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Post-treatment schemes of the outflow from hydrocyclone treating paved-road stormwater runoff

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ABSTRACT

Results of water quality analysis indicated that the outflow from a hydrocyclone treating road runoff still requires further treatment before discharging into receiving waters. Hence, several treatment designs were presented for the post-treatment of the hydrocyclone outflow (including pollutant-concentrated underflow and pollutant-separated overflow). The design criteria were based on some of the main affecting factors, such as treatment level, land availability, and construction cost. With respect to the determination of the treatment goal, the primary consideration should lie on the water quality requirement. The treatment should normally include both underflow and overflow depending on the required discharged water quality. In terms of the treatment method selection, land availability and construction cost should be considered first in the design. In order to achieve the most appropriate treatment, the design process should be based on the overall analysis of the affecting factors and local conditions. In this study, three types of post-treatment (vertical sub-surface flow wetland, baffled settling tank and surface sand filter) were proposed for dealing with highly concentrated underflow from a hydrocyclone. For the treatment of both underflow and overflow, the wetland system equipped with a settling tank or a sand filter was recommended under the conditions that further treatment is required and the land and funding are available.

Keywords: Best management practices; Design criteria; Outflow from hydrocyclone; Post-treatment; Stormwater runoff

1. Introduction

Stormwater runoff from paved areas such as highways, roads, parking lots and bridges has been identified as critical non-point source pollution. It may be discharged directly, or as treated effluent into receiving environments such as aquifers, watercourses, and wetlands [1–3]. The typical pollutant constituents of primary concern include suspended

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solids, nutrients (nitrogen and phosphorus compounds), heavy metals (e.g. Cd, Cr, Cu, Mn, Ni, Pb, Pt, and Zn), Polycyclic Aromatic Hydrocarbons, mineral, oil, and grease [4]. A characteristic of pollutant emissions from stormwater is the first flush (FF) phenomenon, which implies a great discharge rate of pollutant mass or concentration in the early part of the runoff volume compared with the remainder of a storm [5–7].

The receiving environment may be sensitive to flooding, scouring, erosion and siltation problems caused by large volumes of runoff discharged to watercourses [1]. The integrated effects of both pollutants and runoff flow are critical. Their effects include physical habitat changes (such as flooding, erosion, and sediment deposition), dissolved oxygen depletion, eutrophication, public health risks, and esthetic, and public perception. Therefore, more concerns should be paid on the management of road stormwater, and careful consideration is required to guide each stage in the selection, construction and maintenance of the treatment facilities [7–9].

Many types of best management practices (BMPs) have been used in the control of urban runoff [10]. Hydrodynamic separators, sand filters and grit are mainly used for the reduction of sediments and hydrocarbons, while they are inefficient in the removal of dissolved pollutants and finer solids [1,11]. Vegetative systems, including filter strips, swales, detention basins, retention basins (balancing ponds), and constructed wetlands, can provide efficient treatment for many pollutants through physical or biochemical mechanisms [12].

Selection of appropriate methods for controlling stormwater runoff normally includes three aspects: BMP suitability for treating stormwater, physical feasibility of implementing the BMPs, and lastly community and environmental factors. In urban areas, the selection of the most appropriate design criteria is based on the following factors: local climate and storm event properties, traffic loadings, characteristics of served drainage area and site, space availability, size/extent and type of receiving water body, and treatment objectives [13]. A proper BMP design should meet the main affecting factors according to the local conditions.

In the last several years in Korea, a hydrocyclone stormwater treatment device was developed to separate the sediments from paved road runoff as a pre-treatment process. The application of the hydrocyclone is attractive in space-limited urban areas because it is compact in size, cost-saving, has enhanced separation efficiency and is eco-friendly. However, the shortcomings of this device are that it is inefficient in separating dissolved pollutants and finer solids, and the outflow water quality is far from the required water quality. In this study, we focused on the system design for post-treatment. The objective was to give several different treatment schemes and evaluate their applicability based on the design criteria.

2. Problem description

2.1. Hydrocyclone treatment

The pilot-scale test bed was installed under the bridge on a National Road in Seosan City, Korea (fig. 1(a)). As runoff flows through the unit, hydrodynamic forces cause solids to begin settling out. Both the quality and quantity of stormwater runoff can be regulated in this unit. Balancing the runoff storage and water quality requirements, the treatment targets only the highly polluted FF (V_F in fig. 1).

Based on the results of the previous study, approximately 13% of the total runoff was captured as the FF in a rainfall event, and this water was separated into solids-concentrated underflow and solids-diluted overflow (Fig. 2). The volumetric percentages of

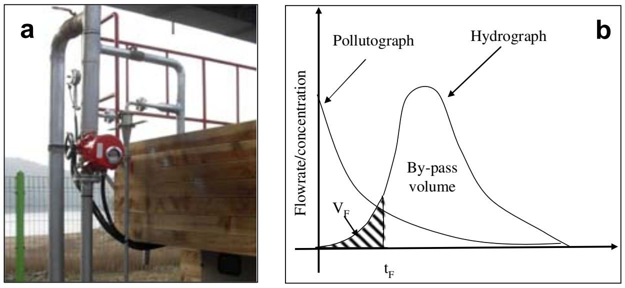

Fig. 1. Treatment of FF runoff using a hydrocyclone: (a), the picture of the hydrocyclone *in situ* (b), the FF needing treatment.

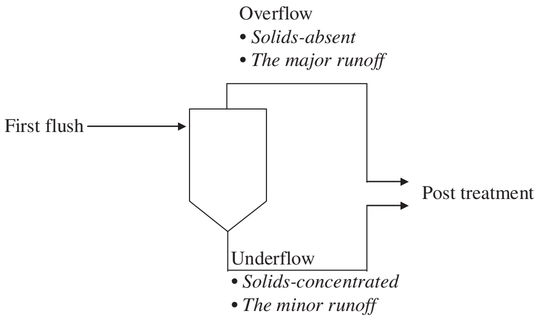

Fig. 2. Separation of the captured FF: pollutants-concentrated underflow and pollutants-diluted overflow.

Table 1
Water quality and significant difference analysis of underflow and overflow

Items	Average concentration (mg/L)		95% confidence interval of the difference		*T* test *P* value	Significant difference between underflow and overflow ($p < 0.05$)
	Under	Over	Lower	Upper		
TSS	360.8 ± 582.5	130.3 ± 174.2	140.9	320.2	0.000	Yes
COD	79.4 ± 65.1	47.0 ± 47.1	18.1	46.7	0.000	Yes
TN	4.19 ± 2.32	3.66 ± 2.36	0.17	0.91	0.005	Yes
TP	0.66 ± 0.69	0.41 ± 0.39	0.13	0.38	0.000	Yes

underflow and overflow were 29 and 71%, respectively. The corresponding percentages for total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) were 71 and 29%, 59 and 41%, 7.6 and 92.4%, and 49 and 51%, respectively. Hence, it can be concluded that the main functions of the hydrocyclone are runoff quantity control (treatment targets only the 13% of the total runoff) and pollutant separation, which are the main purposes of the application of the hydrocyclone in the primary treatment.

2.2. Water quality of outflow from the hydrocyclone

A total of 105 samples collected from 6 rainfall events were used in the water quality analysis. It is evident that the pollutant (including TSS, COD, TN, and TP) concentrations were significantly higher in the underflow than in the overflow. In the underflow, the average concentrations for TSS, COD, TN, and TP were 360.8, 79.4, 4.19, and 0.66 mg/L, respectively. The corresponding values for the overflow were 130.3, 47.0, 3.66, and 0.41 mg/L, respectively. Statistical significance analysis indicated a significant difference between the underflow and overflow (Table 1). This means the underflow is pollutants-concentrated and the overflow is pollutants-separated after the hydrocyclone treatment.

The New Jersey Administrative Code suggests that the TSS concentration of surface runoff should not exceed 40 mg/L and the maximum concentrations of TN and TP should be 1.5 and 0.05 mg/L, respectively [14]. Therefore, the outflow from the hydrocyclone still requires further treatment.

3. Solutions

An appropriate treatment process should meet the local conditions and some main affecting parameters, such as land and funding availability and water treatment objectives. Considering these affecting factors and the water quality of the outflow from the hydrocyclone, the post-treatment design can be initiated with the consideration of the criteria presented in Fig. 3.

As to the target water, the treatment could include both underflow and overflow depending on the water quality required; otherwise, the treatment only targets the highly polluted underflow if further treatment is not required. With respect to the selection of treatment methods, an integrated system can be employed when the land/finance availability is not limited; otherwise, a single method can be used. Most importantly, the design procedures should be based on the overall analysis of the affecting factors and the local conditions in order to determine the most appropriate treatment.

3.1. Treatment underflow

3.1.1. Wetland

In general, stormwater treatment wetlands provide the potential to improve runoff quality for a number of pollutants. It was reported that 65 ~ 80% of TSS, 83% of nitrite and nitrate, 45% of ammonia, and 40 ~ 50% of TP can be removed by wetlands [15]. In principle, two types of constructed wetlands can be used to provide treatment for road runoff: surface flow system and sub-surface flow (SSF) system [1]. In this study, a vertical SSF wetland was applied to treat

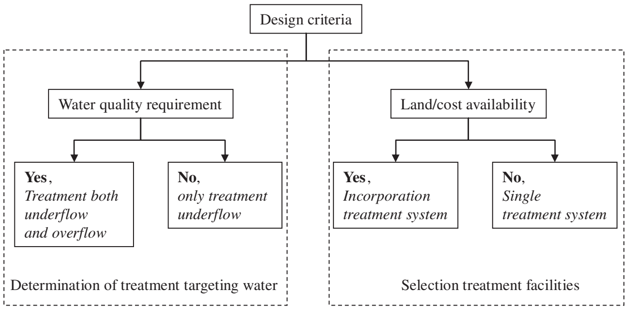

Fig. 3. Design criteria for the post treatment.

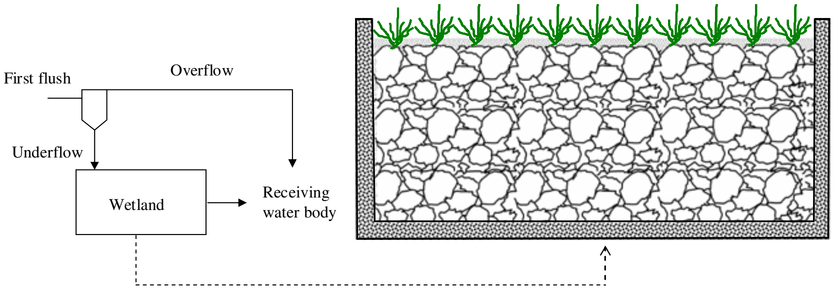

Fig. 4. Schematic diagram of sub-surface vertical flow wetland used for post treatment.

the underflow (Fig. 4). The reason for this selection is that a SSF wetland can provide the maximum potential treatment for the road runoff. Also, the vertical flow wetland requires less land compared with other types of wetlands [16]. Moreover, the post treatment only targets underflow, and thus, SSF can be constructed into a compact size.

In order to achieve a satisfactory treatment, the following factors have to be considered in the design of the wetland: A balance must be struck between the incoming hydraulic and pollutant loads and the size/containment. The minimum ratio of the area of wetland to watershed was recommended to be 1%. Accordingly, this ratio should be reduced to 0.038% in the case of underflow treatment only (1% × 13% × 29%, when the FF runoff is collected and treated with hydrocyclone).

- The aspect of ratio (length to width) should be in the range of 1:1 ~ 1:2, and the minimum substrate bed depth is 0.6 m [17,18].
- As to wetland media, the selection of the proper media involves the specification of grain size, media porosity, media depth, and hydraulic conductivity. Generally, the media should have a high porosity to reduce clogging and should also indicate a low adsorption capacity to prevent the accumulation of pollutants [19,20].
- Hydraulic conductivity is another important determinant in pollutant removal, especially in the SSF wetland where purification processes are largely confined to the root zone. The ideal range of hydraulic conductivity is from 10–3 m/s to 10–2 m/s [1].

Here, we assumed that the served road surface area was $10{,}000\,\mathrm{m}^2$, and thus, the minimum surface area of the wetland was $10{,}000\,\mathrm{m}^2 \times 0.038\% = 3.8\,\mathrm{m}^2$. With the rainfall intensity of 10 mm/h during the FF, the hydraulic loading rate (HLR) can be calculated as follows:

$$\begin{aligned}\mathrm{HLR} &= \frac{10,000\ \mathrm{m}^2 \times 10\ \mathrm{mm/h} \times 10^{-3}\ \mathrm{m/mm} \times 13\% \times 29\%}{3.8\ \mathrm{m}^2}\\ &\approx 1\ \mathrm{m/day}\end{aligned} \tag{1}$$

This means that HLR cannot exceed 1 m/day according to the design criteria discussed above. This is reasonable and acceptable because the optimal HLR should be less than 1 m/day in order to achieve a satisfactory treatment [1].

The advantages of the vertical SSF wetland are simple operation, low maintenance cost, and enhanced esthetics of the site. Also, it can function as a filter during the cold period while vegetation is out of work. The disadvantages are the clogging caused by the high TSS load to the wetland, and seasonal variations in treatment and pollutant removal efficiencies. In addition, a constructed wetland requires 1 ~ 3 years to mature and become efficient [1]. Also, the overall treatment is not good because overflow is discharged directly to the receiving waters.

3.1.2. Settling tank

Settling tanks have been widely used in the treatment of stormwater runoff [21]. They can efficiently remove settleable solids and floating materials [22]. In this case, a baffled tank system is recommended to treat the underflow (Fig. 5). In this system, a single tank is divided into several compartments using a number of baffles. The baffles slow the water down by forcing the water to flow to the left and right.

The design of the settling tank is controlled by four important elements: flow rate, settling time, size of the system, and the removal ability of solids. The flow rate needs to be slow enough and the retention

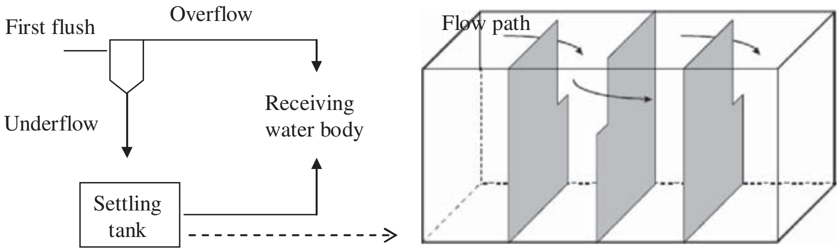

Fig. 5. Baffled tank design for the post treatment of underflow.

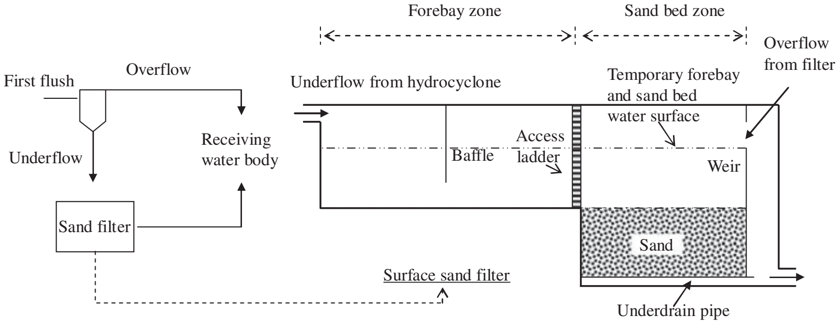

Fig. 6. Treatment underflow using surface sand filter.

time needs to be long enough to allow particles to settle down. In terms of the system size, particle size and tank configuration (length, width, and depth) should be considered. If we assume a served road surface area of 10,000 m^2, the rainfall intensity during the FF is 10 mm/h, and the typical design overflow rate is 1.5 $\text{m}^3/\text{m}^2\,\text{h}$ [22]. The flow rate to the settling tank is:

$$10000\ \text{m}^2 \times 10\ \text{mm/h} \times 10^{-3}\ \text{m/mm} \times 13\% \times 29\% = 3.77\ \text{m}^3/\text{h} \tag{2}$$

Thus, surface area can be calculated using the following formula:

$$\text{Surface area } (\text{m}^2) = \frac{\text{Flow rate } (\text{m}^3/\text{h})}{\text{Overflow rate}} = 2.5\ \text{m}^2 \tag{3}$$

The advantages of this method are low installation and maintenance cost, less skill requirement, little energy use, and less space requirement. The disadvantages are low removal efficiency for fine particles and low overall treatment efficiency.

3.1.3. Filtration

Filtration of stormwater through a specially constructed filter system is one of the possible treatment methods. It is considered as a promising practice for reducing dissolved and particulate pollutants [4,23]. The main removal mechanisms applied in the filtration system include a variety of physical and chemical processes, including sedimentation, precipitation, adsorption, absorption, ion exchange and complexation reactions [5,23,24].

A surface sand filter is recommended for the treatment of underflow in this case. It was developed several decades ago to actively treat runoff on an appropriate technology basis. In general, all sand filters consist of four basic components or zones: (1) Forebay Zone, (2) Sand Bed Zone, (3) Sand Bed Underdrain, and (4) Overflow (Fig. 6). The approximate temporary forebay volume should equal to the temporary sand bed volume, and the volume sum of both the forebay zone and the sand bed zone should equal to the total underflow volume from one rainfall event (Fig. 6). In addition, the length-to-width ratio of the overall sand filter should be no less than 2:1. The area of the filter bed zone (A_{f}) should be sized based on the principles of Darcy’s Law [25]:

$$A_{\text{f}} = \frac{\text{WQV} \times d_{\text{f}}}{k \times (h_{\text{f}} + d_{\text{f}}) \times t_{\text{f}}} \tag{4}$$

where WQV = water quality volume

d_{f} = sand filter bed depth

k = coefficient of permeability for sand bed

h_{f} = average height of water above the sand bed ($\leqslant$ 0.45 m)

t_{f} = time required for the WQV to filter through the sand bed

Table 2
Typical surface sand filter design parameters (source: New Jersey stormwater BMPs manual, 2004)

Parameter	Minimum thickness (d_f)	Porosity	Permeability (k)	Design drain time (t_f)	Minimum surface area (A_f)
Value	0.45 m	0.3	1.21 m/day	1.5 day	See Eq. (1)

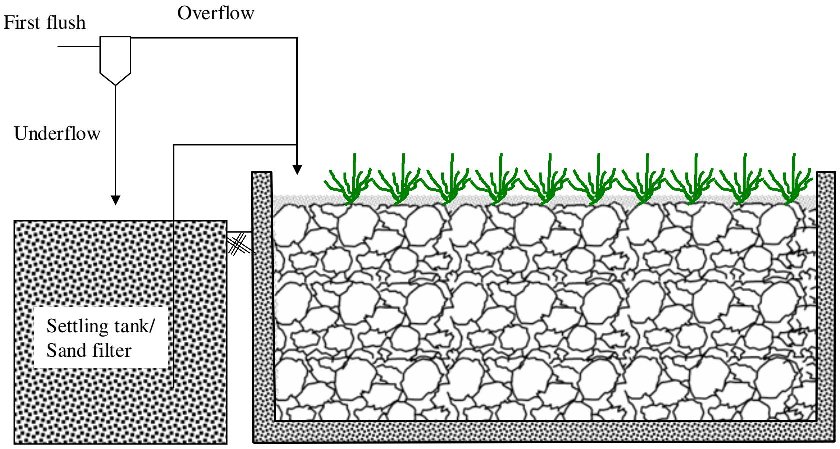

Fig. 7. Schematic diagram of the post treatment system: wetland equipped with a settling tank/sand filter.

Several of the design parameters of the sand bed are shown in Table 2.

As assumed above, the served road area is 10,000 m^2 and the rainfall intensity is 10 mm/h. If the duration of the FF is 0.5 h, the total underflow volume can be calculated as:

$$10,000\ \text{m}^2 \times 10\ \text{mm/h} \times 10^{-3}\ \text{m/mm} \times 0.5\ \text{h} \times 13\% \times 29\% = 1.9\ \text{m}^3 \quad (5)$$

If the average height of water above the sand bed (h_f) is set as 0.45 m, the area of the filter bed zone can be obtained according to Eq. (4). The values are listed in Table 2.

$$A_f = \frac{1.9\ \text{m}^3 \times 0.45\ \text{m}}{1.21\ \text{m/day} \times (0.45\ \text{m} + 0.45\ \text{m}) \times 1.5\ \text{day}} = 0.52\ \text{m}^2 \quad (6)$$

The advantages of this application are that it requires less space than other BMPs, and it can be used on highly developed and steeply sloped sites. The disadvantages are that the operation ends to clogging, requires frequent maintenance [26] and cannot efficiently remove dissolved pollutants.

3.2. Treatment of both underflow and overflow using equipped system

Wetland systems provide efficient treatment, especially for treating runoff with low TSS load or in systems with pre-treatment structures. The incorporation of solids separation facilities to reduce the pollutant load for the next treatment unit was already recommended by Shutes in the treatment of highway runoff [1]. Therefore, a settling tank or surface sand filter was installed prior to the constructed wetland in this case. Both underflow and overflow were treated through the wetland (Fig. 7).

In terms of the wetland size, the minimum ratio of the area of the wetland to watershed should be set as 0.13% (1 × 13%). The design of the settling tank or surface sand filter can follow the criteria presented in Sections 3.2 and 3.3. The advantages of this case are high removal efficiency and low TSS load to wetland. The disadvantages are complications in installation and high-cost requirements, and more land required than the single method treatment.

Overall, some features of the treatment approaches should be taken into considerations at the selection and design stage. Constructed wetland allows for more treatment mechanisms than settling tank and sand filter, and it is effective for stormwater quantity control to a certain extent. However, a major shortcoming of constructed wetlands is the large space they require. For settling tank and sand filter, even though they are space saving, their construction and maintenance cost is high and they are ineffective for stormwater quantity control.

4. Conclusions

The FF from stormwater runoff was captured and separated as solids-concentrated underflow and solids-removed overflow using a hydrocyclone. The water quality of the outflow from the hydrocyclone was analyzed. The result indicated that post-treatment is needed. In terms of the design and selection of post-treatment methods, the overall design criteria are that design has to meet the local conditions (land and funding availability) and the treatment objectives.

According to these criteria, several designs were proposed for the post-treatment of outflow. In consideration of saving cost and space, a single device, such as a vertical SSF wetland, a baffled settling tank or a surface sand filter, can be employed to treat the solids-concentrated underflow. The advantage of this solution is the ease of installation and operation, but the disadvantage is the low treatment efficiency. On the other hand, if the land and funding is not limited and further treatment is required, an integrated system of a wetland with a settling tank or a sand filter can be used to treat both underflow and overflow at the same time. This solution can guarantee high treatment efficiency, although it requires high construction cost and large land space.

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