Physical Experimentation and CFD Modeling to Evaluate Sediment Scour in Catchbasin Sumps

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ABSTRACT

The sediment removal capacity in catchbasin sumps and other hydrodynamic separators does not necessarily imply the ability to prevent the sediment from being scoured, especially when the remaining sediment capacity volume of the device is small and the flow rates are high. The sediment removal ability of catchbasin sumps and hydrodynamic separators must be balanced with their ability to retain the captured material by preventing scour. Therefore, understanding and quantifying scour processes in catchbasin devices is an important need when considering these devices as part of a stormwater management plan. This study investigated the sediment scour from a conventional catchbasin sump for different particle sizes, sediment depths, and flow rates. Full-scale physical experimentation and Computational Fluid Dynamics (CFD) modeling were conducted to determine a wide range of conditions at which different particles sizes are scoured.

METHODOLOGY

The methodology includes two main parts: full-scale physical modeling and computational fluid dynamic (CFD) modeling.

Physical modeling. The geometry of the catchbasin sump used for the experiments was based on the optimal geometry recommended by Lager et al. (1977) and tested by Pitt et al. (1979, 1985, 1998). For this geometry, if the outlet diameter is *d*, the total height of the catchbasin sump is 6.5*d*, and the inside diameter is 4*d*; the outlet has to be located 4*d* above the bottom and 1.5*d* below the top of the catchbasin. The outlet diameter (*d*) was selected as 300 mm (approximately 12 inches) (see Figure 1).

The scour tests consisted of the measurement of the suspended sediment concentration (SSC) at the effluent of the catchbasin sump to determine the sediment mass loss. Turbidity and particle size distribution (PSD) were also measured. A 50-cm wide rectangular inlet was used as the inlet.

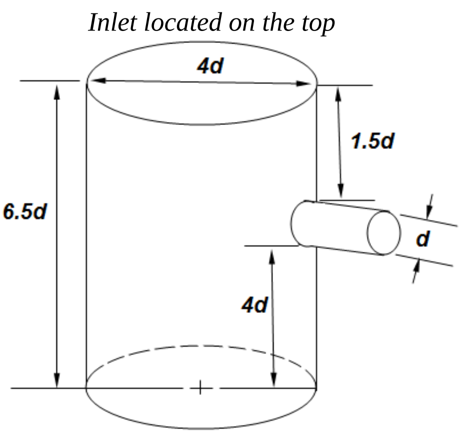

Figure 1. Optimal catchbasin geometry (Larger et al. 1977) used to build the full-scale physical model.

Two types of scour tests were performed. The first series of scour tests were performed with a sediment mixture at Lake Lureen State Park, Northport, AL, as once-through tests using the lake water. The second scour tests were performed with sediment with a homogeneous particle size at the facilities of the University of Alabama. The first PSD mixture was a prepared sediment mixture having a PSD similar to the measured values from deposited sediment sampled from catchbasin sumps observed by Valiron and Tabuchi (1992) and Pitt and Khambhammettu (2006). The characteristic diameters of this sediment mixture are D_{10} = 90 µm, D_{50} = 500 µm, and D_{90} = 2000 µm. Figure 2 shows the PSD of the sediment mixtures and also the particle size distributions for the separate components used to make the mixture. Four overlaying water depths were evaluated: 10, 25, 46, and 106 cm. Each overlaying water depth was tested with five consecutive flow rates, each lasting 25 min; the flow rates were: 0.3, 1.3, 3.0, 6.3, and 10 L/s. Composite samples (1.0 L) were collected for the first 5 min and for the last 20 min of test.

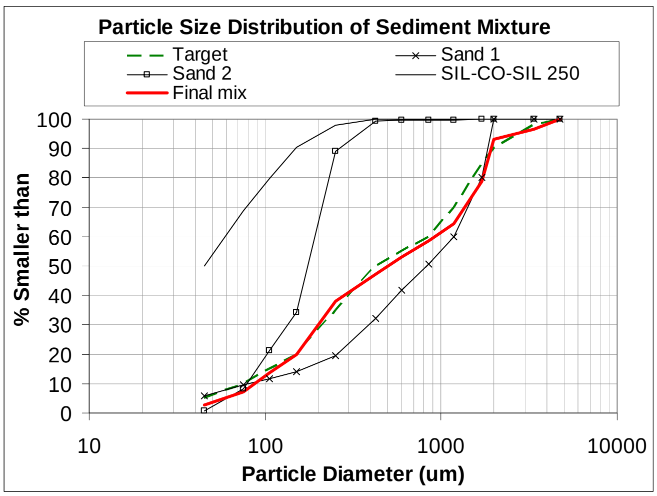

Figure 2. Particle Size Distribution (PSD) of sediment mixture prepared for scour test.

The wide range of this PSD in the sump contributes to the formation of bed armoring, which is the development of an erosion-resistant layer of relatively large particles created by the preferential washing of fine particles from the surface layers due to the velocity field acting on the sediment surface.

The second PSD mixture corresponded to a sediment material with a fairly homogeneous PSD, with D_{10} = 80 μm, D_{50} = 180 μm, and D_{90} = 250 μm (the PSD corresponds to Sand 2 in Figure 2). The sediment scour results obtained with this homogeneous PSD were used for calibration and validation of the CFD model.

CFD modeling. Sediment scour evaluation was conducted for homogeneous sediment materials by using a scour model customized for a 2D-CFD model implemented in *Flow-3D v.9.2.* The simulations were performed assuming a 50-cm wide rectangular inlet. A new scour model code was written and implemented that considered the specific conditions of the phenomenon as well as the limitations of the CFD software package. A total of 40 scenarios, including the calibration and validation cases, were simulated. The scenarios included combinations of three flow rates, five overlaying water depths, and four sediment particle sizes. Figure 3 shows a CFD output from a series of scour simulations.

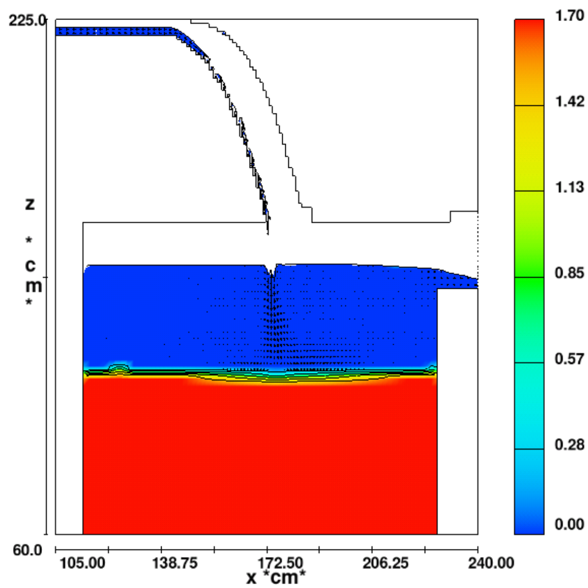

Figure 3. Total sediment concentration (g/cm^3) at 20 min of continuous flow. Flow rate: 10 L/s, overlaying water depth: 24 cm, particle size: 180 μm.

The sediment scour simulations were performed assuming clear water as the influent. The use of clear water is conservative when determining the scour rate. Clear water has a larger sediment-carrying capacity and therefore a larger scour potential compared to heavily silt-laden water. However, this assumption does not greatly differ from typical conditions of stormwater runoff in urban areas. The scour tests with the full-scale physical model were performed with lake water having a maximum SSC of 6 mg/L. The National Stormwater Quality Database reported median suspended solid concentrations of 50 to 100 mg/L for different land uses for data collected throughout the U.S. (Pitt and Maestre 2008); however, concentrations as high as several thousand mg/L were also reported. Stormwater runoff with high suspended sediment concentrations has a somewhat lower carrying capacity and therefore less scour potential than clear water. The list of case scenarios simulated is presented in Table 1.

Table 1. List of Case Scenarios Simulated with the 2D-CFD Model

		Flow rate (L/s)											
		50			180			500			1000		
		Particle size (μm)											
		5	10	20	5	10	20	5	10	20	5	10	20
Overlaying water depth (cm)	15												
	24												
	35												
	40												
	45												

RESULTS OBTAINED WITH A SEDIMENT MIXTURE

The turbidity time series showed that with this specific PSD, the scour had an exponential decay pattern under steady flow conditions, having a maximum turbidity value at the beginning of the flow when the plunging impact of the incoming water had its greatest effect and decreasing exponentially over time. This pattern was more evident when the sediment was located relatively close to the outlet (with shallow water layers over the sediment), where it is more exposed to scour (Figure 4).

The turbidity time series tests showed that an armoring layer of large sediment particles is formed on the sediment surface during steady flow conditions. This finding reveals that if relatively large particles (D_{75}=1500 μm, D_{90}=3350 μm, and D_{max}=4750 μm for this experiment) are present in the pre-deposited sediment in a catchbasin sump, the scour potential of underlying smaller particles is rapidly decreased as an armoring of the larger particles rapidly form on the sediment surface. Therefore, only a few centimeters of the surface sediment will be exposed to scour. However, the effectiveness of the armoring is relative to the fraction or proportion of large particles in the pre-deposited sediment and their proximity to the sediment surface.

The SSC for different flow rates and overlaying water depths for the 0-5 min composite samples is shown in Table 2. SSC increases as a fractional power function of the flow rate. A maximum SSC of 1139 mg/L was measured when the overlaying water depth was 10 cm during the 10 L/s flow rate. The difference between the flux rate at 6.5 L/s (1045 mg/L) and at 10 L/s (1139 mg/L) is not large, considering that an armoring layer had already been formed after 100 min of continuous flow at the lower rate before the 10 L/s flow rate was applied. The pattern for SSC for the 5-25-min composite samples is similar to the pattern seen for the 0-5-min composite samples; however, the SSC values were between 40 and 80% lower (see Table 2).

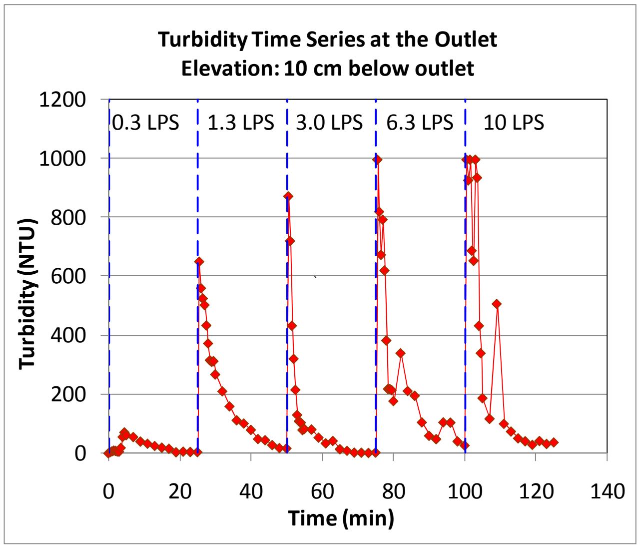

Figure 4. Turbidity time series at the outlet for scour tests: 10 cm (left) and 46 cm (right).

Table 2. Total SSC (mg/L) of Scoured Sediment for the Composite Samples

Depth below the outlet (cm)	**Flow rate (L/s)**									
	0.3	**1.3**	**3.0**	**6.3**	**10.0**	**0.3**	**1.3**	**3.0**	**6.3**	**10.0**
	SSC (mg/L) 0-5 min composite sample					**SSC (mg/L) 5-25 min composite sample**				
10	55.6	392	427	1045	1139	13	55	102	244	684
25	7.0	8.0	42	108	46.4	1.6	5.5	20	22	44
46	4.9	4.1	6.5	12.0	10.6	2.0	1.5	4.8	10.8	11.2
106	1.7	2.6	3.3	2.9	1.7	0.6	1.1	2.0	2.1	4.0

The total scour-mass time series presented in Figure 4 shows that with an overlaying water depth of 10 cm, the maximum scoured mass, after 125 min, was about 16 Kg. The scoured particles were all smaller than 4750 µm. This scoured mass is equivalent to a scour depth of about 0.9 cm in the catchbasin. In contrast, with an overlying water depth of 25 cm, the total scoured mass, after 125 min, was reduced to less than 1 kg (930 g), which is about 17 times less than that observed with the 10 cm water depth. With an overlaying water depth of 46 cm, the total scoured mass was further reduced to only 360 g in the 120 min period of flow. With a 106 cm water depth, the total scoured mass was reduced even further to only 90 g during the 125 min test. At 106 cm below the outlet, only particles smaller than 45 µm were detected in the effluent water.

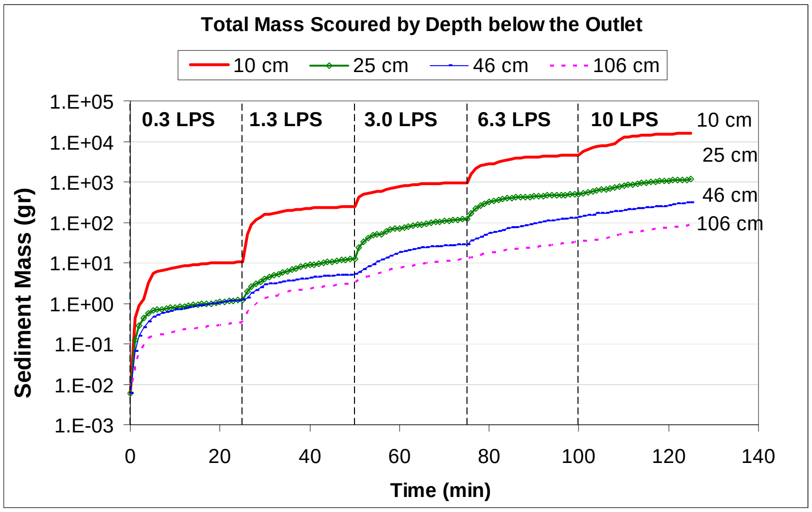

Figure 5. Total sediment mass scoured by water depth over the sediment for all scour tests.

Regression analyses were conducted to examine the effects of overlaying water depth and the scoured sediment mass. The depth of the water was found to be a significant factor, with a highly significant p-value of 0.006. A similar conclusion was also found by Avila et al. (2007) with CFD modeling. These results show that the overlaying water depth over the sediment significantly contributes to a reduction in scour potential. As the overlaying water depth increases, the armoring formation decreases, because the sediment is less exposed to scour. However, at shallow overlaying water depths, the armoring layer plays an important role in reducing the scour potential. If no armoring mechanism is present at shallow overlaying water depths, the sediment scour will be considerably higher. Figures 6 and 7 show the experimental response surfaces of suspended sediment concentrations obtained with the sediment mixture for the 0 -5 and 5 – 25 min composite samples, respectively.

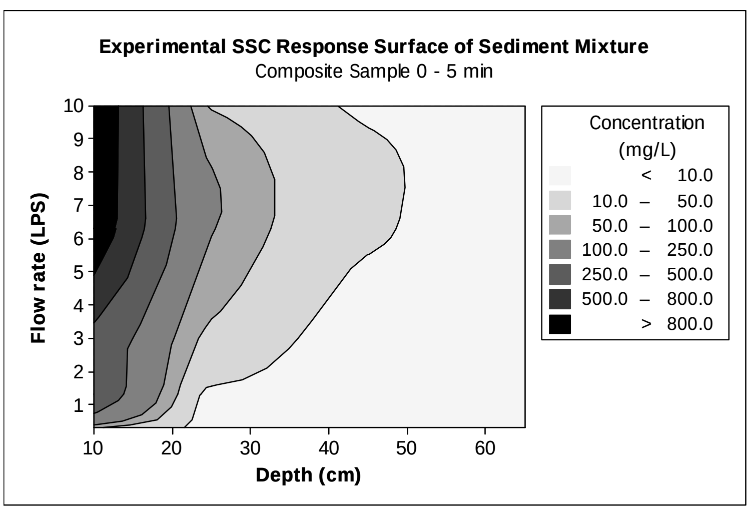

Figure 6. Response surface plots of experimental suspended sediment concentration (SSC), mg/L as a function of flow rate (L/s) and overlaying water depth (cm). 0 – 5 min composite sample.

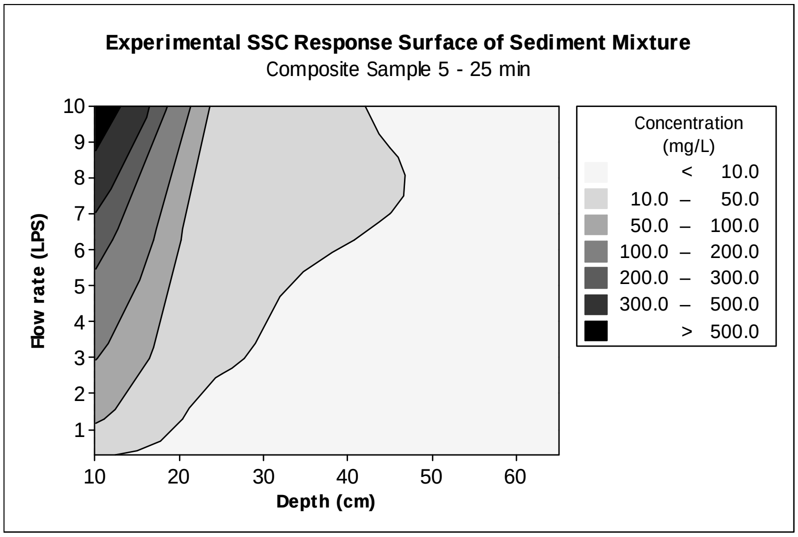

Figure 7. Response surface plots of experimental suspended sediment concentration (SSC), mg/L as a function of flow rate (L/s) and overlaying water depth (cm). 5 – 25 min composite sample.

The regression model for SSC (mg/L) of the 0-5 min composite samples with a $R^2 = 0.92$ is given as:

$$SSC = (670)^2 \cdot H^{-3.32} \cdot Q^{\left(0.92 H^{-0.15}\right)}.$$

The regression model for the 5-25 min composite samples with a $R^2 = 0.93$ is given as:

$$SSC = (115)^2 \cdot H^3 \cdot [\ln(H)]^{-15} Q^{\left(1.6 H^{-0.19}\right)},$$

where *SSC* is the Suspended Sediment Concentration (mg/L), *H* is the overlaying water depth, or depth below the outlet (cm), and *Q* is the flow rate (L/s or L/s).

Both regression models fitted the experimental data very well and the residuals achieved the assumptions of normality.

RESULTS OBTAINED WITH A HOMOGENEOUS SEDIMENT MATERIAL

Initially, it was expected that the SSC values in the effluent with homogeneous sediment material would have an exponential pattern similar to the one obtained with the sediment mixture. However, the results showed that the SSC was approximately constant during the 30 min of continuous flow. This finding is attributed to the absence of an armoring layer formed by large particles which protect smaller particles from scour within minutes after the water jet impact. In the case of sediment with a homogeneous particle size, all particles on the sediment surface were exposed continuously to scour during 30 min of continuous flow. However, the scoured mass was not large enough to increase the overlaying water depth to the point where sediment scour would decrease. Nevertheless, it is expected that after longer periods of time with continuous flow, the scour rate would decrease as the overlaying water depth increased, especially below the plunging water jet, where a hole is created in the sediment surface. Table 3 shows the experimental SSC values obtained for tests with sediment at 24 and 35 cm below the outlet, 10 L/s flow rates, and with a 50-cm wide rectangular inlet.

Table 3. Experimental SSC of 3-min Composite Samples (Scour Tests with Sediment Material with Homogeneous Particle Size, Flow rate: 10 L/s, Overlaying Water Depth: 24 and 35 cm)

Composite Samples - Time Interval (min)	SSC (mg/L) at 24 cm below the outlet	SSC (mg/L) at 35 cm below the outlet
0 – 3	600	170
3 – 6	479	161
6 – 9	491	203
9 – 12	556	182
12 – 15	521	153
15 – 18	425	179
18 – 21	574	172
21 – 24	562	206
24 – 27	569	182
27 – 30	557	178

Table 4 shows the computed SSC obtained with the CFD model. These results show that in the absence of armoring, SSC decreases exponentially as a function of the homogeneous sediment particle size (Figure 8) and approximately linearly as a function of the overlaying water depth above the sediment (Figure 9).

Table 4. Mean SSC obtained with a calibrated CFD modeling for different flow rates, overlaying water depth and sediment particle size. Homogeneous sediment particle size.

		SSC (mg/L)											
Flow rate (L/s)		50			180			500			1000		
		Particle size (mm)											
		5	10	20	5	10	20	5	10	20	5	10	20
Overlaying water depth (cm)	15	1554	1296	1051	1107	1086	838	381	571	565		110	198
	24	348	800	766	225	579	636	17	163	264		14	65
	35	5	527	567	1	189	428		37	111			13
	40		185	428		40	274			55			
	45			218			112			15			

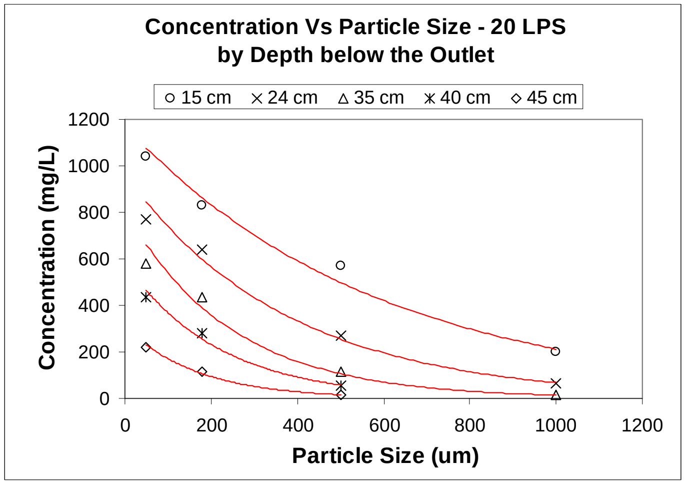

Figure 8. Suspended sediment concentration (mg/L) versus sediment particle size (μm) plotted by overlaying water depth (cm) (20 L/s flow rate).

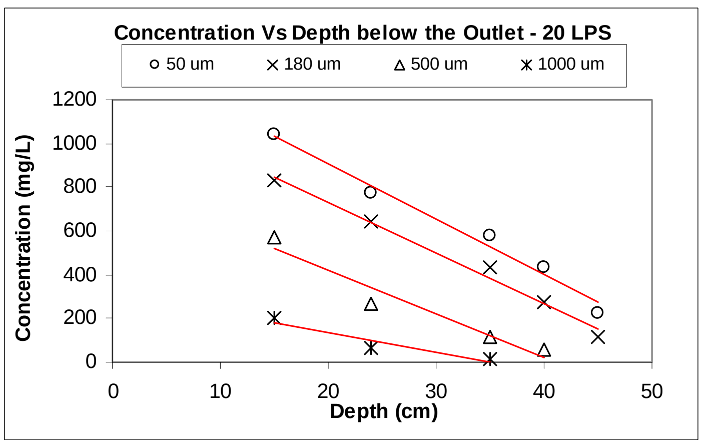

Figure 9. Suspended sediment concentration (mg/L) versus overlaying water depth (cm) plotted by sediment particle size (μm) (20 L/s flow rate.)

CONCLUSIONS

Two protection mechanisms occurred when conducting the tests with the sediment mixture: the overlaying water depth and an armoring layer. In this case, the overlaying water depth protected the sediment surface from the first impact of the plunging water jet. However, the plunging water jet still had enough energy to scour the sediment material directly below it. Then, due to the high shear stresses generated by the first water impact, all particle sizes (large and small) are suspended. Consequently, a *"washing machine effect"* occurs with the suspended sediment while the plunging water jet retreats upward because of the air buoyancy. The washing machine effect consists of the preferential removal of fine material from the suspension of the whole mixture, leaving a layer of large particles on the sediment surface which forms the armoring layer. Only the overlaying water will serve as a protection mechanism against scour if armoring is not present.

In contrast, the variation of SSC over time using sediment having a homogeneous particle size showed that SSC has a magnitude that was statistically constant during the 30 min period of evaluation. Initially, it was expected that the SSC magnitudes with homogeneous sediment material would have an exponential decay pattern similar to the one obtained with the sediment mixture, with high concentrations within the first minutes of flow and then undergoing a substantial decrease for the remaining flow duration. However, the results showed that the SSC maintained an approximate constant magnitude. This phenomenon is attributed to the absence of an armoring layer that protects the sediment from being scoured. SSC will decrease only when the overlaying water depth is high enough to dissipate the eroding energy of the velocity field and therefore reduces the acting shear stress on the sediment surface.

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