \frac{\sum_{i=1}^{n}(C_i \times t_i \times q_i)}{\sum_{i=1}^{n}(t_i \times q_i)} \tag{1}$$

where FMC = flow-weighted mean concentration, mg/L; C_i = pollutant concentration at time i, mg/L; q_i = flow in the ith sample; n = total number of samples for the time period.

$$\text{Removal}\,(\%) = \frac{\text{Average influent FMC} - \text{Average effluent FMC}}{\text{Average influent FMC}} \tag{2}$$

$$M_{\text{in}}\ (\text{input}) = M_{\text{r}}\ (\text{retention}) + M_{\text{p}}\ (\text{plant uptake}) + M_{\text{out}}\ (\text{output}) \tag{3}$$

where M_{in} = input pollutant mass; $M_{\text{r}} = M_{\text{rs}} + M_{\text{rf}} + M_{\text{rh}}$, retained pollutant mass in the sedimentation tank (M_{rs}), FWS CW (M_{rf}), and HSSF CW (M_{rh}); $M_{\text{p}} = M_{\text{pf}} + M_{\text{ph}}$, plant uptake pollutant mass in the FWS CW and HSSF CW; M_{out} = output pollutant mass.

3. Results and discussion

3.1. Overall pollutant removal efficiency of hybrid CW system

Table 2 shows the changes in average FMCs in each unit and type of the hybrid CW. Based on the results, through passing at each unit and type of hybrid CW, the concentrations of most water quality parameters were reduced. The organic, nutrient and metal concentrations were reduced as the synthetic stormwater entered the different treatment units of the hybrid CW. On the other hand, no significant changes were observed between pH, water temperature, and DO of each treatment part of the hybrid CW with the coefficient of variation (CV) ranging from 0.01 to 0.07. Since the hybrid CW system is a bench scale system, the effect of these parameters was not evident.

Fig. 2 shows the pollutant removal efficiency of each unit and type of hybrid CW. The sedimentation tank contributed to 32, 22, 19, 18, 16, 5, and 2% reduction of TP, TSS, COD, total Zn, total Fe, total Cu, and TN, respectively. The TP removal efficiency in the sedimentation tank was governed by physical (sedimentation) and chemical (adsorption) processes [21]. Combining the treatment capacities of sedimentation tank and FWS CW, the removal efficiency was increased to a range of 51–78% for all the pollutants. HSSF CW contributed 9–25% removal of pollutants in the hybrid CW resulting to 65–97% removal of all the pollutants. Almost similar pollutant removal efficiencies were observed in both hybrid types since the treatment mechanisms were mainly sedimentation, adsorption, and filtration; and the pollutant removal through plants yielded rather a tiny effect on the difference between the two types of hybrid CW. Type A (planted with reed and iris) reduced TSS, COD, TN, and TP by 2–3% greater than that of Type B (planted with reed and cattail). In the case of metal pollutants, however, the removal efficiency of Type B was 2–3% greater than Type A, which indicates that the cattail was effective in metal pollutant removal. However, considering the pollutant removal efficiencies of both hybrid CW types, similar results were obtained. The effect of plants did not directly contribute to the pollutant removal since no significant difference was observed between types with varying plant species.

3.2. Water quality changes along the flow path of the hybrid CW system

Fig. 3 shows the changes in the pollutant concentration along the length of the hybrid CW. Water samples were collected at middle ports in each treatment unit of the hybrid CW to identify its appropriate length. The normalized pollutant concentration with

Table 2
FMCs for each unit and type of the hybrid CW (mean ± SD)

Parameters	Unit	Type	Inflow	Sedimentation tank	FWS	HSSF
pH	–	A	7.3 ± 0.4	7.3 ± 0.3	7.3 ± 0.2	7.2 ± 0.2
		B			7.3 ± 0.2	7.1 ± 0.3
Temperature	℃	A	23.0 ± 5.1	21.4 ± 6.3	21.7 ± 6.6	21.7 ± 6.6
		B			21.7 ± 5.2	21.8 ± 7.0
DO	mg/L	A	6.0 ± 1.8	6.3 ± 1.9	6.1 ± 1.9	6.0 ± 2.0
		B			5.2 ± 1.8	5.9 ± 1.5
TSS	mg/L	A	146.7 ± 82.7	116.7 ± 69.1	66.5 ± 38.1	11.0 ± 50.9
		B			76.3 ± 10.2	17.7 ± 17.5
COD	mg/L	A	46.3 ± 44.4	37.5 ± 31.3	28.4 ± 21.0	13.8 ± 21.0
		B			29.0 ± 7.7	15.4 ± 8.5
TN	mg/L	A	2.53 ± 0.53	2.49 ± 0.53	2.38 ± 0.50	1.86 ± 0.60
		B			2.43 ± 0.70	2.07 ± 0.74
TP	mg/L	A	0.34 ± 0.15	0.23 ± 0.09	0.17 ± 0.08	0.09 ± 0.08
		B			0.18 ± 0.04	0.11 ± 0.04
Total Fe	mg/L	A	5.38 ± 3.31	4.35 ± 2.91	3.18 ± 1.99	1.43 ± 2.21
		B			3.41 ± 2.25	0.93 ± 0.56
Total Cu	mg/L	A	0.11 ± 0.09	0.10 ± 0.09	0.10 ± 0.09	0.09 ± 0.09
		B			0.10 ± 0.09	0.09 ± 0.09
Total Zn	mg/L	A	0.31 ± 0.14	0.26 ± 0.13	0.21 ± 0.13	0.14 ± 0.14
		B			0.22 ± 0.14	0.11 ± 0.11

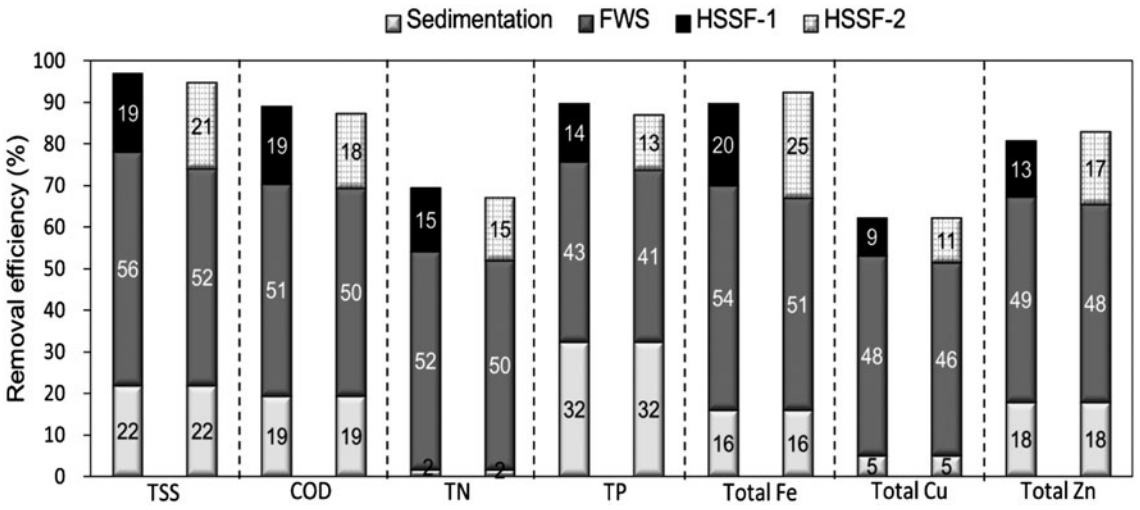
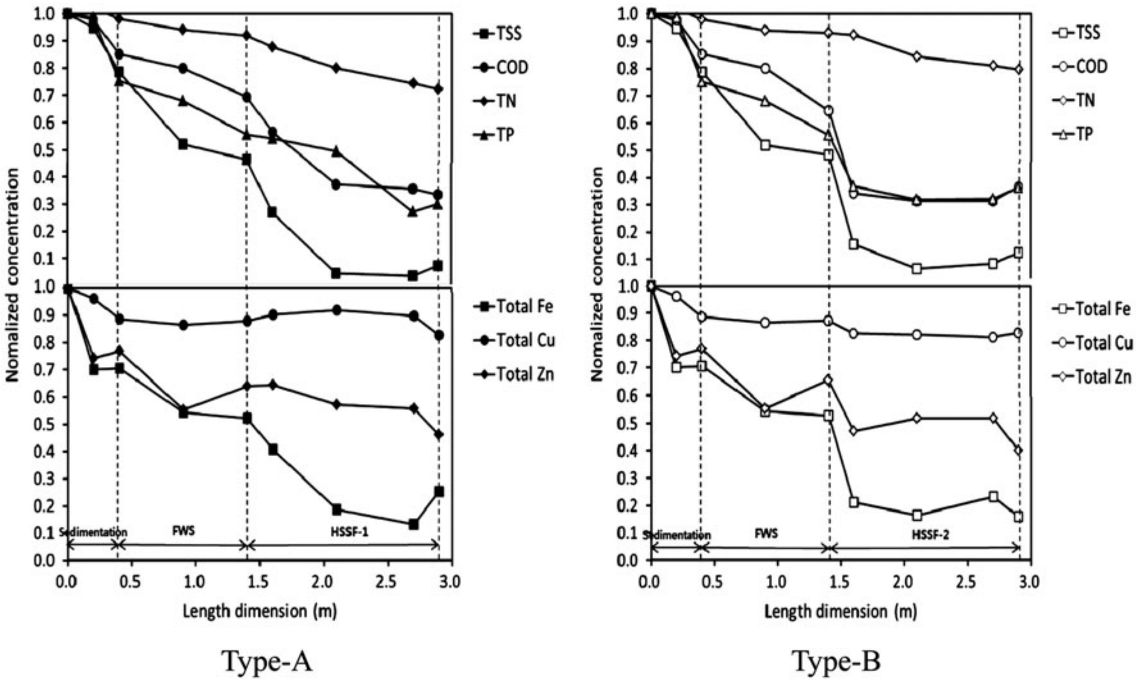


Fig. 2. Pollutant removal efficiency of hybrid CW system.



Type-A

Type-B

Fig. 3. Normalized concentration changes with respect to the length of the hybrid CW system.

respect to distance between each treatment part of hybrid CW was shown in Fig. 3. This finding was associated with the difference between the depth of each plant's roots and pollutant uptake abilities. In the case of nitrogen, the level of uptake through plants was lower than that of other pollutants [12]. Based on the concentration changes of the two types of hybrid wetlands, almost 80–90% of the inflow concentration was achieved and almost stabilized 2 m from the inflow collection port which indicated that the appropriate length of a wetland was at least 2 m.

3.3. *Pollutant mass balance in the hybrid CW system*

The estimated mass balance of each pollutant is presented in Fig. 4. For TSS and COD, it was found out that greater than 90% of the inflow mass was

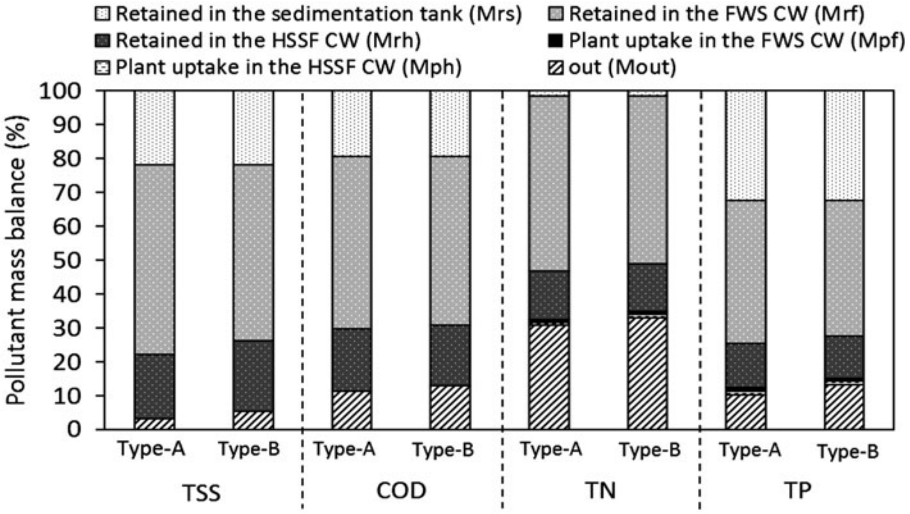


Fig. 4. Pollutant mass balance of hybrid CW system.

reduced through the hybrid CW system while only 3–5% of the inflow mass was discharged. Greater than 50% of TN removal was through FWS CW while the greatest TP fraction amounting to almost 30% was retained in the sedimentation tank. The possible treatment mechanisms for TN reduction in a CW system include plant uptake, sedimentation, volatilization, adsorption by cation exchange, and denitrification [22]. Therefore, intermittent feeding provided high TN removal in FWS CW. According to [12], FWS stage improved water quality in terms of organics, nitrogen, and phosphorus. On the other hand, according to [23], the mechanisms of TP removal in CWs included sorption on antecedent substrates and the formation and accretion of new sediments and soils. In the hybrid CW system developed, TP was reduced through physical and chemical process in the sedimentation tank. Chung et al. [24] found that the TN removal through plant uptake accounted for about 2.6–3.1% while TP removal less than 1% compared to this study which has less than 1% TN and TP uptake by plants. Low percentage of nutrient plant uptake was caused by low influent TN and TP concentration amounting to 2.53 and 0.34 mg/L of TN and TP concentration, respectively. Compared to the influent TN and TP concentration in the wetlands reported by [25,26] receiving stormwater runoff from agricultural and livestock landuse, respectively. In Korea, the mean TN concentration from agricultural and livestock landuse was 4.5 and 137 mg/L, respectively, while the TP concentration was 0.5 and 5.2 mg/L, respectively. Type A discharged less percentage of pollutant ranging from 3.2 to 30.7% which was 5.3–33.0% greater than Type B, which indicates that Type A could be more appropriate than Type B considering pollutant reduction.

4. Conclusions

This study developed a small scale hybrid CW applicable to a small land spaces in urban areas with high efficiency in reducing stormwater runoff pollutants. Based on the findings, several conclusions were drawn as follows.

A hybrid CW system consisting of a sedimentation tank, FWS CW, and HSSF CW was highly effective in removing pollutants such as debris and litter in the sedimentation tank. On the other hand, FWS CW was effective in removing pollutants and nutrients. The filtration mechanism of HSSF CW facilitated the increase in pollutant removal.

Considering the pollutant removal efficiencies of both hybrid CW types, similar results were obtained. Type A planted with reed and iris demonstrated better TSS, COD, TN, and TP removal efficiency compared to Type B planted with reed and cattail. For metal pollutants, however, it was found out that the roots and stems of cattail planted in Type B were effective in metal pollutant removal. Nevertheless, the treatment effect of the plants did not directly contribute to the pollutant removal since no significant difference was observed between types with varying plant species.

Based on the concentration changes of the two types of hybrid wetlands, almost 80–90% of the inflow concentration was achieved and almost stabilized 2 m from the inflow collection port which indicated that the appropriate length of a wetland was at least 2 m.

TN was reduced more than 50% in FWS CW through deposition and plants while TP was reduced through physical and chemical process in the sedimentation tank. The removal of TN and TP through plant uptake only accounted for about 1% attributed to low nutrient concentration in the synthetic stormwater runoff used.

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