Stormwater Treatment with the SAFL Baffle: Debris and Non-standard Sump Testing

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Abstract

The SAFL Baffle is a stormwater treatment device created at the University of Minnesota's St. Anthony Falls Laboratory. Previous research by Howard et al. 2011 showed that when the SAFL Baffle is retrofitted into a sump manhole, it improves the ability of the sump to collect sediment at low flow rates and retain captured sediment at high flow rates. The purpose of this research was to know how a SAFL Baffle performs when:

1. Clogged with debris like trash and vegetation
2. Installed in a sump manhole with an outlet pipe 90 degrees to the inlet pipe
3. Installed in a sump manhole with water entering through an inlet grate and inlet pipe

Tests were performed at the St. Anthony Falls Laboratory on a 6-ft (1.8 m) diameter by 6-ft (1.8 m) deep sump, a 6-ft (1.8 m) diameter by 3-ft (0.9 m) deep sump, a 1-ft (0.3 m) diameter by 1-ft (0.3 m) deep scale model sump, and a 1-ft (0.3 m) diameter by 0.5-ft (0.15 m) deep scale model 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)

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-in (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 90-120 degrees of the inlet pipe, washout sharply decreased. 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.

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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. However, stormwater remains largely untreated throughout the United States as a non-point source. Rainwater falls onto roads, lawns, and farm fields and comes 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.

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 treatment processes. 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 not traditionally thought of as 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 typically only drains to the invert of the outlet pipe, i.e. there is water sitting in the sump. Sump manholes are used as access points for maintenance staff to inspect storm sewers, but they are also known to collect pollutants like sediment and debris through settling.

1.2 The St. Anthony Falls (SAFL) Baffle

Howard et al. 2011 found 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). Howard et al, 2011 also documented that a standard sump retrofitted with a SAFL Baffle, a porous baffle, will capture slightly more solids than an empty sump and reduce sediment washout to near-zero at high flow rates (Figure 1-2).

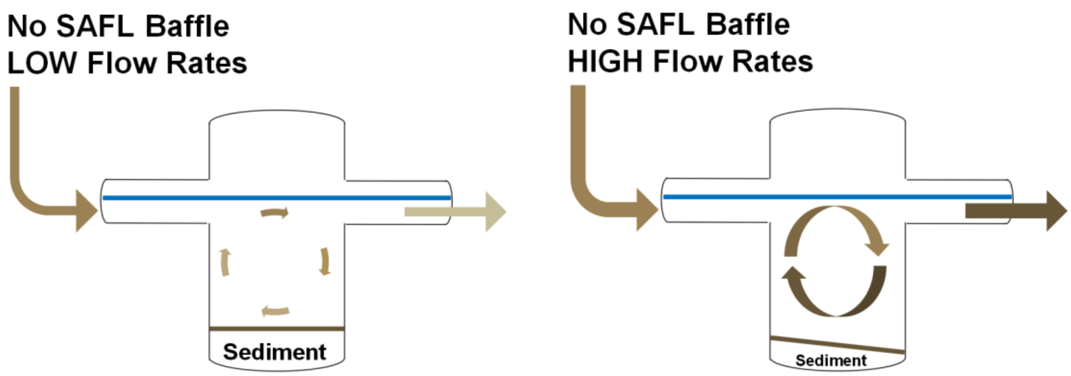

Figure 1-1: (Left) A standard sump manhole collecting sediment at low flow rates. (Right) A standard sump manhole losing sediment to washout at high flow rates.

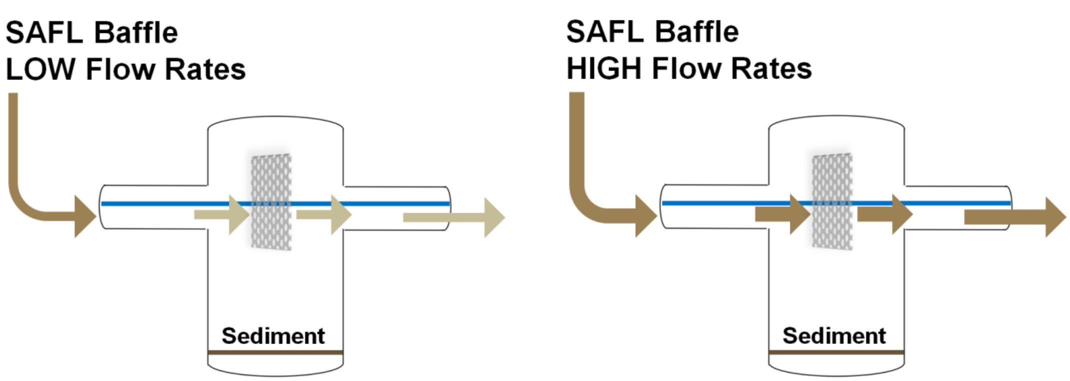

Figure 1-2: (Left) A standard sump manhole equipped with a SAFL Baffle collecting sediment at low flow rates. (Right) A standard sump manhole equipped with a SAFL Baffle at high flow rates.

1.3 Scope of Research

The objective of this research was to know how the SAFL Baffle will perform in the field, such as when the baffle is:

- Clogged with debris like trash and vegetation (Figure 1-3)
- Installed in a sump manhole with an outlet pipe 90 degrees to the inlet pipe (Figure 1-4)
- Installed in a sump manhole with water entering through an inlet grate and inlet pipe (Figure 1-5)

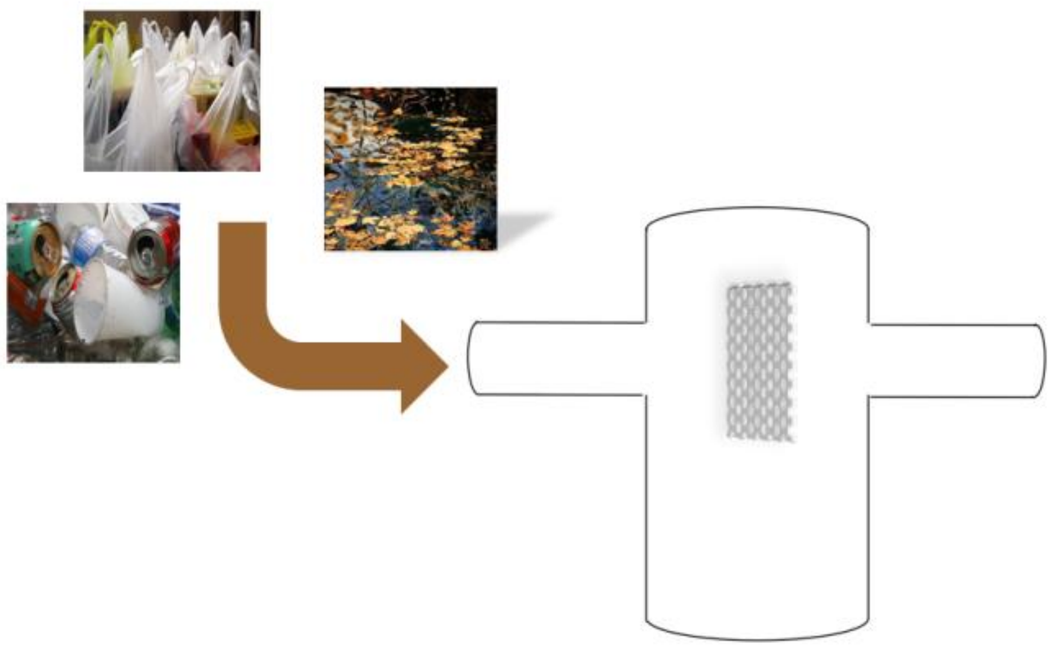

Figure 1-3: A standard sump manhole equipped with a SAFL Baffle, receiving stormwater debris like trash and vegetation

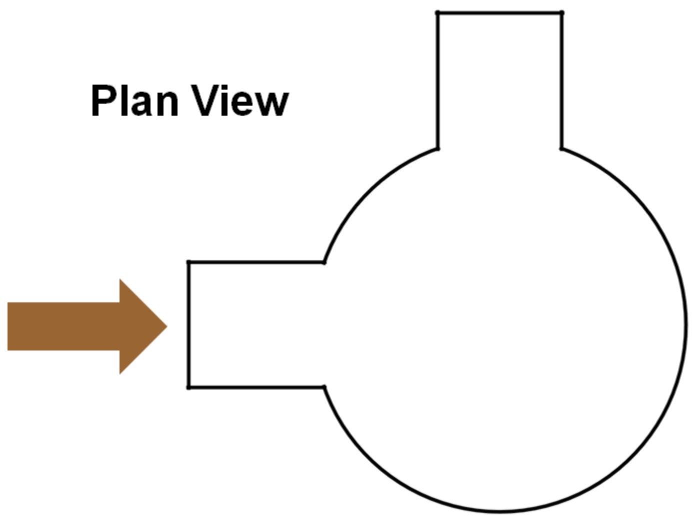

Figure 1-4: A 90 degree outlet sump manhole

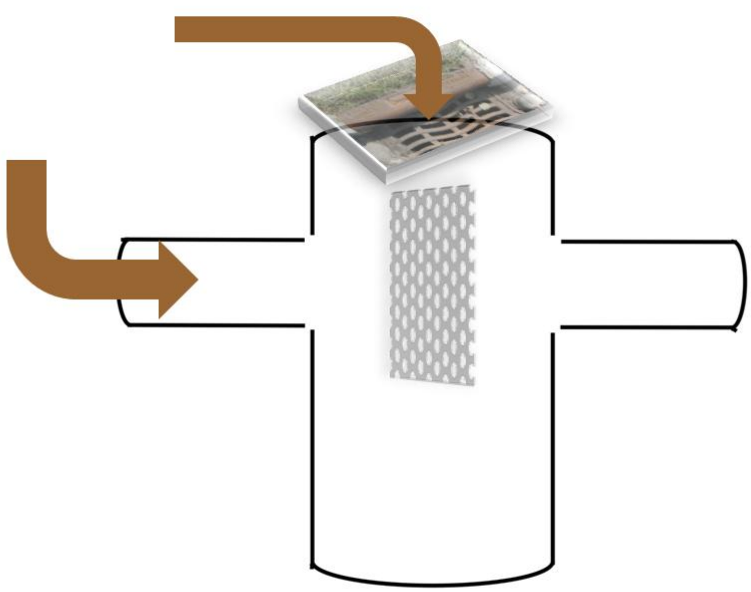

Figure 1-5: A standard sump manhole equipped with a SAFL Baffle, receiving water from an inlet pipe and an inlet grate

2. Impact of Debris on the SAFL Baffle

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

2.1 Debris Composition and Loading

A number of studies were conducted to determine what makes up gross solids 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-in (0.5 cm) in stormwater was roughly composed of 81-90% vegetation, 5-19% trash, and 0-13% sediment. This information is summarized in Table 2-1.

Table 2-1: 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 2-2.

Table 2-2: 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*

2.1.1 Tree Leaf Sizes

Since a majority of stormwater debris is vegetation, it was important to determine the size of leafy debris entering storm sewers. 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 Elem. 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-in (3.8 to 15.2 cm) and greatly varying aspect ratios (DNR, 2011). The data are summarized in Table 2-3.

Table 2-3: Trees and leaf sizes in Minneapolis, MN

Tree Type	Pop. %	Aspect Ratio Leaf Length	Aspect Ratio Leaf Width	Average Length	Average Width
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-in (10 cm), and the average width is 3.2-in (8.1 cm).

2.1.2 Debris Loading Rates

The three studies mentioned in Table 2-4 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 annual rainfall per fraction of impervious area. Using the three studies, a mean, minimum, and maximum loading rate was calculated.

$$LR = NLR * Imp * R * A \tag{2-1}$$

$$NLR = Normalized\ Loading\ Rate, \frac{lb}{acre * in\ annual\ rainfall * impervious\ fraction} \tag{2-2}$$

Where:

$LR = Loading\ Rate, lb$

$Imp = Impervious\ Fraction$

$R = Annual\ Rainfall, inches$

$A = Drainage\ Area, acres$

Despite one study being in Texas, and the other two in California, Table 2-4 indicates that the loading rates were comparable.

Table 2-4: 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

2.1.3 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 Kim et al. 2004 research were used. The data of Weir et al. 2010 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 100 mg/L (0.0062 lb/ft^3). 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-ft (1.8 m) diameter, 6-ft (1.8 m) deep sump 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 (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 in fall and probably spring.

2.2 Experimental Setup

Two laboratory sump manholes were utilized for debris testing. The first was the 1-ft (0.3 m) diameter, 1-ft (0.3 m) deep sump (the scale model), and the second was the 6-ft (1.8 m) diameter, 6-ft (1.8 m) deep sump. For brevity purposes, they will be referred to as the 6×6 sump and the 1×1 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 halve their depths, transforming them into a 6-ft (1.8 m) diameter, 3-ft (0.9 m) deep sump and a 1-ft (0.3 m) diameter, 0.5-ft (0.15 m) sump. The false floor sumps will be referred to as the 6×3 and 1×0.5 sumps.

The 6×6 sump was connected to the SAFL plumbing system which provides approximately 45 feet of head of Mississippi River water. The flow rate was measured in the 12 inch 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 upstream of the sump. 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).

The 1x1 sump model used for testing was a 1:6.26 representation of the 6x6 standard manhole sump. This scale model was connected to a 3.5-in (8.9 cm) diameter inlet and outlet pipe. Its inlet pipe was connected a pump, which 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.

The testing setup on the 1×1 and 1×0.5 scale model sumps 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 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 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 2-1 shows the model scale baffles of the two configurations and Figure 2-2 shows the full scales baffles installed in the sump.

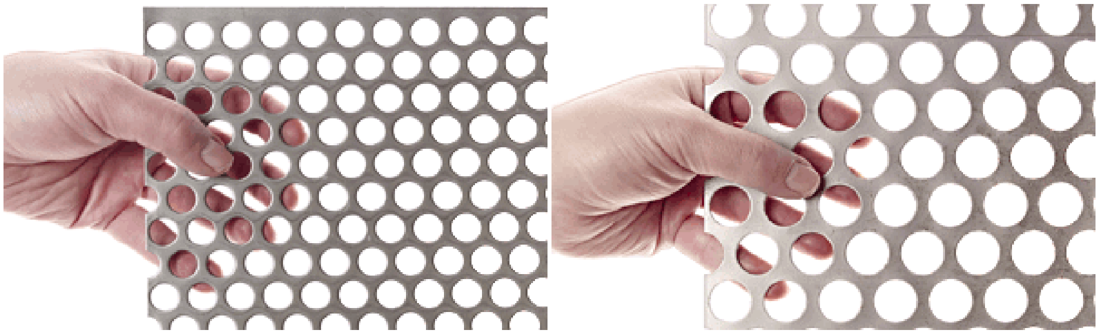

Figure 2-1: (Left) 0.5-in (1.27 cm) and (Right) 0.75-in (1.9 cm) hole diameter SAFL Baffles. Source - McMasterCarr.com

Figure 2-2: (Left) 3-in (7.6cm) and (Right) 5-in (12.7cm) hole diameter SAFL Baffles

2.3 Testing Procedure

Debris washout and removal efficiency 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 so that no sediment in the sump would get washed out. After the debris loading phase, the removal efficiency or washout test was conducted similar to the standard sump tests.

For the debris washout testing on the model scale, the 1×1 sump was filled with 18-lbs (8.2 kg) of sediment more or less a median size of 110 microns (0.0043 in) (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 (82.1 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 gpm to 73 gpm (2.6 to 4.6 L/s), or 9 to 16 cfs (255 to 453 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 oz (0.59 L) soda bottle with dimensions equal to 3/8-in (0.95 cm) in diameter and 1.3-in (3.3 cm) in length (Figure 2-3).

The testing procedure used for the 6-ft (1.8 m) 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 and then 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-ft (2.4 m) upstream of the sump. Debris fed into the sump was comprised of leaves, small plastic grocery bags, plastic bottles, and vinyl leaves (Figure 2-4). 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 2-5). 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 (29.5 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.

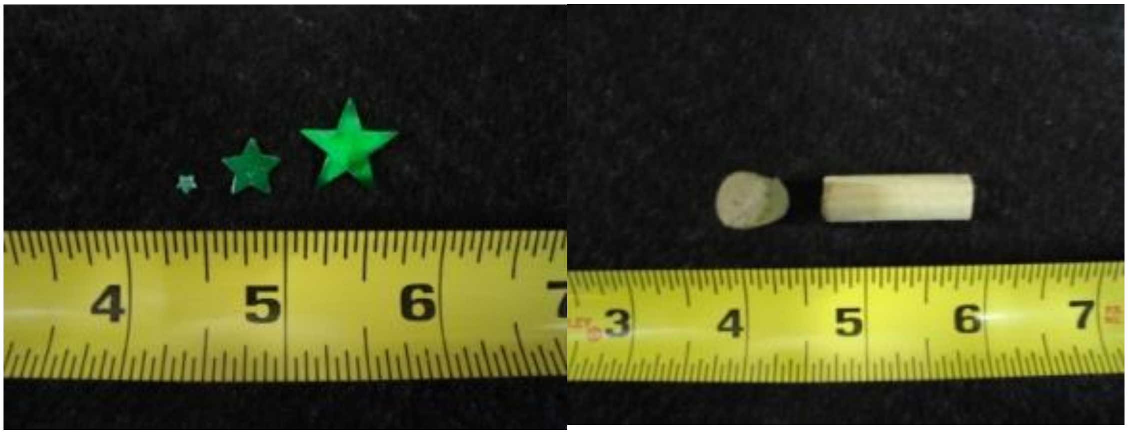

Figure 2-3: Simulated Debris Mixture (Left) 80% Confetti (Right) 20% Wood Dowels

Figure 2-4: (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 2-5: Vinyl leaves, plastic grocery bags, and plastic bottles used as simulated debris

To complete debris removal efficiency tests, debris was loaded upstream of the empty sump, 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. The influent concentrations of the removal efficiency tests varied between 100 to 200 mg/L (0.0062-0.0012 lb/ft^3) and three distinct particle sizes were used for the tests. The median sediment sizes were 545 μm (500 to 589μm) (0.020-0.023-in), 303 μm (250 to 355μm) (0.0098-0.014-in), and 107 μm (88 to 125μm) (0.0035-0.0049-in). 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.

2.4 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 (1.3 cm) 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 (255 to 453 L/s) if scaled to a 6-ft (1.8 m) diameter 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 2-6 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.

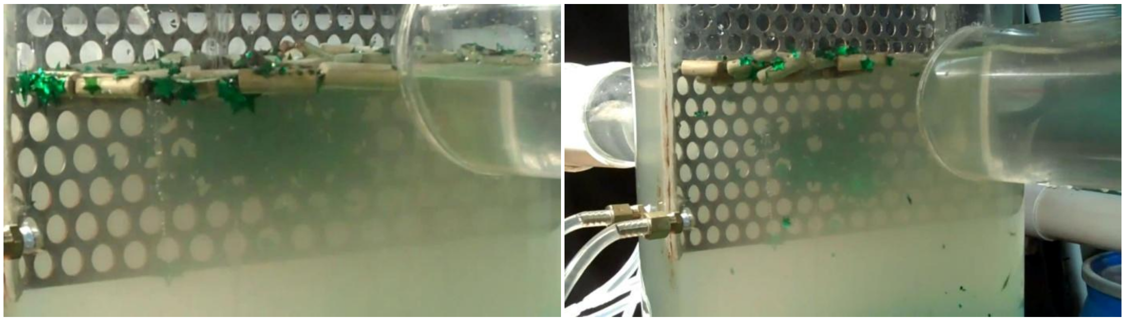

Figure 2-6: (Left) 1×1 scale model during the loading phase and (Right) during the washout phase. Water flow is from right to left.

Table 2-5 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 20 μm ($7.9*10^{-4}$ -in) 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 2-5: 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 319, 0 and 163 g (11.3, 0, and 5.7 oz) (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-in holes, which is roughly equivalent to 4 7/8-in holes full scale. This design has roughly the same percent open area as the 0.5-in, or 3-in hole full scale SAFL Baffle. The second design alternative was a SAFL Baffle with 0.5-in 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 157 mg/L (0.0098 lb/ft^3). This was much higher than the effluent concentrations measured for the 1×1 model scale. Figure 2-7 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.

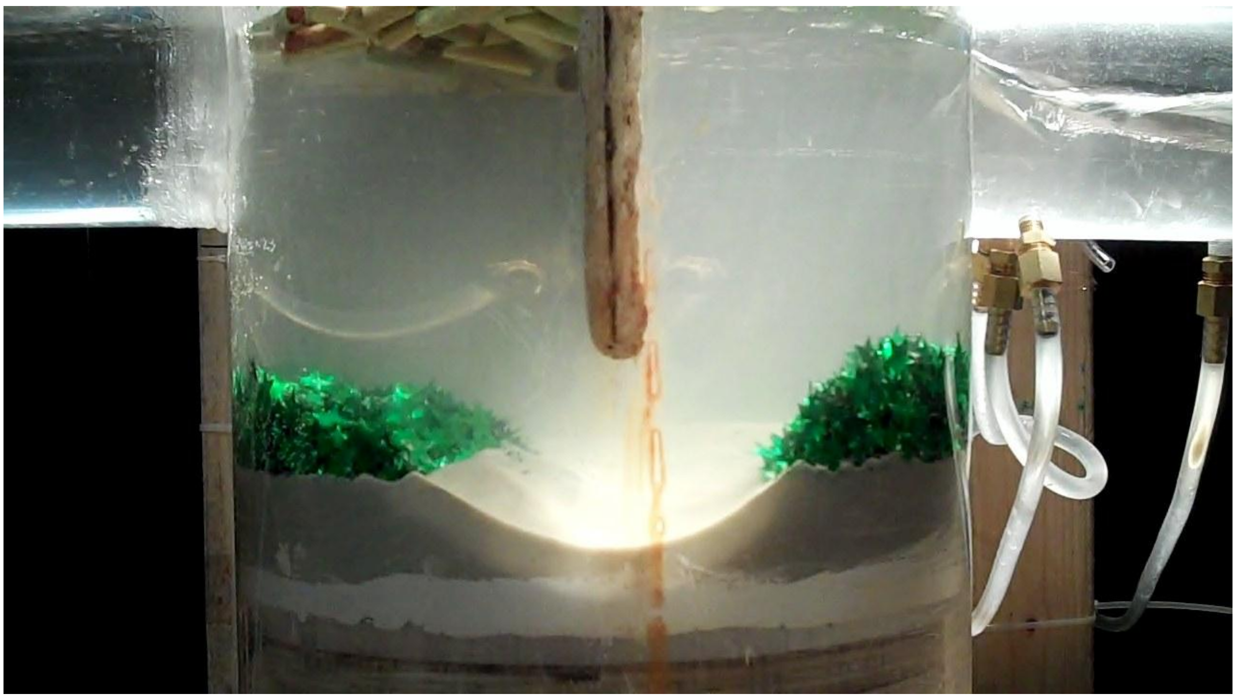

Figure 2-7: The final seconds of Washout Test 1 on the 1×0.5 model. Water is flowing from left to right.

Test 2 (Figure 2-8) was performed with the same conditions as Test 1, but no debris was loaded into the sump. The effluent concentration was measured to be 6 mg/L (0.0037 lb/ft^3) , meaning that little washout occurred. Test 3 was performed with the same conditions as Tests 1 and 2, but 50% of 319 g (11.3 oz) of debris was loaded during the loading phase. The effluent concentration for this test was measured to be 27 mg/L (0.0017 lb/ft^3).

Figure 2-8: 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 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 (1.9 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 12 mg/L (0.00075 lb/ft^3). Finally, Test 5 was conducted with the same parameters as Tests 1 and 4, but made use of a 0.5-in (1.3 cm) hole SAFL Baffle installed at an angle. Figure 2-9 shows snapshots from the final seconds of washout testing of Tests 4 and 5.

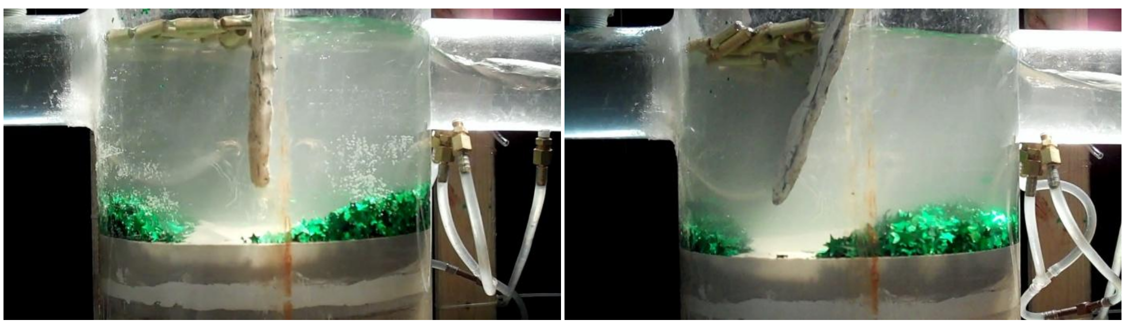

Figure 2-9: The final seconds of Washout Tests 4 and 5 on the 1×0.5 model. Water is flowing from left to right.

Table 2-6 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 319 g (11.3 oz) of debris was 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 2-9.

Table 2-6: 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

2.5 Full Scale Results

2.5.1 Washout Testing

Three tests were conducted on the 6×3, shallow sump using combinations of plastic grocery bags, plastic bottles, and tree leaves. Test 1 had a loading flow rate equal to 1.5 cfs (42.5 L/s), whereas Tests 2 and 3 had a loading flow rate equal to 0.73 cfs (20.7 L/s). All three tests had an average washout flow rate of 6.9 cfs (195.4 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 (1453 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 1305 mg/L (0.081 lb/ft^3). Figures 2-10 and 2-11 show the loading and washout phases of Test 1, as well as evidence of sediment washout in the sump.

Figure 2-10: (Left) Loading phase of Test 1. (Right) Washout phase of Test 1. The flow is from right to left.

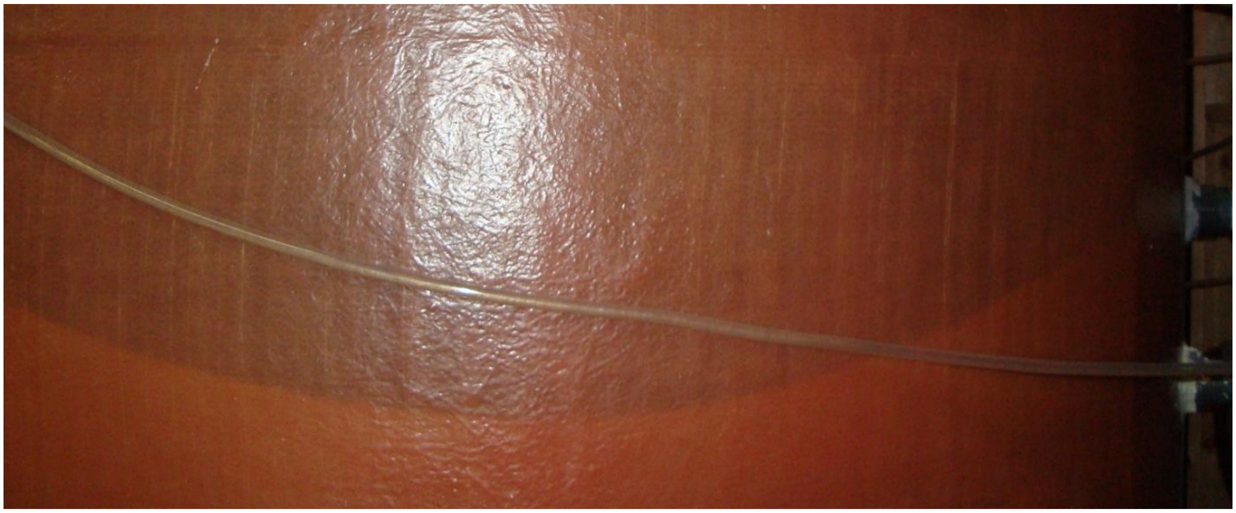

Figure 2-11: The once level sediment bed, shown drastically altered after Test 1. View from outside of the sump.

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 (1095 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 (195.4 L/s) for the washout phase, leaves downstream of the baffle began exiting the sump, and leaves upstream of the baffle traveled underneath of it 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 1003 mg/L (0.063 lb/ft^3). Figures 2-9 and 2-

10 show the clogging due to the debris mixture during the loading phase and the remaining debris during the washout phase.

Figure 2-7: (Left) Loading phase of Test 2. (Right) Washout phase of Test 2. The water flow is from right to left.

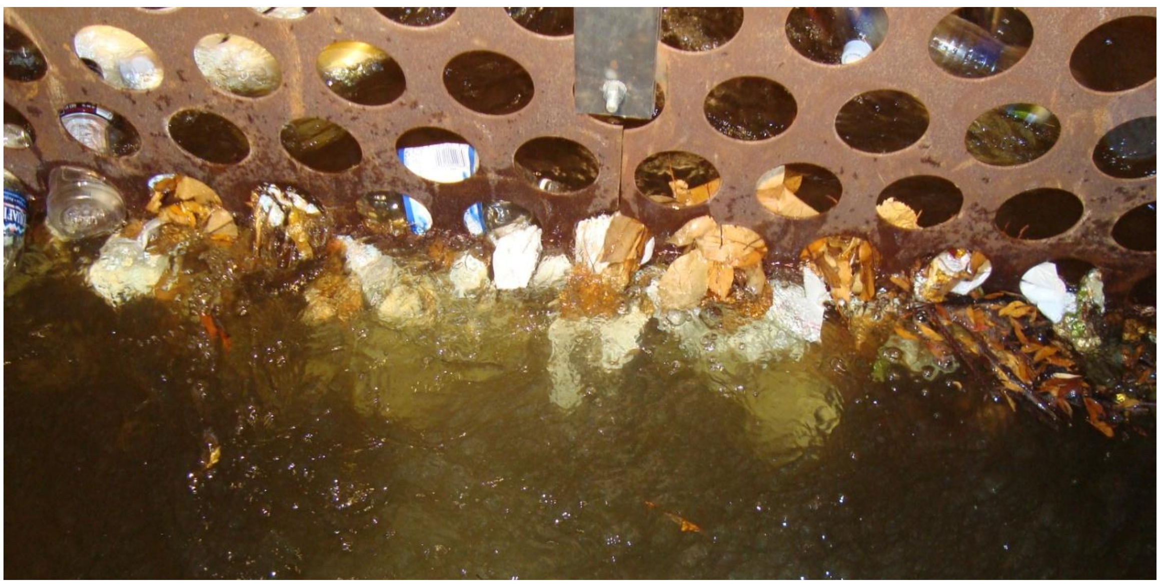

Figure 2-8: Debris stuck in the SAFL Baffle during Test 2. The view is from near the outlet pipe, looking upstream.

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 (1006 kg) of sediment in the sump. The 21 lbs (9.5 kg) of leaves quickly filled the space upstream of the baffle (Figure 2-11). Some leaves traveled through the baffle and under the baffle during the loading phase, and most did not leave the sump.

Figure 2-9: Test 2 from the 6×3 washout testing series during its loading phase. The view is from near the outlet pipe, looking upstream.

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 2-12 shows water traveling through the baffle, despite it partially being clogged with leaf debris.

Figure 2-10: Test 2 from the 6×3 washout testing series during its washout phase. The view is from near the outlet pipe, looking upstream.

Table 2-7 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 2-7: 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, shallow sump (Figure 2-13). These tests utilized vinyl leaves as the simulated debris. All of these tests had loading rates equal to around 0.75 cfs (21.2 L/s), debris loadings equal to 65 lbs (29.5 kg), and initial sediment levels near 3000 lbs (1361 kg). Washout phase flow rates ranged from 2 to 7 cfs (57 to 198 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 3-in (7.6 cm) diameter baffle in a circular pattern directly in line with the inlet pipe (Figure 2-13). The majority of leaves that hit the baffle slowly sank to the bottom of the sump. For the final five tests, with the 5-in (12.7 cm) diameter SAFL Baffle, the clogged area due to vinyl leaves was smaller.

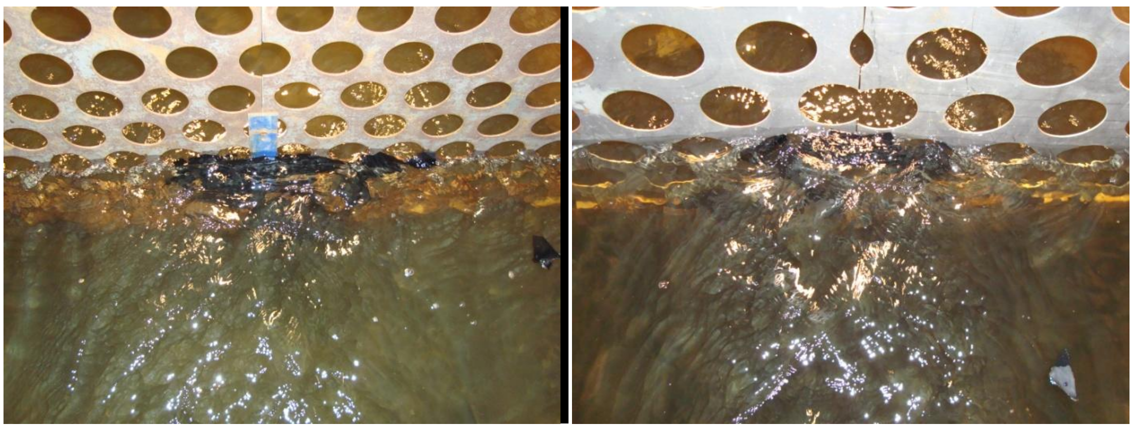

Figure 2-11: (Left) The clogging pattern for vinyl leaves on the 3-inch hole diameter SAFL Baffle and (Right) on the 5-inch hole diameter SAFL Baffle. These views are from above the inlet pipe, looking downstream.

Results for the 6×3 washout testing series with vinyl leaves are shown in Figure 2-14. Flow rates around 4 cfs (113 L/s) exhibited higher washout rates than flow rates near 7 cfs (198 L/s). This may have occurred because nearly all vinyl leaves are washed off of the baffle at flow rates higher than 4 cfs (113 L/s). At 4 cfs (113 L/s), 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 interact with the sediment bed, causing washout. And at flow rates around 2 cfs (56.6 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 2-14 shows these two data points on the same chart as the 6×3 washout test series with vinyl leaves.

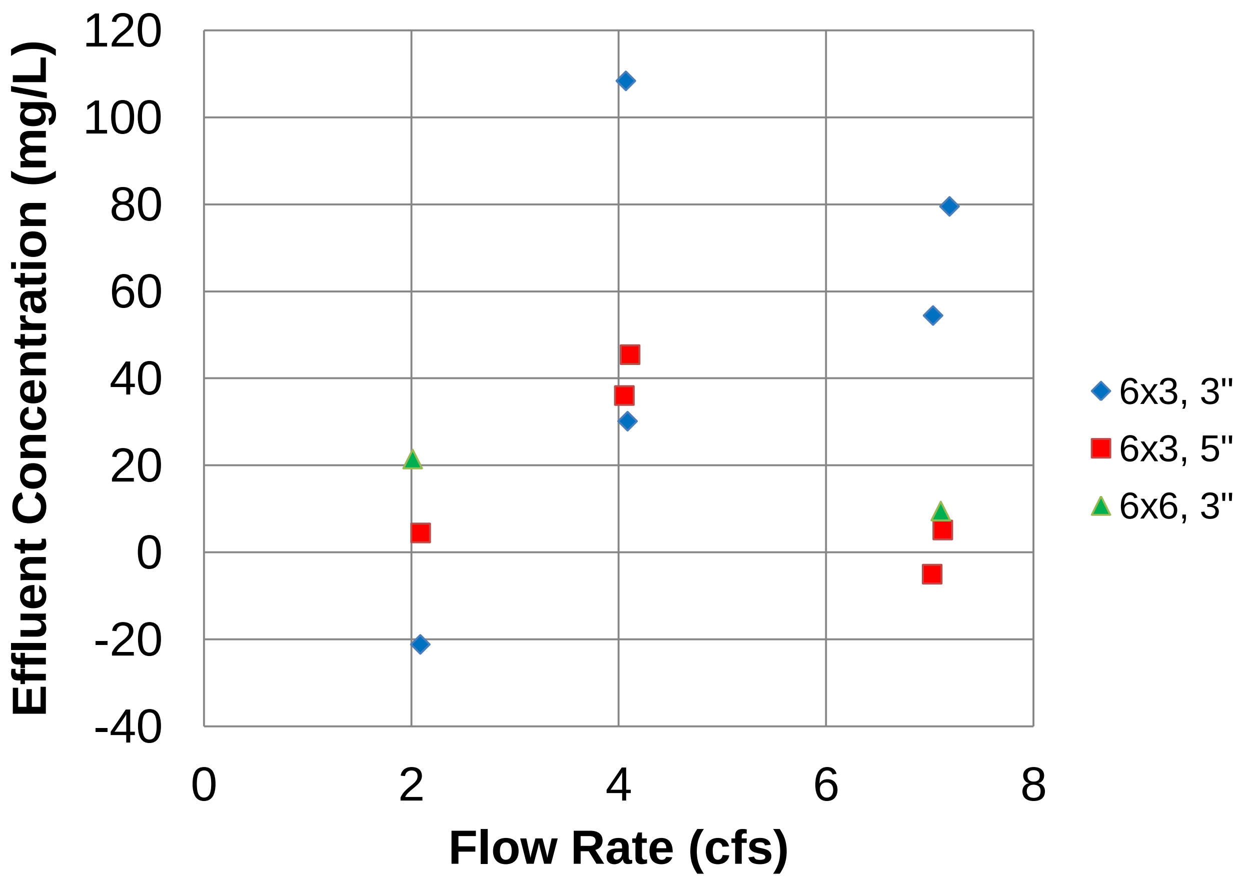

Figure 2-12: Summary of washout tests conducted on 6-ft sumps with 3-inch and 5-inch hole SAFL Baffles clogged with debris

Figure 2-14 indicates that when the 6×6 sump equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle clogged with debris, it would exhibit little washout. Flow rates as high as 7 cfs (198 L/s) would not cause washout with an effluent concentration greater than 20 mg/L (0.0012 lb/ft^3).

In comparison, the 6×3 sump equipped with the same 3-in (7.6 cm) hole SAFL Baffle exhibited higher washout. The maximum recorded effluent concentration occurred at 4 cfs (113 L/s) and was roughly 110 mg/L (0.0069 lb/ft^3). At a higher flow rate of about 7 cfs (198 L/s), the effluent concentration was between 58-80 mg/L (0.0031-0.005 lb/ft^3). This confirms that flow rates above 4 cfs (113 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 were not able to readily clog the baffle, and washout remained at low levels. The maximum effluent concentration for this setup occurred at 4 cfs (113 L/s), and was roughly 50 mg/L (0.0031 lb/ft^3). Again, this indicated that debris clogging was at a maximum around 4 cfs (113 L/s), and flow rates higher than this self cleaned the SAFL Baffle.

2.5.2 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 2-15 and 2-16 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. In addition to this data, Figures 2-15 and 2-16 show Howard et al. 2011's data for standard sumps equipped with a SAFL Baffle that receive no debris. Their data is represented by the category called 3" SAFL Baffle - No Debris.

Howard et al. 2011 showed that the Peclet number (Pe) (Equation 2-1) versus removal efficiency and the Peclet number divided by the Froude jet velocity squared (Equation 2-2) versus removal efficiency accurately represent the sediment removal performance of sumps and sumps installed with a SAFL Baffle. Pe/F_j^2 is a better parameter for showing the performance of standard sumps, but Pe is used to characterize the performance of hydrodynamic separators (Wilson et al. 2009). Low Peclet (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 Peclet and Pe/Fr_j^2 numbers correspond to large sediment particles, low flow rates, large diameter sump manholes, and deep sump manholes.

$$Pe = \frac{v_s * h * D}{Q} \quad (2\text{-}1)$$

$Where$:

$v_s = settling\ velocity\ of\ sediment\ particles$

$h = sump\ depth$

$D = sump\ diameter$

$Q = flow\ rate\ entering\ sump$

$${Fr_j}^2 = \frac{U^2}{gD} \quad (2\text{-}2)$$

$Where$:

$U = velocity\ of\ waterjet\ entering\ the\ sump$

$g = acceleration\ of\ gravity$

$D = sump\ diameter$

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 (29.5 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.

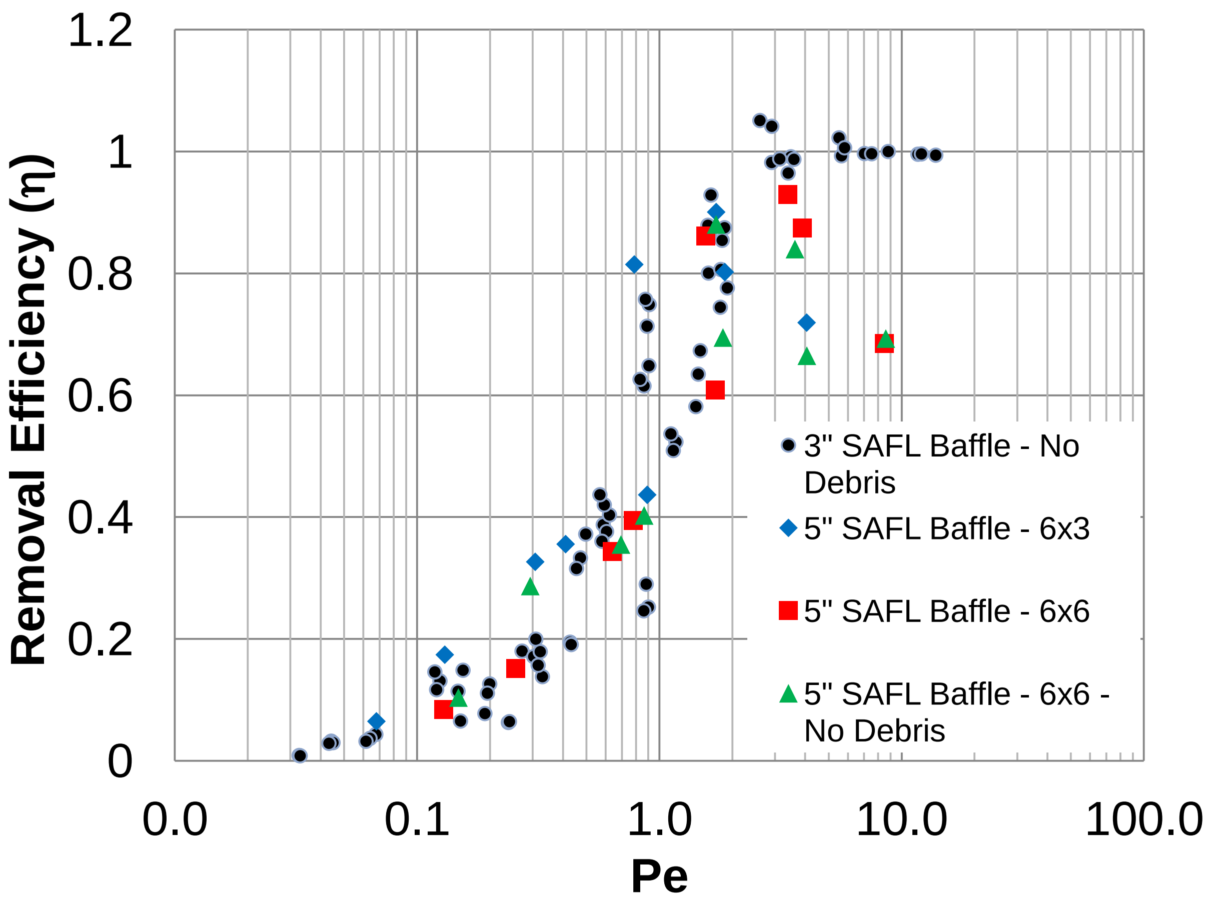

Figure 2-13: Removal Efficiency of debris loaded 6×3 and 6×6 sump manholes equipped with a 5-inch hole diameter SAFL Baffle versus the Péclet number

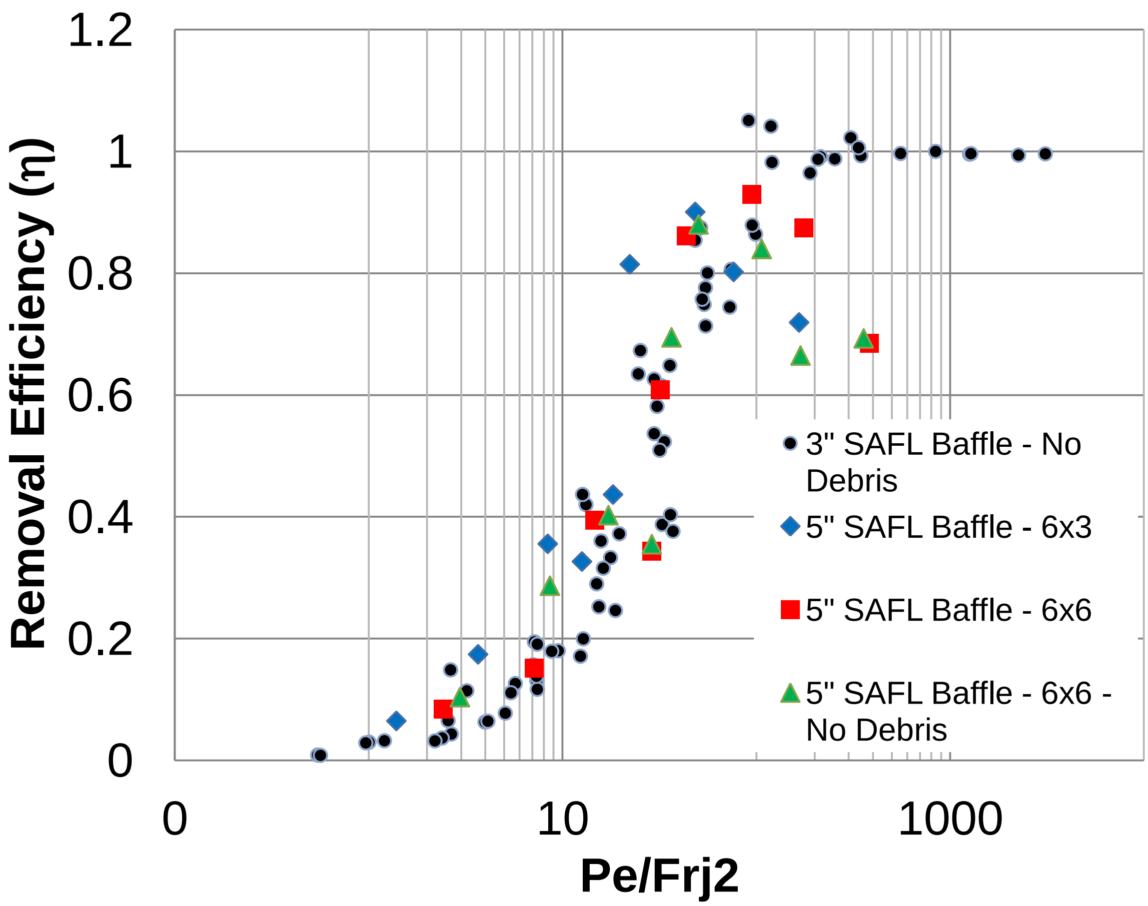

Figure 2-14: Removal Efficiency of debris loaded 6×3 and 6×6 sump manholes equipped with a 5-inch hole diameter SAFL Baffle versus Pe/F_j^2

3. Sumps with 90 Degree Outlets

Tests were run to understand how sumps with 90 degree outlets perform when installed with a 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 (1.8 m) diameter sump scale.

3.1 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. For the remainder of this report, these systems are referred to as the 6×6-90 Degree Outlet sump and 1×1-90 Degree Outlet sump. Figure 3-1 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.

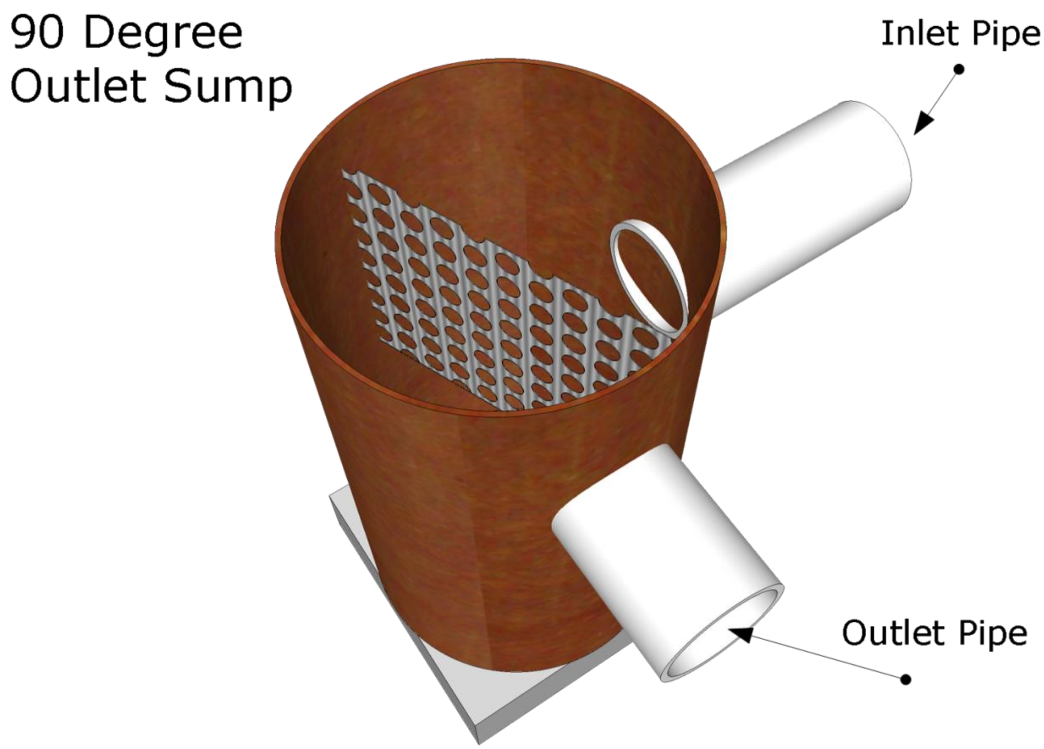

Figure 3-1: A plan view of the 1×1-90 Degree Outlet sump without a SAFL Baffle

3.2 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 debris tests, but without debris loading. Removal efficiency testing was conducted on the 6×6-90 Degree Outlet sump only, and was conducted with a similar procedure to previous debris removal efficiency tests, but without debris loading.

3.3 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 the 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 (1.3 cm) hole (3-in (7.6 cm) in the 6×6 scale) 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 3-2.

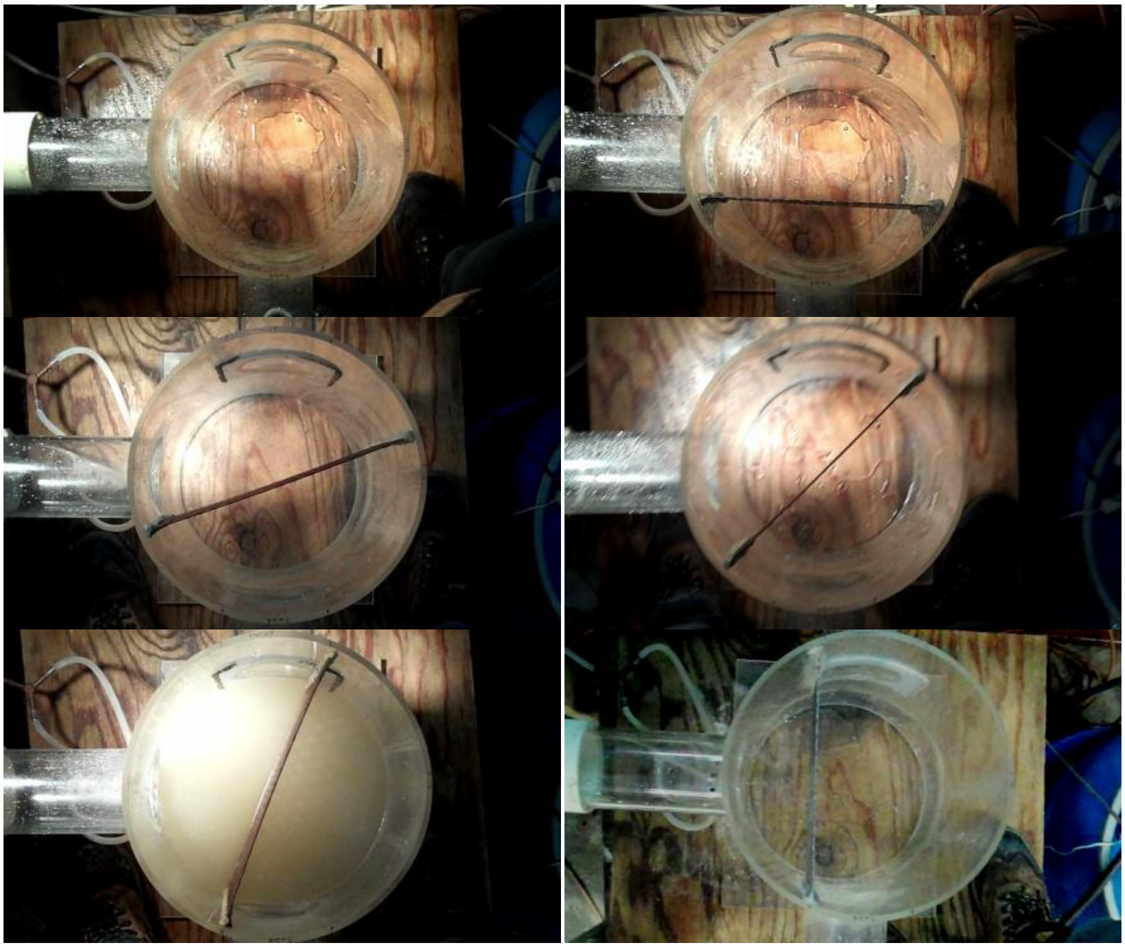

Figure 3-2: 1×1-90 Degree Outlet Washout Testing configurations shown in plan view. (From left to right and top to bottom) No SAFL Baffle, SAFL Baffle oriented at 90 degrees, 112.5 degrees, 135 degrees, 157.5 degrees, and 180 degrees.

Test 1 exhibited the highest amount of washout with an effluent concentration of 1035 mg/L (0.065 lb/ft^3). This indicates that 90 degree outlet sumps exhibit significant washout when a SAFL Baffle is not installed. Figure 3-3 shows the sediment bed 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 18 mg/L (0.0011 lb/ft^3).

Figure 3-3: 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, with 19 mg/L (0.0012 lb/ft^3). Table 3-1 summarizes the results of all six of the washout tests.

Table 3-1: 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 3-4 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.

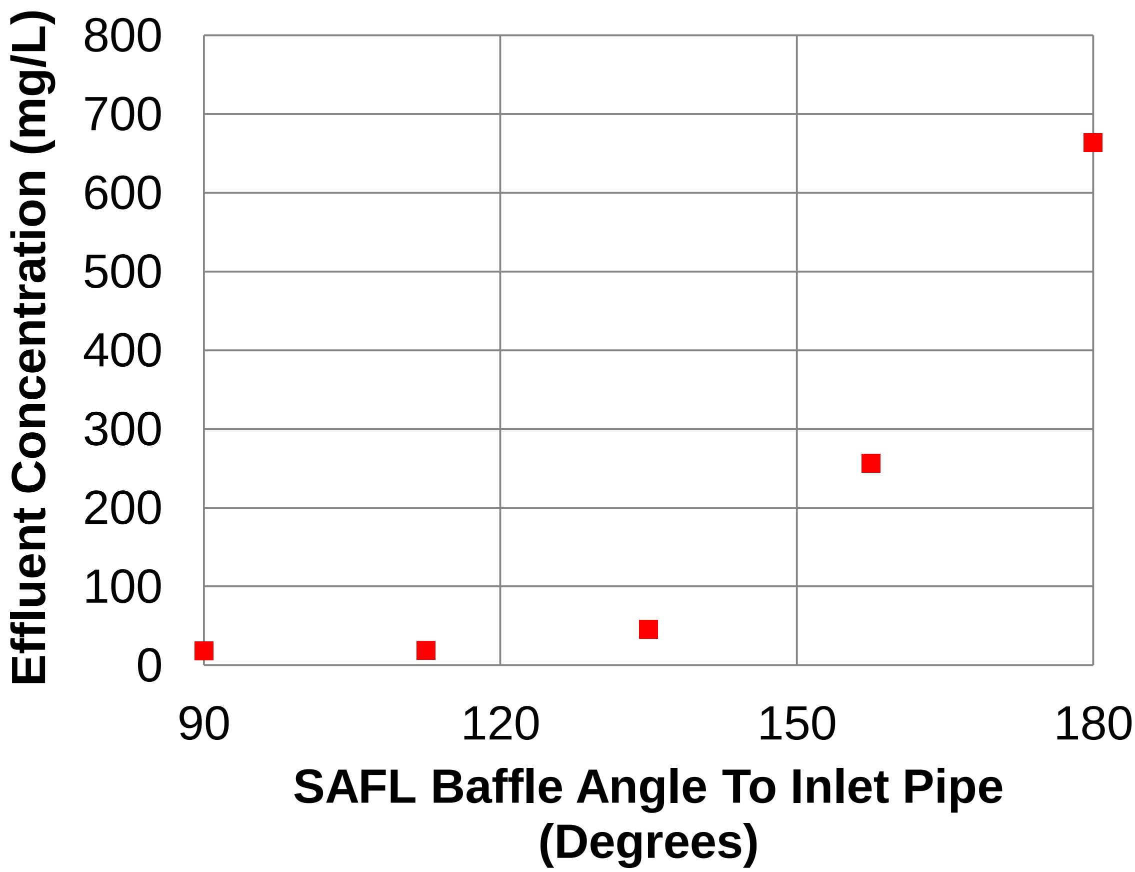

Figure 3-4: 1×1-90 Degree Outlet Washout Testing Summary

3.4 Full Scale Results

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 and removal efficiency testing series.

3.4.1 Washout Testing

Nine washout tests were conducted on the 6×6-90 Degree Outlet sump. 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 3-5 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 (0.0039 lb/ft^3) at 12.7 cfs (359.6 L/s) for Test 8. Effluent concentrations were roughly negligible at 5 cfs (141.6 L/s), and most effluent concentrations were near 50 mg/L (0.0031 lb/ft^3) between 7 and 13 cfs (198 and 368 L/s).

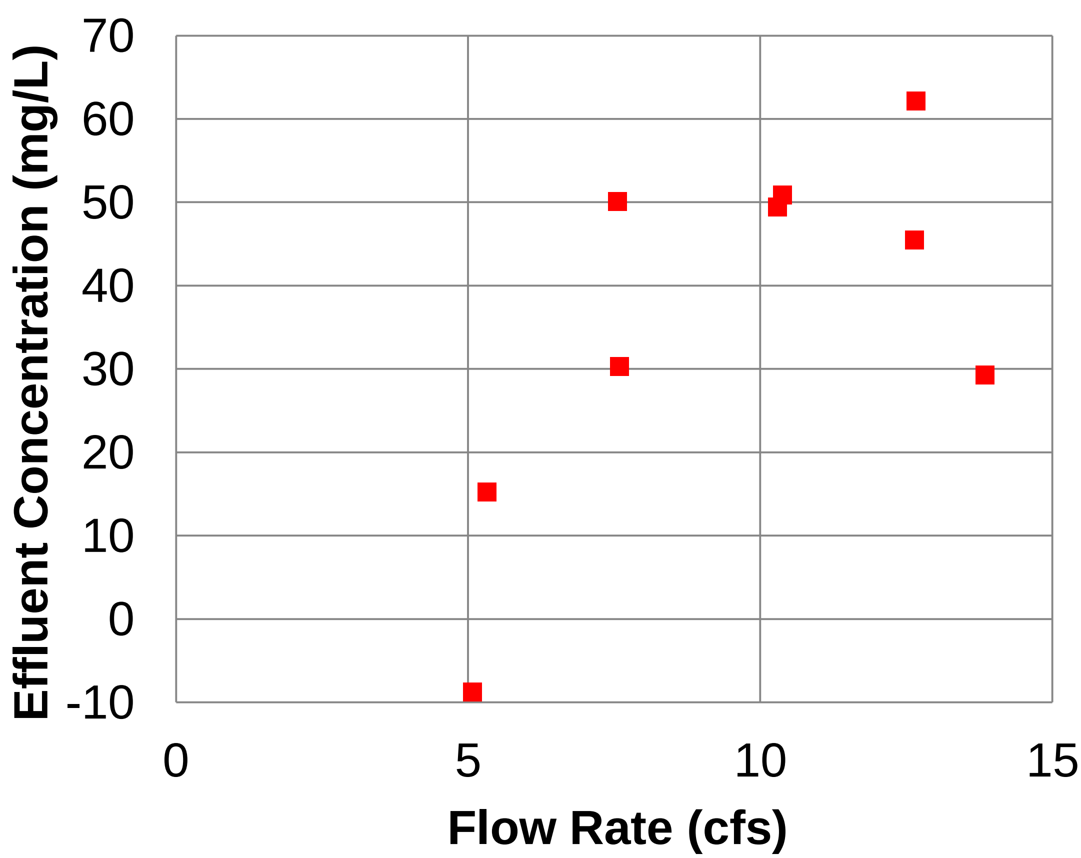

Figure 3-5: 6×6-90 Degree Outlet Testing Summary

3.4.2 Removal Efficiency Testing

Removal efficiency tests were conducted on the 6×6-90 Degree Outlet sump. Tests were performed at flow rates between 0.4 and 9.3 cfs (11.6 and 264 L/s), for durations between 11 and 83 minutes.

Figures 3-6 and 3-7 show the performance of this setup in comparison to the straight flow-through standard sumps with a SAFL Baffle (Howard et al. 2011) using dimensionless parameters Pe and Pe/F_j^2. The majority of the data for the 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.

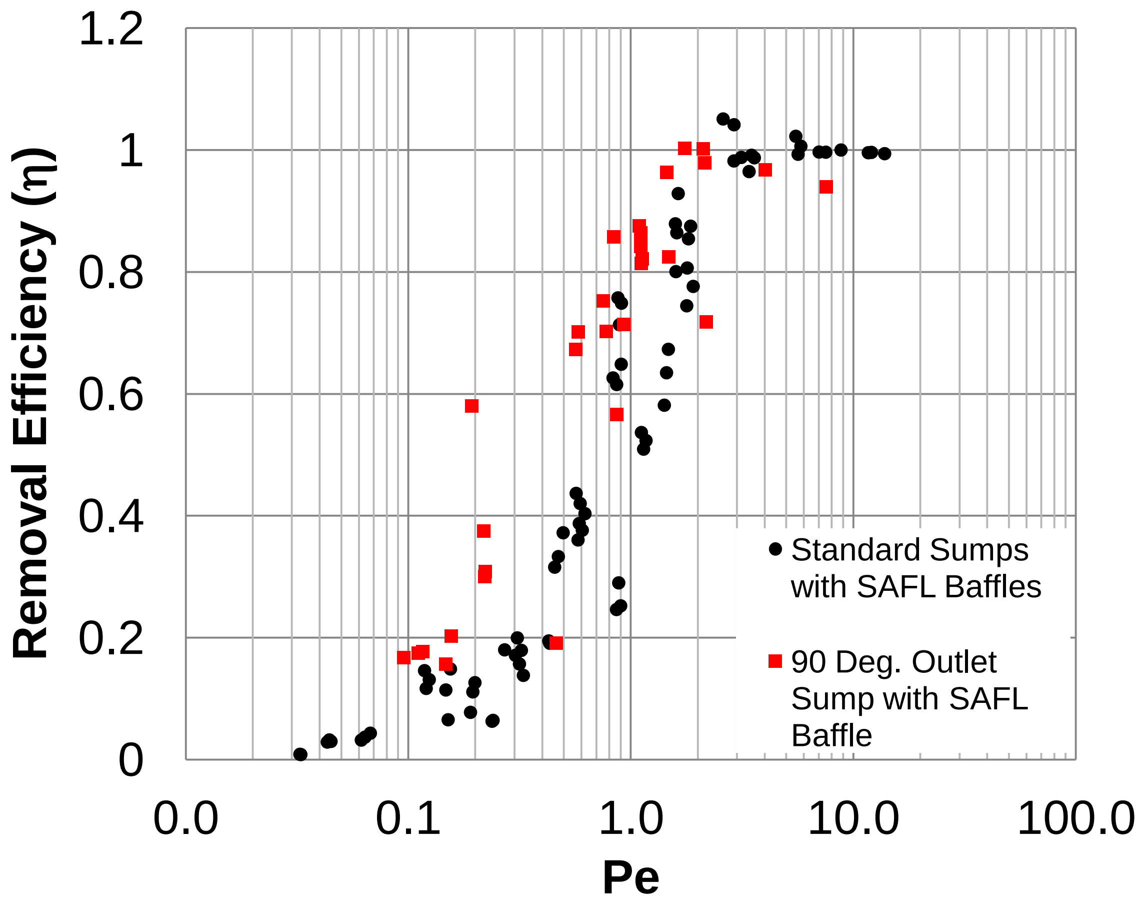

Figure 3-6: Removal Efficiency a 6×6 sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle that is installed at an angle 112.5 degrees relative to the inlet pipe versus the Péclet number

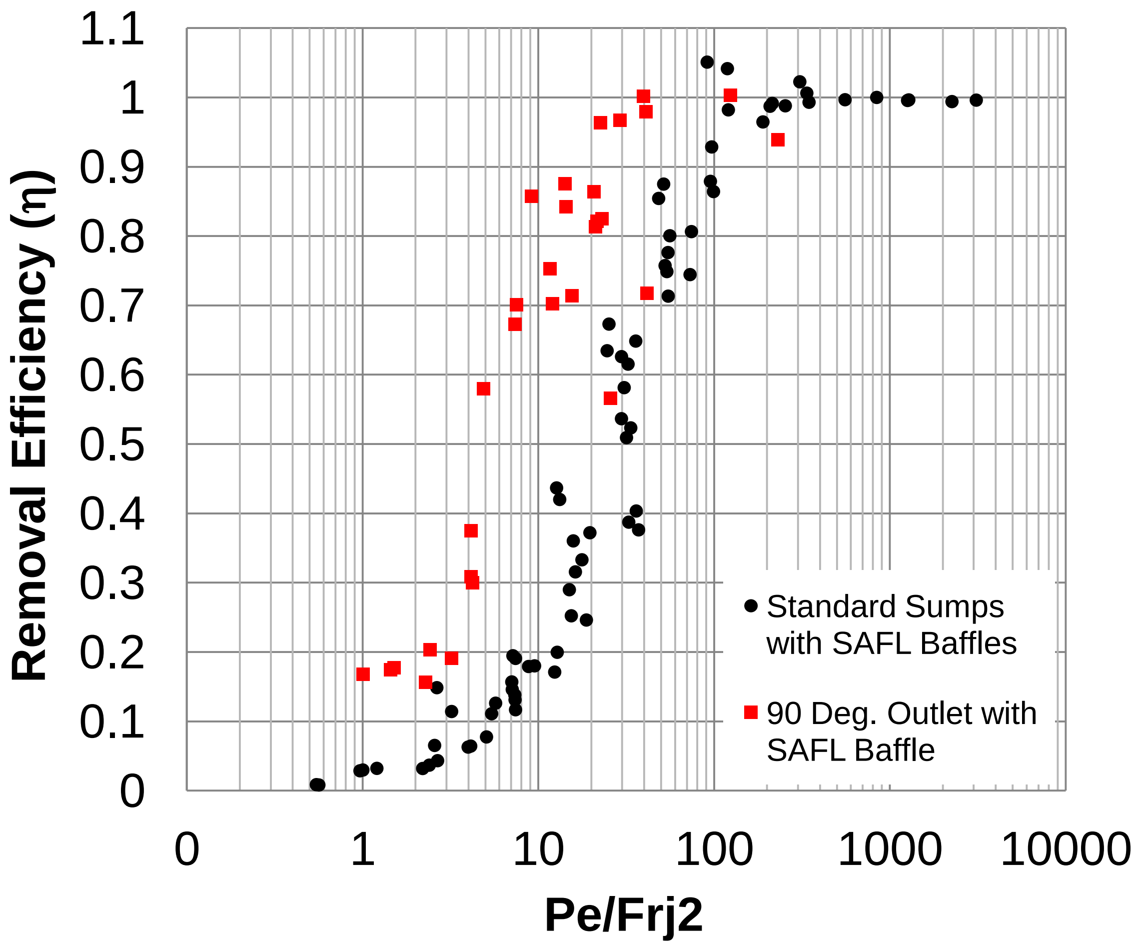

Figure 3-7: Removal Efficiency a 6×6 sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle that is installed at an angle 112.5 degrees relative to the inlet pipe versus Pe/F_j^2

4. Sumps with Inlet Grates

4.1 Experimental Setup

To represent sump manholes that receive water from an inlet pipe and an inlet grate, a system was created using the 6×6 sump. A platform was built around the 6×6 sump and a simulated road surface was installed on top of the platform (Figure 4-1). 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. The simulated road surface had a gutter transverse slope of 6.3%, a street transverse slope of 3.9%, and a longitudinal slope of 1%. From there, water traveled on the road surface to a Minnesota Department of Transportation 816 inlet grate, where it flows through a free fall into the sump. Water exited the system through the outlet pipe that was located 180 degrees to the inlet pipe, i.e. the test was conducted a straight flow-through sump.

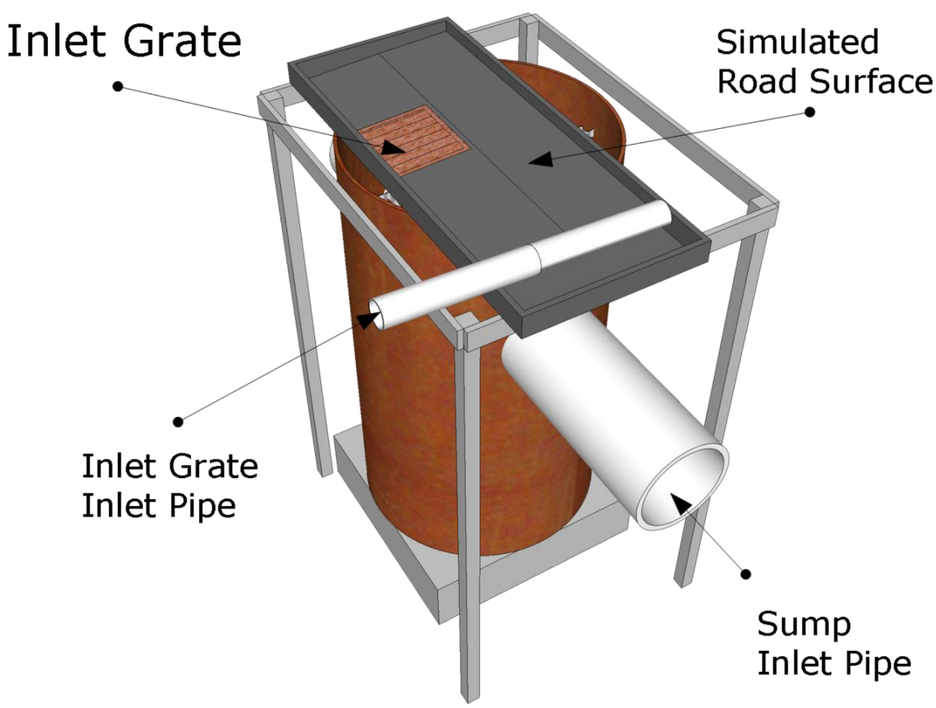

Figure 4-1: A 3D rendering of the 6×6 sump with an elevated road surface and inlet grate laboratory testing setup

4.2 Testing Procedure

Washout tests were conducted on the 6×6 Inlet Grate sump manhole system similar to the 90 Degree 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 the previous removal efficiency tests, but sediment was also added as a slurry through an inlet grate. This means that the same three sediment particle distributions (88-125 μm, 250-355 μm, and 500-589 μm) (0.0035-0.0049-in, 0.0098-0.014-in, and 0.020-0.023-in) were fed into the inlet pipe of the sump as well as the inlet grate at concentrations ranging from 100-200 mg/L (0.0062-0.0012 lb/ft^3). The flow rate through the inlet grate was 0.4 cfs (11.3 L/s).

For both testing series, a 3-in (7.6 cm) hole diameter SAFL Baffle was installed into the 6×6 straight flow-through sump manhole.

4.3.1 Washout Testing

Eleven washout tests were conducted on the 6×6 Inlet Grate sump system. 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 a duration 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 4-2 shows the results of washout testing 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 73 mg/L (0.0046 lb/ft^3) when no 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.

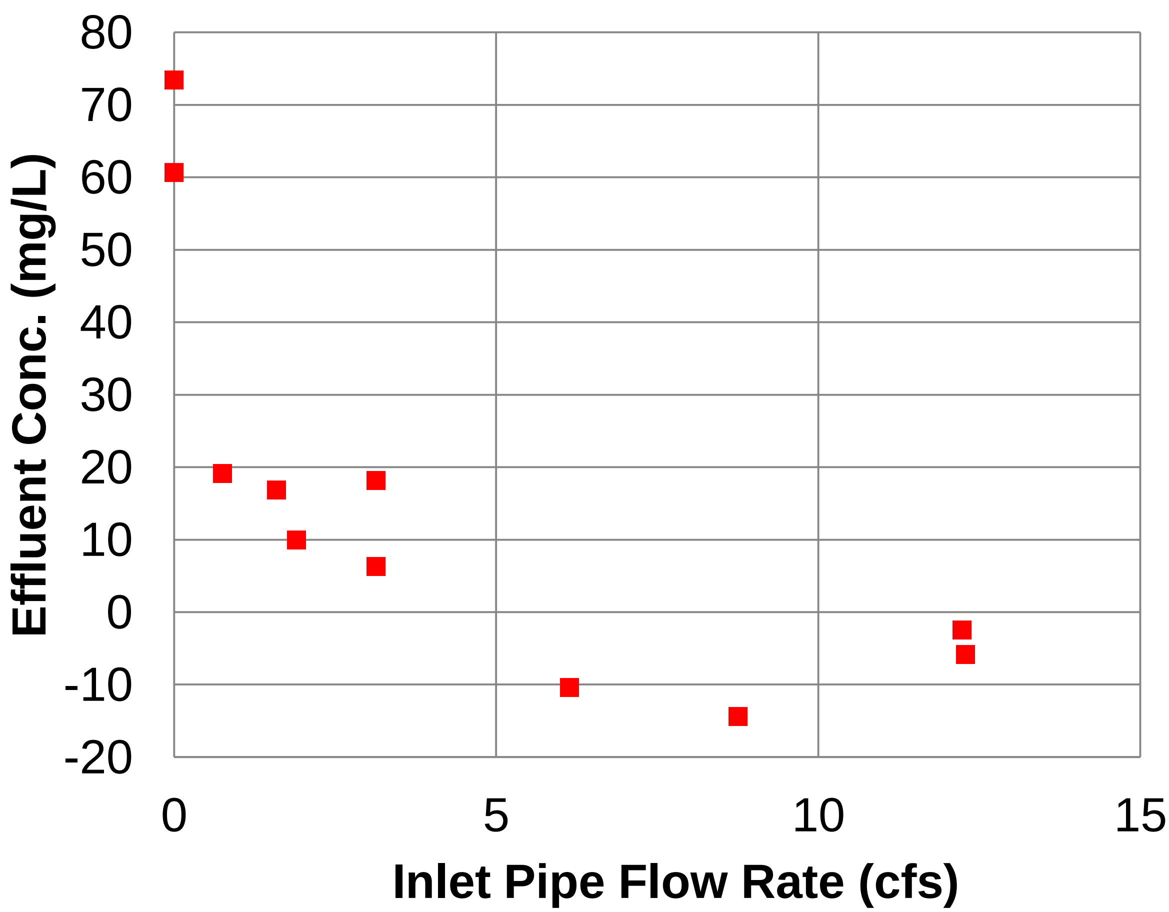

Figure 4-2: 6×6-Inlet Grate Washout Testing Summary

4.3.2 Removal Efficiency Testing

Removal efficiency testing 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 4-3 and 4-4 show the removal efficiency performance of this setup using the dimensionless parameters Pe and Pe/F_j^2. Again, the inlet grate data is compared to Howard et al. 2011's standard sump data. In Figure 4-3, the removal efficiency data obtained for this setup more or less lay on the same curve obtained for the straight flow-through sumps with the SAFL Baffle and no inlet grate. This is not true for Figure 4-4, where two clusters of data do not land on the standard sumps with the SAFL Baffle and no inlet grate (Howard et al 2011's data). The lower cluster represents data points from the smallest sediment size (88-125 μm) (0.0035-0.0049-in) at the lowest inlet pipe flow rate. Similarly, the second cluster of data points represents the medium sediment size (250-355 μm) (0.0098-0.014-in) 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 4-4 is a good indicator of how an inlet grate impacts the flow patterns in a sump with the SAFL Baffle. From Figure 4-4, 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 350 μm (0.014-in) 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.

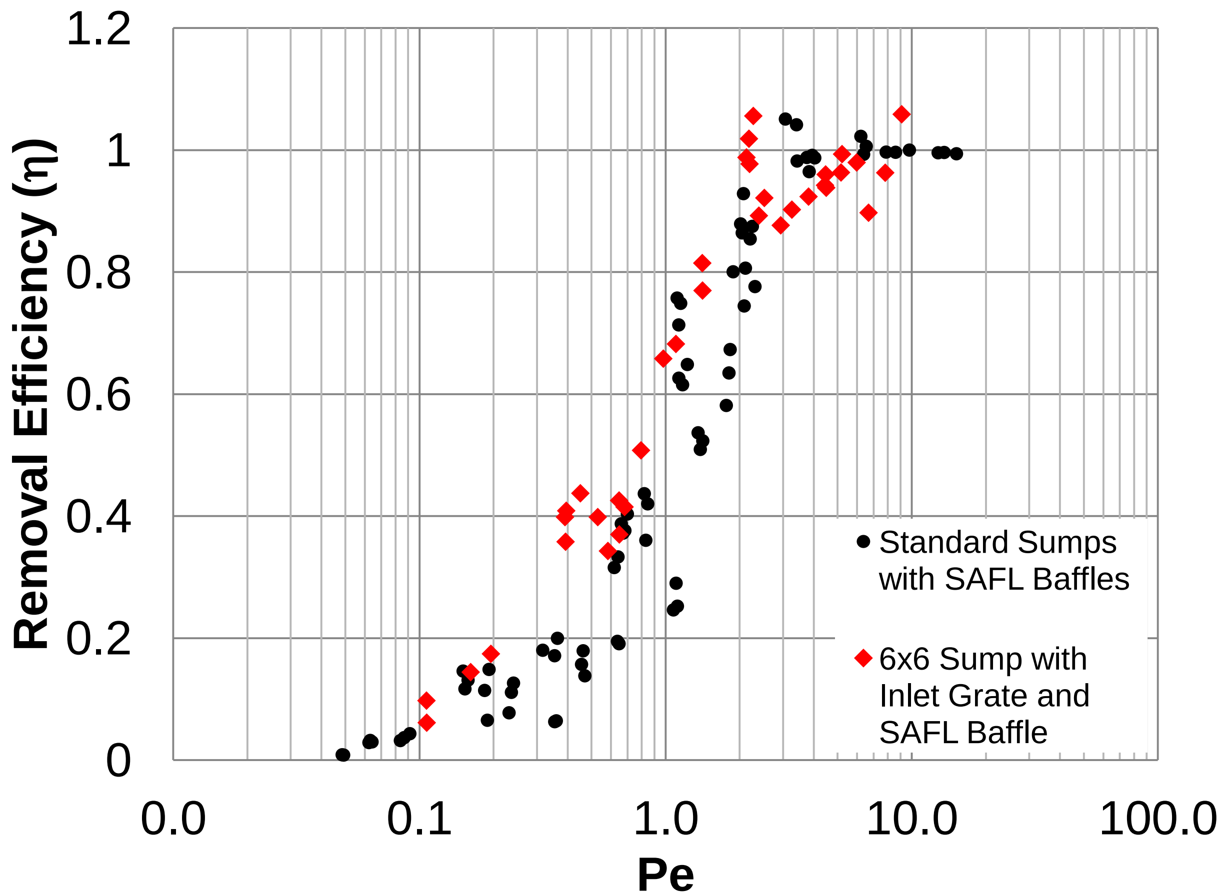

Figure 4-3: Removal Efficiency of a 6×6 Inlet Grate sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle versus the Péclet number

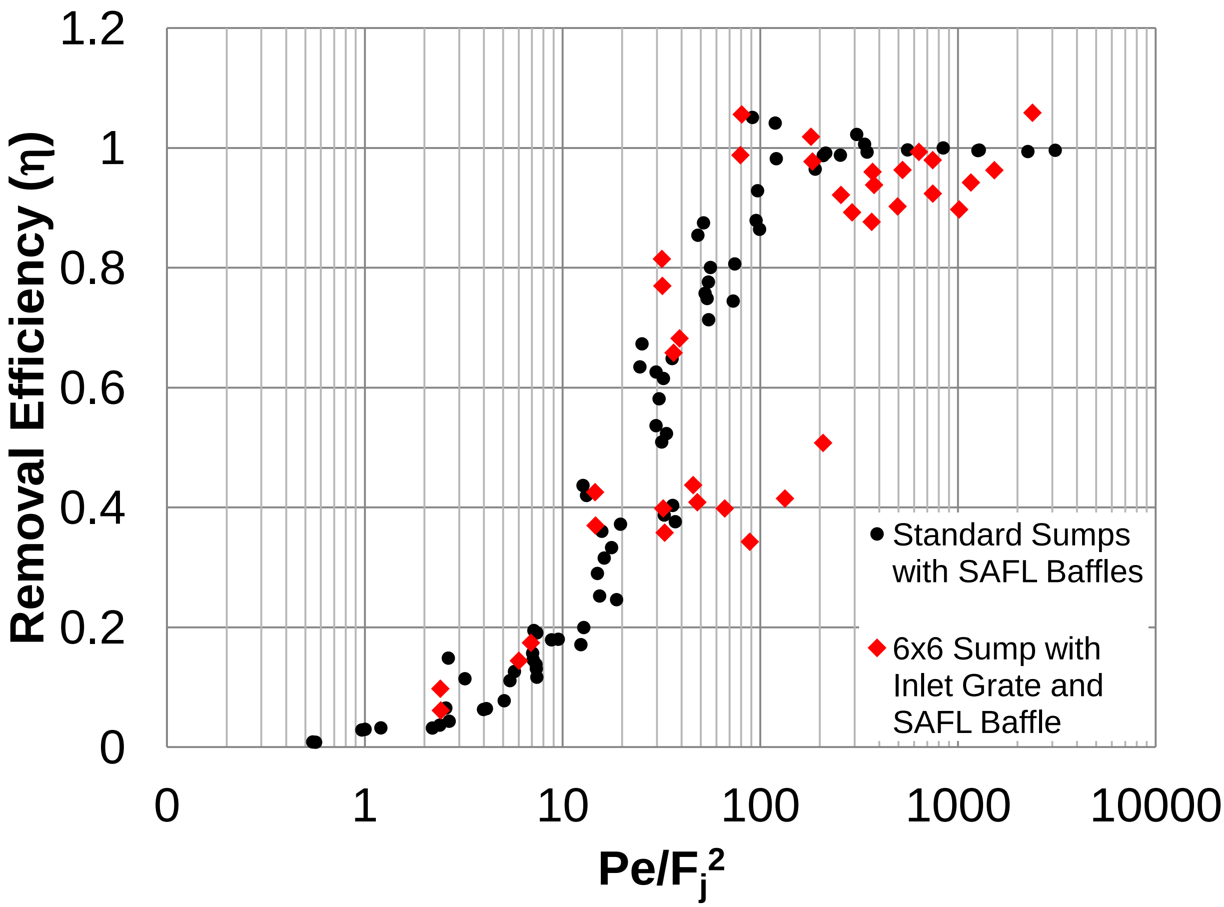

Figure 4-4: Removal Efficiency of a 6×6 Inlet Grate sump manhole equipped with a 3-in (7.6 cm) hole diameter SAFL Baffle versus Pe/F_j^2

5. Head Loss Due to the SAFL Baffle

During removal efficiency and washout testing on the 6-ft (1.8 m) 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 through a sump equipped with a SAFL Baffle using Equation 5-1. 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 conditions at the outlet. Figure 5-1 shows the head loss in a 6×3 sump with and without a SAFL Baffle.

$$h_L = (y_1 - y_2) + (z_1 - z_2) + \left(\frac{{V_1}^2 - {V_2}^2}{2g}\right) \quad (5\text{-}1)$$

Figure 5-1 shows that the SAFL Baffle does not induce a significant head loss at flow rates less than 10 cfs (283 L/s) (the head loss is less than 2-in (5.1 cm)). The head loss becomes significant at very high flow rates, e.g. 15 cfs (424.8 L/s) and more, which are less frequent than a 10-year storm assuming an appropriate design of the system.

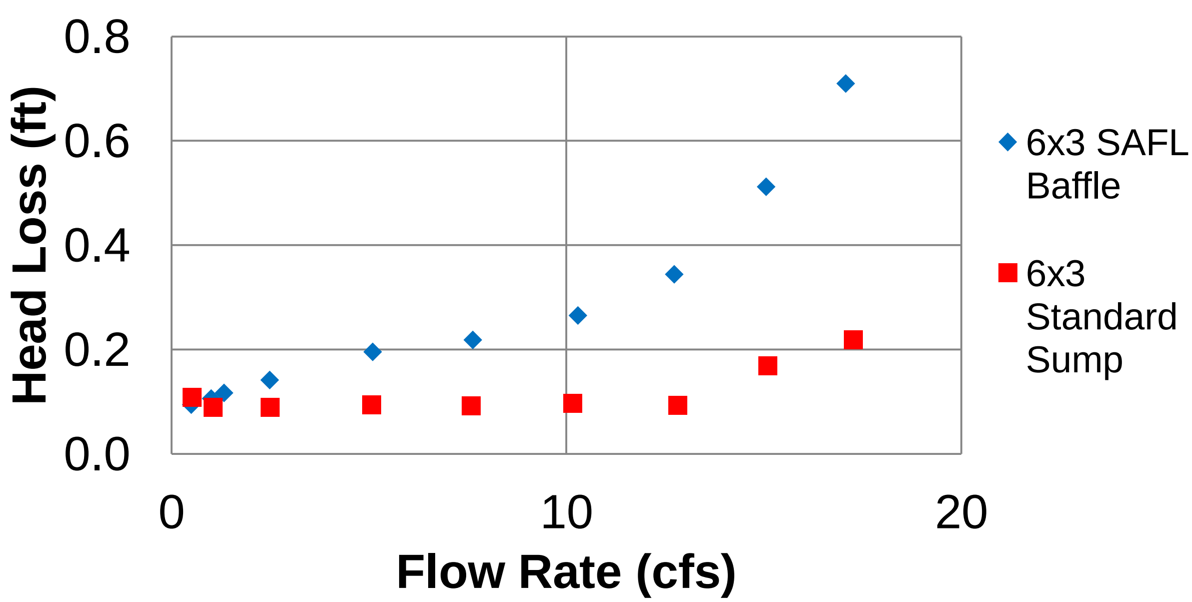

Figure 5-1: Head loss through the 6×3 sump with and without a 3-in (7.6 cm) hole diameter SAFL Baffle. This data was generated with Adam Howard in 2010.

Head loss through the 6×6-90 Degree Outlet sump as a function of discharge is shown in Figure 5-2. At a flow rate of 5 cfs (141.6 L/s), the system head loss is about 0.15-ft (4.6 cm) and at 19 cfs (538 L/s) the head loss becomes 0.26-ft (7.9 cm). From Figure 5-2, 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.

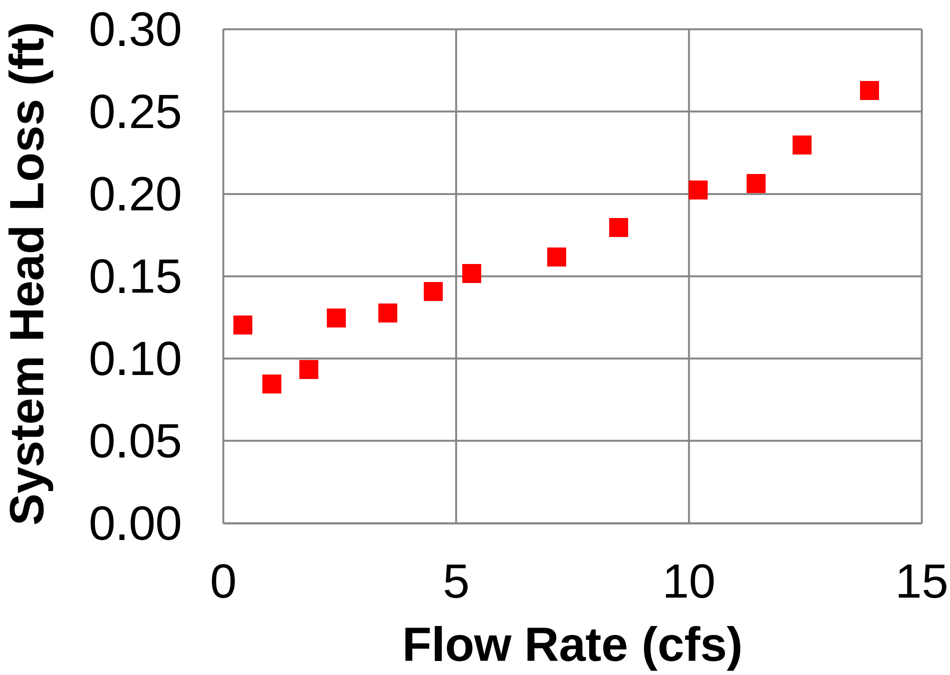

Figure 5-2: Head loss through the 6×6-90 Degree Outlet sump

6. 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 SAFL Baffle (Howard et al. 2011).

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^{o} 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, like the 1×1 and 6×6 laboratory models, exhibited little washout when clogged with debris. This is because water traveled underneath of the baffle when clogged and because of 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, like the 1×0.5 and 6×3 sumps, 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. To mitigate the problem, one option would be to use the SAFL Baffle in deep sumps. 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-inch 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 one, 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 similarly 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.

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