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Determination on the component arrangement of a hybrid rain garden system for effective stormwater runoff treatment

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강우유출수 처리를 위한 하이브리드 빗물정원 시스템의 구성요소 배열 연구

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Abstract

Low impact development (LID) technology has been recently applied for the treatment of nonpoint source pollutants. Rain garden is one of the widely used LIDs since it utilizes various mechanisms such as biological and physico-chemical treatment to reduce pollutants. However, problem such as clogging has been one of the issues encountered by the rain garden that do not undergo constant maintenance. Therefore, this research was conducted to develop and determine the component arrangement of a rain garden system for a more efficient volume and pollutant reduction. Two hybrid rain garden systems having different characteristics were developed and evaluated to determine the optimum design and arrangement of the system. The results showed that the components arranged in a series manner showed a volume reduction of 93% and a pollutant reduction efficiency of approximately 99%, 93% and 95% was observed for particulates, nutrients and heavy metals, respectively. While when the system is connected in a combined series-parallel, the volume and average pollutant reduction efficiency for the TSS, nutrients and heavy metals are 65%, 94%, 80% and 85%, respectively. Moreover, the component arrangement in the order of sedimentation tank, infiltration tank and plant bed exhibited a high pollutant reduction efficiency compared when the infiltration tank and plant bed were interchanged. The findings of this research will help in the further development and optimization of rain garden systems.

Key words : hybrid system, low impact development, nonpoint source, rain garden, urban stormwater runoff

요 약

최근 비점오염물질 처리를 위하여 저영향개발(low impact development) 기술이 적용되고 있으며, 레인가든 기술은 생물학적 및 물리화학적 처리에 의하여 비점오염물질 저감에 기여하기에 광범위하게 적용되고 있는 LID 기술 중 하나이다. 그러나 유지관리를 지속적으로 수행하지 않아 시설 내 막힘 현상 등의 문제가 발생한다. 따라서 본 연구는 효율적인 물수지 및 오염물질 저감을 위해 레인가든 기술의 구성 요소 배치의 개발 및 평가를 위하여 수행하였으며, 서로 다른 2개의 하이브리드 레인가든 시스템 구축을 통하여 시스템의 최적화된 설계 및 구성요소의 배열을 도출하였다. 분석 결과, 시스템의 구성요소를 직렬로 배열 시 저감량은 유출량의 경우 96%, 오염물질 중 입자상 물질은 99%, 유기물질은 93% 및 중금속은 95%로 나타났다. 반면 시스템이 병렬로 배열 될 시, 유출량은 65% 저감되었으며, 평균 오염물질 저감효율은 TSS는 94%, 영양물질은 80% 및 중금속은 85%으로 평가되었다. 또한, 시스템의 구성요소가 비점오염물질 저감에는 침전, 침투도랑 및 식재부의 순서가 중요한 영향인자로 나타났다. 향후 레인가든 시스템 개발 시 최적화 설계 인자로 활용 가능할 것으로 기대된다.

핵심용어 : 하이브리드 시스템, 저영향개발, 비점오염원, 레인가든, 도시 강우유출수

1. Introduction

Climate change, also termed as global warming, is the rise in average surface temperatures on Earth. The phenomenon is a change in the measures of climate lasting for an extended period of time. In addition, climate change includes major changes in temperature, precipitation and wind patterns that occur over several decades or longer. Floods and droughts are some of the main impacts of climate change wherein it affects water availability and surface water

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quality (Delpla et al., 2009). However, climate change is not the only factor affecting water quality degradation. Urbanization, the change from forest or agricultural uses to suburban and urban areas, also contribute in the alteration of not only the water quality but of the natural hydrologic cycle as well (Hamel et al., 2013; US EPA, 1999). Recent studies have determined the effect of climate change on water quality and some are the following: occurrence of milder winter, which results to longer growing season and increased evapotranspiration (Murdoch et al., 2000; Mcknight et al., 1996; Cushing, 1997). It was predicted that an increase in evapotranspiration rate results in lower streamflow, declining lake levels, shrinking wetlands and decreased rates of groundwater recharge (Schindler, 1997; Magnuson et al., 1997; Poiani et al., 1995; Poiani and Johnson, 1991). While in other parts, other countries experience an increase in runoff due to the increase in precipitation caused by climate change and urbanization (Mulholland et al., 1997; Justice et al., 1996). In addition, urban areas experience high pollutant mass emission during storm events coming from unknown or diffused sources also termed as non-point source (NPS). NPS pollution from stormwater runoff contributes pollutants altering the water quality in the receiving water (Pitt et al., 2008; Choi et al., 2016). The pollutants originate from precipitation, soil erosion, accumulation and atmospheric dust, street dirt, fertilizers and pesticides wash-off (Sun & Davis, 2006). One of the identified contributors of NPS pollution are transportation related use such as highways, roads, parking lots and bridges (Maniquiz, 2012). Particulates, organics, nutrients and heavy metals are the pollutants that were being transported from these areas.

In response to the detrimental effects of this phenomenon, the Korean government considered associating both the ecosystem and landscape planning and development termed as low impact development (LID) strategies. Low impact development (LID) is a general term used to describe an alternative innovative comprehensive suite of lot-level development principles and practices designed to create a more hydrologically functional urban landscape to better maintain or restore an ecosystem's hydrologic regime (Coffman, 2002, Flores et al., 2016). The plan of LID is to combine a variety of conservation strategies, minimization measures, strategic timing techniques, integrated small-scale site-level management practices and pollution prevention measures to achieve desired stormwater management or ecosystem protection goals. LID technique offers an overall design philosophy that implements and exemplify multiple small-scale controls throughout the development of site (Clary et al., 2010). Moreover, the technology aims to restore the flow regime closer to the pre-developed level and at the same time enhance the runoff quality (Bratieres et al., 2008). LID incorporates stormwater features into everyday landscape by using techniques that infiltrate, filter, store, evaporate and detain runoff in order to enhance stormwater quality and to preserve the natural hydrologic cycle (Davis, 2005; Shuster et al., 2005; Park et al., 2008). Moreover, LID aims to restore the flow regime closer to the pre-developed level and at the same time enhance the runoff quality (Bratieres et al., 2008).

One of the commonly known LIDs is the bioretention systems, also known as biofilters or rain gardens. These facilities are the most widely used stormwater treatment system in the US and are widely promoted elsewhere (Trowsdale & Simcock, 2010). Rain garden systems are small and aesthetically pleasing and are quite different than the typical landscape since this technology also uses stormwater runoff from impervious surfaces to provide nutrients the plants need for its growth. Furthermore, they are generally depression areas that utilize soil/sand/organic media and plants in order to attenuate flow and remove pollutants in highly urbanized areas (Kazemi et al., 2009; PGCo, 2007; Sun and Davis, 2006; Hong et al., 2016). Due to their nature that behave similarly to natural and non-urban watersheds, they can efficiently use to capture runoff, promote infiltration, promote evapotranspiration, recharge groundwater, protect stream channels, reduce peak flow and reduce pollutant loads owing to native and perennial vegetation such as grasses, shrubs, sedges, rushes and perennial stands, planted on a variety of media configurations (e.g., mixture of soil, sand, mulch and organic matter) (Ahiablame & Engel, 2012; DeBusk and Wyn, 2011; Dietz & Clausen, 2005). The stormwater runoff was collected directly into the rain garden with no prior treatment it utilized combined treatment mechanisms by microorganism, media and plants incorporated in the system. Moreover, rain garden systems reduce stormwater pollutants through biological uptake by plants and soil, evapotranspiration, bioremediation and phytoremediation (Davis et al., 2006). However, when the rain garden does not undergo constant maintenance, problems were encountered and one of this is clogging which were caused by organic matter, fine silts, hydrocarbons and algal matter and may be an additional source of pollutants when the runoff is discharged to the main sewer lines. (Minnesota Pollution Control Agency, 2017). Therefore, this research was conducted to develop and determine the component arrangement of a rain garden system that can treat varying amount of pollutants from various impervious surfaces for a more efficient volume and pollutant reduction.

2. Materials and methods

2.1 Characterization of hybrid rain garden systems

Hybrid is the integration of several functions and incorporating them into one treatment system. Two hybrid rain garden systems (Fig. 1) were developed in order to determine the behavior of the facilities in treating urban stormwater runoff. Both systems consist of three components namely, sedimentation tank (ST), plant bed (RG) and infiltration tank (IT). The lab-scale hybrid rain garden system (HRGS1) having dimensions of (L × W × H) 1.8 m × 0.5 m × 0.5 m, was rectangular in shape with the components connected in series and is designed for a rainfall of 14 mm. The components are arranged in the order of ST >>RG>>IT. On the other hand, the pilot-scale hybrid rain garden system (HRGS2), designed for a 7.5 mm rainfall, have the components arranged in a series-parallel manner in the order of ST>>IT>>RG. HRGS2, with dimensions of (L × W × H) 2.0 m × 0.75 m × 0.225 m, was made of steel and plates and is also rectangular in shape similar to HRGS1. The rainfall that was used in the design of the two hybrid rain garden systems was based on the 80% to 90% relative frequency that occurred in Cheonan City from the year 2009 up to 2016. Shown in Table 1 are the physical characteristics of the two hybrid rain garden systems.

2.2 Experimental Scenarios and monitoring

A synthetic runoff was used in HRGS1, which represents the actual runoff in a catchment area. The runoff was prepared by diluting one to two kilograms of sediments that passed through the No. 100 sieve in a 2.0 m^3 of tap water. The experimental run was conducted from October 2015 to November 2015 wherein the synthetic runoff was continuously stirred in the tank. On the other hand, actual storm events from May 2016 to June 2016 were monitored in HRGS2. Stormwater runoff was collected from an elevated catchment area of 250 m^2 which is a segment of an impervious paved road. The runoff was directed and collected through a drain alongside the roadway that leads to a downspout that conveys the stormwater runoff to the inflow channel of HRGS2.

2.3 Sampling and analyses

Experimental runs and actual storm events were monitored in HRGS1 and HRGS2, respectively. The flow rate in the

Table 1. Physical characteristics of the hybrid rain garden systems

Parameter	Unit	HRGS1			HRGS2		
		ST	RG	IT	ST	IT	RG
Surface area	m^2	0.25	0.5	0.15	0.25	0.375	0.375
Total volume	m^3	0.125	0.2	0.045	0.056	0.094	0.075
Storage volume	m^3	0.1	0.08	0.023	0.056	0.052	0.037
SVcomponent/TV	%	27	22	6	25	23	17
SVcomponent/SV	%	49	40	11	39	35	26
TVcomponent/TV	%	34	54	12	25	42	33
(SVcomponent/SV):(TVcomponent/TV)	-	1.44	0.74	0.92	1.56	0.83	0.79

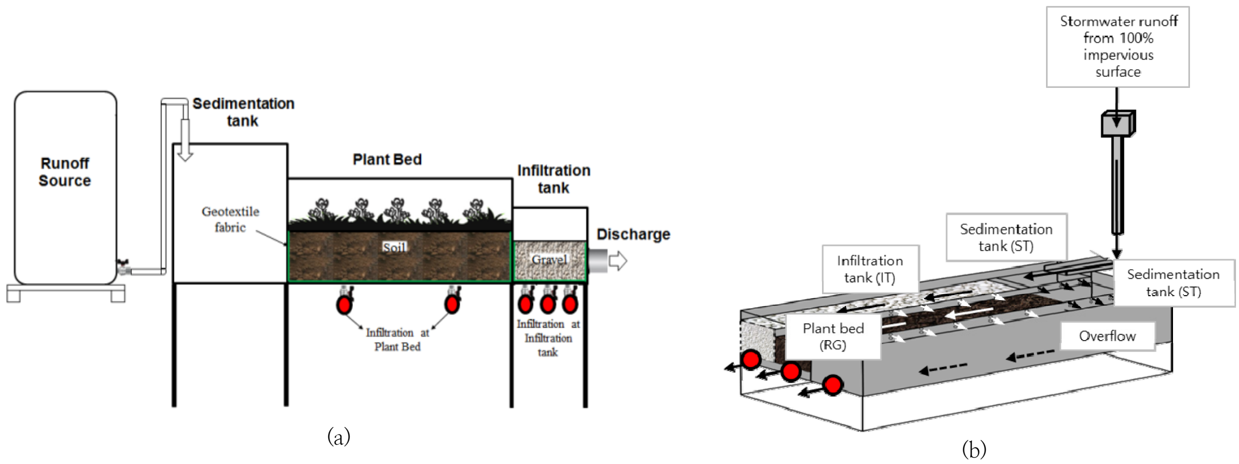

Fig. 1. Schematic diagram of a) HRGS1 and b) HRGS2

inflow (IN), outflow (OUT) and infiltration (I-RG and I-IT) was checked and measured manually every five minutes for HRGS1, while in HRGS2, the flow rate was manually measured in the inflow (IN), infiltration tank (OUT1) and infiltration tank (OUT2). Water samples were collected in the said ports. The samples were obtained with an interval of 0, 5, 10, 15, 30, 60 minutes and will extend until the runoff ends with the first 60 minutes corresponding to the "first flush phenomenon" (Jung et al., 2008). Hydrologic parameters were manually obtained during the experimental runs and storm events. Meanwhile, water quality parameters such as total suspended solids (TSS), Chemical oxygen demand (COD), nitrogen (TN) and heavy metals such as total chromium (Cu), 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 Hydrologic conditions of the two hybrid rain garden systems

Summarized in Table 2 are the characteristics of the experimental runs conducted in HRGS1. On an average, the system had a mean antecedent dry day (ADD) of 5 days with a standard deviation of 2 days. In addition, the volume and flow rate that was applied in the system has an average of 23.42 m^3 and 0.26m^3/min, respectively. It was observed that the inflow was reduced by approximately 95% in the whole system while the average flow rate was decreased by approximately 93% in the outflow. On the other hand, the time before infiltration is the time when the inflow starts and the runoff infiltrated in RG and IT. Hydraulic retention time (HRT) was found to be dependent in both rainfall duration and rainfall intensity. According to Geronimo et al., 2013, the increased rainfall duration with low rainfall intensity or decreased average rainfall intensity corresponded to increased HRT. HRGS1 was observed to have an HRT of 34 minutes, wherein the average infiltration HRT for each component is 14 minutes and 29 minutes for RG and IT, respectively.

According to Flores et al., 2015, the total annual rainfall was highly variable each year, however, a greater variation in rainfall distribution pattern has occurred recently due to climate change. A total of five storm events were monitored in HRGS2. Table 3 summed up the monitored data obtained in HRGS2. It was observed that ADD ranged between 2 and 8 days, wherein the amount of rainfall was between 2 and 23 mm. Of these monitored storm events, four events had rainfall ranging from 2 to 20 mm which represents the 80% rainfall occurrence frequency in Cheonan City. The percentage was based on the design rainfall frequency required by the Ministry of Environment (MOE, 2004). Therefore, it can be said that the five storm events well represent the rainfall that mostly occurs in Cheonan. Furthermore, during the monitoring period, the rainfall duration bounded by 3 to 8 hours having an average rainfall intensity of 0.3 to 4 mm/hr. The HRT of the components of HRGS2 with respect to the inflow start time are 29 minutes and 52 minutes for IT and RG, respectively. The HRT of HRGS2 took longer than HRGS1 due to the distance of the sampling points from the inflow port.

Shown in Fig. 2 is the water balance for HRGS1 and

Table 2. Characteristics of the experimental run in HRGS1

Parameter	Unit	Component			
		Inflow	Plant bed (RG)	Infiltration tank (IT)	Outflow
ADD	Days	5.0±2.0			
Volume	m^3	23.0±8.0	n/a	n/a	1.08±0.03
Flow rate	m^3/min	0.262±0.004	0.018±0.004	0.012	0.016±0.004
Time before infiltration	min	n/a	20.0±5.89	35.0±1.0	n/a
HRT	min	n/a	14.0±1.0	29.0±2.0	34.0±1.0

Table 3. Summary of monitored storm event in HRGS2

Event	ADD (days)	Total rainfall (mm)	Rainfall duration (hr)	Average rainfall intensity (mm/hr)
Mean	6.36	10.64	6.72	1.55
Median	8.00	12.00	7.70	1.56
Minimum	2.60	2.20	3.60	0.31
Maximum	8.30	23.00	7.90	3.54
SD	2.55	8.66	1.84	1.27
n	5	5	5	5

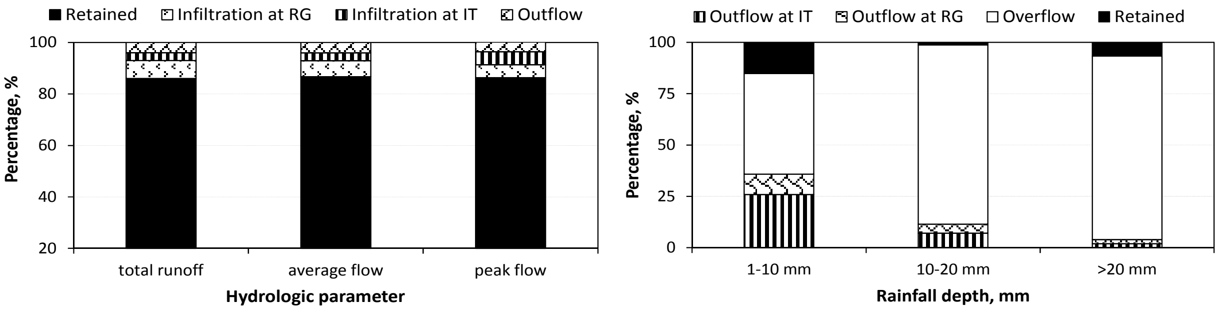

Fig. 2. Water balance in HRGS1 and HRGS2

HRGS2. The water balance for HRGS1 was classified into three hydrologic parameters, total runoff, average flow and peak flow since synthetic runoff was used as stormwater runoff. The division of treated water was divided into four parts, the retained runoff, infiltration at RG (I-RG) and IT (I-IT) and outflow. Based on the figure, more than 80% of runoff was retained in the system with only an average of 9% was infiltrated into the ground and approximately 3% was discharged out of the system. Meanwhile, HRGS2 was classified in varying range of rainfall depths since actual storm events were used. The balance was divided into three parts namely, the retained runoff, outflow at the infiltration tank (OUT1) that served as infiltration port of the component, the outflow at the plant bed (OUT2), which is for the groundwater recharge and the overflow or bypass which directs the runoff back to the drainage system when the system can no longer hold the runoff. As shown in the figure, if the rainfall ranged from 1-10 mm, 15% of the runoff was retained in the system, with a combined percentage of 36% from the outflow at IT and RG. Moreover if the rainfall ranged between 10-20 mm and more than 20 mm, the retained runoff is 1% and 7%, respectively, while the combined outflow at IT and RG is 11% and 4%, respectively. Based on the data obtained, it can be said that using the actual storm events which has varying rainfall, the higher the rainfall depth, the higher the amount of runoff discharged to the drainage system.

3.2 Pollutant removal efficiency of the two hybrid rain garden systems

Pollutant load represents the total mass before and after the system which is determined by multiplying the concentration by the calculated volume for each sample. One of the main goals of rain garden systems in general is to reduce the amount of pollutants in stormwater runoff. Fig. 3 shows the load distribution of the pollutants in each component

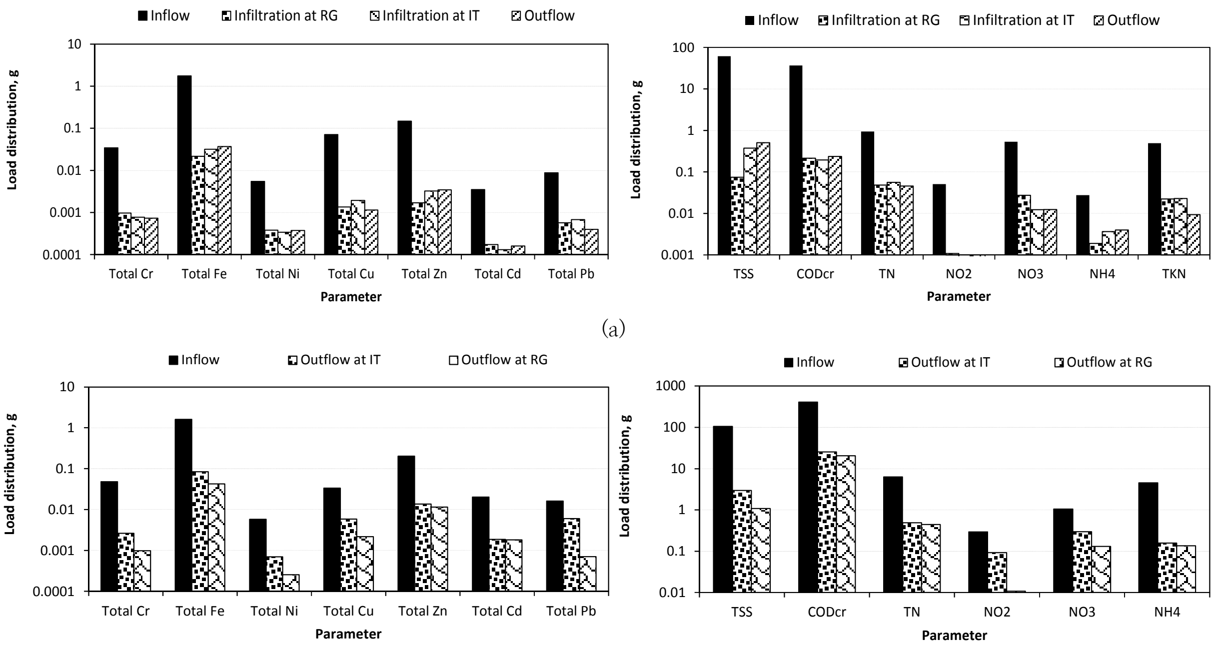

Fig. 3. Pollutant load distribution in a) HRGS1 and b) HRGS2.

of HRGS1 and HRGS2. HRGS1 was able to reduce the TSS load from 61 g to 0.075 g in RG, and was slightly increased to 0.374 g in IT and with a TSS load of 0.51 g discharged out of the system. The abrupt decrease in the pollutant load at I-RG was due to the retention/detention mechanisms of the sedimentation tank combined with the filtration and adsorption capabilities of the soil incorporated in RG that also helps in the reduction of pollutants that goes to the groundwater for recharge. Meanwhile, the increase in the load from I-RG to I-IT was due to the runoff that bypassed RG, overflowed to IT, and was discharged out of the system. Different trend was observed in HRGS2 compared to HRGS1, since the arrangement of RG and IT was interchanged. It was found that there was no increase in the pollutant load during the transition of stormwater runoff from one component to another suggesting that the component arrangement of HRGS2 will provide an optimum pollutant reduction for the hybrid rain

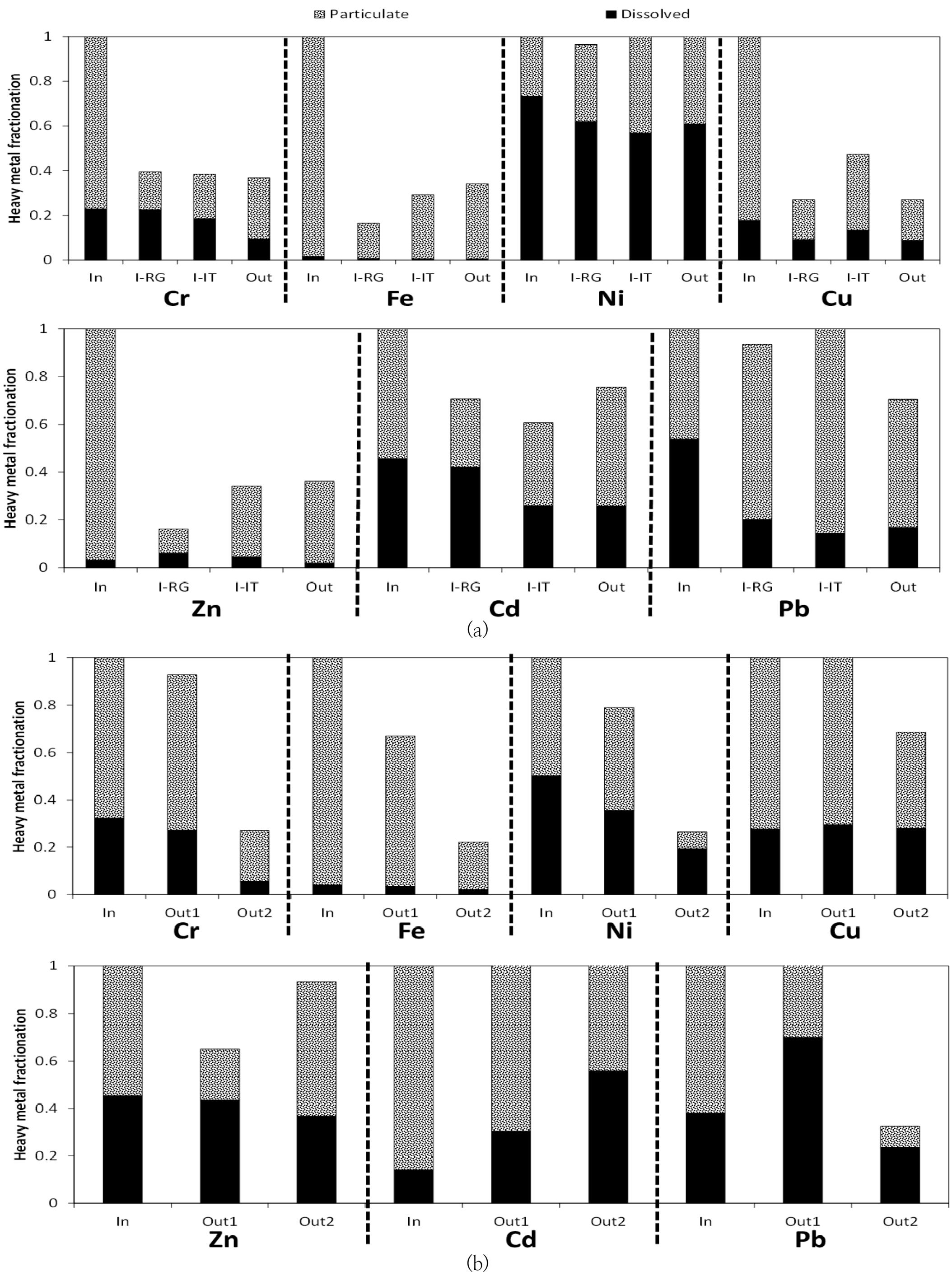

Fig. 4. Heavy metal fractionation in a) HRGS1 and b) HRGS2.

garden system. Furthermore, comparing the two hybrid rain garden systems, it can be said that individually, the soil in the plants helps in the reduction of pollutants in the groundwater.

3.3 Heavy metal fractionation

According to Maniquiz-Redillas and Kim, 2014, transportation land uses is a high contributor of NPS pollution, which includes heavy metals. Although, a large fraction of heavy metal load in transportation land use are often associated with suspended solids, heavy metal control in stormwater runoff is necessary since high metal concentration discharge to surface water may be destructive to animals and other organisms living in the surface water bodies. The partition of relative fractions of dissolved and particulate-bound mass delivered for treatment is of fundamental importance for the treatment of stormwater runoff. The heavy metal partition for HRGS1 and HRGS2 are shown in Fig. 4. It was found that majority of the heavy metals in the synthetic runoff as well as the actual stormwater runoff from a paved road is particulate-bound, which means that the heavy metals found can be adsorbed in particulate matters and be reduced through sedimentation and filtration. However, dissolve-bound heavy metals can be reduced effectively by extending the HRT, but the condition may vary depending on the heavy metal to be reduced.

Comparing the fraction of the particulate and dissolved heavy metals in the inflow and other components of the two hybrid rain garden systems, the fraction of particulate bound metals were reduced. On the other hand, dissolved metals remained in the same level for Cd in HRGS1, Cu and Zn for HRGS2 while Cr showed the same behavior for both systems. With these observations and analysis, it is implied that the relative reduction in TSS would result in the reduction of particulate-bound heavy metals in the stormwater runoff. However, the reduction of heavy metals in general is observed in both HRGS1 and HRGS2, which signifies that two hybrid rain garden systems is an effective tool in the reduction of the pollutants in urban stormwater runoff.

4. Conclusion

Urbanization as well as climate change has been continuously affecting the quality of surface waters and cause local flooding due to the increase in disturbance of natural landscapes caused by urban expansion, increase in precipitation and unpredictable weather conditions. In order to reduce these effects, LID technologies were developed to preserve the natural hydrologic cycle and the pre-developed water quality. This study was conducted by developing two hybrid rain garden systems in order to determine the component arrangement from an optimized rain garden system that can treat varying amounts of pollutants from various impervious surfaces to obtain a more efficient volume and pollutant reduction. Based on the results gathered, HRGS1 which was designed in a series manner was able to reduce approximately 93%, while HRGS2, designed in a series-parallel manner, was able to reduce 65% of the stormwater runoff. In terms of pollutant reduction efficiency, HRGS1 was able to reduce the particulate concentration by 99%, while the nutrients and heavy metals were reduced by an average of 93% and 95%, respectively. On the other hand, HRGS2 reduced the particulates by 94% while the nutrients were reduced by 80% and 85% for the heavy metal concentration. Therefore, it is concluded that the component design of an optimum hybrid rain garden system should be in series since it proved to be effective in reducing the amount of runoff volume and flows. Furthermore, the optimum component arrangement for a hybrid rain garden system is in the order of sedimentation tank (ST), infiltration tank (IT) and plant bed (RG) wherein this arrangement exhibited high pollutant reduction efficiency in stormwater runoff compared to when IT and RG were interchanged. With these findings, further investigation, assessment and evaluation of hybrid rain garden systems are needed for further improvement and development of the system. The findings in this research may be used for the further development and optimization of rain garden systems in the future.

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