St. Anthony Falls Laboratory Project Report No. 573

Minnesota Department of Transportation

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Office of Policy Analysis, Research & Innovation

Assessment and Recommendations for the Operation of Standard Sumps as Best Management Practices for Stormwater Treatment (Volume 2)

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16. Abstract (Limit: 250 words)

In order to improve the performance of standard sumps as a best management practice (BMP) in treating stormwater runoff, a baffle was designed to be installed as a retrofit in standard sumps. The retrofit is a porous baffle called “SAFL Baffle”. The effect of the SAFL Baffle on the performance of standard sumps was assessed by conducting laboratory tests on small scale as well as full scale straight flow-through standard sumps equipped with the baffle.

In addition, a number of tests were conducted to determine the performance of standard sumps with the SAFL Baffle when the baffle is clogged with debris like trash and vegetation. Furthermore, the performance of two other configurations of the baffle was studied: (1) the SAFL Baffle in a sump with an outlet pipe 90 degrees to the inlet pipe, and (2) the SAFL Baffle in a sump with some water entering the sump through an overhead inlet grate. Standard sumps equipped with the SAFL Baffle were evaluated using two metrics: (1) How well the system captures sediment during low flow conditions (Removal Efficiency Testing), and (2) how well the system retains the previously captured sediment during high flow conditions (Washout Testing). The results of the tests showed that the SAFL Baffle dissipates the energy of water entering the sump and as a result, at low flow rates, it captures sediment better than a standard sump with no baffle. More importantly, at high flow rates, the washout of the previously captured sediment reduces to near zero.

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Executive Summary

The Minnesota Department of Transportation report, *Assessment and Recommendations for the Operation of Standard Sumps as Best Management Practices for Stormwater Treatment* (Volume 1), written by Adam Howard, Omid Mohseni, John Gulliver and Heinz Stefan, is the first of two volumes summarizing the results of tests conducted on standard sumps (Howard et al. 2011). That report showed that sump manholes (sumps) capture sediment like sand and course silt during storms. However, the captured sediment is often washed out of the sumps during intense storm events.

The second volume is allocated to the research done on the design of a retrofit to improve the performance of standard sumps in treating stormwater runoff. The design of the retrofit resulted in the development of a porous baffle called "SAFL Baffle". The development of the SAFL Baffle was accomplished by:

1. Testing it as a retrofit in a straight flow-through standard sump
2. Evaluating it when clogged with debris like trash and vegetation
3. Evaluating it when installed in a sump with an outlet pipe 90 degrees to the inlet pipe
4. Evaluating it when installed in a sump with some water entering the sump through an overhead inlet grate

Tests were performed at the St. Anthony Falls Laboratory on a 1-ft (0.3 m) diameter by 1-ft (0.3 m) deep scaled model sump, a 1-ft (0.3 m) diameter by 0.5-ft (0.15 m) deep scale model sump, a 4-ft (1.2 m) diameter by 4-ft (1.2 m) deep sump, a 4-ft (1.2 m) diameter by 2-ft (0.6 m) deep sump, a 6-ft (1.8 m) diameter by 6-ft (1.8 m) deep sump, and a 6-ft (1.8 m) diameter by 3-ft (0.9 m) deep sump. All of the sumps were equipped with the SAFL Baffle and were evaluated using two metrics:

1. How well the system captures sediment at low flow rates (Removal Efficiency Testing)
2. How well the system retains the previously captured sediment at high flow rates (Washout Testing)

Testing showed that a SAFL Baffle installed in a standard sump dissipated the energy of water entering the sump. The circulation pattern witnessed in standard sumps was dissipated and as a result, the standard sump equipped with a SAFL Baffle captured sediment at low flow rates better than a standard sump not equipped with the SAFL Baffle. Similarly, washout of sediment was reduced to near zero at high flow rates. Standard sumps equipped with SAFL Baffles perform as well as proprietary devices.

When a SAFL Baffle was clogged with stormwater debris, water traveled underneath of the SAFL Baffle. If the sump was deep, performance of the sump equipped with a SAFL Baffle did not change significantly. However, if the sump was shallow, significant washout was exhibited in the sump. This washout problem in shallow sumps was mitigated when a SAFL Baffle with hole diameters equal to 5 inches (12.7 cm) was installed in the sump.

Sumps with outlet pipes located 90 degrees to the inlet pipe exhibited significant washout of previously captured sediment during high flow rates. With a SAFL Baffle installed at an angle between 90 and 120 degrees of the inlet pipe, washout was minimal. At low flow rates, a SAFL Baffle installed at a 113 degree angle with respect to the inlet pipe captured more sediment than a SAFL Baffle installed in a standard, straight flow-through sump.

In the sump equipped with a SAFL Baffle that received water from an inlet pipe and an inlet grate from above, washout rates were highest when the flow rate from the inlet pipe was less than the flow rate from the inlet grate. Similarly, the ability of the device to capture sediment decreased when the flow rate from the inlet pipe was less than three times greater than the flow rate from the inlet grate. Through extensive testing, it was determined that the standard sumps equipped with the SAFL Baffle should be used downstream of stormwater sewers such that the drainage basin of the inlet pipe is at least three times the drainage basin of the inlet grate. Under this condition, the flow from an inlet grate from above does not impact the performance of the sump equipped with a SAFL Baffle.

1 Introduction

1.1 Background

With the passing of the Clean Water Act in 1972, point sources of aquatic pollution like water treatment plants and industrial plants were reduced substantially. However, stormwater remains largely untreated throughout the United States as a non-point source. Rainwater falls onto roads, lawns, and farm fields come in contact with a wide variety of pollutants. This water then travels, with pollutants in tow, through manmade drainage systems like storm sewers and drainage ditches to natural rivers and tributaries. Untreated stormwater runoff can potentially make our lakes green, our rivers brown, and our beaches close after a rainstorm.

Engineers and scientists have developed a variety of methods to treat stormwater. In general, these methods seek to separate pollutants from stormwater using physical and chemical processes. Stormwater detention ponds are examples of stormwater best management practices (BMPs) using physical processes of treatment. When stormwater reaches the pond, it slows considerably and pollutants like sands and silts settle to the bottom of the pond, leaving cleaner water to exit.

Sump manholes are structures found in storm sewers and are thought of one the simplest stormwater BMPs. They generally consist of a concrete cylinder with an inlet and outlet pipe whose inverts are few feet above the bottom of the cylinder. This means that water fills the cylinder during storms, but only can drain to the invert of the outlet pipe, i.e. there is always water sitting in the sump. Sump manholes are used as access points for maintenance staff to inspect storm sewers, but it is thought that they can collect pollutants like sediment and debris through settling.

1.2 Sump Manholes

In Volume 1 of this report (Howard et al., 2011), it was shown that standard sumps can capture suspended sediments during low flow conditions. However, the captured sediments are often washed out of the system during intense storm events. High flow rates create a circular flow pattern inside sumps, causing scour, resuspension and washout of the previously captured sediments (Figure 1-1).

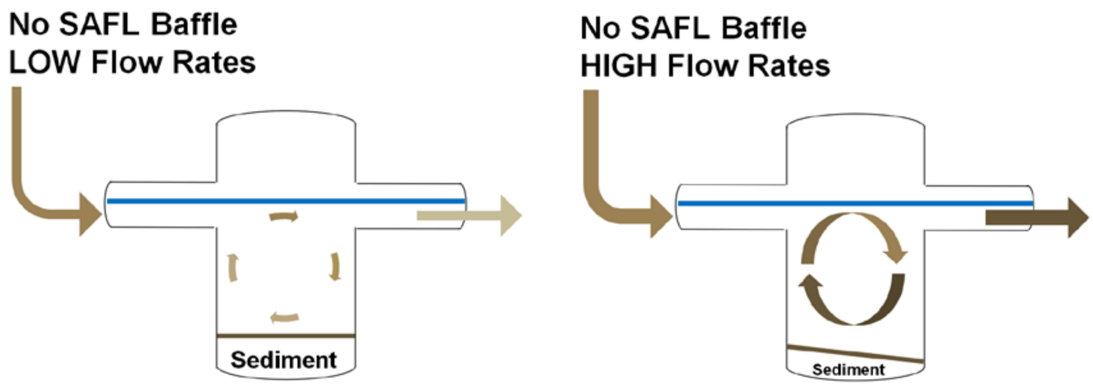

Figure 1-1: (Left) a standard sump manhole collecting sediment at low flow rates. (Right) a standard sump manhole losing sediment due to washout at high flow rates.

1.3 Scope of Research

The objective of this part of the study was to design a baffle (called SAFL Baffle in this report) that would improve the performance of standard sumps as stormwater treatment devices. Part of this research was how the new baffle would perform in the field, such as when the baffle was:

- Installed in a sump manhole with an outlet pipe 180 degrees to the inlet pipe
- Clogged with debris like trash and vegetation (Figure 1-2)
- Installed in a sump manhole with an outlet pipe 90 degrees to the inlet pipe (Figure 1-3)
- Installed in a sump manhole with water entering through an inlet grate and inlet pipe (Figure 1-4)

Volume 2 is organized as follows: the development of the SAFL Baffle is presented in Chapter 2, the effects of trash on the performance of the SAFL Baffle are discussed in Chapter 3, the performance of sump manholes with a 90-dgree outlet pipe and equipped with the baffle is presented in Chapter 4, sumps with inlet grates and the SAFL Baffle in Chapter 5, the measured head losses in Chapter 6, comparing sumps equipped with the SAFL Baffle to a number of proprietary separators in Chapter 7, and summary and conclusion in Chapter 8. The laboratory set up for testing the sumps with the SAFL Baffle is presented in Appendix A, the testing procedures in Appendix B, and sieving operation in Appendix C. Appendix B provides the information regarding the maintenance procedure of sumps equipped with the SAFL Baffle. In addition, examples are provided using the software SHSAM to estimate the sump cleaning intervals.

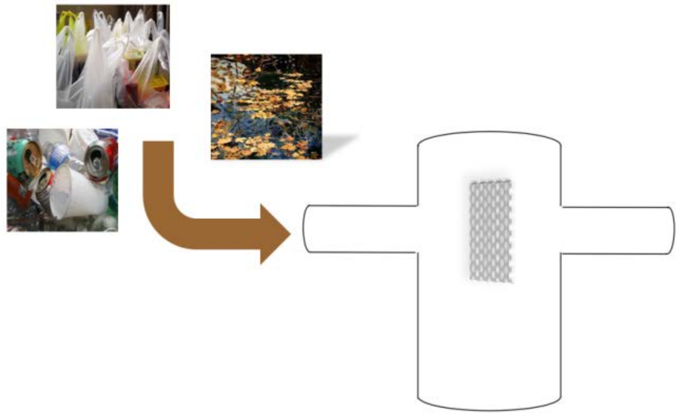

Figure 1-2: A standard sump manhole equipped with a SAFL Baffle, receiving stormwater debris like trash and vegetation.

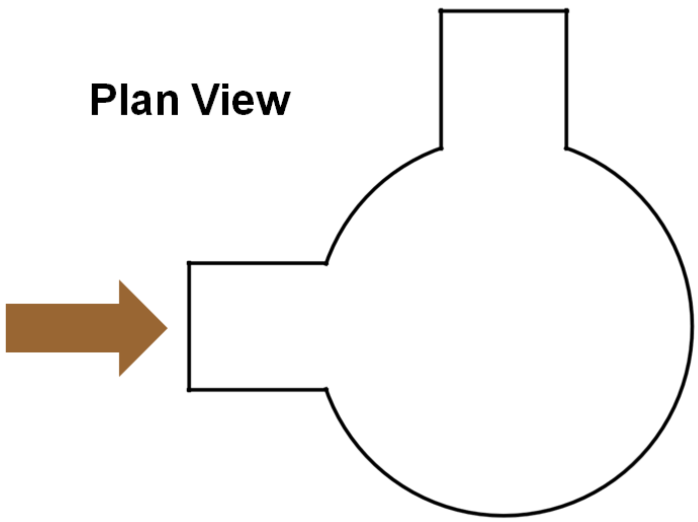

Figure 1-3: A 90 degree outlet sump manhole.

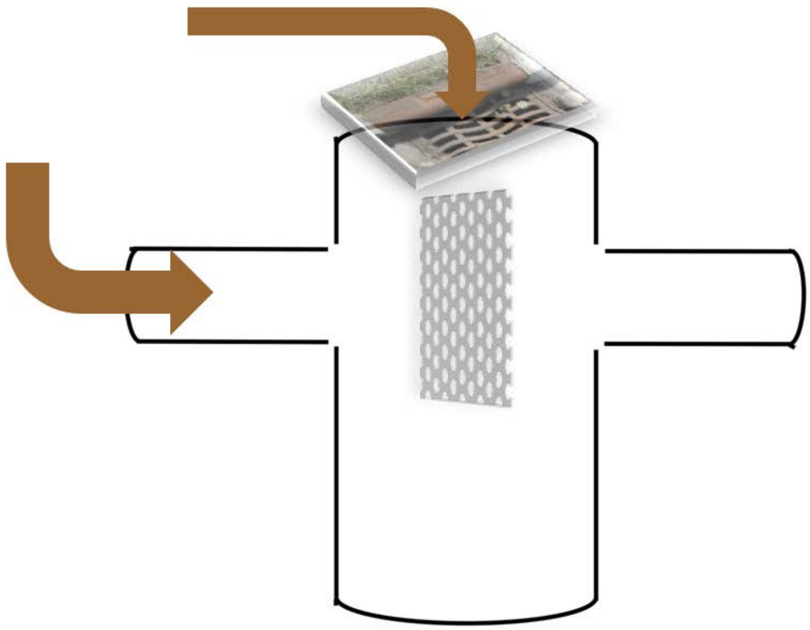

Figure 1-4: A standard sump manhole equipped with a SAFL Baffle, receiving water from an inlet pipe and an inlet grate.

2 Development of the SAFL Baffle

The SAFL Baffle was developed by studying flow patterns in standard sumps (Howard et al., 2011). Once the flow patterns were understood, prototype SAFL Baffle designs were created and installed in a scale model of a standard sump. With an ideal prototype SAFL Baffle design created, it was tested in full-scale 4-ft (1.2 m) diameter and 6-ft (1.8 m) diameter sumps.

2.1 Flow Patterns

Extensive flow mapping using a 3-Dimensional Acoustic Doppler Velocimeter (ADV) was conducted in standard sumps. As flow enters the sump there is a plunging action, which creates downward velocity at the downstream end, upstream velocity near the sediment bed, and upward velocity at the upstream end. The flow pattern described above can be seen in the vector plot provided in Figure 2-1, where water enters the sump from the right. The circulation pattern, shown in Figure 2-1, can result in scouring the sediment deposit at the downstream end and more deposition at the upstream end of the sump. It was determined that an effective baffle should break the circulation pattern through energy dissipation of the plunging flow.

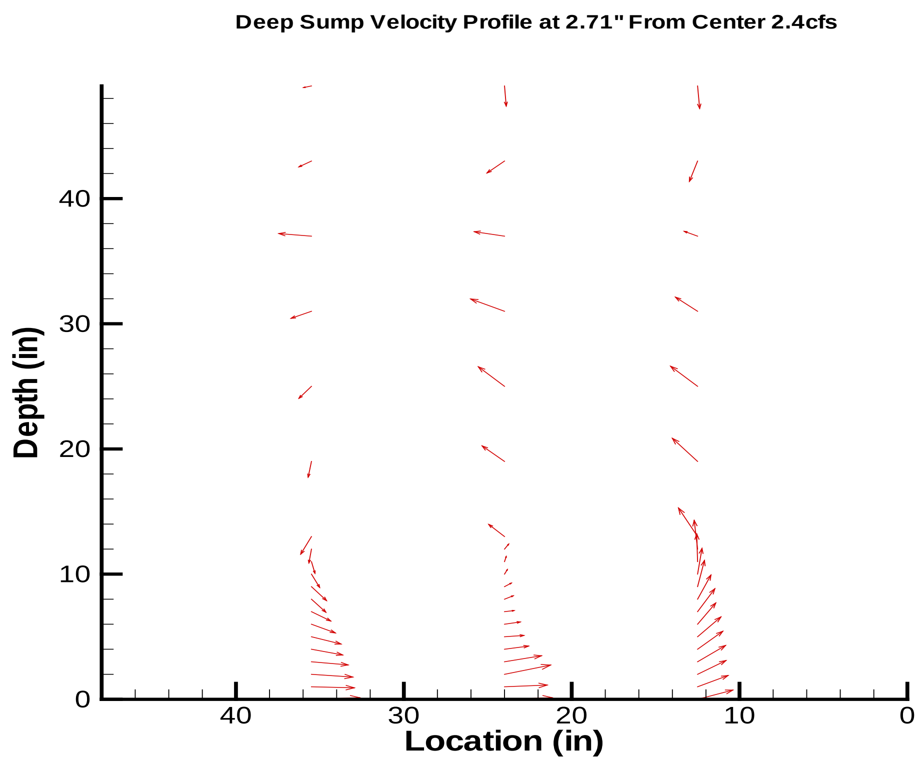

Figure 2-1: A velocity profile of a deep sump along its centerline (Howard et al., 2011).

2.2 Scale Model SAFL Baffle Design

Utilizing the knowledge of the flow pattern, testing of various baffles was initially conducted in a 1:4.17 Froude scale model. This sump scale model had a diameter of one foot (0.3 m) and with a depth of one foot (0.3 m) (called 1×1 for brevity). Its inlet pipe was connected to a pump that circulates tap water through the system from two head tanks. A valve was on the pump, which allowed precision control of the flow rate through the system. Water leaving the outlet pipe of the manhole sump traveled through two 90-degree bends, a drop, a mesh screen, a 0.00079-in (20 μm) filter, and finally into a head tank. Detailed schematics of the 1×1 sump and the testing setup can be found in Appendix A.

Several retrofit prototypes were created to reduce the power available for the strong circulation pattern. The first two prototypes were solid baffles, and were placed perpendicular to the flow in the center of the sump with a space between the bottom of the baffle and the top of the sediment. Solid baffle designs have already been implemented in the field in many locations across the country.

Washout tests were completed on the scale model to quantify how well these devices performed. Using the procedure defined in Howard et al. (2011), washout tests were conducted by filling the scale model sump with sediment, passing water at high flow rates through the sump, and measuring the amount of sediment washed out of the sump during a set test duration. A detailed washout testing procedure for the 1-ft (0.3 m) diameter, 1-ft (0.3 m) deep sump can be found in Appendix B.

The results of the scale model washout tests with the solid baffle in the scale model are provided in Figure 2-2. The results presented in Figure 2-2 indicate a standard sump with a solid baffle will have significantly higher washout rates than a sump without a baffle. The solid baffle increased washout rates because the same flow rate was directed to pass through a smaller cross section near the sediment bed. The reduction in cross sectional area increased the velocities near the sediment deposit, which increased washout. The bottom of solid baffle 1 in Figure 2-2 was located 5.5-in (14 cm) above the sediment deposit. Thus, solid baffle 1 further decreased the flow cross sectional area, causing more washout when compared to solid baffle 2 which was 6.8-in (17.3 cm) above the sediment deposit in the model.

The results of the tests on sumps with solid baffles and the observed flow patterns in standard sumps showed that the main utility of a baffle in a sump should be on dissipating the energy and not redirecting of the flow. A solid baffle reduces the cross-section where water flows through and can result in higher velocities in the sump, which could eventually result in more washout than a standard sump with no baffle. To minimize the changes in the cross-sectional area of the flow and to reduce the high velocities of the inlet jet, porous baffles were tested at various angles of attack and with different porosities. Figure 2-3 presents the washout results of a variety of porous baffles in the 1:4.17 scale model.

Baffles 1 and 2 were tested with angles of attack of $+20^o$ (striking face pointing down) and -20^o (striking face pointing up), respectively, and porosities of 33%. Baffles 3 through 7 where oriented vertically with porosities of 33%, 36%, 40%, 46% and 51%, respectively. The flow rates for the tests shown in Figure 2-3 were 0.2 cfs (5.8 L/s), or 7 cfs (202 L/s) when scaled to a 4-ft (1.2 m) diameter sump, and the sediment preloaded in the model was U.S. Silica F-110 (with a median size of 0.0043-in (110 μm)). The duration of all tests shown in Figure 2-3 was 40 minutes.

The tests on the scale model showed that the washout effluent concentration becomes negligible with a porous baffle of a porosity of 46% to 51% and vertical orientation (porous baffles 6 and 7). In Figure 2-3, the standard sump with no baffle had an effluent concentration of about 0.0044 lb/ft^3 (70 mg/L), almost two orders of magnitude more than standard sumps with porous baffles 6 and 7.

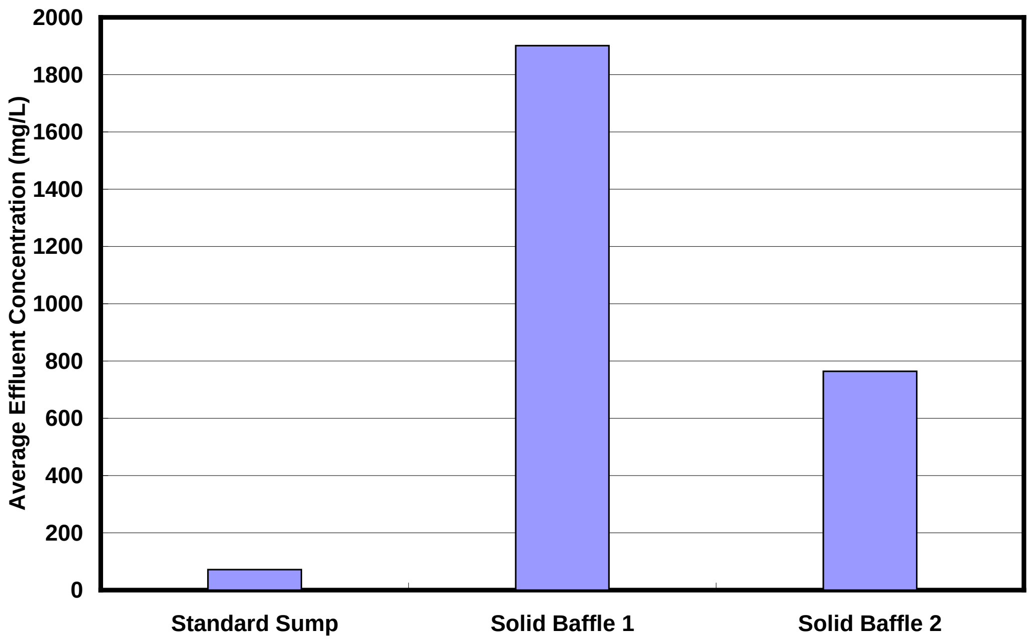

Figure 2-2: Scale model solid baffle washout results.

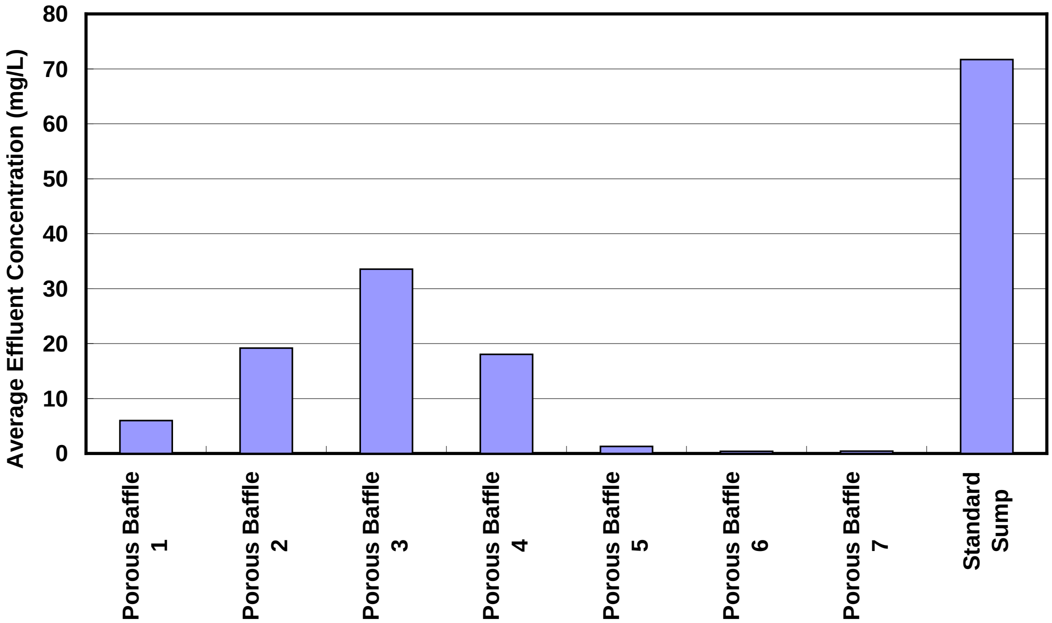

Figure 2-3: Scale model porous baffle washout results.

The porous baffles tested proved a simple retrofit could be designed to reduce sediment washout from standard sumps. For the same flow rate and particle size, a baffle with an appropriate orientation and porosity will produce effluent concentrations near zero. With an appropriate porosity, the baffle will dissipate the energy of the plunging flow by redistributing the flow across the entire sump width.

The improvements to the sump during washout tests were also examined visually. Figure 2-4 shows a picture of the standard sump scale model following a washout test without any retrofits, where flow was from left to right of the photo. As can be seen in Figure 2-4, the scour downstream and deposition upstream of the sump were evident in the 1:4.17 scale model. Figure 2-5 is a photo following the washout test on a standard sump with a porous baffle, where flow was once again from left to right. The surface of the sediment deposit remained flat. Porous baffle number 6 (Figure 2-3) was determined to be the optimum configuration and was given the name SAFL Baffle. The SAFL Baffle was then tested at the full scale for both sediment washout and removal efficiency.

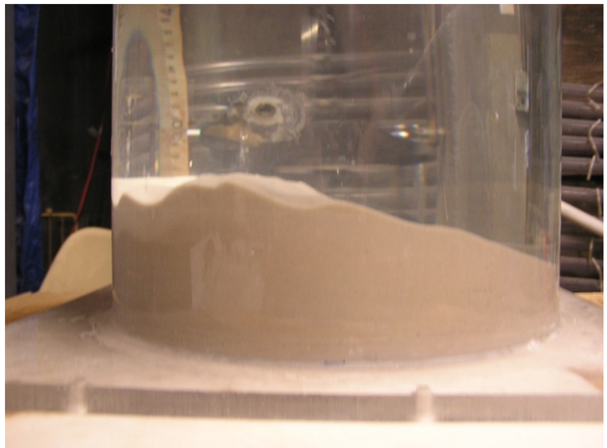

Figure 2-4: A photo of the deposit in the 1:4.17 scale model of standard sump without any baffles after a washout test at 0.2 cfs (5.8 L/s) flow rate.

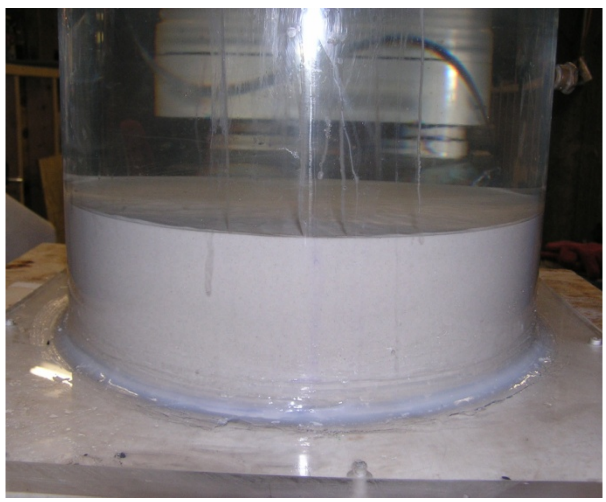

Figure 2-5: A photo of the deposit in the 1:4.17 scale model of standard sump with baffle no. 7 after a washout test at 0.2 cfs (5.8 L/s) flow rate.

2.3 Full Scale Experimental Setup

Two full-scale fiberglass sumps were constructed for testing and placed on a test stand in the St. Anthony Falls Laboratory (SAFL) of the University of Minnesota in Minneapolis, Minnesota. The first straight flow-through sump evaluated with the SAFL Baffle was four feet (1.2 m) in diameter and four feet (1.2 m) deep (the height of the inlet pipe invert from the sump bed), and had 15-in (38 cm) inlet and outlet pipes. There was a one percent drop between the inverts of inlet and outlet pipes in the sump.

The baffle for this setup had one-inch holes and 46% porosity with a frame built around it, as shown in Figure 2-6. The frame was bolted to the walls of the sump. For better access to the sump and maintenance requirements in the field, the baffle was installed perpendicular to the flow direction from the inlet pipe (i.e. mounted in a vertical position).

The second straight flow-through sump evaluated with the SAFL Baffle was six feet (1.8 m) in diameter and three feet (0.9 m) deep with 24-in (0.6 m) inlet and outlet pipes. This baffle had three inch holes and a 46% porosity. The baffle was installed in the sump in a similar manner as was done for the 4-ft (1.2 m) sump. Schematics and detailed information about the testing sump setups can be found in Appendix A

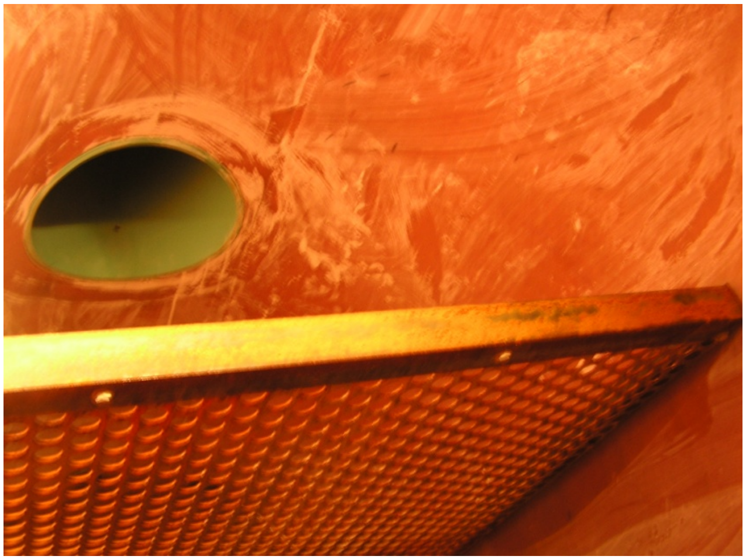

Figure 2-6: SAFL Baffle in the 4-ft (1.2 m) by 4-ft (1.2 m) sump.

Each sump was connected to the SAFL plumbing system which provides approximately 45 feet (13.7 m) of head of Mississippi River water. The flow rate was measured in the 12-in (0.3 m) supply pipes through the use of two pitot cylinders (Silberman, 1947). The flow rate for both configurations was controlled using a hydraulic gate valve on the supply pipe. When water exited the outlet pipe of the device, it freely fell into a tail box

For removal efficiency testing, sediment was fed as a slurry from a Schenk AccuRate sediment feeder into the inlet pipe approximately one foot (0.3 m) upstream of the sump (Figure 2-7). For washout testing, the sump was mounted on precision strain gauge load cells. The load cells allow for the accurate measurement of weight before, during and after tests (Saddoris et al., 2010).

To simulate the physical geometry of shallow sump manholes or deep sump manholes which are full of sediment, a false floor was installed in the 4×4 and 6×6 sumps. When installed, the false floor halved the depth of the 4×4 and 6×6 devices, transforming them into a 4-ft diameter (1.2 m), 2-ft deep (0.6 m) sump and a 6-ft diameter (1.8 m), 3-ft deep (0.9 m) sump (called 4×2 and 6×3, respectively). The false floor could be installed or removed from each device.

Figure 2-7: A view of the slurry pipe used to feed sediment into the sump.

2.4 Full Scale Testing Procedure

Washout tests involved preloading the sump with sediment and then applying high flow rates to the sump. Prior to each washout test, 12 inches (25 cm) of the U.S. Silica sand F-110 with a median particle size of 0.00433-in (110 μm) was placed in the sump. The initial conditions were similar for all tests. Detailed procedures for removal efficiency and washout tests can be found in Appendix B.

Two methods were used to measure the weight of sediment in the sump before and after each test. In the first method, measurements were taken to determine the depth of wet sediment at 24 locations, which were then used to estimate an average depth of the wet sediment. The difference between the average depths of sediment before and after each test was used to determine the volume of the washed out sediment. A number of tests were also conducted on several sediment samples to determine the bulk density of wet sediment. The bulk density typically varied from 103 to 108 lb/ft^3 (1.62 to 1.70 kg/m3) for the 8 to 10 samples taken from different locations and depths within the sump.

In the second method, precision strain gauge load cells were used to weigh the sediment before and after each test. The 5,000 lb-ft (6779 N-m) precision strain gauge load cells from Tovey Engineering, Inc. provided accurate measurements of weight throughout each test. In order to take accurate weight measurements it was necessary to record both the initial and final weight measurements with the same water surface elevation in the sump. A water surface elevation difference of 0.003 feet (1 mm) between the initial weight and the final weight would incur an error of approximately 6 lbs (2.7 kg). With this information, a correction was made for the amount of water in the sump before and after each test through the use of a static monometer. The flow rate of washout tests on the 4-ft and 6-ft sumps varied from 2.75 to 5.5 cfs (72 to 159 L/s) and 5 to 19 cfs (145 to 550 L/s), respectively. During each test, the flow rate was kept constant.

For the 4×4 sump removal efficiency testing, removal efficiency was measured at flow rates of 0.6, 1.2, 1.8, and 2.4 cfs (17, 35, 52 and 69 L/s) in triplicate. The 6-ft (1.8 m) sump was tested at flow rates of 1.8, 3.5, 5.3, and 7 cfs (52, 101, 153 and 203 L/s). Additional removal efficiency tests were conducted at lower flow rates, i.e. 0.3, 0.4, and 0.5 cfs (9, 12 and 14 L/s), to obtain removal efficiencies of approximately 100% to develop a performance function for the entire domain of performance.

The influent concentrations of the removal efficiency tests varied between 0.00624 to 0.0125 lb/ft^3 (100 to 200 mg/L). Wilson et al. (2009) found that 22 to 44 lbs (10 to 20 kg) of sediment input minimized the errors associated with sediment collection at the bottom of the sump. The duration of each test was estimated so that 22 to 44 lbs (10 to 20 kg) of sediment would be fed for each test. Subsequently, the test duration was one hour for the lowest flow and 18 minutes for the higher flow rates. Three distinct particle sizes were used for the tests. The median sediment sizes were 0.0215 inches with a range of 0.0197 to 0.0232 inches (545 µm, with a range of 500 to 589 µm), 0.0119 inches, with a range of 0.00984 to 0.0140 inches (303 µm, with a range of 250 to 355 µm), and 0.00421 inches, with a range of 0.00346 to 0.00492 inches (107 µm, with a range of 88 to 125 µm). The preparation of these distinct sediment sizes is explained in Appendix C.

2.5 Full Scale Results

2.5.1 Results of Washout Tests

Figure 2-8 provides the results of the washout tests both with and without the SAFL Baffle. As can be seen, the baffle reduced effluent concentrations from 0.0312 lb/ft^3 (500 mg/L) to nearly 0 lb/ft^3 (0 mg/L) at a 5.5 cfs (159 L/s) flow condition. The maximum uncertainty of the load cells used in the tests was +/- 10 lbs (4.5 kg) and the majority of tests conducted with the SAFL Baffle resulted in less than 10 lbs (4.5 kg) of washout after two hours of testing. Several tests resulted in negative washout, i.e. by the end of the test the weight of the system increased, which were within the uncertainty of the load cells and water level measurements in the sump. In order to obtain results outside of the uncertainty of the load cells, it was decided to use finer sediments which could result in higher washout rates. This was accomplished by replacing the top three inches (7.6 cm) of the F110 Silica sand (with a median size of 0.004330 inches, or 110 µm) with SCS250 (with a median size of 0.00177 inches, or 45µm), and repeating the tests. Similar results were obtained with the SCS250, i.e. effluent concentrations stayed near zero after the sump was subject to high flow rates for two hours (Figure 2-8).

The tests conducted on the 4×4 sump with the SAFL Baffle were successful, so it was decided to test the SAFL Baffle in the 6×3 shallow sump to impose more challenging conditions, i.e. increasing the flow rates. The baffle used in this test series had the same porosity, but had 3-in (7.6 cm) holes as compared to the 1-in (2.5 cm) holes used for the tests conducted on the 4×4 sump with the SAFL Baffle.

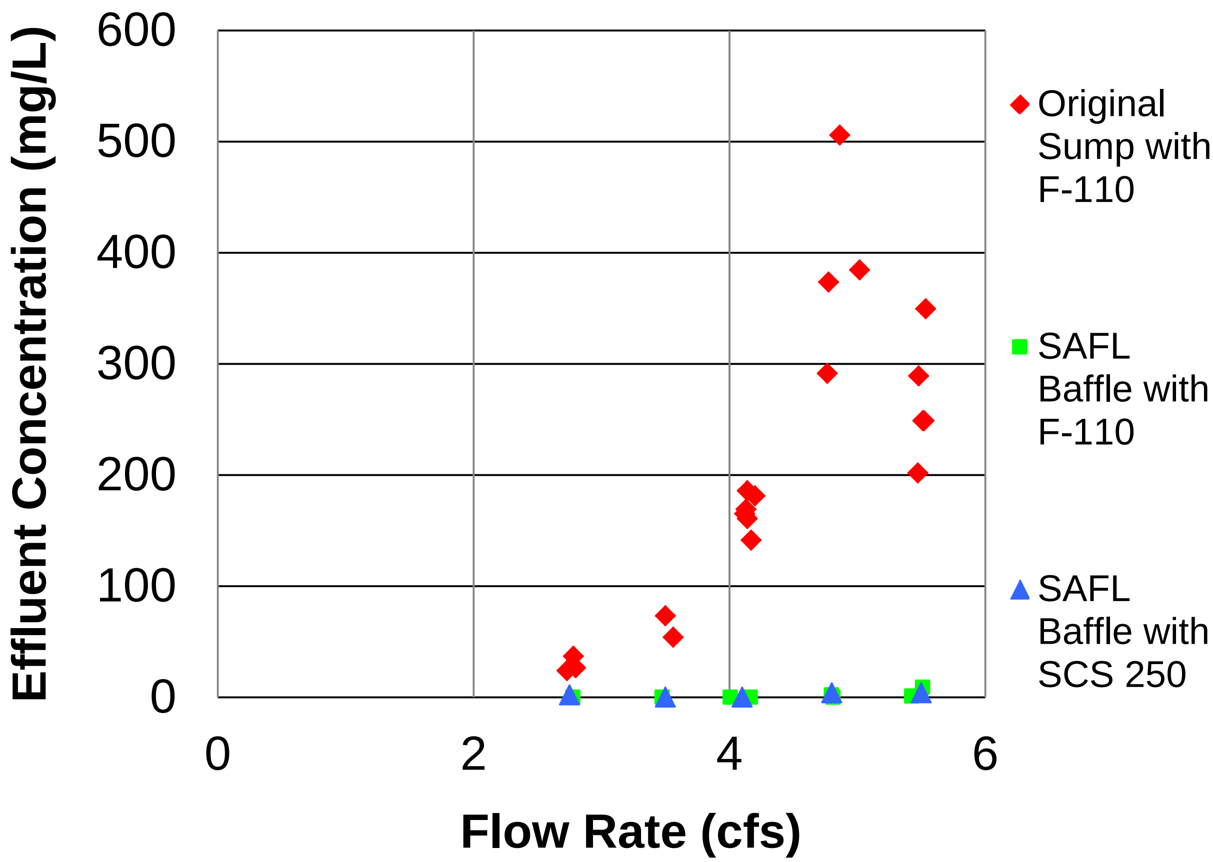

Figure 2-8: Comparison of the 4×4 sump with and without SAFL Baffle.

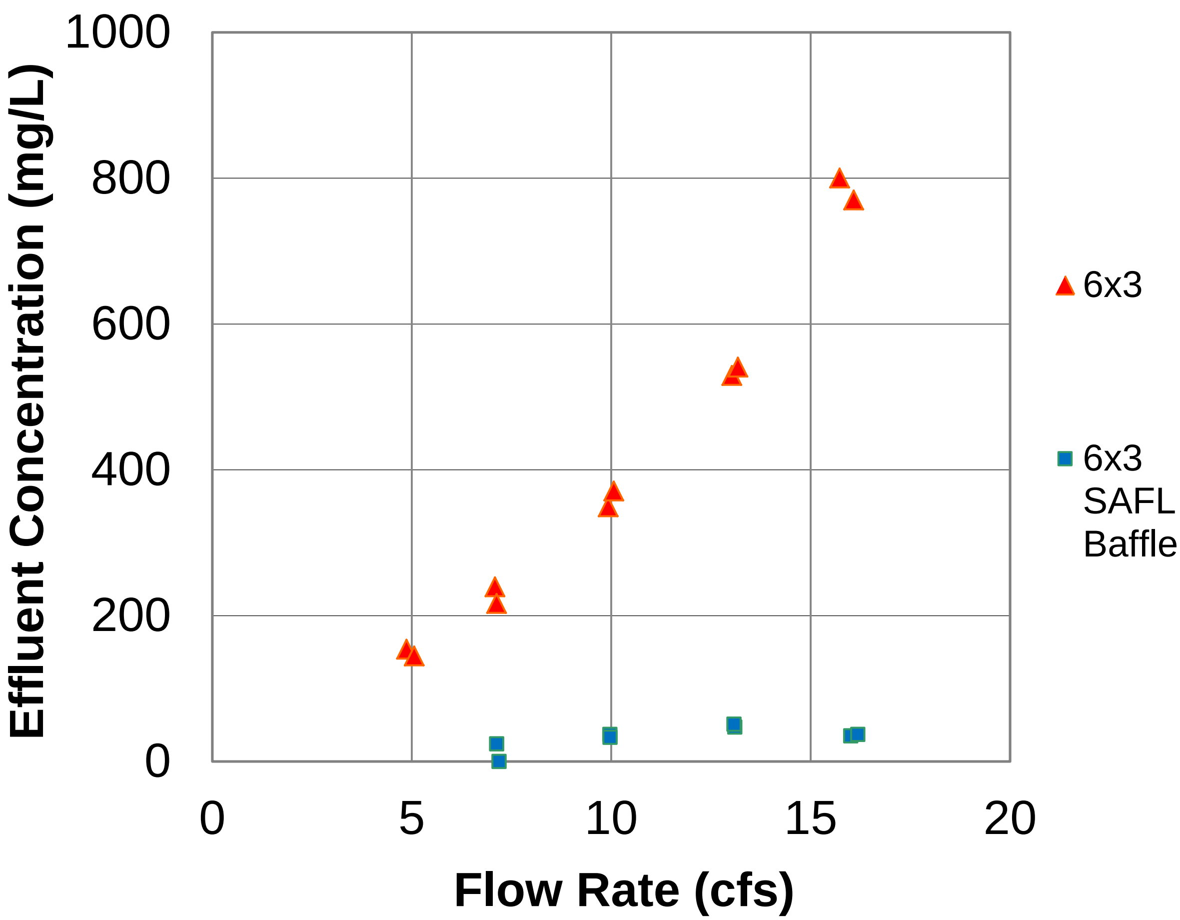

Figure 2-9: Comparison of the 6×3 sump with and without SAFL Baffle.

Figure 2-9 provides a comparison of the results of the tests conducted on the 6×3 ft sump with and without the SAFL Baffle. The baffle greatly improved the ability of the sump to retain sediment. At the 16 cfs (0.46 cms) flow condition, the SAFL Baffle decreased the sediment washout from 0.0499 to 0.00312 lb/ft^3 (800 mg/L to 50 mg/L).

2.5.2 Results of Removal Efficiency Tests

The results of the removal efficiency tests conducted on the 4×4 ft sump can be seen in Figure 2-10. With the SAFL Baffle installed, at low flow rates, e.g. 0.5 cfs (14 L/s), there is a significant increase in removal efficiency (approximately 15%) of small size particles (0.00433 inches or 110 μm). The SAFL Baffle will not improve the removal of larger particles at 0.5 cfs (14 L/s) and below because the sump without the baffle is already achieving near 100% removal. At medium flow rates (around 1 cfs or 29 L/s) for all particles tested, however, standard sumps with the SAFL Baffle exhibited between 10 to 20% increase in removal efficiency. At higher flow rates, i.e. above 1.5 cfs (43 L/s), smaller sediment particles were not removed more efficiently with the SAFL Baffle in place, but larger sediment sizes were removed at approximately 10% greater efficiency.

The results of the removal efficiency tests conducted on the 6×3 ft sump are shown in Figure 2-11. At very high and very low flow rates the removals were more or less the same for all particles tested. However, at median flow rates and median particle sizes, the system on average exhibited a 15% increase in sediment capture with the SAFL Baffle in place.

A review of the removal efficiency and washout test data shows that with the SAFL Baffle retrofit in place, any particle size which is collected in the sump will remain in the sump at high flow conditions. For instance, a 4×4 ft sump can capture 0.00421-in (107-µm) particles during a flow event with a magnitude of 0.6 cfs (17 L/s). Even though only 18% of this sediment may be captured, all of what is captured will remain in the sump even when a 5.5 cfs (159 L/s) flow passes through the sump. Without the SAFL Baffle, all of this sediment may be washed out of the sump during this large storm event.

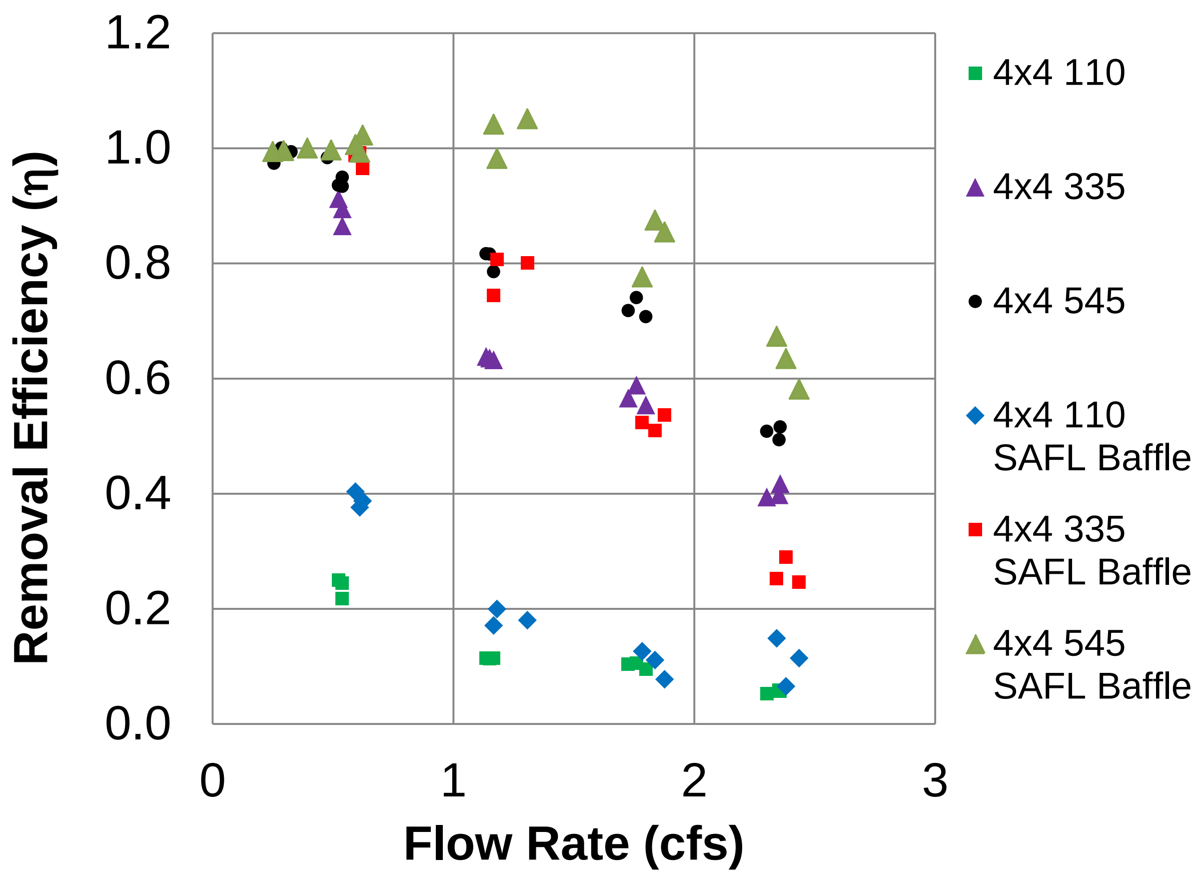

Figure 2-10: **The 4×4 ft sump performance results with and without the SAFL Baffle.**

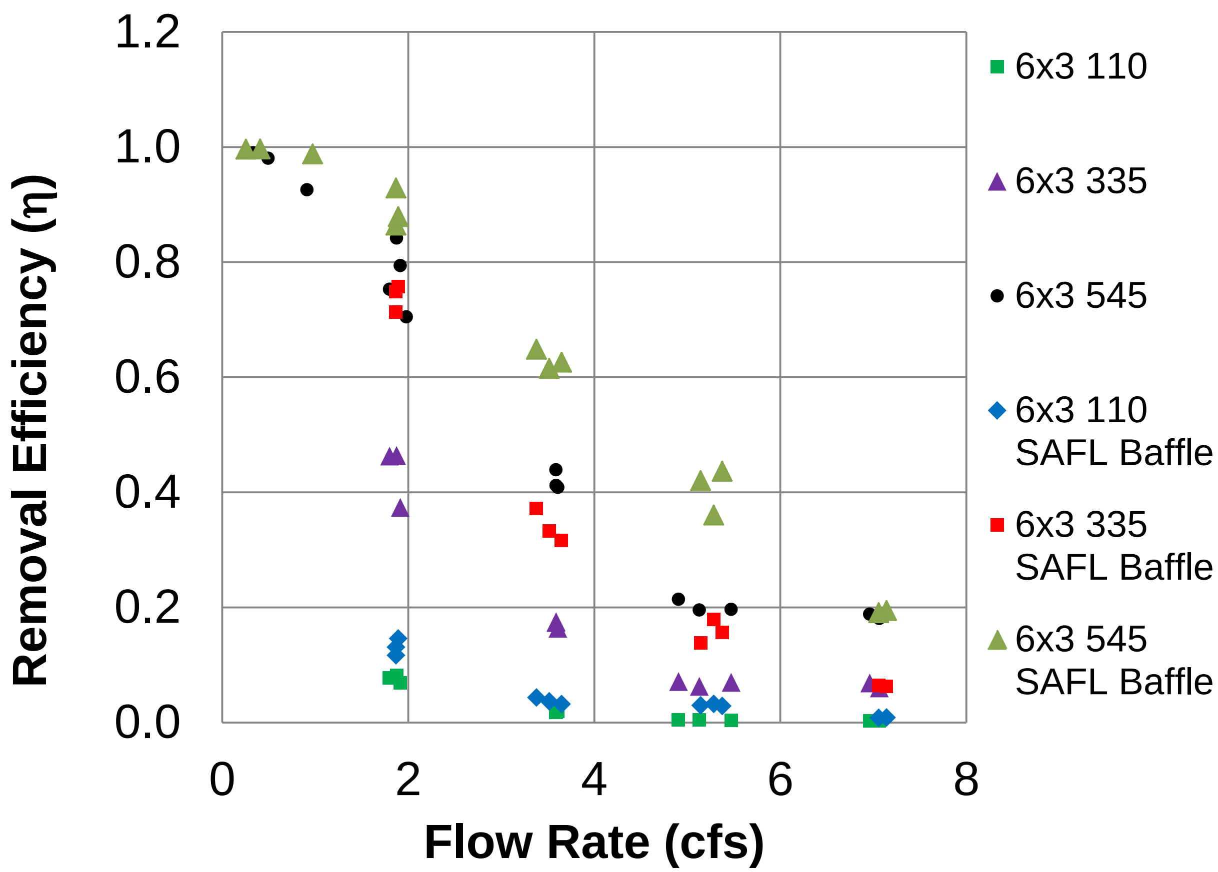

Figure 2-11: The 6×3 ft sump performance results with and without the SAFL Baffle.

2.5.3 Performance Functions

In Volume 1 of this report (Howard et al., 2011), it was shown that removal efficiency and washout data for sumps can be collapsed into a single curve using the Péclet number (Pe) (Equation 2-1) or the Péclet number over the Froude number squared (Pe/Fr_j^2) of the jet entering the inlet pipe (Equation 2-2). Low Péclet (Pe) and Pe/Fr_j^2 numbers correspond to small sediment particles, high flow rates, small diameter sump manholes, and shallow sump manholes. Conversely, high Péclet and Pe/Fr_j^2 numbers correspond to large sediment particles, low flow rates, large diameter sump manholes, and deep sump manholes.

$$Pe = \frac{v_s * h * D}{Q} \tag{2-1}$$

Where:

$v_s = settling\ velocity\ of\ sediment\ particles$
$h = sump\ depth$
$D = sump\ diameter$
$Q = flow\ rate\ entering\ sump$

$$Fr_j{}^2 = \frac{U^2}{gD} \tag{2-2}$$

Where:

$U = velocity\ of\ waterjet\ entering\ the\ sump$
$g = acceleration\ of\ gravity$
$D = sump\ diameter$

Washout rates for a myriad of particle sizes, sump sizes, and flow rates can be characterized by a dimensionless concentration given in Equation 2-3:

$$\hat{C} = \frac{C(SG-1)}{\rho_w SG} = \frac{\alpha}{Pe/Fr_j{}^2} + \beta e^{-\lambda Pe/Fr_j{}^2} \tag{2-3}$$

Where:

$C = effluent\ concentration$
$\rho_w = water\ density$
$SG = specific\ gravity\ of\ particles$
$\alpha, \beta, \lambda = fitting\ parameters$

Equations 2-4 and 2-5 show the washout functions for standard sumps and standard sumps with the SAFL Baffle, respectively.

$$\hat{C} = \frac{C(SG-1)}{\rho_w SG} = \frac{8.3\times10^{-6}}{\frac{Pe}{F_j{}^2}} + 4.7\times10^{-4} e^{-3.18\frac{Pe}{F_j{}^2}} \tag{2-4}$$

$$\hat{C} = \frac{C(SG-1)}{\rho_w SG} = \frac{1.67\times10^{-6}}{\frac{Pe}{F_j{}^2}} + 5.16\times10^{-4} e^{0.69\frac{Pe}{F_j{}^2}} \tag{2-5}$$

Figure 2-12 displays these functions plotted in terms of $\hat{C}$ versus Pe/Fr_j^2 values.

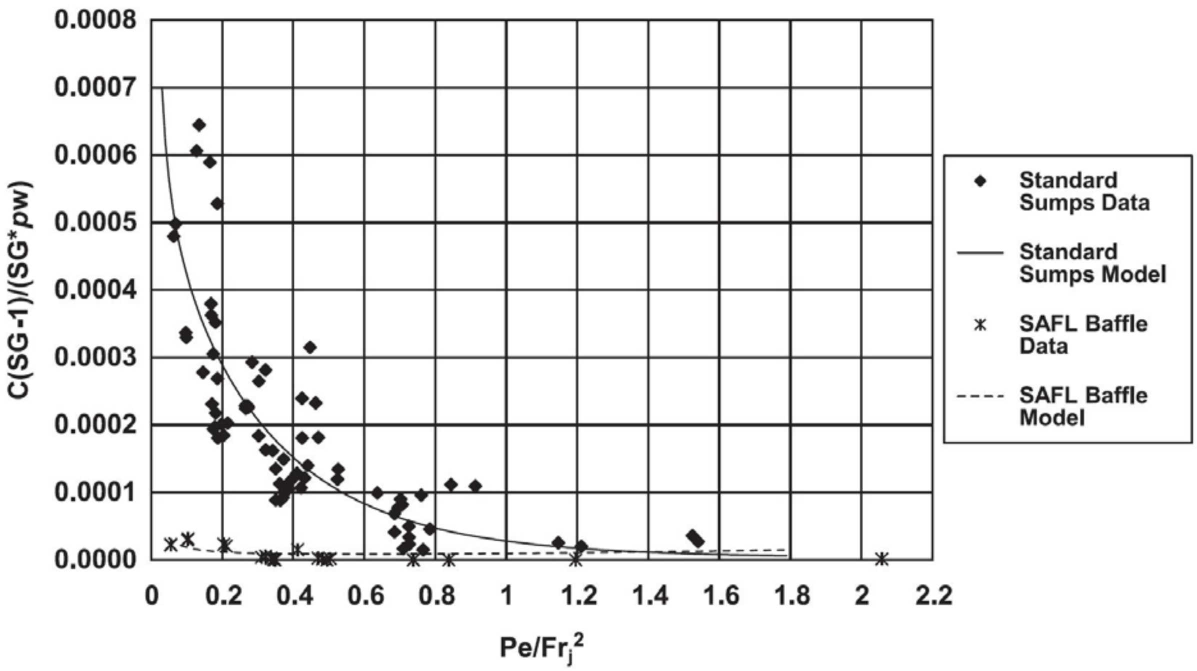

Figure 2-12: Washout functions for standard sumps and standard sumps with SAFL Baffles.

Similarly, the measured removal efficiencies were plotted versus the Péclet number and Pe/Fr$_j^2$ values computed for each test. Figure 2-13 shows the data of standard sumps equipped with a SAFL Baffle versus the Péclet number. This data includes the 4×4 and 6×3 straight flow-through sumps, equipped with a 1-in (2.5 cm) hole diameter and 3-in (7.6 cm) hole diameter SAFL Baffle, respectively. Figure 2-14 shows the same information, but in terms of Pe/Fr$_j^2$.

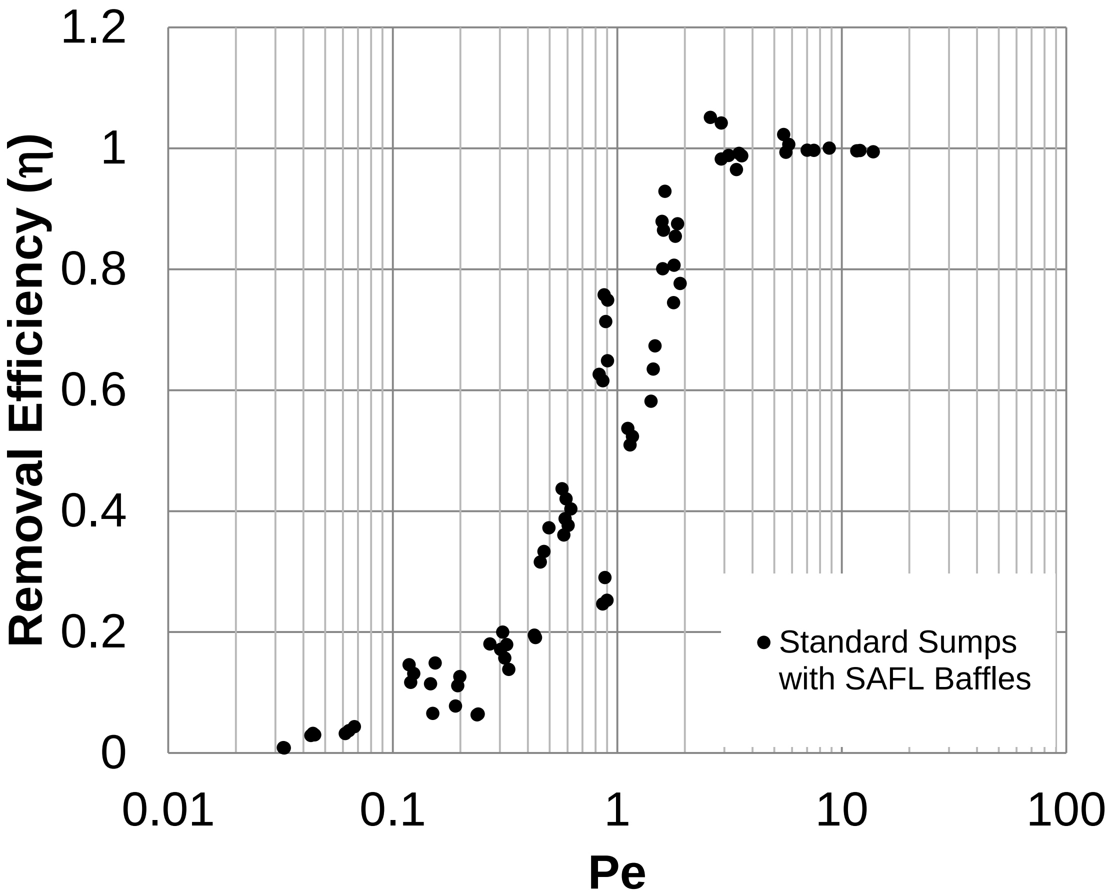

Figure 2-13: Removal efficiency of standard sumps equipped with SAFL Baffles versus Pe.

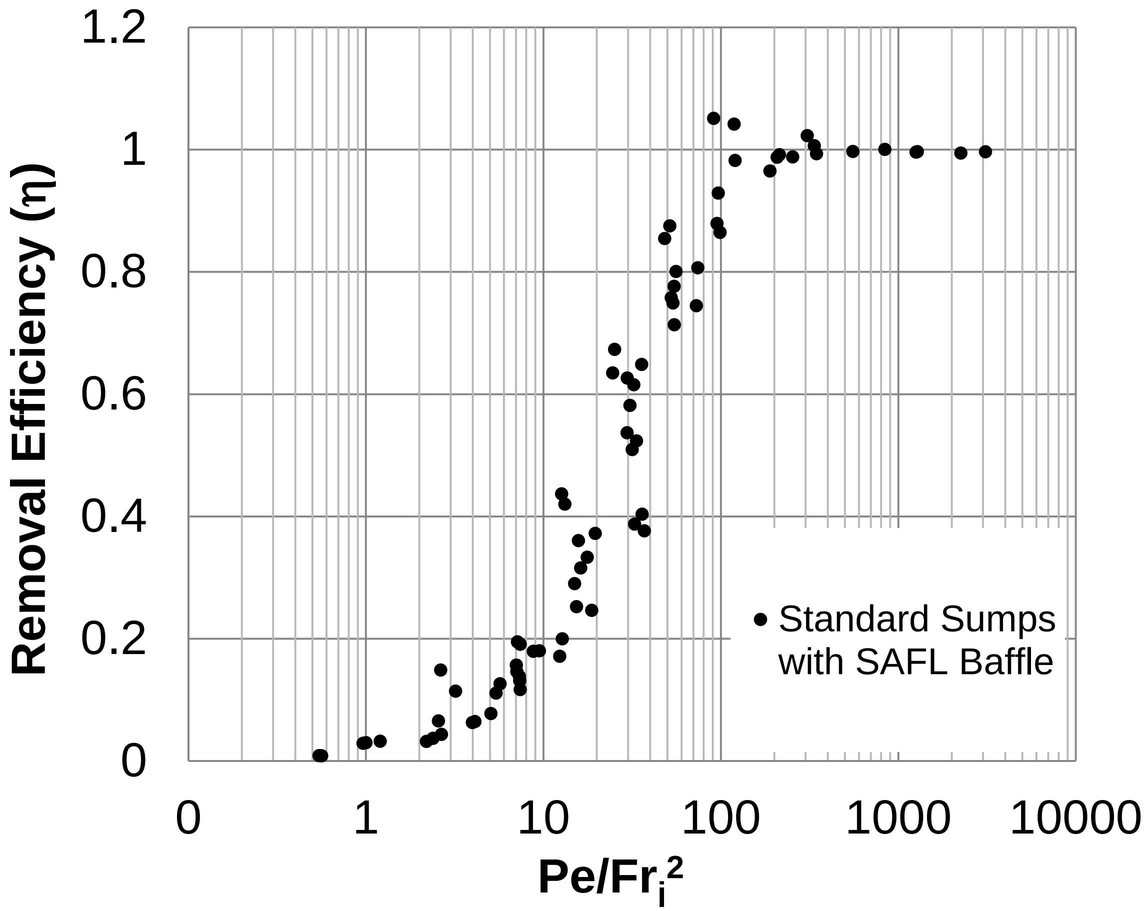

Figure 2-14: Removal efficiency of standard sumps equipped with SAFL Baffles vs. Pe/Fr$_j^2$.

Figure 2-15 shows the removal efficiency performance function for a standard sump and for a standard sump equipped with a SAFL Baffle. The results shown in Figure 2-15 may seem to show no significant difference between the removal efficiency of a standard sump with and without the SAFL Baffle. However, it is important to note that for the same flow rate, the jet velocity entering a sump with a SAFL Baffle is smaller than in a sump with no baffle. The smaller jet velocity is due to the head loss and backwater from the baffle. This difference results in smaller Froude number and thus larger Pe/Fr$_j^2$ values which result in higher removal efficiency. Based on our assessment of different conditions, on average a sump equipped with the SAFL Baffle is between 10 and 15 percent more efficient than a sump with no baffle in removing suspended sediment from stormwater runoff.

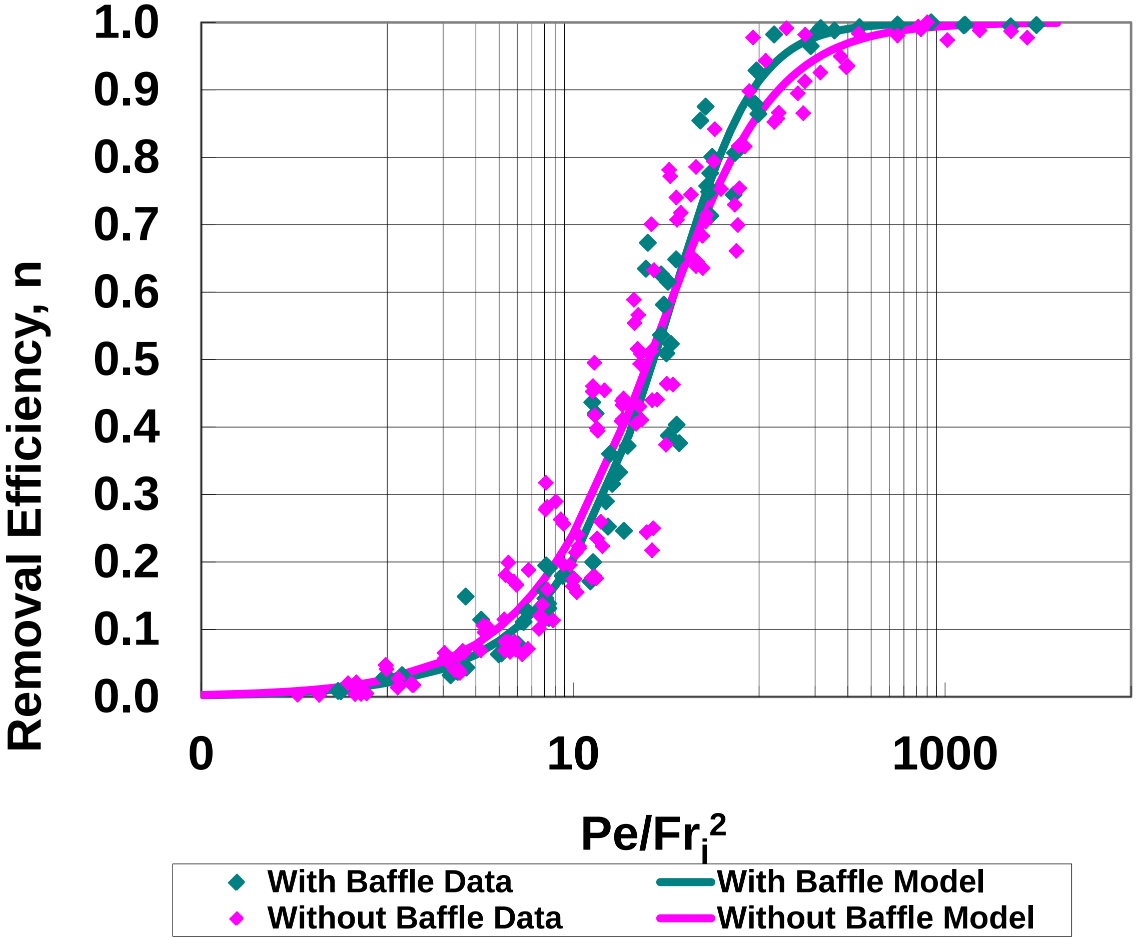

Figure 2-15: Removal efficiency of standard sumps with and without the SAFL Baffle.

3 Impact of Debris on the SAFL Baffle

In order to know how a SAFL Baffle performs when clogged with debris, it was necessary to know what constitutes the debris in stormwater runoff and also to quantify it so that a testing method could be developed. For the purposes of this study, only items that could potentially clog the SAFL Baffle were considered for testing. This means that solids which quickly sink, or are too small to clog the holes of the baffle, were not within the testing scope.

3.1 Debris Composition and Loading

A number of studies have been conducted to determine what makes up debris in the United States. Studies of highways in Southern California (CALTRANS, 2000 and Kim et al., 2004) and with a proprietary trash collector in a Texas neighborhood (Weir et al., 2010) showed debris larger than 0.2 inches (0.5 cm) in stormwater is roughly composed of 81-90% vegetation, 5-19% trash, and 0-13% sediment. This information is summarized in Table 3-1.

Table 3-1: Stormwater debris composition from three studies.

Source	Trash	Vegetation	Sediment
CALTRANS, 2000	19%	81%	0%
Weir et al., 2010	5%	82%	13%
Kim et al., 2004	-	90%	-

Studies by Younis et al. (2005) and Caltrans (2000) indicated that trash encompasses a variety of items including, but not limited to, plastics, paper, cigarette butts, wood, glass, and metal. A summary of this information can be seen in Table 3-2.

Table 3-2: Stormwater trash composition from two studies.

Category	% by Air Dried Weight, Younis et al. 2005	% by Air Dried Weight, CALTRANS 2000	% of Air Dried Weight Within Scope of Project
Cardboard/chipboard	11	10	10.5
Cigarette butts	14	10	0
Cloth	7	6	6.5
Metal	8	13	0
Paper	15	9	12
Plastic-film	6	7	6.5
Plastic-moldable	22	21	21.5
Styrofoam	4	5	4.5
Wood	10	16	0
Glass	1	1	0
Other	2	2	2
Total	*100*	*100*	*63.5*

3.1.1 Tree Leaf Sizes

According to the City of Minneapolis, the five most common types of deciduous, simple leafed trees within the city limits are Green Ash, Sugar Maple, Norway Maple, Littleleaf Linden, and American Elm. These trees represent over 60% of the trees in Minneapolis (City of Minneapolis, 2011). According to the Minnesota Department of Natural Resources, these trees produce leaves with lengths ranging from 1.5 to 6 inches (3.8 to 15.2 cm) and greatly varying aspect ratios (Department of Natural Resources, 2011). The data are summarized in Table 3-3.

Table 3-3: Trees and leaf sizes in Minneapolis, MN.

Tree Type	Pop. %	Aspect Ratio Leaf Length	Aspect Ratio Leaf Width	Average Length (in)	Average Width (in)
Sugar Maple	13.1	1	1	4.0	4.0
Littleleaf Linden	10.4	3	2	2.3	1.5
American Elm/ Green Ash	24.3	2	1	4.4	2.2
Norway Maple	11.8	4.5	6	4.5	6.0

By calculating a weighted average leaf length and width of these most common Minneapolis trees in Minneapolis, the size of vegetation entering the storm sewer could be estimated. The average Minneapolis leaf length is 4 inches (10 cm), and the average width is 3.2 inches (8.1 cm).

3.1.2 Debris Loading Rates

The three studies mentioned in Table 3-1 collected enough data to create a "normalized" loading rate. Each study published data about the amount of gross solids collected in lbs per acre per year. With the impervious fraction of the study sites and the annual rainfall, a loading rate could be created in terms of lbs per acre per year per inch annual rainfall per fraction of impervious area. Using the three studies, a mean, minimum, and maximum loading rate was calculated.

$$LR = NLR * Imp * R * A \tag{3.1}$$

Where:

$LR = Loading\ Rate\ \ (lb/year)$

$NLR = Normalized\ Loading\ Rate\ \left(\frac{lb/year}{acre * in\ of\ annual\ rainfall * impervious\ fraction}\right)$

$Imp = Impervious\ Fraction$

$R = Annual\ Rainfall\ \ (inches)$

$A = Drainage\ Area\ \ (acres)$

Despite one study being in Texas, and the other two in California, Table 3-4 indicates that the loading rates were comparable.

Table 3-4: Normalized loading rates (NLR) for various locations in the US.

Source	Location	Imp	R (in/)	Mean NLR (lb/ac/yr/in. ann. rain/imperv.)	Min NLR (lb/ac/yr/in. ann. rain/imperv.)	Max NLR (lb/ac/yr/in. ann. rain/imperv.)
Bob Weir 2010	Rowlett, TX	0.50	38.2	9.46*	2.01	23.7
CALTRANS 2000	CA	0.80	15.1	5.09	2.98	7.20
Kim et al. 2004 & Northfield MN Weather Data	LA, CA	0.99	15.1	4.18	1.45	11.7

* Each lb/ac/yr/in ann rain/imperv is equal to 0.27 kg/ha/year/cm rainfall/fraction impervious

3.1.3 Simulated Debris from a Minneapolis Watershed

To estimate the amount of debris that would enter a sump manhole in Minneapolis, loading rates from CALTRANS (2000) and Younis et al. (2005) research were used. Weir's (2010) data were collected at only one location, so they were not used for computations. A program for Sizing Hydrodynamic Separators and Manholes, SHSAM (Mohseni et al., 2011), was then utilized to determine a drainage area for the simulated sump manhole, assuming that the sump is expected to remove 50% of OK110 sediment distribution from stormwater runoff.

The SHSAM software was run by using 15-minute precipitation data from Northfield, MN between 1991 and 2007. Additionally, daily air temperature data were used from the same location during the same dates. The curve number (Mays 2005) for pervious surfaces in the theoretical watershed was set equal to 70 and the sediment influent concentration was assumed to be 0.0062 lb/ft^3 (100 mg/L). Finally a 3:1 watershed length to width ratio was used to determine the hydraulic length of the drainage basin.

With the above information, SHSAM calculated that a 3.3 acre (1.3 hectares) drainage area required a 6×6 sump manhole equipped with a SAFL Baffle to collect 50% of the OK110 sediment.

By using a drainage area of 3.3 acres (1.3 hectares), an impervious fraction of 0.35, 26 inches per year (66 cm per year) of annual rainfall, and a mean normalized loading rate of 4.6 lbs/acre/yr/inches of annual rainfall/impervious fraction, the loading rate was calculated to be 139 lbs (63 kg) per year. This amount was then used as the basis for determining how much debris would be fed into the sump during washout and removal efficiency testing. It is important to note that this amount of debris does not enter the sump in one event but most likely during a number of intense storm events.

3.2 Experimental Setup

Two laboratory sump manholes were utilized for debris testing. The first was the 1-ft (0.3 m) diameter sump (the scale model), and the second was the 6-ft (1.8 m) diameter sump. Each sump was retrofitted with a SAFL Baffle that was orientated orthogonal to the floor of the sump and was located between the inlet and outlet pipes. Additionally, water entered through an inlet pipe and exited through an outlet pipe located 180 degrees to the inlet pipe, i.e. a straight flow-through sump was used. Both sumps had false floors, which could be installed to transform them into a 6×3 sump and a 1×0.5 sump. Schematics and detailed information about the testing sump setups can be found in Appendix A.

The testing setup on the 1×1 and 1×0.5 scale models required the use of a SAFL Baffle with a 0.5-in (1.27 cm) hole diameter to model 3-in (7.6 cm) hole diameter, another with 0.75-in (1.9 cm) hole diameter to model 4.5-in (12.7 cm) hole diameter, and one with a 0.5-in (1.27 cm) hole diameter SAFL Baffle orientated vertically at a 45 degree angle away from the inlet pipe. This means that the bottom of the baffle was closer to the inlet pipe, and the top of the baffle was closer to the outlet pipe.

Two SAFL Baffle configurations were used during the 6-ft (1.8 m) diameter sump testing: a baffle with 3-in (7.6 cm) holes and a baffle with 5-in (12.7 cm) holes. Both SAFL Baffles had open areas between 45% and 48%. Figure 3-1 shows the 0.5-in (1.27 cm) model scale baffle and Figure 3-2 shows the full scales baffles installed in the sump.

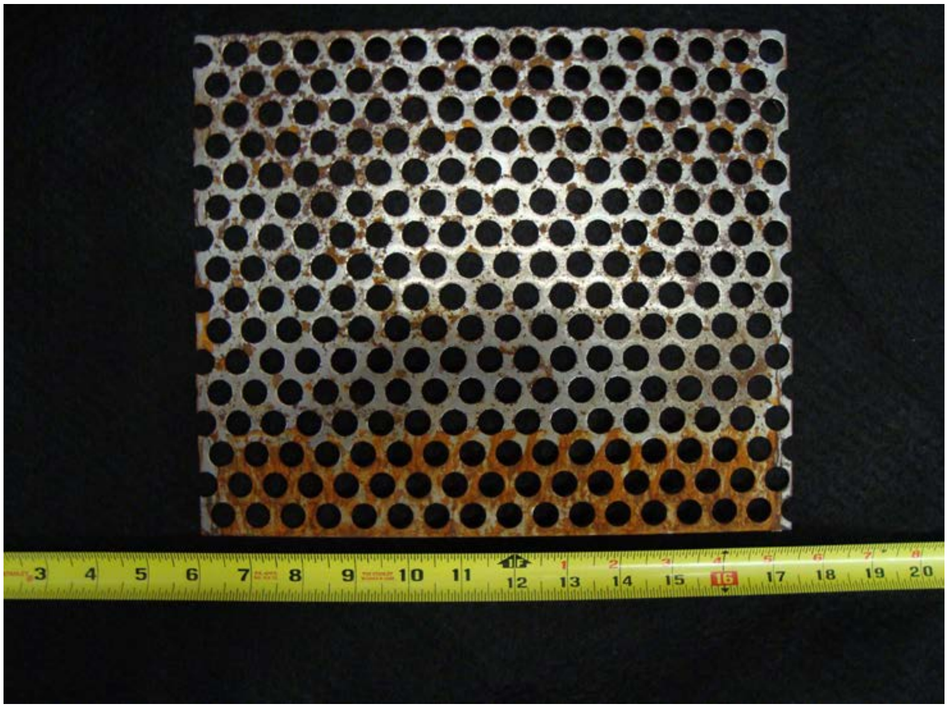

Figure 3-1: The SAFL Baffle with 0.5-in (1.27 cm) hole diameter.

Figure 3-2: SAFL Baffles with (left) 3-in (7.6cm) and (right) 5-in (12.7cm) hole diameters.

3.3 Testing Procedure

Debris washout tests and removal efficiency tests followed procedures that were similar to those conducted on the standard sumps, except that debris tests were conducted in two phases. The first phase, called a debris-loading phase, was conducted by feeding debris into the sump through a hole in the inlet pipe. The loading phase took place at flow rates significantly lower than the flow rates for washout tests. After the debris-loading phase, the removal efficiency or washout test was conducted similar to the standard sump tests. Detailed testing procedures can be found in Appendix B.

For the debris washout testing on the model scale, the 1×1 sump was filled with 18 lbs (8.2 kg) of sediment with a median size of 0.00433-in (110 µm) (the sediment was a mix of 60% AGSCO #100-140 and 40% AGSCO #140-270). For the 1×0.5 sump, it was filled with 11.5 lbs (5.2 kg) of the same material. The test started with the debris-loading phase, where a mixture of 19.8 oz (560 g) of scaled debris was loaded upstream of the device at a flow rate of 13.1 gpm (0.83 L/s), or 2.9 cfs (84 L/s) if the flow rate is scaled to a 6-ft (1.8 m) diameter sump. Following the debris-loading phase, the flow rate was increased to a desired washout magnitude between 41 and 73 gpm (2.6 to 4.6 L/s), or 9 to 16 cfs (260 to 463 L/s) full scale.

The debris mixture used for washout testing was 80% star shaped plastic confetti and 20% wood dowels. To mimic the size of Minneapolis tree leaves, the star shaped plastic confetti were 1/16-in (0.16 cm), 1/4-in (0.64 cm), and 1/2-in (1.3 cm) in diameter. Similarly, the wood dowels mimicked an average 20 ounce (0.59 L) soda with dimensions equal to 3/8-in (0.95 cm) in diameter and 1.3-in (3.3 cm) in length (Figure 3-3).

The testing procedure used for the 6-ft diameter sump was similar to the procedure for the scale model sump. After the initial filling of the sump with sediment and water, the sump was weighed, the valve was opened and the flow rate through the sump was increased to between 0.75 and 1.5 cfs (21.2 L/s and 42.5 L/s). Subsequently, debris was loaded into the sump through a hole roughly 8 feet upstream of the sump. Debris fed into the sump was comprised of leaves, small plastic grocery bags, plastic bottles, and vinyl leaves (Figure 3-4). The plastic bottles were about 2.5-in (6.4 cm) diameter by 5- to 8-in (12.7-20.3 cm) long plastic soda bottles. The grocery bags were all the same size, with dimensions equal to 8-in (20.3 cm) wide by 5-in (12.7 cm) deep by 16-in (40.6 cm) tall. Another simulated debris type was vinyl cut into rhombi and other various shapes (Figure 3-5). The rhombi are 3-in (7.6 cm) across horizontally and 4-in (10.2 cm) vertically. These dimensions are shaped in order to roughly match the average size of a tree leaf in Minneapolis. For tests completed with the vinyl debris, 65 lbs (30 kg) of debris was fed upstream of the device (roughly 50% of the annual load). Next, the flow rate was increased to the target value. After each test, the flow rate was quickly stopped and debris was removed from the sump, without removing sediment. Finally, the sediment remaining in the sump was weighed.

Figure 3-3: Simulated debris mixture (left) 80% confetti (right) 20% wood dowels.

Figure 3-4: (Left) loading simulated debris upstream of the manhole sump. (Right) water leaving the sump's outlet and traveling through the tail box, where debris is collected.

Figure 3-5: Vinyl leaves, plastic grocery bags, and plastic bottles used as simulated debris.

To complete debris removal efficiency tests, debris was loaded upstream of the device, over a period of about 10 minutes at 0.75 cfs (21.2 L/s) flow rate. The flow rate was then increased to the target value for the removal efficiency testing, and then sediment feeding began. Otherwise, the procedure was similar to the removal efficiency testing on the standard sumps. Post-test clean-up required separating the sump-captured sediment and the debris captured in the sump. Sediment captured in the sump was dried, sieved, and weighed just as with the removal efficiency tests described in Volume 1 of this report.

3.4 Scale Model Results

Three debris washout tests were completed on the 1×1 scale model. All three tests were completed with the 0.5-in hole SAFL Baffle, constant loading phase flow rates, durations, debris loading, and initial sediment pre-loading. The three tests had washout flow rates ranging from 41 gpm to 73 gpm (2.6 to 4.6 L/s), or 9 to 16 cfs (260 to 463 L/s) if scaled to a 6×6 sump.

During the loading phase, confetti debris that traveled into the sump either hit the SAFL Baffle and sank to the bottom of the sump or hit the SAFL Baffle and stayed in place. Small amounts of confetti traveled through the baffle. Some confetti impinged on the SAFL Baffle was later blown off due to turbulence and sank to the bottom of the sump. Wood dowels floated in the water, and did not impinge to the Baffle, instead, they circled upstream of the baffle due to the effect of separation zone at the inlet of the sump. This rotation stopped when the upstream portion of the sump was jammed with wood dowels. Very few wood dowels traveled through the baffle holes, despite the dowels' diameter being smaller than that of the baffle. All sediment at the bottom of the sump remained stationary during this loading phase.

At the onset of the washout test, the flow rate through the sump was increased. Most of the confetti stuck on the baffle screen was blown away due to power of the water entering the sump and hitting the screen. Blown away confetti either passed through the sump, or sank to the bottom of the sump. Wood dowels simply rose with the increase in water elevation due to the increased flow rate. Figure 3-6 shows the debris stuck on the SAFL Baffle at the end of the loading phase, and then during the washout phase. In these photos, water was traveling from right to left, meaning the inlet is at the right hand side of each picture. Despite clogging from debris, little washout of sediment was recorded at the end of each test.

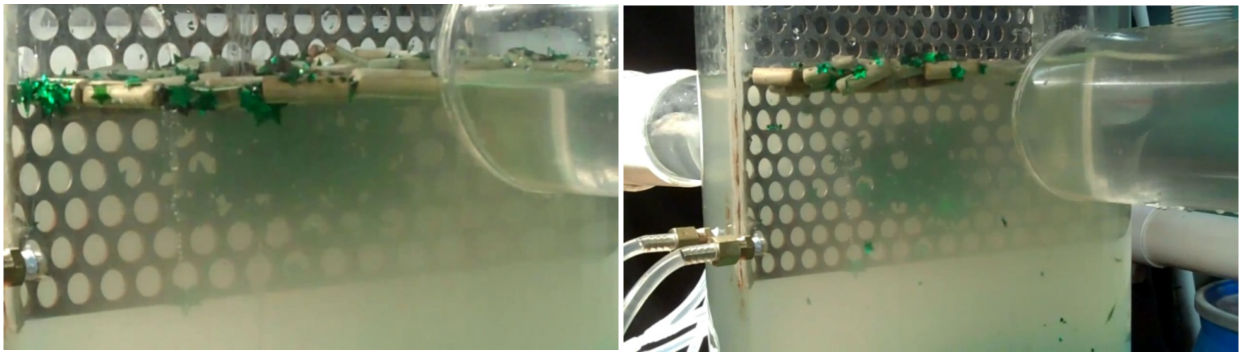

Figure 3-6: (Left) 1×1 scale model during the loading phase and (right) during the washout phase. Water flow is from right to left.

Table 3-5 shows the effluent concentration of sediment washed out of the sump at three flow rates. Two different methods were used to measure the amount of sediment leaving the sump during testing. The first method required the sediment captured in the downstream 0.00079-in (20 μm) filter be dried and weighed. This amount of sediment mass was then used with the flow rate through the system during the washout phase to determine an effluent concentration. The second method required that all sediment in the sump, post washout test, be dried and weighed. By using these two methods, an average effluent concentration was calculated.

Table 3-5: Summary of debris washout testing on a 1×1 sump model equipped with a SAFL Baffle.

Test	Scale model Flow Rate (gpm)	Full Scale Equivalent Flow Rate (cfs)	Gross Pollutants Load (g)	Effluent Concentration (mg/L)
1	63	14	554.5	-0.8
2	73	16	560.5	19.1
3	41	9	560.0	9.1

Five washout tests were completed on the 1×0.5 scale model. Between these tests, the loading phase flow rate was constant at 3.5 gpm (0.2 L/s), the washout flow rate was constant at 33 gpm (2.1 L/s), the washout phase duration was constant at 24 minutes, and the sediment pre load amount was constant at 11.5 lbs (5.2 kg). However, several variables did not remain constant between the five tests. The first three tests were the same, except the amount of debris loaded into the device was varied between 11.3, 0, and 5.7 ounces (319, 0 and 163 g or 100%, 0%, and 51%). Tests 4 and 5 utilized two design alternatives for the SAFL Baffle. The first alternative was a SAFL Baffle with 0.75 inch holes, which is roughly equivalent to 4 7/8-in (12.4 cm) holes full scale. This design has roughly the same percent open area as the 0.5-in (12.7 cm), or 3-in (7.6 cm) hole full scale SAFL Baffle. The second design alternative was a SAFL Baffle with 0.5-in (12.7 cm) holes installed at an angle with respect to the standard vertical SAFL Baffle design.

The debris loading process was the same as with the 1×1 washout testing series. Confetti either hit the baffle and sank to the bottom of the sump, or became pressed against it. Wood dowel debris remained floating in the upstream half of the sump.

Test 1 was performed at a lower washout flow rate, i.e. 32.9 gpm (2.1 L/s), than the three tests performed on the 1×1 scale model, but the effluent concentration was measured to be 0.0098 lb/ft^3 (157 mg/L). This was much higher than the effluent concentrations measured for the 1×1 model. Figure 3-7 shows the scour hole underneath the SAFL Baffle, indicating that water traveled underneath of the SAFL Baffle, and out of the outlet pipe. This flow path is close to the sediment bed, resulting in sediment washout.

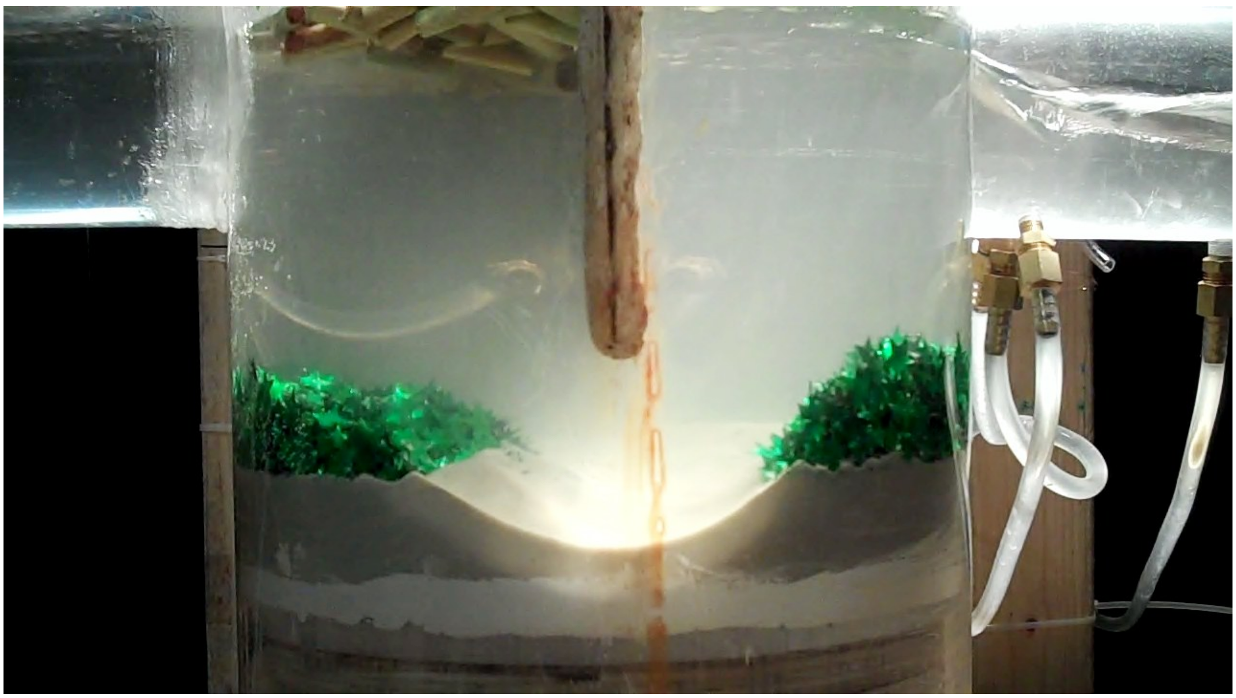

Figure 3-7: The final seconds of washout Test 1 on the 1×0.5 model. Water is flowing from left to right.

Test 2 was performed with the same conditions as Test 1, but no debris was loaded into the sump. The effluent concentration was measured to be 0.00037 lb/ft^3 (6 mg/L), meaning that little washout occurred (Figure 3-8). Test 3 was performed with the same conditions as Tests 1 and 2, but 50% of 11.3 ounces (319 g) of debris was loaded during the loading phase (Figure 3-8). The effluent concentration for this test was measured to be 0.0017 lb/ft^3 (27 mg/L).

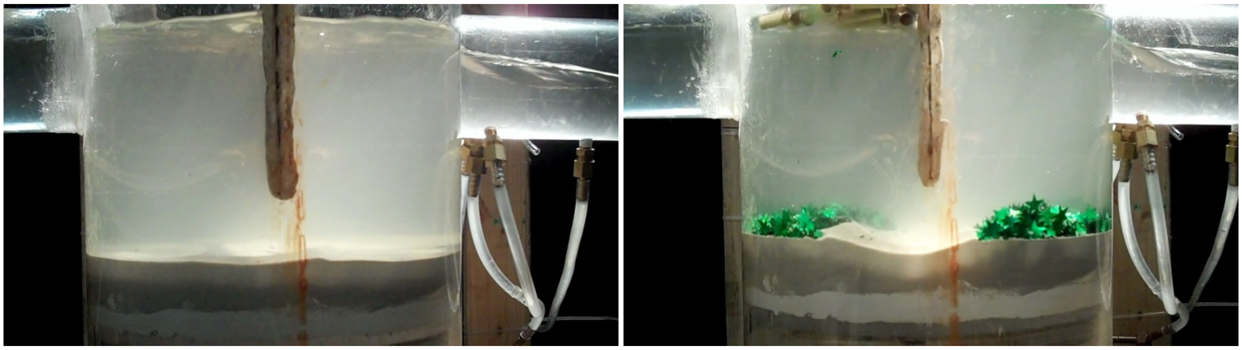

Figure 3-8: The final seconds of washout Tests 2 and 3 on the 1×0.5 model. Water is flowing from left to right.

Tests 4 and 5 (Figure 3-9) were conducted with alternative SAFL Baffle configurations to find ways to mitigate the high washout rates in shallow sumps. Test 4 was conducted with the same parameters as Test 1, but a SAFL Baffle with 0.75-in (12.7 cm) holes was used. This means that the SAFL Baffle had larger holes, but had fewer of them to maintain a constant open area. The effluent concentration for this test was low, and measured to be at 0.00075 lb/ft^3 (12 mg/L). Finally, Test 5 was conducted with the same parameters as Tests 1 and 4, but made use of a 0.5-in (12.7 cm) hole SAFL Baffle installed at an angle. Figure 3-9 shows snapshots from the final seconds of washout testing of Tests 4 and 5.

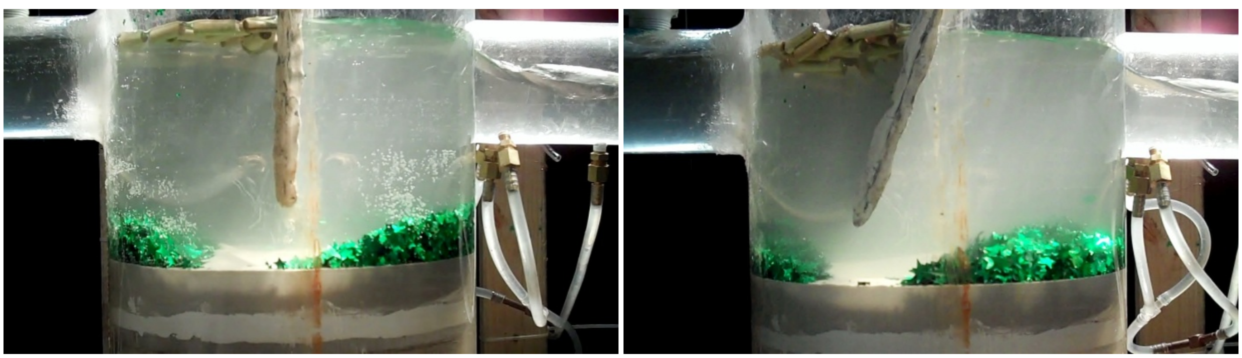

Figure 3-9: The final seconds of washout Tests 4 and 5 on the 1×0.5 model. Water is flowing from left to right.

Table 3-6 shows the testing parameters and results for the 1×0.5 washout testing series. Test 1 had the highest effluent concentration, and Test 2 had the lowest effluent concentration. When 100% of 11.3 ounces (319 g) of debris is loaded into the sump, Test 4 exhibited the lowest effluent concentration. The results of these tests on a scale model show that a shallow sump can be subject to high washout rates when clogged with debris, and it is recommended to use the SAFL Baffle in deep sumps. However, if the baffle is a retrofit and the sump is shallow, then a SAFL Baffle with larger holes would be appropriate, or if the access allows, the original SAFL Baffle can be installed at an angle similar to that shown in Figure 3-9.

Table 3-6: 1×0.5 Debris washout testing summary.

Sediment In Sump (%)	Gross Pollutants Load (%)	Washout Flow Rate (gpm)	6×3 Scaled Washout Flow Rate (cfs)	Effluent Concentration (mg/L)	Test Code Name
100	100	32.9	7.2	157	3" 100% Load
100	0	33.9	7.4	6	3" 0% Load
100	51	31.4	6.9	27	3" 50% Load
100	98	33.4	7.3	12	5" 100% Load
100	100	32.3	7.1	26	Angle 100% Load

3.5 Full Scale Results

3.5.1 Washout Testing

Three tests were conducted on the 6×3 sump using combinations of plastic grocery bags, plastic bottles, and tree leaves. Test 1 had a loading flow rate equal to 1.5 cfs (43 L/s), whereas Tests 2 and 3 had a loading flow rate equal to 0.73 cfs (22 L/s). All three tests had an average washout flow rate of 6.9 cfs (200 L/s) with a 3-in (7.6 cm) hole SAFL Baffle installed in the sump.

Test 1 included a mixture of roughly 70% plastic grocery bags and 30% plastic bottles. The initial sediment in the sump for this test was 3205 lbs (1457 kg). Most of the plastic bags and bottles floated, and were unable to pass through the SAFL Baffle. Once the upstream half of the sump became inundated with plastic bags and bottles, plastic bags began traveling underneath the baffle. Surprisingly, the majority of the plastic bags that traveled under the baffle remained inside of the sump, and stayed next to the downstream side of the SAFL Baffle.

During the test, these plastic grocery bags on the downstream side of the SAFL Baffle exited through the outlet pipe of the sump. Since the upstream portion of the SAFL Baffle was clogged with bags, the sump's water flow patterns changed dramatically - from traveling through the baffle to traveling under the baffle. Additionally, plastic bags that were once upstream of the baffle began traveling underneath of it in large numbers and quickly exited the sump. By the end of the test, 10% of the plastic bags that were loaded into the sump stayed in the sump, 90% of the plastic bottles loaded into the sump stayed in the sump, and the effluent concentration was measured to be 0.08147 lb/ft3 (1305 mg/L). Figures 3-10 and 3-11 show the loading and washout phases of Test 1, as well as evidence of sediment washout in the sump.

Figure 3-10: (Left) loading phase of Test 1. (Right) washout phase of Test 1. The flow is from right to left.

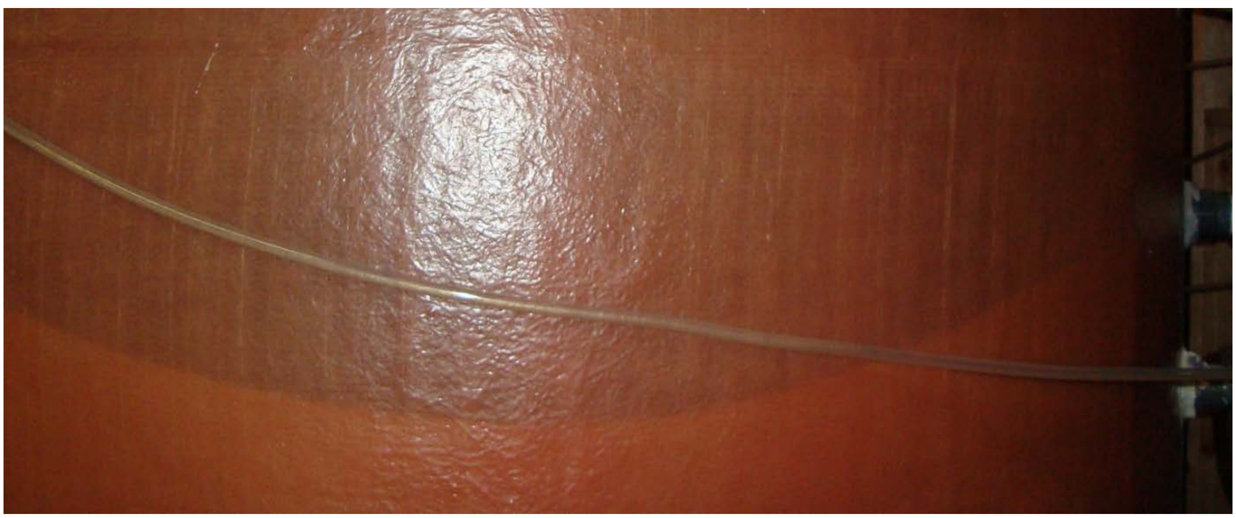

Figure 3-11: The once level sediment bed, shown drastically altered after Test 1. View from outside of the sump.

Test 2 was conducted similar to Test 1, but a mixture of 85% leaves, 7% plastic bottles, and 8% plastic grocery bags was loaded upstream of the sump. The amount of trash loaded for this test was 50% less than that for Test 1 and the sump contained 2415 lbs (1098 kg) of sediment before the test started.

The amount of debris loaded into the sump was larger than the area available upstream of the SAFL Baffle, so debris began backing up into the inlet pipe. Additionally, some leaves traveled underneath and through the sump and stuck to the downstream edge of the SAFL Baffle. When the flow rate increased to 6.9 cfs (200 L/s) for the washout phase, leaves downstream of the baffle began exiting the sump, and leaves upstream of the baffle traveled underneath the baffle and exited the sump. On the downstream side of the sump, leaves could be seen rising from underneath the water and flowing out of the sump. Again, this indicates that a significant portion of the water entering the sump was traveling underneath of the baffle. Since the baffle was not completely clogged, a smaller portion of the water traveled through the baffle. At the end of Test 2, 29% of loaded plastic bags, 90% of loaded bottles, and 5% of loaded leaves remained in the sump. The effluent concentration was determined to be 0.06262 lb/ft^3 (1003 mg/L). Figures 3-12 and 3-13 show the loading and washout phases of Test 2.

Figure 3-12: (Left) loading phase of Test 2. (Right) washout phase of Test 2. The water flow is from right to left.

Figure 3-13: Debris stuck in the SAFL Baffle during Test 2. The view is from near the outlet pipe, looking upstream.

Test 3 of this series was conducted similar to Test 2, but utilized tree leaves as the only form of debris entering the shallow sump and the test started with 2218 lbs (1008 kg) of sediment in the sump. The 21 lbs (9.6 kg) of leaves quickly filled the space upstream of the baffle. Some leaves traveled through the baffle and under the baffle during the loading phase, and most did not leave the sump (Figure 3-14).

However, during the washout phase, a mere 3% of leaves remained in the sump. The rest were pushed through the baffle and out of the sump. Leaves clogged the baffle to a lesser degree than plastic bags, so flow patterns were split between traveling through the baffle and traveling under the baffle. Figure 3-15 shows water traveling through the baffle, despite it partially being clogged with leaf debris.

Figure 3-14: Test 2 from the 6×3 washout testing series during its loading phase. The view is from near the outlet pipe, looking upstream.

Figure 3-15: Test 2 from the 6×3 washout testing series during its washout phase. The view is from near the outlet pipe, looking upstream.

Table 3-7 summarizes the data from the three 6×3, shallow sump washout tests. The largest effluent concentration was measured in Test 1, and the lowest in Test 3.

Table 3-7: Summary of debris washout testing on a 6×3 sump equipped with a SAFL Baffle.

Test	Sediment In Sump (lbs)	Bags (lbs)	Bottles (lbs)	Leaves (lbs)	Effluent Concentration (mg/L)
1	3205	18.5	5.9	-	1305
2	2415	1.7	1.4	18.6	978
3	2218	-	-	20.9	434

Ten washout tests were conducted on the 6×3 sump (Figure 3-16). These tests utilized vinyl leaves as the simulated debris. All of these tests had loading rates equal to around 0.75 cfs (22 L/s), debris loadings equal to 65 lbs (30 kg), and initial sediment levels near 3000 lbs (1360 kg). Washout phase flow rates ranged from 2 to 7 cfs (58 to 202 L/s). The first five tests were completed with a 3-in (7.6 cm) hole diameter SAFL Baffle, and the last five were completed with a 5-in (12.7 cm) hole diameter SAFL Baffle.

During the first five tests, vinyl leaves clogged the baffle in a circular pattern directly in line with the inlet pipe. The majority of leaves that hit the baffle slowly sank to the bottom of the sump. For the final five tests, the clogged area due to vinyl leaves was smaller.

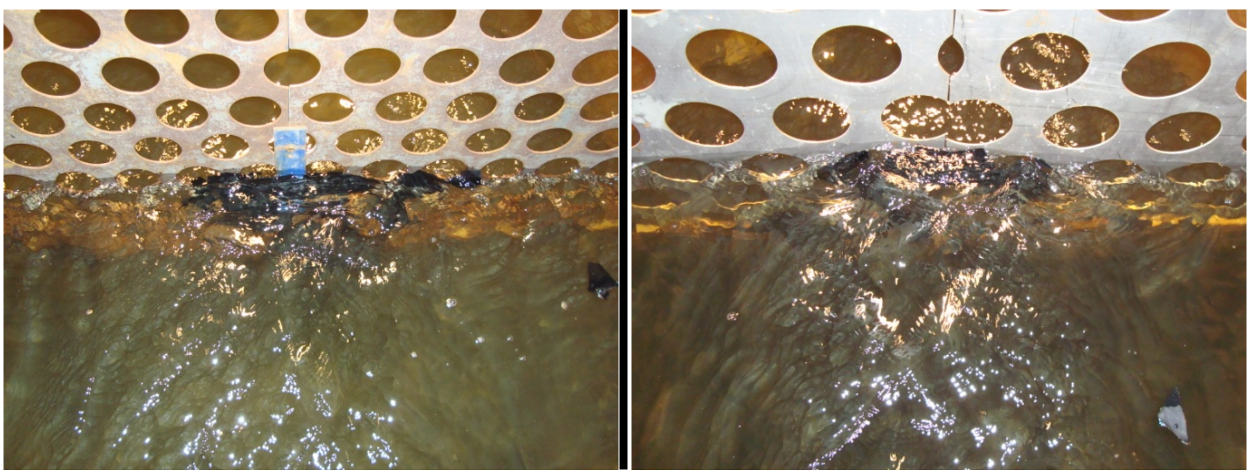

Figure 3-16: (Left) the clogging pattern for vinyl leaves on the 3-inch (7.6 cm) hole diameter SAFL Baffle and (right) on the 5-inch (12.7 cm) hole diameter SAFL Baffle. These views are from above the inlet pipe, looking downstream.

Results for the 6×3 washout testing series with vinyl leaves are shown in Figure 3-17. Flow rates around 4 cfs (116 L/s) exhibited higher washout rates than flow rates near 7 cfs (202 L/s). This may have occurred because nearly all vinyl leaves are washed off of the baffle at flow rates higher than 4 cfs (116 L/s), where the vinyl leaves were pressed against the SAFL Baffle, and stayed there for the duration of the test. This clogged area caused some water to flow underneath the baffle and scour the sediment bed, causing washout. At flow rates around 2 cfs (58 L/s), the flow rate was not high enough to cause measurable washout, even if a portion of the water flow was traveling underneath the baffle and interacting with the sediment bed.

Two washout tests were conducted on the 6×6 sump with a 3-in (7.6 cm) hole diameter SAFL Baffle. The testing procedure is identical to the first five tests of the 6×3 sump washout tests with vinyl leaves. Figure 3-17 shows these two data points on the same chart as the 6×3 washout test series with vinyl leaves.

Figure 3-17 indicates that when the 6×6 sump equipped with a 3-inch (7.6 cm) hole diameter SAFL Baffle clogged with debris, it would exhibit little washout. Flow rates as high as 7 cfs (202 L/s) would not cause washout with an effluent concentration greater than 0.00125 lb/ft^3 (20 mg/L).

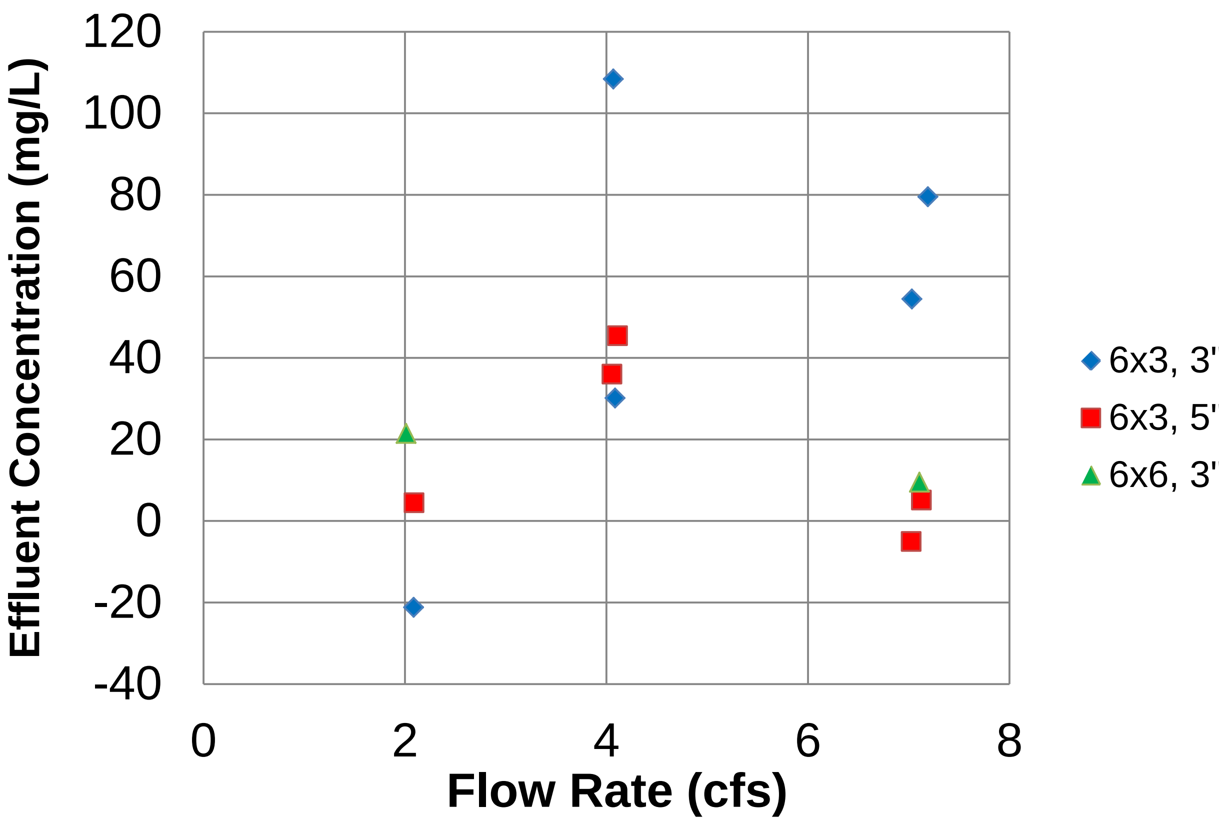

Figure 3-17: Summary of washout tests conducted on 6-ft sumps with 3-inch (7.6 cm) and 5-inch (12.7 cm) hole SAFL Baffles clogged with debris.

In comparison, the 6×3 sump equipped with the same 3-inch (7.6 cm) hole SAFL Baffle exhibited higher washout. The maximum recorded effluent concentration occurred at 4 cfs (116 L/s) and was roughly 0.00687 lb/ft^3 (110 mg/L). At a higher flow rate of about 7 cfs (202 L/s), the effluent concentration was between 0.0036-0.0050 lb/ft^3 (58-80 mg/L). This confirms that flow rates above 4 cfs (116 L/s) pushed away vinyl leaves clogging the SAFL Baffle, resulting in self-cleaning. Once the SAFL Baffle was no longer clogged, washout decreased.

When clogged with debris, the 5-in (12.7 cm) hole SAFL Baffle exhibited less washout than the 3-in (7.6 cm) hole diameter baffle. Leaves could not readily clog the baffle, and washout remained at low levels. The maximum effluent concentration for this setup occurred at 4 cfs (116 L/s), and was roughly 0.0031 lb/ft^3 (50 mg/L). Again, this indicated that debris clogging was at a maximum around 4 cfs (116 L/s), and flow rates higher than this self-cleaned the SAFL Baffle.

3.5.2 Removal Efficiency Testing

Removal efficiency testing was completed on the 6×6 and 6×3 sump manholes. All tests were completed with a 5-in (12.7 cm) hole diameter SAFL Baffle installed in the sump manhole. Testing flow rates ranged from 0.8 to 3.7 cfs (22 to 104 L/s) and lasted between 12 and 25 minutes.

Figures 3-18 and 3-19 show the removal efficiency of the 6×3 and 6×6 sump manholes while inundated with debris using the Péclet number and the Péclet number divided by the Froude jet velocity squared, as presented in Volume 1. In addition, the data from Figures 2-10 and 2-11, standard sumps with the SAFL Baffle and no debris, are also shown in these figures.

The 6×6 and 6×3 testing done for this testing series was conducted while the 5-in (12.7 cm) hole diameter SAFL Baffle was inundated with 65 lbs (30 kg) of vinyl leaves, yet the data is similar to SAFL Baffle with no trash. When these same debris removal efficiency tests were conducted on the 6×6 sump without debris loading, the results generally fell on the same curve. This means that the 5-in (12.7 cm) hole diameter SAFL Baffle prevents clogging and performs just as well as a 3-in (7.6 cm) hole diameter SAFL Baffle that is not clogged.

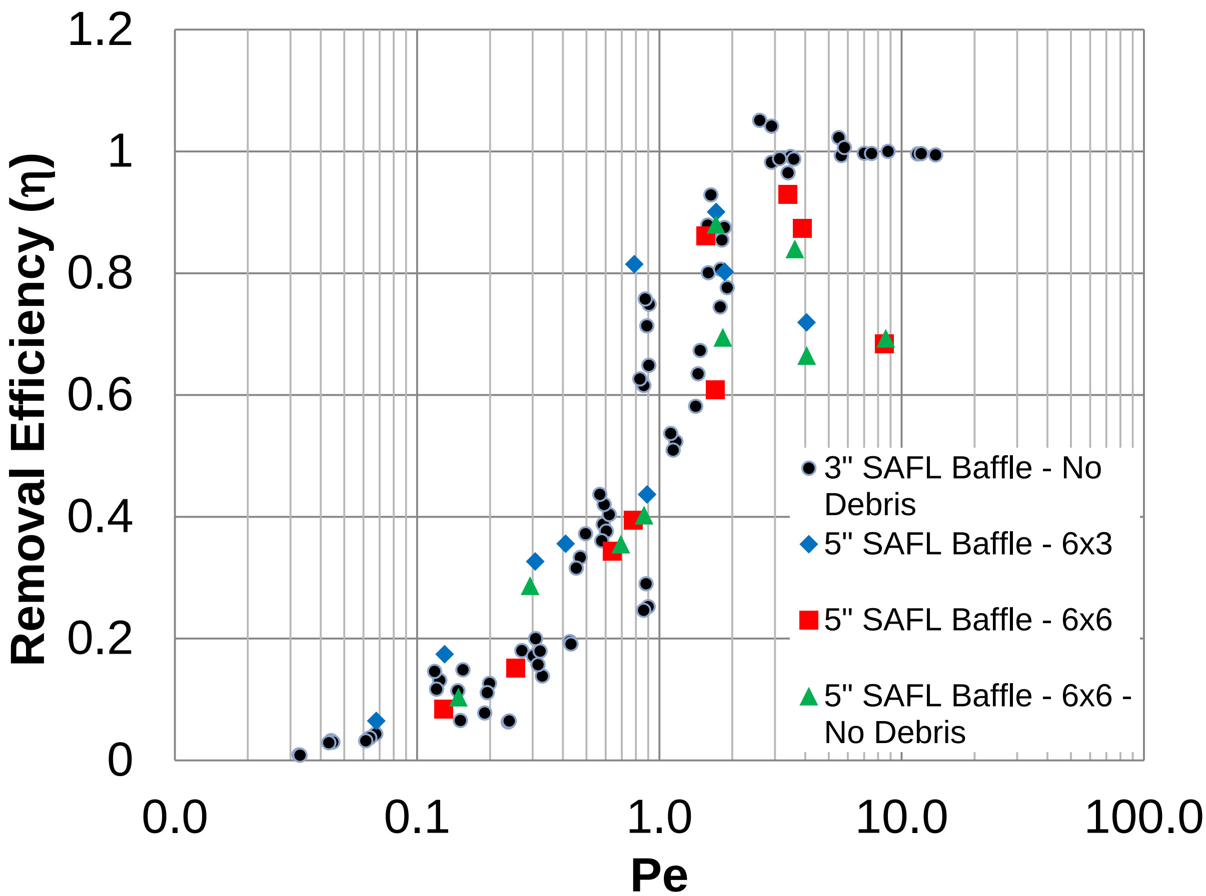

Figure 3-18: Removal efficiency of debris loaded 6×3 and 6×6 sump manholes equipped with a 5-in (12.7 cm) hole diameter SAFL Baffle.

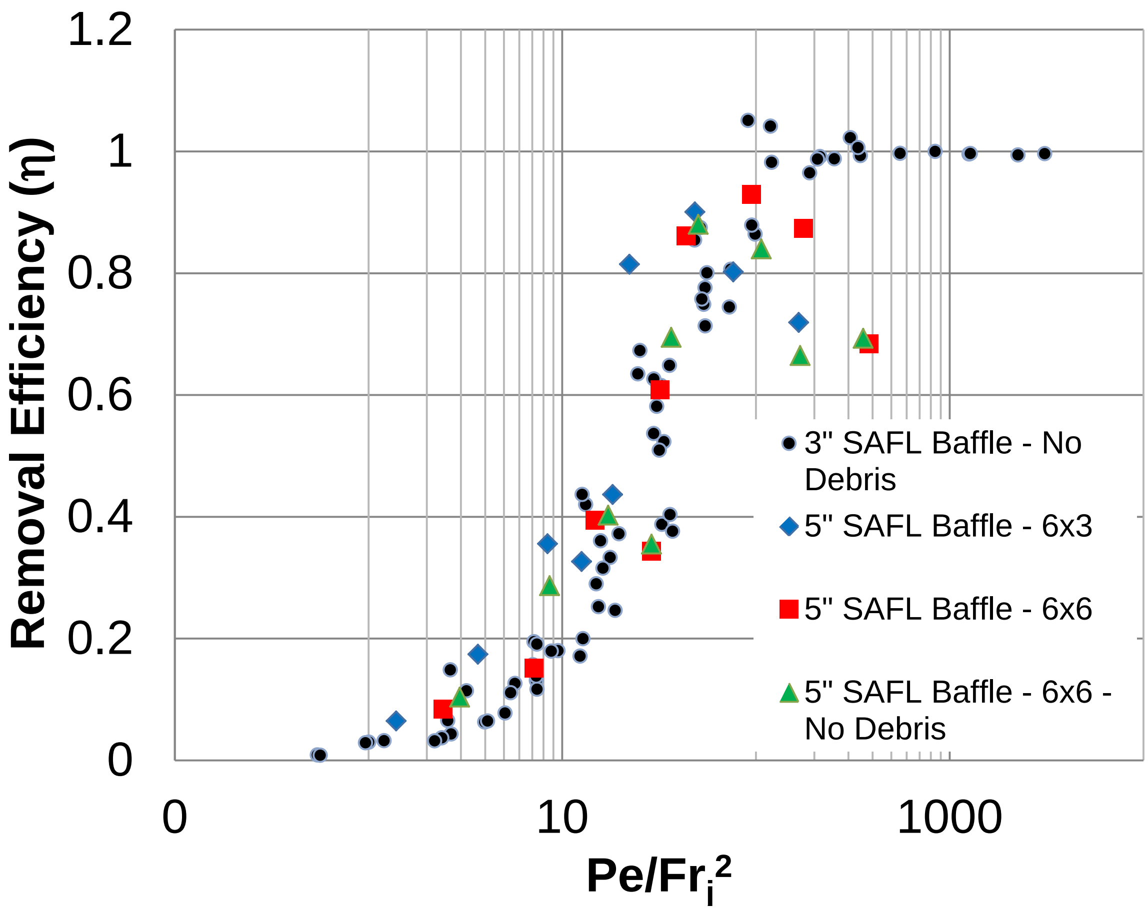

Figure 3-19: Removal efficiency of debris loaded 6×3 and 6×6 sump manholes equipped with a 5-in (12.7 cm) hole diameter SAFL Baffle.

4 Sumps with 90 Degree Outlets

In order to understand how sumps with 90 degree outlets perform when installed with a SAFL Baffle a new series of tests was conducted on a 6-ft diameter sump equipped with the SAFL Baffle. Scale model washout testing was used to determine the best configuration of the SAFL Baffle when installed in a 90 degree outlet sump. Once a SAFL Baffle configuration was deemed optimal on the model scale, this design was tested on the 6-ft diameter sump.

4.1 Experimental Setup

A new testing configuration was created by blocking the outlet pipe and opening a new outlet pipe 90 degrees to the inlet pipe. Herein, these systems are referred to as the 6×6-90 Degree Outlet sump and 1×1-90 Degree Outlet sump. Figure 4-1 shows the 6×6-90 Degree Outlet sump in a 3-dimensional view from above. Water travels through the inlet pipe at the bottom of the picture, and takes a left turn to exit the system through the outlet pipe. From there, the water travels through three 90 degree bends and spills into the 0.00079-in (20 µm) filter. In the case of the 6×6-90 Degree Outlet sump, Mississippi water travels through the inlet pipe, and takes a left turn through the system. At this point, water free falls into a tail box that returns the water to the river. More information about the experimental setup can be found in Appendix A.

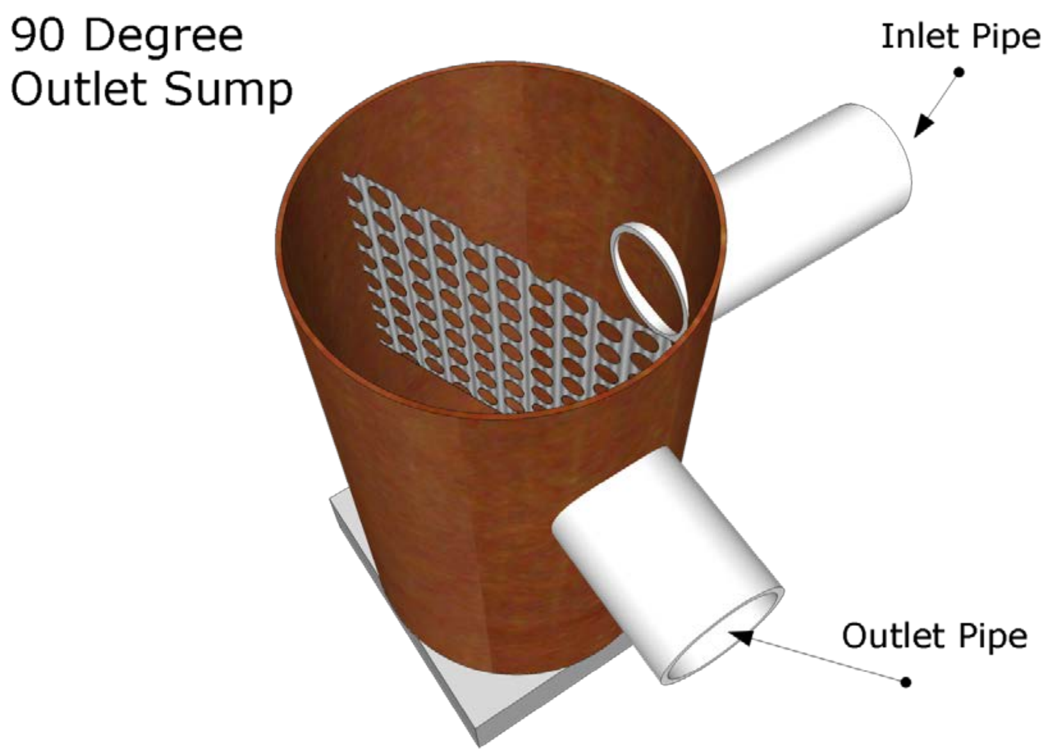

Figure 4-1: A plan view of the 1×1-90º sump manhole with a SAFL Baffle.

4.2 Testing Procedure

Washout tests on the 1×1-90 Degree Outlet sump and 6×6-90 Degree Outlet sump were conducted with a procedure similar to the previous configurations. Removal efficiency testing was conducted on the 6×6-90 Degree Outlet sump only, and was conducted with a similar procedure to previous configurations. Detailed washout and removal efficiency testing procedures can be found in Appendix B.

4.3 Scale Model Results

The first set of 90 degree outlet washout tests were conducted on the 1×1 sump manhole. Six tests were completed following the procedure outlined in Section 2.1.2. The washout testing flow rates were between 3.1 and 3.3 L/s (10.8-11.5 cfs when scaled to a 6×6 sump) for all six tests, and they were conducted for durations ranging from 9 to 10 minutes. A 0.5-in (12.7 cm) hole (3-in (7.6 cm) in the 6×6) SAFL Baffle was installed into the sump for Tests 2 through 6, and no SAFL Baffle was installed for the first test. For Tests 2 through 6, the SAFL Baffle was oriented at different angles relative to the inlet pipe as shown in Figure 4-1.

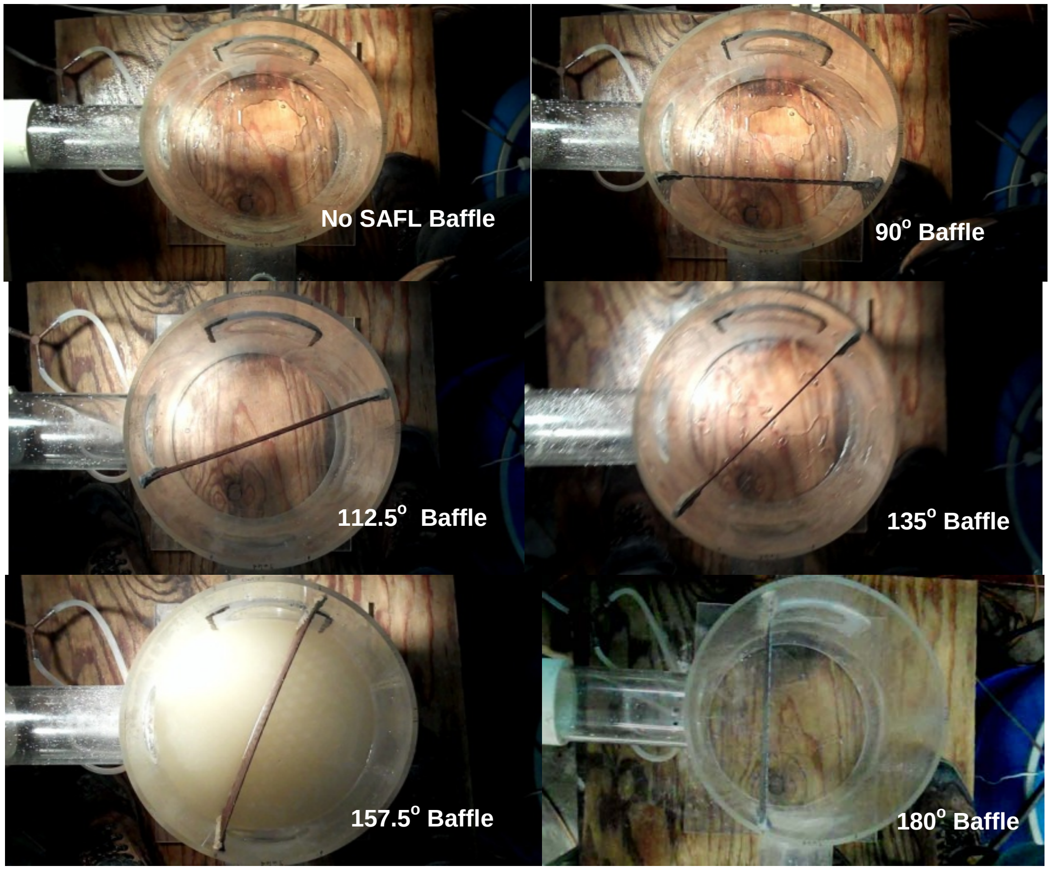

Figure 4-2: Plan views of 1×1-90 degree outlet washout testing configurations: no baffle, SAFL Baffle oriented at 90 degrees, 112.5 degrees, 135 degrees, 157.5 degrees, and 180 degrees. Water enters the sump from the bottom of picture and leaves from the left.

Test 1 exhibited the highest amount of washout with an effluent concentration of 0.06461 lb/ft^3 (1035 mg/L). This indicates that 90 degree outlet sumps exhibit significant washout when a SAFL Baffle is not installed. Figure 4-3 shows the sediment beds after the washout test occurred for Tests 1 and 2. In this figure, flow enters the system on the left and travels into the page through the outlet pipe. The pipe on the right hand side of the picture is blocked so water cannot exit through it. For Test 1, much of the washout occurred on the downstream end of the sump, where water would traditionally leave if the sump was a straight flow-through. Conversely, Test 2 exhibited the smallest washout of all six tests, with an effluent concentration of 0.0011 lb/ft^3 (18 mg/L).

Figure 4-3: Post washout test on the 1×1-90 degree outlet sump without a SAFL Baffle and with a SAFL Baffle oriented at 90 degrees to the inlet pipe.

In Tests 3, 4, 5, and 6, effluent concentrations varied between the effluent concentrations of Tests 1 and 2. For Test 3, the SAFL Baffle was oriented at a 112.5 degree angle relative to the inlet pipe and exhibited an effluent concentration very close to that of Test 2, (i.e. 0.0012 lb/ft^3 (19 mg/L)). Table 4-1 summarizes the results of all six of the washout tests.

Table 4-1: 1×1-90 degree outlet washout testing summary.

Test	SAFL Baffle angle in degrees with respect to the inlet pipe	Effluent Concentration (mg/L)
1	No SAFL Baffle	1035
2	90.0	18
3	112.5	19
4	135.0	46
5	157.5	257
6	180.0	664

Figure 4-4 shows the washout testing data from Tests 2 through 6 and the relationship between effluent concentration and the SAFL Baffle orientation relative to the inlet pipe. As the SAFL Baffle angle increased from 90 degrees relative to the inlet pipe, the effluent concentration increased.

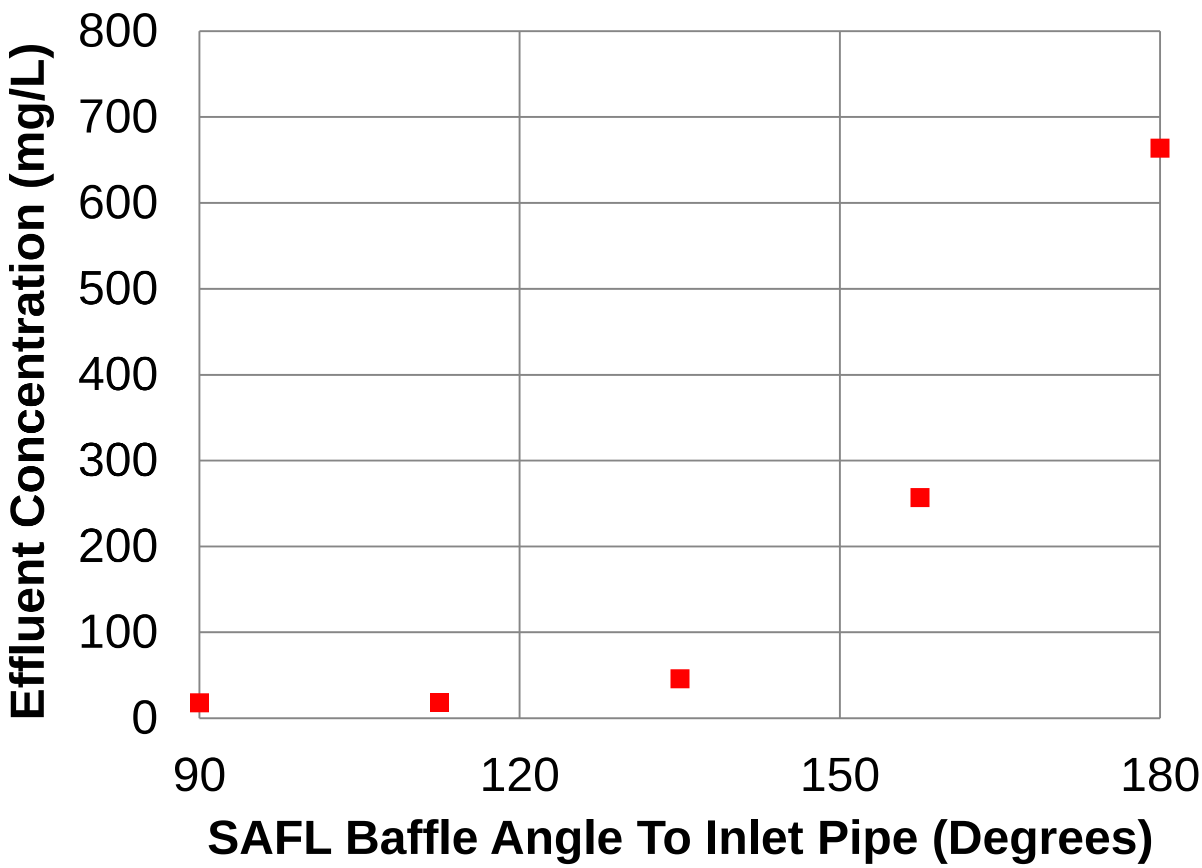

Figure 4-4: 1×1-90 degree outlet washout testing summary.

4.4 Full Scale Results

4.4.1 Washout Testing

Nine washout tests were conducted on the 6×6-90 Degree Outlet sump. The 3-in (7.6 cm) hole diameter SAFL Baffle was installed at a 112.5 degree angle relative to the inlet pipe for this washout testing series. Installing a SAFL Baffle at 90 degrees relative to the inlet pipe may create access problems to the inlet pipe in some sump manholes, so the 3-in (7.6 cm) hole diameter SAFL Baffle was installed at a 112.5 degree angle relative to the inlet pipe for this washout testing series. Tests were conducted at flow rates ranging from 5.1 to 13.8 cfs (144 to 391 L/s) for durations ranging from 11.5 to 25.3 minutes.

Figure 4-5 shows all nine tests with this setup in terms of washout effluent concentration versus flow rate. These tests exhibited effluent concentrations that generally increased with flow rate. The highest effluent concentration recorded was 62 mg/L at 12.7 cfs (367 L/s) for Test 8. Effluent concentrations were roughly negligible at 5 cfs (142 L/s), and most effluent concentrations were near 0.0031 lb/ft^3 (50 mg/L) between 7 and 13 cfs (202 and 376 L/s).

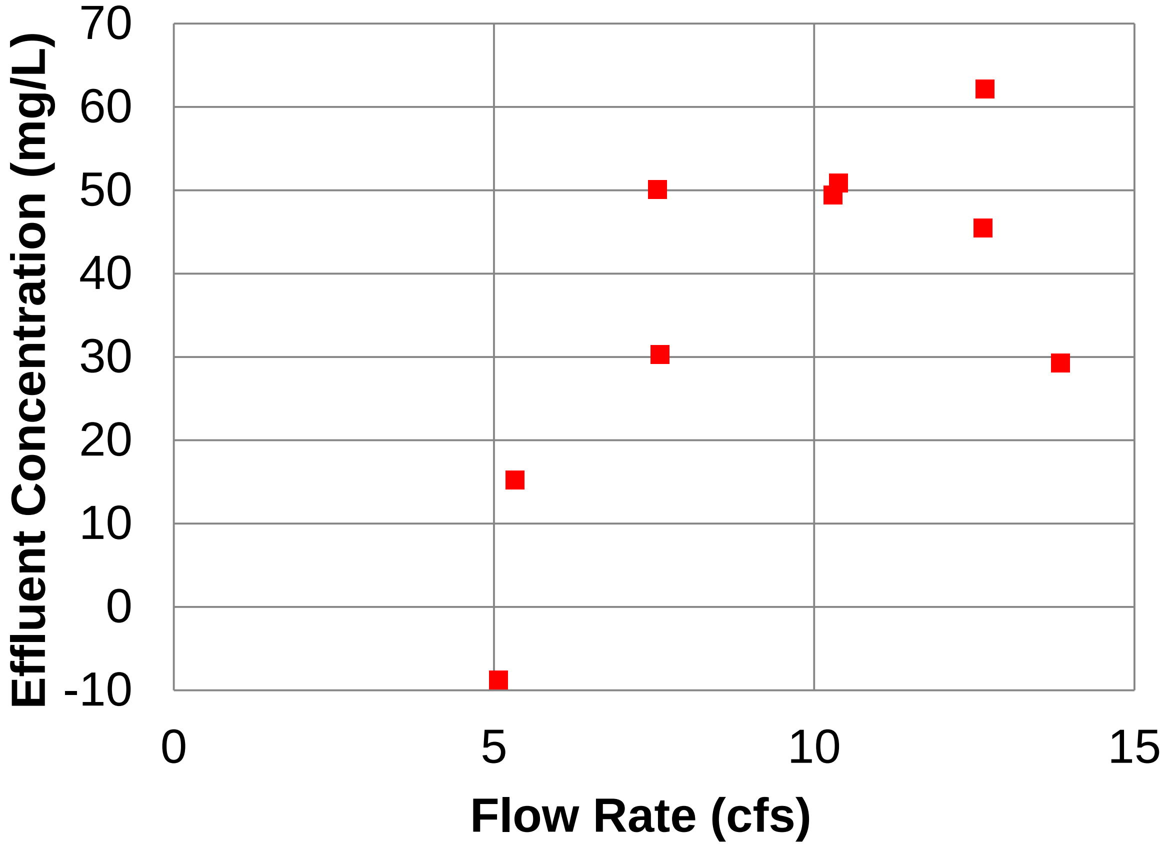

Figure 4-5: 6x6-90 degree outlet testing summary.

4.4.2 Removal Efficiency Testing

Removal efficiency tests were conducted at flow rates between 0.4 and 9.3 cfs (11.6 and 264 L/s), for durations between 11 and 83 minutes, with the 3-in (7.6 cm) hole diameter SAFL Baffle installed at a 112.5 degree angle relative to the inlet pipe.

Figures 4-6 and 4-7 show the performance of this setup in comparison to the straight flow-through standard sumps equipped with a SAFL Baffle using dimensionless parameters Pe and Pe/F_j^2. The majority of the data for this 90 degree outlet sump are to the left of the straight flow-through standard sumps with the SAFL Baffles, i.e. the 6×6-90 Degree Outlet sump equipped with a 112.5 degree angle SAFL Baffle will capture more sediment than a 6×6 straight flow-through sump.   Better removal efficiency is most likely due to flow patterns in a 90 degree sump where more energy is dissipated as streamlines turn 90 degrees to leave the sump.

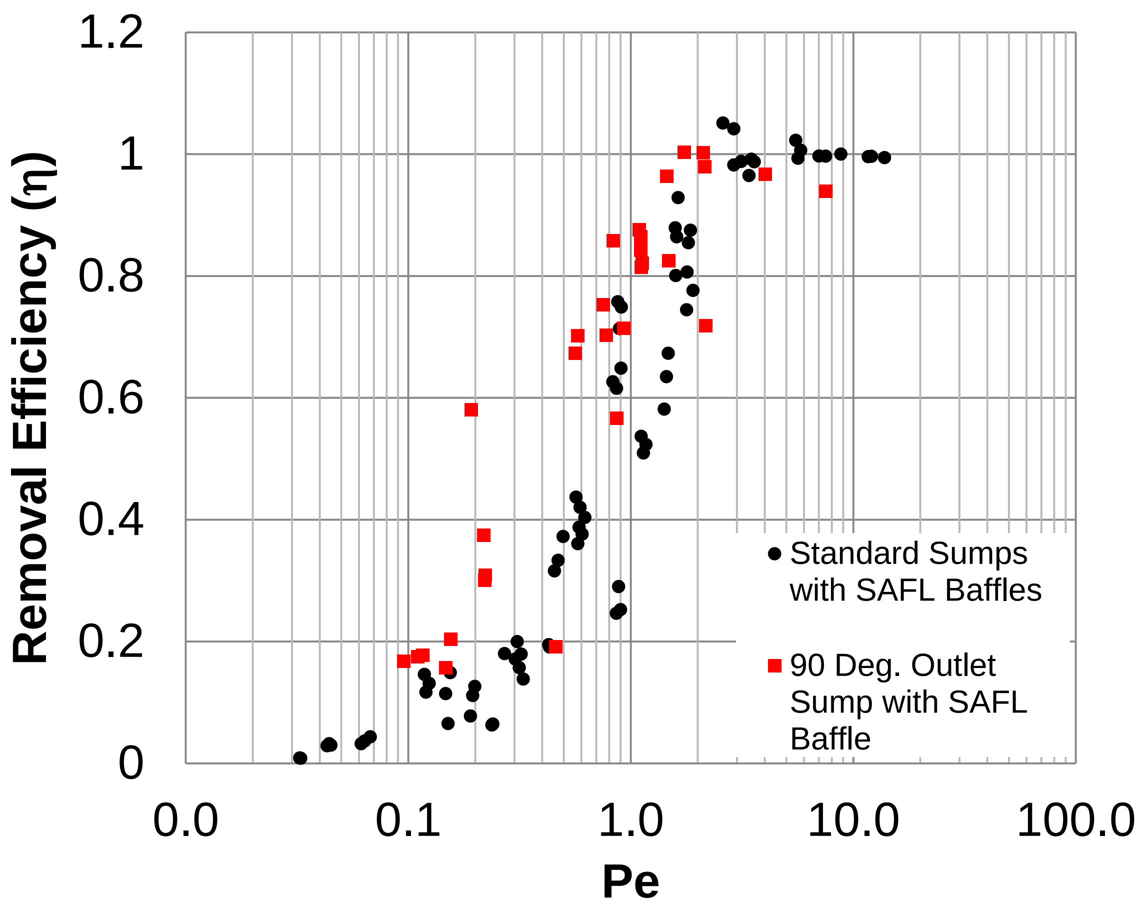

Figure 4-6: Removal efficiency of a 6×6 sump manhole equipped with a 3-inch (7.6 cm) hole diameter SAFL Baffle that is installed at an angle of 112.5 degrees relative to the inlet pipe.

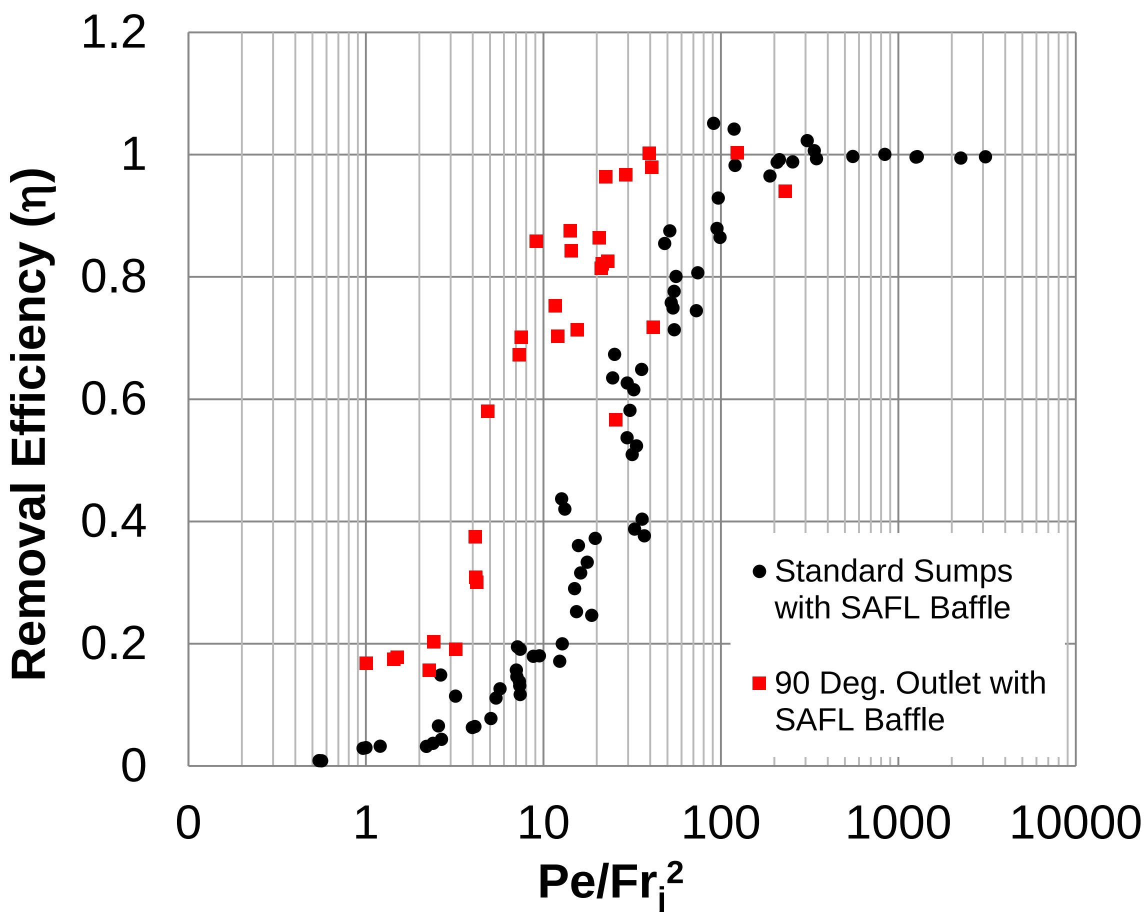

Figure 4-7: Removal efficiency a 6×6 sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle that is installed at an angle of 112.5 degrees relative to the inlet pipe.

5 Sumps with Inlet Grates

5.1 Experimental Setup

To represent sump manholes that receive water from an inlet pipe and an inlet grate, a platform was built around the 6×6 sump and a simulated road surface was installed on top of the platform (Figure 5-1). A pipe network transported water from the St. Anthony Falls Laboratory supply channel to the top of the platform, where it discharged into the simulated road surface. From there, water traveled on the simulated road surface to a Minnesota Department of Transportation 816 inlet grate, where it flowed through a free fall into the sump. Water exited the system through the outlet pipe that was located at 180 degrees with respected to the inlet pipe, i.e. the test was conducted on a straight flow-through sump. Detailed schematics can be found in Appendix A.

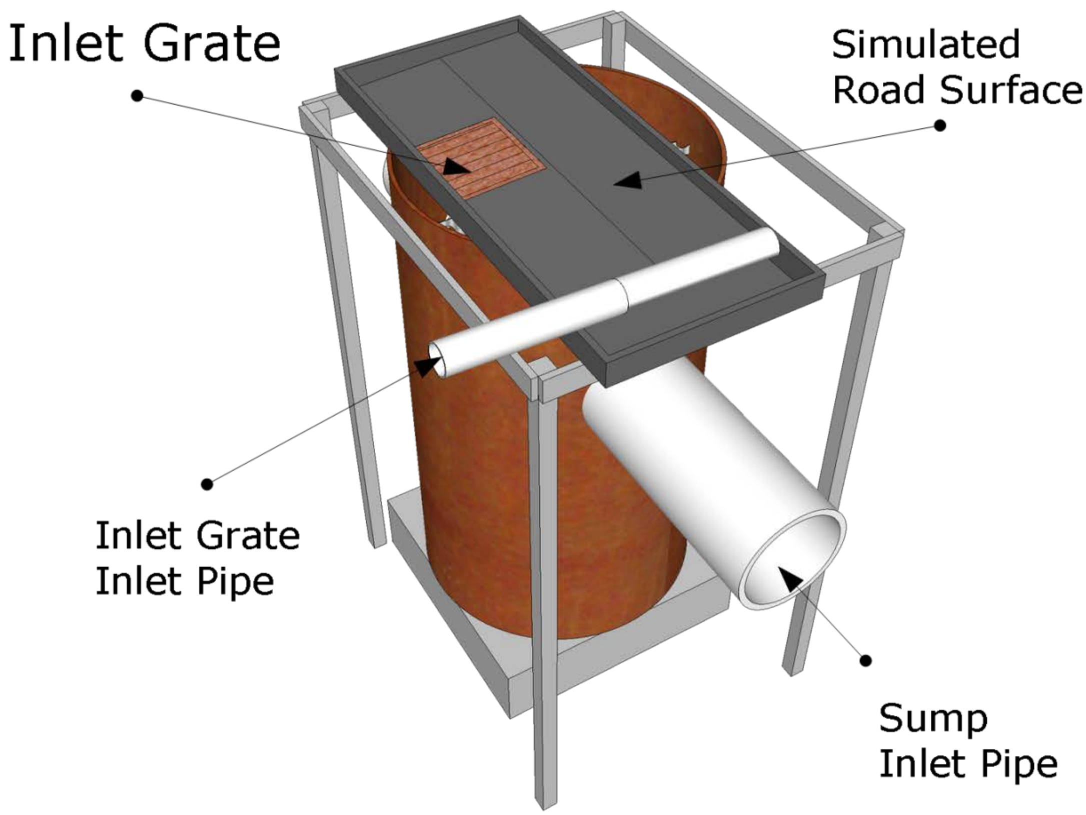

Figure 5-1: A 3D rendering of the 6×6 sump with an elevated road surface and inlet grate laboratory testing setup.

5.2 Testing Procedure

Washout tests were conducted on the 6×6 inlet grate sump manhole system similar to the standard washout tests, but water also entered the sump through an inlet grate elevated above the system. Water traveled through the inlet grate at flow rates from 0.7 to 0.8 cfs (19.8 L/s to 22.6 L/s).

Removal efficiency tests on the 6×6 inlet grate sump manhole system were completed similar to other removal efficiency tests, but sediment was also added as a slurry through the inlet grate. This means that the three sediment particle distributions 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm) were fed into the inlet pipe of the sump as well as into the inlet grate at concentrations ranging from 0.00624-0.0125 lb/ft^3 (100-200 mg/L). The flow rate through the inlet grate was 0.4 cfs (11.3 L/s). Detailed procedures can be found in Appendix B.

5.3 Full Scale Results

5.3.1 Washout Testing

Eleven washout tests were conducted on the 6×6 inlet grate sump system. A 3-in (7.6 cm) hole diameter SAFL Baffle was installed in the 6×6 straight flow-through sump manhole. Water also entered through an inlet grate elevated above the sump. For these tests, the inlet pipe flow rate ranged between 0 and 12.3 cfs (0 and 348.3 L/s). Tests were run for durations of 15 to 76 minutes. The tests with low flow rates through the inlet pipe were run for closer to 76 minutes and the high flow rate tests were run closer to 15 minutes.

Figure 5-2 shows the results of washout tests in terms of effluent concentration versus inlet pipe flow rate. Washout effluent concentration was small when the inlet pipe flow rate was larger than 0.6 cfs (17 L/s), but reached as high as 0.0046 lb/ft^3 (73 mg/L) when there was no flow through the inlet pipe. These results indicate that washout is highest when water is entering through the inlet grate and low or no flow is entering the sump manhole through the inlet pipe.

With no flow through the inlet pipe, the outfall from the inlet grate plunges deep into the sump and scours the bed sediment. Since the SAFL Baffle is not blocking the flow path from the inlet grate, the energy of the outfall is not dissipated and the washout of previously captured sediment is inevitable. As the flow rate from the inlet pipe increases, the outfall from the inlet grate is directed towards the baffle and its energy is dissipated and thus the washout of the sediment deposit in the sump diminishes.

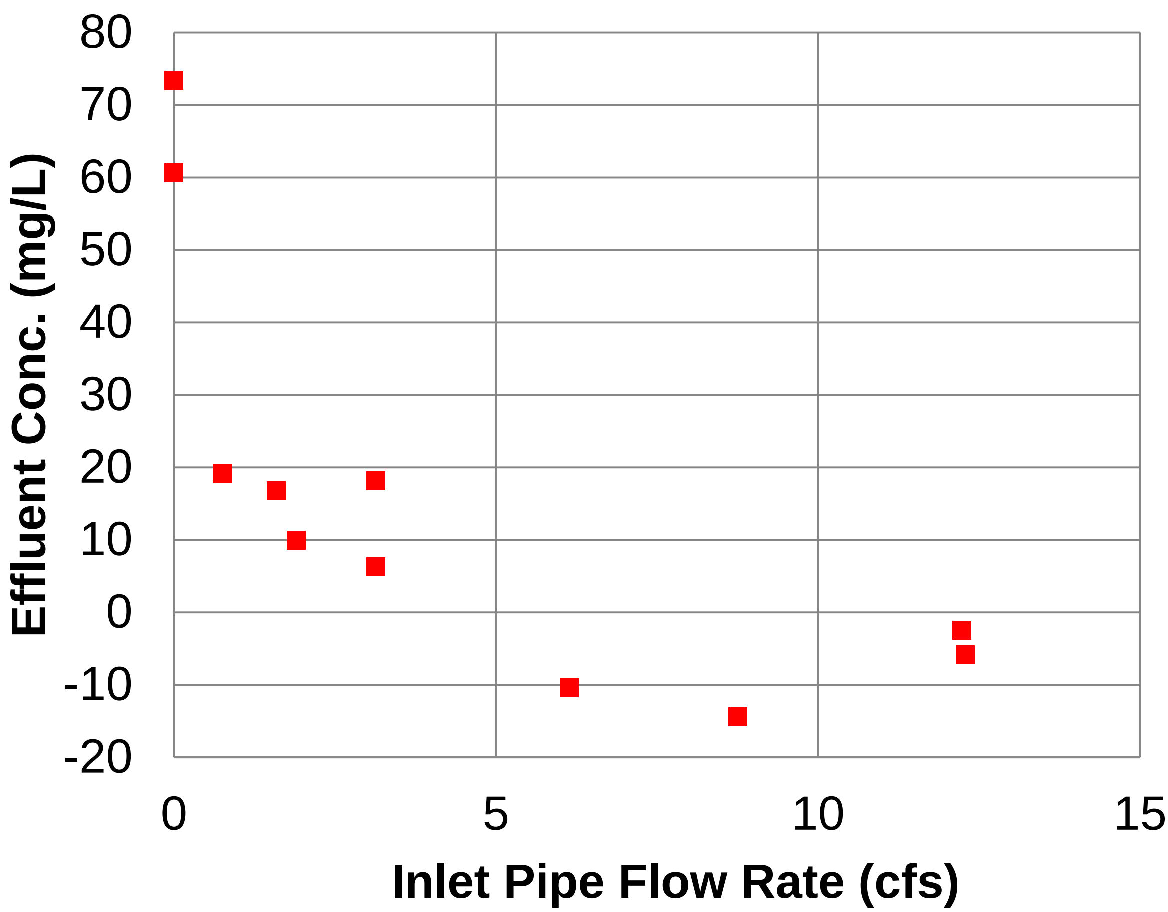

Figure 5-2: Summary of 6×6-inlet grate washout tests. In all washout tests, the flow from the inlet grate was between 0.7 and 0.8 cfs (19.8 L/s to 22.6 L/s).

5.3.2 Removal Efficiency Testing

Removal efficiency test series was conducted on a 6×6 inlet grate sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle. During testing, water entered the sump through an inlet grate elevated above the sump at a flow rate of 0.4 cfs (11.3 L/s) for all tests and water entered through the inlet pipe at flow rates ranging from 0.4 to 4.0 cfs (11.3 to 113 L/s). These tests ranged in duration from 20 to 99 minutes. Tests conducted at higher flow rates through the inlet pipe were run for shorter durations, and tests run at lower flow rates were conducted for longer durations, to minimize the effects of measurement errors.

Figures 5-3 and 5-4 show the removal efficiency performance of this setup using the dimensionless parameters Pe and Pe/F_j^2. In Figure 5-3, the removal efficiency data obtained for this setup more or less lay on the same performance curve obtained for the straight flow-through sumps with the SAFL Baffle and no inlet grate. This is not true for Figure 5-4, where two clusters of data do not land on the standard sumps with the SAFL Baffle and no inlet grate. The lower cluster represents data points from the smallest sediment size (0.0035-0.0049-in, or 88-125 μm) at the lowest inlet pipe flow rate. Similarly, the second cluster of data points represents the medium sediment size (0.0098-0.0140-in or 250-355 μm) at the lowest inlet pipe flow rate. Since the dimensionless parameter Pe/F_j^2 is a better parameter showing the performance of standard sumps, the discrepancy evident in Figure 5-4 is a good indicator of how an inlet grate impacts the flow patterns in a sump equipped with the SAFL Baffle. From Figure 5-4, it is evident that when the flow rate from the inlet pipe is comparable to the flow from the inlet grate, the fine particles (herein up to 0.0138-in, or 350 μm particles) are not removed from the stormwater as efficiently as with no inlet grate. Under such conditions, the flow from inlet grate increases the intensity of turbulence which results in fewer opportunities for particles to settle.

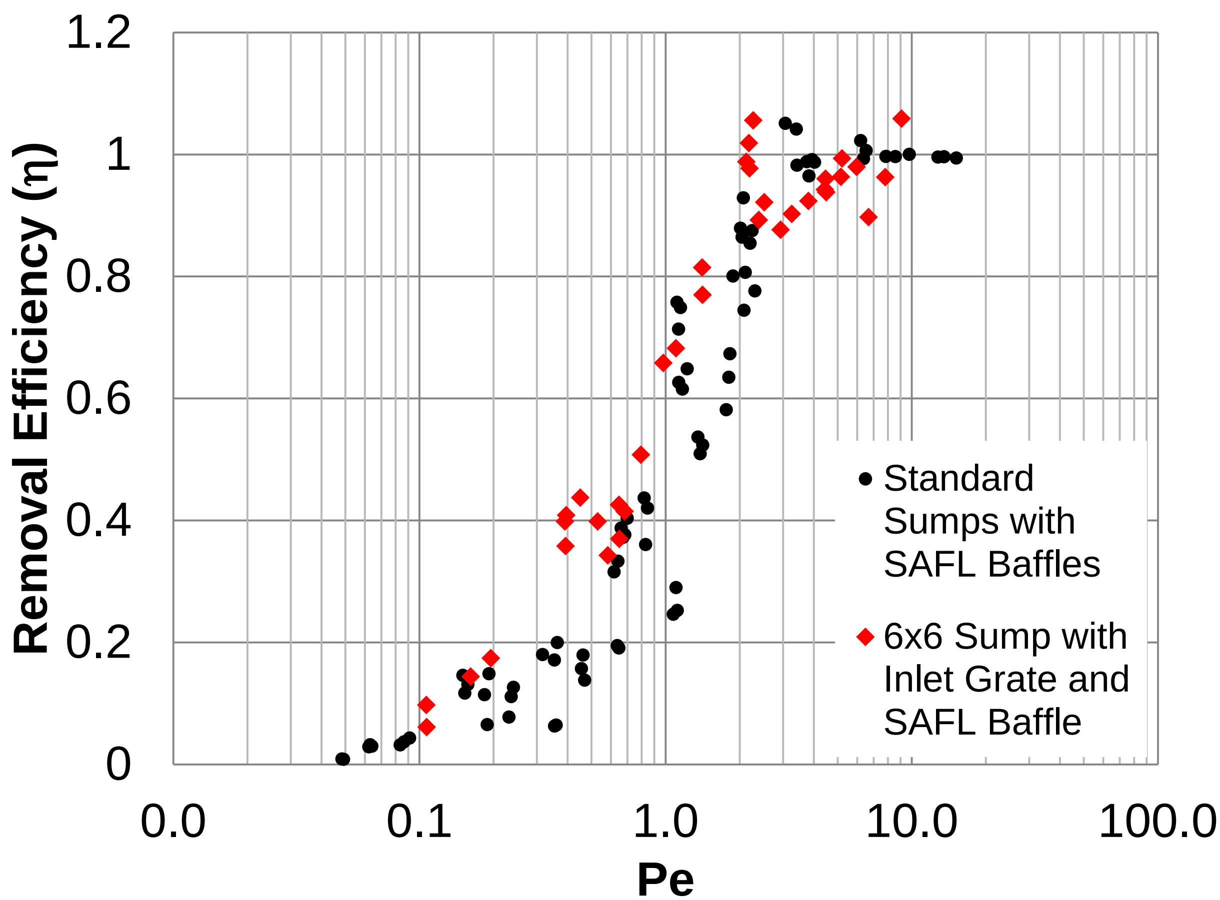

Figure 5-3: Removal efficiency of a 6×6 inlet grate sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle versus the Péclet number.

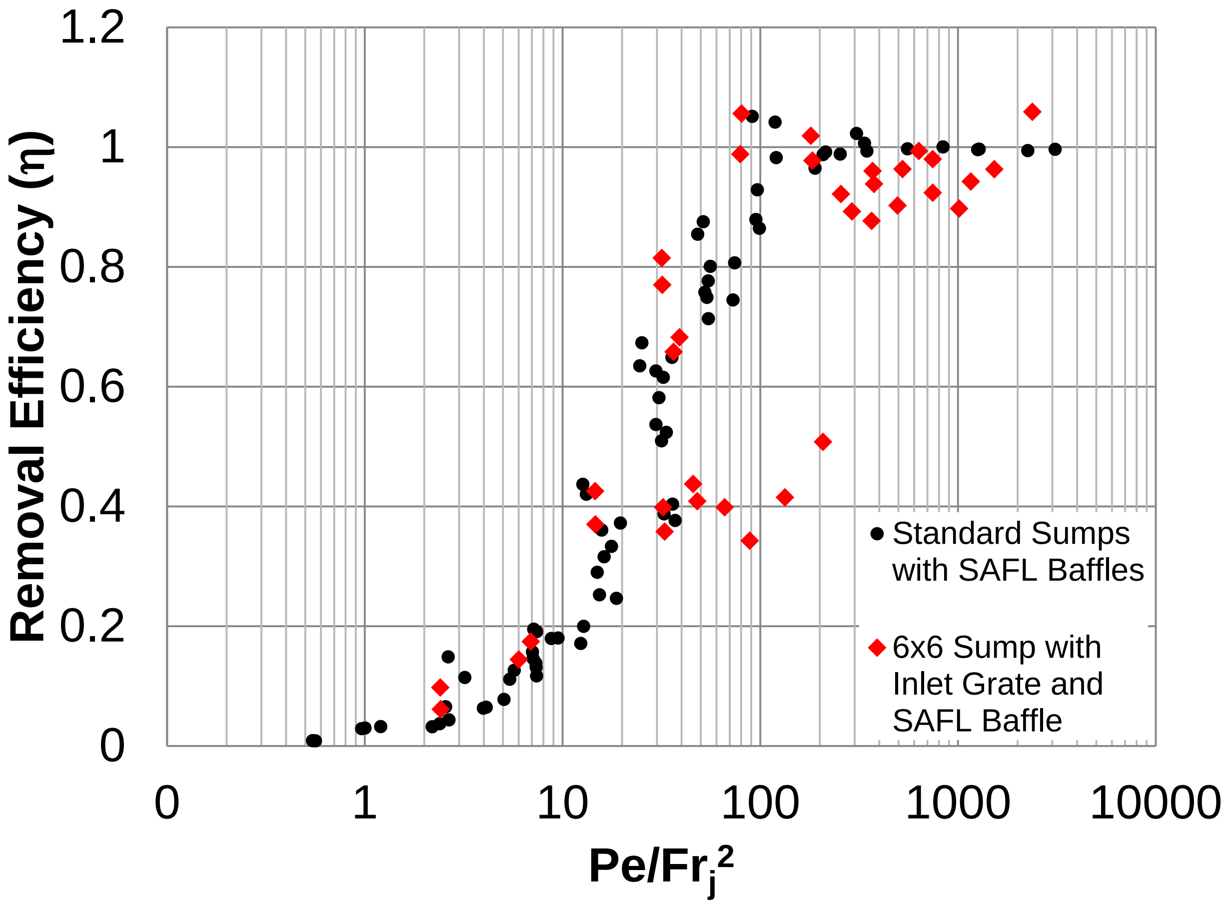

Figure 5-4: Removal efficiency of a 6×6 inlet grate sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle versus Pe/Fr$_j^2$.

6 Head Loss Due to SAFL Baffle

During removal efficiency and washout testing on the 6-ft diameter sumps, static pressure taps were used to measure the water surface elevations in the inlet pipe, the outlet pipe, upstream of the SAFL Baffle, and downstream of the SAFL Baffle. The data were then used to calculate the head loss, h_L, through a sump equipped with a SAFL Baffle using Equation 6.1.

$$h_L = (h_1 - h_2) + (z_1 - z_2) + \left(\frac{{V_1}^2 - {V_2}^2}{2g}\right) \quad (6.1)$$

In equation 6.1, h_1 and h_2 are hydrostatic pressures (or water depths) in the inlet and out pipes, z_1 and z_2 are the elevations of the inlet and outlet pipe inverts, V_1 and V_2 are average flow velocities in the inlet and outlet pipes and g is gravity.

Since all the sump configurations resulted in water free falling out of the outlet pipe, the pressure and velocity in the outlet pipe were calculated assuming critical flow conditions at the outlet. Figure 6-1 shows the head loss in a 6×3 sump with and without a SAFL Baffle.

Figure 6-1 shows that the SAFL Baffle does not induce a significant head loss at flow rates less than 10 cfs (289 L/s) or the head loss is less than 2-in (5.1 cm). The head loss becomes significant at very high flow rates, i.e. at 15 cfs (434 L/s) and higher, which are less frequent than a 10-year storm assuming an appropriate design of the system (see Volume 1 of this report).

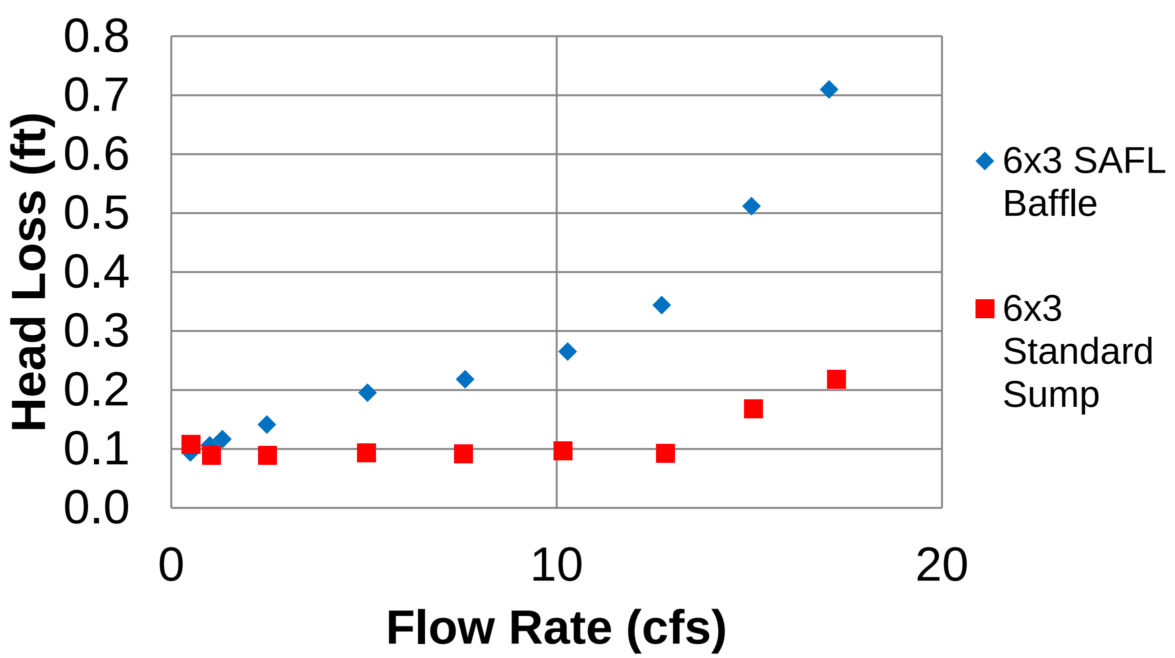

Figure 6-1: Head loss through the 6×3 sump with and without a 3-in (7.6 cm) hole diameter SAFL Baffle.

Head loss through the 6×6-90 Degree Outlet sump as a function of discharge is shown in Figure 6-2. At a flow rate of 5 cfs (145 L/s), the system head loss is about 0.15-ft (0.046 m) and at 19 cfs (550 L/s) the head loss becomes 0.26 feet. From Figure 6-2, it is evident that head loss through a 6×6-90 Degree Outlet sump equipped with a SAFL Baffle is very small, and even though the base condition is not given in the figure, the SAFL Baffle should not have any significant adverse effect regarding surcharging the inlet pipe during very high flow conditions.

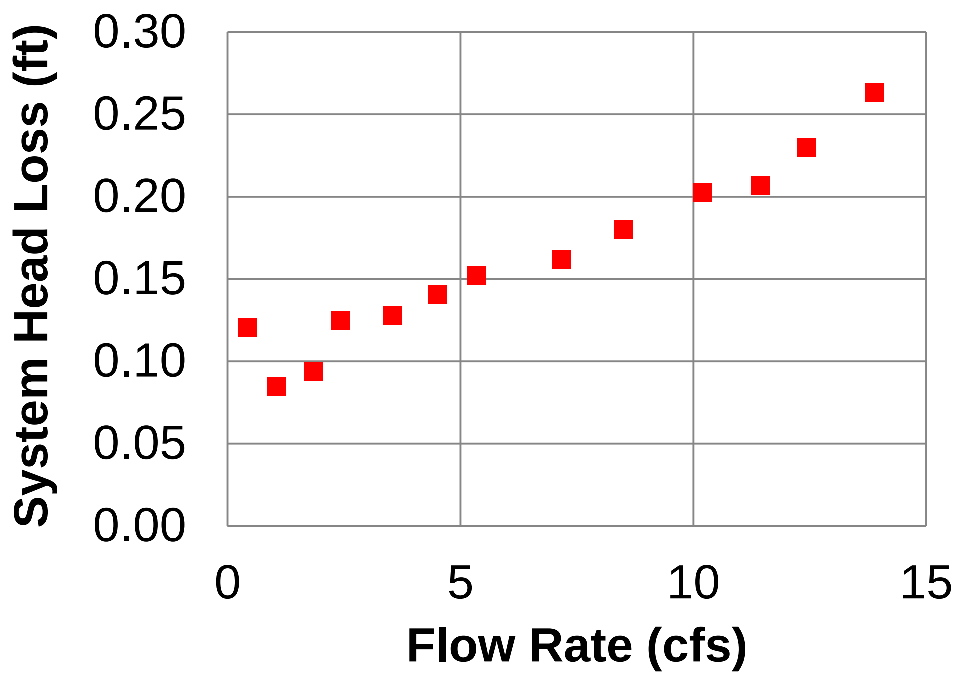

Figure 6-2: Head loss through the 6×6-90 degree outlet sump with the SAFL Baffle.

7 Comparison of Treatment Devices

To fully understand the capabilities of the SAFL Baffle, it is important to compare the performance of the SAFL Baffle, when installed in a sump, to other hydrodynamic separators and stormwater treatment devices. Previous research conducted at St. Anthony Falls Laboratory by Howard et al. (2011), Saddoris et al. (2010), and Wilson et al. (2009) quantified the performance and washout of ecoStorm, Downstream Defender, Environment21, Stormceptor, and Standard Sumps. The performance of the aforementioned devices was measured by determining how well a device captures sediment at low flow rates (removal efficiency) and how well a device retains sediment at high flow rates (washout). The Péclet number detailed in Equation 2-1 can reliably explain the removal efficiency, and the Péclet number over the Froude number square, as explained in Volume 1, can explain washout in these devices. The data obtained from testing proprietary devices are limited, i.e. only a single model of e.g. Downstream Defender has been tested, while several sizes of standard sumps with and without the SAFL Baffle have been tested and the developed performance functions can be used more or less for all standard sumps. Therefore comparing the performance of standard sumps with SAFL Baffles with proprietary devices cannot be very accurate. Nevertheless, a comparison among more or less similar model sizes tested can provide a better picture of the overall performance of standard sumps with SAFL Baffles.

To compare these devices, the overall removal efficiencies of ecoStorm, Downstream Defender, Environment21, Stormceptor, and Standard Sumps with and without the SAFL Baffle were estimated using SHSAM (Mohseni et al., 2011). In this exercise, the SHSAM model was applied to a 5-acre drainage basin in Minneapolis, MN, and it was assumed that the particle size distribution (PSD) of suspended sediments in stormwater runoff is similar to the PSD of OK110.

The model sizes used in this comparison have heights and diameters more or less similar to a 6×6 sump. The ecoStorm and Environment 21 have dimensions of 5.2×6.8 and 7×4.9, respectively. The efficiencies predicted for these devices are not as accurate as the other four devices because of the difference between the model size tested and model size used in this exercise. In this exercise, the inlet pipe of all devices assumed to be 18 inches in diameter.

The overall efficiencies of all devices are shown in Figure 7-1. In this exercise, the overall removal efficiency of a device gives how well a device removes suspended sediments from stormwater and how well it retains the captured sediments over a period of 17 years.

It is evident that Stormceptor performs better than other devices and standard sumps with SAFL Baffles perform nearly as well as Stormceptor. The main reason for better performance of Stormceptor is the presence of an internal bypass which prevents any runoff resulting from large storms from passing through the sump. For other devices, a bypass can be installed to divert large flows. Figure 7-2 shows the overall efficiency of the same devices if flows in excess to 1 cfs are bypassed. The bypass has little effect on the overall performance of standard sumps with SAFL Baffles, but it significantly impacts the performance of Downstream Defender, ecoStorm and Environment21, with Environment21 and ecoStorm performing better than Stormceptor.

It is important to note that a better comparison of devices is to compare the dollar spent on a unit weight of sediment removed from stormwater runoff, i.e. incorporating the capital cost, the installation cost and the maintenance cost of the device. Bypassing some of the flow will add to the overall cost by adding additional manholes upstream and downstream of the device.

In summary, it is evident that sumps with SAFL Baffles perform as well as the proprietary devices in the market.

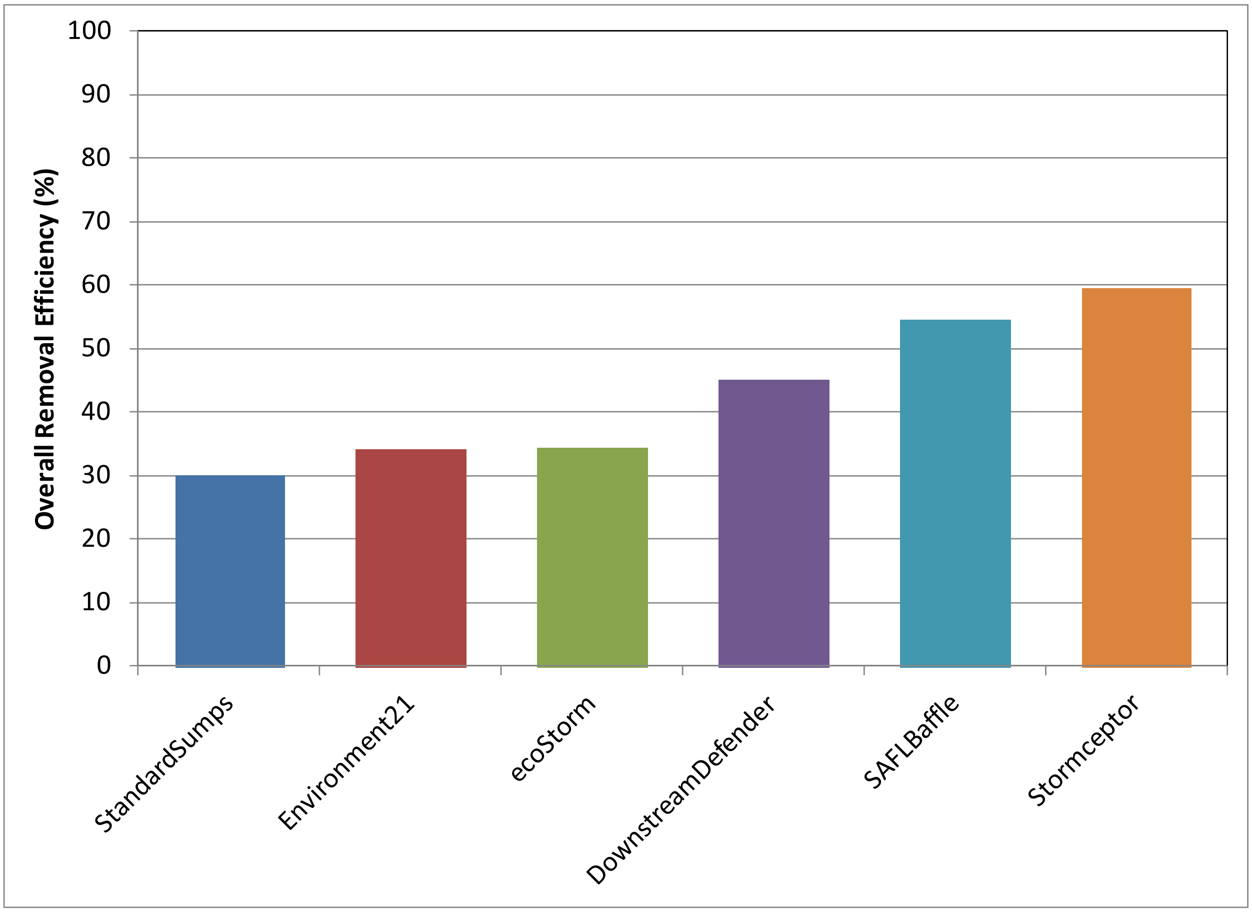

Figure 7-1: Overall removal efficiencies of ecoStorm, Downstream Defender, Environment 21, Stormceptor, Standard Sumps, and Standard Sumps equipped with a SAFL Baffle in removing OK110 from stormwater runoff of a 5-acre watershed in Minneapolis, MN, area.

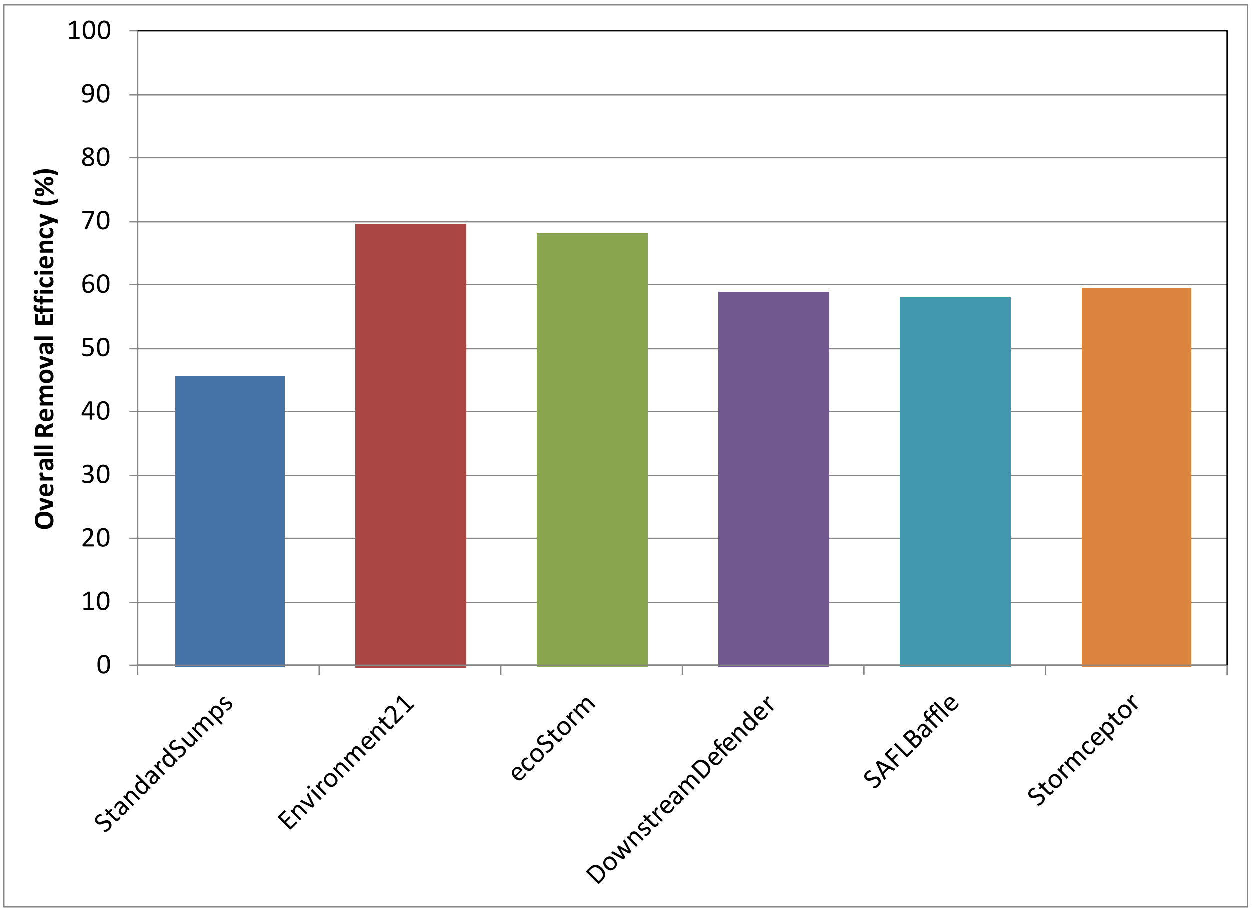

Figure 7-2: Overall removal efficiencies of ecoStorm, Downstream Defender, Environment 21, Stormceptor, Standard Sumps, and Standard Sumps equipped with a SAFL Baffle in removing OK110 from stormwater runoff of a 5-acre watershed in Minneapolis, MN, area by diverting flows larger than 1 cfs (except for Stormceptor which is equipped with an internal bypass).

8 Summary and Conclusions

Standard sumps can remove suspended sediment from stormwater runoff under low flow conditions. A major deficiency of standard sumps is their inability to retain the captured sediment under high flow conditions. This drawback can be overcome by either frequent maintenance (sediment removal by maintenance crew) of a sump or by retrofitting a sump with a porous baffle.

The circulation pattern in standard sumps results in the observed high washout rate. This circulation pattern consists of a downward flow due to the plunging of the incoming jet, a lateral flow near the sediment bed, and an upward flow at the upstream end of the standard sump enhancing the washout of previously deposited sediment at the bottom of the sump.

To break the adverse circulation pattern and to dissipate the energy of the incoming and plunging flow, a porous baffle, called SAFL Baffle, was designed in this study. The SAFL Baffle with 46% porosity and a vertical orientation was first evaluated in a scale model. After the baffle was evaluated in the scale model, it was installed in 4×4 ft and 6×3 ft sumps for prototype-size testing of both sediment removal efficiency and washout.

The results of the full scale testing showed that the SAFL Baffle can improve sediment capture by 10 to 15% and decrease effluent concentrations from 0.05 lb/ft^3 (800 mg/L) to a maximum of 0.0031 lb/ft^3 (50 mg/L) for sediment washout. Removal efficiency and washout functions were developed from the measured values using the dimensionless parameter Pe/Frj^2, i.e. the ratio of Péclet number to the square of the inflow jet Froude number. The performance functions can be used for the prediction of removal efficiencies of standard sumps retrofitted with the SAFL Baffle and aid in the design of sumps including a SAFL Baffle.

Further studies were conducted to determine the effects of trash or debris on the performance of sumps equipped with a SAFL Baffle as well as the effectiveness of the SAFL Baffle, when the outlet pipe is at a 90 degree angle with respect to the inlet pipe and when water also enters the sump from above through an inlet grate.

Deep sumps equipped with the 3-in (7.6 cm) hole diameter SAFL Baffle exhibited little washout when clogged with debris. This is because water traveled underneath of the baffle when clogged and, with the space provided underneath the baffle, the flow did not impact the sediment bed and washout did not occur.

Shallow sumps equipped with the 3-in (7.6 cm) hole diameter SAFL Baffle exhibited significant washout when clogged with trash/debris. When the baffle was clogged, water traveled underneath the baffle and, due to a lack of space underneath the baffle, scoured the sediment bed and sediment washout occurred. If the baffle is used as a retrofit and the sump is shallow, then trash should be collected at an upstream manhole, otherwise during intense storm events in fall, the baffle will not be effective. However, the results of the laboratory testing showed that using a SAFL Baffle with larger openings (5-in (12.7 cm) openings instead of 3- or 1-in (7.6 or 2.5 cm) openings) will allow most debris to pass through the system without clogging the baffle.

The removal efficiency testing series on the 6×3 and 6×6 sumps showed that sediment retention of a SAFL-Baffle with 5-in (12.7 cm) hole diameter is similar to that of the 3- and 1-in (7.6 and 2.5 cm) hole diameter baffles. This means that there are no drawbacks in using the 5-in (12.7 cm) hole diameter SAFL Baffle when retrofitting a shallow standard sump.

Sump manholes that have an outlet located 90 degrees to the inlet pipe can be installed with a SAFL Baffle if capturing sediment is desired. Without a SAFL Baffle, they will exhibit significant washout. In these sumps, the SAFL Baffle should be installed at an angle from 90 to 120 degrees with respect to the inlet pipe. Testing showed that washout increases exponentially when the baffle orientation varies between 120 and 180 degrees. Within the range of 90 to 120 degree orientation angle, washout remains negligible.

Removal efficiency testing was conducted only on a sump with a SAFL Baffle installed at 113 degrees with respect to the inlet pipe. Results showed that this setup actually captured more sediment than a straight flow-through sump, indicating that an orientation angle less than 113 degrees (but greater than 90) would capture sediment well.

The tests conducted in a 6×6 sump with an inlet grate and equipped with a SAFL Baffle showed significant washout and a decrease in removal efficiency when flow rates through the inlet grate were higher than flows through the inlet pipe. When the flow rate through the inlet pipe was equal to or greater than the flow through the inlet grate, washout decreased to near zero. Conversely, removal efficiency remained low until the flow through the inlet pipe was three times or greater than that of the inlet grate.

Therefore, the capture and retention of sediment in inlet grate sumps can be maximized by installing SAFL Baffles in sumps where the drainage area of the inlet pipes are three times greater than the drainage area of the inlet grates (Figure 8-1).

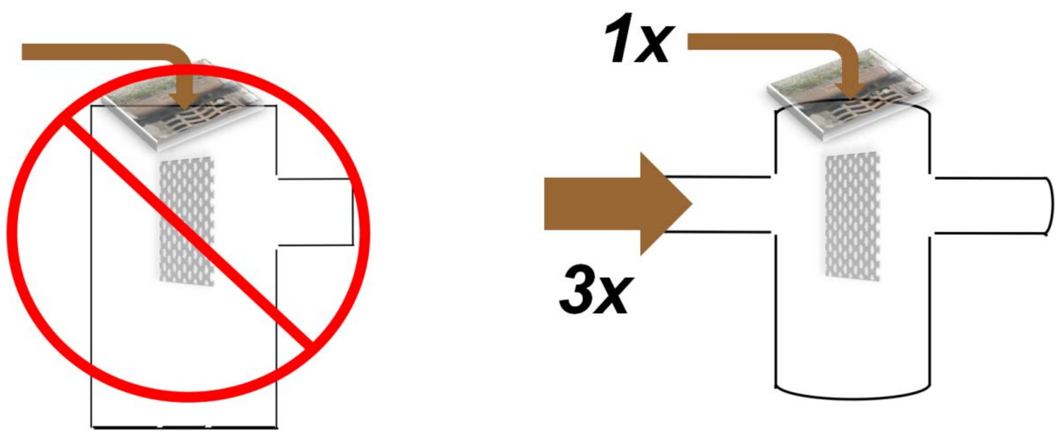

Figure 8-1: (Left) inlet grate flows into sump manholes cause washout and decrease removal efficiency of the device. (Right) install SAFL Baffles in sumps where the catchment feeding the inlet pipe is three times the size of the catchment feeding the inlet grate.

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Appendix A: Sump Setup

Table A-1: Dimensions of the laboratory sump manholes.

Sump	SAFL Baffle Hole Diameter (in)	Inlet Invert From Floor (ft)	Outlet Invert From Floor (ft)	Sump Diameter (ft)	Pipe Inside Diameter (ft)
6×6	3	6	5.91	6	1.87
6×3	3	3	2.91	6	1.87
6×3	5	3	2.91	6	1.87
4×4	1	4	3.93	4	1.27
4×2	1	2	1.93	4	1.27
1×1	0.5	1	0.95	1	0.29
1×0.5	0.5	0.5	0.45	1	0.29
1×0.5	0.75	0.5	0.45	1	0.29
6×6-90°	3	6	5.91	6	1.87
1×1-90°	0.5	1	0.95	1	0.29
6×6 Inlet Grate	3	6	5.91	6	1.87

A.1 4-ft (1.2 m) Sump Setup

The 4-ft (1.2 m) diameter by 4-ft (1.2 m) deep (4×4, for brevity) sump used for laboratory testing was made out of fiberglass and had one PVC inlet and one PVC outlet pipe. Both of these pipes were 15.2-in (38.6 cm) in inner diameter. Each was located 180 degrees from one another. The inlet pipe was connected to a 10-ft (3 m) section of PVC pipe with a rubber fitting secured with pipe clamps. About 1-ft (0.3 m) upstream of the sump, an open slot allowed debris to be fed into the sump.

Upstream of this section was a metal wye that connected to two systems of 12-in (30.5 cm) outer diameter PVC. From there, the two PVC pipes were connected to two separate gate valves which could be controlled electronically. Beyond the gate valves a Pitot and orifice system was used to measure flow rate through each of the 12-in (30.5 cm) PVC pipes. Finally, the 12-in (30.5 cm) diameter pipes upstream of the Pitot system were connected to St. Anthony Falls Laboratory's supply channel, a channel that transports Mississippi River water through the laboratory. Downstream of the sump, the outlet pipe of the sump did not connect to anything. After leaving through the outlet pipe, water free-fell into a tailbox where it ultimately returned to the Mississippi River.

The sump manhole sat on a wooden frame that sat on a steel frame. Underneath of the steel frame were four load cells which measured the weight of the system and sent the data to a nearby computer. When making accurate weight readings of the sump, the inlet pipe was disconnected from the upstream corrugated plastic pipe. By doing this, the entirety of the sump's weight was transferred into the load cells.

Throughout the sump were a series of taps with gate valves. These valves could be opened to drain water from the sump. Additionally a vacuum hose could be attached to one of the taps. When a person was inside of the sump, a second vacuum hose could be attached to the inside end of the tap. With this hose-tap-hose system in place, sediment could be sucked into a vacuum on the outside of the device. Several taps were not for draining the sump. Instead, these smaller taps were used to measure the water elevation throughout the inlet pipe, the sump, and the outlet pipe.

The 4×4 sump was transformed into a 4-ft (1.2 m) diameter, 2-ft (0.8 m) deep (4×2) sump using a false floor. Made of wood, the false floor was secured inside the sump. Water could not travel through the false floor because it was painted with epoxy and glued at the seams.

A 1 inch hole diameter SAFL Baffle was installed in the 4-ft (1.2 m) sump orthogonal to the inlet pipe. This means that the SAFL Baffle was installed vertically in the sump at the halfway point between the inlet and outlet pipes.

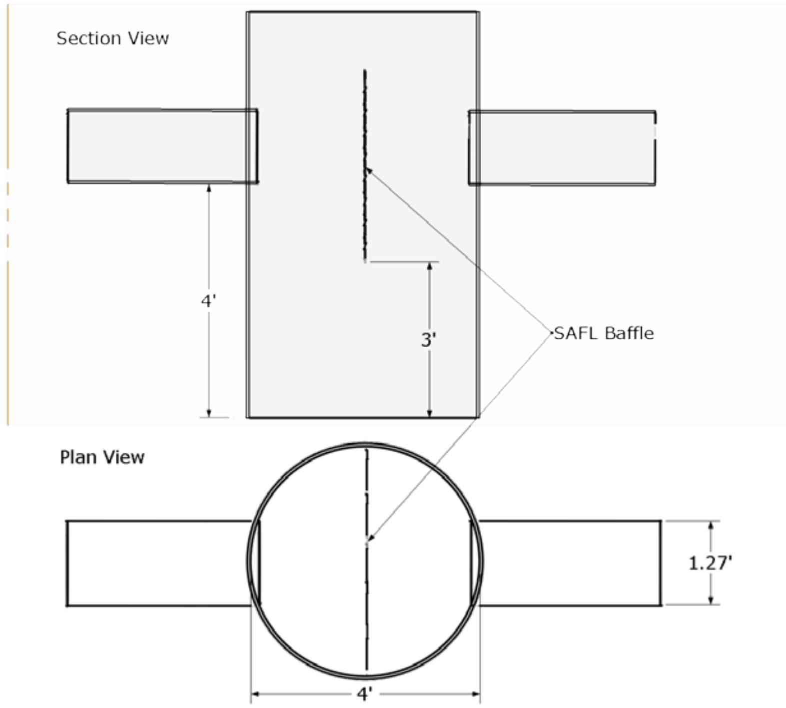

Figure A-1: A schematic of the deep 4×4 sump manhole.

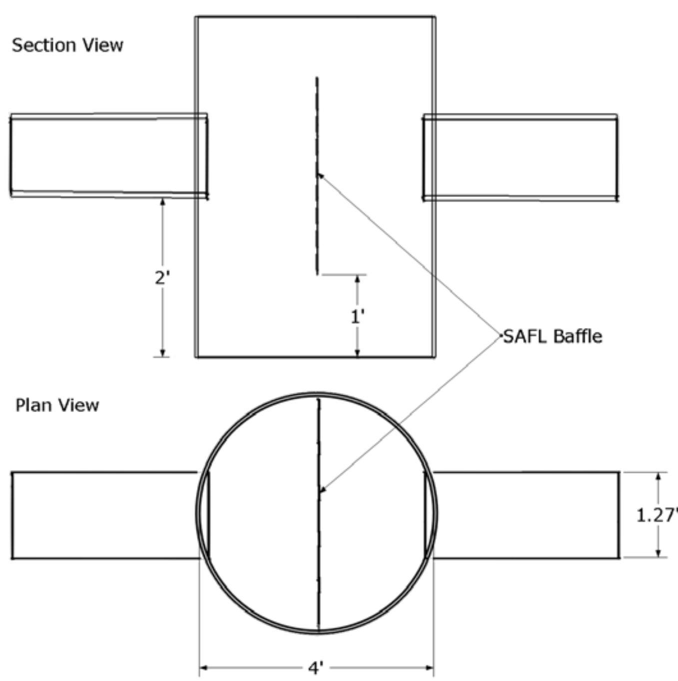

Figure A-2: A schematic of the shallow 4×2 sump manhole.

A.2 6-ft (1.8 m) Sump Setup

The 6-ft (1.8 m) diameter by 6-ft (1.8 m) deep sump, called 6×6, used for laboratory testing was similar to the to 4×4 sump. Both relied on similar plumbing and systems. Similarly, the called 6×6 sump was transformed into a 3-ft (0.9 m) deep sump (called called 6×3) with the help of a false floor. Various SAFL Baffles were installed in the 6-ft (1.8 m) diameter sump. In all cases, the bottom of the SAFL Baffle was installed at an elevation one foot below the invert of the inlet pipe.

Figure A-3: A view of the 6×6 sump manhole setup. The inlet pipe is to the right and the outlet pipe is not shown in this picture. A shadow of the SAFL Baffle can be seen since the sump is lit from the inside.

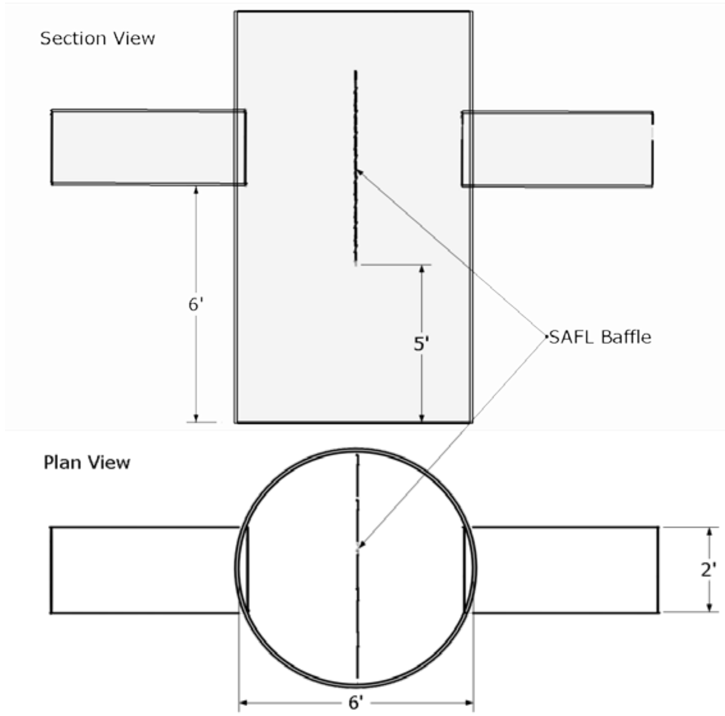

Figure A-4: A schematic of the deep 6×6 sump manhole.

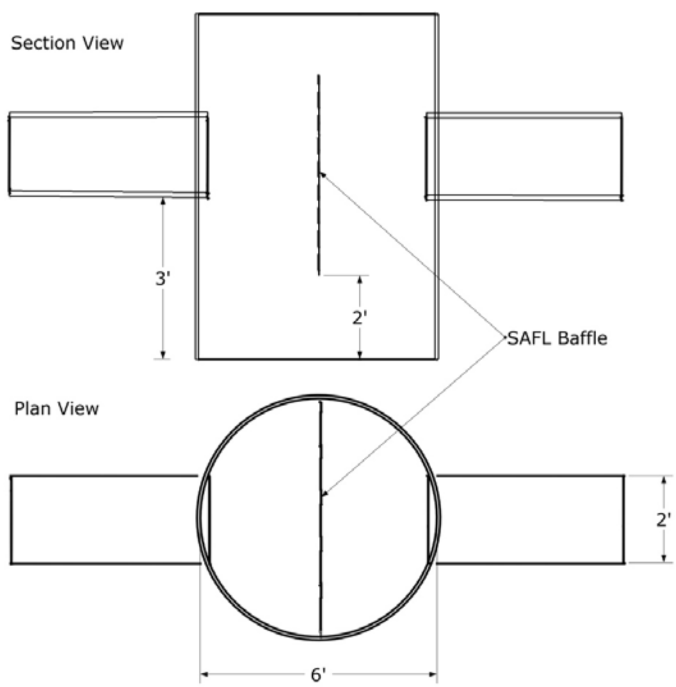

Figure A-5: A schematic of the shallow 6×3 sump manhole.

A.3 1-ft (0.3 m) Sump Setup

The 1-ft (0.3 m) diameter, 1-ft (0.3 m) deep sump manhole was a 1:6.26 scale representation of the 6×6 sump manhole. It was referred to as the 1×1 sump. For these tests, a pump was used to circulate potable water from two head tanks to the sump. From the head tanks, water traveled through the pump to the sump through a 3.5-in (8.9 cm) inner diameter PVC pipe. Upon leaving the sump through the outlet pipe, the water traveled through two 90 degree bends, a 90 degree drop, and through a 4-ft (1.2 m) stretch of PVC angled at a 2 degree slope. From there, water freely fell into the second head tank. Before water could travel into the head tank it passed through a mesh screen and a 0.00079-in (20 µm) filter. This ensured that sediment removed from the sump during testing would not be re-introduced into the head tanks, and subsequently, the sump.

The final stretch of PVC pipe, before the mesh screen and 0.00079-in (20 µm) filter, could be rotated to discharge into a 30-gal (114 L) garbage can. This garbage can sat on top of a scale for weight measurement. With the aid of a stopwatch, the discharge through the system could be measured. Taps throughout the inlet pipe, outlet pipe, and sump were used for water surface elevation measurements.

Water could also be sent through the 1×1 sump without recirculation. Tap water hoses could also be inserted into the head tanks, and their flow regulated to ensure a constant head. With this setup water could be discharged into a 30-gal (114 L) garbage can with a PVC tap. Water entering this garbage can would travel through the PVC tap into a discharge channel which led to the Mississippi River.

Similarly to the 6-ft (1.8 m) diameter sump, the 1×1 sump was transformed into a 1-ft (0.3 m) diameter, 1-ft (0.3 m) deep sump for one test series with the help of a false floor. In the case of this scale model, the false floor was made of an acrylic cylinder that was glued to the inside of the sump. Water could not travel through the seams of the acrylic cylinder because it was sealed with silicone. When the false floor was in place, the depth of the sump was halved.

In the case of the 1×1 and 1×0.5 sumps, the bottom of the SAFL Baffle was installed 1.9-in (4.8 cm) below the inlet pipe.

Figure A-6: Scale model testing system. (Left) water travels from right to left through the sump. (Right) water exits the sump through a PVC pipe system and travels into a head tank protected by a mesh screen and 0.00079-in (20 μm) filter.

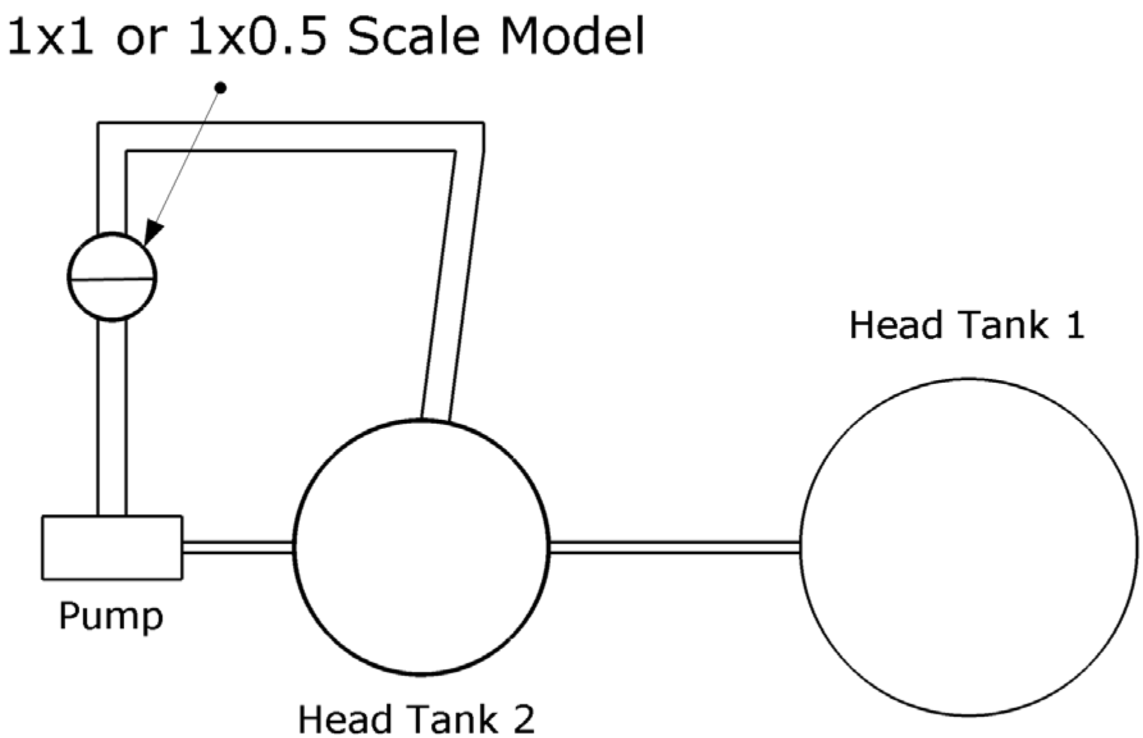

Figure A-7: Scale model testing system.

A.4 6×6-90 Degree Outlet Setup

The 6×6 sump was transformed into a 90 degree outlet sump by blocking the outlet pipe and installing a new outlet pipe. Water traveled through the same plumbing system as the straight flow-through 6×6 sump, but exited through the new outlet. Upon exiting, water free fell into a tailbox below that conveyed the water back to a channel leading to the Mississippi River.

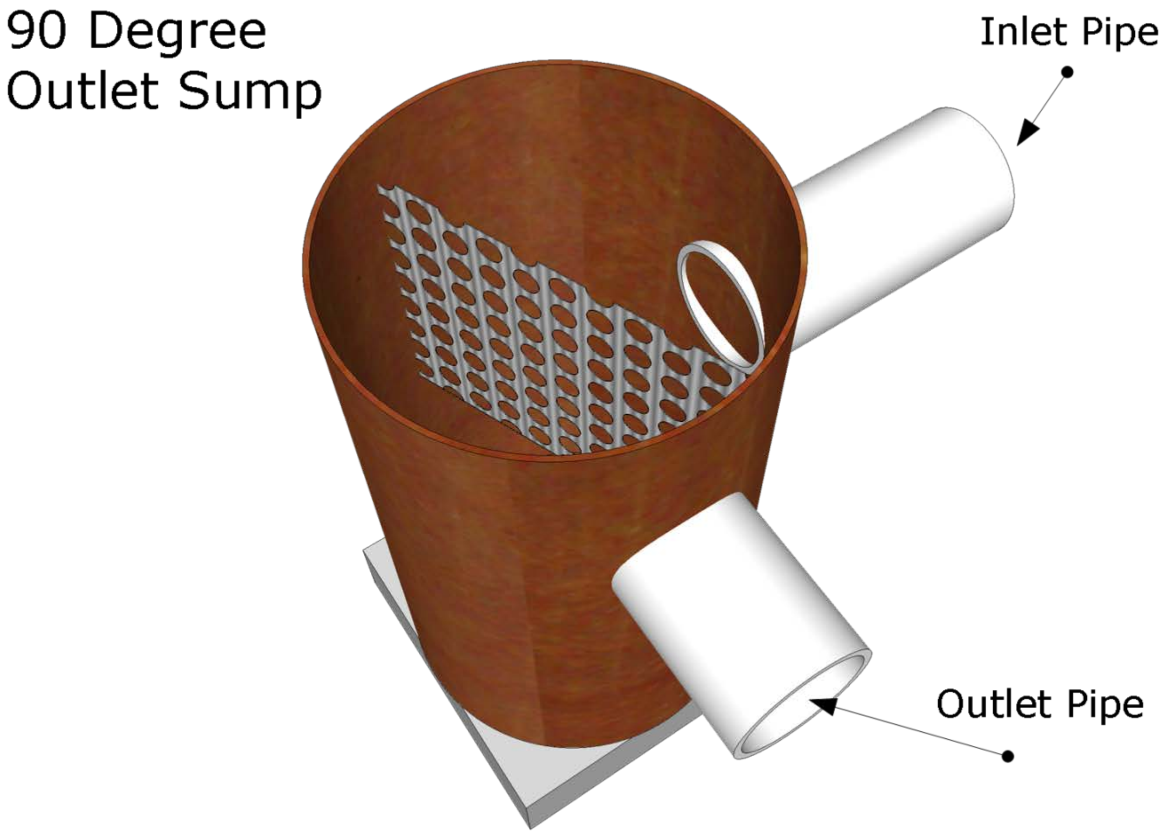

Figure A-8: The 6×6-90 degree outlet sump setup.

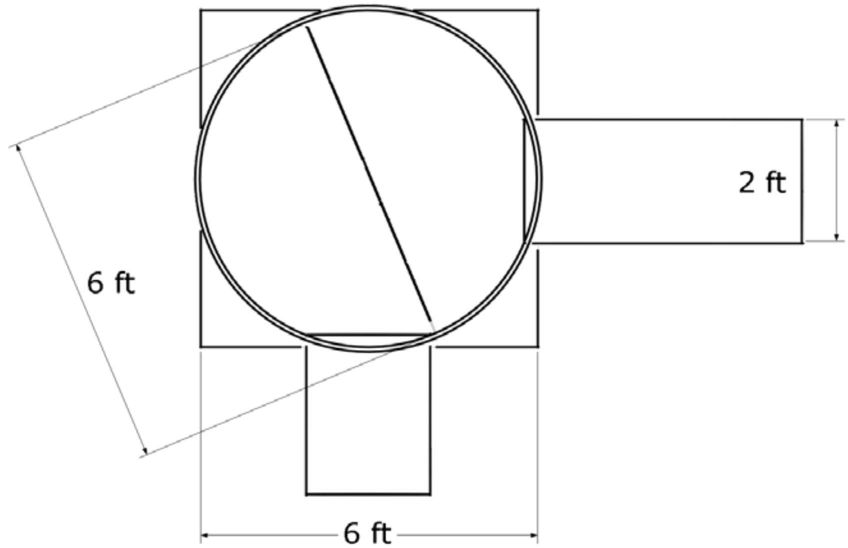

Figure A-9: A plan view of the 6×6-90 degree outlet sump setup. The sump rests on a square wooden platform.

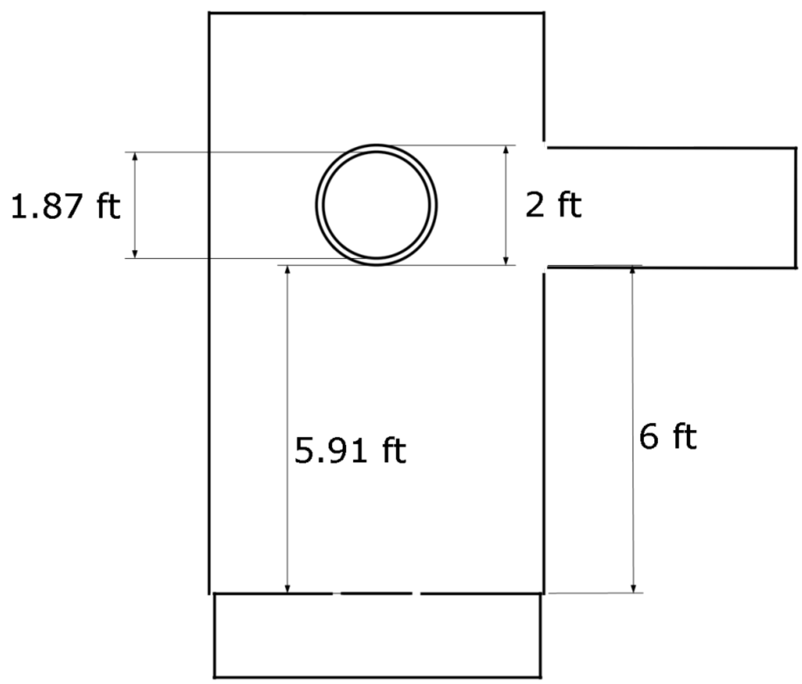

Figure A-10: A section view of the 6×6-90 degree outlet sump setup. The sump rests on a square wooden platform.

A.5 1×1-90 Degree Outlet Setup

The 1×1-90 Degree Outlet sump was created by blocking the outlet pipe of the 1×1 straight flow-through model, and installing a new outlet pipe at a 90 degree angle relative to the inlet pipe. Water traveled through two head tanks, a pump, the sump, and returned to the second head tank through a PVC piping network. Similarly to the 1×1 straight flow-through model, water traveled through a mesh screen and a 0.00079-in (20 µm) filter before returning to the second head tank.

Figure A-11: A plan view of the 1×1-90 degree outlet sump setup.

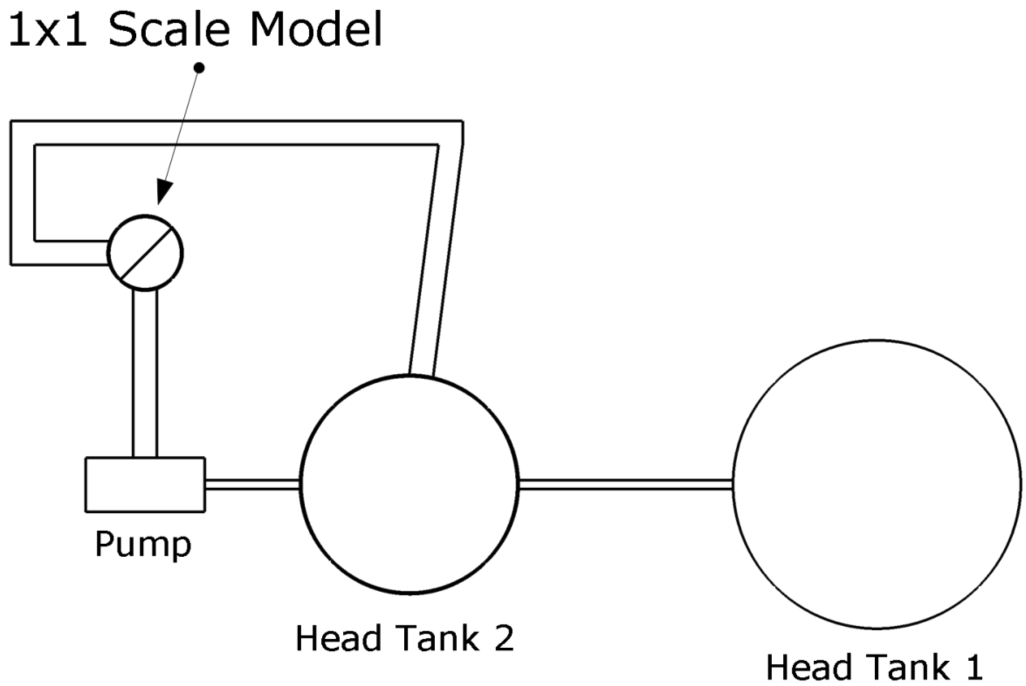

Figure A-12: A plan view of the 1×1-90 degree outlet sump setup.

A.6 6×6-Inlet Grate Setup

For sump testing with an inlet grate, the standard, straight flow-through 6×6 sump was used. Since the sump's weight was measured with load cells for these tests, nothing could touch the sump. To convey water through an inlet grate and ensure nothing touched the sump, a platform was built. This platform suspended a simulated road surface with an inlet grate over 12-ft (3.7 m) in the air. A piping network connected to SAFL's main channel discharged water into the simulated road surface. From here, water traveled across the simulated road surface and into the sump. The inlet grate straddled the SAFL Baffle such that 50% of the inlet grate was upstream of the SAFL Baffle and 50% was downstream of the SAFL Baffle.

Sediment was fed into this system through the inlet pipe and the inlet grate. Two Schenck Accu-Rate feeders were located two floors above the sump. These fed sediment into two separate piping networks which each received tap water from a hose. Sediment met the water in these networks and was transported into the inlet pipe and onto the simulated road surface. Sediment traveling onto the simulated road surface traveled into the inlet grate through the gutter.

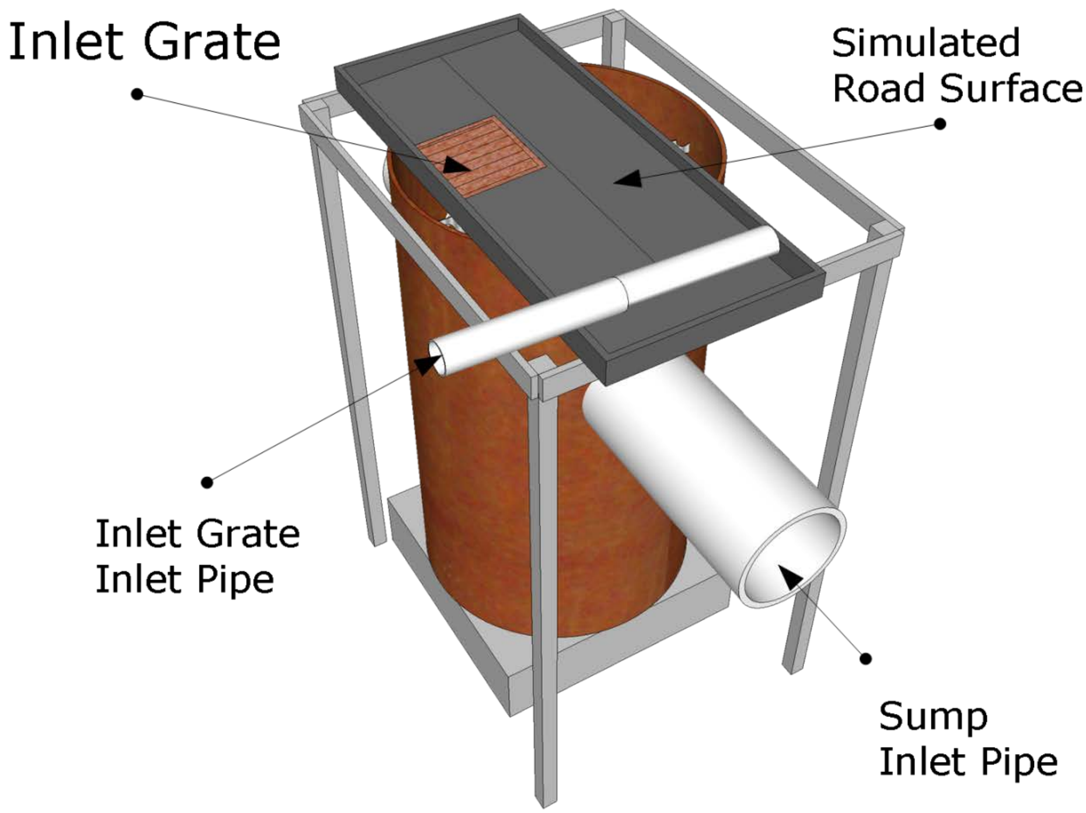

Figure A-13: A 3D view of the 6×6-inlet grate sump setup.

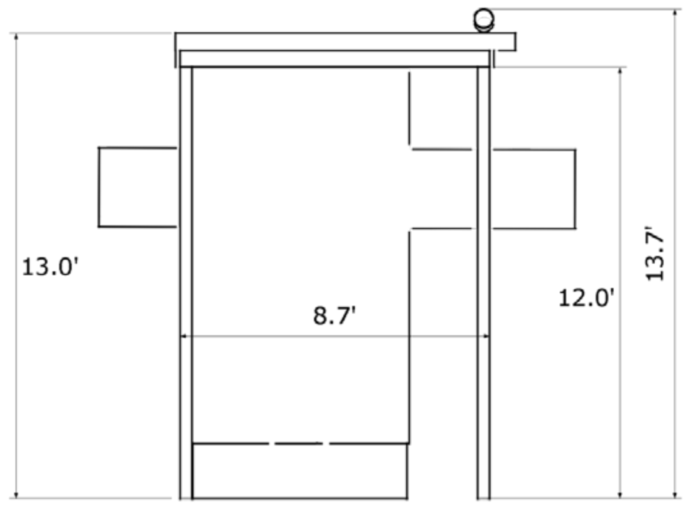

Figure A-14: A section view of the 6×6-inlet grate sump setup.

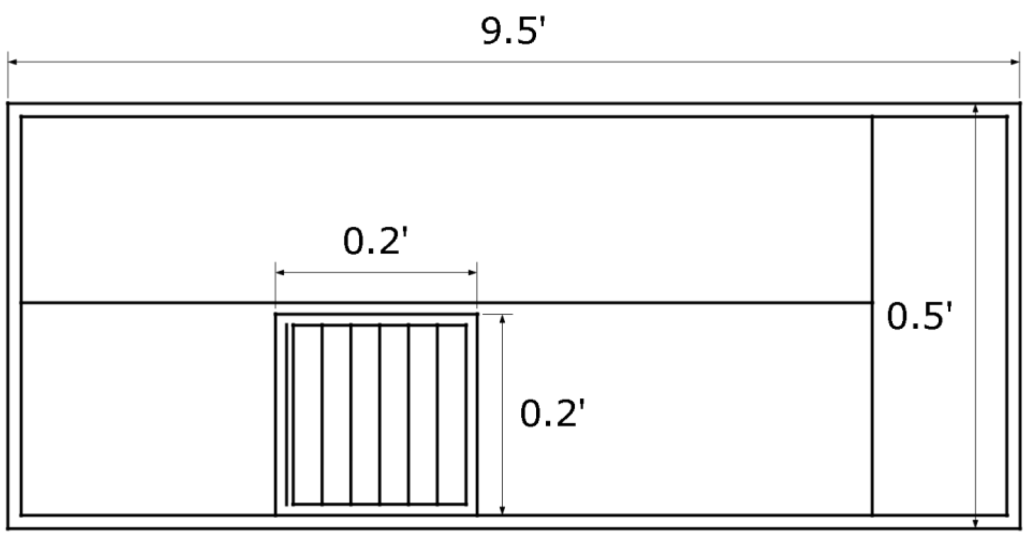

Figure A-15: A plan view of the simulated road surface.

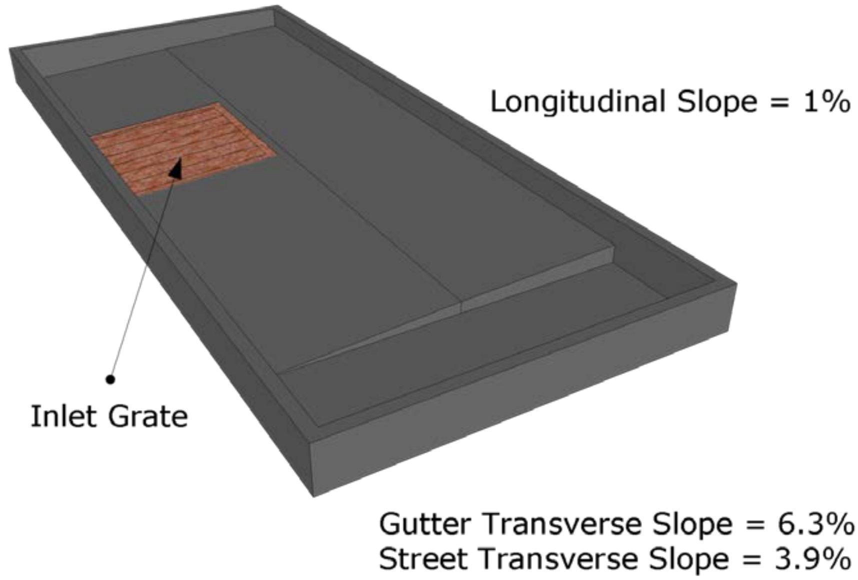

Figure A-16: A 3D view of the simulated road surface.

Appendix B. Testing Procedures

B.1 Removal Efficiency Testing Basics

Removal efficiency tests are conducted to measure how well a stormwater treatment device captures pollutants. In a device like the SAFL Baffle, sediment is captured entirely through settling processes. Settling can only occur if sediment is able to fall below regions of high velocities near the surface of the water. At high flow rates, settling of the majority of sediment particles will not occur. Instead, sediment entering the device will simply pass through the sump. In addition, previously captured sediment can be washed out of the device.

Removal efficiency tests start by cleaning the sump. Then, water is sent through the sump at a constant flow rate. Once the flow rate remains constant, sediment of three specific size distributions 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 µm, 250-355 µm, and 500-589 µm) are loaded upstream of the sump as a slurry (Figure B-1). Depending on the flow rate of the test, various quantities of each sediment distribution will collect in the sump.

Once the test is complete, the flow rate will be quickly reduced to zero and the water in the sump will be allowed to settle for 20 minutes. Water is then drained from the system, ensuring all sediment stays in the bottom of the sump. Once drained, the sediment from the sump is collected using a vacuum. This sediment is then dried in an oven and sieved into its original sediment distributions.

With this information, it is possible to know, for a given flow rate and device, the removal efficiency of each of the three sediment distributions. All removal efficiency testing is conducted in a similar manner to what is described in this section.

Figure B-1: The Schenck AccuRate feeder loading a slurry of sediment and water into an upstream feed pipe.

B.2 Debris Removal Efficiency Testing

1. Equal parts of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm) sediment are mixed, weighed, and dumped into a sediment feeder sitting on a large scale
2. The sump is cleaned to ensure no sediment is present
3. The gate valve is opened and the flow rate is set at the desired loading phase magnitude
4. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle
5. Debris is slowly loaded upstream of the sump
6. Pictures are taken to record the amount of debris clogging
7. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle to compare with pre-loading readings
8. The flow rate is increased to the desired removal efficiency magnitude
9. Pictures are taken to record the amount of debris clogging
10. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle to compare with pre-loading readings
11. A hose connected to the sediment feed pipe, upstream of the sump, is turned on
12. A sediment feeder is set to its desired feed rate and turned on, feeding sediment into the feed pipe as a slurry with the hose water
13. The feeder start time is noted
14. The initial feeder weight is noted
15. Water elevation and flow rate readings are taken
16. Once the desired duration of the removal efficiency phase is reached, the sediment feeder is turned off
17. The feeder "off" time is noted
18. The feeder weight is noted
19. The feed pipe hose is turned off
20. The upstream gate valve is closed, and water no longer enters the sump
21. After 10 minutes, a series of taps are used to slowly drain the water in the sump to a level 1-ft (0.3m) above the floor. The first gallon or two from these taps is collected in a clean barrel
22. The remaining 1-ft (0.3m) of water is drained into clean barrels
23. Any sediment left over in the bottom of the sump is vacuumed and emptied into the barrels
24. By decanting, water is removed from the barrels, leaving the sediment at the bottom of the barrel
25. Remaining sediment and water is poured into a metal pan and placed in an oven until dry
26. Dry sediment is sieved into its original distributions of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm)
27. Each distribution is weighed and compared to the amounts inputted into the sump

B.3 90 Degree Outlet Removal Efficiency Testing

1. 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm) sediment are mixed, weighed, and dumped into a sediment feeder in a ratio of 3, 5, 3
2. The sump is cleaned to ensure no sediment is present
3. The gate valve is opened and the flow rate is set at the desired loading phase magnitude

4. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle
5. The flow rate is increased to the desired removal efficiency magnitude
6. A hose connected to the sediment feed pipe, upstream of the sump, is turned on
7. A sediment feeder is set to its desired feed rate and turned on, feeding sediment into the feed pipe as a slurry with the hose water
8. The feeder start time is noted
9. Water elevation and flow rate readings are taken
10. Once the desired duration of the removal efficiency phase is reached, the sediment feeder is turned off
11. The feeder "off" time is noted
12. The feeder weight is noted
13. The feed pipe hose is turned off
14. The upstream gate valve is closed, and water no longer enters the sump
15. After 10 minutes, a series of taps are used to slowly drain the water in the sump to a level 1-ft (0.3 m) above the floor. The first gallon or two from these taps is collected in a clean barrel
16. The remaining 1-ft (0.3m) of water is drained into clean barrels
17. Any sediment left over in the bottom of the sump is vacuumed and emptied into the barrels
18. By decanting, water is removed from the barrels, leaving the sediment at the bottom of the barrel
19. Any remaining sediment in the sediment feeder is dried, and sieved into its original distribution of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm)
20. Remaining sediment and water is poured into a metal pan and placed in an oven until dry
21. Dry sediment is sieved into its original distributions of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm)
22. Each distribution is weighed and compared to the amounts fed into the sump

B.4 Inlet Grate Removal Efficiency Testing

1. 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 μm, 250-355 μm, and 500-589 μm) sediment are mixed at a ratio of 3, 5, 3, weighed, and dumped into two sediment feeders
2. The sump is cleaned to ensure no sediment is present
3. The inlet grate gate valve is opened and the flow rate is set at the desired loading phase magnitude of 0.4 cfs (11.6 L/s)
4. The inlet pipe grate valve is opened and the flow rate is increased to the desired removal efficiency magnitude
5. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle
6. Two hoses, each connected to a sediment feed pipe, upstream of the sump, are turned on
7. The sediment feeders are set to their desired feed rate and turned on, feeding sediment into the feed pipes as a slurry with the hose water
8. The feeder start times are noted
9. Water elevation and flow rate readings are taken

10. Once the desired duration of the removal efficiency phase is reached, the sediment feeders are turned off
11. The feeder "off" time is noted
12. The feeder weight is noted
13. The feed pipe hose is turned off
14. The upstream gate valve is closed, and water no longer enters the sump
15. After 10 minutes, a series of taps are used to slowly drain the water in the sump to a level 1-ft (0.3m) above the floor. The first gallon (3.8 L) or two (7.6 L) from these taps is collected in a clean barrel
16. The remaining 1-ft (0.3m) of water is drained into clean barrels
17. Any sediment left over in the bottom of the sump is vacuumed and emptied into the barrels
18. By decanting, water is removed from the barrels, leaving the sediment at the bottom of the barrel
19. Any remaining sediment in the sediments feeders is dried, and sieved into its original distribution of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 µm, 250-355 µm, and 500-589 µm)
20. Remaining sediment and water is poured into a metal pan and placed in an oven until dry
21. Dry sediment is sieved into its original distributions of 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 µm, 250-355 µm, and 500-589 µm)
22. Each distribution is weighed and compared to the amounts fed into the sump

B.5 Washout Testing Basics

Washout tests are conducted to measure how well a stormwater treatment device retains sediment at high flow rates.

Washout tests are performed by pre-loading the sump with sediment. Next, the system is weighed. From here, water is sent through the device at a constant flow rate for a set duration. After this duration, the flow rate is quickly lowered to zero and any suspended sediment still in the sump is allowed to settle. Finally, the system is weighed to measure the difference in weight between pre-test and post-test.

In the case of the full scale, 6-ft (1.8 m) diameter sumps, the initial weight is measured using load cells and a water surface elevation tap. With a pre-test and post-test weight and water surface elevation, the amount of sediment washed out of the sump during testing can be calculated.

For the 1-ft (0.3 m) diameter scale sumps, the dry sediment fed into the sump is weighed. After the test, the sediment is cleaned from the sump, placed in the oven, dried, and then weighed. The difference in sediment weight between pre-test and post-test is the amount of sediment washed out of the sump during testing.

The following tests follow this basic principle, but with minor variations.

B.6 6-ft (1.8 m) Debris Washout Testing

1. 3200 lbs (1451 kg) of a mix of 60% AGSCO #100-140 and 40% AGSCO #140-270 was initially placed in the sump (in the case of subsequent tests, sediment was replenished to reach an average starting value of about 3000 lbs (1360 kg))
2. Sediment was leveled using a garden rake
3. The sump was filled with water to an elevation about one foot below the outlet pipe
4. Load cell weight readings were recorded
5. Water elevation readings are taken using a stilling basin
6. Additional water is slowly added to the sump through the inlet pipe until almost exiting the sump
7. Sediment in the sump is allowed to settle for a duration of 10 minutes
8. The gate valve is opened and water is allowed to flow through the device
9. The desired loading phase flow rate is set at 0.75 cfs (21.7 L/s)
10. Water elevations in the inlet pipe and immediately upstream and downstream of the SAFL Baffle are recorded
11. Debris is slowly loaded upstream of the sump
12. Pictures are taken to record the amount of debris clogging
13. Water elevations are recorded in the inlet pipe and immediately upstream and downstream of the SAFL Baffle to compare with pre-loading readings
14. The flow rate is increased to the desired washout phase magnitude
15. Pictures are taken to record the amount of debris clogging
16. Water elevations in the inlet pipe and immediately upstream and downstream of the SAFL Baffle are recorded to compare with pre-loading readings
17. After the desired test duration is reached, the gate valve is closed and the flow is stopped.
18. Sediment in the sump is allowed to settle for 10 minutes
19. All but one foot of water is drained from the sump
20. Debris is removed from the sump, and care is taken to minimize the amount of sediment removed with the debris
21. The sump is filled with water to a level about one foot below the inlet pipe
22. Weight and water levels are recorded

B.7 1×1 Debris Washout Testing

1. 18 lbs (8.2 kg) of a 60/40 mixture was initially placed in the sump
2. Sediment was allowed to settle for a duration of 5-10 minutes
3. Water was pumped through the sump at a very low flow rate (< 2cfs (58 L/s) 6×6 Prototype scale or < 9 gpm (0.6 L/s) Model Scale) until water became visibly more clear. This step is to remove any very fine particles in the sediment that are out of our testing scope.
4. Sediment trapped in the downstream filter was removed, dried, and weighed
5. Roughly 19.8 oz (560 g) of simulated gross pollutants (80% vegetation 20% litter) were loaded into the sump at low flow rates (13.1 gpm (0.8 L/s) Model Scale) for 12 minutes
6. The flow rate was increased to the desired washout test flow rate
7. The test was run for a duration of 24 minutes
8. Sediment was allowed to settle for a duration of 5-10 minutes
9. Sediment captured in the downstream filter was removed, dried, and weighed
10. Confetti captured in the downstream filter was removed, dried, and weighed

11. Sediment and simulated gross pollutants captured in the sump were removed, separated, dried, and weighed

B.8 1×0.5 Debris Washout Testing

1. 11.5 lbs (8.2 kg) of U.S. Silica sand F-110 was initially placed in the sump
2. Sediment was allowed to settle for a duration of 5-10 minutes
3. Water was pumped through the sump at a very low flow rate (0.75 cfs (21.7 L/s) 6×6 Prototype Scale or 3.4 gpm (0.21 L/s) Model Scale) until water became visibly more clear. This step is to remove any ultra fine particles present in the 60/40 sediment mixture that are out of the scope of testing.
4. Sediment trapped in the downstream filter was removed, dried, and weighed
5. Simulated gross pollutants (80% vegetation 20% litter) were loaded into the sump at 3.5 gpm (0.22 L/s) Model Scale) for 12 minutes
6. The flow rate was increased to the desired washout test flow rate of 33 gpm (2 L/s) Model Scale, and 7.2 cfs (208 L/s) prototype scale.
7. The test was run for a duration of 24 minutes
8. Sediment was allowed to settle for a duration of 5-10 minutes
9. Sediment captured in the downstream filter was removed, dried, and weighed
10. Confetti captured in the downstream filter was removed, dried, and weighed
11. Sediment and simulated gross pollutants captured in the sump were removed, separated, dried, and weighed

B.9 6-ft (1.8 m) 90 Degree Outlet Washout Testing

1. 3200 lbs (1451 kg) of a mix of 60% AGSCO #100-140 and 40% AGSCO #140-270 was initially placed in the sump (in the case of subsequent tests, sediment was replenished to reach an average starting value of about 3000 lbs (1360 kg))
2. Sediment was leveled using a garden rake
3. The sump was filled with water to an elevation about one foot below the outlet pipe
4. Load cell weight readings were recorded
5. Water elevation readings are taken using a stilling basin
6. Additional water is slowly added to the sump through the inlet pipe until almost exiting the sump
7. Sediment in the sump is allowed to settle for a duration of 10 minutes
8. The gate valve is opened and water is allowed to flow through the device
9. The flow rate is increased to the desired washout phase magnitude
10. After the desired test duration is reached, the gate valve is closed and the flow is stopped.
11. Sediment in the sump is allowed to settle for 10 minutes
12. All but one foot of water is drained from the sump
13. Debris is removed from the sump, and care is taken to minimize the amount of sediment removed with the debris
14. The sump is filled with water to a level about one foot below the inlet pipe
15. Weight and water levels are recorded

B.10 1-ft (0.3 m) 90 Degree Outlet Washout Testing

1. 18 lbs (8.2 kg) of a 60/40 mixture was initially placed in the sump
2. Sediment was allowed to settle for a duration of 5-10 minutes
3. Water was pumped through the sump at a very low flow rate (< 2cfs (58 L/s) 6×6 Prototype Scale or < 9 gpm (0.56 L/s) Model Scale) until water became visibly more clear. This step is to remove any very fine particles in the sediment that are out of our testing scope.
4. Sediment trapped in the downstream filter was removed, dried, and weighed
5. The flow rate was increased to 52-gpm (197 L/s)
6. The test was run for a duration of 10 minutes
7. Sediment was allowed to settle for a duration of 5-10 minutes
8. Sediment captured in the downstream filter was removed, dried, and weighed

B.11 Inlet Grate Washout Testing

1. 3200 lbs (1451 kg) of a mix of 60% AGSCO #100-140 and 40% AGSCO #140-270 was initially placed in the sump (in the case of subsequent tests, sediment was replenished to reach an average starting value of about 3000 lbs (1360 kg))
2. Sediment was leveled using a garden rake
3. The sump was filled with water to an elevation about one foot below the outlet pipe
4. Load cell weight readings were recorded
5. Water elevation readings are taken using a stilling basin
6. Additional water is slowly added to the sump through the inlet pipe until almost exiting the sump
7. Sediment in the sump is allowed to settle for a duration of 10 minutes
8. The inlet grate gate valve is opened to allow water to flow through the inlet gate and into the sump
9. The flow rate for the inlet grate gate valve is set to 0.7 cfs (19.8 L/s)
10. The gate valve is opened and water is allowed to flow through the device through the inlet pipe
11. The flow rate is increased to the desired washout phase magnitude
12. After the desired test duration is reached, the gate valve is closed and the flow is stopped.
13. Sediment in the sump is allowed to settle for 10 minutes
14. All but one foot of water is drained from the sump
15. Debris is removed from the sump, and care is taken to minimize the amount of sediment removed with the debris
16. The sump is filled with water to a level about 1-ft (0.3 m) below the inlet pipe
17. Weight and water levels are recorded.

Appendix C. Sieving Operation

C.1 Manufacturer Particle Size Distributions

Howard et al. (2011) utilized U.S. Silica F110 product for removal efficiency and washout testing. This product was discontinued at the being of this study, so the sediment used for testing was entirely AGSCO products. The AGSCO #100-140 and #140-270 products were used for washout testing and the #20-40,#40-70, and #140-270 products were used for removal efficiency testing. Figure C-1 shows the manufacturer's advertised distributions of these three products.

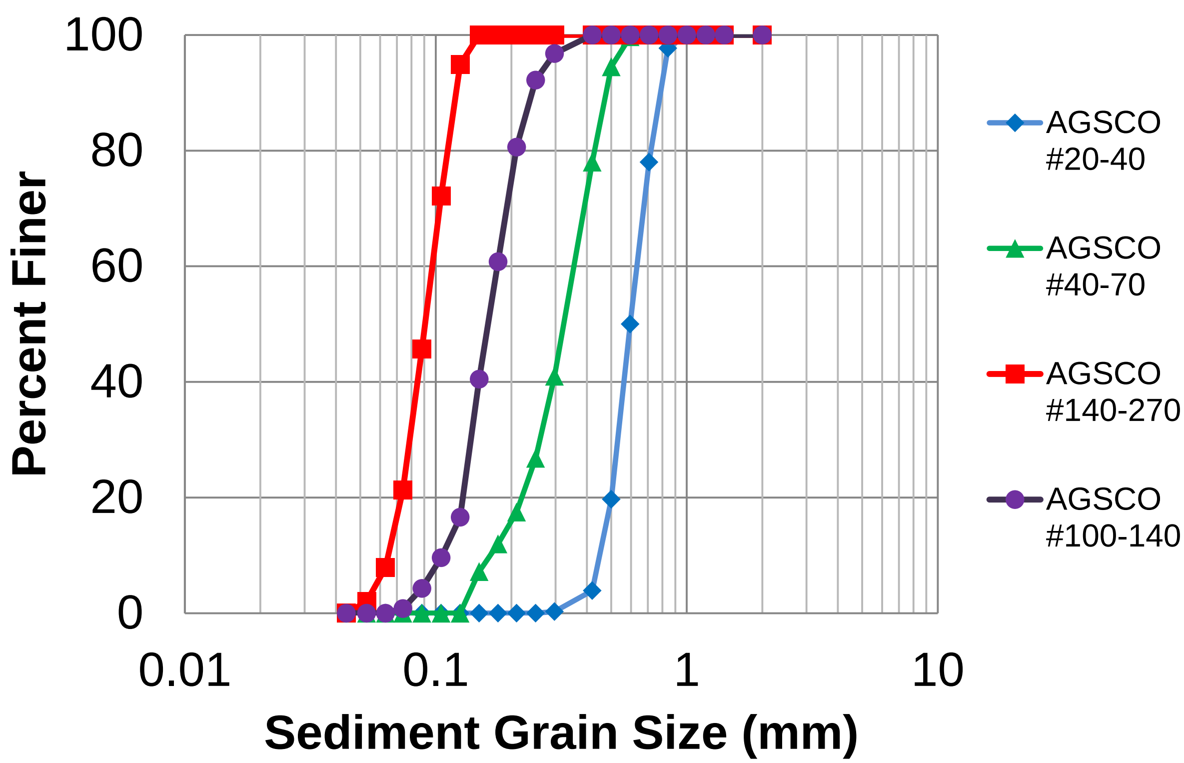

Figure C-1: Sediment grain sizes for four AGSCO products.

C.2 Testing Particle Size Distributions

Debris and Inlet Grate washout testing sediment was a mix of 60% AGSCO #100-140 and 40% AGSCO #140-270. It was mixed inside of a cleaned concrete mixer and stored in barrels for use. For the 90 Degree washout testing, however, a special mix was created. It contained 25% waste sediment from previous removal efficiency tests, 37.5% AGSCO #100-140, and 37.5% AGSCO #140-270. Figure C-2 shows F110 (Howard et al. , 2011), the 60/40 mix used for 1×1, 6×3, and 6×6 debris testing and 6×6-Inlet Grate testing, and the custom mix used for 1×1-90 Degree Outlet and 6×6-90 Degree Outlet washout testing.

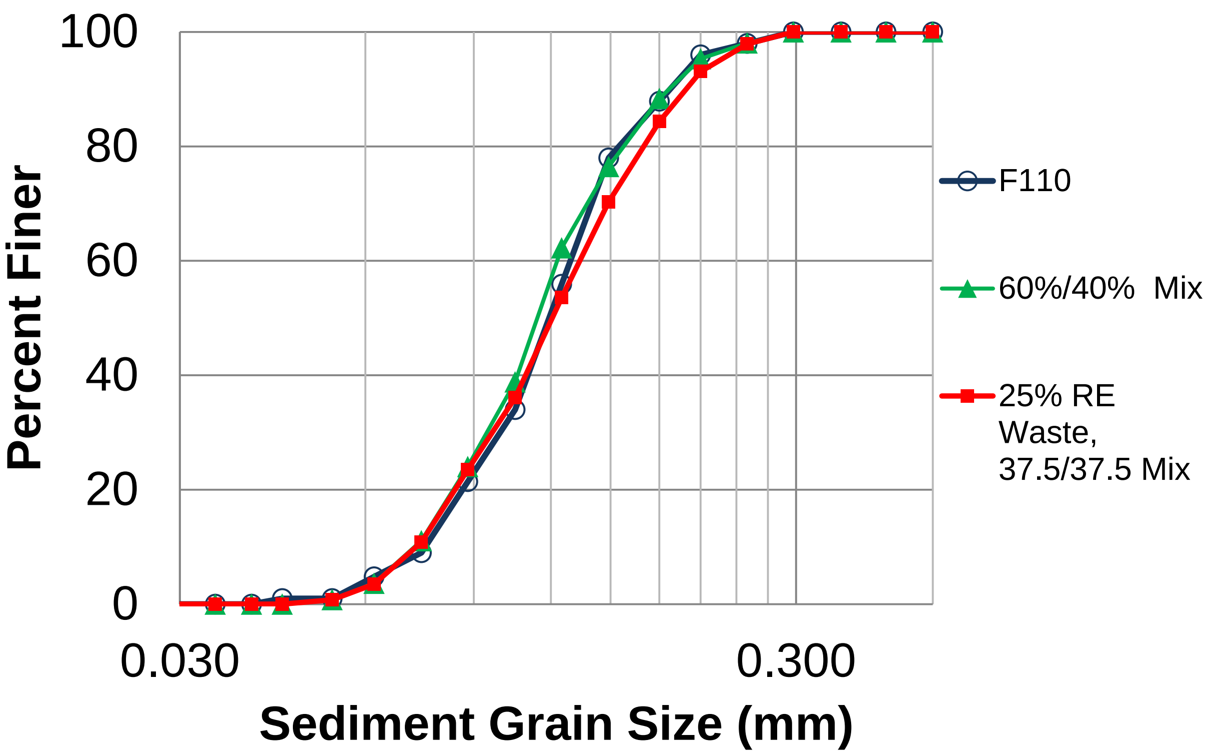

Figure C-2: Washout testing sediment size distribution.

For removal efficiency testing, three sediment distributions were used: 0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in (88-125 µm, 250-355 µm, and 500-589 µm). The distributions were created by sieving AGSCO #140-270, #40-70, and #20-40, respectively.

C.3 Sieving Procedure

Sediment was sieved to create the distributions required for removal efficiency testing. This completed on large sieve shaker tables created at St. Anthony Falls Laboratory, using a specific procedure. For example, 250-355 µm sediment was conducted with the following procedure:

1. A 0.0165-in, 0.0140-in, and 0.00984-in (420 µm, 355 µm, and 250 µm) sieve were each cleaned and placed on the shaker table in order from smallest sieve size to largest
2. 5.5 lbs (2.5 kg) of AGSCO #140-270 was poured on the top sieve, which was the 0.0165-in (420 µm) sieve for this case
3. The shaker table was turned on and allowed to shake for 5 minutes
4. After 5 minutes, the shaker table was turned off
5. The operator lifted the 0.0165-in (420 µm) sieve and taps the bottom of it for a few seconds, allowing any clogged sediment to fall through to the 0.0140-in (355 µm) sieve or remain on the 0.0165-in (420 µm) sieve
6. The operator repeated this process for the 0.0140-in and 0.00984 (355 and 250 µm) sieves
7. Sediment on the sieves was spread evenly over each sieve to ensure an equal opportunity for sediment to pass through

8. The shaker table was turned on and allowed to shake for 5 minutes
9. After 5 minutes, the shaker table was turned off
10. Sediment from the 0.00984-in (250 µm) sieve was collected in a plastic barrel
11. The 0.00984-in (250 µm) sieve sediment was weighed
12. The weight of the sediment captured on the 0.00984-in (250 µm) sieve was compared to the manufacturer's predicted yield and the previous yield
13. If the sediment yield matched with previous yields and the manufacturer's data, the 0.00984-in (250 µm) sieve sediment was dumped into a clean plastic garbage can labeled "250-355"
14. If the sediment yield did not match, it was discarded
15. The sediment on the 0.0140-in and 0.0165-in (350 and 420 µm) sieves was discarded
16. Any sediment passing through the 0.00984-in (250 µm) sieve was discarded

Appendix D. Maintenance Manual

As with any stormwater treatment device, the SAFL Baffle must be maintained. In this appendix, the procedure required for the maintenance of sumps equipped with the SAFL Baffle is described and an example using the software SHSAM is provided.

D.1 Visual Inspection

Often the characteristics of trash and sediment load from drainage basins are not known, therefore, after installing the SAFL Baffle into a sump manhole, the system should be visually inspected three times per year for the first two years. The visual inspection checklist is as follows.

Visual Inspection Checklist:

1. Previous Inspection - Has this SAFL Baffle been inspected before? If so, when?
2. Rainfall - Has it rained recently? If so, when? How many inches?
3. Access - Is the sump manhole accessible? If not, why?
4. Pipes - How many inlet pipes connected to the sump?
5. Flow - How does water flow through the sump?
6. Debris - Is trash or vegetation in the sump? If so, what types of trash or vegetation are present?
7. Structural Integrity - Is the SAFL Baffle broken? Is it rusting? Are there pieces of the baffle that have become dislodged? Do any parts of the SAFL appear weak or damaged?
8. Clogging - Is anything clogging the baffle? If so, what is causing the clogging?

During this inspection, it is important to determine whether or not the SAFL Baffle is physically compromised. In addition, the sediment captured at the bottom of the sump should be measured. This can be done by using a stick ruler with a point that can penetrate the sediment and reach the bottom of the sump, and a stick ruler with a flat disk that will stop when reaching the surface of the sediment deposit. The difference in distance measurements between these rulers is the depth of sediment in the sump. Several measurements should be taken upstream and downstream of the baffle to determine an average sediment depth in the sump, because the sediment bed may not be perfectly flat.

When visually inspecting the SAFL Baffle, it is important to check for clogging of the baffle due to debris like trash and vegetation. Debris clogging the SAFL Baffle can cause washout in shallow sumps. Any debris stuck in the sump upstream of the SAFL Baffle and on the baffle should be removed.

If during the visual inspections, a significant amount of trash (i.e., plastics and leaves) is observed on the baffle or in the sump, it is recommended to install trash collectors in the catch basins upstream of the sump equipped with the SAFL Baffle.

D.2 Sump Cleaning

Sump cleaning has to be done to sustain a near maximum efficiency of the sump. If sediment in the sump is not removed, sediment will accumulate at the bottom of the sump, causing the sediment bed to rise towards the bottom of the SAFL Baffle and converting it to a shallow sump.

A shallow sump (with the top of the sediment deposit at about one foot or less below the SAFL Baffle) is likely to exhibit washout during intense storm events.

Cleaning should be done with a truck mounted vacuum. If the manhole's casting and SAFL Baffle is designed properly, the SAFL Baffle should not get in the way of the truck's vacuum.

SHSAM (Mohseni et al. 2011) software can be used to estimate the initial sump cleaning interval. After the first two years of inspection, the cleaning intervals can be modified based on the date obtained during the inspections. Below is an example of using SHSAM to provide the initial estimate of cleaning interval.

D.3 Initial Estimate of Cleaning Intervals Using SHSAM

In order to provide an initial estimate of sump cleaning interval required for a sump equipped with the SAFL Baffle (i.e. the number of sump cleaning per year), the SHSAM software can be used as a guide. Herein, an example of using SHSAM is presented. In this example, the drainage basin presented in Volume 1 is employed.

The area of the example drainage basin is 19.9 acres, where 35% of the area is impervious and the rest including the disconnected impervious area has a curve number of 75. The hydraulic length of the drainage basin is 4600 feet and the average slope of the drainage basin is 2%. Assuming the drainage basin is located in Minneapolis, MN (i.e. using the rainfall and temperature records of Northfield, MN from 1991 to 2007) the SHSAM model was run with two different particle size distributions (PSD): OK110 and the MnDOT Road Sand. It was also assumed that the inlet pipe had a diameter of 24 inches.

The model shows that the overall removal efficiency (including washout) of a 6×6 sump equipped with the SAFL Baffle is 33% if the PSD of suspended sediments in stormwater is similar to OK110 and 62% if the PSD is similar to the MnDOT Road Sand. The model also shows that on average the 6×6 sump equipped with the SAFL Baffle has to be cleaned 1.94 times per year if the PSD is OK110 and 3.35 times per year if the PSD is the MnDOT Road Sand. A better removal efficiency of the device results in more sediments captured in the sump, which requires more frequent cleaning of the sump. Using the above information, it is recommended to plan for three cleaning of the sump per year. During the first two years of inspection of the device, the number of sump cleaning per year can be adjusted to reflect the actual PSD in stormwater runoff.

If a 10×6 sump is used instead of a 6×6 sump, with the same inlet pipe size, the overall removal efficiency becomes 41% and 69% for OK110 and the MnDOT Road Sand, respectively. The number of sump cleaning per year also changes to 1 and 1.76 for OK110 and the MnDOT Road Sand, respectively. It is evident that a larger sump would result in a better efficiency and a less frequent sump cleaning per year.

If the SAFL Baffle is not used as a retrofit, it is recommended to install standard sumps equipped with the SAFL Baffle for drainage basins significantly smaller than 19.9 acres, i.e. divide the 19.9 acre drainage basin into a number of subbasins. Then, if a 6×6 sump equipped with a SAFL Baffle is installed at the outlet of e.g. a 5-acre subbasin with a hydraulic length of 2300 feet and a land cover similar to the example above, the overall removal efficiency increases to 68% and

86% for OK110 and the MnDOT Road Sand, respectively. The number of sump cleaning per year becomes 1 and 1.6 for OK110 and the MnDOT Road Sand, respectively.

D.4 Running SHSAM

This program can be downloaded for free from the Barr Engineering website.

SHSAM Cleaning Interval Estimate

1. Install SHSAM and start the program
2. Read the first tab titled 1. Introduction
3. Select the second tab, titled 2. Root Directory. Set a root directory where SHSAM output files can be sent and input files can be placed. It is important to choose a file path that does not include spaces. For example, "C:\Users\Kurt\SHSAMOutputs" is an acceptable file path, but "C:\Users\Kurt\SHSAM Outputs" is not.
4. Select the third tab, titled 3. BMP. Select the radio button titled Standard Sumps with SAFL Baffle. A pop up window will display, asking whether or not washout should be incorporated into the calculations. Select Yes for washout, and select whether or not a bypass is used upstream of the sump to prevent high flow rates from reaching the sump. Next, select the size of the sump to be analyzed.
5. Next, select the fourth tab, titled 4. Weather Station Precipitation. From the top-most drop down menu, select the weather station precipitation to be used for the estimate. Each weather station contains data for a number of years. Select the range of dates that are deemed appropriate for the estimate. Follow SHSAM's instructions if a custom weather station data set is used.
6. Select the fifth tab, titled 5. Particle Size Distribution. Use the drop down menu to select the particle size distribution (PSD) to represent the influent sediment entering the sump. If the onsite data give a distribution different from those provided by SHSAM, follow SHSAM's instructions for entering custom PSD.
7. Click on tab six, titled 6. Watershed Data. Enter the drainage area, percent pervious, hydraulic length, average slope, and curve number for the watershed. Follow SHSAM's instructions for using watershed data previously stored in the root directory.
8. Next, select the seventh tab, titled 7. Temperature. Click “yes” if a constant water temperature of 68 degrees Fahrenheit is to be used for the estimate, or click “no” to use the drop down menu for water temperature data. Alternatively, a custom water temperature data set can be used. Follow SHSAM's instructions for using custom data sets.
9. For the final step of entering input parameters, select the eighth tab, titled 8. Influent Concentration / Count Sump Cleanings. Enter the influent concentration of sediment reaching the sump, and select the “yes” radio button to keep count of the sump cleanings.
10. Press the button in the bottom right hand corner called Run Model.
11. Select Tools-Output Data from the File Menu. Select the tab titled Summary.