Nutrient concentration in sediments accumulated in pre-treatment basins of urban LID technologies

F. K. F. Geronimo, M. C. Maniquiz-Redillas, J. S. Hong and L. H. Kim

ABSTRACT

In this study, the contribution of pre-treatment basins of low impact development (LID) technologies to nutrient reduction performance was evaluated by understanding the distribution of nutrient in sediments accumulated in each system. The captured sediments were mostly silt to medium sand ranging from 9% to 92% of the sediments collected. Greater average N and P concentrations were found in silt particles amounting to 345 mg/kg and 696 mg/kg, respectively compared to sand and gravel. Although, N concentrations in accumulated sediments were found to be highly variable at different particle sizes (CV: 0.24 to 0.77) compared to P concentration (CV: 0.08 to 0.36) attributed to effective P treatment mechanism through deposition compared to complex nitrogen removal mechanisms. In addition, the difference between N and P concentrations of sediments collected in the pre-treatment basins of LID technologies and in-situ soil was attributed to the continuous pollutant input to the LID technologies during storm events. The study proved that pre-treatment basins of stormwater LID technologies reinforced the nutrient removal performances through sediment retention. The findings of this research may be used to design pre-treatment basins of LID technologies considering nutrients as a limiting factor.

Key words low impact development, nutrients, pre-treatment basins, sediments

INTRODUCTION

The transition of inherent landscape to an extremely developed environment increases the impervious surfaces covered by building rooftops, landscaping and transportation land uses such as roads, highways, parking lots and sidewalks. Development of urban surfaces prevents infiltration, thereby increasing the runoff directed to stormwater network and deteriorating the water resources in highly urbanized areas (Qiu 2013). Substantial amount of nutrients in urban storm runoff contributes to the eutrophication of receiving water bodies leading to algal bloom (Taylor et al. 2005). Excess phosphorus can lead to decreased biological productivity while excess nitrogen is harmful to marine ecology. These pollutants were usually transported as sediment-bound contaminants (Vaze & Chiew 2004).

An innovative way of controlling nutrients in stormwater runoff was through low impact development (LID) technologies an example of a nature-based solution to address the negative effects of climate change and urbanisation to natural urban water cycle (Zölich et al. 2017). LID technologies mimic the predeveloped state of an area, thereby preventing the water cycle disruption by employing different physical, chemical and biological mechanisms. Ahiablame et al. 2012 have already summarized and reported the performance of the LID technologies in controlling several pollutants including nutrients in urban stormwater runoff from different studies. TN and TP were removed by 7% to 99% and -3% to 99%, respectively. High variability of nutrient removal in LID technologies was due to the complexities of the chemistry of these pollutants making it difficult to attain relatively similar removal efficiencies, especially when applied to different site and environmental conditions (Geronimo et al. 2015). Designs of LID differ depending on target pollutants. Pre-treatment units were usually employed to LID technologies to reduce the flow of incoming runoff or receive the initial highly polluted runoff commonly known as first flush (Maniquiz-Redillas et al. 2014). Since the pre-treatment units receive the first flush of pollutants, sediments, in which particulate-bound pollutants were attached, settle, resulting to minimized clogging in the filter media unit, thereby reducing maintenance cost.
Currently, limited studies about sediment accumulation, its corresponding nutrient concentration and its implication to the performance of LID technologies has been studied. As such, hydrologic and hydraulic factors affecting nutrient transport in urban catchments and inside LID technologies were identified in this study. The contribution of pre-treatment basins of LID technologies to nutrient reduction performance was also evaluated by understanding the distribution of nutrient in sediments accumulated in each system. In order to apply similar design of LID with pre-treatment units to other urban catchments, design criteria considering nutrient load accumulation in pre-treatment basin of LID technologies were derived.

**MATERIAL AND METHODS**

**Description of LID technologies**

Three LID technologies were developed and monitored during selected storm events from May 2009 to October 2016 with design characteristics summarized in Table 1. An infiltration trench (IT) and two hybrid constructed wetlands (HCW1 and HCW2) were installed inside Kongju National University, Cheonan City, South Korea to treat urban stormwater runoff from 100% impervious road and parking areas. The three LID facilities were similarly designed with pre-treatment basin. However, IT was designed with infiltration capability while there were no infiltration capabilities employed in the design of HCW1 and HCW2. The schematic diagram of each LID technologies including the sampling points and flow path were exhibited in Figure 1. The site location and media configuration of the three LID technologies were already previously reported by Maniquiz-Redillas et al. 2014. The pretreatment basins of these LID technologies comprised almost 23% to 38% of the total facility storage volume.

**Storm event monitoring, pre-treatment basin maintenance, and analytical analysis**

Selected storm events were monitored from the year of construction of LID technologies, 2009 for IT and 2010 both for HCW1 and HCW2, up to 2016 to evaluate the efficiency in urban storm water runoff management. Following the typical sampling scheme in South Korea, first grab sample was collected as soon as the runoff entered the inflow ports of the LID technologies or when discharge was produced by the LID technologies. This was followed by grab sample collection at a time interval of 5, 10, 15, 30 and 60 min, respectively. After the first hour of runoff and discharge, one grab sample was collected for each succeeding hour until a maximum of 12 samples were collected or until the storm event ended. The collected water samples were analytically tested for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) concentration according to Standard Methods for the Examination of Water and Wastewater (APHA et al. 1992). In addition to water samples, hydrologic and hydraulic parameters including antecedent dry days (ADD), rainfall depth and intensity, rainfall and runoff duration, runoff and discharged volumes and inflow and outflow rates were measured and recorded in the location of LID during storm events.

Part of the maintenance routine conducted for the LID technologies was sediment collection in the pre-treatment basin. Sediment samples accumulated in the pre-treatment basins of the three LID technologies were collected once every one to two years from 2011 to 2015. Sediment accumulation rate was calculated by dividing the weight of sediments collected in the pre-treatment basins to the product of the catchment area and time between sediment collections. Particle size analysis was conducted to determine the size distribution of the collected sediments. Chemical characteristics of the sediments including nitrogen (N) and phosphorus (P) were analytically tested based on the method reported by Carter & Gregorich (2006).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Infiltration trench (IT)</th>
<th>Small hybrid wetland (HCW1)</th>
<th>Hybrid sub-surface flow wetland (HCW2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff source</td>
<td>Road</td>
<td>Road and parking lot</td>
<td>Road and parking lot</td>
</tr>
<tr>
<td>Catchment area (m²)</td>
<td>520</td>
<td>323</td>
<td>425</td>
</tr>
<tr>
<td>Infiltration capability</td>
<td>Yes</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Filter media</td>
<td>Woodchip, sand and gravel</td>
<td>Woodchip, sand and gravel</td>
<td>Bioceramic, sand and gravel</td>
</tr>
<tr>
<td>Facility aspect ratio (L:W:H)</td>
<td>1.0:0.2-0.26</td>
<td>1.0:15.0:0.1</td>
<td>1:0.14:0.1</td>
</tr>
<tr>
<td>SV/TV&lt;sup&gt;a&lt;/sup&gt; (%)</td>
<td>45.4</td>
<td>33.9</td>
<td>30.6</td>
</tr>
<tr>
<td>PV/SV&lt;sup&gt;b&lt;/sup&gt; (%)</td>
<td>22.9</td>
<td>37.8</td>
<td>26.2</td>
</tr>
</tbody>
</table>

<sup>a</sup>Facility storage volume to total volume. 
<sup>b</sup>Pre-treatment basin storage volume to facility storage volume.
In addition, phosphorus types including organic phosphorus (organic P), apatite phosphorus (apatite P), non-apatite inorganic phosphorus (NAIP) and labile phosphorus (labile P) which comprises the total phosphorus in sediments were tested using the method reported by Hieltjes & Lijklema (1980). Nutrient load accumulation rate was calculated by multiplying the sediment accumulation ratio with the corresponding nutrient concentration of the sediments.

Event mean concentration (EMC) was calculated by dividing the total inflow or total outflow pollutant load with the runoff or discharged volume, respectively. In addition, pollutant removal efficiency of the system was
calculated by subtracting the fraction of outflow load to inflow load to 1 multiplied to 100. Results were statistically analyzed using SYSTAT 9.0 and OriginPro 8 software package including analysis of variance (one-way ANOVA) and Pearson correlation analysis. Significant differences were accepted at the $p = 0.05$, signifying 95% confidence level.

**RESULTS AND DISCUSSION**

**Stormwater characteristics and hydrologic factors affecting its transport in stormwater runoff**

The mean hydrologic and hydraulic characteristics of monitored storm events were summarized in Table 2. Storm events with rainfall depth ranging from 1 to 91 mm were monitored in the LID technologies. 76% of the 96 monitored rainfall events were less than 20 mm which was equal to the percentage of small rainfall occurring in Cheonan City, South Korea reported by Maniquiz et al. (2010). Antecedent dry days (ADD) in between monitored storm events were ranging from 0.2 to 34.21 days with the shortest usually occurring in the summer season and the longest between winter to spring season. Hydrologic parameters including ADD, rainfall depth, average rainfall intensity, rainfall duration and runoff duration of the three LID technologies were not significantly different ($p < 0.05$). This finding was attributed to the proximity of each LID technology subjecting them to the same environmental conditions (Maniquiz-Redillas & Kim 2016). Among the three LID facilities, IT attained the highest mean stormwater runoff volume reduction efficiency amounting to 62% which was significantly different from HCW1 and HCW2 which only has 41% and 36%, respectively ($p < 0.05$). The infiltration mechanism employed in IT was found to be the affecting factor in enabling more storm water volume to be reduced since infiltration processes smear peak flows and emphasizes groundwater recharge (Davis et al. 2006).

In order to effectively analyze the nutrient concentration in the accumulated sediment of the pre-treatment basins of LID technologies, it is important to determine the characteristics of the stormwater which is the source of these nutrients. Exhibited in Figure 2 are the ranges of EMC from stormwater runoff and discharged by the LID technologies. IT, HCW1 and HCW2 significantly reduced the inflow TSS, TN and TP EMC with an average removal efficiency of 65%, 29% and 30%, respectively ($p < 0.05$). TN and TP load were also found to be highly correlated with TSS load both in runoff, and discharge of the LID technologies ($r = 0.86$ to 0.97). Linear regression analysis, however, revealed that only TP load removal efficiency by the LID technologies was a function of TSS load removal efficiency ($R^2 = 0.65$, $p < 0.001$). These findings implied that the retained TN and TP will be stored in the system until physicochemical or biological treatment will take place in the LID technologies or when maintenance procedures such as accumulated sediment collection will be performed. Hydrologic and hydraulic parameters including ADD, rainfall depth, rainfall duration and runoff duration was found to affect the inflow TSS, TN and TP load with Pearson correlation coefficient ($r$) ranging from 0.76 to 0.99. These findings implied that higher inflow TSS, TN and TP load can be measured from the stormwater runoff from the urban catchment areas with higher ADD and rainfall depth or longer rainfall and runoff duration. In addition, TSS, TN and TP removal were found to be inversely proportional to the several hydrologic and hydraulic factors including ADD, rainfall depth, rainfall duration, runoff duration, runoff volume and average inflow rate ($r = 0.63$ to 0.99). The factors identified in these results may be used to design LID that targets nutrients in urban stormwater runoff. Hydrologic and hydraulic factors including volume, average flow, peak flow, HRT and runoff duration were also identified to have significantly affected the performance of a tree box filter, an infiltration type LID technology (Geronimo et al. 2016).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>IT</th>
<th>HCW1</th>
<th>HCW2</th>
</tr>
</thead>
<tbody>
<tr>
<td>N storm events</td>
<td></td>
<td>38</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>Antecedent dry days$^a$</td>
<td>day</td>
<td>5.51</td>
<td>6.45</td>
<td>6.73</td>
</tr>
<tr>
<td>Rainfall depth$^a$</td>
<td>mm</td>
<td>10.14</td>
<td>6.94</td>
<td>8.25</td>
</tr>
<tr>
<td>Average rainfall intensity$^a$</td>
<td>mm/hr</td>
<td>3.19</td>
<td>2.94</td>
<td>4.59</td>
</tr>
<tr>
<td>Rainfall duration$^a$</td>
<td>hr</td>
<td>3.82</td>
<td>3.40</td>
<td>2.98</td>
</tr>
<tr>
<td>Runoff duration$^a$</td>
<td>hr</td>
<td>2.81</td>
<td>2.07</td>
<td>2.19</td>
</tr>
<tr>
<td>Runoff volume$^a$</td>
<td>m$^3$</td>
<td>4.28</td>
<td>1.57</td>
<td>1.94</td>
</tr>
<tr>
<td>Discharge volume$^a$</td>
<td>m$^3$</td>
<td>2.47</td>
<td>1.26</td>
<td>1.97</td>
</tr>
<tr>
<td>Average inflow rate$^a$</td>
<td>m$^3$/hr</td>
<td>1.33</td>
<td>11.77</td>
<td>5.78</td>
</tr>
<tr>
<td>Average outflow rate$^a$</td>
<td>m$^3$/hr</td>
<td>1.00</td>
<td>0.76</td>
<td>1.86</td>
</tr>
<tr>
<td>Peak inflow rate$^a$</td>
<td>m$^3$/hr</td>
<td>8.10</td>
<td>3.74</td>
<td>2.73</td>
</tr>
<tr>
<td>Peak outflow rate$^a$</td>
<td>m$^3$/hr</td>
<td>3.75</td>
<td>3.03</td>
<td>2.35</td>
</tr>
</tbody>
</table>

$^a$Mean.
Distribution of nutrient concentration in sediments

The log-normal particle size distribution of sediments collected in the pre-treatment basins was exhibited in Figure 3. Apparently, the captured sediments were mostly silt to medium sand ranging from 9% to 92% of the sediments collected. Silt comprises less than 1% to 14% of the sediments collected in the LID facilities. Usually, the pre-treatment facilities of stormwater LID were designed to treat first flush during storm events. These findings complement the results of Egodawatta & Goonetilleke (2008) and Muthusamy et al. (2018) that most of the sediments washed off during the first flush were either <200 μm or 0 to 1,000 μm, respectively. As shown in Figure 4, greater average N and P concentrations were found in silt particles amounting to 345 mg/kg and 696 mg/kg, respectively, compared to sand and gravel. However, silt was found to be the lowest contributor of N and P loads in the sediment of about 5% to 7% only due to its relatively low fraction of the total weight of the sediments collected compared to sand and gravel. Sand contributed the highest nutrient load in the sediments collected from the pre-treatment basins of the LID technologies containing 80% and 79% of the present N and P loads, respectively. Although, N concentrations in accumulated sediments were found to be highly variable at different particle sizes with coefficient of variation (CV) ranging from 0.24 to 0.77 compared to P concentration (CV: 0.08 to 0.36). This finding was attributed to the effective P treatment mechanism through deposition compared to complex nitrogen removal mechanisms (Boers et al. 1998). By enhancing the silt deposition or settling in the sedimentation basins of the LID technologies, the overall nutrient treatment performance of the LID technologies may be expected. It was found that the P concentrations found in the sediments of the different stormwater LID technologies of this study were almost in the same range as that of the study conducted by Dalu et al. 2018. It was also found in the same study that P concentrations in urban sediments may be as high as 2.5 times that of agricultural sediments (Dalu et al. 2018).
On the other hand, the N concentration in sediments collected from an urban river receiving runoff from agricultural areas were found to be ten folds higher than the N concentration in this study (Huang et al. 2018). Sediment accumulation rate was greater in IT by almost three to four times compared to HCW1 and HCW2 due to the recurring wet and dry state of the pre-treatment basin of IT. This occurrence was the result of employing infiltration mechanism in IT which was not present both in HCW1 and HCW2 causing the pre-treatment basins to be ponded even during the days without storm events. The comparison between N and P concentrations of collected sediments and in-situ soil is shown in Figure 5. Sediment N concentrations were 10% to 66% greater than the in-situ soil. On the other hand, P concentrations of the sediments collected in LID pre-treatment basins were almost two to three times greater than the P concentration of in-situ soil. The difference between the concentrations was attributed to the continuous pollutant input to the LID technologies during storm events which were initially received by the pre-treatment basins. It was identified that the dominant P form in sediment was organic P followed by NAIP. The difference in P concentration in collected sediment and soil was mainly due to the loss of organic P in soil. The dynamics of soil organic P forms were greatly influenced by the interactions of biological, chemical and physical properties of soil (Stewart & Tiessen 1987).

Design of pre-treatment basin of LID technologies considering nutrient load accumulation rate

Design criteria for LID technologies such as bioretention focus on rainfall, flood and water-quality control which were estimated based on the surface to catchment area ratio (Chin 2017). However, in Korea, designers of stormwater treatment technologies considered first flush criteria for sizing (Lee et al. 2010). In order to effectively design similar LID technologies considering the nutrient load accumulation rate, regression plots shown in Figure 6 were generated. The relationship of both pre-treatment basin volume to catchment area ratio (PV/CA) and the storage volume to catchment area ratio (SV/CA) to the nutrient load accumulation rate in the pre-treatment basins of LID technologies were considered in the development of this design criteria. Apparently, an increase in the PV/CA or SV/CA corresponded to increased nutrient load accumulation capacity of the LID technologies. Considering an LID facility with N or P load accumulation rate of 50 mg/m²-yr, PV/CA and SV/CA ratio ranging from 0.19 to 0.21 and 0.57 to 0.82, respectively, must be considered.

CONCLUSIONS

Understanding the nutrient concentration variability in sediments accumulated in LID technologies proved the importance of pre-treatment basins in reinforcing the nutrient removal performances of stormwater LID technologies through sediment retention. Based on the results of this study, it was found that hydrologic factors including ADD, rainfall depth, rainfall duration and runoff duration affected the transport of TSS, TN and TP in urban catchments. Transport of TSS in urban catchments and inside LID facilities was also identified as an affecting factor for nutrient transport. However, linear regression analysis revealed that only TP load removal efficiency was found to be highly affected by TSS load removal efficiency (R² = 0.63, p < 0.001). The analysis of nutrient concentration in varying sediment particle sizes demonstrated that greater N and P
concentrations were found in silt particles compared to sand and gravel. In addition, the difference between N and P concentrations of sediments collected in the pre-treatment basins of LID technologies and *in-situ* soil was attributed to the continuous pollutant input to the LID technologies during storm events. Depending on the target nutrient load accumulation rate, estimation of PV/CA and SV/CA may be conducted based on the regression model developed in this study. It is recommended that nutrient concentrations of accumulated sediments in the pre-treatment basins of LID technologies be used to classify the treatment mechanisms occurring inside each unit in the system. The findings of this research may be used to design pre-treatment basins of LID technologies considering nutrients as a limiting factor.

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