Journal of Wetlands Research
Vol. 18, No. 4, November 2016, pp. 481-487
ISSN 1229-6031 (Print) / ISSN 2384-0056 (Online)
DOI http://dx.doi.org/10.17663/JWR.2016.18.4.481

Transport of nonpoint source pollutants and stormwater runoff in a hybrid rain garden system

Precious Eureka D. Flores · Marla C. Maniquiz-Redillas · Franz Kevin F. Geronimo · Jawara Christian P. Alihan · Lee-Hyung Kim†

Department of Civil and Environmental Engineering, Kongju National University

하이브리드 빗물정원 시스템에서의 비점오염물질 및 강우유출수 이송 특성

Precious Eureka D. Flores · Marla C. Maniquiz-Redillas · Franz Kevin F. Geronimo · Jawara Christian P. Alihan · 김이형†

공주대학교 공과대학 건설환경공학부

(Received : 04 November 2016, Revised: 15 November 2016, Accepted: 15 November 2016)

Abstract

In this research, a pilot scale hybrid rain garden system was developed in order to investigate the efficiency in the different components of the hybrid rain garden system and at the same time evaluate the initial efficiency of the system in treating urban stormwater runoff prior to its actual use in the field. Experimental runs were conducted using synthetic runoff having target concentrations similar to that of the typical runoff characteristics found in different countries and in Korea. With the employment of the hybrid rain garden system, hydrologic improvement was observed as the system demonstrates an approximately 95% reduction in the influent runoff volume with 80% retained in the system, and 15% recharged to groundwater. The reduction was contributed by the retention capabilities of ST and infiltration capabilities in PB and IT. With the combined mechanisms such as filtration-infiltration, biological uptake from plants and soil and phytoremediation that are incorporated in PB and IT, the system effectively reduces the amount of pollutant concentration wherein the initial mean removal efficiency for TSS is 87%, while an approximate mean removal efficiency of 76%, 46% and 56% was observed in terms of organics, nutrients and heavy metal, respectively. With these findings, the research helps in the further improvement, innovation and optimization of rain garden systems and other facilities as well.

Key words : low impact development, pollutants, rain garden, runoff

요 약

본 연구는 도시 강우유출수 처리를 위한 하이브리드 빗물정원 시스템을 개발하고자 수행되었으며, Pilot scale 모니터링을 통하여 시스템 내의 서로 다른 구성요소간의 효율을 검증하였다. 유입수는 국내·외 도로강우유출수의 농도를 고려한 인공강우유출수를 이용하여 수행하였다. 모니터링 결과 하이브리드 빗물정원은 시설 내 저류 80%, 지하수의 침투 15%로 유입수의 약 95% 저감되는 것으로 나타났다. 이는 ST의 저류 및 PB와 IT의 침투 기작이 물순환 효과에 기여한 것으로 판단된다. 또한 오염물질 저감효율을 산정한 결과, TSS의 경우 평균 87%으로 나타났으며, 유기물은 76%, 영양염류는 46%, 중금속은 56%으로 나타났다. 이는 PB와 IT에 포함된 여재의 여과, 침투 및 식생과 토양의 생물학적 흡수 기작 영향에 의해 나타난 결과로 판단된다. 이러한 연구 결과는 향후 빗물정원의 효율을 향상시키기 위한 시설의 개선 및 설계방안으로 활용 가능할 것으로 평가된다.

핵심용어 : 저영향개발, 오염물질, 빗물정원, 강우유출수

1. Introduction

Urbanization is the changing of land use from forest or agricultural uses to suburban and urban areas. It is the increase in disturbance of natural landscapes due to urban expansion which in turn affects water resources and water quality (US EPA, 2015). Mostly, highly urbanized areas comprising of transportation, commercial, residential and industrial land uses were 100% impervious, thus preventing the stormwater to naturally infiltrate into the ground

† To whom correspondence should be addressed.
Department of Civil and Environmental Engineering, Kongju National University
E-mail: leehyung@kongju.ac.kr

(Geronimo et al., 2013). Furthermore, the development of these surfaces increases runoff while deteriorating the water resources in highly urbanized areas (Walsh, 2004). Typically, urbanized areas experience high pollutant mass emission during storm events coming from unknown or diffused sources also termed as non-point (NPS). Nonpoint source pollution from stormwater runoff contributes pollutants altering the water quality in receiving water (Pitt et al., 2004). NPS pollution originates from soil erosion, accumulation and atmospheric dust, street dirt, fertilizers and pesticides wash-off (Sun and Davis, 2006). NPS pollution includes constituents such as particulates, organics, nutrients and heavy metals were being carried by sediments from these areas.

In response to the growing effects of urban development and NPS pollution to stormwater runoff, the Korean government considered integrating and linking both the ecosystem and landscape planning and development termed as low impact development (LID) strategies. Low impact development (LID) technology is an improved approach that allows the full development of areas while maintaining the essential hydrologic functions of the site while providing social and ecosystem benefits (Prince George's County, 1999). Furthermore, LID provides economic sustainability by providing less costly practices and technologies and is designed to restore and mimic the pre-developed hydrology by reducing runoff using infiltration, evapotranspiration or stormwater reuse (Dietz, 2007; Flynn and Traver, 2013). There are numerous practices that have been used in LID such as rain garden facilities, infiltration trench, wetland, vegetated swales, etc. Rain garden which is commonly termed as bioretention or biofilters are considered as the most widely implemented stormwater management practice in most of the countries during the recent years. Furthermore, rain garden systems are employed to highly urbanized land uses due to its capacity to obtain numerous stormwater management objectives. Rain gardens are used to efficiently capture runoff, promote infiltration, evapotranspiration, recharge groundwater, protect stream channels, reduce peak flow and reduce perennial stands, planted on a variety of medium configurations. Several studies have been conducted in order to examine and prove the pollutant removal efficiencies of rain garden systems. According to Trowsdale and Simcock (2010), rain garden systems generally report high removal of sediments, heavy metals and phosphorus from synthetic stormwater. Furthermore, the removal of nitrogen, particularly nitrate has been found to be fitful (Hatt et al., 2007; Henderson et al., 2007). As stated in Davis et al (2006), the rain garden system demonstrated a good removal ranging from 55-80% for the Total Kjeldahl Nitrogen (TKN) and ammonia (NH3). For the Total Phosphorus removal, the system can reduce from 55-85% as stated in the study of Hsieh et al., 2007. Finally a very high (>90%) reduction in heavy metal concentrations has been demonstrated by several laboratory studies (Bratieres et al., 2008; Hatt et al., 2007; Sun and Davis, 2007). Therefore, the objective of this research is to investigate the efficiency in the different components of the hybrid rain garden system and evaluate the initial efficiency of the system before its actual use in the field.

2. Materials and Methods

2.1 Description of the hybrid rain garden system

According to Geronimo et al., 2013, hybrid is the integration of several functions and incorporating them into one treatment system. A pilot scale hybrid rain garden system shown in Figure 1 was developed to provide opportunities to study the LID hydrologic and water quality performance. Table 1 shows the physical characteristics of each component of the hybrid rain garden system. The system has a storage volume of 0.2025 m^3 and a design rainfall of 14 mm. In addition, the system has an SA/CA ratio and hydraulic loading rate of 0.0081 and 0.0049 m/s, respectively. The system having dimensions (L x W x H) of 1.8 m x 0.5 m x 0.5 m were comprised of three tanks and connected in series. The sedimentation tank, where the runoff initially flows and serves as a pre-treatment had a relative storage volume of 49.4%. When the runoff exceeds the capacity of the sedimentation tank, it flows to the plant bed which is 39.5 % of total volume. The plant bed (PB) has a 16 cm depth of soil as filter media and a total of 10 plants which can be classified into two kinds of shrubs namely, *Chrysanthemum zawadskii var. latibolum* and *Aquilegia flabellate var. Pumila*. Before the runoff was discharged through the system, it flows through the infiltration tank (IT) having a relative storage volume equivalent to 11.1% of the total volume. The infiltration tank has a 15 cm depth of gravel. Both the plant and infiltration tank incorporates treatment mechanisms such as filtration-infiltration, biological uptake by plants and soil, evapotranspiration, bioremediation, phytoremediation as well as CO_2 reduction. Moreover, both PB and IT used geotextile which was used to hold the media and to reduce possible contamination of the in-situ soil surrounding the developed system.

Table 1. Characteristics of each component of the hybrid rain garden system

Parameter	Unit	Component		
		Sedimentation Tank (ST)	Plant Bed (PB)	Infiltration Tank (IT)
Surface Area	m^2	0.25 (28%)	0.5 (56%)	0.15 (17%)
Storage Volume	m^3	0.1 (49%)	0.08 (40%)	0.0225 (11%)
Total Volume	m^3	0.125 (34%)	0.2 (54%)	0.045 (12%)
SV/TV	%	80	40	50
Vegetation	-	N/A	Chrysanthemum zawadskii var. latibolum Aquilegia flabellata var. Pumila	N/A
Filter media	-	N/A	Soil	Gravel
Others	-	N/A	geotextile	geotextile

Values in parentheses are the relative percentage of ST, PB and IT with respect to the whole system.

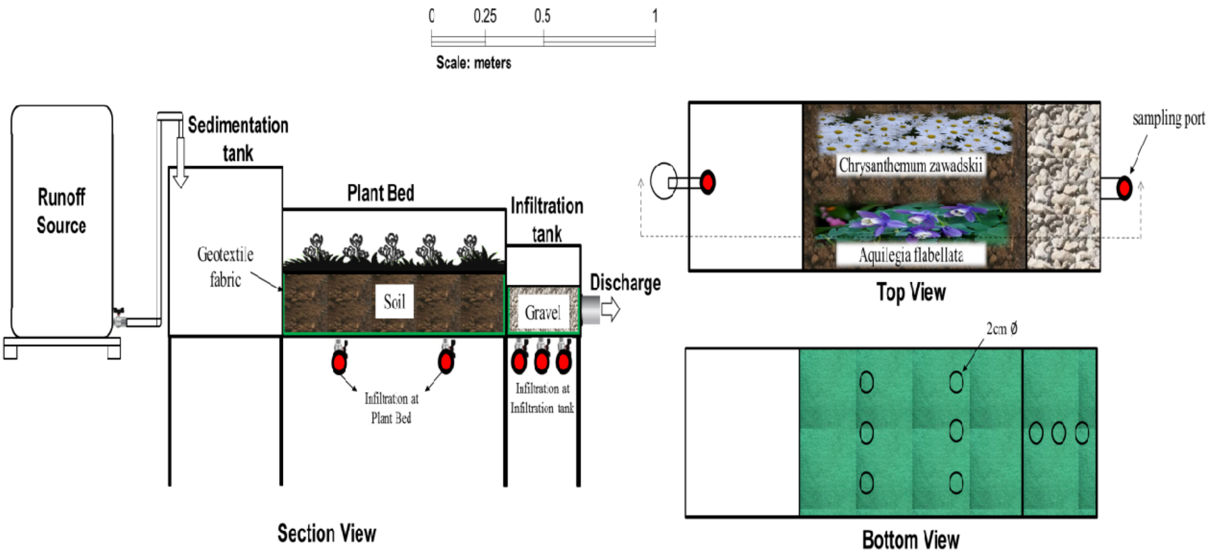

Fig. 1. Schematic diagram of the hybrid rain garden system.

2.2 Experimental scenarios

The synthetic influent was prepared in a tank using the sediments collected in highway with total suspended solids (TSS) concentration ranging from 75 to 300 mg/L that passed through the No. 100. The sediments and the concentration that were used represent the actual suspended solids found in various land uses (Mercado et al., 2012). In addition the synthetic influent was prepared by diluting one to two kilograms of sieved sediments in 2.0 m^3 of tap water. Before the influent was supplied to the system, the runoff was consistently stirred in the tank and still undergoes the same process during the whole experiment period. The influent was supplied through a 2.0 cm diameter pipe connected from the runoff source with a pump to help in the production of influent the same condition as the actual flow of runoff during storm events. The flow rate in the inflow (IN), outflow (OUT), and infiltration (I-PB and I-IT) was checked and measured every five minutes by measuring the volume over time, the same way an actual LID facility is monitored during rainfall events.

2.3 Water sampling and analyses

A total of three experiments were conducted to initially test the efficiency of the hybrid rian garden system. Water samples were collected in the I-RG and I-IT in the same procedure as the inflow and outflow in order to determine the quality of the water that will infiltrate the groundwater for recharge. The average duration of each experiment is approximately two hours. The samples were obtained with an interval of 0, 5, 10, 15, 30, 60 minutes and will extend in the end of runoff, with the first 60 minutes corresponding to the "*first flush phenomenon*" of an actual storm event (Jung et al., 2008). Hydrologic parameters were manually obtained during the experimental runs. On the other hand, water quality parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (TN), phosphorus (TP) and heavy metal such as Total chromium (Cr), Total iron (Fe), Total nickel (Ni), Total lead (Pb), Total copper (Cu), Total cadmium (Cd) and Total zinc (Zn) were analyzed based on the Standard Test Methods for the Examination of Water and Wastewater (2012).

3. Results and Discussion

3.1 Characteristics of stormwater runoff

Figure 2 shows the representative cumulative runoff volume and pollutograph during the experimental run. TSS concentration at the inflow ranged between 150-350 mg/L, while COD and TN ranged from 100-200 mg/L and 3.0-4.0 mg/L, respectively. Heavy metals such as Cr, Fe, Ni, Cu, Zn, Cd and Pb ranged between 0.02-0.04 mg/L, 0.05-0.2 mg/L, 0.01-0.02 mg/L, 0.02-0.07 mg/L, 0.3-0.8 mg/L, 0.009-0.01 mg/L and 0.03-0.04 mg/L, respectively. In terms of runoff, the cumulative volume that was employed ranged from 1000 to 2000 L. The study found that most pollutants are indirectly proportional to the runoff volume wherein, as the stormwater runoff volume increases, the inflow pollutant concentration decreases. Pollutants tend to reduce over time since the initial concentration has already been wash-off on the first hour of runoff. The figure also shows TSS concentration has similar trend as most of the pollutants in which can be said that TSS is a limiting factor in reducing pollutants and is considered to be an important insoluble pollutant among other water quality parameters since pollutants are known to be adsorbed in these particles. However, different observation was noticed in the behavior of TN since the production of the said pollutant is directly proportional, which means that the amount of TN concentration increases over time.

3.2 Hydrologic conditions of the hybrid rain garden system

Shown in Table 2 is the event table for each experimental run conducted in the hybrid rain garden system. The conditions in each component were also stated in the table with Figure 3 showing the trend of the average runoff volume and flow rate in the hybrid rain garden system as a whole. Furthermore, the graph of the time before infiltration and hydraulic retention time shows the difference between each component. During the experimental run, a sequence of high and sharp values of peak flows and volumes were observed in the inflow. However, as the runoff pass through the system, the values decreased which was caused by the reduction in the peak flows and volume. The mean inflow volume was 23420 L, with a standard deviation of ±8000

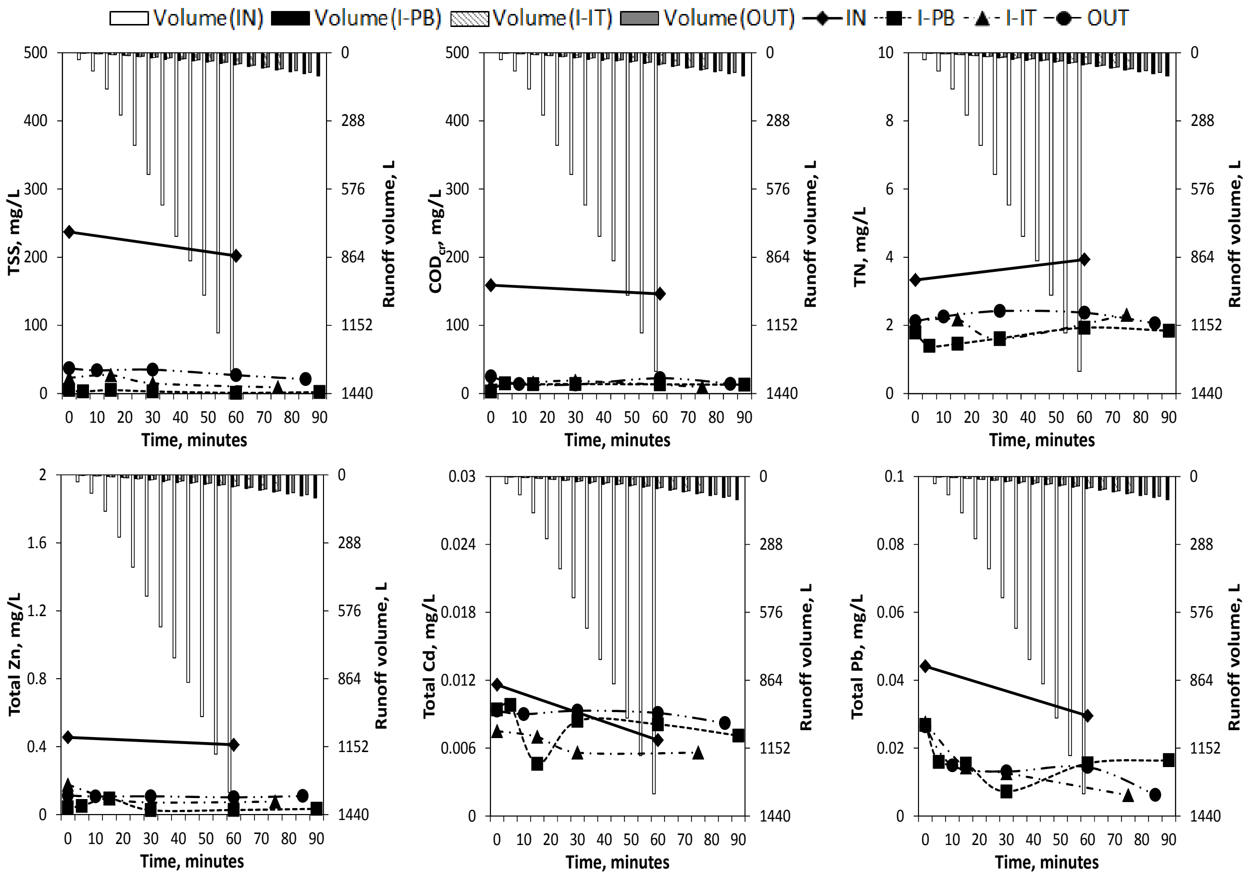

Fig. 2. Representative pollutograph for each experimental run with corresponding cumulative volume.

Table 2. Event table of each experimental run

Component	Parameter	Unit	1st Run	2nd Run	3rd Run	Average
	ADD	Days	6	7	2	5
IN	Volume	m^3	34.2	20.79	15.27	23.42
	Flow rate	m^3/min	0.2533	0.2772	0.2545	0.2620
PB	Flow rate	m^3/min	0.0233	0.0180	0.0137	0.0180
	Time before infiltration	min	14	18	28	20
	HRT	min	n/a	15	13	14
	Flow rate	m^3/min	n/a	0.0119	0.0121	0.012
IT	Time before infiltration	min	n/a	34	36	35
	HRT	min	n/a	31	27	29
	Volume	m^3	n/a	1.11	1.05	1.08
	Flow rate	m^3/min	n/a	0.0185	0.0123	0.0150
OUT	HRT	min	n/a	35	33	34
	Flow rate	m^3/min	n/a	0.0185	0.0123	0.0154
	Volume	m^3	n/a	1.11	1.0455	1.0778

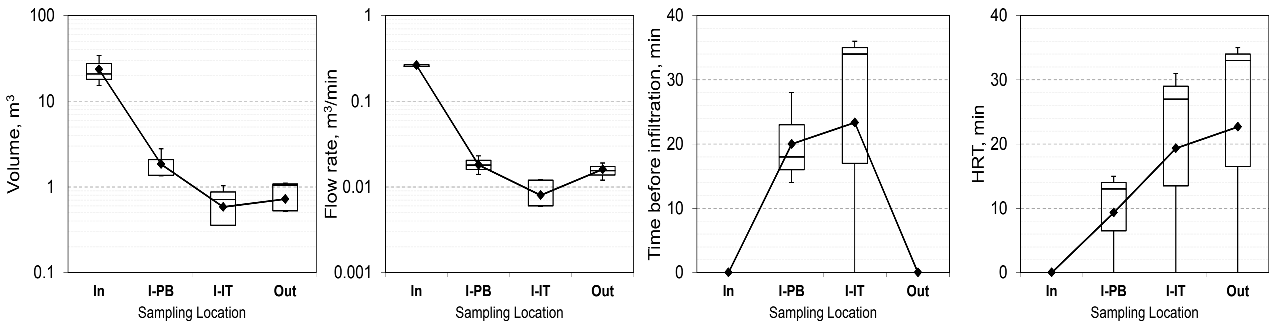

Fig. 3. Hydraulic and hydrologic conditions in the hybrid rain garden system.

L. It was observed that approximately 80% was retained in the system with 15% recharged to groundwater and only 5% of outflow generated after passing through the system. The findings suggest that incorporating different components and having infiltration functions, is an effective tool in the reduction of runoff in a highly impervious surface.

One of the main goals of the rain garden is to demonstrate a delay and change in frequency of runoff and peak flows and a delay in time which was observed in the hybrid rain garden system. In the study, the system which was designed to hold as much runoff as possible for retention, reduction and treatment of runoff and peak flows has a mean hydraulic retention (HRT) of 34 minutes. HRT is dependent on rainfall duration and average intensity, wherein an increase in rainfall duration or a decrease in average rainfall intensity corresponds to an increase in HRT (Geronimo et al., 2013). As shown in Figure 3, a decrease in flow rate with an approximate value of 94% was observed after the runoff passed through the system. The observed mean percentage of infiltration in the combined infiltration in the plant bed and infiltration tank suggest the installation of infiltration pipes are needed in order to optimize and improve the capability of the hybrid rain garden system.

3.3 Pollutant Concentration in the hybrid rain garden system

According to Maniquiz et al., 2010, event mean concentration (EMC) is one of the critical and commonly used factors in estimating the pollutant removal efficiency of a treatment system. The average EMC at the inflow (IN), infiltration at plant bed (I-PB), infiltration at the infiltration tank (I-IT) and outflow (OUT) of the hybrid rain garden system was exhibited in Figure 4. The TSS concentration showed to have decreased as the runoff passed through the different components of the system wherein the mean inflow concentration of 236 mg/L was reduced to 3.78 mg/L in I-PB with a slight increase in I-IT of 22.97 mg/L. The increase in concentration in I-IT was due to the transport of soil medium from PB to IT. Still, the system showed an overall TSS reduction of approximately 90% indicating that the sedimentation tank helps in the reduction of particulate matter prior to the entrance of runoff in PB.

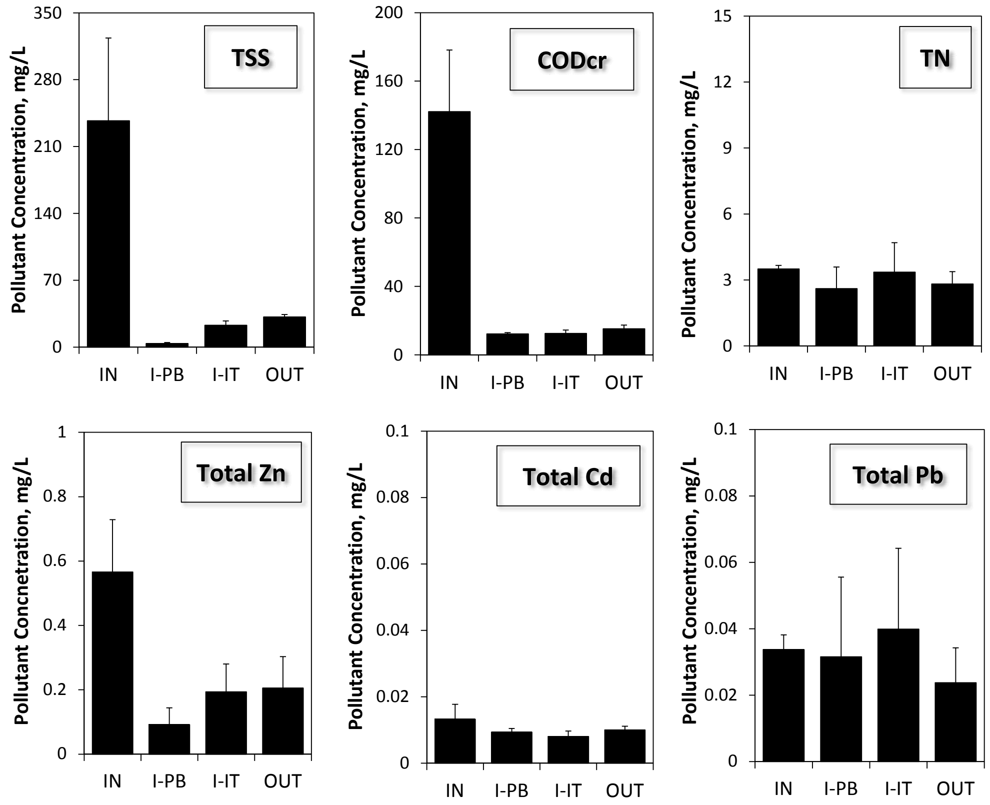

Fig. 4. Average EMC in the inflow and outflow of the hybrid rain garden system.

Furthermore, the media incorporated in both PB and IT helps in the filtration of smaller particles which in turn reduces the concentration of particulate matter in the runoff that goes through the groundwater fro recharge. For the organics (COD), the concentration of 142 mg/L was reduced to 12.17 and 12.514 mg/L for PB and RG, respectively. Soluble heavy metals showed an average initial concentration of 0.034 mg/L which was reduced to 0.023 mg/L in I-PB and 0.020 mg/L in I-IT. In addition to this, the total heavy metal showed has an initial concentration of 0.855 mg/L which was reduced to 0.153 mg/L and 0.265 mg/L for I-PB and I-IT, respectively. Overall, the system effectively reduces the concentration of pollutants as it pass through the different parts of the system. TSS concentration was reduced by an approximately 87% after the inflow passed through the hybrid rain garden system. Same observation was detected in the BOD and COD concentration which was reduced by approximately 89% and 63%, respectively. As for the nutrient concentration such as TN and TP, the inflow was reduced by 19% and 74%, respectively. Heavy metal constituents like Cr, Fe, Ni, Cu, Zn, Cd and Pb, the inflow concentration was adequately reduced up to an approximate percentage of 65%, 40%, 87%, 72%, 64%, 27% and 35%, respectively.

4. Conclusion

Urbanization has been continuously affecting the quality of surface waters due to the increase in disturbance of natural landscapes caused by urban expansion and in order to reduce these effects, LID technologies were developed to preserve the natural hydrologic cycle. In this research, investigation on the efficiency of the hybrid rain garden system as a whole and the initial efficiency of its components were determined and the major findings are as follows:

- The system aims to mimic the behavior of the actual system to test the overall efficiency and performance in managing stormwater runoff as well as pollutant concentration and to optimize the design before its possible on-site application.
- The system showed a decrease in runoff volume of approximately 94%, indicating that incorporating various LID technologies into one can greatly help in the reduction of stormwater runoff.
- Installation of pre-treatment in the system helps in the reduction of the concentration of particulate matter which in turn also reduces other pollutants as well.
- In constructing LID facilities, having infiltration functions is needed for the improved volume reduction

and increased groundwater recharge.
- The results and findings of this research will help improve the efficiency and applicability of hybrid rain garden system prior to its actual use in the field.

Acknowledgement

The funding for this research was financially supported by a grant (14CTAP-C086804-01) from the Technology Advancement Research Program funded by the Ministry of Land, Infrastructure and Transport in Korea. The authors were grateful for their support.

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