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Performance assessment of an urban stormwater infiltration trench considering facility maintenance

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침투도랑 유지관리를 통한 도시 강우유출수 처리 성능 평가

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Abstract

Stormwater runoff containing considerable amounts of pollutants such as particulates, organics, nutrients, and heavy metals contaminate natural bodies of water. At present, best management practices (BMP) intended to reduce the volume and treat pollutants from stormwater runoff were devised to serve as cost-effective measures of stormwater management. However, improper design and lack of proper maintenance can lead to degradation of the facility, making it unable to perform its intended function. This study evaluated an infiltration trench (IT) that went through a series of maintenance operations. 41 monitored rainfall events from 2009 to 2016 were used to evaluate the pollutant removal capabilities of the IT. Assessment of the water quality and hydrological data revealed that the inflow volume was the most relative factor affecting the unit pollutant loads (UPL) entering the facility. Seasonal variations also affected the pollutant removal capabilities of the IT. During the summer season, the increased rainfall depths and runoff volumes diminished the pollutant removal efficiency (RE) of the facility due to increased volumes that washed off larger pollutant loads and caused the IT to overflow. Moreover, the system also exhibited reduced pollutant RE for the winter season due to frozen media layers and chemical-related mechanisms impacted by the low winter temperature. Maintenance operations also posed considerable effects of the performance of the IT. During the first two years of operation, the IT exhibited a decrease in pollutant RE due to aging and lack of proper maintenance. However, some events also showed reduced pollutant RE succeeding the maintenance as a result of disturbed sediments that were not removed from the geotextile. Ultimately, the presented effects of maintenance operations in relation to the pollutant RE of the system may lead to the optimization of maintenance schedules and procedures for BMP of same structure.

Key words : Infiltration trench; low impact development; maintenance; seasonal variations; unit pollutant load

요 약

강우유출수 내 포함된 입자상 물질, 유기물, 영양물질, 중금속 등의 오염물질은 수계에 악영향을 미친다. 이러한 강우유출수 내 포함된 오염물질 감소와 처리를 위해 최적관리기법(BMP)을 도입하고 있으며, 비용효율적인 방법으로 평가되고 있다. 하지만, 잘못된 설계와 유지관리 부족은 시설의 성능을 저하시켜 원활한 기능을 수행하지 못하고 있는 실정이다. 따라서, 본 연구에서는 지속적인 유지관리가 진행된 침투도랑(IT)의 시설에 대한 평가를 수행하였다. 2009년부터 2016년까지 총 41회의 모니터링을 수행하였으며 침투도랑(IT)의 오염물질 저감효율 평가를 수행하였다. 수질 및 수문학적 분석결과, 시설에 유입되는 유입수는 단위 오염 부하량에 영향을 미치는 요인으로 나타났다. 또한, 계절의 변화는 오염물질 저감능력에 영향을 미치는 것으로 분석되었다. 여름철 강수량 및 강우강도의 증가로 인해 Overflow 및 유량의 증가가 발생되었으며, 이로 인해 저감효율이 감소하였다. 또한, 겨울철 낮은 온도로 인해 여재 및 화학적 메카니즘의 효과 감소로 오염물질 저감 효율이 감소되는 것으로 분석되었다. 침투도랑(IT)의 유지관리는 시설의 효율에 영향을 미치는 것으로 평가되었다. 시설 설치 이후 2년 동안 유지관리 부족으로 오염물질 저감효율이 낮은 것으로 나타났으며, 일부 모니터링에서 지오텍스타일 내 제거 되지 않은 퇴적물로 인해 오염물질 저감효율의 감소를 보였다. 본 연구를 통하여, 시설의 유지관리는 오염물질 저감효과에 영향을 미치는 것으로 나타났으며, BMP 시설의 최적 유지관리 기간 및 방법 등은 향후 유용한 자료로 사용 될 수 있을 것으로 사료된다.

핵심용어 : 최적관리기법, 침토도랑, 저영향개발, 유지관리, 계절별 변화, 단위 부하량

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1. Introduction

Contamination of natural streams and water bodies is one of the most alarming concerns associated with urbanization. Stormwater runoff from urbanized areas may contain chemicals, heavy metals, and organic matters from anthropogenic, animal, and other natural sources (Sidhu et al., 2013). At present, different best management practice (BMP) were already designed to address the different types of pollutants found in stormwater (Reddy et al., 2014). The use of low impact development (LID) techniques has been an effective alternative in treating urban stormwater runoff. Its application varies widely from parking lots, roadsides, and even roof runoff. LID mainly functions to reduce the runoff volume and pollutant concentrations in a cost-efficient manner compared to other conventional stormwater treatment mechanisms (Houle et al., 2013).

For over 10 years, Korea has been utilizing BMP facilities to treat stormwater. Some of the commonly-used facilities installed throughout the region include grass swales, constructed wetlands, and infiltration trenches (IT), among others (Yu et al., 2013). Generally, IT is a type of LID facility that aids in runoff volume and improvement of water quality by means of its sorption and filtration capabilities (Lewellyn et al., 2015). IT utilizes engineered subsoil layers and filter media to attenuate flood flow and retain pollutants in the system. Installation of IT along roadsides became advantageous due to its relatively-small sizes and functional design (Li, 2015).

Despite the increasing popularity and proven effectiveness of roadside IT in treating urban stormwater, various factors should be considered to ensure that the facility performs its intended purpose. On temperate regions as in the case of South Korea, seasonal variations and environmental conditions may also influence the effectiveness of IT due to the profound changes in hydrologic patterns. Long-term performance of infiltration facilities is also greatly affected by its hydraulic functionalities (Barraud et al., 2014). The deposition of sediments affects the efficiency of most filtration systems by reducing the porosity of the filter media (Mercado et al., 2015). To address the challenges concerning the utilization of IT in urban stormwater treatment, this study identified the factors affecting the long-term performance of an IT which has undergone a series of maintenance operations. Event-based pollutant loading in the catchment area and seasonal variations in the pollutant removal performance of the IT were also evaluated to determine possible patterns in the treatment mechanisms of the IT. Moreover, the efficiency of the IT before and after maintenance operations was considered in this study.

2. Materials and Methods

2.1 Study Area and Infiltration Trench Design

The stormwater IT located at the Kongju National University (KNU), Cheonan City, Chungnam Province, South Korea was illustrated in Figure 1. The facility can be separated into three zones, namely: pre-treatment zone, media zone, and effluent zone. The pre-treatment zone basically served as a sedimentation tank. The bottom of the tank contains geotextile, underlain by sand and gravel layers. A vertical geotextile layer was also installed to further reduce the amount of sediments in the stormwater before entering the media zone. The media zone can be subdivided into vertical and horizontal media layers. The vertical media layer was made of wood chip, zeolite, and sand, respectively. The combination of zeolite and woodchips increases the performance of a filter due to its high adsorption and ability to retain moisture in the media (Baltrėnaitė et al.,

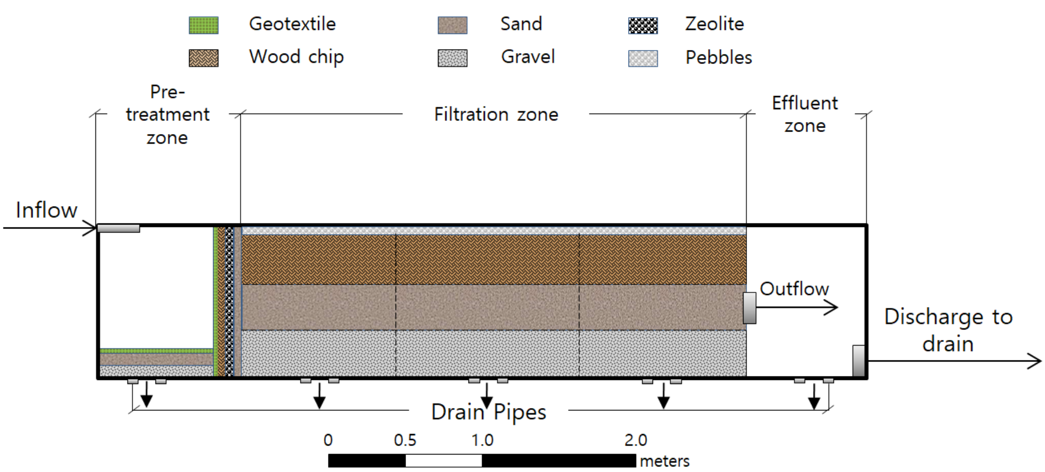

Fig. 1. Schematic diagram of the IT located at Kongju National University

2016). Moreover, the vertical media layer was composed of pebbles (20mm to 30mm), wood chips (10mm to 20mm), sand (2mm to 5mm), and gravel (20mm to 30mm), with corresponding porosities of 48%, 43%,40%, and 46%, respectively. Underdrain pipes were also installed to allow the drainage of vertical flow through the media. The filtered stormwater was directed towards the effluent zone before finally discharging into the sewer system. The facility characteristics were summarized in Table 1.

Table 1. Properties of the infiltration trench and its catchment area

Parameter	Unit	Characterization/Value
Surface area	m^2	6.5
Storage volume	m^3	3.85
Design total rainfall	mm	25
Design HRT	hours	3
Aspect ratio (L:W:H)	m	5:1.3:1

2.2 Sampling Scheme and Maintenance Procedure

A total of 41 monitored rainfall events covering the period from May 2009 to September 2016 were utilized to assess the long-term performance of the IT. The 520-m^2 catchment area was generally characterized by roadways and parking spaces with 100% imperviousness rate. Grab samples were collected in the inflow and outflow ports as soon as the runoff started entering and leaving the facility, respectively. Additional samples were collected after 5, 10, 15, 30, and 60 minutes. Succeeding samples were collected at a one-hour interval throughout the rainfall duration. Inflow and outflow rates were also measured every five minutes for the whole event duration. Water quality evaluation was conducted for all collected samples by applying standard methods for the examination of water and wastewater (APHA, AWWA, & WEF, 1992). Analyzed water quality parameters include biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and turbidity. The presence of total heavy metals, including cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), nickel (Ni), and zinc (Zn), were also tested in the water samples. A total of five maintenance operations were conducted from 2011 to 2015. Maintenance procedure includes mechanical removal of fallen leaves accumulated on top of the facility and sedimentation tanks, clearing of the inflow and outflow ports, replacement of the geotextile installed in the facility, and washing of the filter media to remove the sediments.

2.3 Data Sources and Statistical Analyses

Hydrologic factors such as antecedent dry days (ADD), rainfall depth, and temperature were gathered from the Korea Meteorological Administration (KMA). The pollutant removal efficiency (RE) of the system was evaluated by calculating the pollutant load reduction in the influent stormwater considering hydraulic factors such as inflow and outflow volume (Maniquiz, 2009). The calculation of the inflow pollutant load, outflow pollutant load, and pollutant load reduction in the runoff was determined using equations 1 through 3, respectively.

$$\text{Inflow pollutant(mg)} = \Sigma_{t=1}^{t=T}\ C_{in}(t)\ q_{in}(t)) \quad (1)$$

$$\text{Outflow pollutant load(mg)} = \Sigma_{t=1}^{t=T}\ C_{out}(t)\, q_{out}(t) \quad (2)$$

Mass removal efficiency(%)

$$= \frac{\Sigma_{t=1}^{t=T}\ C_{in}(t)\, q_{in}(t) - \Sigma_{t=1}^{t=T}\ C_{out}(t)\, q_{out}(t)}{\Sigma_{t=1}^{t=T}\ C_{in}(t)\, q_{in}(t)} \quad (3)$$

Where $C_{in}(t)$ and $C_{out}(t)$ represented the pollutant concentrations of the influent and effluent, respectively, and $q_{in}(t)$ and $q_{out}(t)$ corresponded to the inflow and outflow rate at time t, respectively.

Furthermore, the unit pollutant load (UPL) was calculated to determine the amount of pollutants washed off per unit area of the catchment for the whole rainfall duration (Li et al., 2015). Equation 4 illustrated the equation for the calculation of unit pollutant load.

$$UPL(mg/m^2) = \frac{\Sigma\ C_t q_t \triangle t}{A} \quad (4)$$

Where C_t denoted the pollutant concentration at time t, q_t represented the flow rate at time t, and A corresponded to the catchment area of the facility. Moreover, statistical analyses, such as determining Pearson correlation coefficient (r) and probability value (p-value), and one-way analysis of variance (ANOVA), were conducted using Systat 12 (© SYSTAT Software, Inc., 2007) and OriginPro 8 to assess the stormwater runoff characteristics and the contributory factors that may affect the pollutant removal performance of the IT.

3. Results and Discussion

3.1 Characteristics of monitored rainfall events

The statistical summary of the 41 monitored rainfall events was presented in Table 2. Majority of the events were monitored during the summer and spring season, constituting 37% and 39% of the total monitored events, respectively. Rainy season in South Korea usually begins in the spring season, and reaches its peak during the summer months of June to August. For

Table 2. Summary of monitored rainfall events

Parameter	Unit	Min	Max	Mean	Median	Std. dev
ADD	days	1.00	35	6.3	4.5	6.49
Total rainfall	mm	1.00	90.50	9.36	5.36	14.62
Rainfall duration	hr	0.85	11.03	3.4	2.93	2.30
Rainfall intensity	mm/hr	0.38	17.06	2.80	1.29	3.76

the monitoring period from May 2009 up to September 2012, 16% (1,475 mm) and 58% (5,282 mm) of the total rainfall depth were recorded during the spring and summer seasons, respectively. The longest ADD was recorded on winter season (34 days), whereas shortest ADDs and greater rainfall intensities were observed during summer with mean values of six days and 5 mm/hr, respectively. 20% of the monitored events did not produce outflow in the facility. Complete attenuation of the stormwater runoff volume was mostly attained for rainfall depths less than 5mm.

3.2 Stormwater pollutant concentrations and removal efficiency of the facility

Untreated urban stormwater may contain loads of particulates, organics, nutrients, and heavy metals. The event mean concentrations (EMC) of various pollutants in the collected inflow and outflow stormwater samples were reported in Figure 2. Generally, all the mean values of the constituents are greater than the median values, implying that all samples have low pollutant concentrations for all the constituents. Significant reduction in the pollutant concentration can also be observed for particulates and nutrients ($p<0.05$). This can be attributed to the pre-treatment mechanism incorporated in the IT design. Removal of particulate-bound pollutants greatly reduces the initially-high runoff pollutant concentrations through the process of sedimentation (Maniquiz-Redillas et al., 2014). However, it can be noted that the mean outflow concentration of some heavy metals were 32% to 92% greater compared to the inflow concentration. It was observed that leaching can occur for a rainfall depth and intensity as low as 2.5 mm and 0.7 mm/hr, respectively, and was further intensified by higher rainfall depths and intensity. The accumulated particles within the voids of the filter media were released during particular storm events, thereby causing pollutant leaching and contributing higher pollutant concentration in the effluent stormwater. This observation was similar to the results of the filter column experiment conducted by Hatt et al. The point beyond the clogging layer in the filter column exhibited that pollutant concentrations increased as a result of longer detention times. Moreover, since incoming TSS were trapped on top of the filter, finer particles can easily percolate to the media (Hatt et al., 2007). Similar to the results shown in Figure 2, increase in the outflow concentrations of Cr, Fe, and Ni were also exhibited in the filtration system studied by Birch et al. Heavy metals bound in the clay minerals and overlying topsoil leached through the sand filters, thus resulting to an apparent increase in pollutant concentration of the treated stormwater (Birch et al., 2005). Looking closely at Figure 2, median outflow concentrations of the heavy metals were relatively lower compared to the mean influent concentration. Overall, the IT exhibited an efficient treatment of urban stormwater runoff as manifested by the significant reduction of pollutant concentrations.

The intensity of pollutant concentrations may vary depending on the location being considered. In a high-traffic density roadway studied by Hilliges et al., 2013, Zn EMC was 136% higher compared to the KNU catchment. Increase in particulate-bound heavy metals deposited on roadsides was especially noted on highways due to vehicular emissions. KNU has decreased traffic density during the summer and winter seasons, hence resulting to a reduced particulate deposition from vehicular activities. Valtanen et al., 2014 monitored a low-traffic density residential catchment with a total imperviousness rate of 19%. Results showed that the heavy metal EMC of the residential catchment were 61% to 99% lower as compared to the influent heavy metal EMC observed at KNU. Since the residential catchment area provides greater infiltration potential and lower vehicular emissions, runoff volume and pollutant concentrations were thereby reduced. Generally, non-point sources (NPS) of pollution generated from activity-related, land cover-related, behaviour-related, and atmospheric deposition, among others, provide a wide range of variations in the urban stormwater runoff quality (Petrucci et al., 2014).

IT installed on roadsides usually exhibit different levels of efficiency in treating urban stormwater runoff. Catchment area characteristics and structural design greatly influence the performance of LID facilities. Comparison of the IT at KNU and the Austin sand filters studied by Barrett, 2003 revealed that the IT at KNU was 49% to 69% more efficient in removing nutrients in stormwater, but exhibited 4% to 11% lower performance in terms of heavy metal reduction as compared to the sand filters. The removal of metals in the sand filters can be attributed to the adsorption of sand grains and physical

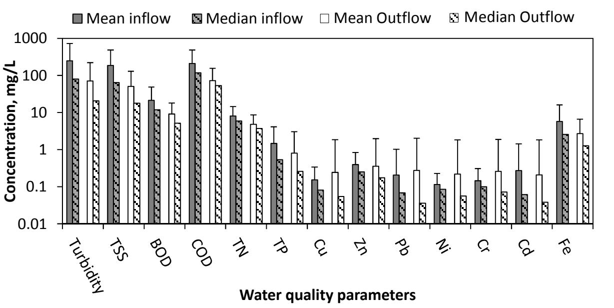

Fig. 2. Inflow and outflow pollutant event mean concentrations

processes such as settling, particle attachment, and straining in the sedimentation basin. Moreover, the infiltration basin investigated by Natarajan and Davis, 2016 exhibited 12% to 15% greater removal of nutrients in stormwater as compared with the IT at KNU. Since the surface area to catchment area (SA/CA) ratio of the infiltration basin is relatively larger than the IT's (13.6%), the infiltration basin can accommodate higher runoff volumes and have higher detention times, thus resulting to a more efficient treatment of stormwater.

3.3 External variables affecting unit pollutant loads within the catchment area

UPL can be used as an indicator of pollutant characteristics in stormwater. It is basically a means of describing the intensity of pollutant loads per unit area of the catchment (Qin et al., 2013). Fluctuations in the pollutant concentrations can be attributed to the pollutant deposition on the surface emanating from anthropogenic and natural sources (Göbel et al., 2007). External variables were mostly hydrologic in nature (i.e. Antecedent dry days, inflow volume, and rainfall depth). Among the external factors considered, the inflow volume had the strongest correlation (r = 0.50 to 0.77, p 〈0.05) with the inflow UPL. A similar observation was also noted by Valtanen et al., 2014 which stated that positive correlations exist between pollutant loads and runoff volumes on an impervious catchment area. In an urban area where the rainfall-to-runoff conversion is relatively high, the wash off potential of pollutants also increased along with the runoff volume.

Assessment of the seasonal variability of water quality is essential in designing management strategies for non-point source pollution control (Poudel et al., 2013). Likewise, climatologic patterns also affected the pollutant removal of infiltration BMP. Figure 3 provides a graphical summary of the IT's removal efficiency as influenced by seasonal changes. It can be noted that the lowest pollutant RE of the system for COD (78%), TN (60%), and Zn (66%) was recorded during the winter season. Moreover, the lowest RE for TSS, TP, Cr, Cu, and Pb were identified on summer, corresponding to 82%, 66%, 52%, 70%, and 63%, respectively. Lower facility performance during winter was attributed to the increased accumulation of pollutants on snow packs and frozen media layers. More toxic forms of pollutants present in the snow were released on snowmelt (Drake et al., 2014). Low winter temperature in Korea, with an average of −1° C from 2009-2016, also affected the metabolic activities of nitrifying

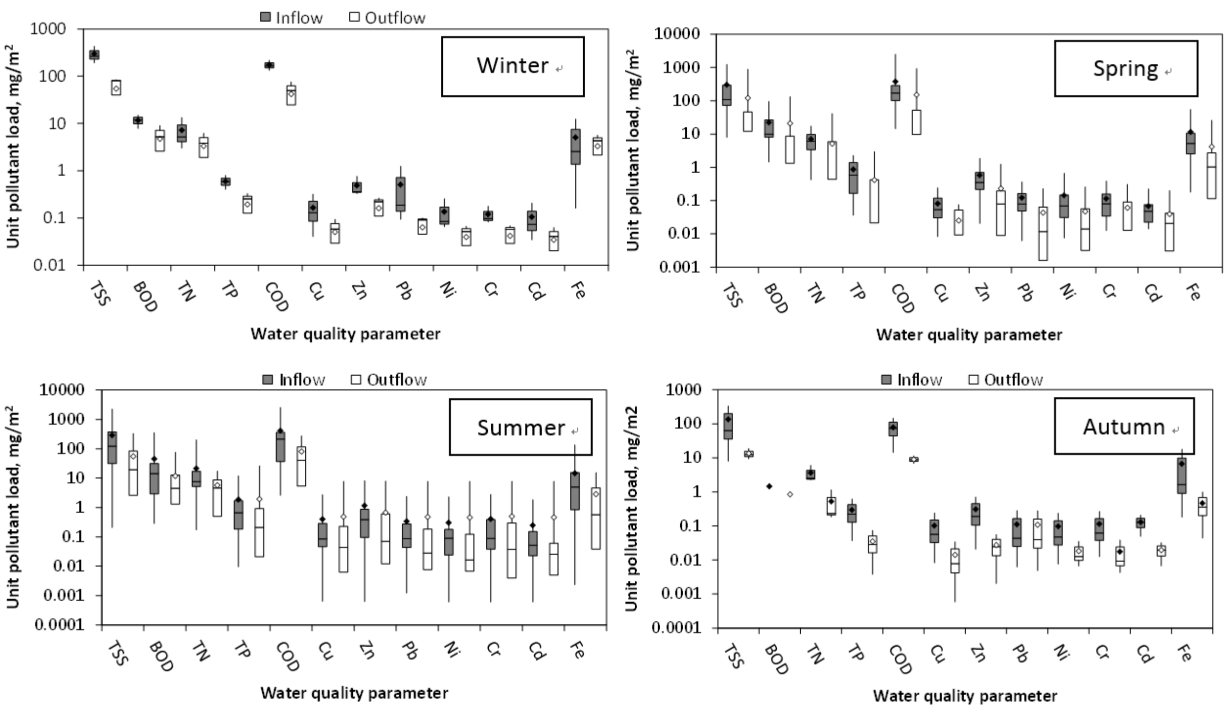

Fig. 3. Seasonal inflow and outflow unit pollutant loads

and denitrifying bacteria which resulted to low nitrogen removal efficiency (Yan & Xu, 2013). The mean daily rainfall on summer season amounted to 17.55 mm. This relatively-high value, as compared to winter (2.98 mm), spring (8.20 mm), and autumn (9.33 mm), caused greater runoff volumes that contain higher pollutant concentrations. Pollutant build-up on urban areas usually occurs on dry season and flushed by stormwater on rainfall events (Ma et al., 2016). Specifically, rainfall intensity and duration was associated with increased amount of metals in the wash off water (Zhao & Li, 2013). Since heavy metals are associated with fine particles (Gunawardana et al., 2014), increased runoff volumes washed off greater heavy metal loads into the IT. Generally, the mean seasonal pollutant RE of the IT was 8% to 41% and 8% to 31%lower on summer and winter seasons, respectively.

3.4 Evaluation of RE considering maintenance operations

One of the most profound problems of infiltration type facilities is clogging. Regular maintenance operations were conducted on the IT to remove the accumulated sediment deposits in the facility. Figure 4 exhibited the pollutant RE of the system before and after a series of maintenance operations. For the first two years of operation without maintenance, the IT exhibited a 13% to 37% decline in pollutant removal performance. It was evident that the aging of the facility without maintenance resulted to a decline in its filtration mechanism. However, despite the lack of maintenance, 7% to 46% increase in the RE of the system was recorded for turbidity, TSS, BOD, COD, TN, TP, Fe, Zn, and Cd on the third year of operation. This phenomenon can be associated with the rainfall of monitored events. For the third year of operation, the rainfall depth only ranged from 1.5 mm to 5 mm, as compared to the 2.5 mm to 22.5 mm depth of rainfall experienced in the monitored events of the second year. Due to the very small amount of rainfall received during the third year of monitoring, the whole runoff volume was impounded in the system, thereby producing no outflow and a 100% pollutant RE.

After the first maintenance period, the pollutant removal performance of most parameters was increased by 1% to 22%. Maintenance measures positively impacted the infiltration capacities of IT (Al-Rubaei, 2016). The removal of sediment deposits in the geotextile and media layers enhanced the filtering mechanism of the system and thus, restoring the IT's pollutant reduction capabilities. However, a decline in the mean pollutant RE was observed subsequent to the second (13% to 29%), third (7% to 45%), and fifth (15% to 24%) maintenance operations. Specifically, most of the first monitored events after the maintenance showed low pollutant RE. Residual and disturbed sediments within the tanks and the geotextile were associated with the runoff water, hence increasing the pollutant loads. It can also be noted that events with greater rainfall depths (i.e. 90.5 mm, 22.5 mm, and 18.3 mm) incurred low pollutant removal performance ranging from 0% to 91%. Increased rainfall depths caused the facility to overflow. The turbulence induced by high flow rates prevents the settling of sediments in the pre-treatment zone. Generally, A poorly-maintained facility may still be functional, but the pollutant removal efficiency may be reduced greatly (Maniquiz et al., 2018).

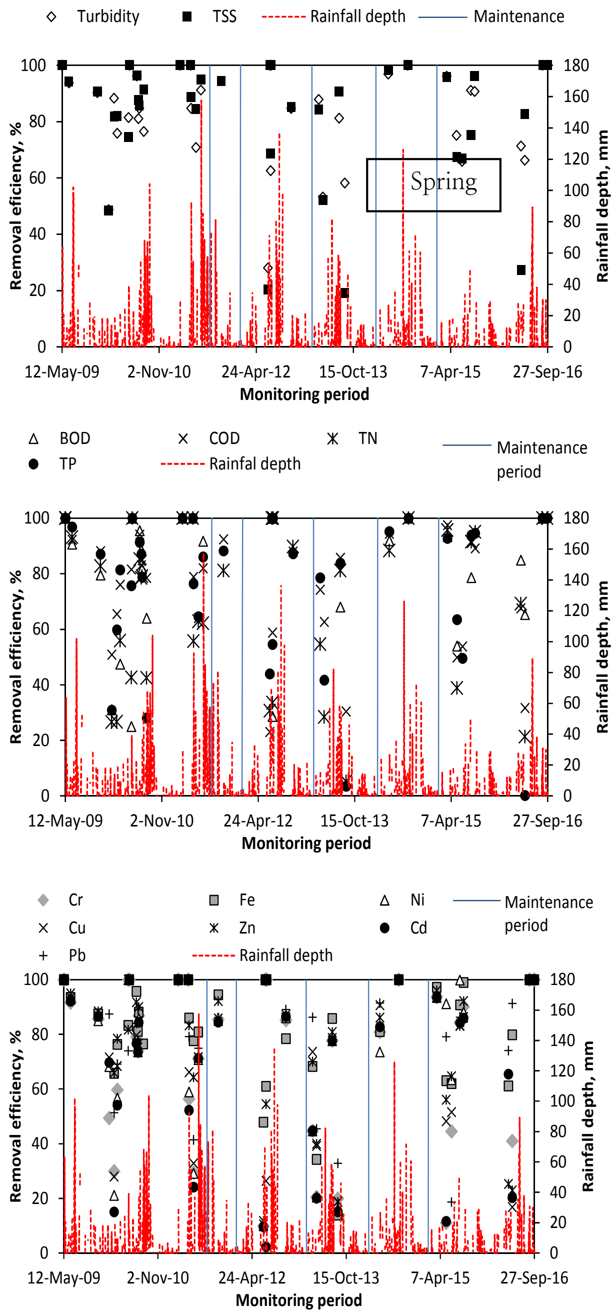

Fig. 4. Pollutant removal performance of the IT prior and succeeding maintenance operations

4. Conclusion

Infiltration BMP were designed to reduce stormwater runoff volumes in conjunction with pollutant load reduction. However, the filtering mechanisms of the infiltration systems were susceptible to clogging and sedimentation problems. Seasonal patterns were seen to affect the performance of the infiltration trench. Increased rainfall depths on summer season caused stormwater to wash off more pollutants in the catchment area. Due to high rainfall-to-runoff conversion in urban areas, the wash off potential of fine particles deposited along the roadside was also affected. Moreover, the pollutant RE of the IT was also low during the winter season due to the accumulation of pollutants in the snow pack. The pollutants released during snowmelt period can be higher as compared to rainfall events.

Assessment of the UPL was beneficial in characterizing the stormwater runoff in the catchment area. UPLs varied widely as a result of anthropogenic and natural patterns that affected the deposition of pollutants. It was also known that the runoff volume was the most relative among the external factors that affected unit pollutant loading in an impervious catchment. In order to prevent the deterioration of IT, regular maintenance operations should be administered in the facility. Since summer season in Korea marks the period of frequent and high rainfall depths, it may be necessary to conduct maintenance operations prior to periods of high rainfall events. Removal of sediment deposits in the filter media can facilitate an increase infiltration, thus also improving the treatment mechanism of the facility.

The IT at KNU exhibited a decline in the first two years of operation without maintenance. The pollutant RE of the IT has improved after the first maintenance operation. However, a decline in the pollutant removal performance of the facility was observed for the monitored rainfall events subsequent to other maintenance activities. Disruption of the filter media and residual sediments were seen to be the main cause of lower RE. This inquiry is essential in establishing factors that affect the pollutant removal performance of an IT. The findings about the seasonal performance of the IT can be advantageous in the design and construction of facilities experiencing similar rainfall and climatic patterns. The presented effects of maintenance operations in relation to the pollutant RE of the system can also lead to the optimization of maintenance schedules and procedures for BMP of same structure.

Acknowledgements

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