Journal of
Environmental & Analytical Toxicology

Lee et al., J Environ Anal Toxicol 2015, 5:4
DOI: 10.4172/2161-0525.1000280

Research Article Open Access

Performance Evaluation of the Free Water Surface Constructed Wetland Treating Nonpoint Source Pollutants in the Agricultural Area

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Abstract

Water quality impairment from nonpoint source pollution is one of the critical causes of surface water eutrophication in rivers and lakes surrounding agricultural area, Korea. In the Songchon Constructed Wetland (SCW) located in Yeongsan (YS) watershed which has about 1,000 km^2 (total watershed area: 3,471 km^2) for agricultural area, 19 times of intensive field monitoring in 2010 were conducted with various rainfall patterns and about more 1,000 water samples were measured and analyzed in field and laboratory. To identify the relationship between meteorological conditions and removal efficiency of the constructed wetland, principal component analysis (PCA) and ternary plot analysis was used for 19 field experiment data. Mean treatment performance of TSS, BOD_5, COD, TN, and TP was 16.4%, 42.1%, 43.7%, 36.6%, and 57.1%, respectively, as a method of pollutant load reduction for multiple tests of storm events. PCA results revealed that rainfall depth, rainfall intensity, and antecedent dry days (ADDs) can be major components as a representative in each component. Also, ternary contour plots results showed that the treatment performance of SCW in agricultural area during storm events can be affected by three meteorological conditions. These results and phenomena can be applicable to develop the NPS discharge model and to elucidate the relationship between rainfall and storm water runoff using rain radar in a drainage area.

Keywords: Free water surface constructed wetland; Nonpoint source pollution; Ternary analysis; Principal component analysis

Introduction

Constructed wetlands (CWs) as a kind of detention pond systems are generally used and preferred to remove naturally the nonpoint source (NPS) pollutants for urban or agricultural runoff [1-6]. Because CWs can be designed and engineered to control hydrological aspects, removal mechanisms using vegetation and hydraulic loading to use the natural removal mechanisms which are similar with natural wetlands. From this reason, many researchers and engineers tried to use the CWs in terms of storm water management. The first adaptor who tried to use CWs as a storm water treatment system is Reddy in 1982 [3]. Higgins was a first user of full-scale CWs as an agricultural storm water control in 1993 [7]. The results from Reddy and Higgins were potentially a chance to expand the storm water control system using CWs. A number of studies show that the treatment performances were relatively reasonable to remove the NPS pollutants including nitrogen, phosphorus, suspended solids, organics, heavy metals, and pesticides [4,8-12]. These researches were not only to identify the treatment performance of CWs but also to imply several methodologies how to improve and optimize the removal efficiency.

To optimize the treatment efficiency about NPS pollutants in the CWs, one or more treatment ponds which have different removal functions including settling pond and facultative pond are installed with aquatic vegetation such as reeds, cattail, and lotus. These structural characteristics for the various functions to remove the NPS pollutants are based on the biological, physical, and chemical removal mechanisms [13]. The performance evaluation of the CWs used for the control of the NPS pollutants in the agricultural area usually depends on the a number of dependent factors such as shape of CWs, size compared to drainage area, hydrological detention time, vegetation conditions, runoff characteristics related to the rainfall types, and human activities including land development, cultural practices for production, pest management, and irrigation practices [6,14]. Many studies dealt with the importance of these factors address that the CWs performance is affected by all factors related with the operating of the CWs [15-18]. However, in case of CWs for storm water treatment, the performance mainly depends on a function of inflow or hydraulic loading rate (HLR), detention time which have the information about the storm intensity, runoff volume, and wetland size[19-21]. As an extension of the previous research, Braskerud suggested a method to determine the critical factor affecting the NPS pollutants retention using a first-order model [22].These results mentioned that the removal efficiency of CWs is affected by the hydraulic retention time (HRT) which related with hydraulic loading with respect to the meteorological conditions such as rainfall depth, rainfall intensity, and antecedent dry days (ADDs)

This study investigated the performance of a CW which is a free water surface constructed wetland for treating the agricultural storm water runoff with an operating time for one year. Based on the field and laboratory experiment data analysis, the objectives are 1) to statistically identify the key meteorological parameters affecting storm water runoff 2) to generalize the removal efficiency related with meteorological conditions in a free water surface constructed wetland.

Materials and Methods

Description of study area

As one of the techniques for nonpoint source pollution management, Songchon Constructed Wetland (SCW) is spherically

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Received February 06, 2015; **Accepted** February 24, 2015; **Published** February 28, 2015

Citation: Lee SH, Cha SM, Lee JC, Lee JY (2015) Performance Evaluation of the Free Water Surface Constructed Wetland Treating Nonpoint Source Pollutants in the Agricultural Area. J Environ Anal Toxicol 5: 280. doi:10.4172/2161-0525.1000280

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located in 126°35'43" as east longitude, and 35°01'57" as north latitude and is administratively located in Naju (NJ) city, South Jeolla province, Korea. SCW, as a test-bed wetland to mitigate the nonpoint source pollutants in the agricultural area, was designed and constructed from 2006 to 2008 from Ministry of Environment, Korea.

SCW, as a free water surface wetland, is comprised of four ponds which have different volume and hydraulic retention time (HRT) as shown in Table 1. The size of SCW is 250 m for length, 50 m for width. Total volume for four ponds is 13,127 m^3. HRT is 59.8 hour that depends on the base flow and meteorological conditions such as rainfall depth, rainfall intensity. Each pond is linked with polyvinyl chloride culvert (φ 450 mm) to convey the treated water to next pond or stream (only last pond). In the inflow part of this system, the maximum flow rate is about 500 CMH (Cubic Meter per Hour) in accordance with the monitoring data from 2008 to 2010. SCW has some planted vegetation area including reed, cattail, iris, and lotus to mitigate the NPS pollutants in the second and third pond (Figure 1, Table 1).

	Pond1	Pond2	Pond3	Pond4	Total
Area (m^2)	1841	2282	6921	2250	13294
Volume (m^3)	1889	2271	6606	2361	13127
Aspect Ratios	0.50	0.77	2.33	0.63	-
Vegetation	X	O	O	X	-
Minimum HRT (hr)	3.78	4.54	14.21	4.72	26.52

Table 1: Detail information of each pond in Songchon Constructed Wetland (SCW).

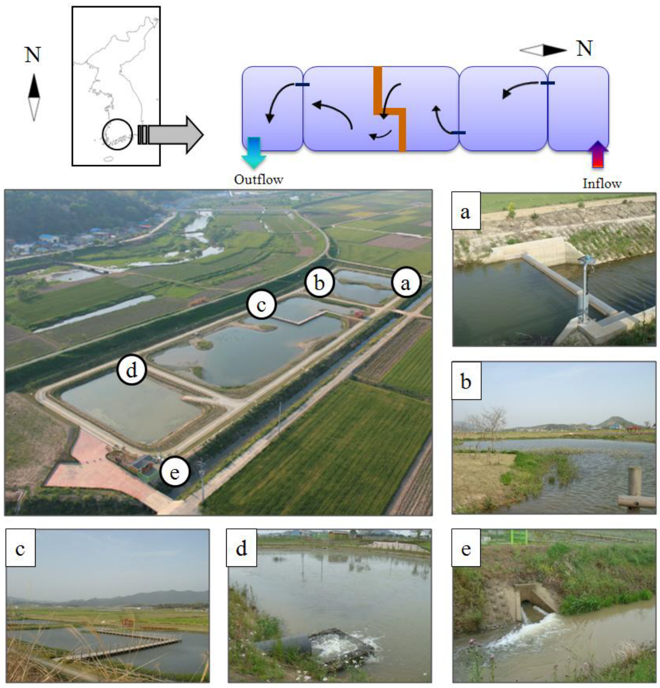

Figure 1: Representative pictures of Songchon constructed wetland (SCW) in spring 2011: (a) inflow point with movable weir and ultrasonic wave water gage; (b) 1st treatment process with vegetation; (c) site overview of 2nd treatment process and observation deck; (d) a culvert to connect each pond; (e) outflow point to the main drainage canal.

Field Experiment and Data Acquisition

Intensive field experiments during rainfall events were conducted for one year from January to December 2010. Total experiments were 19 times including two times for spring, eleven times for summer, five times for autumn, and one time for winter (Figure 2). All water samples were collected after the excessive rainfall and transported to the laboratory within six hours under 4°C. For this study, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total suspended solid (TSS) were measured by standard method (APHA, 1995) and other measuring methods used in general.

The flow rate was measured by electronic vortex flow meter installed in the inlet and outlet of SCW. The vortex flow meter is a product of Woojin Inc., Korea and basic principle of the vortex flow is von Karman Vortex shedding street theory. Precipitation was measured and automatically logged by stainless steel tipping bucket rain gage made by WEDEAN (Model number: WDR-205) and automatic logger installed in SCW. The accuracy of rain gage was validated by Korea Meteorological Administration (KMA).

Statistical approach

Analysis of variance test and t-test: In this study, analysis of variance (ANOVA) test and *t*-test was used to statistically identify the difference of mean for the meteorological parameters including rainfall depth, rainfall intensity, and ADDs and five water quality parameters including TSS, BOD, COD, TN, and TP. Three meteorological parameters are well-known as key factors in diffuse pollution. Also, five water quality parameters are key factors for management of diffuse pollution in Korea. In this study, meteorological parameters are used as grouping variables because they are independent variables during storm water runoff event.

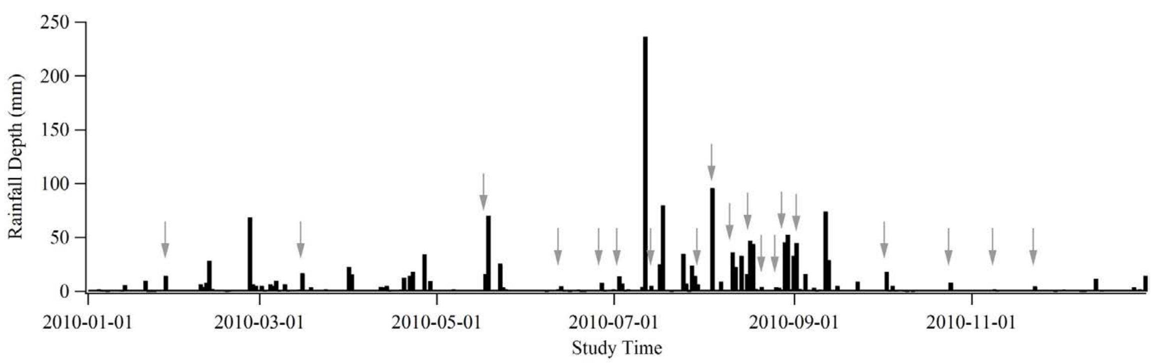

Figure 2: Daily rainfall depth data for a year from January to December, 2010. Horizontal axis indicates study time and vertical axis indicates rainfall depth. Gray arrows in the figure are monitoring events. (Data source from Korea Meteorological Administration).

Both methods finally provide the *p*-value which can be an objective criterion for whether there is difference between mean/variance of each group at the significance level.

Principal component analysis: Principal component analysis (PCA), as a nonparametric method of classification, can be defined as a linear combination of optimally-weighted observed variables. It is commonly used to condense a number of variables by eliminating relatively irrelevant variables, which means that some variables are correlated with other variables. Based on this reason, PCA provides reasonable information with minimum loss of original variables data [18]. In this study, PCA was used to identify whether the parameters related with rainfall conditions including ADD, rainfall intensity, and rainfall depth are reasonable. ANOVA test, *t*-test, and PCA were carried out using SPSS 17.0 for windows (IBM Corporation).

Ternary plot analysis

Ternary plot, as a barycentric plot on three variables which sum to a constant K, is widely used in chemical engineering, geology, and petrology as a practical method to illustrate the distribution of observed data concerning three compositional components. K should be 1 or 100. To set up the ternary plot, three variables which have representativeness in all variables of data should be selected by reasonable methods such as principal component analysis. Then, the variables selected should be normalized and transformed to make coordinates in the ternary plot. Finally, each coordinate will indicate the treatment performance of each storm event. In this study, ternary plot was performed using MATLAB R2009b.

Results

Treatment performance of SCW and meteorological conditions

The treatment performance of SCW was calculated by the method of pollutant load reduction for multiple tests of storm events with five water quality parameters such as TSS, BOD_5, COD, TN, and TP. Table 2 shows the information of the field experiment, meteorological conditions and the SCW treatment performance for 19 monitoring events. Mean removal efficiency of five water quality parameters is 30.1% for TSS, 37.8% for BOD, 44.4% for COD, 37.1% for TN, and 59.4% for TP. In the paired *t*-test results of five water quality parameters, except for the mean of TSS and TP, *p*-values are greater than 0.05 ($p>0.05$) when the significance level $\alpha=0.05$ (Table 3C). It can be explained that the removal efficiency in each water quality parameter do not have statistical difference at the significance level $\alpha=0.05$. This result implies that removal efficiency of each water quality parameter is independent except for TSS and TP.

ADDs has the range from 1 to 15 and analysis of variance (ANOVA) test results shows that ADDs between rainy season from June to August and non-rainy season from September to May was significant difference ($p<0.05$) at the significance level $\alpha=0.05$ (Table 3B). In case of rainfall depth and rainfall intensity, there is no significant difference between two seasons (summer and non-summer) ($p>0.05$).

Extraction of key variables

The PCA can explain the entire data set by eliminating the less important parameters with minimum loss of original information. To elucidate the suitability of treatment performance data set for factor analysis, Kaiser-Meyer-Olkin (KMO) and Bartlett test were conducted. KMO is a measure of sampling adequacy that indicates the proportion of variance. If KMO is close to 1, it means that factor analysis may be useful with data set. In the case of this study, KMO value shows 0.501 and this data is useful for the application of PCA (Table 4). Also, Bartlett test of sphericity means whether correlation matrix is an identity matrix, which world indicates that variables are unrelated. If significance level was less than 0.05, there are significance relationships

		Meteorological condition			Treatment Performance				
	Date	Dep. (mm)	Intensity (mm/hr)	ADDs (days)	TSS (%)	BOD (%)	COD (%)	TN (%)	TP (%)
1	01/20/2010	10.0	3.0	7.0	43.0	28.4	58.4	48.4	70.3
2	03/14/2010	16.0	3.5	3.0	54.2	52.9	57.9	48.3	64.4
3	05/17/2010	86.0	14.5	10.0	75.0	29.5	35.5	43.4	75.8
4	06/11/2010	4.5	1.0	3.0	38.2	-24.3	16.4	25.5	32.0
5	07/02/2010	30.5	20.3	1.0	10.7	39.9	26.4	35.0	63.0
6	07/13/2010	55.0	11.5	3.0	40.2	46.2	56.2	48.2	55.0
7	07/25/2010	12.5	30.0	1.0	48.6	-23.8	-35.2	19.1	55.7
8	07/28/2010	15.5	7.2	1.0	-2.0	2.5	43.4	56.8	-27.3
9	08/10/2010	53.0	2.7	3.0	37.7	72.8	69.1	83.1	74.3
10	08/15/2010	33.0	22.0	2.0	79.7	74.2	66.7	54.2	82.0
11	08/16/2010	30.5	8.5	1.0	76.1	80.1	82.1	45.6	91.3
12	08/26/2010	13.5	9.0	1.0	56.5	85.7	40.2	58.1	70.8
13	08/27/2010	1.5	1.0	1.0	-51.6	< -100	23.4	< -100	23.4
14	08/28/2010	40.5	11.5	1.0	25.1	83.4	62.1	-32.0	67.6
15	09/01/2010	46.0	21.0	1.0	87.7	86.3	74.9	76.8	94.2
16	10/02/2010	20.5	5.0	10.0	< -100	47.7	0.8	39.4	43.8
17	10/24/2010	8.5	1.5	15.0	-8.2	60.5	77.0	80.5	74.1
18	11/08/2010	2.0	1.0	15.0	< -100	79.0	-1.6	-5.8	13.8
19	11/22/2010	4.5	3.0	13.0	< -100	79.2	76.7	80.6	7.0
Mean		26.0	7.2	11.9	16.4	42.1	43.7	36.6	57.1
StDev		22.8	4.9	15.7	61.8	48.9	32.0	42.0	31.8

ADDs: Antecedent Dry Days
Dep.: Depth
StDev: Standard Deviation

Table 2: 19 Field experiment information and SCW treatment performance.

A. Group Statistics					
	Season	# of samples	Mean	Standard Dev.	
Rainfall depth	non-summer summer	8 11	24.19 26.36	28.55 18.38	
Rainfall intensity	non-summer summer	8 11	6.56 11.34	2.55 2.80	
ADDs	non-summer summer	8 11	9.25 1.64	1.86 0.28	
B. ANOVA test results					
		Rainfall depth	Rainfall intensity	ADDs	
p-value Mean Difference		0.853 -2.176	0.225 -4.774	0.004 7.614	
C. Paired *t*-test results (*p*-value)					
	TSS	BOD	COD	TN	TP
TSS		0.146	0.062	0.181	0.002
BOD			0.870	0.606	0.263
COD				0.494	0.215
TN					0.130
TP					

ADDs: Antecedent Dry Days

Table 3: Results of seasonal ANOVA test for three meteorological conditions.

Parameter	PC1	PC2	PC3
Rainfall Depth	**0.573**	0.288	0.419
Rainfall Duration	**0.765**	-0.064	0.244
Rainfall Intensity	-0.376	**0.694**	**0.501**
ADDs	-0.116	**-0.841**	0.170
Base Flow	**-0.909**	**0.826**	-0.227
TSS	0.581	**0.650**	-0.081
BOD	0.400	-0.379	**0.698**
COD	**0.868**	-0.204	-0.014
TN	0.178	-0.213	**0.822**
TP	**0.662**	0.197	0.402

ADDs: Antecedent Dry Days

Table 4: Rotated loading matrix by VARIMAX.

among variables which are the case of this study: significance level=0.000. Table 4 shows the loading matrix extracted PCs and water quality parameters described as NPS pollutants. The values in loading matrix have a range from -1, as a negative relationship, to 1 as a positive relationship. The loading matrix results showed that the eigenvalues of three principal components stand for 73.46% of the total variance (PC1 33.54%; PC2 26.74%; PC3 13.18%) of the observation based on the Kaiser criterion which means that eigenvalues is greater than 1 and assessment of scree plots. As shown in Figure 3, the treatment performance of SCW was interpreted as three components. Extraction method is principal component analysis and rotated method is Varimax with Kaiser normalization. The rotated PCs by Variamax rotation contain some parameters such as rainfall conditions. PC1 was related to two meteorological terms with rainfall duration (0.765) and rainfall depth (0.573). PC2 was related to two meteorological parameters with rainfall intensity (0.694) and ADDs (-0.841). PC3 was correlated with one meteorological parameter with rainfall intensity (0.501). Each PC has at least one factor related with the meteorological parameters. Based on the loadings about meteorological factors, rainfall duration for PC 1, ADDs for PC 2, and rainfall intensity for PC 2 were selected as the representative of meteorological parameter in each PC.

Ternary analysis

As shown in Figure 4, there are five 2-dimensional ternary plots to illustrate the treatment performance of the SCW and one data point plot to provide the meteorological information of each rainfall event. The three axes of the ternary plot in this research correspond to rainfall depth, rainfall intensity, and ADDs. On the color index, blue index indicates the low treatment performance and red index indicates the removal efficiency of each pollutant in SCW. Group A, B, and C means the predominant area for rainfall intensity, rainfall depth, and ADDs, respectively. Overall patterns for removal efficiency in SCW revealed that the relatively high rainfall intensity showed the low treatment performance in all parameters.

Group A and B showed the relatively low ADDs. In overall, the removal efficiency of Group A and B described as growing season (summer and early autumn) was reasonable than Group C described as the summer, autumn, and winter. The reason is assumed that the NPS pollutant removal function of SCW was increased by aquatic plants during growing season. In case of meteorological parameters, Group B, as the predominant area for rainfall depth, showed the most reasonable removal efficiency in BOD_5, COD, and TP, Group A, as the predominant area for rainfall intensity, indicated the relatively high removal efficiency for TSS and TN (Table 5). The characteristics of removal efficiency in each group can be summarized as follows.

- Group A: Summer (growing season), relatively high removal efficiency for TSS, BOD_5, and TN, dominant area for high rainfall intensity.
- Group B: Summer (growing season) and autumn, relatively

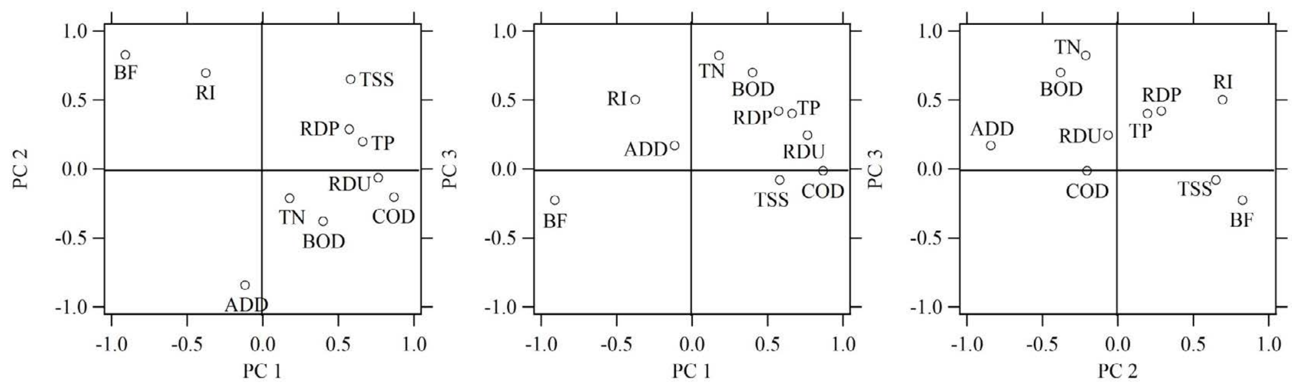

Figure 3: Rotated Loading Matrix obtained from the principal component analysis of SCW treatment performance data, in the PC1-PC2, PC1-PC3, and PC2-PC3 planes. ADD: Antecedent Dry Days, BF: Base Flow, RDP: Rainfall Depth, RDU: Rainfall Duration, RI: Rainfall Intensity.

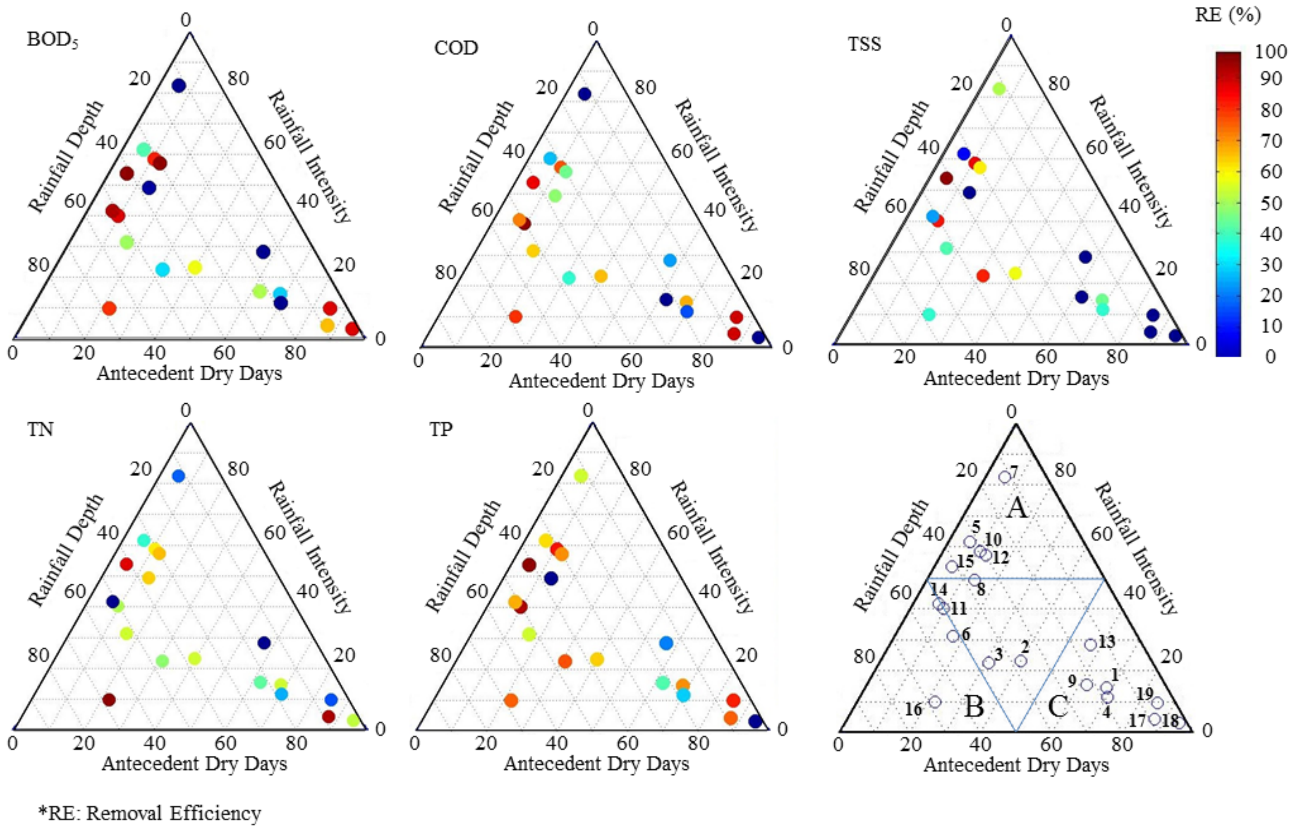

Figure 4: Ternary contour of Antecedent dry days-Rainfall depth-Rainfall intensity for five plots of water quality parameters and one plot of data points. On data point plot, the numbers are monitoring order. Color index indicates the removal efficiency of SCW.

Group	Season	Mean Removal Efficiency (%)				
		TSS	BOD_5	COD	TN	TP
A	Summer	46.85	44.15	36.06	50.00	56.38
B	Summer Autumn	10.36	64.34	50.32	25.27	64.42
C	Winter Autumn Summer	-20.12	27.94	45.61	28.98	49.85

Table 5: Mean removal efficiency of three groups in ternary plot.

high removal efficiency for COD and TP, dominant area for high rainfall depth.

- Group C: Winter, summer, and autumn, relatively low removal efficiency in TSS, BOD, and TP, dominant area for high ADDs.

Conclusion and Discussion

The water quality of streams or rivers surrounded in the agricultural area is exposed to be deteriorated during rainfall events and human activities because of massive discharge of NPS pollutants. To mitigate the negative impact of NPS pollution to the aquatic environment, SCW was operated and monitored from 2008. Data analysis from the field and laboratory experiments revealed that removal efficiency of SCW can be explained by meteorological parameters such as rainfall intensity, rainfall depth, and ADDs. The ternary contour plots show that the removal efficiency of SCW.

To generalize the treatment performance of BMPs is considerably difficult because of many factors affecting the removal mechanisms. This study was tried to apply the ternary plot using three meteorological variables extracted from PCA. On the ternary plot, there are three groups to explain the treatment performance of SCW. Each group has own physical meaning about meteorological conditions and seasonal characteristics. If NPS management area using the constructed wetland is located in the Group A, we can expect the relatively high removal efficiency for TSS, BOD_5, and TN. In the same concept, if TSS is target component, we can expect high removal efficiency when meteorological condition is Group A.

Of course, there is no doubt that 19 field monitoring are not enough to determine the exact factors and performance prediction in all constructed wetland. However, this study revealed that 1) rainfall characteristics such as ADD, rainfall intensity, and rainfall depth are obviously dependent factors and 2) seasonal characteristics related with hydrological aspects have potentially their own treatment performances. These results and phenomena can be applicable to develop the NPS discharge model and to elucidate the relationship between rainfall and storm water runoff using rain radar in a drainage area.

Acknowledgements

This research was supported by National Research Foundation of Korea (NRF-2012R1A6A3A03037921).

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