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Analysis of the Factors Affecting Nutrients Removal in Hybrid Constructed Wetland Treating Stormwater Runoff

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강우 유출수 처리를 위한 하이브리드 인공습지의 영양물질 저감 인자 분석

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Abstract

Nutrients generated from various land uses lead to eutrophication during the influx of water, and it is necessary to apply the LID techniques to reduce nutrients from nonpoint sources in order to mitigate the occurrence of the algal bloom. This study was carried out to derive the design factors of hybrid artificial wetland (HCW) to increase the removal efficiency of nutrients. HCW system was constructed in the year 2010 for the treatment of rainfall runoffs from parking lots and roads composed of 100% impervious floors in the Cheonan campus of Kongju University. The average nutrients removal efficiency of TN and TP was 74% and 72%, respectively. Both TN and TP removal efficiencies were higher than those of free surface wetlands and subsurface flow wetlands due to activated physical and ecological mechanisms. The critical design parameters for the efficient nutrients removal in the artificial wetlands were the ratio of the surface area to the catchment area (SA/CA), land use, the rainfall runoff, and the rainfall intensity. The optimal carbon to nitrogen (C/N) ratio was estimated at 5: 1 to 10.3: 1. The results of this study can be applied to the efficient design of hybrid artificial wetlands to treat nutrients in urban runoff with high efficiency.

Key words : Design, factors, hybrid constructed wetland, nutrients removal

요 약

다양한 토지이용에서 발생된 영양염류는 수계 유입시 부영양화를 유발하며, 녹조발생의 원인물질이 되기에 비점오염원으로부터 영양염류를 저감하기 위한 LID 기법의 적용이 필요하다. 본 연구는 영양물질의 저감효율을 높이기 위한 하이브리드 인공습지(HCW)의 설계인자를 도출하고자 수행되었다. 하이브리드 인공습지는 공주대학교 천안캠퍼스내 100% 불투수층으로 이루어진 주차장 및 도로의 강우유출수 처리를 위하여 2010년에 조성되었으며, 현재까지 모니터링이 수행 중이다. 하이브리드 인공습지의 조성 이후 현재까지 수행 중인 모니터링 결과를 활용하여 산정한 TN의 평균 제거효율은 74%였으며, TP의 평균 제거효율은 72%로 나타났다. 이러한 TN 및 TP 제거효율은 일반적인 인공습지에 비하여 높은 제거효율이며 자유수면 습지 및 지표하 흐름습지에서의 활성화된 물리적 및 생태학적 기작에 기인한다. 하이브리드 인공습지의 효율적 영양물질 저감을 위한 중요 설계인자는 유역면적 대비 시설면적의 비(SA/CA), 강우유출량, 강우강도 등으로 나타났으며, 영양물질 제거를 위한 최적 유입수의 C/N 비는 5:1에서 10.3:1로 산정되었다. 본 연구 결과는 도시지역의 강우유출수 내 영양염류를 고효율로 처리하고자 하는 하이브리드 인공습지의 효율적 설계에 사용 가능하다.

핵심용어 : 설계,인자, 하이브리드 인공습지, 질소저감

1. Introduction

Due to rapid and unmanaged urbanization, most of the cities in the world are facing many problems such as polluted urban environment, urban heat island effect, flooding and pollution of river, streams, wells and groundwater sources. During storm events, urban stormwater runoff contributes higher pollutant concentrations such as total suspended solids (TSS), nutrients (nitrogen and phosphorus), heavy metals, and organics to the nearby bodies. In order to mitigate such problems, low impact development (LID) technologies and green infrastructures (GI) have been practiced in different cities of world. LID/GI technology includes constructed wetland (CW), bio-retention, green roof, permeable

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pavement, bio swales systems and infiltration trenches. LID technology uses mechanism such as infiltration, filtration, retention, and evapotranspiration to detain runoff and enhance storm water quality and restore natural hydrological condition (Flores *et al.*, 2016a). CW technologies have been widely practiced treating domestic, agricultural, industrial, and urban storm water runoff from highway, parking lots, and roofs (Lee *et al.*, 2009).

CW technology is as an artificial basin constructed based on engineering design and parameter that mimic natural wetland environment and treat wastewater using biological, physical and chemical mechanisms (Sayadi *et al.*, 2012). There are different types of wetland system under practice based on flow, types of plants and hydrology. Based on hydrology, single stage CWs such as horizontal subsurface flow (HSSF), free water surface flow (FWS) and vertical subsurface flow (VF) wetland are under practice. HSSF wetlands have low nutrients removal efficiency due to existence of only aerobic or anaerobic state of decomposition. On the other hand VF wetlands have better nutrients removal efficiency due to enhanced oxygen transfer (Vymazal, 2013). Various types of CW systems are combined to achieve better nutrients removal efficiency. By utilizing the advantages of individual systems and creating both aerobic and anaerobic environment within the wetland, hybrid constructed wetlands (HCW) were developed (Vymazal, 2010). Ammonification, nitrification-denitrification, plant uptake, and physicochemical methods such as sedimentation, ammonia stripping, breakpoint chlorination, and ion exchange are considered as nutrient removal mechanisms in a wetland (Lee *et al.*, 2009). Nitrification, followed by denitrification, is generally considered as prime nitrogen removal mechanism in wetlands (Fisher and Acreman, 2004). On the other hand, phosphorus and its components are treated involving mechanisms like sedimentation, adsorption/desorption with aluminum and iron, physical separation, plant and microbial uptake, fragmentation and leaching, and mineralization (Vymazal, 2006).

Nutrients are considered as primary sources of water pollution and limiting factors for algal blooms in lakes and ponds. At present, nutrients concentration in different land uses and control mechanism studies in LID systems is a subject of primary concern among researchers (Koch *et al.*, 2014). Nutrients compounds such as organic nitrogen (Org-N), nitrite (NO_2), nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4-P) forms are found naturally (Weiner and Matthews, 2003). Furthermore, human activities such as agricultural work, industrial, wastewater treatment plants, animal wastes, septic system, sediment mobilization, vehicles and atmospheric deposition lead to increment in natural quantity of nutrients (Leisenring *et al.*, 2010). Excess concentrations of these components cause different implications to aquatic life, plants, and animals including humans.

Nutrients removal efficiency in wetland is affected by different parameters such as watershed, wetland condition and different internal processes involved within the system (Bastviken, 2006). Primarily, this study investigated nutrients removal efficiency of HCW system receiving storm water runoff from 100% impervious parking lots and road. In addition, the study was also focused on identification of different factors affecting nutrients removal efficiency in the stormwater wetland system.

2. Material and Methods

2.1 Site description

From Fig 1, HCW system was constructed in the year 2010 to treat storm water runoff from 100% impervious parking lot and road in Kongju National University,

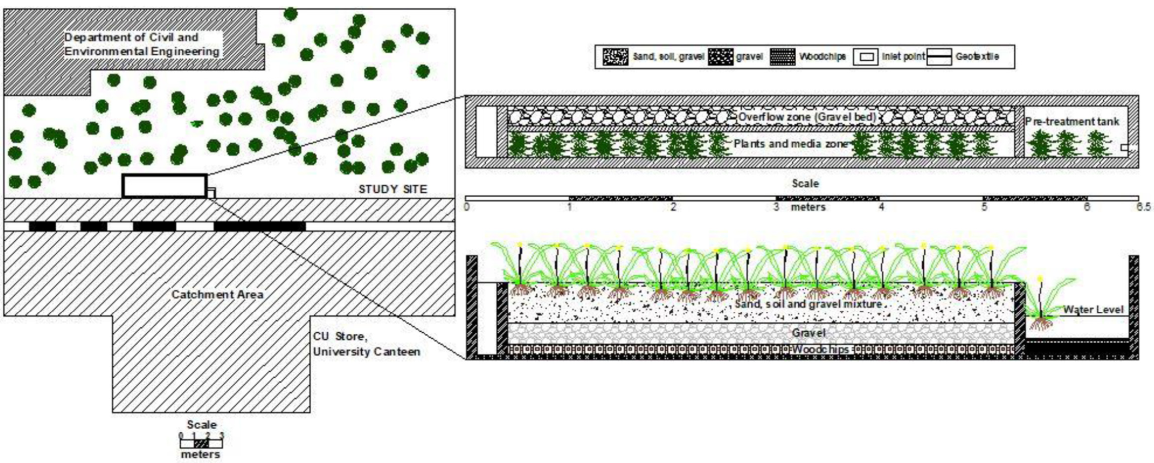

Fig. 1. Schematic diagram of HCW system location, top view and section view

Cheonan South Korea having an aspect ratio of 1:0.7:0.1 (L:W:H). The system has a surface-to-catchment area (SA/CA) ratio of 1.6%, storage-to-total volume (SV/TV) ratio of 33.9% and pre-treatment-to-storage volume ratio (PV/SV) of 37.8%. Russian iris (*Acorus calamus*) was planted on a filter media consisted of sand, gravel, and woodchip layers to improve treatment efficiency by phytoremediation and filtration mechanism. The HCW system was designed for accumulated total rainfall depth of 5 mm with a design hydraulic retention time (HRT) of 1.7 hours.

2.2 Monitoring and analyses of samples

Monitoring was undertaken during six events in the year 2015 and 2016. Manual flow measurement and recording were conducted every five minutes. Manual grab sampling was performed at inflow and outflow port of wetland during storm events. The first sample was collected as soon as runoff started, Moreover, four samples were collected every five minutes within the first 15 minutes then another sample was collected after 30 minutes of runoff. After collecting the 5^{th} sample, a sample was collected every hour before the runoff ends (Flores *et al.*, 2016b). Water sample collected were analyzed for total nitrogen (TN), NO_2, NO_3, NH_4, total Kjeldahl nitrogen (TKN), total phosphorus (TP) and PO_4-P using standard test methods for the examination of water and wastewater (APHA, AWWA & WEF, 1992). Event mean concentration (EMC) was calculated as the total mass load of parameter divided by the total runoff volume discharged during storm events (Alihan *et al.*, 2017). In addition, the nutrient removal efficiency of the system was calculated by dividing the difference of the summation of influent and summation of effluent loading with the summation of influent loading, also known as summation of loads method (Maniquiz *et al.*, 2012). Chemical oxygen demand (COD) and TN were utilized in determining the C/N ratio in the study. Since, the wetland systems have capacity to remove nutrients and organics under different carbon and nitrogen loading conditions (Zhao *et al.*, 2013).

The results obtained were statically-analyzed using Microsoft excel for descriptive statistics, correlation, regression and analysis of variance (one way ANOVA). Parameters with 95% confidence level, corresponding to a probability value (p value) of less than 0.05, were considered as significantly different.

3. Results and Discussion

3.1 Characteristics of monitored events and parking lots runoff EMC

The HCW system was designed to treat the first flush runoff amounting to five mm (5mm) of accumulated rainfall from parking lots and roadway with an observed HRT of 1.7 hours. The statistical summary of monitored events was shown in Table 1. Almost 50% of monitored events were less than the design rainfall depth of five mm. These monitored rainfall events represent almost 54 to 58% of the total rainfall depth in the years 2015 and 2016, respectively. Relatively shorter antecedent dry days (ADD) of 1.4 days was observed during autumn season while relatively higher ADD of 6.4 days was observed during summer. The mean HRT was observed to be higher than the designed HRT, implying improvement of nutrients removal from wetland by decreasing flow short circuit and improvement in biological and chemical mechanism. The pollutants removal mechanism in CW system was improved and stabilized during whole process due to higher value of HRT (Ghosh *et al.*, 2010). According to Flores *et al.*, (2016a) HRT was dependent on rainfall duration time and vice versa.

The statistical summary of inflow EMC (EMC_{in}) and outflow EMC (EMC_{out}) was shown in Table 2. The median EMC_{in} was less than the mean EMC_{in}, which signifies that all nutrient components transported to HCW system have low concentration. TN transported into the system was composed of 2.3%, 30.5%, 19.5%, and 58.4% of NO_2, NO_3,

Table 1. Statistical summary of monitored rainfall events in 2015-2016

Parameters	Unit	Minimum	Maximum	Mean	Standard deviation
ADD	day	1.3	6.6	4.0	2.2
Rainfall	mm	1.5	18.5	7.8	6.3
Total rainfall duration	hrs	0.6	12.3	4.4	4.2
Average rainfall intensity	mm/hr	0.8	12.9	3.5	4.7
Inflow volume	m3	0.1	3.8	1.4	1.4
Outflow volume	m3	0.0	1.1	0.5	0.4
HRT	hrs	0.1	8.3	2.7	3.2

Table 2. Statistical summary of EMC

Parameter		n	Units	Mean	Median	Standard deviation	Maximum	Minimum
TN	influent	6	mg/l	6.34	5.86	2.37	9.9	3.31
	effluent	6	mg/l	4.52	2.49	2.49	7.86	1.44
NO_2	influent	6	mg/l	0.15	0.06	0.16	0.43	0.01
	effluent	6	mg/l	0.11	0.05	0.12	0.28	0.01
NO_3	influent	6	mg/l	1.93	1.93	0.93	3.32	0.83
	effluent	6	mg/l	0.51	0.9	1.31	3.01	0.14
NH_4	influent	6	mg/l	1.23	1.08	1.11	2.69	0
	effluent	6	mg/l	0.81	0.82	0.67	1.63	0
TKN	influent	6	mg/l	3.7	3.25	1.68	6.31	1.85
	effluent	6	mg/l	2.91	2.24	2.31	6.91	0.34
TP	influent	6	mg/l	1.11	0.26	2.25	7.08	0.08
	effluent	6	mg/l	1.08	0.23	2.29	7.15	0.05
PO_4-P	influent	6	mg/l	0.09	0.05	0.12	0.42	0
	effluent	6	mg/l	0.07	0.03	0.12	0.38	0

Note: n= Number of events

NH_4 and TKN, respectively. Taylor's study regarding the treatment of stormwater runoff from roads and parking lots observed 36% higher NO_3 EMC_{in} compared to the current study (Taylor *et al.*, 2005). Higher NO_3 EMC_{in} was attributed to the larger catchment area and higher daily traffic loads in Taylor's study area compared with current study. NO_2 is short and intermediate in nature, while NO_3 is considered as mobile and persistent in nature (Leisenring *et al.*, 2010). The inorganic nitrogen such as NO_2, NO_3 and NH4 has higher impact on water bodies and readily available for plant and animal uptake (Taylor *et al.*, 2005). The NO_2 concentration in influent was observed least compared with other nitrogen constituents due to unstable and short nature of components. Likewise, urban storm water runoff contains low concentration of NO_2 unless contaminated by agriculture, drainage, and industrial flow (Vymazal, 2006). On the other hand, TP is composed of particulate and dissolved forms (Rossen *et al.*, 2010). TP transported in HCW system was composed of 7.7% of orthophosphate (PO_4-P) and 92.3% of particulate phosphorus. PO_4-P was regarded as the most reactive form of phosphate and available for algal bloom and plant growth (Leisenring *et al.*, 2010). The pretreatment structure in the system collected the higher percentage of particulate phosphorus in EMC_{in} thereby improving TP removal efficiency of system (Maniquiz *et al.*, 2014).

3.2 Factors affecting nutrients removal

3.2.1 Land uses

The comparative analysis of nutrients removal from different types of CW system applied in different land uses were shown in Table 3. The CW systems were applied to treat different types of runoff from impervious parking lots and road, highways, agricultural and mixed land uses. It was observed that the HCW nutrient removal efficiency in the current study was higher compared with other studies. Terzakis *et al.*, (2008) studied CW system applied to treat storm water runoff from highway with relatively low nutrient removal compared to the current study. Similarly, Birch *et al.*, (2004) concluded that due to highly-urbanized area and limited space availability, the designed SA/CA ratio of the CW system was insufficient, resulting lower nutrients removal performance. However, the CW systems studied by Kovacic *et al.*, 2000 and Terzakis *et al.*, 2008 were designed considering one to five percent SA/CA ratio. Various factors affecting the nutrients removal efficiency of the CWs were observed in both studies. The performance of the CW systems was influenced by land use and influent characteristics, thereby affecting the influent water quality. As presented in Table 3, CW systems applied to treat agricultural and stormwater runoffs exhibited low nutrients removal efficiency due to higher pollutant concentrations compared to other land uses. Generally, the nutrients removal efficiency of the wetland systems was found to be affected by the CA land use and influent characteristics.

3.2.2 Hydrology and hydraulic parameters

The relationship among volume reduction, outflow volume, rainfall intensity, and HRT with respect to nutrient removal efficiency was shown in Fig 2. The volume reduction from the system was significantly correlated with the TN removal efficiency, having a Pearson correlation coefficient (r) equal to 0.96, with p value less than 0.05. The positive trend of TN removal with respect to volume reduction

Table 3. Nutrients removal from different land use

Parameters	Units	References						
		Study result	Maniquiz *et al*, 2012	Birch *et al*., 2004	Terzakis *et al*, 2008	Jordan *et al*, 2003	Chavan *et al*., 2008	Kovacic *et al*., 2000
Land use		Impervious parking lots and roads	Mixed land use1	Residential	Highway runoff	Agriculture Land use1	Mixed land use2	Agriculture land use 3
Types of CW		Hybrid	FWS	FWS	Hybrid	Hybrid	FWS	Hybrid
Runoff characteristics		Storm Water runoff	Storm water runoff and stream	Storm water runoff	Stormwater runoff from road	Agriculture and storm water runoff	Storm water runoff	Agricultural and Stormwater runoff
Substrate		Media, woodchip, sand	–	–	–	–	–	–
Vegetation		Russian iris	–	–	Arundo donax, Phragmites australis	blunt spike rush, Schult	Cattail, meadow rush	–
Surface area (SA)	m^2	6.5	3282	700	130	13000	162	150
Catchment area (CA)	m^2	323	465000	480000	2750	140000	777000	6000
SA/CA		0.020	0.0007	0.001	0.047	0.093	0.0002	0.025
TN	%	74	28	22	49	38	70	46
TP	%	72	67	12	60	59	35	35

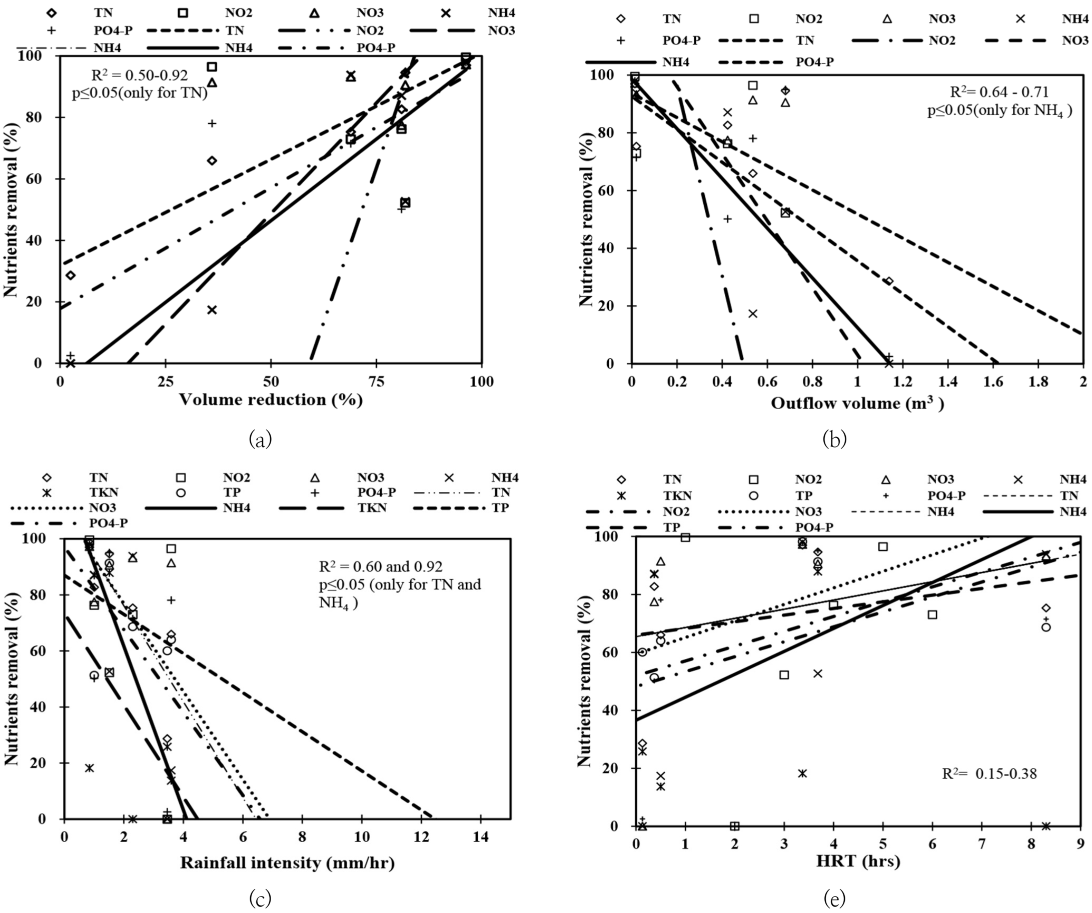

Fig. 2. Relationship between nutrients reduction with (a) volume reduction (b) outflow volume (c) rainfall intensity (d) HRT

suggested that the sufficient volume attenuation capacity of system facilitated the improvement of TN removal efficiency. The system exhibited at least 40% to 65% of nutrients removal by reducing approximately 50% of runoff volume in the system. NH4 removal from HCW was significantly correlated with the outflow volume from the system, having r = −0.84 with p value less than 0.05. The inverse relation implied that increase in outflow volume from system will decrease the removal efficiency of the system and vice versa. Jordan *et al.*, (2003) concluded that this type of inverse correlation exists when the outflow volume from the system increases, indicating higher passage of water from the wetland. Furthermore, rainfall intensity was significantly correlated with TN and NH_4 removal, having p value less than 0.05 and r values of 0.78 and 0.96, respectively. This result signified that higher rainfall intensity decreases the nutrients removal efficiency of wetland. The leaching problem might be observed if the system will receive the higher rainfall intensity of 12 mm/hr. On the other hand, HCW system did not show a significant correlation between HRT and nutrient removal due to varying ranges of HRT (0.13 to 8.3 hours). Wetland treating storm water runoffs were affected by high outflow, and short and varying HRTs, which cause short circuiting and resuspension mechanisms within the wetland and thus, affecting nutrients removal (Spieles and Mitsch, 2000). The factors like short circuit and resuspension mechanism in wetland treating storm water runoff decreases the nutrients removal efficiency (Vymazal, 2013). No significant correlation among NO_3 removal, volume reduction, outflow volume, rainfall intensity, and HRT were observed in the HCW. Lu *et al.*, (2009) concluded that, the relation between volume reduction, outflow volume, rainfall intensity and HRT with NO_3 removal did not exist due to complicated relation between these parameters.

3.2 Water quality

3.2.1 Nutrients concentration

Fig 3 presented the relationship between the EMC_{in} and EMC_{out} from the HCW system. TN, NH4, and TKN EMC_{in} were significantly correlated with EMC_{out}, having r equal to 0.91, 0.81 and 0.91, respectively, and a p value less than 0.05. On the other hand, TP EMC_{in} was significantly correlated with the EMC_{out}, having r = 0.99 and a p value less than 0.05. These findings suggested that the EMC_{out} from the wetland system can be estimated from the linear relation between EMC_{in} and EMC_{out}. When four mg/L of EMC_{in} nutrients in inflow was transported to HCW system, the estimated EMC_{out} of the nutrients from the system will be around two to 3.5 mg/L. Storm events dated October 10, 2015 and October 27, 2015 observed higher TP EMC_{out} 1.5 and 0.01 times higher than discharged from system due to higher rainfall depth of 11.5 mm compared to the designed rainfall of five millimeters (5 mm), thereby causing resuspension mechanism. Similarly, higher TKNout

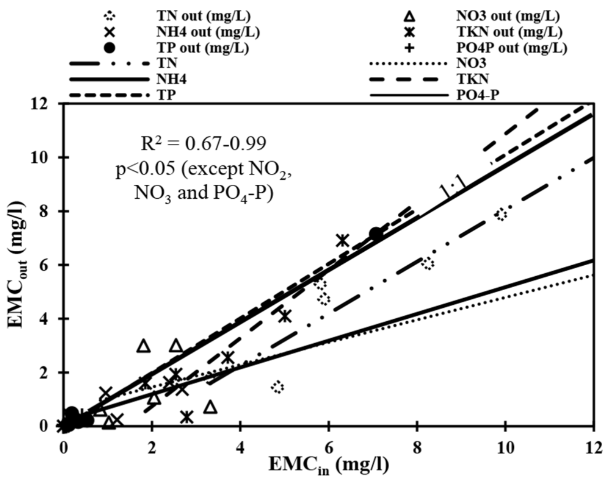

Fig. 3. Relationship between EMC_{in} and EMC_{out}

was observed from the HCW system on October 7, 2016 storm event due to high EMC_{in} 0.09 times higher transported into the system compared to other events. In addition, the trend line fall below the 1:1 line suggested that the EMC_{out} from the system was lower than the EMC_{in}. This implied an improvement in the removal efficiency of the system due to higher 61% volume reduction.

3.2.2 Inflow C/N ratio

The nutrients removal at varying inflow C/N ratio was shown in Fig 4. The COD EMC from parking lot and roads ranged from 38 mg/L to 232.6 mg/L, while inflow C/N ratio varied from 5:1 and 28:1, respectively. The events monitored in June 11, 2015 and October 17, 2015 were observed to have the least nutrient removal efficiency of 29% and 66%, while the corresponding inflow C/N ratio was recorded to be 28.2:1 and 22.7:1, respectively. The maximum nutrient removal efficiency of 97% was observed with a corresponding inflow C/N ratio of 6.5. Similarly, the inflow C/N ratios for other events with higher nutrients

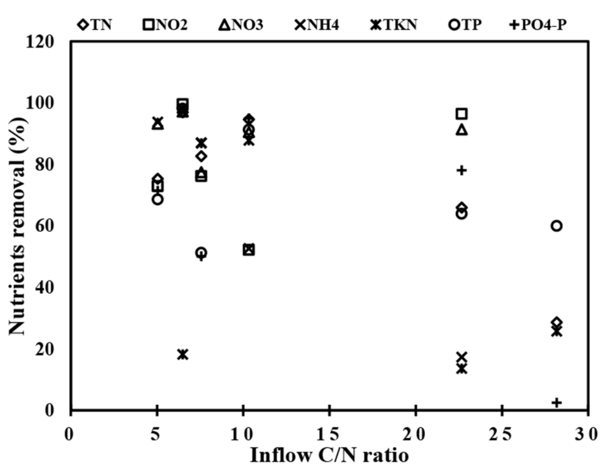

Fig. 4. Nutrients removal at varying inflow C/N ratio

removal were observed within the range of 5 to 10.3. These results signified that higher inflow C/N ratio decreased the nutrients removal efficiency of HCW system. The low nutrients removal efficiency was observed due to the change in primary nutrients balance between carbon (C) and nitrogen (N) adaptive for denitrifying bacteria (Xinshan *et al.*, 2010). The events with inflow C/N ratio of 5:1 to 10.3:1 observed higher nutrients removal efficiency. Zhao *et al.*, (2013) concluded that the inflow C/N ratio for optimum nutrients removal efficiency was observed within the range of 5:1 to 10:1.

3.3 Design methods

Guidelines for wetlands suggested minimum SA/CA ratio for the design ranges from 1 to 5% with extended detention time and treatment volume to capture 80% to 90% of flow generated due to storm events depending on rainfall intensity (Carleton *et al.*, 2001). The SA/CA ratio considered for this study ranges from 0.02 to 9%. TN removal from wetland was not observed to have relation with SA/CA ratio of wetlands due to different mechanisms involved in TN removal process, such as nitrification and denitrification, microbial and plant uptake, and ammonification (Vymazal, 2013). Furthermore, the above mentioned mechanisms in the wetland were affected by pH, carbon content, temperature, oxygen, and presence of denitrifies. The logarithmic regression of TP removal at varying SA/CA ratio was exhibited in Fig 5 for a specific TP removal requirement, a corresponding SA/CA ratio may be considered for the design of CW. Carleton *et al.*, (2001) suggested a careful application of such equation can be useful for the preliminary design of wetlands for nutrients removal.

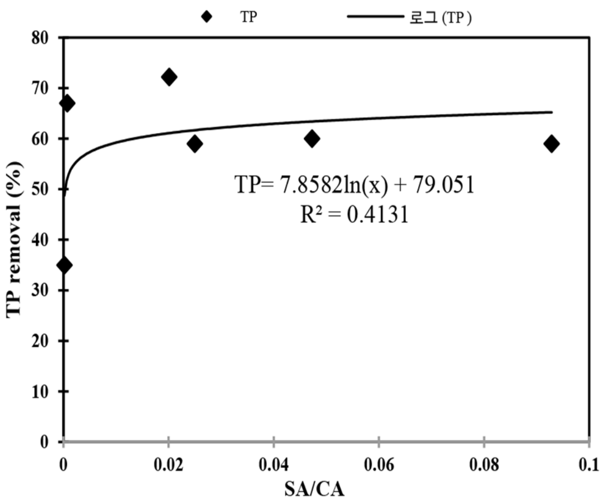

Fig. 5. Logarithmic relation between TP and SA/CA ratio

4. Conclusion

CW systems are regarded as best management practices for the storm water runoff onsite control and treatment. Besides volume attenuation and pollutant treatment, CWs provide biodiversity to ecosystem by providing habitat for plants and animals. The nutrient removal efficiency of the HCW system considered in this study was observed to be higher compared to previous inquiries that utilized a similar type of CW. The nutrients removal efficiency of the CW systems was found to be affected by the CA land use and influent characteristics. In addition, the significant correlation between nutrients removal with factors such as volume reduction, outflow volume, and rainfall intensity ($p<0.05$) was observed. This correlation can be applied in designing similar types of CWs. The nutrients removal from HCW system was positively affected by volume reduction, outflow volume and rainfall intensity while due to variable HRT the nutrients removal did not observed significant correlation ($p<0.05$). Likewise, the optimal inflow C/N ratio for the better nutrients removal was observed at the range of 5:1 to 10.3:1. The events having higher inflow C/N ratio observed lower nutrients removal efficiency due to change in primary nutrients balance between C and N required for the adaptation of denitrifying bacteria. On the other hand, the linear relation between EMC_{in} and EMC_{out} of nutrients can be applied to estimate effluent concentration from the similar CW system. Lastly, the logarithmic regression equation plotted between SA/CA to TP removal can be applied for preliminary design of similar type of CW. Overall, the nutrients removal efficiency of system showed better results compared to similar CW system compared to other parts of the world. The different factors affecting nutrients removal from HCW system can be improved by the application of identified factors while designing the similar type of CW system treating storm water runoff.

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