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Development of a hybrid constructed wetland system for treating stormwater runoff from road

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ABSTRACT

Hybrid constructed wetland (CW) is a combination of various types of wetland that has different water treatment capabilities integrated into a single wetland system. However, most hybrid CWs have been formed in a larger scale, wherein the application of a hybrid CW to a limited space such as an urban area is recommended. Therefore, this study was performed to develop a hybrid CW technology which overcomes the limitations in space. The hybrid CW considered in this study was composed of a forebay, a free water surface (FWS) flow and horizontal subsurface flow (HSSF) wetlands. To evaluate the efficiency and applicability of the technology, a pilot and test-bed scale experiments were performed. The pilot experiment results showed that the removal rate of most the pollutants, including particulate matter, organic matter, and nutrients, were ranging from 3% to 31% in the forebay, 44% to 54% in the FWS CW, and 12% to 19% in the HSSF CW. With respect to the removal efficiency of each pollutant according to the vegetation, a combination of reed and cattail plants showed high removal efficiency for particulate matter and heavy metals. As for the combination of reed and iris, high removal efficiency was observed for the organic matter and nutrients. To evaluate the applicability of a hybrid CW, a test-bed was developed adjacent to a campus road. Monitoring results showed that the removal efficiency for TSS, COD, TN, TP, and heavy metals was at least 60%, which was 10%–0% higher than that of a single CW. In addition, the particle size of particulates removed by the hybrid CW was analyzed, and the result showed that diameter of 8.0–24 μm of the particulates in the inflow were removed.

Keywords: Hybrid constructed wetland system; Stormwater runoff; Road; Free water surface flow wetland (FWS); Horizontal subsurface flow wetland (HSSF)

1. Introduction

A constructed wetland (CW) emulates the treatment processes of a natural wetland such as bioremediation and microbial activities [1]. Some of the advantages of a CW include low energy requirements in comparison with other environmental facilities, uncomplicated operation and maintenance, and so on [2]. In addition, a CW may be utilized as a recreational location and biological habitat for its scenic and ecological characteristics [3]. The types of CWs are typically categorize according to the flow type such as free water surface (FWS) flow, subsurface flow (SSF), hybrid CWs, and so on. A FWS flow CW resembles a natural wetland wherein the water surface is exposed to the air and applied in a large scale area, especially in cases where influent volume is large and inflow is continuous. Although a FWS flow CW has positive effects such as providing animal and plant habitats and waterside space, it also causes some problems such as generation of foul smell, pests, and algae due to the continuous pollutant inflow. SSF CWs can be a horizontal subsurface flow (HSSF) or a vertical subsurface flow (VSSF) depending

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on the water flow in a soil and filter layer. Compared with a FWS flow CW, a SSF CW has only a minor foul smell or harmful insect problems because the water surface is not exposed to the air. However, pores may be occluded by continuous inflow of pollutants, and the water may be frozen in winter. A hybrid CW is formed by a combination of various types of CW to overcome the limitations of a single type wetland and thereby improve the water treatment capability [4].

A hybrid CW was initially introduced by Seidel, Germany, in the 1960s as a VF-HSSF hybrid type. From 1980s onwards, a hybrid CW has also been studied in the United Kingdom and France. From 1990s up until recently, the study on a hybrid CW has been extended worldwide in countries including Australia, Slovenia, Norway, Ireland, United States, Canada, South Africa, Nepal, China, and so on. A hybrid CW is usually applied to domestic sewage treatment; livestock, agricultural and urban region, milking facility, and so on. Various types of hybridization such as VF-HSSF, HSSF-VF, HSSF-FWS, and FWS-HSSF are being applied at present [5].

Recent climate change and catchment land use developments caused various urban environmental problems such as generation of various pollutant sources and ecological system disconnection and destruction. Since 2010, “green infrastructure” (GI) technology for a smooth network between natural spaces and infrastructures has come to the forefront as a means to resolve such problems caused by climate change and urbanization. The GI technology is introduced to conserve environmental, aesthetic, and ecological values and functions and thereby provide various benefits to humans, animals, and plants. CW is one of the important GI technologies; however, it is impossible to apply a wide CW to a limited space in an urban area such as a road. Thus, a hybrid CW technology that minimizes space applicable to small landscape areas is needed. This study was conducted to develop a hybrid CW technology enabling to overcome the space limitations in an urban region. Pilot and test-bed scale experiments were performed to evaluate the efficiency and applicability of the new technology.

2. Materials and methods

2.1. Site description

Pilot and test-bed scale experiments were performed to develop a hybrid CW technology. Table 1 shows the specifications of the pilot and the test-bed. The pilot scale CW was located at the Kongju National University campus in Cheonan City, Korea. The facility has a total volume of 1.39 m^3, and a total area of 2.41 m^2. The hybrid CW has a forebay, a FWS flow CW, and a HSSF CW. The filling filter materials were sand and gravel. Reeds, irises, and cattails were the wetland vegetation planted in the hybrid CW. The plants were selected based on a number of factors such as (native species, low maintenance, fast growing, capability of contaminant removal, high tolerance towards toxicities, etc.).

The test-bed was located on the side of the National Road 38 in Dangjin City, Korea. The 31.71 m^2 facility that was 13 times greater than the pilot facility drains a catchment area of 1,298 m^2. The test-bed consists of a FWS flow CW and a HSSF CW that functions as a forebay. The filling filter materials were in situ ground soil and gravel. Reeds and irises were also planted. Fig. 1 shows the structure and actual images of the pilot scale and the test-bed of hybrid CWs.

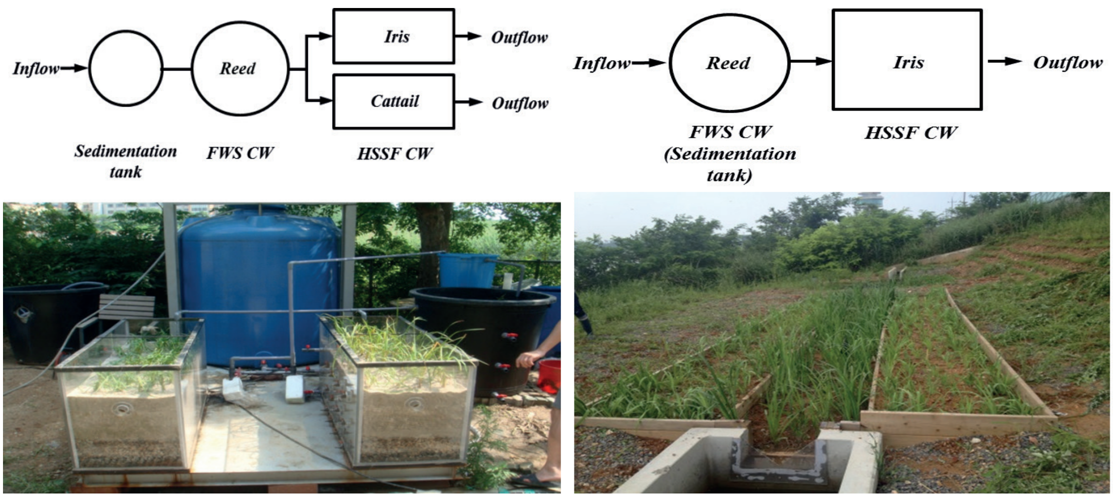
2.2. Monitoring of the pilot scale and test-bed wetland

The synthetic influent used in the pilot scale CW was a mixture of a sediment (passing sieve #100) collected from a 450 m^2 area of a road and tap water producing a pollutant concentration similar to the average event mean concentration (EMC) of typical road stormwater runoff [6, 7]. The influent flow rate was 138.8 cm^3/s and 278.3 cm^3/s, which were calculated with reference to the pollutant quantity for an appropriate road area (250 m^2). The particle sizes used were 5 mm and 10 mm, corresponding to the average particle generation frequency in 60% and 80% of Korean roads, respectively. The experiment was performed 12 times from July 2011 to October 2012. During an experiment, the influent and the effluent samples were taken in a time interval of 0, 15, 30, 60, and 120 min, and the flow rate was measured every 5 min. The test-bed CW construction was finished in May 2013, and monitoring was performed with respect to a total of five rainfall events from August to November 2013. Continuous flow measurements were performed at the inflow and outflow units of the gravel wetland system every 5- or 10-min interval. Rainfall data were also collected including the rainfall intensity, rainfall duration, antecedent dry period, and so on. The total sampling time was adjusted to approximate the time during which the “first flush” was processed [8]. Generally, at least 12 samples were manually collected for the influent and effluent.

Table 1
Characteristics of the pilot and test-bed hybrid CW system

Type	Pilot scale			Test-bed	
	Sedimentation tank	FWS CW	HSSF CW	FWS CW	HSSF CW
Facility aspect ratio	0.4:1 (r:H)[a]	0.5:1 (r:H)	0.7:2.1:1 (L:W:H)[b]	3.0:4.3:1 (L:W:H)	6.3:2.2:1 (L:W:H)
Surface area (m^2)	0.126	0.785	0.75	6.21	25.5
Plant	–	Reed (*Phragmites australis*)	Iris (*Acorus calamus*), Cattail (*Typha angustata*)	Reed (*Phragmites australis*)	Iris (*Acorus calamus*)
Media	–	Sand (2–5 mm), Gravel (10–20 mm)	Sand (2–5 mm), Gravel (10–20 mm)	Soil, Gravel (25–40 mm)	Soil, Gravel (25–40 mm)

[a] r:H = radius:height.
[b] L:W:H = length:width:height.



(a) Pilot scale (b) Test-bed

Fig. 1. Arrangement of CW units and picture of the hybrid CW systems: (a) pilot scale (b) test-bed.

2.3. Data analyses

Analytic analyses of the typical water quality parameters such as total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total iron (Fe) and total zinc (Zn) were conducted in accordance with ASTM standard methods for the examination of water and wastewater [9]. EMC was calculated by the summation of loadings during each sampling period using the volume (or flow rate) for that period. The equation below was used for the determination of EMC. The pollutant removal efficiency (RE) was calculated based on the "efficiency ratio" (ER) method defined in terms of average removal efficiency of pollutants for the time period [10]:

$$\mathrm{EMC} = \frac{\sum_{i=1}^{n}(C_i \times q_i)}{\sum_{i=1}^{n}(q_i)} \tag{1}$$

where EMC is event mean concentration, mg/L; C_i is pollutant concentration at time i, mg/L; q_i is flow in the ith sample; n is total number of samples for the time period.

$$\mathrm{RE}\ (\%) = \frac{\mathrm{EMC}_{\mathrm{in}} - \mathrm{EMC}_{\mathrm{out}}}{\mathrm{EMC}_{\mathrm{in}}} \tag{2}$$

where $\mathrm{EMC}_{\mathrm{in}}$ is average inflow EMC and $\mathrm{EMC}_{\mathrm{out}}$ is average outflow EMC.

3. Results and discussion

3.1. Performance of hybrid CW pilot scale studies

As shown in Table 2, the pilot scale CW operation results were used to calculate the EMC concentration and the pollutant removal efficiency in each CW process. The removal rate of most pollutants including particulate

Table 2
Pollutants EMC with removal efficiency of pilot scale hybrid CW

Parameters	Unit	Inflow	Sedimentation tank	FWS CW (Reed)	HSSF CW (Iris)	HSSF CW (Cattail)
TSS	mg/L	153.8 ± 79.3 (100%)	115.1 ± 63.0 (25%)	69.0 ± 39.0 (54%)	11.0 ± 10.2 (17%)	18.6 ± 16.0 (19%)
COD	mg/L	59.7 ± 51.0 (100%)	43.4 ± 31.5 (25%)	29.0 ± 19.0 (47%)	13.8 ± 7.7 (16%)	16.0 ± 8.0 (14%)
TN	mg/L	2.50 ± 0.50 (100%)	2.40 ± 0.52 (3%)	2.28 ± 0.57 (53%)	1.86 ± 0.70 (16%)	1.92 ± 0.75 (14%)
TP	mg/L	0.35 ± 0.14 (100%)	0.24 ± 0.09 (31%)	0.18 ± 0.07 (44%)	0.09 ± 0.04 (14%)	0.12 ± 0.05 (12%)
Total Fe	μg/L	5,454 ± 3,015 (100%)	4,238 ± 2,658 (19%)	3,108 ± 1,938 (54%)	1,426 ± 2,247 (20%)	1,064 ± 601 (22%)
Total Zn	μg/L	337.6 ± 150.4 (100%)	277.1 ± 128.7 (18%)	226.3 ± 122.2 (49%)	141.4 ± 140.5 (13%)	133.5 ± 107.2 (16%)

matter, organic matter, and nutrients were ranging from 3% to 31% in the forebay, 44% to 54% in the FWS flow CW, and 12% to 19% in the HSSF CW. The forebay played the role of reducing pollutant load on the succeeding CW region through the mechanism of sedimentation. The key functions of the subsequent FWS flow CW were to block and settle down the pollutants by means of vegetation and to remove the pollutant through bioremediation and microbial activities. The main treatment mechanisms of removing the pollutant in the following HSSF CW were filtration, plant and media adsorption, bioremediation and microbial activities.

The hybrid CW pilot experiment results showed that TSS was removed with the highest removal efficiency of 96%–98%, followed by Total Fe, COD, Total Zn, TP, and TN. TSS was removed by settlement and filtration while the heavy metals and TP were removed by physical mechanism along with the particulate matter. About 25% of the organic matter was removed by settlement, while more than 60% of the organic matter was removed by microbial activities and bioremediation. However, removal of TN by settlement was negligible as most TN was removed by microbial activities and plants. With respect to the removal efficiency of each pollutant according to vegetation, a combination of reed and cattail showed significant removal efficiency for the particulate matter and heavy metals. While a combination of reed and iris showed high removal efficiency for organic matter and nutrients. This result may serve as a guideline in determining the appropriate vegetation for on-site CW conditions.

Fig. 2 shows the monthly mean temperature, duration of sunshine, and plant height of reed, iris, and cattail from 2011 to 2013 monitoring period for the pilot scale CW in the Cheonan region. The monthly average temperature in each season was between –4.4 and –0.7°C in winter (December–February), 4.5°C–18.4°C in spring (March–May), 23.1°C–26.4°C (June–August), and 7.4°C–20.5°C in fall (September–November). The duration of sunshine in each season was 5.2–6.2 h in winter, and 7.2–7.4 h in spring, which was considered as the longest. The duration of sunshine in summer was relatively short as 4.1–7.1 h due to the effect of rainy days and typhoons. Meanwhile, the duration of sunshine in fall was 5.1–7.5 h. The plant height in each month showed that the plants bloom in April and grew until mid-July. The growth became slow due to the reduced sunshine and rainy days in summer, and then reached the maximum height in September. Afterward, the plants withered gradually. The maximum plant height of cattail was 102 cm, which was the highest, followed by the reed (84 cm) and iris (54 cm). Plant withering of cattail was the earliest in November, followed by the reed and iris in December. As it was shown that the plant height was generally affected by the duration of sunshine than temperature, the determination of the CW formation considering the exposure of sunlight could contribute to the efficiency of a CW.

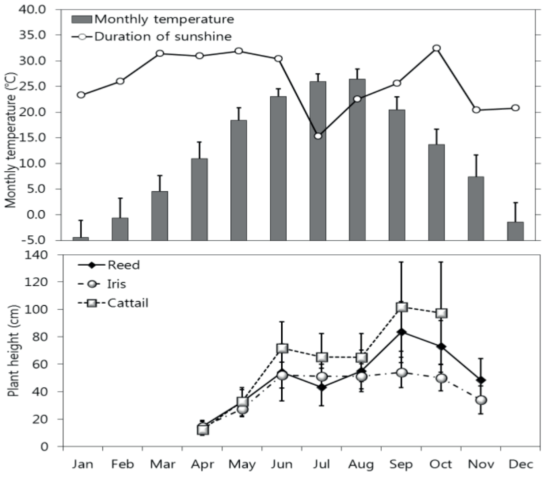


Fig. 2. Monthly average temperature, duration of sunshine and plant height (2011–2013).

3.2. Performance of hybrid CW test-bed studies

The operation and monitoring of the test-bed CW was performed using actual rainfall events. Table 3 shows the results of the test-bed CW monitoring. The monitored storm events generated a total rainfall depths ranging from 3.5 to 25.5 mm. The average rainfall duration was 6.2 h, and the average rainfall intensity was 3.2 mm/h. It was found out that 20% of the rainfall runoff flowing in to the CW facility was stored in the facility, while 80% of the rainfall runoff was discharged after pollutant removal.

Table 4 shows the average EMC and the calculated removal efficiency for each pollutant. The average influent EMC was 47.9 mg/L for TSS; 39.1 mg/L for COD; 2.11 mg/L for TN; 0.12 mg/L for TP; 3,126 μg/L for total Fe; and 253.2 μg/L for total Zn.

Table 3
Summary of monitored rainfall events (*n* = 5)

Parameters	Unit	Min	Max	Mean	SD
Antecedent dry day (ADD)	day	1.4	10.6	5.7	3.4
Total rainfall	mm	3.5	25.0	12.3	10.5
Rainfall duration	h	4.3	9.6	6.2	2.5
Avg. rainfall intensity	mm/h	0.6	5.3	2.1	1.9
Total runoff	m^3	0.3	39.8	13.4	16.0
Total Discharge	m^3	2.1	19.4	10.7	12.3

Table 4
Pollutants EMC with removal efficiency of test-bed hybrid CW

Parameters	Unit	Inflow	Outflow	Removal efficiency (%)
TSS	mg/L	47.9 ± 19.0	58.7 ± 21.9	95.1 ± 9.9
COD	mg/L	39.1 ± 23.3	16.8 ± 2.1	89.9 ± 17.3
TN	mg/L	2.11 ± 0.83	1.65 ± 0.93	77.4 ± 43.2
TP	mg/L	0.15 ± 0.08	0.12 ± 0.01	72.7 ± 52.2
Total Fe	μg/L	3,126 ± 1,037	4,969 ± 164.8	67.7 ± 63.8
Total Zn	μg/L	253.2 ± 101.7	231.3 ± 43.5	84.5 ± 26.6

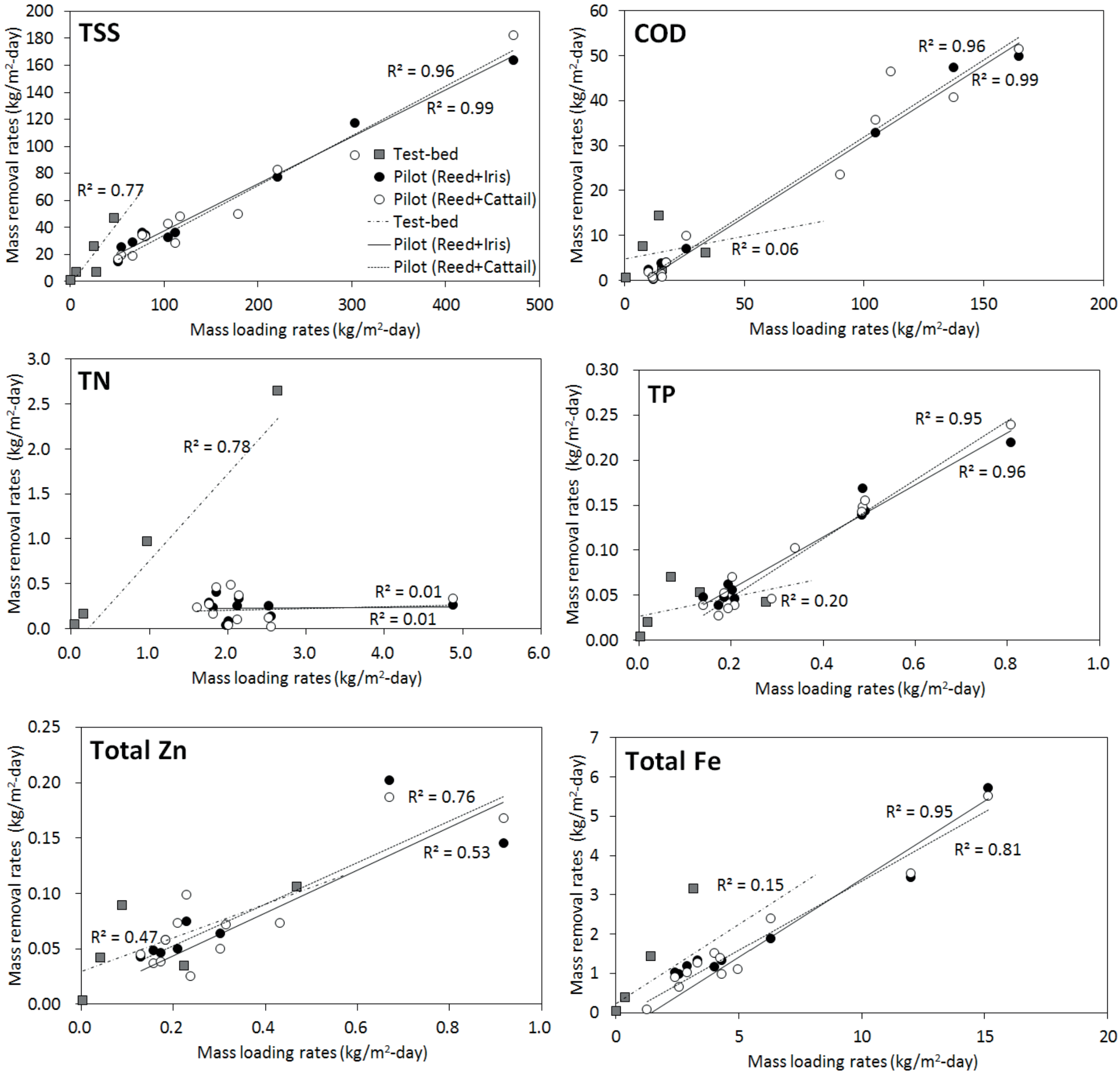


Fig. 3. Relationship between mass loading rates vs. mass removal rates of pollutants in the pilot scale and test-bed hybrid CWs.

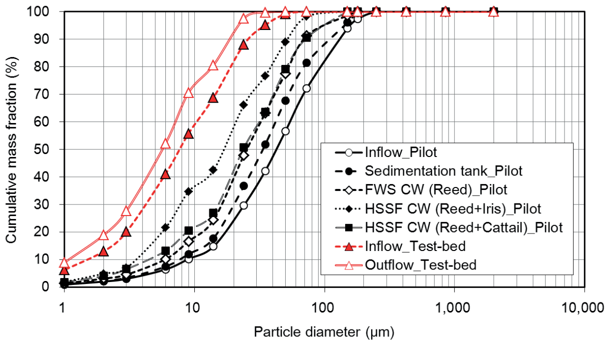


Fig. 4. Particle size distribution of water samples in the pilot and test-bed hybrid CW.

The average EMC of the rainfall runoff flowing into the CW of this study was lower than the typical concentration in urban roads and parking lots [6, 7]. The lower pollutant concentration was due to the varying traffic volume, maintenance activities, pavement conditions, and land use [11].

The highest removal efficiency was attained for TSS having a 95.1% reduction followed by COD (89.9%), total Zn (84.5%), TN (77.4%), TP (72.2%), and total Fe (67.7%). For all of the pollutants, the removal efficiency was at least 60%. According to the previous studies, in a single FWS flow CW and HSSF CW where rainfall runoff is treated in an urban area, the average removal efficiency for TSS, COD, TN, and TP were 75%, 50%, 54%, and 58%, respectively, indicating that the removal efficiencies of the hybrid CW were significant [12–15]. Therefore, a hybrid CW may improve the water treatment effect by at least 10%–20% in comparison with that of a single type CW.

Table 5
Comparison of performance results from the literature studies

Reference	CW type	Influent wastewater	Plant	Surface area (m^2)	Removal efficiency (%)			
					TSS	COD	TN	TP
[16]	FWS,HSSF	Sewage	*T. latifolia, P. australis*	200	85	–	51	25
[17]	HSSF,FWS	Fish industry	*Cyperus flabelliformis – Canna hybrida*	320	73	63	37	–
[18]	HSSF,FWS	Sewage	*P. australis*	441	–	85	99	99
[19]	HSSF,FWS	Sewage	*T. latifolia*	8,068	94	89	68	46
This study	FWS,HSSF (Pilot)	Road runoff	*P. australis, A. calamus, T. angustata*	2.41	97	87	71	88
	FWS,HSSF (Test-bed)	Road runoff	*P. australis, A. calamus*	31.7	95	90	77	72

3.3. Comparison of hybrid CW pilot scale and test-bed studies

Fig. 3 shows the correlation between the mass loading rate and mass removal rate of each pollutant in the pilot and test-bed scale CWs. In the pilot scale CW, the coefficient of determination (R^2) for the mass loading rate and the mass removal rate in the CW was 0.5 in all the pollutants except TN. The results indicate that the mass loading rate and the mass removal rate was correlated. Specifically, the R^2 value for the TSS, COD, and TP were significant for having a value of 0.9. With respect to the wetland plant combination in the hybrid CW, a higher correlation was found in the reed and cattail combination than the reed and iris combination. In the test-bed scale CW, the R^2 value between the mass loading rate and the mass removal rate in TSS and TN was at least 0.7, indicating that the mass removal rate was directly proportional to the mass loading rate. On the contrary, the mass removal rate remained unchanged even though the mass loading rate was increased, indicating the limitations in natural pollutant removal capability.

Fig. 4 shows the particle size distribution in the water samples collected from each component of the pilot and test-bed scale CWs. In the pilot scale experiment, the average particle size in the influent were 60 ± 52 μm, which was decreased into 47 ± 42 μm after passing through the forebay, 36 ± 32 μm after passing through the FWS CW, and 24 ± 23 (reed and iris combined) or 32 ± 25 μm (reed and cattail combined) after passing through the HSSF CW. The result showed that the combination of reed and iris was more effective than the combination of reed and cattail in removing the particulate matter. In the test-bed scale CW, the average particle size was 9.4 ± 8.5 μm in the influent and 8.0 ± 7.9 μm in the effluent. Therefore, application of a hybrid CW may reduce the particle size of the TSS to 8.0 or 24 μm through settlement and filtration regardless of the particle size in the influent.

As shown in Table 5, the results of this study were compared with the hybrid CW results of other studies. In most previous studies, a hybrid CW was applied to treat sewage, and the facility size was wider in a range of 200–8,068 m^2. The pollutant removal efficiency in the previous studies was at least 70% for the TSS, but the nutrient removal efficiency was widely distributed. However, the CW developed in this study, despite the small size, showed higher pollutant removal efficiency than that of the CWs in the previous studies. Particularly, the nutrient removal efficiency of the pilot and test-bed scale CWs was more stable. Therefore, the application of a small-scale hybrid CW to a small space in an urban area may remove pollutants and secure a wide ecological green space.

4. Conclusions

Climate change and catchment land use changes causes environmental hydrologic problems such as discharge of various non-point pollutants, changed hydrologic phenomena, and damage to ecological systems. GI technology is considered as a means to solve such environmental problems. CW is one of the important and well implemented GI technologies. However, the development of a CW was limited to large-scale area. Therefore, this study was conducted to develop a hybrid CW technology applicable in various areas even to a small space (e.g., road). The conclusions drawn from this study are as follows:

(1) In the pilot scale experiment, the removal rate of pollutants including particulate matter, organic matter, and nutrients were ranging from 3% to 31% in the forebay, 44% to 54% in the FWS CW, and 12% to 19% in the HSSF CW. The particulate matter, TP, and heavy metals were removed by physical mechanisms such as settlement and filtration. About 25% of the organic matter was removed by settlement, while more than 60% of the organic matter was removed by bioremediation and microbial activities. However, the removal of TN by settlement was negligible: most TN was removed by microbial activities and plants.

(2) The results about the removal efficiency of each pollutant depending on the plants showed that the combination of reed and cattail was more effective in removing the particulate matter and heavy metals, while the combination of reed and iris was more effective in removing organic matter and nutrients. The maximum plant height was in the order of cattail, reed, and iris. The plant height was more dependent on the duration of sunshine than the temperature.

(3) The results of the test-bed scale CW operation showed that the pollutant removal efficiency was at least 60%. In addition, a comparison with the results of other

studies were analyzed and showed that the application of a hybrid CW may improve the water treatment effect by at least 10%–20% in comparison with that of a single type CW.

(4) It was found that the hybrid CW discharged an effluent of which particle size was 8.0–24 μm, regardless of the particle size in the influent. In addition, because the hybrid CW of this study showed pollutant removal efficiency higher than that of the CWs in previous studies, despite the small size, a small-sized hybrid CW may be applied even to a small space such as an urban region.

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