Article
Assessment of Factors Affecting the Removal Efficiency of Suspended Solids and Particulate Matters for Pretreatment Units in a Stormwater Management Facility

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Abstract: Non-point source (NPS) pollution is one of the primary sources of contamination in aquatic systems, such as rivers and lakes. Various techniques and devices, including low impact development (LID) and best management practice (BMP) devices, can reduce NPS pollution. These devices are installed with pretreatment units to remove NPS pollutants more efficiently and to facilitate maintenance. In this study, suspended solids (SS) and particle size distributions (PSD) were investigated in a pilot-scale facility to determine the effect of various pretreatment unit types and inflows on SS removal. We found that the efficiency of SS concentration and particulate matter removal changed significantly (p < 0.05) based on the aspect ratio of the pretreatment unit. Three flow conditions were also tested (10, 15, and 20 m³/h); SS removal was most efficient at 15 m³/h. These findings can be applied to the design of NPS management facilities, which is expected to help increase the efficiency of new NPS facilities while reducing operating costs.

Keywords: stormwater runoff; pretreatment unit; aspect ratio; water quality management

1. Introduction

Non-point source (NPS) pollution is a primary source of pollution affecting water quality [1–3]. The discharge characteristics of sediment-related pollutants, which include nutrients, heavy metals, pathogens, and suspended solids (SS), vary according to the land use; roads, industrial areas, and paddy fields create different types of sediment-related pollutants. Recent changes in rainfall patterns due to climate change and an increase in impermeable surfaces due to urbanization are accelerating the discharge of sediment-related pollutants [4,5]. NPS pollution in urban areas is characterized by a high initial concentration and a rapid decrease in concentration; these characteristics are important for water-quality management.

To mitigate these first-flush NPS discharges, many technologies and techniques, including stormwater best management practice (BMP) devices, sustainable urban drainage systems (SUDS), low-impact development (LID), and green infrastructures (GI), have been installed on various surfaces in urban areas [6,7]. Several factors affect the performance of stormwater treatment technologies and techniques: 1) runoff characteristics, such as particle size distribution and the concentrations of pollutants; 2) hydraulic loading rate (HLR); 3) runoff volume; and 4) treatment type, such as hydrodynamic, filtration, and bio-media mix [8–10].

These technologies may include one or more pretreatment units to more efficiently remove sediment-related pollutants from stormwater, to dissipate the incoming runoff energy, and to facilitate sustainable maintenance [11,12]. The pretreatment unit removes particles, solids, and floating materials...
before the stormwater flows into the main system. This role of pretreatment units helps to reduce the maintenance cost of NPS pollution management facilities and improve the main treatment function of the filtration units.

Multiple studies on pretreatment at NPS management facilities have evaluated the efficiency of pretreatment units, especially the effect of a pretreatment unit’s sedimentation function. Maniquiz et al. reported the relationship between surface area (SA) and storage volume (SV) of the pretreatment section based on field experiments conducted under various rainfall conditions [12]. The research revealed that the storage volume ratio could determine the treatment capacity of stormwater runoff and sediment and also affect maintenance frequency, such as sediment dredging. Edwards et al. revealed that when designing a dry well for the purpose of preventing contamination of groundwater by initial rainfall-runoff, the inclusion of a pretreatment function can reduce clogging due to siltation and reduce contamination levels [11]. The Technology Acceptance Reciprocity Partnership (TARP) for California, Massachusetts, Maryland, New Jersey, Pennsylvania, and Virginia State and the Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies (TAPE) for Washington State, the NPS pollution management facilities in the United States, use particle size distribution (PSD), percent solids, and grain size to define the sedimentation function of the pretreatment unit [13,14]. This implies that the main function of the pretreatment unit is related to the sedimentation of particulate matter, and the evaluation of the function of the pretreatment unit might be directly related to the evaluation of the efficiency of removal of NPS pollution.

Pretreatment units can be applied to rainwater management facilities, such as stormwater BMP units or LID practices, to facilitate maintenance and maintain high efficiency in pollutant treatment units. Since stormwater BMP devices are often installed in urban areas, the size and shape of the pretreatment unit affect the cost of installing the facility. However, even though multiple studies addressing the function of the pretreatment units have been conducted, little research has been conducted to improve the SS reduction efficiency of the pretreatment units. Therefore, the objectives of this study are: (1) to investigate the differences in SS removal efficiency by type of pretreatment unit; and (2) to identify the factors that affect pretreatment removal efficiency.

2. Materials and Methods

2.1. Manufacturing Stormwater; Pilot-Scale Tests

The simulated stormwater was produced according to the test water production method described in the Non-Point Pollution Reduction Facility Performance Test Manual of the Ministry of the Environment (NPPT manual), Korea [15]. Particles up to 200 µm were used in the preparation, and the product concentration was between 150 and 350 mg/L SS. According to the NPPT manual, particles under 64 µm account for 60% to 70% of the total volume; and particles that are 64 µm to 200 µm account for 20% to 30% of the total volume (Figure 1). The soil used to produce the test water was loess. The loess mixture was shaken in a 200-µm sieve shaker for 10 min. Loess particles smaller than 200 µm were stirred with a propeller in a 5-ton agitator. The stormwater produced in this way was pumped into the stormwater BMP device under test conditions at a maximum flow rate of 20 m³/h using a submersible pump (Model IP-835N-F, produced by Hanil electric Co., Ltd., Seoul, Korea).

2.2. Description of Stormwater Best Management Practice (BMP) Devices

Two types of stormwater BMP devices were selected for this study based on their pretreatment aspect ratios. Both devices were made of stainless steel. These devices had aspect ratios of 4:1 and 1:1. The inlet for the stormwater manufactured in the agitator was located at the upper left side of the filter section. The outlet for the treated water was located at the upper right side of the filter section. Each device had two pretreatment units: pretreatment unit1 (PTU 1) and PTU 2 (Figure 2a,b). The experimental water was pumped into each device and then sequentially passed through PTU 1
and PTU 2. The diameter of the inlet was 65 mm, and the outlet was 100 mm. Both devices had a minimum filtration area of 1 m² required by the NPPT manual.

Figure 1. PSD profiles of the simulated stormwater for this study.

Figure 2. Schematic figure for stormwater best management practice (BMP) devices used in this study. The figure on the left (A) indicates the aspect ratio 1:1, and the figure on the right (B) indicates the aspect ratio 1:4. The dotted lines show the flow direction of the manufactured stormwater, and the stars indicate sampling points. Aspect ratio means that the ratio of width to length in the pretreatment unit.

2.3. Analysis of Particle Size Distribution (PSD) and Suspended Solids (SS)

The sediment particles on each PTU were measured using a particle size analyzer (LIXELL, QICPIC, produced by Sympatec GmbH, Clausthal-Zellerfeld, Germany). This instrument can measure particles from 1 to 2000 µm; its main method of particle size analysis is laser diffraction. The laser diffraction method measures particle distribution by measuring the variation in the angle of the light scattered when the laser beam passes through the water sample. Large particles scatter light at smaller angles, while small particles scatter light at larger angles. The refractive index value was an automated process by the laser diffraction unit. Particle size distribution, thus measured, is reported as the volume equivalent sphere diameter.

SS concentrations in the initial inflow, after passing through PTU 1, and after PTU 2, were measured using the standard method [16]. This method involves first weighing the glass fiber filter (1.2 µm) attached to the filter, filtering a certain amount of the sample, drying at 105 °C for more than 1 h in a
2.4. Inflow Rate and SS Removal Performance Test in the Pretreatment Section

To identify the efficiency of SS removal during the pretreatment process, water samples were collected at inflow, after PTU 1, and after PTU 2. The sampling interval was 10 min, and seven samples were taken at each step. All samples were collected using a vertical point water sampler (Model number: CL-MW13L, produced by Daihan Chemlab, Incheon, Korea). To measure SS removal efficiency, seven inflow and outflow SS concentrations were analyzed for each flow condition and for each aspect ratio. Each sample was analyzed in triplicate to guarantee data quality, and the average value was used to calculate the processing efficiency. The removal efficiency calculation was as follows:

\[
\text{Removal efficiency} (\%) = \frac{\text{SS Concentration}_{\text{inflow}} - \text{SS Concentration}_{\text{outflow}}}{\text{SS Concentration}_{\text{inflow}}} \times 100
\]

The efficiency of SS removal during each step of the pretreatment unit was analyzed; three inflow rates were compared to identify how the inflow rate affects SS removal efficiency. The inflow was adjusted to 20, 15, and 10 m³/h based on the standard linear velocity of 20 m/h or less, which is recommended by the NPPT manual [15].

Each flow rate was controlled by the flow regulating valve. The inflow rate is important for two reasons. Not only is the design capacity of the stormwater BMP facility determined based on inflow rate, but also the performance of the facility in terms of SS removal efficiency can be calculated based on the inflow rate.

2.5. Statistical Approach

One-way analysis of variance (ANOVA) with post hoc tests was used to compare SS removal efficiency under the different shapes of pretreatment units and flow rates at a significance level of \( p < 0.05 \). \( t \)-tests were used to compare SS removal efficiency and flow rates. A Shapiro–Wilk test was performed to confirm the normal distribution. \( p \)-values of Shapiro-Wilk Test in flow rate 10 m³/h, 15 m³/h, and 20 m³/h were 0.740, 0.915, 0.379 for PTU 1 and 0.985, 0.161, 0.861 for PTU 2, respectively. This means that the data is normal distribution. All statistical analyses were conducted using IBM statistical product and service solution (IBM SPSS, New York, NY, USA) 21.0 for Windows.

3. Results

3.1. Removal Efficiency of Each Pretreatment According to the Aspect Ratio

SS removal efficiency was higher with the aspect ratio of 1:4 than 1:1 for all three inflow rates (see Figure 3 and Supplementary Information Tables S1 and S2). The highest removal efficiency (37.2%) occurred with the aspect ratio 1:4 and inflow of 15 m³/h. The lowest SS removal efficiency (13.9%) occurred with the aspect ratio 1:1 and inflow of 20 m³/h (Supplementary Information Table S1). This indicates that the SS removal efficiency of pretreatment units likely differs depending on the type of pretreatment unit and the inflow rate.

At an inflow rate of 10 m³/h, SS removal efficiency differed significantly for the two aspect ratios at PTU 1 (\( p < 0.05 \)); there was no difference at PTU 2 (\( p > 0.05 \)) for the two aspect ratios. At a flow rate of 15 m³/h, removal efficiency at PTU 2 differed significantly (\( p < 0.05 \)) from that at a linear velocity of 10 m/h. At a flow rate of 20 m³/h, removal efficiency differed significantly at PTU 1, PTU 2, and TOTAL (Table S2). These results show that, although the aspect ratio might not affect removal efficiency during the pretreatment stage, it makes a clear difference to total SS removal efficiency.
3.2. Removal Efficiency of Each Pretreatment According to Inflow Rate

Table 1 shows the differences in removal efficiency according to the influent flow rate. At PTU 1, several groups show significant differences in SS removal efficiency. The 10 m$^3$/h and 15 m$^3$/h flow rates differ significantly at PTU 1; 15 m$^3$/h and 20 m$^3$/h differ at PTU 1 when the aspect ratio is 1:1 ($p < 0.05$); and for factors 10 m$^3$/h and 20 m$^3$/h ($p > 0.05$), there is no difference at PTU 1. The 10 m$^3$/h and 20 m$^3$/h flow rates differ significantly with the aspect ratio 1:4 ($p < 0.05$); there is no difference between the other groups when the aspect ratio is 1:4.

| Unit | Factor 1 (Flow Rate) | Factor 2 (Flow Rate) | p-Value at 0.05 Significant Level |
|------|----------------------|----------------------|----------------------------------|
|      |                      |                      | Aspect Ratio 1:1 | Aspect Ratio 1:4 |
| PTU 1 | 10 m$^3$/h           | 15 m$^3$/h           | 0.034              | 0.849              |
|       | 15 m$^3$/h           | 20 m$^3$/h           | 0.177              | 0.030              |
|       | 20 m$^3$/h           | 10 m$^3$/h           | 0.034              | 0.849              |
|       | 15 m$^3$/h           | 20 m$^3$/h           | 0.001              | 0.089              |
|       | 20 m$^3$/h           | 10 m$^3$/h           | 0.177              | 0.030              |
|       | 15 m$^3$/h           | 15 m$^3$/h           | 0.001              | 0.089              |
| PTU 2 | 10 m$^3$/h           | 15 m$^3$/h           | 0.010              | 0.022              |
|       | 15 m$^3$/h           | 20 m$^3$/h           | 0.328              | 0.170              |
|       | 20 m$^3$/h           | 10 m$^3$/h           | 0.010              | 0.022              |
|       | 15 m$^3$/h           | 20 m$^3$/h           | 0.000              | 0.559              |
|       | 20 m$^3$/h           | 10 m$^3$/h           | 0.328              | 0.170              |
|       | 15 m$^3$/h           | 15 m$^3$/h           | 0.000              | 0.559              |

Note. Bold refers to a value with a p-value less than 0.05.

At PTU 2, 10 m$^3$/h and 15 m$^3$/h differ significantly when the aspect ratio is 1:1 or 1:4 ($p < 0.05$). The 15 m$^3$/h and 20 m$^3$/h flow rates differ when the aspect ratio is 1:1 ($p < 0.05$). There is no significant difference between 10 m$^3$/h and 20 m$^3$/h for aspect ratio 1:1 or 1:4, nor for 15 m$^3$/h and 20 m$^3$/h for aspect ratio 1:4 ($p > 0.05$). These results show that the flow rate significantly affects SS removal efficiency at both PTU 1 and PTU 2.

3.3. Particle Size Distributions of Sediments on the Bottom of Pretreatment Unit 1 (PTU 1) and PTU 2

After SS removal efficiency was tested at PTU 1 and PTU 2, the sediments on the bottom of each PTU were collected and measured to identify changes in particle sizes. Figure 4 shows the cumulative distribution and density distribution for PTU 1 and PTU 2 for each aspect ratio. At the 1:1 aspect ratio, PTU 2 contains relatively more particles up to 50 µm (corresponding to fine sand), and PTU 1
contains more particles larger than 50 µm. This indicates that relatively heavy particles were deposited on the bottom of PTU 1, and most smaller particles were deposited in PTU 2. At the 1:4 aspect ratio, the distribution of particulate matter in PTU 1 and PTU 2 is similar to that for aspect ratio 1:1. These results mean that it is necessary to review the aspect ratio adjustment of the pretreatment unit in order to increase the SS removal efficiency of the pretreatment unit according to the characteristics of particulate matter discharged from the watershed during rainfall. The results also indicate that it is necessary to install an aspect ratio of 1:4 for areas where the particulate matter of various sizes continuously flows into the device during rainfall.

Figure 4. Particle density distributions for sediment on the bottom of each pretreatment unit. The eight lines indicate the cumulative distributions and density distribution for aspect ratios 1:1 and 1:4, respectively.

4. Discussion

Pretreatment units are part of the design and construction of NPS management facilities; the costs associated with pretreatment units are related to the total operational costs of the facility. Therefore, it is important to determine the optimal flow rate to minimize costs [12,17–19].

To reduce the construction and maintenance costs of the NPS management facility, the capacity of the pretreatment unit should be minimized [2,20,21]. For NPS management facilities installed in Korea, SS treatment efficiency should be guaranteed to be more than 80% [22]. In this study, pilot-scale experiments were conducted under three inflow conditions to ascertain the maximum available capacity. The results indicate that, of the three inflow rates tested, the pretreatment unit’s SS removal efficiency was highest at an inflow rate of 15 m$^3$/h.

To improve the SS removal efficiency, a pretreatment unit aspect ratio of 1:4 is likely better than 1:1, and a test flow condition of 15 m$^3$/h is likely better than 20 m$^3$/h. That is, the conditions in which the highest removal efficiency can be expected are when the aspect ratio is 1:4, and the flow rate is 15 m$^3$/h. The 15 m$^3$/h inflow rate is 75% of the maximum inflow rate permitted by the NPPT manual (20 m$^3$/h). This means that the NPS management facility will require 33% more space than when the pretreatment unit’s inflow is 20 m$^3$/h. As a result, construction costs and maintenance costs could increase after construction.

An additional point to consider when designing the pretreatment unit is the particle sizes that each pretreatment unit can handle. As shown in Figure 4, with an aspect ratio of 1:1, most particles
larger than 67 µm were reduced and deposited on the bottom of PTU 1, and most particles smaller than 67 µm were reduced and deposited on the bottom of PTU 2. With an aspect ratio of 1:4, relatively uniform particle size ranges were deposited in PTU 1 and PTU 2. This means that it is possible to improve the efficiency of NPS pollution reduction by selecting an appropriate aspect ratio according to the distribution of particulate matter washed out in the watershed or by enlarging the scale of a specific pretreatment unit (PTU 1 or PTU 2) to handle the more common particle sizes.

Therefore, the following issues should be considered in the design of the pretreatment tank:

- The characterization of the particulate matter washed out from the watershed during rainfall events.
- The optimal aspect ratio for the pretreatment unit considering operation and maintenance costs.
- The capacity of each pretreatment unit with respect to inflow rates.

5. Conclusions

Based on these results and the discussion of the findings, we present the following conclusions:

- Pretreatment units play an important role in NPS management facilities, and the removal efficiency of these units may vary depending on their shape and structure.
- Among the variables considered in this study, aspect ratio and flow rate were found to affect the SS removal efficiency. In addition, there was a difference in particle sizes settling in each pretreatment unit.
- To improve the efficiency of SS reduction in pretreatment units, it is necessary to design pretreatment units that can take into account the NPS pollution discharge characteristics of the watershed and control the inflow rate.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/6/1529/s1, Table S1: Changes of SS concentrations (mg/L) and removal efficiency (%) by pretreatment stage according to aspect ratio and inflow rate., Table S2: Comparison of SS at 1:1 versus 1:4 rations at the three sampling points by flow rate.

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