Improving sediment removal in standard stormwater sumps
Yiyi Ma and David Z. Zhu

ABSTRACT

Standard sumps are an important component of our stormwater drainage system. Recently they have received significant attention as a stormwater pre-treatment device to remove sediment from stormwater runoff. The objective of this research is to explore some simple structures to be installed inside standard sumps to improve sediment removal efficiency. A number of structures were tested and two structures were found to be most effective in sediment removal. Both structures can increase the sediment removal rate by around 20–25% for sediment sizes of 80–140 μm and 110–170 μm under all tested flowrates, and 10–20% for sediment of 160–240 μm. The flow patterns in these structures were simulated using a numerical model, and the energy loss was also examined. The results of this study offer a new direction for the development of stormwater treatment devices.

Key words | flow, sediment removal, settling structure, stormwater, sumps

INTRODUCTION

Urban stormwater runoff is recognized as one of the pollution sources for the receiving water body. There are many contaminants in stormwater, such as total suspended solids, heavy metals, polycyclic aromatic hydrocarbons and nutrients. Sediment in stormwater is found to be the carrier for many pollutants (Aryal et al. 2010). Meantime, sediment itself increases the turbidity of the receiving water and thus impacts the photosynthesis of the organisms in water. It also can clog fish gills. After settling in water, sediment can influence water quality by sediment oxygen demand and the toxins accumulated in it.

The particle size distribution in stormwater sediment varies with catchment characteristics, rainfall intensity, surface runoff and its peak discharge, antecedent rainfall depth and dry period, etc. (Memon & Butler 2005; Brodie 2007; and Bai et al. 2013). Sansalone et al. (1998) measured the physical characteristics of solids transported in lateral pavement sheet flow from a roadway and found that nearly 10% of the solids by mass were smaller than 100 μm, 25–60% were 100–400 μm, and 40–70% were larger than 400 μm. German & Svensson (2002) characterized street sediment and showed that about 80% of the sediment was 75–2,000 μm. They also demonstrated that the largest amounts of metals, more than 50% of the heavy metals were found in fractions >125 μm. Similar findings were also reported by Sansalone & Tribouillard (1999), Ellis & Revitt (1982) and Stone & Marsalek (1996). However, some researchers have also reported much finer particle distribution. Roger et al. (1998) demonstrated that 90% of the solid matter by weight was in the form of particles smaller than 100 μm. Herngren et al. (2005) showed that up to 85% of the particles belonged to the size class of 0.45–75 μm while those larger than 300 μm only occupied 22%.

A variety of technologies have been reported for removing sediment in stormwater. Underground devices, which include hydrodynamic separators, underground settling devices and filters, are attractive due to their small footprint (Wilson et al. 2009). In recent years, it has been recognized that standard sumps can remove the sediment in stormwater. Given that standard sumps are commonly used in stormwater sewer systems, retrofitting them can be one method of stormwater treatment.

Howard et al. (2012) measured the sediment removal efficiency of several standard sumps in a laboratory setting. The sumps were 1.2 and 1.8 m in diameter, with various depths. Sediment groups of 89–125, 251–355 and 500–589 μm were chosen in the experiments. Their results show that when the flowrate was lower than 50 L/s and the sediment was 500–589 μm, the standard sumps could remove nearly
100% of the sediment. However, when the sediment was 89–125 μm at flowrates higher than 150 L/s (for the 1.8 m sumps) and 50 L/s (for the 1.2 m sumps), the removal rates were less than 10%. They also found that the standard sumps showed substantial washout of previously captured sediment at high flows and they could therefore be sediment sources at that time. Howard et al. (2011) designed and tested a porous baffle named the SAFL Baffle as a retrofit to the sump. The standard sumps used in the experiments were 1.2 × 1.2 m and 1.8 × 0.9 m (diameter × depth). They demonstrated that with the help of the SAFL Baffle, sediment washout from the sump at high flowrates could be virtually eliminated. In addition, the removal efficiency could be increased by 10–20% at about 28.4 L/s for the 1.2 m sump and 15% on average for the 1.8 m sump. However, the SAFL Baffle had limited removal efficiency under high flowrates. The objective of this study is to explore some simple structures that can be installed inside stormwater standard sumps to improve their sediment removal efficiency.

METHODS

The experimental setup was consisted of a square sump of length \( L = 450 \text{ mm} \) and a total height of 900 mm, with the inlet and outlet pipes of \( D = 150 \text{ mm} \) in diameter; see Figure 1. The inlet/outlet pipes were 450 mm above the bottom of the sump (\( h \)), leaving 300 mm (\( h' \)) above them. The inlet pipe had a length of 3 m, sediment was fed from a sand feeder into the inlet pipe at approximately 1 m (or 6.7\( D \)) upstream of the sump. Three size groups of sands (80–140 μm, 110–170 μm, and 160–240 μm) were used. The particle size distribution was measured with Malvern Mastersizer 2000 particle size analyzer. The \( d_{50} \) (50% finer than this size) of these three sand groups were 117, 130 and 184 μm respectively.

A water tank and a pump re-circulated the water, and a filter screen was installed in the tank to prevent the washed-out sediment entering the system again. The flowrate was controlled by a valve and measured by a magnetic flow meter.

In each test, a total of 2 kg sand was added and its mass flowrate was controlled at a pre-determined rate by adjusting the feeder bottom opening size. As shown in Cai et al. (2010), the sand flowrate was constant during the experiment period of about 30 min. For the groups of finer particles, the majority of the particles were suspended and well mixed before they entered the sump. For the particles of 160–240 μm, about one-third of the particles were carried into the sump as bed load. In sediment transport, the suspended load and bed load is typically separated when the particle settling velocity \( U_s \) equals the shear velocity \( u^* \) (García 2008). In our experiments, the shear velocity was obtained from the Manning’s equation, \( u^* = (gR_sS_f)^{0.5} \) where \( S_f \) is the friction slope. In the majority of our experiments \( U_s < u^* \) so the particles were in suspension.

Water depth in the pipes was measured with two plastic tape measures twining around pipes to calculate the submerged arc length. The water surface elevation of the inlet and outlet (needed for calculating energy losses) was measured with a laser range finder. The mass balance approach (Wilson et al. 2009; Howard et al. 2011, 2012) was used in the experiment to assess the sediment removal efficiency. At the end of the experiment, the sediment captured in the sump was dried and weighed. The removal efficiency of the sump was then obtained from the ratio of the captured sediment to the total weight.

A few simple structures i.e., A1, A2 and A3 were first studied, as shown in Figure 2. A1 was simply a porous screen placed 150 mm above the bottom. The porous screen was 450 mm × 450 mm, the same size as the standard sump model bottom. The 25 mm holes on the screen were arrayed 14 × 14 and its porosity was around 50%. The porous screen was designed to reduce the water velocity, help sediment settle and prevent it from re-suspending. A2 was a combination of the porous screen and a 20 cm wide board, which was diagonally positioned in the standard sump model. The board was to cut off the ‘short circuit’, as discussed below, and to direct the water downwards. A3 consisted of the porous screen and a vertically positioned board. Unlike A2, the board in A3 blocked the path totally, thus all the water had to move downwards and flow through the porous screen. The removal efficiencies of the standard sump...
model with these three preliminary structures and the original model (without any retrofits inside) were tested. The experiments were conducted under three flowrates of 7.4, 5.1 and 2.5 L/s and only one sediment size group (110–170 μm) was used.

Based on the performance of the preliminary designs, a number of improved structure designs were tested. Finally, two structures, B1 and B2 as shown in Figure 3, were found to have the best performance in sediment removal. Both structures contained two oblique baffles, two horizontal plates and a porous screen. The oblique baffles were designed to cut off the ‘short circuit’ and to increase the water flow path. Similarly a porous screen was added here. The difference between B1 and B2 was that B2 leaves an open area for water to overflow when the flowrates were large. For the experiment, the flowrate was set at 9.9, 7.3, and 5.1 L/s, which gave an input sediment concentration of 217, 152 and 112 mg/L respectively, similar to that in Howard et al. (2011). Three size groups of sands (80–140 μm, 110–170 μm, and 160–240 μm) were chosen for the sediment removal efficiency tests. Under each condition, the test was repeated three times.

Figure 3 | Sediment settling structures: (a) B1; (b) B2. All the boards in B1 and B2 are 450 mm in width (not labeled in figure). All dimensions are in millimeters.
RESULTS AND DISCUSSION

Sediment removal efficiency of the preliminary designs

The experimental results of the preliminary designs and the improved designs are shown in Table 1. For the preliminary designs, when the flowrates were 7.4, 5.1 and 2.5 L/s, the original model could remove around 34, 42 and 50% of the sediment, respectively. Structure A1 does not seem to show any improvement. It is surprising that A3 does not have effect, while A2 improves the sediment removal efficiency by about 10–12% under the test flowrates.

Referring to the flow pattern measured by Howard et al. (2012), the motion of sediment in the sump model can be mainly divided into two parts: the 'short circuit' and the circular motion. ‘Short circuit’ refers to sediment that flows out of the model with water from the inlet direct to the outlet, without entering the circular motion below. Most sediment moves out of the model by means of this ‘short circuit.’ The rest is driven to the lower part of the model by the downward flow. Some of them will be deposit and captured by the model. Due to the water velocity near the bottom, a portion of sediment will be scoured. The sediment that has been deposited previously also can be re-suspended and enter into the upper water, especially under high flowrates.

For the preliminary designs, structure A2 performs best. The solid board of A2 prevents water passing through the sump directly and directs the flow carrying the sediment to move downwards. With the help of the porous screen, which can dissipate water energy, of sediment near the bottom can be deposited more easily and little can be scoured out of the model again. Structure A2 redirects the water flow and causes energy dissipation. Thus, it improves the performance of the model relatively effectively.

Sediment removal efficiency of the improved designs

The repeatability of the experiments is shown in Table 1. The deviations among the three repeated experiments are all within 3%. When the sediment size is 80–140 μm, the sediment removal efficiencies of the original model under 9.9, 7.3 and 5.1 L/s are 24, 33 and 35%, respectively. Both the structures B1 and B2 improve the sand removal significantly by about 24% at these three flowrates. The results are similar when the sediment size is 110–170 μm, as shown in Table 1. When the sediment group is 160–240 μm, the original model removes around 50, 54 and 63% sediment at the tested flowrates. There is 16–21% more sediment removed using B1 and B2 structures. As the flowrate decreases to 5.1 L/s, structure B1 improves

<table>
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<tr>
<th>Preliminary design</th>
<th>Sediment size</th>
<th>Configuration</th>
<th>7.4 L/s</th>
<th>5.1 L/s</th>
<th>2.5 L/s</th>
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<tr>
<td></td>
<td>110–170 μm</td>
<td>Original</td>
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<td>50.3%</td>
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<tr>
<td></td>
<td></td>
<td>A1</td>
<td>37.9%</td>
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<tr>
<td></td>
<td></td>
<td>A2</td>
<td>45.7%</td>
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<tr>
<td></td>
<td></td>
<td>A3</td>
<td>33.3%</td>
<td>43.7%</td>
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<table>
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<tr>
<th>Improved design</th>
<th>Sediment size</th>
<th>Configuration</th>
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<th>7.3 L/s</th>
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<tr>
<td></td>
<td>80–140 μm</td>
<td>Original</td>
<td>24.0 ± 1.5%</td>
<td>33.3 ± 1.0%</td>
<td>35.1 ± 1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1</td>
<td>48.9 ± 2.0%</td>
<td>55.0 ± 1.5%</td>
<td>59.0 ± 2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>47.6 ± 0.5%</td>
<td>51.1 ± 1.0%</td>
<td>62.1 ± 2.0%</td>
</tr>
<tr>
<td></td>
<td>110–170 μm</td>
<td>Original</td>
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<td>31.6 ± 2.5%</td>
<td>43.8 ± 2.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1</td>
<td>54.3 ± 2.0%</td>
<td>52.3 ± 2.0%</td>
<td>59.7 ± 2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>52.8 ± 1.5%</td>
<td>55.2 ± 3.0%</td>
<td>60.8 ± 1.5%</td>
</tr>
<tr>
<td></td>
<td>160–240 μm</td>
<td>Original</td>
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<td>55.9 ± 2.0%</td>
<td>62.8 ± 2.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1</td>
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<td>69.7 ± 2.0%</td>
<td>71.1 ± 2.0%</td>
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<tr>
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<td></td>
<td>B2</td>
<td>68.8 ± 3.0%</td>
<td>71.9 ± 2.5%</td>
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the sediment removal efficiency by 8% while the corresponding figure for B2 is 18%.

The flow patterns in the model with structures B1 and B2 were simulated by the ANSYS FLUENT 2D model, as illustrated in Figure 4. The two flow patterns look similar. Water enters the sump from the inlet and moves downward with the direction of oblique boards. Structures B1 and B2 obviously increase the path of sediments in the sump model, which is beneficial to the sedimentation process. According to Figure 4, there is a circulate flow between the two oblique boards. This flow pattern is formed by the driving of the nearby upward-moving water. Sediment carried by this circulate flow will move downward and some of it will eventually deposit on the short horizontal board. The improved designs also include the functions of flow redirection and energy dissipation, and the circulating flow between the two oblique boards makes them more effective. While there are a few computer models for predicting sediment transport in open channels, e.g. Fang & Rodi (2003), modeling on sediment removal in stormwater sumps is still limited (Nowakowski et al. 2004; Pathapati & Sansalone 2009) due to the difficulties in turbulence modeling and water–solids interactions.

**Head loss**

The head loss through the sump model under the different conditions can be obtained and the head loss coefficient K is calculated as $H_l = K(v_{out}^2/2g)$, where $H_l$ is the head loss and $v_{out}$ is the outflow velocity. Results are shown in Table 2.

![Figure 4](image-url) Schematic diagram of flow patterns in the standard sump model with (a) structure B1 and (b) structure B2.

It can be seen that B2 has a smaller $K$ than B1 in all cases. For B2, at a large flow rate, part of the flow goes over the top of the structure, thus it significantly reduces the total energy losses. As we are mostly concerned with stormwater quality when the flowrate is small, such as the first flush, B2 is a suitable design for dealing with stormwater: it is effective in sediment removal at small flowrates, while it can bypass the flow when the flowrate is large.

**Scaling analysis**

Here we discuss the effect of the model scale on the results of the removal efficiency. In our study, the scale law is based on the similarity of Froude numbers between the model and the prototype (commonly known as Froudian models). As these models typically have large Reynolds numbers with fully turbulent flows, the effect of viscosity is negligible. Thus, Froudian models can properly simulate the velocity field of the prototype (at a scale of $L_r^{0.5}$ for Froudian models where $L_r$ is the model scale). For a prototype size of 1.2 m square sump with a depth of 1.2 m, similar to that used in Howard et al. (2012), $L_r = 2.7$, and the discharge ratio $Q_r/L_r^{2.5} = 12.0$. For the flowrate of 2.5–9.9 L/s in the model, the prototype flowrate will be 50.0–118.8 L/s.

The hydraulic modeling of sediment transport (or sedimentation), however, is still an active area of research. As the flow velocities and shear stresses in models are smaller than those in the prototype, the sediment particle size and density will need to be adjusted for the models to properly simulate sediment transport (Pugh 2008). Howard et al. (2012) proposed that the sediment removal efficiency $\eta$ can be described as a function of $P/F_j^2$, where $P$ is the Peclet number, $P = U_jhL/Q$, ($U_j$ is the particle settling velocity, $h$ is the depth of the sump, $Q$ is the flowrate) and $F_j^2 = U_j^2/gL$ ($U_j$ is the mean inlet flow velocity, $g$ is gravitational acceleration). Using the measurements obtained for the B2 structure, the removal efficiency $\eta$ can be related to $P/F_j^2$ as shown in Figure 5, along with the data for the original model.

For sediment size group 110–170 μm and a flowrate of 7.3 L/s, the sediment removal efficiency in the model with B2 is 55.2%. For a prototype 2.7 times larger, the corresponding flowrate will be 87.6 L/s, and the sediment...
removal efficiency of the prototype with B2 can be predicted from the fitting curve in Figure 5 to be about 53.8%. While the slightly reduced removal rate is expected given the larger flow velocity, further study is needed before this simple relationship can be generally applied due to the difficulty of modeling sediment transport.

SUMMARY AND CONCLUSIONS

In this study, a number of structures were tested to find the ones which could effectively improve the sediment removal efficiency in standard stormwater sumps. In the experiments, preliminary designs A1–A3 were tested to lay the foundations for designing the improved structures, and two improved structures (B1 and B2) were found to have the best performance. In general, they could increase sediment removal rate by 20–25%. Although their performance seemed similar, the water passing ability of the standard sump model with B2 was better than that with B1. At a large flowrate, part of the flow could go over the top of structure B2 but not B1. Besides, B2 was relatively simpler in design and required less material. Therefore, structure B2 is recommended in this study. Although the effectiveness of these structures are significant compared with that without the structures in the laboratory experiments, the actual values of the relative effectiveness can vary when the prototype discharge is much larger as sediment transport does not follow Froude law. The practical applicability still needs to be examined and improved in future studies.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from the National Science and Technology Specific Projects (2011ZX07301-004), the National High-Tech R&D Program (863) (2012AA062608), and the Program for Zhejiang Leading Team of S&T Innovation (2010R50037).

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First received 17 August 2013; accepted in revised form 24 February 2014. Available online 10 March 2014