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Performance Assessment of Modified ecoStorm Hydrodynamic Separator

By

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Abstract

Royal Environmental Systems, Inc. requested a series of tests to be conducted on their Model 3 ecoStorm hydrodynamic separator to determine its efficiency in removing suspended solids as well as its scouring potential under high flow conditions. A Model 3 ecoStorm was brought into St. Anthony Falls Laboratory (SAFL) and set up for testing. After conducting a series of tests, Royal Environmental Systems, Inc. modified the Model 3 ecoStorm. The report herein is a summary of the tests conducted at SAFL to determine the removal efficiency and the scouring potential of the Modified Model 3 ecoStorm.

Acknowledgements

The work reported herein was funded by Royal Environmental Systems, Inc. Mr. Jerry Swanson and Mr. Steve Gentry from Royal Environmental Systems, Inc. were the project officers. We would like to thank Matthew Lueker of St. Anthony Falls Laboratory for his contribution to the system set up, instrumentation, and data collection.

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a	slope of the performance function at $Pe = 0$
b	a measure of the sharpness of the performance function curvature
C	concentration
d	particle size
d_{50}	median particle size
D	pipe diameter
D_1	the outer cylinder of ecoStorm
D_2	the inner cylinder of ecoStorm
D_3	the bypass outlet of ecoStorm
f	feed rate
g	gravitational acceleration
h	the height measured from the manhole bed to the invert of the influent pipe
h_0	head of water in the influent pipe
h_1	water surface elevation inside the D_1 manhole
h_2	head of water in the effluent pipe
L', L_1 and L_2	length scales
MHR	maximum hydraulic rate
MD2	the maximum discharge before overtopping the D_2 manhole
Pe	Peclet number
Q	discharge
R	maximum removal efficiency in the performance function
Re_p	particle Reynolds number
V	manhole velocity
V_s	settling velocity
η	removal efficiency
ν	kinematic viscosity
ρ_s	density of solids
ρ	density of water

1. Introduction

In 2006, Royal Environmental Systems, Inc. requested an independent party performance evaluation of the Model 3 ecoStorm hydrodynamic separator in a full-scale laboratory setting. The separator manhole tested was made of fiberglass unlike the manholes installed in the field which are made of concrete. The scope of the laboratory testing was to determine its maximum hydraulic rate, to assess the sediment removal efficiency of the unit, and to determine the performance of the system against scouring. The maximum hydraulic rate (MHR) is the maximum flow passing through the system without any overflow from the manhole. After a series of tests conducted on the Model 3 ecoStorm, Royal Environmental Systems, Inc. decided to modify the design and to assess the modified model.

The modified ecoStorm hydrodynamic separator is an in-line stormwater treatment system for the removal of solids and oil products. The system is comprised of a manhole (D_1) and a second smaller cylinder (D_2) inside the manhole which is designed to remove floatables from stormwater runoff (Figure 1.1). D_3 is a bypass outlet under high flow conditions. The system is designed to remove the suspended solids from stormwater before it enters the second cylinder. A 10-inch wide rectangular weir on the wall of the D_2 passes the flow from the D_1 manhole into the second cylinder. All flows less than the MD2 (maximum discharge before overtopping the manhole D_2) pass through this weir. A flow straightener is installed inside of the D_1 manhole to suppress additional turbulence under the effluent pipe (Figure 1.2). A deflector plate is installed inside the D_1 manhole near the entrance of the influent pipe to establish a circular flow pattern and to prevent short circuiting of the flow (Figure 1.3).

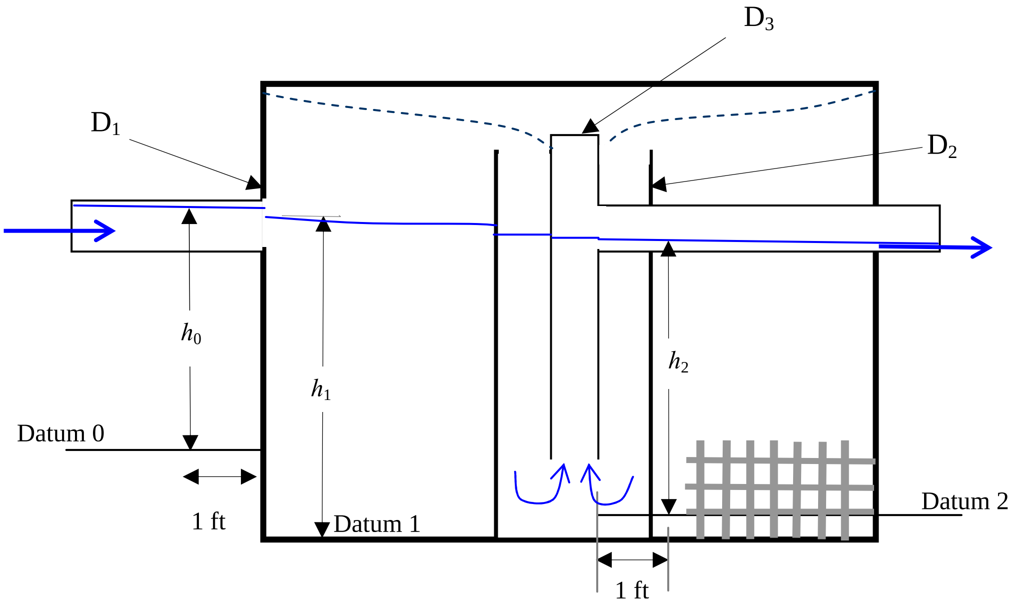

Figure 1.1. Schematic of the Modified Model 3 ecoStorm.

Separation occurs within D_1 by pushing the heavier particles against the outer wall of D_1 while water leaves D_1 through the weir in the D_2 structure. The suspended particles which do not settle out in D_1 are skimmed from the near surface and conveyed into D_2. A vertical pipe is mounted in the center of the D_2 manhole, with an inlet near the bed, and is connected to the effluent pipe allowing floatables to be trapped in D_1 or D_2 (Figure 1.1). High flow velocities near the inlet of the vertical pipe do not allow the suspended solids to settle in the D_2 manhole. As flow exceeds MD2, a portion of stormwater flows over the top edge of D_2 into the D_2 manhole. Under the MHR, most of the flow passes over the top edge of D_2.

This report summarizes the tests and analyses done on the Modified Model 3 ecoStorm. The tests were conducted at St. Anthony Falls Laboratory (SAFL). The test stand is described in section 2, the techniques used to determine the removal efficiency are explained in section 3, the results of the tests performed on the modified design to assess its removal efficiency are presented in section 4 and the scour tests are presented in section 5. The summary is given in section 6.

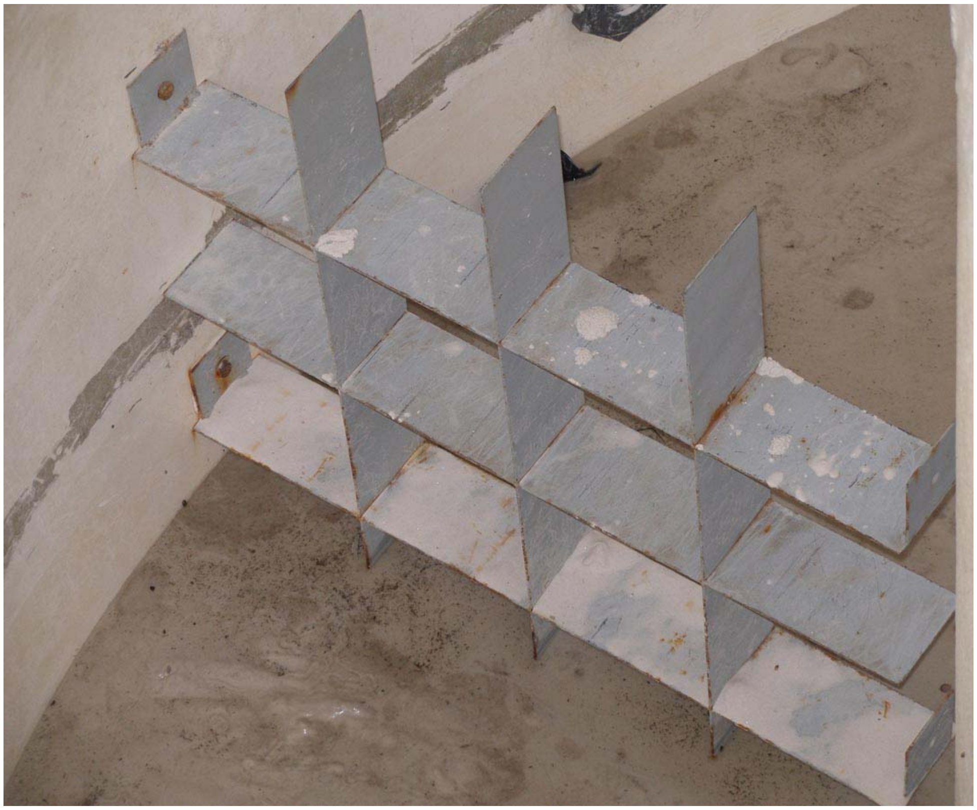

Figure 1.2. The flow straightener for suppressing turbulence installed inside the D_1 manhole underneath the effluent pipe.

Figure 1.3. The diversion plate inside the manhole at the outlet of the influent pipe.

2. Experimental Facility Setup

The test stand was set up on the lowest floor of SAFL. Mississippi River water for the experiment was initially supplied through a single 12-inch diameter pipe with approximately 45 feet of head. The SAFL intake in the Mississippi River is away from the river bed, therefore, the concentration of the suspended sediments is less than 3 mg/l. According to the samples taken from the influent pipe, the background concentration varies between 10 to 30 mg/l with mostly organic materials, which cannot be removed by hydrodynamic separators.

To supply the flow for the scour tests a second 12-inch pipe was connected to the first pipe using a 90-degree tee fitting (Figure 2.1). An expansion was used to convert the 12-inch pipe to a 24-inch pipe. The 24-inch influent pipe was a 20-ft long PVC pipe and was laid at a slope of 1.2% (Figure 2.2). The flow rate for the experiments was controlled using a gate valve and a butterfly valve on the 12-inch supply pipes.

Figure 2.1. The 12-inch supply pipes, the 12 to 24-inch expansion and the control valves of the test stand.

Royal Environmental Systems supplied a Modified Model 3 ecoStorm with fiberglass manholes. The inside diameter of D_1 was 10 feet and the outside diameter of D_2 was 4 feet. The width of the flow path between the D_1 manhole and the D_2 cylinder was 3 feet. .

Total discharge was measured using an orifice plate on one supply pipe and an elbow meter on the second pipe. Pressure taps upstream and downstream of the orifice plate and the elbow were connected to two different Meriam manometers (Figure 2.3).

A sediment feeder was used to control sediment supply rates and concentrations (Figure 2.4). The influent concentrations were also measured by weighing all the sediments fed into the feeder prior to each test, timing the feeding period, and measuring the flow rate.

Figure 2.2. The 24-inch influent pipe and a Modified Model 3 ecoStorm on the Turbine level of SAFL.

Figure 2.3. A Meriam manometer connected to pressure taps mounted on an elbow via plastic tubes.

Figure 2.4. The sediment feeder at the upstream end of the 24-inch influent pipe.

3. Removal Efficiency Measurement Techniques

To determine the solids removal efficiency of the Modified Model 3 ecoStorm, test runs were performed under steady state conditions with relatively constant influent concentrations. In this section, the sediment size distributions used in the experiments and the test procedures are presented.

3.1. Particle Size Distribution

To minimize the errors in the final analysis, only three particle sizes were selected, weighed, mixed and fed into the system for assessing the performance of the Modified Model 3 ecoStorm. The particle sizes were 545, 303 and 107 microns. These particle sizes were obtained by sieving silica sands of different gradations. The 545 micron particles were obtained from particles passed through sieve no. 30 and retained on sieve no. 35, 303 micron particles from sieve nos. 45 and 60, and 107 micron particles from sieve nos. 120 and 170. On average between 20 to 35 lbs (10 to 15 kg) of solids were fed into the system during each test.

3.2. Testing Methodology and Estimating Removal Efficiency

To determine the removal efficiency of the Modified Model 3 ecoStorm under steady state conditions, a known amount of solids was fed into the system at a relatively constant rate. After each test, all solids retained in D_1 were collected using a shop-vac. Based on the tests done at SAFL, collecting the solids removed by a shop-vac has a repeatability of less than 3% and an accuracy of 3%. The ratio of the amount collected to the amount fed gave the removal efficiency.

The flow rates used in these tests were approximately 1.9, 3.4, 4.1, 4.5 and 5.5 cfs. The maximum discharge of the Modified Model 3 ecoStorm before overtopping the D_2 manhole was measured to be 5.5 cfs.

3.2.1. Influent Concentration

The influent solids concentration was controlled by the feed rate of a Schenke Accurate sediment feeder. The solids were fed into the system at the upstream end of the 24-inch PVC pipe. The feed rate of the feeder was determined beforehand by the following formula,

$$f = \frac{28.32QC}{1000} \tag{3.1}$$

where f is the feed rate in grams per second, Q is the target flow rate in cfs, C is the desired concentration in milligrams per liter and 28.32 is a conversion factor.

Through trial and error, the speed of the feeder would be set to match the desired feed rate. This was done by weighing a sample of the desired sediment metered out over a recorded period of time. To verify the average feed rate, before an experiment started, a known mass of solids was weighed and placed in the hopper of the feeder. The period that the feeder operated was recorded. Then any solids remaining in the hopper after the feeder was turned off was weighed. The difference between the two masses gave the total mass that was fed into the system. The ratio of the mass to the recorded period would give the average feed rate, f. Rearranging Equation 3.1, the average influent concentration could be determined as follows:

$$C = \frac{1000f}{28.32Q} \tag{3.2}$$

3.2.2. Estimating Removal Efficiency

Prior to testing, the D_1 manhole was cleaned and vacuumed. After a test ended, i.e. water was shut off, the water in the manhole was allowed to stand for a minimum of 15 minutes to allow any heavy suspended solid to settle out (settling velocity of a 100-micron sand particle is approximately 0.025 fps and would take about 3 minutes to settle in the D_1 manhole). Then the D_1 manhole was drained slowly. The wet solids in the manhole were dried in an oven, sieved and finally weighed. Removal efficiency for a particular solid size was the ratio of the weight of that solid size removed by the D_1 manhole to the weight of the same size solids which were fed into the device during each test.

The removal of suspended solids in ecoStorm or any hydrodynamic separator depends upon two opposing mechanisms: (1) the settling of the solids due to their weight in water, and (2) the resuspension of solids due to turbulence in the manhole. Settling is a function of the viscosity of water and the weight of solids, and the turbulence is a function of the manhole geometry and the flow patterns in the manhole. In order to develop a universal relationship for all ecoStorms, the removal efficiency was plotted versus a Peclet number, which is the ratio of advection (settling) to diffusion (turbulence). Therefore, the Peclet number here is defined as

$$Pe = \frac{V_s \, L_1}{D_t} \tag{3.3}$$

In equation 3.3, Pe is the dimensionless Peclet number, V_s is the settling velocity of a particle (ft/sec), L_1 is a length scale (ft) and D_t is the turbulence diffusion coefficient (ft^2/sec). The settling velocity of a solid particle can be estimated from the Stokes law for low grain Reynolds numbers, i.e. for particles approximately smaller than 100 microns. Cheng (1997) proposed equation 3.4 to estimate the settling velocity for all particle sizes, which is in a very good agreement with measured settling velocities of natural solids of all sizes.

$$V_s = \frac{\nu}{d}\left(\sqrt{25 + 1.2\left(d\left(\frac{g\,\frac{\rho_s - \rho}{\rho}}{\nu^2}\right)^{1/3}\right)^2} - 5\right)^{1.5} \tag{3.4}$$

In equation 3.4, g is gravitational acceleration (ft/sec^2), ρ_s is the density of the particle, ρ is the density of water, d is the particle size, and ν is the kinematic viscosity of water. It is important to note that ρ and ν are both temperature dependent.

Turbulent diffusion can be approximated by

$$D_t = coeff\ U\ L' \propto \frac{Q}{L_2} \tag{3.5}$$

In equation 3.5, U is the flow velocity through the D_1 manhole (settling compartment of ecoStorm), Q is the flow through that compartment, *coeff* is a dimensionless coefficient, and L' and L_2 are length scales. Replacing D_t in the denominator of equation 3.3 by equation 3.5, the following equation can be obtained for the Peclet number.

$$Pe = \frac{V_s\ L_1\ L_2}{Q} \tag{3.6}$$

The length scales L_1 and L_2 represent the geometry of the device and can be assumed constant for the tests conducted, but they change as the ecoStorm model changes. For the Modified Model 3 ecoStorm, L_1 can be set equal to the height of water in the D_1 manhole. If L_1 does not vary significantly under different flow conditions, it is easier to set it equal to the distance from the invert of the orifice/weir on the D_2 manhole to the bottom of the manhole. The parameter L_2 can be set equal to the diameter of a manhole with the surface area of the D_1 manhole. Therefore, L_1 and L_2 were set equal to 5 ft and 9.16 ft, respectively. As the system is filled with solids, L_1 decreases, thus, the Peclet number decreases. If removal efficiency increases as the Peclet number increases and vice versa, then as the system is filled with solids, removal efficiency decreases.

4. Performance Assessment of ecoStorm

A total of 18 tests were conducted to determine the removal efficiency of the Modified Model 3 ecoStorm. The flow rates were 1.9, 3.4, 4.1, 4.5 and 5.5 cfs. The results of these tests are summarized in Table 4.1. Due to the diameter of the influent pipe and the backwater caused by diversion plate, the flow velocity in the influent pipe became low enough to cause deposition along the invert of the pipe (Figure 4.1). Subsequently, some of the solids did not reach the manhole and reduced the amount of solids supplied for each test. If a mix of several particle sizes was used and the amount of deposit for a certain particle size exceeded 10% of the solids fed, the result for that solid size was discarded. The shaded cells in the last column of Table 4.1 show the discarded results.

Test numbers 10 to 12 and 16 to 18 were conducted on a single particle size, e.g. 106.5 microns to avoid any deposition in the influent pipe. The results of the tests summarized in Table 4.1 were used to determine the Peclet numbers of each test for every particle size. Finally, removal efficiencies were plotted against Peclet numbers in Figure 4.2. A three-parameter function was then fitted to the data. The function fitted to the data has a general form as shown in equation 4.1.

$$\eta = \left(\frac{1}{R^b} + \frac{1}{(aPe)^b} \right)^{-\frac{1}{b}} \tag{4.1}$$

In equation 4.1, η is removal efficiency, and a, b and R are three fitted parameters. The parameter a is the slope of the function at $Pe = 0$, R is the maximum efficiency of the device, and b is a measure of the sharpness of the function curvature. The function fitted to the data summarized in Table 4.2 is given in equation 4.2.

$$\eta = \left(\frac{1}{0.905^{2.732}} + \frac{1}{(1.262\, Pe)^{2.732}} \right)^{-\frac{1}{2.732}} \tag{4.2}$$

The Nash-Sutcliff Coefficient goodness of fit and the root mean square error were 0.985 and 0.6%, respectively.

The head loss through the new design was also estimated by measuring pressure heads one foot upstream of the influent pipe, inside the D_1 manhole and one foot downstream of the effluent pipe inlet. The head loss was then estimated using equation 4.3 which is derived from Bernoulli's equation.

$$H_l = h_0 - h_2 + \left(\frac{V_0^2}{2g} - \frac{V_2^2}{2g} \right) \tag{4.3}$$

In equation 4.3, H_l is the device total head loss, h_0 and h_2 are the pressure heads in the influent and effluent pipes, respectively, and V_0 and V_2 are the velocities in the influent and effluent pipes, respectively. The measured data are summarized in Table 4.2. The head loss calculated from equation 4.3 is plotted versus discharge in Figure 4.3. It is important to note that the head loss above 13.2 cfs drops significantly because as water passes the crest of the vertical pipe, D_3, in the center of the D_2 manhole, the flow path for that portion of the flow becomes very short and a significant amount of flow leaves the device through the vertical shaft (Figure 4.4). Therefore, the head loss for the flows above 13 cfs is not plotted in Figure 4.3.

As the amount of flow entering the D_2 manhole from the upper edge of the cylinder exceeds MD2, the character of energy loss through the device changes. Therefore, two different functions were fitted to the data. The upper function is only valid within the range presented. The lower function can be applied with care to the data lower than the range.

The rectangular weir on the D_2 manhole is a sharp-crested weir with an angled approach flow, i.e. it is a side weir. Therefore, the coefficient of discharge used for sharp-crested weirs do not apply to this weir. By utilizing the measured flow one can, however, back calculate the coefficient of discharge for this specific sharp-crested rectangular weir. By doing so, the coefficient of discharge varied from 0.42 to 0.50 which is typical of side-weirs[1].

Normalized head loss using the MD2 is plotted versus flow rate in Figure 4.5. Dimensionless relationships were also developed between the heads in the manhole, inside the influent and effluent pipes and discharge. The results are presented in Figure 4.6.

Figure 4.1. Deposition of the solids in the influent pipe under low flow conditions.

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[1] In these back calculations, the submergence of the weir was taken into account using Villemonte's equation.

Table 4.1. Results of removal efficiency tests on the modified ecoStorm.

General Test Information					Water Elevations (inches)					Sediments Fed and Removed												
Run	Date	Water Temp (F)	Duration of feeding sediment (sec)	Flow Rate (CFS)	Manhole Water Height	Upstream Tap Height	Upstream Tap Height above the floor	Downstream Tap Height	Downstream Tap Height above the floor	Sediment Supply (g)	d_{50} (microns)	Collected from Manhole (gr)				Collected from Supply Pipe (gr)				Sediment remaining in Feeder post run (g)	Average sediment concentration (mg/l)	Removal Efficiency
1	8/15/2007	81	570	5.55	**84.75**			262.63	**72.16**	5303	544.5	11.7	3323.7	1008.7						299	177	83.5%
										5303	302.5	1377.9	2537.2	397.1								82.9%
										5303	106.5	990.3	679.8	49.6	4.8							33.1%
2	8/16/2007	81.5	570	5.55	**84.69**	204.50	**84.97**	262.63	**72.16**	5303	544.5	10.0	3759.6	849.6						255	177	88.5%
										5303	302.5	1527.1	2472.7	323.1								82.8%
										5303	106.5	832.1	808.1	18.0	2.3							31.8%
3	8/16/2007	81.5	585	5.55	**84.69**	204.50	**84.97**	262.56	**72.09**	5303	544.5	10.5	3782.4	902.5						364	173	90.6%
										5303	302.5	1522.2	2531.7	257.2								83.2%
										5303	106.5	836.5	679.3	9.6	0.5							29.4%
4	8/17/2007	82	705	4.1	**81.00**	200.88	**81.34**	260.50	**70.03**	4908	544.5	5.5	1184.0	413.8		2.2	2531.2	291.9		442.4	180	82.8%
										4908	302.5	1129.9	1319.6	196.1		861.6	820.7	86.4				88.4%
										4908	106.5	1207.0	553.0	3.6	0.4	7.7	105.7	0.6	0.0			38.0%
5	8/18/2007	80	750	4.1	**80.94**	200.81	**81.28**	260.50	**70.03**	4908	544.5	5.8	1063.0	410.8		3.5	2643.1	359.1		399	169	83.6%
										4908	302.5	1092.6	1240.6	259.7		819.5	825.4	104.7				85.7%
										4908	106.5	1075.5	703.3	2.9	0.0	13.2	103.2	1.2	0.0			38.3%
6	8/18/2007	80	675	4.1	**81.00**	200.88	**81.34**	260.50	**70.03**	4908	544.5	7.5	1216.9	401.4		7.9	2817.6	238.6		238	188	92.1%
										4908	302.5	1594.6	1059.1	181.9		943.7	641.1	62.5				89.1%
										4908	106.5	1105.7	604.2	1.2	0.0	14.9	82.4	0.5	0.0			36.2%
7	8/18/2007	80	540	3.4	**78.63**	198.56	**79.03**	259.06	**68.59**			3.2	7.1	8.8		0.1	0.0	2.0		140	154	
										4000	302.5	424.8	825.0	122.2		1531.3	732.5	82.1				85.4%
										4000	106.5	899.6	659.0	22.4	1.1	12.3	215.9	10.3	1.2			42.6%
8	8/19/2007	77	540	3.4	**78.69**	198.56	**79.03**	259.13	**68.66**			3.5	0.6	1.2		0.0	0.0	1.4		90	154	
										4000	302.5	416.6	785.5	124.0		1712.4	652.7	81.8				87.1%
										4000	106.5	875.7	694.4	27.8	3.2	17.0	214.2	7.5	0.6			42.9%
9	8/20/2007	73	540	3.4	**78.69**	198.56	**79.03**	259.06	**68.59**			3.6	1.4	1.4		0.0	0.0	0.8		90.3	154	
										4000	302.5	377.1	839.7	124.8		1792.1	464.6	64.4				81.4%
										4000	106.5	752.8	772.3	26.2	6.4	101.1	99.4	6.5	1.7			41.4%
10	8/21/2007	73	510	1.92	**73.31**	192.94	**73.41**	256.25	**65.78**			2329.1				1213.4				135	180	62.2%
										5000	106.5											
11	8/22/2007	73	525	1.92	**73.25**	192.94	**73.41**	256.25	**65.78**			2345.7				1212.4				0	175	61.9%
										5000	106.5											
12	8/22/2007	73	510	1.92	**73.19**	192.94	**73.41**	256.25	**65.78**			2375.2				1041.3				0	180	60.0%
										5000	106.5											
13	8/23/2007	73	375	4.5	**82.13**	201.94	**82.41**	261.19	**70.72**			10.4	8.7	0.0		0.0	0.0	0.0		0	209	
										5000	302.5	338.1	3233.6	281.8		64.5	479.5	27.1				87.0%
										5000	106.5	278.6	1172.5	90.7	5.6	1.5	3.6	1.0	0.0			31.0%
14	8/24/2007	74	375	4.5	**82.13**	201.94	**82.41**	261.25	**70.78**			10.2	5.8	3.5		0.5	0.1	0.0		0	209	
										5000	302.5	133.2	3030.9	461.6		50.2	506.6	44.1				82.4%
										5000	106.5	221.9	1285.8	120.8	6.4	4.5	6.4	2.2	0.0			32.8%
15	8/28/2007	77	385	4.5	**82.13**	201.88	**82.34**	261.19	**70.72**			8.0	5.3	4.9		0.0	0.0	0.0		0	203	
										5000	302.5	102.3	3018.8	552.0		0.5	388.9	53.1				80.6%
										5000	106.5	215.8	1200.1	156.8	1.3	5.5	3.6	1.8	0.0			31.5%
16	8/29/2007	78	405	3.4	**78.88**	198.94	**79.41**	259.25	**68.78**			2934.0				0.0				0	205	36.7%
										8000	106.5											
17	8/31/2007	76.5	410	3.4	**78.88**	198.75	**79.22**	259.25	**68.78**			3037.5				0.0				0	202	38.0%
										8000	106.5											
18	8/31/2007	76.5	410	3.4	**78.88**	198.75	**79.22**	259.25	**68.78**			2845.0				0.0				0	202	35.6%
										8000	106.5											

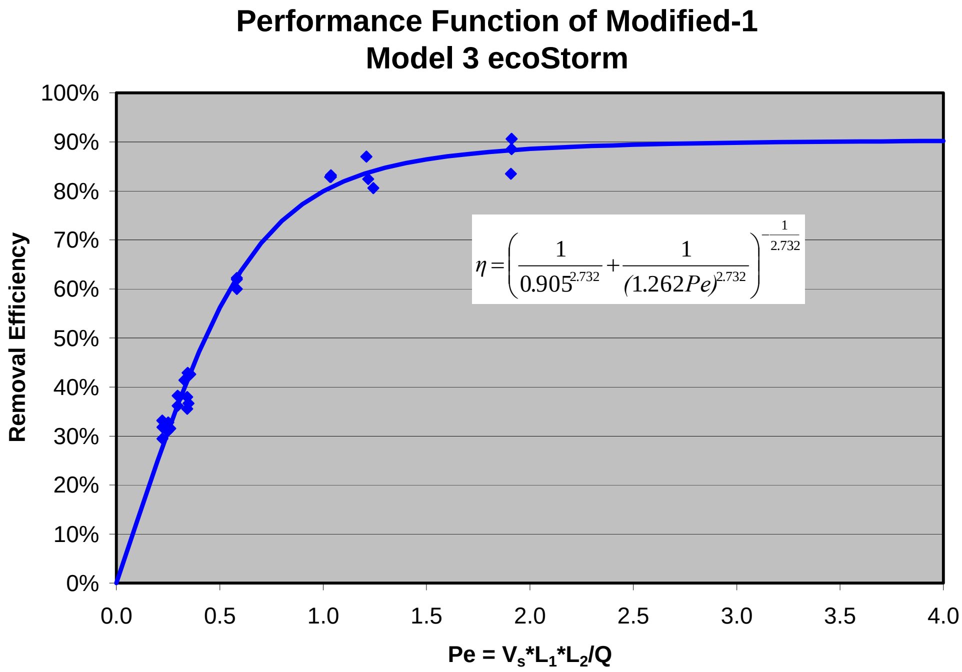

Figure 4.2. Removal efficiency versus Peclet number and the performance function of the modified ecoStorm.

Table 4.2. Pressure heads measured inside the manhole, in the influent and effluent pipes and the computation of head loss through the modified ecoStorm.

Flow Rate (CFS)	Manhole Water Height (in)	Upstream Tap Height (in)	Upstream Tap Height above the floor (in)	Downstream Tap Height (in)	Downstream Tap Height above the floor (in)	θ_0	θ_2	A_0 (ft^2)	A_1 (ft^2)	V_0 (fps)	V_1 (fps)	Head Loss (ft)
5.55	**84.69**	204.50	**84.97**	262.63	**72.16**	6.28	3.38	**2.79**	**1.69**	**1.99**	**3.29**	0.961
5.55	**84.69**	204.50	**84.97**	262.56	**72.09**	6.28	3.37	**2.79**	**1.68**	**1.99**	**3.31**	0.964
4.5	**82.13**	201.94	**82.41**	261.19	**70.72**	5.95	3.13	**2.79**	**1.46**	**1.61**	**3.09**	0.866
4.5	**82.13**	201.94	**82.41**	261.25	**70.78**	5.95	3.14	**2.79**	**1.47**	**1.61**	**3.07**	0.863
4.5	**82.13**	201.88	**82.34**	261.19	**70.72**	5.89	3.13	**2.79**	**1.46**	**1.61**	**3.09**	0.861
4.1	**81.00**	200.88	**81.34**	260.50	**70.03**	5.35	3.01	**2.73**	**1.35**	**1.50**	**3.05**	0.833
4.1	**80.94**	200.81	**81.28**	260.50	**70.03**	5.32	3.01	**2.73**	**1.35**	**1.50**	**3.05**	0.828
4.1	**81.00**	200.88	**81.34**	260.50	**70.03**	5.35	3.01	**2.73**	**1.35**	**1.50**	**3.05**	0.833
3.4	**78.63**	198.56	**79.03**	259.06	**68.59**	4.66	2.76	**2.51**	**1.12**	**1.35**	**3.05**	0.754
3.4	**78.69**	198.56	**79.03**	259.13	**68.66**	4.66	2.77	**2.51**	**1.13**	**1.35**	**3.02**	0.751
3.4	**78.69**	198.56	**79.03**	259.06	**68.59**	4.66	2.76	**2.51**	**1.12**	**1.35**	**3.05**	0.754
3.4	**78.88**	198.94	**79.41**	259.25	**68.78**	4.75	2.79	**2.56**	**1.15**	**1.33**	**2.97**	0.776
3.4	**78.88**	198.75	**79.22**	259.25	**68.78**	4.70	2.79	**2.53**	**1.15**	**1.34**	**2.97**	0.761
3.4	**78.88**	198.75	**79.22**	259.25	**68.78**	4.70	2.79	**2.53**	**1.15**	**1.34**	**2.97**	0.761
1.92	**73.31**	192.94	**73.41**	256.25	**65.78**	3.53	2.25	**1.73**	**0.69**	**1.11**	**2.80**	0.533
1.92	**73.25**	192.94	**73.41**	256.25	**65.78**	3.53	2.25	**1.73**	**0.69**	**1.11**	**2.80**	0.533
1.92	**73.19**	192.94	**73.41**	256.25	**65.78**	3.53	2.25	**1.73**	**0.69**	**1.11**	**2.80**	0.533
15.20	**116.69**	237.75	**118.22**	305.63	**115.16**	6.28	6.28	**2.79**	**2.93**	**5.44**	**5.18**	0.30
15.20	**117.25**	238.00	**118.47**	305.88	**115.41**	6.28	6.28	**2.79**	**2.93**	**5.44**	**5.18**	0.30
13.20	**111.53**	232.31	**112.78**	269.63	**79.16**	6.28	4.76	**2.79**	**2.69**	**4.73**	**4.91**	2.77
13.15	**111.28**	231.94	**112.41**	269.31	**78.84**	6.28	4.68	**2.79**	**2.65**	**4.71**	**4.96**	2.76
10.00	**106.31**	226.50	**106.97**	266.75	**76.28**	6.28	4.13	**2.79**	**2.32**	**3.58**	**4.32**	2.47
8.15	**100.25**	220.25	**100.72**	266.34	**75.88**	6.28	4.05	**2.79**	**2.26**	**2.92**	**3.61**	2.00
8.15	**100.53**	220.63	**101.09**	266.41	**75.94**	6.28	4.06	**2.79**	**2.27**	**2.92**	**3.59**	2.03
6.55	**94.25**	214.25	**94.72**	265.97	**75.50**	6.28	3.98	**2.79**	**2.20**	**2.35**	**2.97**	1.55
6.55	**94.31**	214.72	**95.19**	265.84	**75.38**	6.28	3.96	**2.79**	**2.19**	**2.35**	**3.00**	1.60

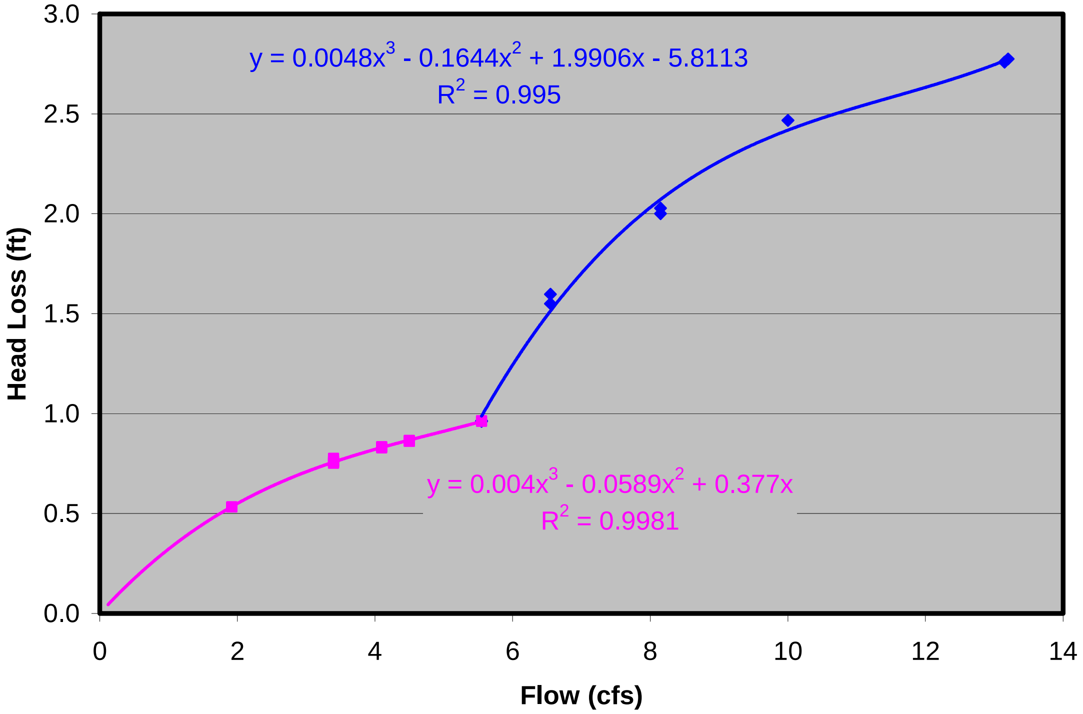

Figure 4.3. Head loss (ft) versus discharge in the Modified Model 3 ecoStorm.

Figure 4.4. Water flowing over D_3 under high flow conditions.

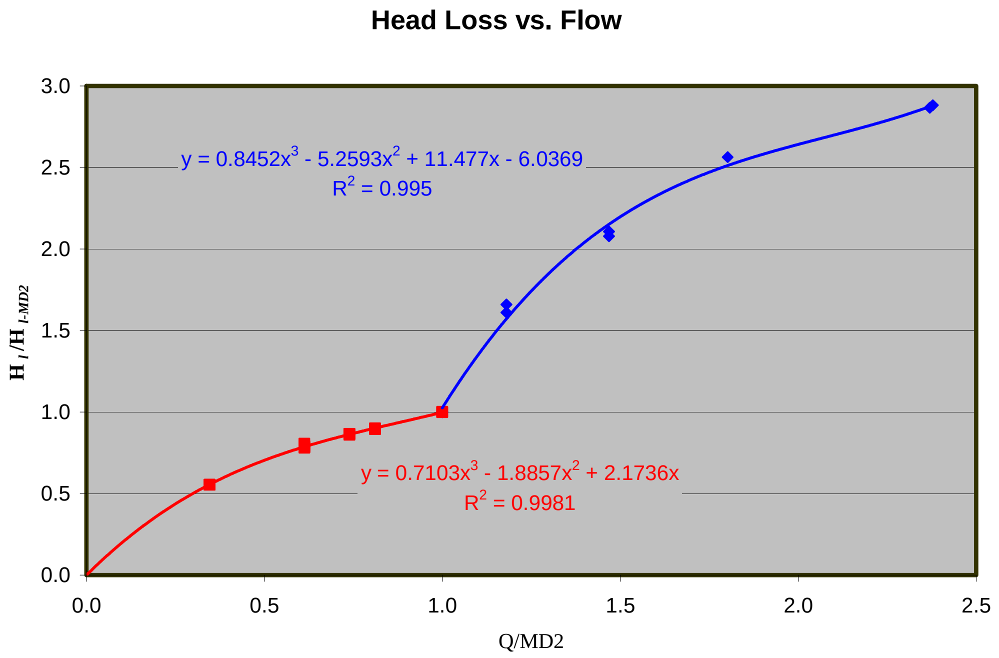

Figure 4.5. Dimensionless plot of head loss versus discharge in the modified ecoStorm. Head loss was non-dimensionalized using the head loss associated with the MD2 (5.5 cfs for the Modified Model 3 ecoStorm) and flow was non-dimensionalized using the MD2.

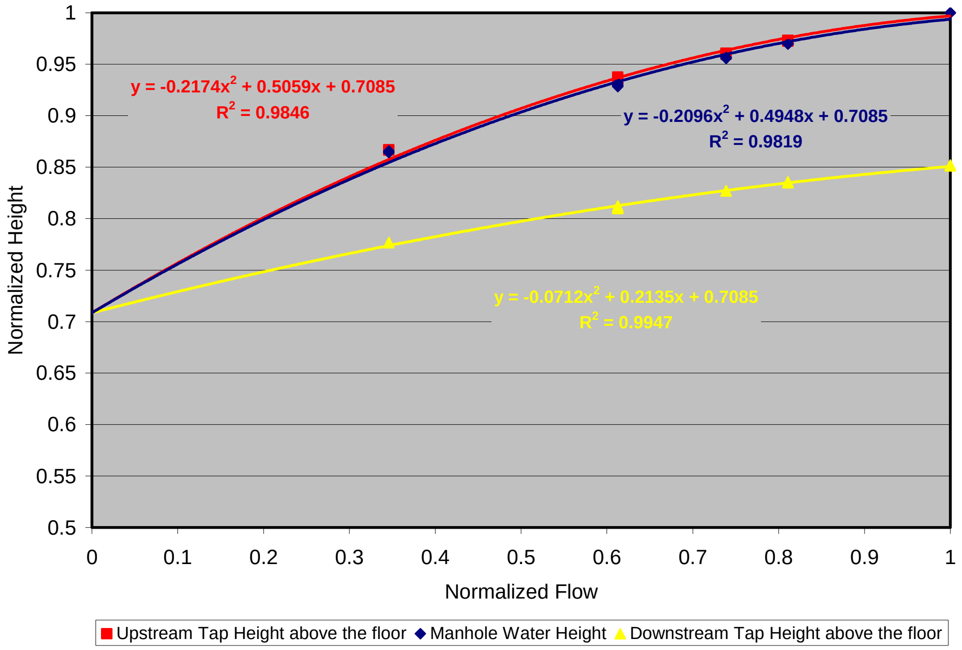

Figure 4.6. Dimensionless relationships between flow and the heads inside the D_1 manhole, and in the influent and effluent pipes. Flows and heights were normalized using MD2 and the heights associated with MD2.

5. Scouring Potential of ecoStorm: Resuspension Tests

5.1. Testing Procedure and Methodology

To assess the performance of ecoStorm against scouring, i.e. to determine how the solids deposited in the device are scoured under the flow rates near MHR, 10 tests were conducted. Prior to each test, sediments were placed inside the D_1 manhole and wetted with water. Level indicators were marked all around on the manhole wall to show the level of silica sand before and after each test. A trowel was used to flatten and level the surface of the sand and a 2 foot level was used to check if the deposit was truly level at the proper elevation in the manhole. Then, the manhole was slowly filled with water up to the invert of the rectangular weir. Ten minutes was allotted for settling of any sand particles that might have been re-suspended in the filling process of the manhole. The water supply was then turned on and set at the desired flow rate. After 60 minutes, the valves were closed and 15 minutes was allotted for the suspended solids to settle before draining the manhole.

Once the manhole was drained, pictures were taken from the deposit. The deposit was then redistributed around the manhole floor and then evened out using a trowel and level similar to the pre-run setup. A hand ruler was used to measure the thickness of the remaining deposit. The ruler was also used to ensure that the deposit had been redistributed evenly. Measurements were taken around the circumference of the manhole floor at several positions and then averaged if there were small differences in the deposit thickness.

The tests were conducted at 100% of MHR and other flow rates larger than the MD2. The MHR of the manhole was determined to be 15.2 cfs. The maximum deposit capacity of the Modified Model 3 ecoStorm was 2 ft above the bed. Tests were conducted with about 12 inches of sediment or 50% of the capacity. The sediment placed inside the D_1 manhole was silica sand with the F110 gradation.

The effluent concentration was estimated from equation 5.1.

$$C = \frac{35.25\, W}{Q\, \Delta t} \tag{5.1}$$

In equation 5.1, C is the effluent concentration in mg/l, W is the weight of solids washed out in grams, Q is the flow rate in cfs, Δt is the duration of the test in seconds and 35.25 is a conversion factor. The bulk specific gravity of the dry F110 gradation silica sand was measured in the laboratory to be 1.53.

Initially, it was decided to plot the effluent concentration versus the particle Reynolds number. This is calculated in equation 5.2 as:

$$\mathrm{Re}_p = \frac{V\, d_{50}}{\nu} \tag{5.2}$$

In equation 5.2, Re_P is the particle Reynolds number and V is the average flow velocity in the D_1 manhole. The average velocity was estimated using the flow rate and the cross-sectional area of the D_1 manhole below the invert of the influent pipe. For Model 3 ecoStorm, the cross-sectional area of the D_1 manhole without any deposit is 15 ft^2. Obviously, a higher flow through the device results in a larger particle Reynolds number and a higher effluent concentration.

5.2. Test Results

A total of 10 tests were conducted under five flow conditions with a duration of 60 minutes. Each test was repeated twice. The results of the 10 tests are summarized in Table 5.1. In these tests, the simple method of using a hand ruler to measure the depth of the deposit was compared with a laser probe with an accuracy of 0.0039 inch (0.1 mm). The difference between the two methods was less than 0.14 inches in one test and less than 0.05 inches for all other tests. The test with a difference of 0.14 inches had a smaller number of measurements around the manhole (see columns 4 and 5 of Table 5.1). As the number of measurements increased, the two methods gave very similar results.

The fifth test (Test no. 5) gave erroneous flow results and was omitted from further analysis. The results of the other 9 tests are displayed in Figure 5.1.

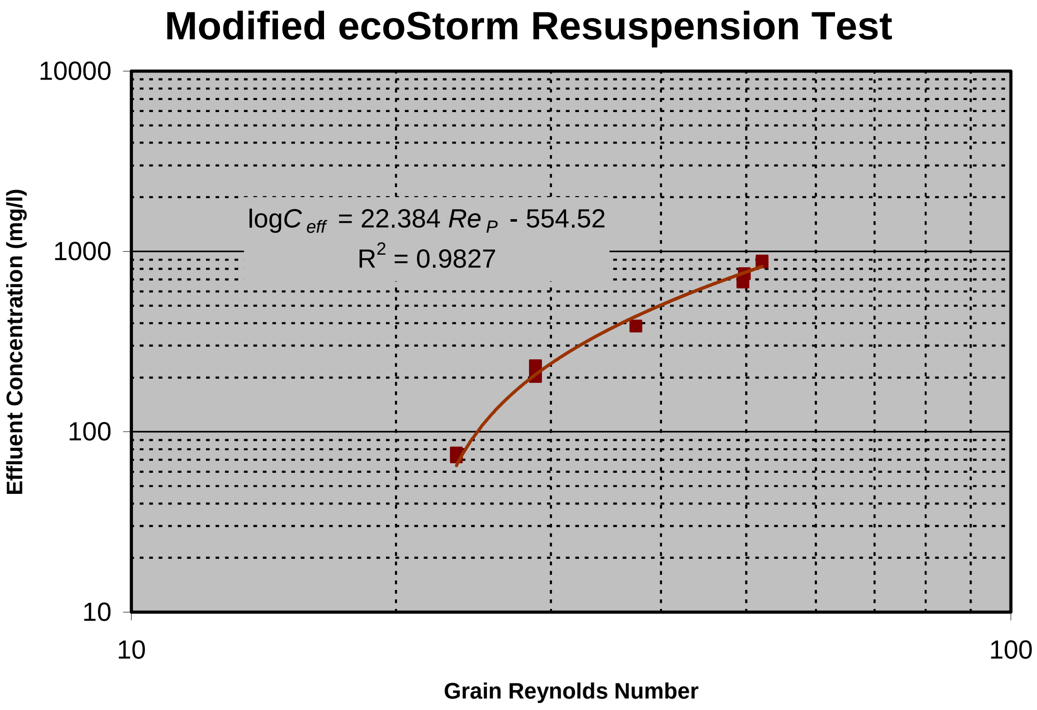

Figure 5.1. The results of resuspension tests conducted on the modified ecoStorm.

Table 5.1. Results of the 60-minute scouring tests on the modified ecoStorm. The h-values in the table have been introduced in Figure 1.1.

Test Number	Flow (cfs)	Water Temp (°F)	F-110 Placed Measured Using Stick (in)	F-110 Placed Measaured Using Laser (in)	h_1	h_1	h_1	h_0	h_0	h_0-adjusted (in)	h_2	h_2	h_2-adjusted (in)	F-110 Remained (in)	F-110 Remained (in)	Sediment Scoured Measured Using Stick (in)	Sediment Scoured Measaured Using Laser (in)	Effluent Concentration (mg/l)
					Manhole Water Height (in)	second reading (in)	Average (in)	Upstream Water Height (in)	second reading (in)		Downstream Water Height (in)	second reading (in)						
1	15.20	80.0	12.00	-	116.69	-	116.69	237.75	-	118.22	305.63	-	115.16	6.31	-	5.69	-	873
2	15.20	80.0	12.00	-	117.25	-	117.25	238.00	-	118.47	305.88	-	115.41	6.25	-	5.75	-	883
3	13.20	87.0	12.00	-	110.94	112.13	111.53	231.88	232.75	112.78	269.25	270.00	79.16	7.75	-	4.25	-	751
4	13.15	87.0	12.00	-	111.13	111.44	111.28	231.75	232.13	112.41	269.13	269.50	78.84	8.19	-	3.81	-	676
5	10.00	86.5	12.00	-	108.00	106.44	107.22	228.44	226.25	107.81	273.81	276.63	84.75	10.50	-	1.50	-	350
6	10.00	86.5	12.00	11.859	106.31	-	106.31	226.50	-	106.97	266.75	-	76.28	10.25	10.31	1.75	1.554	385
7	8.15	82.0	12.11	12.120	100.06	100.44	100.25	220.06	220.44	100.72	266.13	266.56	75.88	11.33	11.28	0.78	0.844	232
8	8.15	82.0	12.11	12.066	100.31	100.75	100.53	220.50	220.75	101.09	266.25	266.56	75.94	11.33	11.43	0.78	0.639	203
9	6.55	83.0	12.00	12.017	94.50	94.00	94.25	214.50	214.00	94.72	266.00	265.94	75.50	11.83	11.78	0.17	0.241	73
10	6.55	83.0	12.00	12.019	94.13	94.50	94.31	214.88	214.56	95.19	265.75	265.94	75.38	11.80	11.79	0.20	0.227	76

To determine the scour potential function, several dimensionless parameters were examined to capture the crucial processes affecting scouring in the device. The settling of particles as well as the bed shear stress and turbulence were determined to be the key parameters. Therefore, the normalized effluent concentration ($C/g.\rho_s$) was plotted versus:

$$K = \frac{Q^{2.5}}{\nu^2 \, V_s^{0.5} \, h^3} \tag{5.3}$$

Effluent concentration is expected to increase with K, while K increases as flow increases, water temperature increases, the particle size decreases and the effective depth of the manhole decreases.

In Figure 5.2, the effluent concentrations obtained for the modified ecoStorm have been plotted versus K.

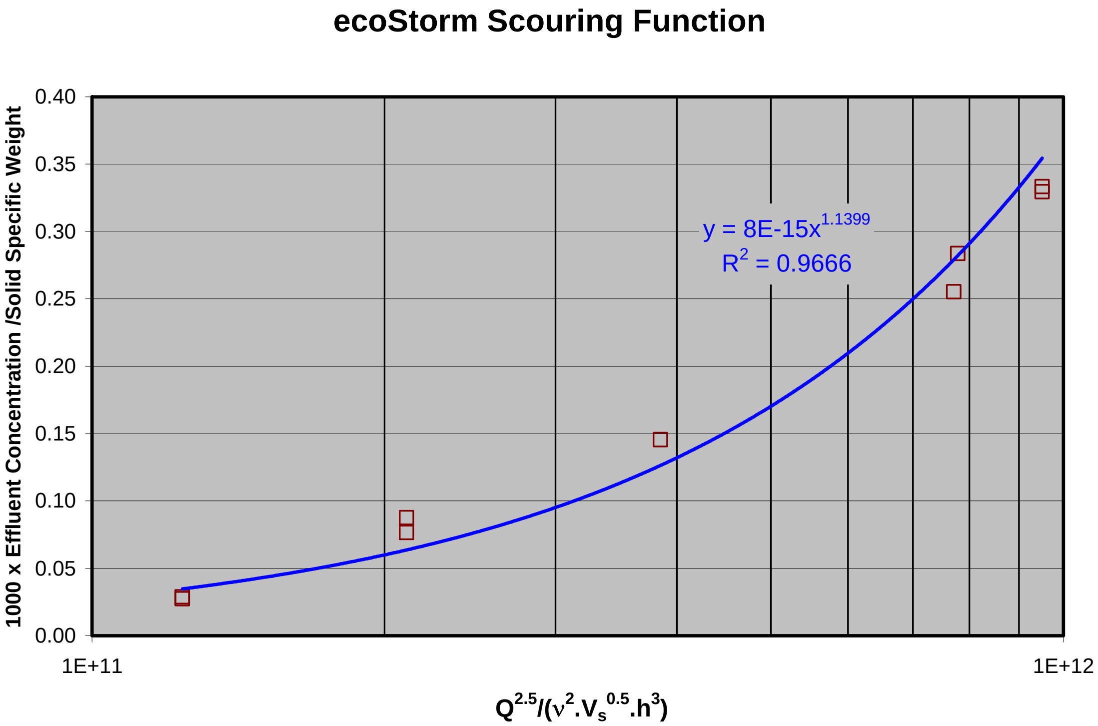

Figure 5.2. Normalized effluent concentration versus a dimensionless number to assess the scouring potential of the modified ecoStorm.

To show the implementation of the performance and scouring potential functions of the Modified Model 3 ecoStorm (Figure 5.2 and equation 5.3) during a hypothetical storm event, the following example has been provided.

Assume a storm event with a hydrograph given in the first two columns of Table 5.2. The peak runoff during this hypothetical storm event is approximately 8 cfs and lasts about 30 minutes. If the stormwater suspended solids concentration is 200 mg/l with 150 micron particles, then the settling velocity of the suspended solids under a water temperature of 68 ^{o}F becomes 0.04 fps. Assuming 1 ft of deposit with 150 micron particles prior to the storm event, the effluent concentration remains below 15 mg/l for 5.5 hours of the storm and only during the 0.5-hour peak flow does it reach 98 mg/l. A combination of scouring and solid removal by this model will result in a deposit depth of 1.02 ft at the end of the 6-hr storm.

Table 5.2. An example to depict scouring potential in a 10-ft modified ecoStorm under a 6-hr storm event with a peak runoff of 8 cfs.

t	Q	Load	h1	Real h1 ft deposit	Peclet #	% removed	volume deposited	h deposited	C-effluent	Volume washed out	h washed out	deposit depth
hr	cfs	gr	ft				ft^3	ft	mg/l	ft^3	ft	ft
0.0	0.00	-	5.00									1.000
0.5	0.18	1,859	5.14	4.14	8.58	90%	0.03	0.001	0.0	0.000	0.000	1.001
1.0	0.36	3,718	5.26	4.26	5.19	90%	0.07	0.001	0.0	0.000	0.000	1.002
1.5	0.91	9,295	5.60	4.60	2.08	89%	0.17	0.003	0.2	0.000	0.000	1.004
2.0	2.28	23,237	6.23	5.23	0.83	75%	0.36	0.005	2.7	0.007	0.000	1.010
2.5	8.00	81,713	8.31	7.30	0.24	29%	0.50	0.008	97.8	0.830	0.013	1.005
3.0	4.10	41,827	6.74	5.74	0.46	53%	0.46	0.007	14.4	0.063	0.001	1.011
3.5	2.28	23,237	6.23	5.22	0.83	75%	0.36	0.005	2.7	0.007	0.000	1.016
4.0	1.37	13,942	5.85	4.83	1.38	86%	0.25	0.004	0.6	0.001	0.000	1.020
4.5	0.91	9,295	5.60	4.59	2.08	89%	0.17	0.003	0.2	0.000	0.000	1.022
5.0	0.36	3,718	5.26	4.24	5.19	90%	0.07	0.001	0.0	0.000	0.000	1.023
5.5	0.23	2,324	5.17	4.14	8.30	90%	0.04	0.001	0.0	0.000	0.000	1.024
6.0	0.09	929	5.07	4.04	20.76	90%	0.02	0.000	0.0	0.000	0.000	1.024

6. Summary

To assess the removal efficiency and scouring potential of the Modified Model 3 ecoStorm, a unit was installed in the St. Anthony Falls Laboratory. The system is comprised of a manhole (D_1) and a second smaller cylinder (D_2) inside the manhole. The maximum discharge before overtopping the manhole D_2 was measured to be 5.5 cfs and the maximum hydraulic rate of the unit was measured to be 15.2 cfs.

A total of 18 tests were conducted under a variety of flow conditions. In these 18 tests, three different sand particle sizes with a specific gravity of 2.65 were fed into the device. The solids removed by the device were dried, sieved and weighed to determine the removal efficiency of the device. Using the data collected, a performance function was developed for the modified ecoStorm. The performance function gives the removal efficiency of the Modified Model 3 ecoStorm as a function of a dimensionless Peclet number. In addition, 10 resuspension tests were conducted to determine the scouring potential of the device. A different function was fitted to the resuspension test data to estimate the effluent concentration from the device under high flow conditions.

7. References

Cheng, N. S. (1997). “A simplified settling velocity formula for sediment particle.” *Journal of Hydraulic Engineering*, 123(2), 149-152.