

## Characteristics and Fate of Stormwater Runoff Pollutants in Constructed Wetlands

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## 도시지역에 적용가능한 인공습지에서의 강우유출수 함유 오염물질의 거동과 특성

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(Received : 06 December 2016, Revised: 24 January 2017, Accepted: 24 January 2017)

### Abstract

Nonpoint source (NPS) pollution continues to degrade the water quality. NPS pollutants signals high concerns against a sustainable environment. Low impact development (LID) is the leading management practice which regulates and treats stormwater runoff especially in highly impervious urban areas. Constructed wetlands are known to have efficient removal capability of NPS pollutants. Likewise, these LID facilities were intended to maintain the predeveloped hydrologic regime through series of mechanisms such as particle settling, filtration, plant uptake, and etc. In this study, the objective was to investigate the characteristics, fate and treatment performance of the two in-campus constructed wetlands (SW1 and SW2) which were installed adjacent to impervious roads and parking lots to treat stormwater runoff. A total of 42 storm events were monitored starting from July 2010 until November 2015. Manual grab sampling was utilized at the inlet and outlet units of each LID facilities. Based on the results, the wetlands were found to be effective in reducing 37% and 41% of the total runoff volume and peak flows, respectively. Aside from this, outflow EMCs were generally lower than the inflow EMCs in most events suggesting that the two wetlands improved the water quality of stormwater runoff. The average removal efficiency of pollutants in facilities were 63~79% in TSS, 38~54% in TN, 54% in TP and 32%~81% in metals. The results of this study recommend the use of constructed wetlands as efficient treatment facility for urban areas for its satisfactory performance in runoff and pollutant reduction.

**Key words** : constructed wetlands, low impact development (LID), nonpoint source pollution (NPS), stormwater runoff

### 요약

도시지역은 인구가 집중되어 토지이용이 집약적이며 불투수면의 비율이 높아 강우시 비점오염에 의한 영향이 높은 지역이다. 비점오염원은 강우시 다양한 토지이용으로부터 발생되며 수계에 직접적인 영향을 미치고 오염물질의 종류와 양에 따라 불확실성이 높은 오염원이므로 점오염원과 함께 관리가 필요하다. 이러한 비점오염원을 관리하기 위한 방안으로 국내·외에서는 자연적인 기작을 이용한 비점오염원 관리기법인 저영향개발기법 (Low impact development, LID)을 도입하였으며 침투도랑, 식생체류지, 인공습지 등 다양한 요소기술이 포함된다. 이중 인공습지는 수질정화 (비점오염물질 저감)와 더불어 물을 저류하는 기능을 가진 친환경적인 시설로 잘 알려져 있다. 본 연구는 비점오염원 관리를 위한 LID 기술의 효과를 알아보기 위하여 수행되었으며 도시지역에 조성된 두 종류의 인공습지를 운영한 결과를 분석하고 평가하고자 한다. 연구대상 인공습지는 HSSF형과 Hybrid형으로 두 시설 모두 2010년에 조성되어 현재까지 운영 중에 있으며 본 논문에서는 2010년부터 2015년까지의 총 42회의 모니터링 결과를 이용하였다. 분석결과, 두 인공습지를 통해 강우유출유출량을 평균 37~41% 범위로 저감되었으며 오염물질별 저감효율의 경우 TSS는 63~79%, TN은 38~54%, TP는 54%, 중금속은 32~81% 범위로 나타나 도시지역내 인공습지 적용시 비점오염원 저감에 도움이 될 수 있을 것으로 판단된다.

**핵심용어** : 인공습지, LID, 비점오염, 강우유출

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## 1. Introduction

Urban stormwater runoff which contains pollutants was identified as one of the leading causes of degradation in the quality of receiving waters (Li et al., 2006; US EPA, 1998; Characklis and Wiesner, 1997). Highly urbanized areas such as residential, commercial, and industrial land uses which are 100% impervious are highly vulnerable to deterioration of water quality and incapable of infiltration to groundwater (Geronimo et al., 2012). Urban areas have various land uses where accumulated pollutants during the dry period and these pollutants are eventually washed off with the stormwater during the rainfall event (Kim et al., 2014; Son et al., 2008). Also, the other studies (Pitt et al., 1995; Sansalone and Buchberger, 1997; Abrishamchi et al., 2010), pollutants in stormwater runoff associated with transportation facilities are considered a major quality concern and efforts to characterize the runoff quality are in progress.

To address the concerns, the Ministry of Environment (MOE) in South Korea funded several projects related to the management of stormwater runoff. Therefore, low impact development (LID) technologies are introduced and currently applied to restore the natural water cycle and use techniques that effectively capture, infiltrate, filter, store, evaporate and detain runoff close to the source (PGC, 1999; Park et al., 2008). LID practices are beneficial because these can be integrated into infrastructures, cost-effective, and aesthetically pleasing than conventional systems. Most common practices in LID technology are bioretentions, rain gardens, grass wales, infiltration trenches, planter boxes and constructed wetlands. By implementing LID principles and practices, water can be managed in a way that reduces the impact of urban areas and promotes the natural movement of water within an ecosystem or watershed. Applied on a broad scale, LID can maintain or restore a watershed's hydrologic and ecological functions (US EPA, 2000).

Constructed wetlands (CWs), usually decentralized or secondary treatment systems, are small-scaled engineered systems utilizing wetland vegetation, soils, and microbial activities to treat contaminants in surface water, groundwater or water streams (ITRC, 2003). These are designed to emphasize specific characteristics of wetland ecosystems for improved treatment capacity. Treatment of pollutants in constructed wetlands is based on the biological and physical processes including adsorption, filtration, nitrification, particulate settling (presence of pretreatment tanks), and decomposition (Hoffman et al., 2011). There

are different types of constructed wetlands such as free water surface (FWS), horizontal subsurface flow (HSSF), vertical subsurface flow (VF) or hybrid wetlands. Each type of constructed wetlands differs in operations. In FWS wetlands, water flows through open water areas or vegetative areas with shallow depth of water. HSSF wetlands are filled with filter media within which water flows horizontally. Contrary to HSSF wetlands, water flows on the surface and subsequently percolates down through the filter media in VF wetlands. Combinations of various types of constructed wetlands are called hybrid wetlands which can be designed according to desired treatment efficiency.

According to a study by Ogata et al., (2015), constructed wetlands with a horizontal subsurface flow have higher pollutant removal efficiencies than FWS. On the other hand, hybrid constructed wetlands aim to achieve higher treatment performance. Urban areas with high infrastructure environment have led to limited spaces, in such a way; there is a need to manage stormwater. A constructed wetland is an applicable technique for stormwater management and protection of water quality and associated aquatic habitat. Therefore, this study aimed to investigate the characteristics and treatment performance of the two small constructed wetlands installed in an urbanized campus. Specifically, the study was conducted to determine the hydraulic, hydrologic, and water quality characteristics of stormwater runoff and pollutants conveyed from roads and parking lots entering the constructed wetlands. In addition, another goal of the study was to predict the runoff treatment efficiency of the wetlands from values obtained from storm events.

## 2. Materials and Methods

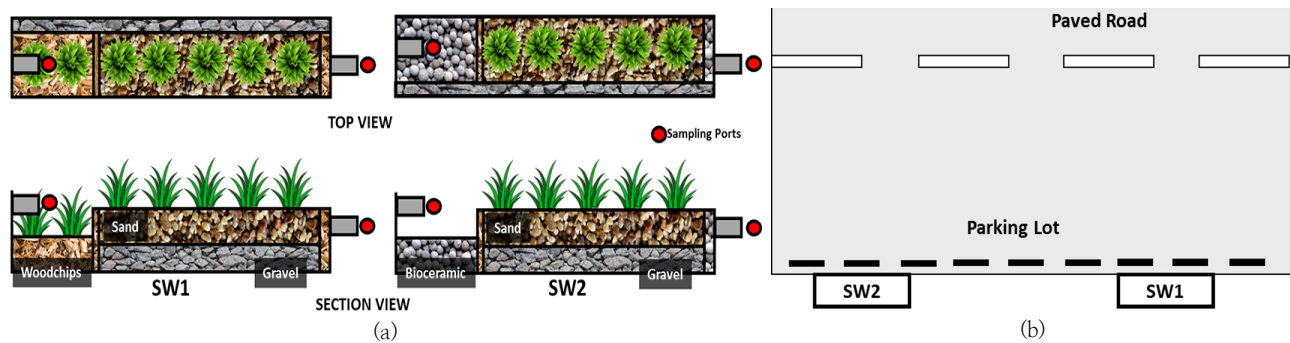
### 2.1 Physical Characteristics of Facilities

Two constructed wetlands were utilized in the study namely, the Small Hybrid Wetland (SW1) and Small HSSF Wetland (SW2). The facilities are located in Kongju National University in Cheonan City, South Chungcheong Province, South Korea. Fig. 1 shows the locations of SW1 and SW2 with roads and parking lots as land uses and catchment area for runoff sampling. The catchment areas are 323 m<sup>2</sup> and 424 m<sup>2</sup> for SW1 and SW2, respectively. SW1 has an aspect ratio of 1:0.2:0.1 (L: W: H) while 1:0.1:0.1 for SW2. The constructed wetlands were designed for a 5 mm rainfall. Table 1 summarizes the physical characteristics of the constructed wetlands in the campus.

The wetlands consist of pretreatment, plants and filter bed zone. The wetlands are capable of pre-treating the

**Table 1.** Physical characteristics of constructed wetlands

Facilities	Surface Area, m <sup>2</sup>	Catchment Area, m <sup>2</sup>	Storage Volume, m <sup>3</sup>	Total Volume, m <sup>3</sup>	SV/TV, m <sup>3</sup> /m <sup>3</sup>
Small Hybrid Wetland (SW1)	6.50	323	1.61	4.55	0.35
Small Horizontal Subsurface Flow Wetland (SW2)	7	424	1.56	4.91	0.32

**Fig. 1.** Physical characteristics of the constructed wetlands. (a) Schematic diagram of media compositions in the constructed wetlands, (b) Location of the constructed wetlands

runoff through the sedimentation tanks. Each sedimentation tank has a capacity of 0.61 m<sup>3</sup> (SW1) and 0.67 m<sup>3</sup> (SW2). The sedimentation tanks of both facilities have different media composition wherein SW1 has woodchips with plants on top while SW2 has bioceramics as filter media for sedimentation. The filter bed for each wetland was composed of compacted sand and gravel beddings. *Acorus calamus* (Russian iris) which were identified to as a hyper accumulator of some metals have good accumulation of heavy metals (Usman et al., 2012) were planted on both wetlands. SW1 has two vertical plates composed of woodchips for further treatment. Meanwhile, the first vertical plate placed before the filter bed of SW2 consists of woodchips and the second vertical plate placed after the filter bed consists of bioceramics. Fig. 1 provides a graphical summary of the location and media compositions of both wetlands.

## 2.2 Monitoring and Analysis of Samples

Manual grab sampling was done at the inflow and outflow ports of the wetland to effectively obtain the water quality and quantity of the runoff for every storm events. Six samples were collected from the initial runoff that flows through the system with a time interval of 0, 5, 10, 15, 30 and 60 minutes. Another six samples were collected with a 1 hour interval until the end of runoff. However, in cases where the events are short, sampling intervals are adjusted. Moreover, continuous flow measurements were manually performed and recorded in a 5-minute interval. The monitoring of storm events for both constructed wetlands has a total of 42 events, 26 for SW1 and 16 for SW2, which spanned from July 2010 to November 2015. Storm

events that produced outflows in the wetland were considered in order to prevent biased comparisons between the inflow and outflow samples. Hydrologic parameters such as rainfall, intensity, antecedent dry day (ADD) were monitored onsite. Water quality parameters such as total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and total heavy metals such as Cr, Fe, Ni, Cu, Zn, Cd and Pb were analyzed in accordance to the Standard Method for the Examination of Water and Wastewater.

Event mean concentration (EMC) which was used to quantify the pollutant concentrations is defined as the total mass load of a parameter divided by the total runoff volume discharged during storm events (Sansalone & Buchberger, 1997). Another means of the water quality analysis is determining the pollutant loading reduction which can be calculated by dividing the difference of the total inflow and outflow loads by the total inflow load (Maniquiz et al., 2010). Statistical analyses was done using SYSTAT 12 and accepting correlation values with  $r$  greater than 0.5 and  $p$  values less than 0.05.

## 3. Results and Discussion

### 3.1 Hydrologic and Hydraulic Characteristics of Monitored Events

Shown in Table 2 are the hydrologic and hydraulic characteristics of the monitored events in SW1 and SW2. Most hydrologic parameters attained high standard deviations along the five year monitoring period which incites varied characteristics in each storm event; thus allowing

**Table 2.** Statistical summary of selected monitored events (July 2010–November 2015)

Hydrologic Parameters		Minimum	Maximum	Mean	Median	SD*
Antecedent Dry Days, days	SW1	0.20	34.21	6.65	4.52	7.47
	SW2	0.20	20.70	5.89	4.21	5.35
Total Rainfall, mm	SW1	1.50	22.50	7.23	4.50	6.32
	SW2	1.00	33.00	9.16	5.00	9.57
Rainfall Duration, hr	SW1	0.87	12.25	3.39	2.27	2.66
	SW2	0.53	4.63	2.10	1.78	1.21
Average Rainfall Intensity, mm	SW1	0.55	16.42	3.19	1.56	3.93
	SW2	0.72	27.36	5.85	2.24	7.12
Hydraulic Characteristics						
Runoff Volume Reduction, %	SW1	2.45	96.23	39.11	35.71	27.46
	SW2	2.25	97.39	33.91	27.38	25.75
Average Flow Rate, m <sup>3</sup> /hr	SW1	0.04	6.70	0.85	0.39	1.31
	SW2	0.08	4.80	0.83	0.34	1.28
Peak Flow Reduction, %	SW1	3.85	89.84	43.98	38.95	26.14
	SW2	2.43	73.12	37.73	40.00	23.24
Hydraulic Retention Time, hr	SW1	0.03	3.68	0.69	0.29	0.97
	SW2	0.05	0.83	0.21	0.16	0.21

\* SD: Standard Deviation

unbiased analysis. Rainfall duration for both facilities occurred with an average of almost 3 hours.

The runoff volume reduction in SW1 attained an average of 39%. Similar reduction was also observed for SW2 at 34%. The median values of both facilities for volume reduction were slightly lower than the means (SW1: 39.11>35.71, SW2: 33.91>27.38). This indicates that the wetlands were capable of reducing the runoff more than the average values. Hydraulic retention time (HRT) in the facilities appeared to have averages of 41 and 13 mins for SW1 and SW2, respectively.

### 3.2 Event Mean Concentration and Correlations

Fig. 2 is a presentation of the inflow and outflow EMC of all monitored events in the wetlands. Comparing the box plots of inflow and outflow concentrations of each water quality parameters, most constituents had significant reductions. Specifically, the mean values of EMCs for each pollutant from both facilities were higher than the median which imposes that the pollutant concentration was generally lower in most of the storm events (Maniquiz, 2012).

Most of the pollutants had significant reductions for both facilities. 117.31±93.64 mg/L and 143.26±88.18 mg/L TSS inflow EMC was reduced to 48.40±52.95 mg/L and 47.78±31.92 mg/L in SW1 and SW2, respectively. COD inflow EMC was reduced from 114.57±84.74 mg/L to 72.08±64.99 mg/L (SW1) and 155.74±106.87 mg/L to 80.16±52.17 mg/L (SW2), which is lower compared to

TSS. Considering nutrients, 5.60±4.49 mg/L and 8.52±4.92 mg/L inflow EMCs of TN was reduced to outflow EMCs of 3.86±2.96 mg/L and 6.42±3.74 mg/L in SW1 and SW2, respectively. Meanwhile for TP, inflow EMCs were lowered from 0.42±0.53 mg/L to 0.33±0.30 mg/L in SW1 and 0.56±0.32 mg/L to 0.32±0.17 mg/L in SW2. Overall, TN and TP attained *r* values of 0.872 and 0.860 for SW1 and 0.804 and 0.681 in SW2 suggesting significant reduction between the inflow and outflow concentrations. Among the heavy metals, Fe attained the highest concentrations 10.59 mg/L and 11.19 mg/L in SW1 & SW2, respectively. Fe in SW1 has an inflow EMC of 3.19±2.53 mg/L and outflow EMC of 2.02±1.63 mg/L. However, Zn was the only pollutant found to have no significant reduction in SW1 (*r*<0.5, *p*=0.055). Inflow and outflow EMCs of all heavy metals in SW2 had significant differences (*r*>0.5, *p*<0.05). According to overall values of inflow and outflow EMCs, the inflow EMCs were higher the outflow EMCs indicating that the constructed wetlands were capable of efficiently improving the water quality of runoff.

Correlation was done in the study to determine which factors affect the amount of inflow EMC concentrations. ADD, rainfall amount, duration, and runoff volume were the hydrologic characteristics selected for correlation with pollutant EMCs. However, results showed that the pollutants were not significantly correlated with the hydrologic characteristics in both wetlands. Many studies have shown that a strong correlation exists between potential runoff impacts and storm characteristics, however, the low

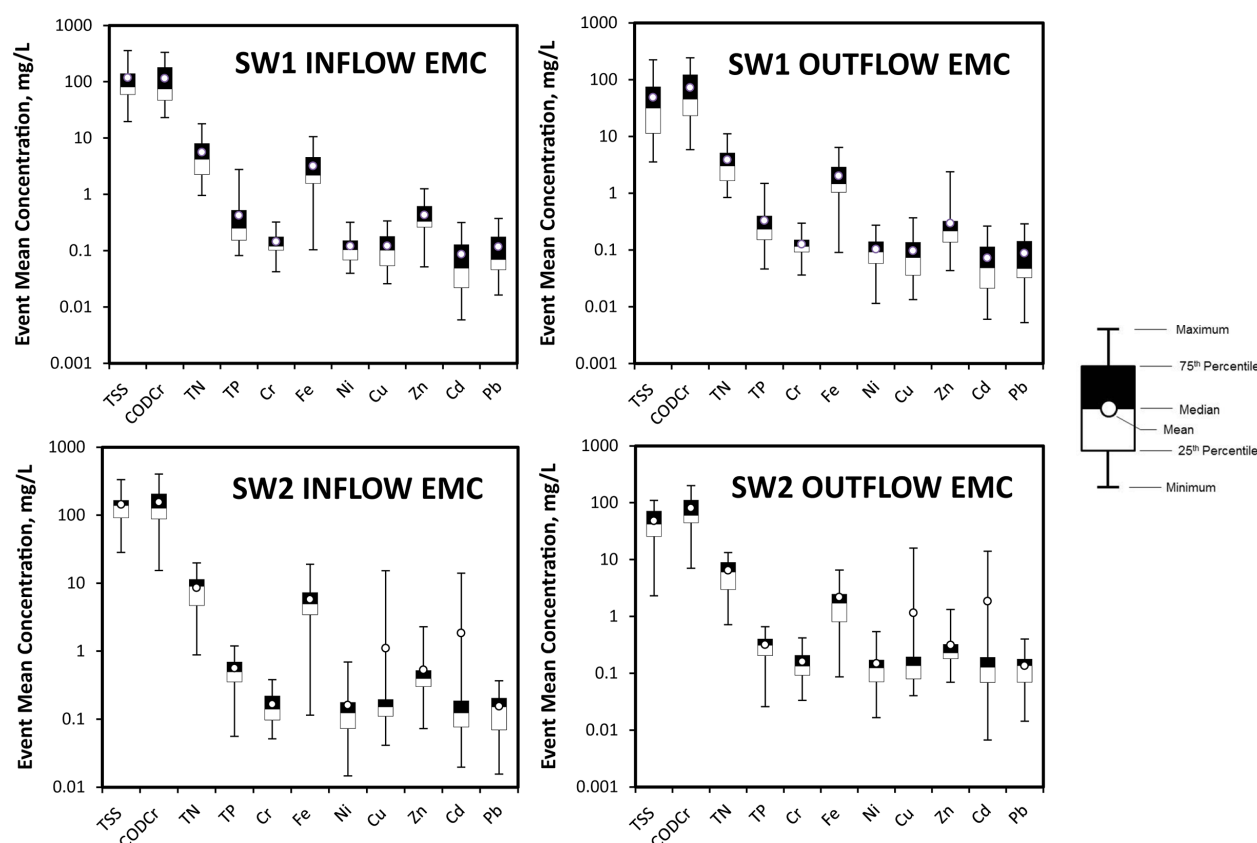


Fig. 2. Box-plot representation of inflow and outflow event mean concentrations for SW1 and SW2.

correlations suggest that not only monitoring parameters contribute to stormwater pollutants EMC but other factors should also be considered (Lee et al., 2011; Li et al., 2015).

### 3.3 Characteristics of Flow and Pollutant Concentrations during a Storm Event

Runoff flow rates and pollutograph for water quality constituents on April 27, 2014 are presented in Fig. 3 to show the variations during a storm event. 6.50 mm rainfall in a duration of 5.65 hours was recorded during this storm event. The peak flow was reduced by 12.5% (0.32 m<sup>3</sup>/hr to 0.28 m<sup>3</sup>/hr) which is due to the delay performed by the wetlands. Generally, the outflow in all storm events showed lower and delayed peak flows, thus establishing the capability of the wetlands to effectively delay and lower the volume and peak flows of the captured runoff.

As inflow was introduced to the facilities, high concentrations of pollutants for the first 30 minutes were observed which is known as first flush phenomenon. In all storm events, the pollutant concentrations were apparently high during the first flush. Initial concentrations of pollutants were high but gradually decreased as further introduced in the systems. Combined treatment mechanisms such as media adsorption and plant uptake can be credited to the decreasing trend

of pollutant concentration. The decrease takes place during the storm event which seemingly describes the roles of filter media and plants in the wetlands. Figure 4 displays the high concentration for TSS and COD as well as the other pollutants. Based on the study of Hranova (2006), significant amount of organics were particulate bound in nature.

It was observed that COD in runoff were in particulate form; therefore, it is correlated to TSS particulates ( $r=0.657$ ). Most pollutants positively correlate ( $r>0.5$ ) with TSS in both wetlands. Therefore, TSS particulates are insoluble pollutants which are considered adsorbents to other water quality constituents entering the wetlands. Thus, as shown in Fig. 3, the reduction trend of the other pollutants is similarly patterned to how TSS was reduced.

### 3.4 Pollutant Loadings Reduction

The TSS loading delta values are shown in Fig. 4. The shaded area represents the range of the expected values of retained pollutant loads. Each delta of a pollutant loading in a certain event was computed by obtaining the difference between the inflow and outflow loadings of pollutants. The percentage of flow retentions was arranged from lowest to highest values to consolidate and demonstrate the trend of deltas. TSS and COD constituents in the wetlands

exhibited increasing delta values as volume retention also increases. Due to nutrients and heavy metal concentration variability, the delta values have been stable in relation to

volume retention. The highest delta value for TSS was computed as 0.883 kg with 67.60% of runoff reduction. Similar delta values apparently appeared to be retained in

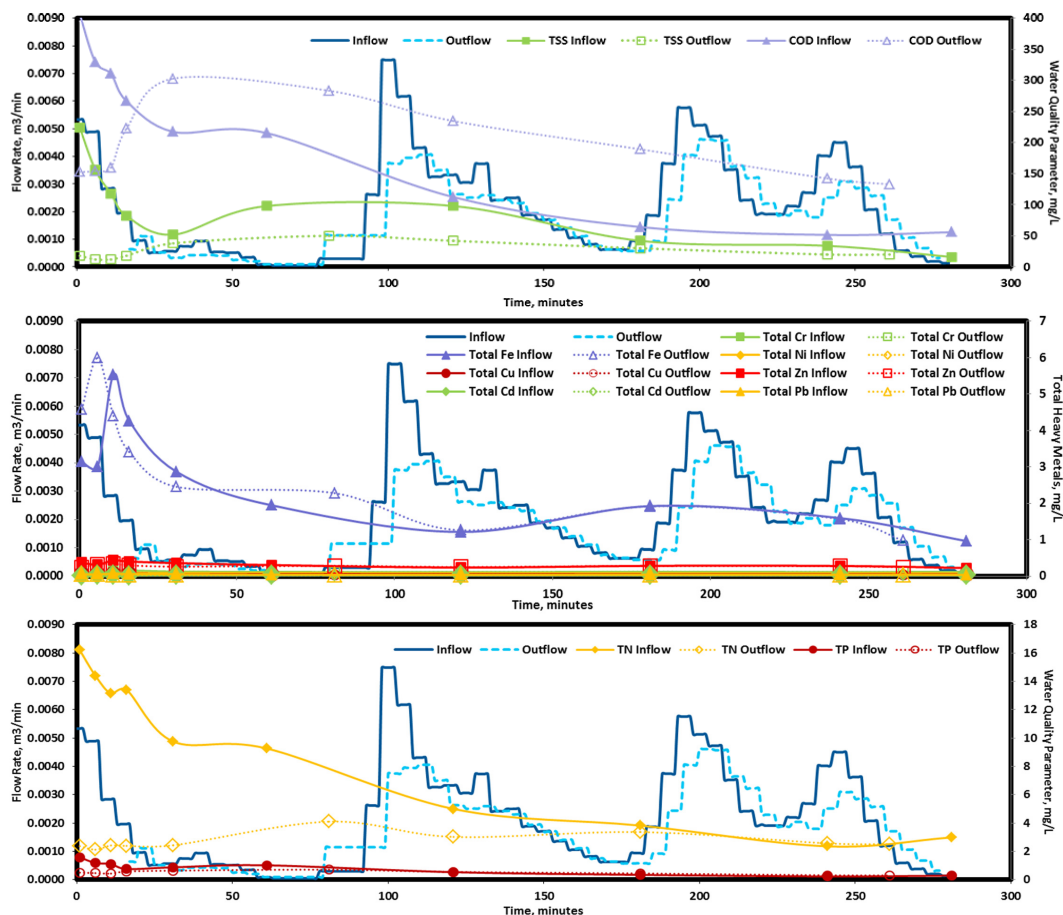


Fig. 3. Representative hydro-pollutographs

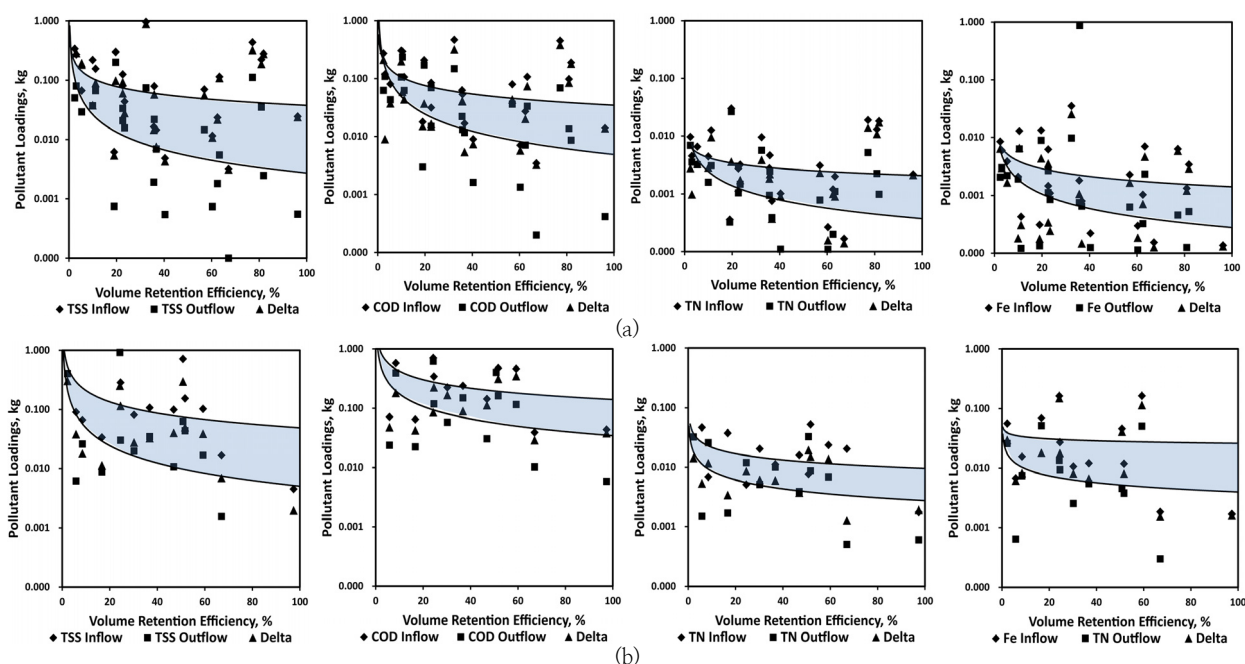


Fig. 4. Pollutant loadings of selected water quality parameters with respect to volume retention efficiency of (a) SW1 and (b) SW2.

the facility for COD and nutrients (TN & TP). Heavy metals showed least delta values ranging from  $1 \times 10^{-6}$  kg to  $7.05 \times 10^{-6}$  kg compared to other constituents. The constructed wetlands showed reductions of Fe loadings with maximum deltas of  $3.04 \times 10^{-6}$  kg (SW1) and  $7.05 \times 10^{-6}$  kg (SW2). Zn and Pb, likewise, had bigger deltas than other heavy metals. As a result, Fe, Zn, and Pb were also in particulate form when correlated with TSS ( $0.551 < r < 0.679$ ).

Effective pretreatment is necessary for HSSF wetlands wherein suspended solids that are not removed in a sedimentation tank are further subjected to removal by filtration (Cooper et al., 1996). SW1 and SW2 have accomplished adequate removal of TSS loads due to presence of sedimentation tanks and filter materials such as woodchips and bioceramic (SW1: 79%, SW2: 63%). According to Vymazal (2005), HSSF wetlands known to have insufficient oxygenation (incomplete nitrification of ammonia to nitrate) have resulted SW2 to reduce TN loads at 38%. SW1, a hybrid wetland, had a higher reduction of TN loads (54%) which emphasizes the advantage of combining two types of constructed wetlands. The wetlands exhibited the same significant TP load reductions at 68%. As for the heavy metals, there were no significant differences among the reduction efficiencies of metal loadings for a hybrid and HSSF wetland.

Fig. 5 shows the linear regression model of the rainfall and volume retention efficiency using five years of monitoring data of the constructed wetlands. The figure allows the determination of runoff retention efficiency through amount of precipitation which is useful for pollutant removal prediction. A 10.50 mm rainfall corresponded to 60% of runoff volume in SW1. And for that 60% volume

retention, using a logarithmic scale for Figure 5a, loading reduction of TSS has a range from 0.0045 to 0.058 kg. Thus, it is possible to predict the amount of pollutants that can be reduced in a certain amount of rainfall in the constructed wetlands. However, the reliability of predicting the loading reduction using the rainfall amount still depends on the different in situ characteristics of the catchment area. Future monitoring observations will strongly validate the efficiency of the model.

## 4. Conclusion

In this study, the behavior, relationship, characteristics and fate of pollutants in the runoff were described and their correlation with respect to the hydrologic-hydraulic characteristics was also determined. The study concluded that runoff volume and peak flow reductions can be fairly performed by the wetlands even without infiltration capabilities. Inflow EMCs were significantly higher than outflow EMCs which indicates the constructed wetlands were capable of efficiently improving the water quality of the inflow. Hydrologic characteristics, nevertheless, does not correlate with the water quality parameters. The low correlations suggest that not only monitoring parameters contribute to stormwater pollutants EMC, but other factors should also be considered. TSS loads reduction were adequately reduced but can be improved if the wetlands will undergo continuous maintenance and replacement of media. Nitrogen removal was limited in SW2 since HSSF wetlands are known to be less exposed to oxygen. Despite the long term monitoring, it was suggested that the constructed wetlands have varying performances but mostly effective in treating stormwater runoff. The results of this study recommend the use of constructed wetlands as efficient treatment facility for impervious areas for its satisfactory performance in runoff and pollutant reduction.

## Acknowledgment

This research was supported by a grant (E416-00020-0602-0) from Public Welfare Technology Development Program funded by Ministry of Environment of Korean government.

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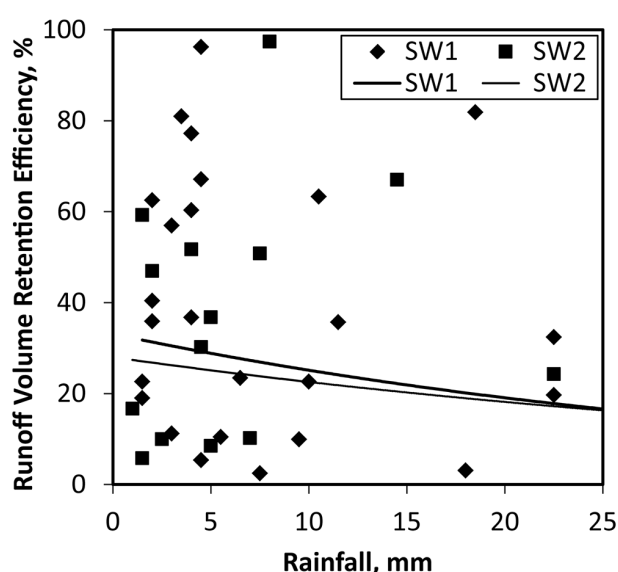


Fig. 5. Rainfall and volume retention efficiency of monitored events



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