Experimental design analysis applied to factors related to migration of sediment out of a stormwater catchbasin sump

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Abstract

The sediment-capture performance in conventional catchbasin sumps has been reported to be in the wide range between 14 and 99% (USEPA, Metcalf & Eddy 1977); obviously, the higher performance is obtained by combining low flowrates, large particle sizes, and high specific gravities. Typically, up to about 30% of the total stormwater particulates are captured during actual rainfall tests (Pitt 1985). The accumulation rate, or sediment-retaining performance, depends on the size and geometry of the device, the flow rate, sediment size, and specific gravity of the sediment. In the same way, scour phenomenon includes all those parameters previously mentioned, in addition to the water protection layer and the consolidation of the sediment bed due to aging.

In order to evaluate the importance of the parameters and their interactions on the phenomenon of scour of sediment out of a conventional inlet catchbasin, a modeling experiment was designed (2^4 full-factorial) and performed examining four parameters (flow rate, sediment size, water protection depth, and specific gravity). Each factor was evaluated at 2 levels: flow rates at 1.6 L/s and 20.8 L/s, sediment diameters at 50 μm and 500 μm, water protection depths at 0.2 m and 1.0 m over the sediment, and sediment specific gravities at 1.5 and 2.5. A 2-dimensional Computational Fluid Dynamic (CFD) model was implemented in Fluent 6.2, using the Eulerian multiphase model. The evaluation consisted of determining the reduction of sediment mass from the chamber over time. When examining the loss of sediment after 1,000 sec of continuous flow (17 min), the results showed that the expected important parameters of flow rate, sediment size, and water protection depth, were statistically significant when explaining sediment scour. The water protection depth over the sediment is related to the extent of exposure of the sediment layer to the in-flowing water. However, it was also found that specific gravity of the sediment was not an important factor affecting sediment scour.

Key Words: Sediment, Models, Methods, Nonpoint Source Pollution.

Introduction

The sediment-capture performance in conventional catchbasin sumps has been reported to be in the wide range between 14 and 99% (Metcalf & Eddy 1977); obviously, the higher performance is obtained by combining low flowrates, large particle sizes, and high specific gravities. Typically, about 30% of the total stormwater particulates are captured in properly designed catchbasin sumps during actual rainfall tests (Pitt 1985). The accumulation rate of sediment in a catchbasin sump depends on the size and geometry of the device, the flow rate, sediment size, and specific gravity of the sediment. In the similar way, scour phenomenon likely includes all these parameters, in addition to the depth of the water protection layer above the sediment and the consolidation of the sediment bed due to aging.

A series of tests was conducted to evaluate the importance of the parameters and their interactions on the phenomenon of sediment scour out of a conventional catchbasin sump located at a stormwater inlet. A 2-dimensional computational fluid dynamics model (CFD), using Fluent 6.2, was used to conduct a full 2^4 factorial experiment that examined four parameters: flow rate, sediment size, overlying water protection depth, and specific gravity of the sediment.

Flow rate, sediment size, and the depth of water over the sediment, were the significant main factors that explained sediment scour. However, specific gravity of the sediment material was not as important as these other factors.

These scour observations are similar to what has been observed during field tests of catchbasins in the past. The next stage of this research program is directly measure the 3-D velocity fields in the laboratory using a full-sized catchbasin with a sump to confirm these calculations. The last research phase will include selected controlled scour tests for further confirmation. Finally, the results will be implemented in the WinSLAMM stormwater model to better consider sediment scour from small hydrodynamic devices.

Geometry of the Computational Model

The geometry of the manhole was the same as the optimal manhole geometry recommended by Larger, et al. (1977), and tested by Pitt (1979; 1985; and 1993). For this geometry, if the outlet diameter is D, the total height of the manhole is 6.5D and the inside diameter is 4D; the outlet has to be located 4D above the bottom and 2.5D below the top of the manhole. The outlet diameter (D) was selected as 300 mm (12 inches) for these experiments. A 2-dimentional model (2D) was implemented in Fluent 6.2 by using the longitudinal center-line cross section on the predominant flow direction (see Figure 1).

Experimental Design for Four Factors

A 2^4-full factorial experimental design (without replicates) (Box, et al. 1978) was used to determine the significance of four factors (flow rate, sediment particle size, water depth, and specific gravity), and their interactions, on the scour of previously captured sediment from a catchbasin sump. The model used a continuous flow of a submersible-water jet (the impact geometry was previously determined after detailed evaluations of the cascading water from the inlet flows) during a 3,600 sec (1 hr) period of time. There were obvious changes in the flow field and resulting shear stress values with time, so model results from several time periods were examined. Table 1 shows the factors with their corresponding low and high values that were used during the different experiments.

A multiphase Eulerian model was implemented for the 2^4-full factorial experimental design, with which it is possible to consider two phases: water, and a dense sediment bed. Because the multiphase Eulerian model is a mixture model and does not allow an immiscible water-air interphase, the flow was assumed to be a vertical-submersed water jet. The conditions of the inflow jet were previously determined by

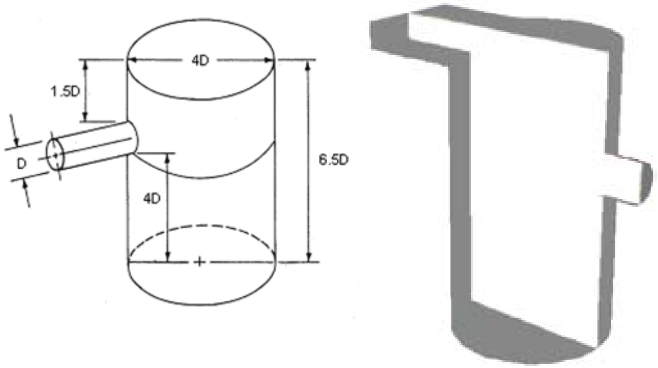

Figure 1. Typical catchbasin geometry by Larger, et al. (1977) (left) - 2D longitudinal center-line cross section (right).

Table 1. Factors and Settings for the 2^4-full factorial experimental design.

	Factor	Low Values	High Values
A	Flow rate (L/s)	1.6	20.8
B	Particle size (μm)	50	500
C	Water depth (m)	0.2	1.0
D	Specific gravity	1.5	2.5

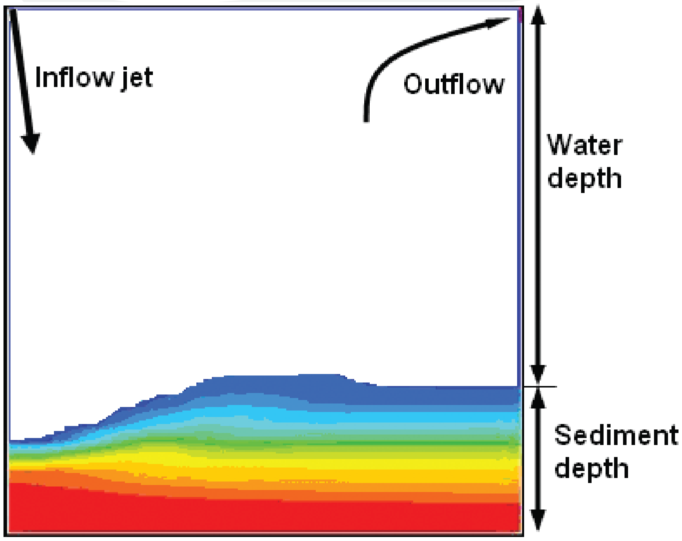

Figure 2. Inflow, and outflow directions, water and sediment depth of the 2D model implemented for the 2^4-full factorial experimental design.

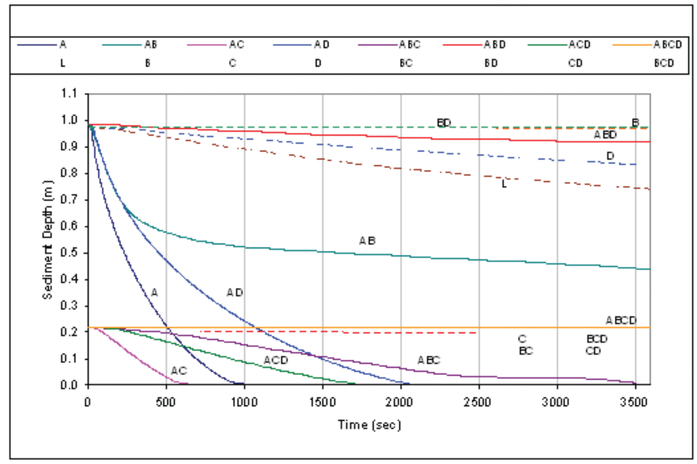

Figure 3. Reduction of Sediment Depth as a function of Time for each treatment. Results of the 2^4-full factorial experiment (A: flow rate; B: particle size; C: water depth; and D: specific gravity).

CFD modeling of the cascading water from a circular and from a rectangular inlet. Figure 2 shows the location of the inlet, outlet, the water depth, and the sediment depth.

Results of the 2^4-Full Factorial Experimental Design

After simulating all 16 treatments for the 3,600 sec durations, the reduction of sediment depth (sediment loss) was plotted as a function of time. The sediment depth is the complement of the water protection depth; if the water depth is 0.2 m, the sediment depth is 1.0 m.

Figure 3 shows the changes in the sediment depth with time, making it possible to see the effects of the factors and their interactions. As expected, high flows with shallow water depths (AC) result in the fastest washout of the sediment, followed by high flows alone (A). Particle size alone (B) and particle size and specific gravity combined (BD) had little effect on scour.

The significance of the factors and their interactions were examined at six different times: 60, 300, 600, 1,000, 1,800, and 3,000 sec. Each analysis included the determination of the effects of the factors, the normal probability plot of the effects, the ANOVA (with no replicates), and the evaluation of resulting residuals.

The coefficients of the effects for all the evaluated times show that flow rate (A), water depth (C), particle size (B), and the interaction of flow rate and water depth (AC) are the most significant factors in the calculated scour (Figure 4). In contrast, specific gravity (D) is located at the sixth or eighth position, which indicates that specific gravity is not as relevant as the other main factors and several of the 2-way interaction terms.

Similar results were obtained when the factors and interactions were examined using normal probability plots (Figure 5); flow rate (A), particle size (B), and water depth (C) were found to be significant, along with flow rate-water depth (AC) interactions for all time steps and flow rate-particle size (AB) interactions for half of the time steps. As noted above, specific gravity (D) was not identified as a significant factor, either alone, or in any of the significant interaction terms. In order to further validate these results using a more quantitative criterion, an ANOVA analysis was applied to detect the significant factors and interactions at the 95%, or better, confidence level.

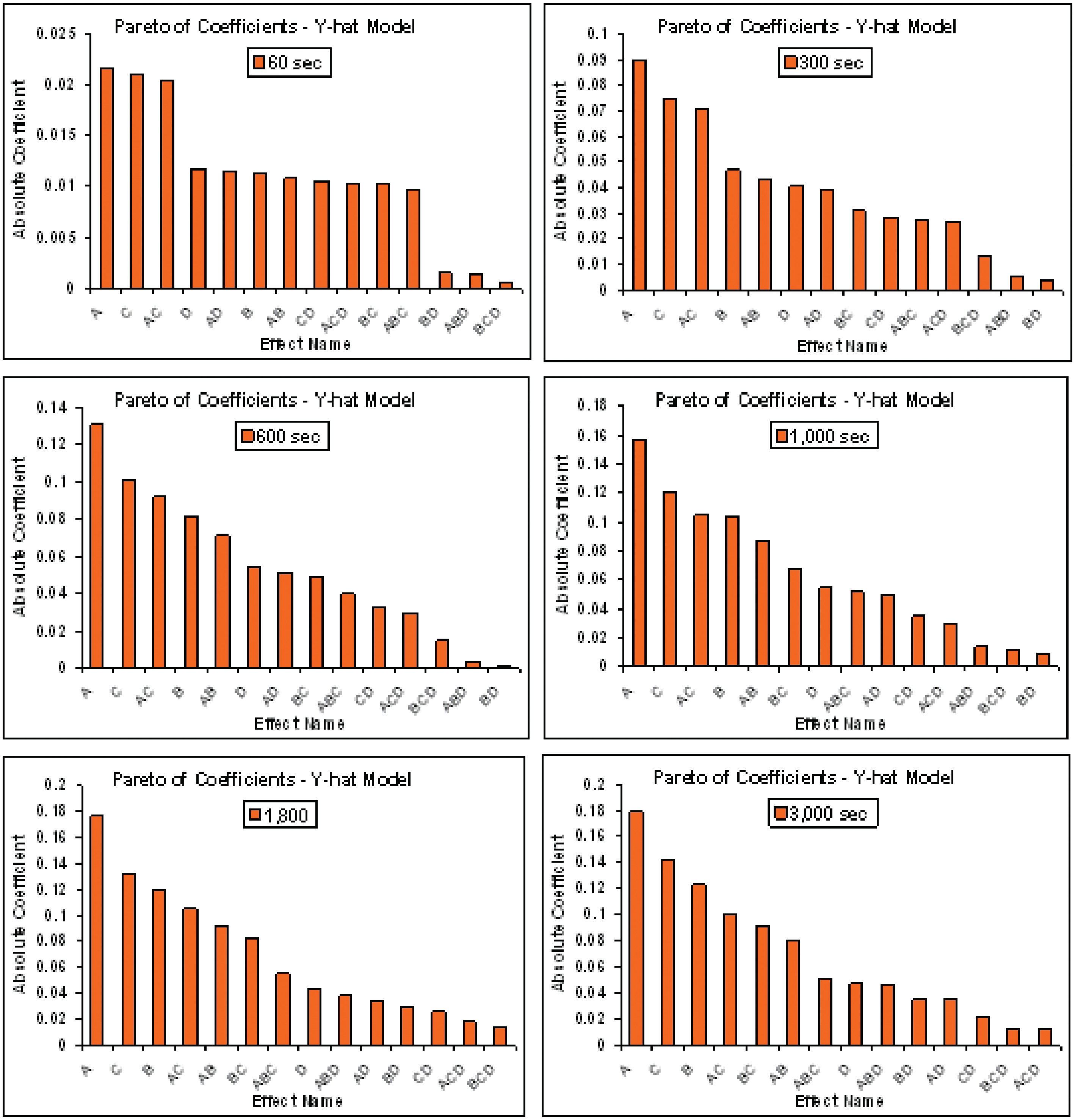

Figure 4. Coefficients of effects for each treatment at times 60, 300, 600, 1,000, 1,800, and 3,000 sec (A: flow rate; B: particle size; C: water depth; and D: specific gravity).

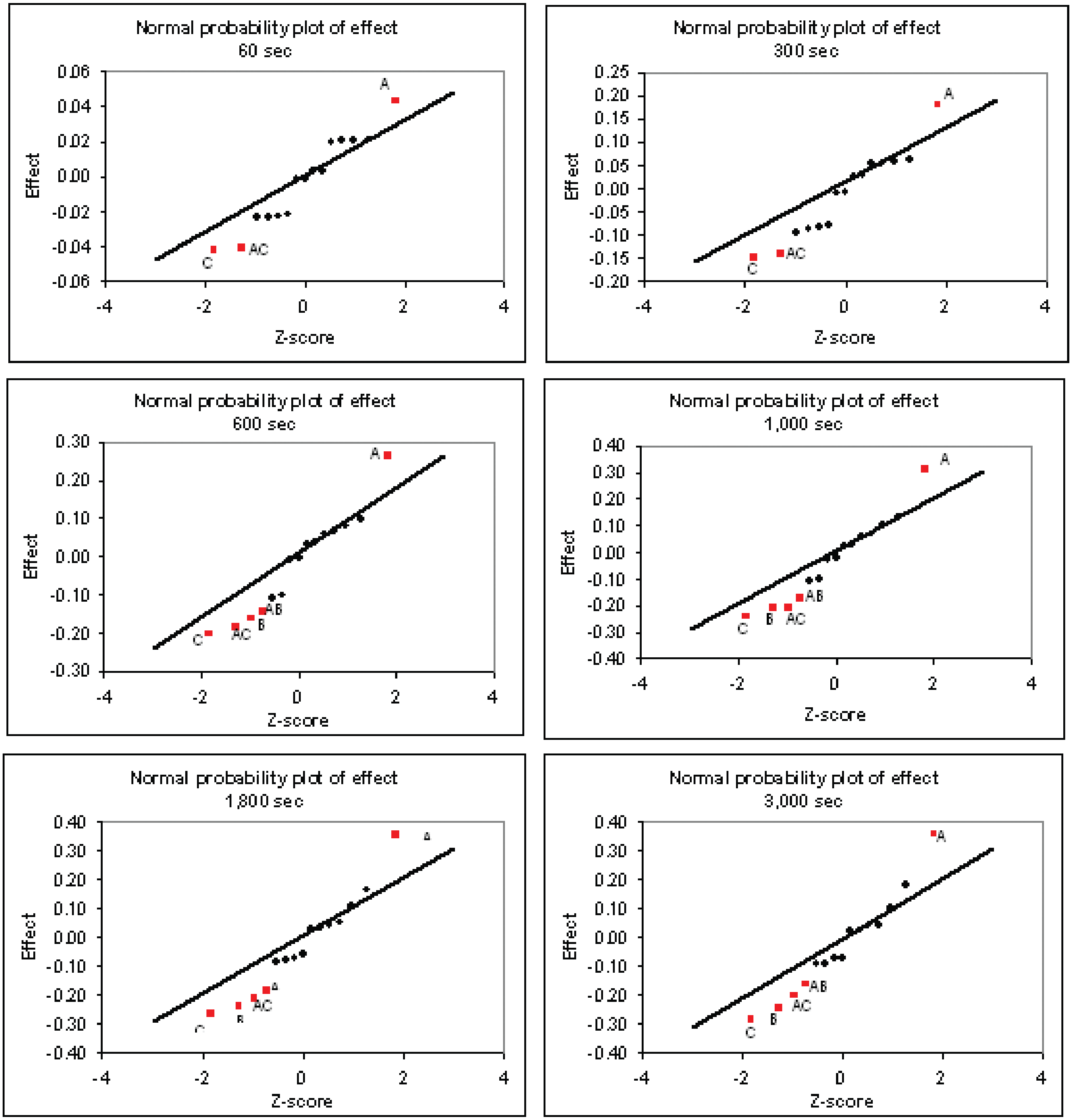

Figure 5. Normal probability plot of the effect estimated for times 60, 300, 600, 1,000, 1,800, and 3,000 sec (A: flow rate; B: particle size; C: water depth; and D: specific gravity).

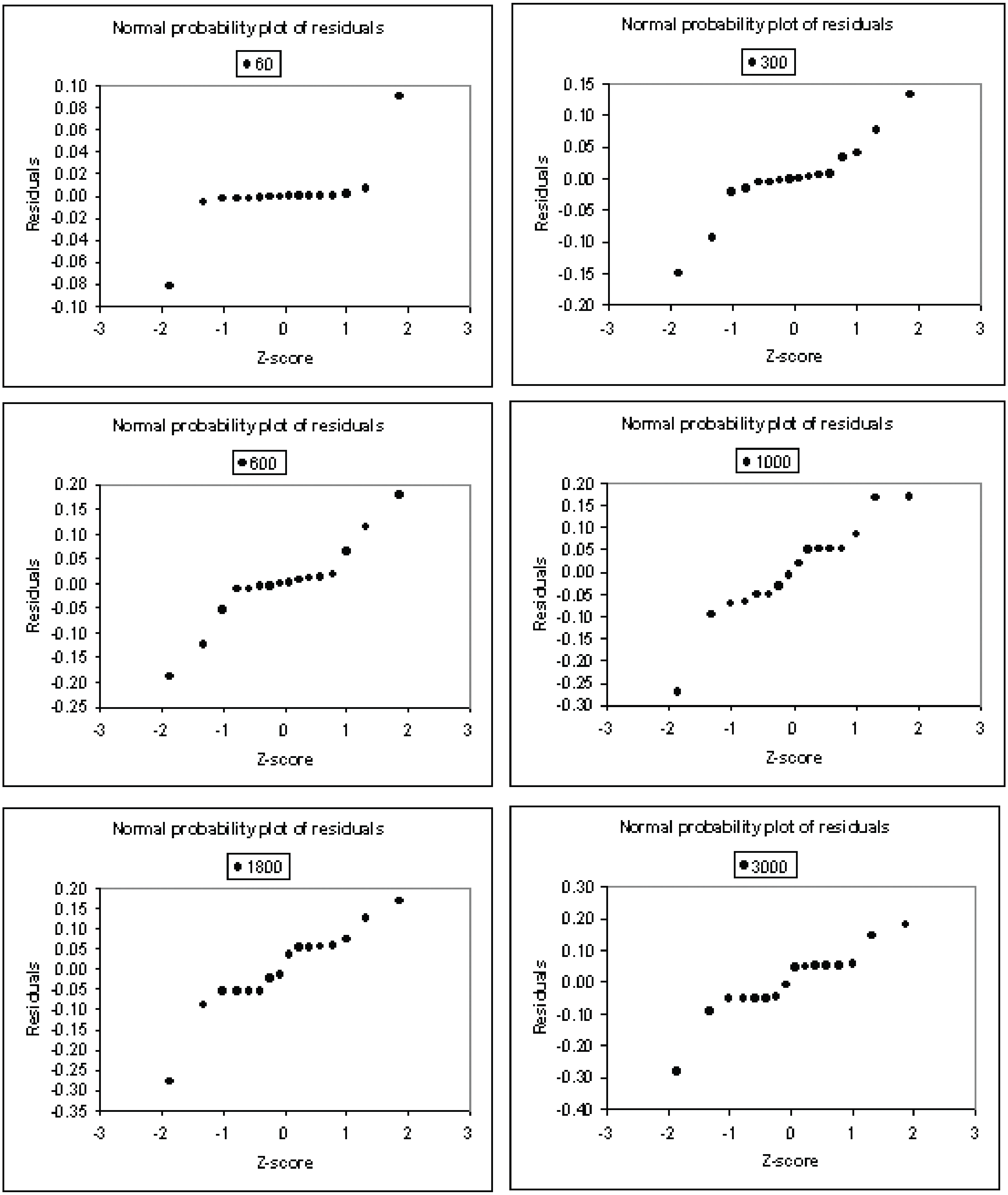

Figure 6. Normal probability plot of residuals estimated for times 60, 300, 600, 1,000, 1,800, and 3,000 sec.

Table 2. ANOVA results: p-values for each treatment at different times of the simulation.

	Time (sec)					
Treat-ment	60	300	600	1000	1800	3000
A	0.02	0.006	0.003	0.003	0.003	0.003
B	0.14	0.06	0.02	0.02	0.01	0.01
C	0.02	0.01	0.009	0.009	0.01	0.008
D	0.13	0.09	0.08	0.12	0.24	0.22
AB	0.15	0.08	0.03	0.03	0.04	0.06
AC	0.02	0.01	0.01	0.01	0.02	0.03
AD	0.13	0.10	0.09	0.15	0.34	0.34
BC	0.17	0.17	0.10	0.07	0.05	0.04
BD	0.82	0.86	0.97	0.77	0.41	0.34
CD	0.16	0.21	0.24	0.28	0.47	0.54

An ANOVA with no replicates was used to determine the p-values for each factor and interaction (Table 2). A confidence level of 95%, or better, would have a p-value of 0.05, or smaller, and these are indicated with values in bold typefaces. These results are the same as the previous evaluations; they show that flow rate, particle size, and water depth are significant factors for times greater that 600 sec (10 min). Additionally, the interactions of flow rate-particle size, flow rate-water depth, and particle size-water depth were also significant. However, specific gravity, or any interaction containing specific gravity, was not significant at the 95% confidence level for any of the evaluated times.

Additionally, residuals were calculated to determine normality and independency. Figure 6 shows that the residuals appear normal for times greater than 1,000 sec (17 min). However, shorter times show lack of normality. On the other hand, considering that there are only several data points, it is not possible to have a clear impression of homoscedastic or heteroscedastic patterns. However, homoscedastic behavior of the residuals was typically achieved for times greater than 1,000 sec.

As expected, flow rate and particle size were identified as significant factors. Moreover, the water depth was also found to be a significant factor that protects the sediment layer from being scoured. However, specific gravity (for the range observed) was not identified as a significant factor.

Conclusions

Flow rate, particle size, water depth, and their interactions, are significant factors that affect the scour of sediment in a conventional catchbasin sump. Specific gravity is not as important as these other factors over time under continuous flow conditions in terms of loss of sediment mass out of a conventional catchbasin sump.

The overlying water layer depth above the sediment has an important function in protecting the sediment layer from scour. High shear stresses caused by the impacting water jet will not easily reach the sediment surface if the water is deep. However, once the flow is stabilized, the developed velocity field will reach the sediment surface at all depths, so the important shear stress may be best representative in this condition. Moreover, with deeper water, the resulting shear stress conditions on the sediment surface are less than for shallower water, for all modeled conditions.

Consolidation of the deposited sediment bed and cohesive properties of clay were not included in these analyses. These are relevant factors that suggest a greater permissible shear stress of the sediment bed before scour, and therefore require further analysis.

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