Comparison of the treatment performance of hybrid constructed wetlands treating stormwater runoff

J. Y. Choi, M. C. Maniquiz-Redillas, J. S. Hong, S. Y. Lee and L. H. Kim

ABSTRACT

This study was conducted to compare the treatment performance of two hybrid constructed wetlands (CWs) in treating stormwater runoff. The hybrid CWs were composed of a combination of free water surface (FWS) and horizontal subsurface flow (HSSF) CWs. Based on the results, strong correlation exists between potential runoff impacts and stormwater characteristics; however, the low correlations also suggest that not only the monitored parameters contribute to stormwater event mean concentrations (EMC) of pollutants, but other factors should also be considered as well. In the hydraulic and treatment performance of the hybrid CWs, a small surface area to catchment area (SA/CA) ratio, receiving a high concentration of influent EMC, will find it hard to achieve great removal efficiency; also a large SA/CA ratio, receiving low concentration of influent EMC, will find it hard to achieve great removal efficiency. With this, SA/CA ratio and influent characteristics such as EMC or load should be considered among the design factors of CWs. The performance data of the two CWs were used to consider the most cost-effective design of a hybrid CW. The optimum facility capacity (ratio of total runoff volume to storage volume) that is applicable for a target volume reduction and removal efficiency was provided in this study.

Key words | constructed wetland design, hybrid constructed wetland, road, stormwater runoff

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INTRODUCTION

Urbanization is one of the adverse forces affecting water quality and quantity imbalance (Lee *et al.* 2011; Lenhart & Hunt 2011; Li *et al.* 2015). Several measures have been applied in order to reduce and mitigate the effects of stormwater runoff in urban areas, many of which particularly require the implementation of stormwater management practices. Constructed wetlands (CWs), wet ponds, and bioretention cells are typically designed to retain a specific water quality amount and then slowly release it. CWs have become popular in low-lying environments, offering a hybrid between larger retention practices and newer green infrastructure technologies, and provide additional benefits such as carbon sequestration, biodiversity, recreation and education opportunities (Moore & Hunt 2012; Mitsch *et al.* 2013; Merriman & Hunt 2014). A CW is an aquatic ecosystem created using natural mechanisms like vegetation, soil and microorganisms, and is well known to be a simple and an effective treatment system that requires low energy and operational costs (Vymazal 2005). The CWs have been widely used for the treatment of wastewater, and also for stormwater runoff (Carleton *et al.* 2001). In general, CWs are classified by the type of flow such as free water surface flow (FWS), horizontal subsurface flow (HSSF), vertical flow (VF), and hybrid CW.

Hybrid CWs were first introduced by Seidel in Germany in the 1960s. Research on hybrid CWs began in England and France in the 1980s, and the scope of research has been growing worldwide since the 1990s in the United States, Canada, China and many other countries. Hybrid CWs are applied in various fields such as sewage treatment, stormwater management, stockbreeding areas, and farm runoff control (Vymazal 2005, 2013; Masi & Martinuzzi 2007). Various types of hybrid CWs such as VF-HSSF, HSSF-VF, HSSF-FWS, and FWS-HSSF are applied at present (Vymazal 2013). Greater removal efficiency is expected in hybrid CWs due to the physical removal mechanisms such as adsorption and filtration as well as the activity of plants and microorganisms (Vymazal 2005; Kadlec 2009). Hybrid CWs are effective for organics and nitrogen reduction compared to other types of CWs (Masi & Martinuzzi 2007).

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According to Kantawanichkul *et al.* (2009) and Yeh & Wu (2009), the removal efficiency of hybrid CWs in which FWS-HSSF CWs were applied, generally showed a range of 73–85% for total suspended solids (TSS), 63–85% for chemical oxygen demand (COD), 37–99% for total nitrogen (TN), and 25–99% for total phosphorus (TP).

Despite various advantages of hybrid CWs, there are difficulties in adopting the hybrid CWs in urban areas they require large-scale space, are difficult to maintain, have clogging problems, etc. Therefore, the aim of this study was to compare the performance efficiency of two types of hybrid CW treating stormwater runoff from roadways. Based on the (hydraulic and treatment) performance efficiency, the design of a hybrid CW was considered using performance-affecting factors such as wetland configuration, hydraulic loading characteristics, influent pollutant concentrations and effects of the land-use conditions.

MATERIALS AND METHODS

Site description and design attributes of the hybrid CWs

The two hybrid CWs are located at Dangjin City (Type 1) and Cheonan City (Type 2) in the Chungnam Province of Korea. Dangjin City received on average, 1,279 mm of rainfall annually, which is a little lower compared to Cheonan City with 1,431 mm of annual rainfall (data from 2009–2014). The average standard deviations of rainfall for the two sites were ±115 cm annually and ±1 cm monthly. Since both cities are located on the same latitude and in close proximity to each other, the climate condition was also comparable.

The Type 1 CW located in Route 38 received stormwater runoff from an impervious two-lane road with a total catchment area of 1,298 m^2. The Type 2 CW was installed inside Kongju National University campus draining a 597 m^2 impervious road that is also utilized for short-term parking. The main pollutant sources generated at both sites were from vehicular/transportation activities. On average, the annual pollutant loading rate in the Type 2 site was 142,839 kg/yr for TSS, 77,511 kg/yr for COD, 4,142 kg/yr for TN and 337 kg/yr for TP. For the Type 1 site, the pollutant loading rates were 52,792 kg/yr (TSS), 43,044 kg/yr (COD), 2,320 kg/yr (TN) and 166 kg/yr (TP).

Figure 1 shows the schematic diagram of the hybrid CWs for Type 1 (9.2 m × 2.5 m × 1.0 m) and Type 2 (1.0 m × 6.5 m × 0.7 m). The hybrid CWs consisted of a combination of FWS and HSSF wetlands. The FWS wetland serves as the initial sedimentation tank, contributing to the capture of large particulate matters by settling and reduction in stormwater flow velocity. The HSSF wetland, utilizing plants and filter media, provides treatment of pollutants by the mechanisms such as filtration, adsorption, and plant uptake. Type 1 was planted with reed and iris, while Type 2 was planted with only iris. 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. (Choi *et al.* 2012, 2015). The filter media used were soil (foundation) and gravel (25–40 mm) in Type 1, and gravel (25–40 mm) and sand (0.25–0.5 mm) in Type 2. The surface area of the CWs corresponds to only 2.5% and 1.1% of the catchment area drained for Types 1 and 2, respectively. The surface area to storage volume ratio (SA/SV) of Type 1 is 1.7 and 2.38 for Type 2.

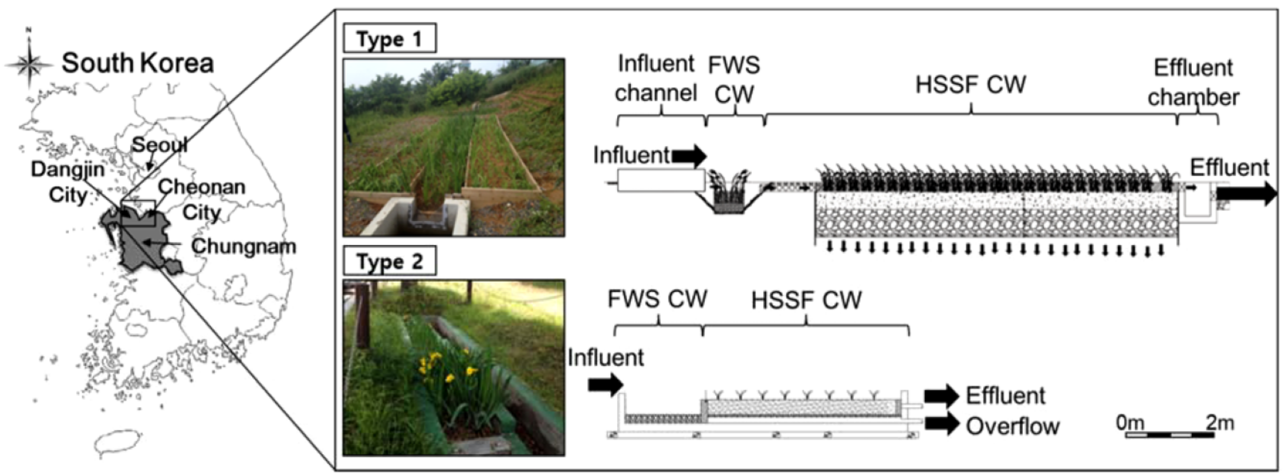

Figure 1 | Location and schematic diagram of the hybrid CWs.

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Monitoring and sampling methods

The monitoring of five storm events in Type 1 was conducted between August 2013 and November 2013 just after the completion of its construction in May 2013. Type 2 was built in June 2010, and the monitoring of 18 storm events spanned from July 2010 to October 2013. Manual 'grab' sampling technique was utilized for all storm events. Runoff samples were collected using a 4 L container in the influent and effluent units of the CWs. Four samples were taken every 5 min for the first 15 min, with the first sample collected as soon as runoff was evident, and two samples after 30 min and 1 hour, and more samples hourly thereafter until a maximum of 12 samples. For most of the shorter events, the scheme was modified by adjusting the number of samples until the runoff flow ended (Maniquiz-Redillas *et al.* 2013). Continuous measurements were also performed to monitor the influent and effluent flow rates every 5 or 10 min using a 5 L capacity graduated measuring container and a timer. The rainfall data were taken from the Korea Meteorological Administration (KMA) with reference from weather stations near the monitoring sites. Other *in situ* data gathered during the monitoring included antecedent dry days (ADD), rainfall duration, average rainfall intensity, time before effluent starts and hydraulic retention time (HRT).

Water quality and data analyses

The concentration of typical stormwater quality parameters were analyzed including TSS, COD, TN, TP and total heavy metals such as copper (Cu), zinc (Zn) and lead (Pb) based on *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 1992). The runoff volumes and flow rate were calculated for each storm event using simple numerical integration of flow rate measurements over time increments for the entire flow duration. The event mean concentration (EMC) was calculated by the summation of loadings during each sampling period using the volume (or flow rate) for that period (Kim *et al.* 2005). The pollutant removal efficiency was calculated based on the 'efficiency ratio method' defined in terms of average removal efficiency of pollutants for the time period (US EPA 1983).

Results were statistically analyzed using SYSTAT 12 and Excel software, including normality test and analysis of variance. Pearson correlation coefficient (R) was used to determine the dependence between each water quality parameter. Significant differences between parameters were accepted at 95% confidence level, signifying that the probability (P) value was less than 0.05.

RESULTS AND DISCUSSION

Correlations of monitored parameters

Based on the analyses of storm events monitored in the Types 1 and 2 sites, the average (mean ± standard deviation) ADD were 5.7 ± 3.4 and 6.9 ± 9.2 days for Type 1 and Type 2, respectively. The average rainfall depth was between 1.5 and 25 mm and the average rainfall duration was between 0.9 and 9.6 hr. While Type 1 received slightly more rainfall (12.3 ± 10.5) than Type 2 CW (7.1 ± 7.3), the average rainfall intensity in Type 2 was greater, with an average of 3.8 ± 4.7 mm/hr, than Type 1 (2.1 ± 1.9 mm/hr). In addition, one event monitored in Type 2 generated a maximum of 16.4 mm/hr intensity. Type 1 with bigger catchment only received a maximum of 5.3 mm/hr intensity. Based on the storm conditions monitored on both sites, the maximum HRT was less than 2.0 hr, with higher average HRT on Type 1 (0.9 ± 1.2 hr) than Type 2 (0.4 ± 0.6).

To determine relationships between the monitored parameters, a Pearson correlation matrix was generated as shown in Table 1. It was found out that ADD, rainfall duration, runoff, and pollutant influent EMC among other monitored parameters have strong correlations. Rainfall was shown to have highly affected the runoff and discharge for Type 1 ($R > 0.63$) and Type 2 ($R > 0.91$). Runoff was highly correlated with discharge for Type 1 ($R = 0.94$) and Type 2 ($R = 0.95$) as well. ADD (all $R > -0.85$) and rainfall duration (all $R = -0.56$ to -0.67) were observed to be negative and highly correlated with the influent EMC of all pollutant parameters in Type 1, indicating that the longer the ADD and rainfall duration, the lower the influent concentration of pollutants and vice versa. However, it was not evident in Type 2 with a smaller facility and catchment area. Due to the high variability in the data gathered, it was shown that poor correlations existed between the monitored parameters in Type 2. Among the pollutant parameters, only TSS showed high influence on the influent EMC of all other pollutants in Type 1 (all $R > 0.99$); but only on COD ($R = 0.75$), TN ($R = 0.64$) and TP ($R = 0.53$) for Type 2.

Many studies have shown that a strong correlation exists between potential runoff impacts and storm characteristics, i.e., rainfall patterns, volume and intensity; ADD; traffic

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Table 1 | Pearson correlations (*R* value) between monitored parameters and influent pollutant event mean concentration (EMC_{In}) in Type 1 (lower triangle) and Type 2 (upper triangle)

Parameters	ADD	Total rainfall	Rainfall duration	Average rainfall intensity	HRT	Total runoff	Total discharge	TSS EMC_{In}	COD EMC_{In}	TN EMC_{In}	TP EMC_{In}	Cu EMC_{In}	Zn EMC_{In}	Pb EMC_{In}
ADD		−0.207	0.056	−0.272	0.161	−0.193	−0.186	−0.471	−0.243	−0.302	−0.102	0.115	0.099	0.092
Total rainfall	−0.385		0.145	**0.809**	−0.078	**0.930**	**0.908**	−0.114	−0.423	−0.372	−0.183	−0.174	−0.451	−0.235
Rainfall duration	**0.689***	0.337		−0.347	0.454	−0.106	−0.093	0.137	−0.088	0.113	0.203	0.182	−0.013	0.157
Average rainfall intensity	− **0.702**	**0.822**	−0.191		−0.331	**0.855**	**0.791**	−0.179	−0.351	−0.387	−0.34	−0.077	−0.262	−0.190
HRT	0.196	0.473	**0.752**	−0.072		−0.241	−0.215	0.072	0.211	0.167	−0.035	0.422	0.405	0.482
Total runoff	− **0.673**	**0.789**	−0.218	**0.994**	**0.936**		**0.935**	−0.161	−0.320	−0.356	−0.202	−0.164	−0.454	−0.290
Total discharge	− **0.709**	**0.627**	−0.357	**0.950**	**0.998**	**0.953**		−0.263	−0.486	−0.469	−0.329	−0.309	−0.542	−0.418
TSS EMC_{In}	− **0.864**	0.263	− **0.611**	0.415	0.314	0.385	0.321		**0.753**	**0.643**	**0.528**	0.142	0.189	0.341
COD EMC_{In}	− **0.877**	0.212	− **0.669**	0.405	0.33	0.379	0.333	0.997		**0.739**	0.492	0.409	**0.505**	0.47
TN EMC_{In}	− **0.851**	0.302	− **0.562**	0.421	0.299	0.388	0.311	0.998	0.991		**0.701**	0.278	0.365	0.323
TP EMC_{In}	− **0.858**	0.281	− **0.589**	0.418	0.307	0.387	0.316	1	0.995	0.999		0.069	0.190	0.22
Cu EMC_{In}	− **0.86**	0.277	− **0.594**	0.417	0.309	0.386	0.317	1	0.995	0.999	1		**0.846**	**0.888**
Zn EMC_{In}	− **0.875**	0.218	− **0.662**	0.406	0.328	0.380	0.331	0.998	1	0.992	0.996	0.996		**0.850**
Pb EMC_{In}	− **0.854**	0.293	− **0.574**	0.420	0.303	0.388	0.313	0.999	0.993	1	1	1	0.994	

ADD: Antecedent dry days.
HRT: hydraulic retention time.
*Bold values were considered highly correlated for *R* greater than 0.500 and *P* value less than 0.05.

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volume; landuse; geographic and geologic characteristics of the region; maintenance practices; and drainage system configuration (Lee *et al.* 2011; Li *et al.* 2015). The low correlations also suggest that not only the monitored parameters contribute to stormwater pollutants EMC, but other factors should also be considered.

Hydraulic performance of hybrid CWs

The hydraulic performance of the hybrid CWs was exemplified by the boxplots in Figure 2. Since Type 1 was draining a larger catchment than Type 2, the maximum runoff volume received by Type 2 was almost four-fold in magnitude greater than Type 1. However, the hydraulic loading appeared to be not significantly different between the two types with a maximum of 1.73 m^3/m^2 and 1.52 m^3/m^2 for Types 1 and 2, respectively. The average volume reduction in Type 1 and Type 2 was approximately 88% and 30%, respectively. The mean average and peak flow rates were both reduced in Types 1 and 2. Type 2 was able to reduce the maximum peak flow by 54%. But, in terms of average flow rate, Type 2 performed better than Type 1 with 10% greater reduction than Type 2. As apparent in the boxplots, high variability was observed in the flow rates in the influent and effluent of both Types 1 and 2 hybrid CWs.

Treatment performance of hybrid CWs

The pollutant treatment performance was manifested by the influent and effluent EMC, shown in Figure 3. Although Type 1 received more runoff compared to Type 2, the runoff generated in Type 2 was significantly more highly polluted than Type 1. In Type 1, the average EMC was 47.9 mg/L for TSS, 39.1 mg/L for COD, 2.11 mg/L for TN, and 0.15 mg/L for TP; in Type 2, TSS was 220.0 mg/L, COD was 113.0 mg/L, TN was 5.8 mg/L, and TP was 0.5 mg/L. Based on the experimental data, the first flush effect observed in the influent during the initial 30 min of runoff had increased the TSS EMC by 240% and 120% for Type 1 and Type 2, respectively. Previous studies have shown the first flush effect by hydro-pollutographs (Maniquiz-Redillas & Kim 2014; Li *et al.* 2015).

The high pollutant EMC versus smaller ratio of area size to catchment area served by Type 2 CW has resulted in lower but satisfactory pollutant removal efficiencies of 71% for TSS, 51% for COD, 49% for TN, and 42% for TP. The higher volume reduction in Type 1 has also resulted in high pollutant removal of more than 90% for all the pollutant parameters. The results was because an initial monitoring period had been conducted for Type 1, with CW conditions being better than Type 2. Type 1 was not yet polluted or clogged. Furthermore, monitoring was conducted over a short period with only five monitored storm events, which is why further monitoring is required. On the other hand, high variability was observed in the influent and effluent EMC of the Type 2 hybrid CWs. In order to compare the results with other studies, Table 2 shows similar influent condition (stormwater runoff) in CWs including surface area to catchment area (SA/CA) ratio, average volume reduction, influent EMC and removal efficiency. Based on the references in Table 2, the common CW types were FWS, HSSF and a combination of both facilities (FWS + HSSF). The CW SA/CA ratio ranged from 0.3 to 4.7%, with a mean value of 2.2 ± 1.3%. Despite the influent EMC characteristics of the stormwater runoff for the Type 1, the TSS EMC was wide-ranging, from 19 to 100 mg/L, compared to this study. Similar to TSS, the TN and TP ranged from 0.66 to 7.18 mg/L and 0.23 to 1.45 mg/L, respectively. However, total heavy metals were less variable and ranged from 0.30

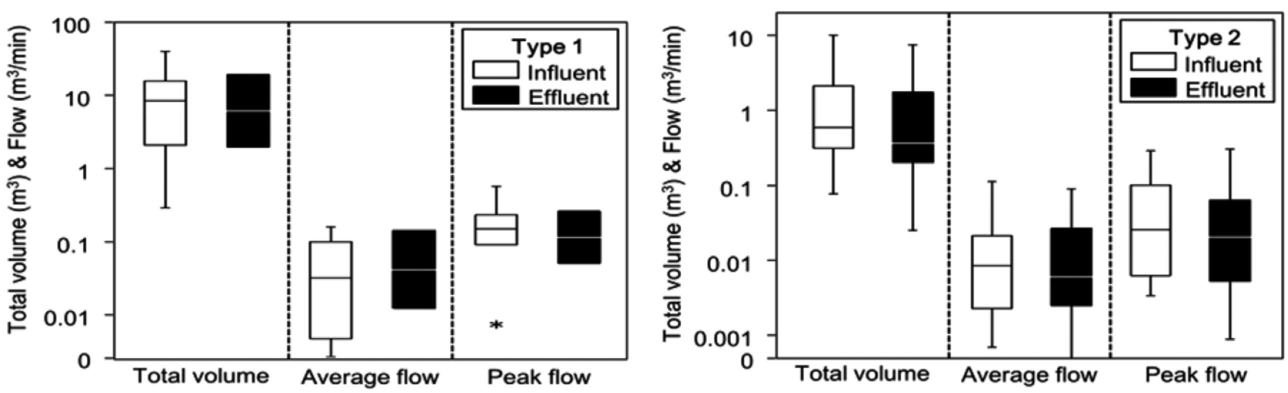

Figure 2 | Comparison of the influent and effluent runoff volume and flow rates for the two types of hybrid CWs.

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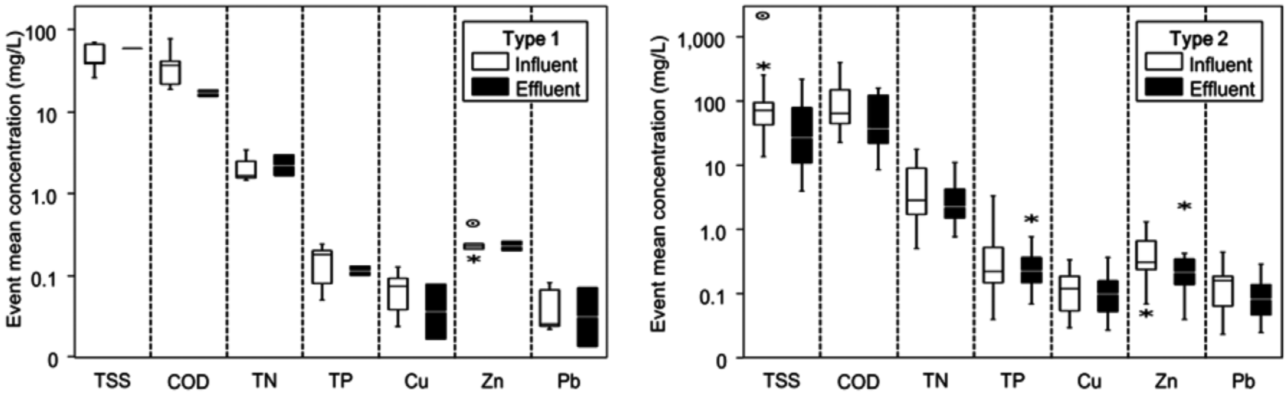

Figure 3 | Comparison of the influent and effluent runoff volume, flow rates, and event mean concentration for the two types of hybrid CWs.

Table 2 | Comparison of the pollutant removal efficiency with other CW studies receiving urban stormwater runoff (all values refer to mean values)

References	CW Type	Land Use	SA/CA (%)	Average volume reduction (%)	Influent EMC (mg/L)					Removal efficiency (%)				
					TSS	TN	TP	Zn	Pb	TSS	TN	TP	Zn	Pb
Hathaway & Hunt (2010)	FWS	Urban runoff	2.5	–	77	1.74	0.31	–	–	84	62	52	–	–
Lenhart & Hunt (2011)	FWS	Urban runoff	0.3	54	31	0.73	0.23	–	–	49	47	36	–	–
Line *et al.* (2008)	FWS	Urban runoff	4.7	–	100	0.66	0.27	–	–	83	42	52	–	–
Korea Institute of Construction Technology (2013)	FWS	Road runoff	1.6	49	62	3.20	0.50	0.30	0.15	92	74	88	70	65
Korea Institute of Construction Technology (2013)	HSSF	Road runoff	2.5	94	19	4.70	0.25	0.35	0.18	83	85	83	79	78
Korea Institute of Construction Technology (2013)	FWS + HSSF	Road runoff	2.7	93	36	7.18	1.45	0.33	0.18	93	97	91	89	89
This study (Type 1)	FWS + HSSF	Road runoff	2.5	88	48	2.11	0.15	0.25	0.04	95	97	96	84	88
This study (Type 2)	FWS + HSSF	Road runoff	1.1	30	220	5.80	0.50	0.42	0.15	71	49	42	58	52

EMC: Event mean concentration.
FWS: Free water surface flow.
HSSF: Horizontal subsurface flow.
SA/CA: Surface area to catchment area ratio.

to 0.35 mg/L for Zn and 0.15 to 0.18 mg/L for Pb. The values seem to appear similar to that of the metal EMC values of this study. It was shown that a strong correlation exists between potential runoff impacts and stormwater characteristics; even the low correlations also suggest that not only the monitored parameters contribute to stormwater pollutants EMC, but other factors should also be considered. Meanwhile, the Type 2 which has a smaller CW size, received high pollutant concentration compared to other CWs. Likewise, the removal efficiency showed similar trend to the influent EMC. TSS removal efficiency was wide-ranging, from 49 to 93%. Similar to TSS, the TN ranged from 42 to 97% while TP ranged from 36 to 91%. However, total metals were less variable, ranging from 70 to 89% for Zn and 65 to 89% for Pb. Furthermore, if the SA/CA ratio was increased, ranging from 2 to 3%, the volume reduction and most pollutant removal efficiencies were observed to be 70% higher. Also, considering the influent EMC with SA/CA ratio and removal efficiency, if the SA/CA ratio is small but receiving a high concentration of influent EMC, the

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facility will find it hard to achieve high pollutant removal efficiency. On the other hand, if the facility has a big SA/CA ratio and receiving a low concentration of influent EMC, it is hard to achieve high removal efficiency, too. With this investigation, SA/CA ratio and influent characteristics such as EMC or load should be considered among the design factors of CWs.

Design of hybrid CWs

To provide guidelines in designing hybrid CWs applicable to urban road land use, regression analyses were generated to determine relationships between volume reduction and pollutant removal efficiency of hybrid CWs and two design ratios, the SA/CA and the ratio of the total runoff volume to the storage volume of the hybrid CW (TRV/SV), as shown in Figure 4.

Based on the figure, the SA/CA and TRV/SV showed influence on the volume reduction and pollutant removal efficiency. Increasing the size of the hybrid CWs (surface area and storage volume) could result in higher volume reduction and pollutant removal efficiency, but it could be impractical and more costly. Thus, determining optimum size of the hybrid CW is important to establish a satisfactory performance efficiency with minimal costs. The plots indicate that large SA/CA and TRV/SV were not always necessary to achieve high performance. For a cost-effective design of hybrid CW, a surface area of less than 3% the size of the contributing impervious surface area is recommended. It is also important to understand the characteristics of runoff to decide on the cost-effective storage volume. A storage volume corresponding to less than 1/2.5 or 40% of the total runoff to be treated is recommended for a cost-effective hybrid CW design.

Although the regression curves were not the best fit of the measured data, the relationships observed among the variables were still valuable as they could aid in the understanding of stormwater runoff management using hybrid CWs. In addition, the study on the design of hybrid CWs is relatively new and research in this field is still lacking. Thus, the initial findings from this study could be beneficial and useful in establishing knowledge on the application of hybrid CWs in urban stormwater runoff in the future. As more data are collected, it is believed that the uncertainty could be greatly reduced.

CONCLUSION

This study was conducted in order to compare the treatment performance of hybrid CWs treating stormwater runoff. The following results were obtained.

1. Based on the analyses of the storm events monitored, studies have shown that a strong correlation exists between potential runoff impacts and storm characteristics, i.e., rainfall patterns, volume and intensity; ADD; traffic volume; landuse; geographic and geologic characteristics of the region; maintenance practices; and drainage system. The low correlations also suggest not only the monitored parameters contribute to stormwater pollutant EMC, but other factors should also be considered as well.
2. In the hydraulic and treatment performance of the hybrid CWs considering the influent EMC with SA/CA ratio and removal efficiency, a small SA/CA ratio, receiving a high concentration of influent EMC, will be hard to achieve great removal efficiency. Moreover, a large SA/CA ratio, receiving a low concentration of influent EMC, will also be hard to achieve great pollutant removal efficiency. With this, SA/CA ratio and influent characteristics such

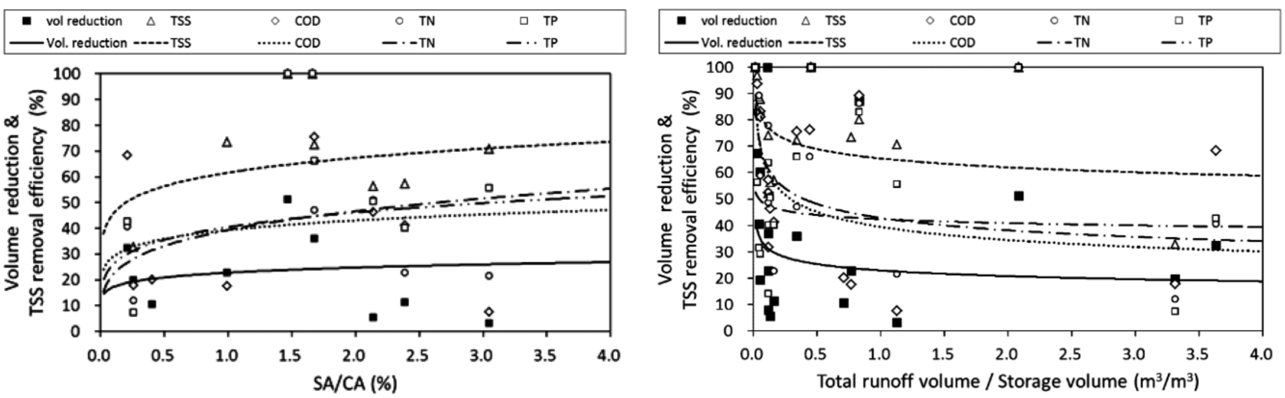

Figure 4 | Regression analysis for design of hybrid constructed wetland.

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as EMC and load should be taken into consideration in the design factors of CWs.

3. For the cost-effective design of hybrid CWs, the performance data of the Types 1 and 2 were used to consider the relationship between volume reduction/pollutant removal efficiency and two design ratios. An optimum facility capacity (TRV/SV) that is applicable for a target volume reduction and removal efficiency was also provided in this study. However, it should also be noted that these are only guidelines resulting from the study and must be used cautiously.

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