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Verification Testing of the Hydroworks HS 4 Stormwater Treatment System

In Accordance with the New Jersey Department of Environmental Protection

"Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device", 2013

Technical Evaluation Report

Alden Report No. : 1152HS 4 SVT-NJDEP-R1

Submitted to:

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1.0 Introduction

Under a contract from Hydroworks, LLC, verification testing of a HydroStorm 4 ft diameter Hydrodynamic Separator (HS 4), was conducted at Alden Research Laboratory, Inc. (Alden), Holden, Massachusetts. The purpose of the testing was to define the performance characteristics of the HS 4 under controlled laboratory conditions, utilizing established standard testing methodologies. The testing was conducted in accordance with The New Jersey Department of Environmental Protection “Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device”, 2013”, to establish the following parameters:

a) **Hydraulic Characteristics Curves:**
Define the flow capacity and system losses

b) **Sediment Scour Testing:**
Quantify the sediment mass that is washed out of the unit at 200% MTFR.

c) **Sediment Removal Efficiency Curve:**
Quantify the sediment removal characteristics at 25%, 50%, 75%, 100% and 125% Maximum Treatment Flow Rate (MTFR).

2.0 Test Unit Description

The HS 4 test unit was a full scale concrete cylindrical device measuring 4 feet in diameter with a sump depth of 4 ft and a collection sump area of 12.57 ft^2. Aluminum inlet and outlet pipes, 14-inch in diameter, were oriented along the centerline of the unit, with the inverts located 49 and 47 inches above the sump floor, respectively. The pipes were set with 0.25% slopes. The internal geometry was divided into an annular pretreatment channel, 2-ft diameter inner chamber, and lower collection sump. The pretreatment channel extended 12 inches below the outlet pipe invert and contained three (3) intermediate low-flow weirs, 12 inches high (flush with the outlet invert), and two (2) downstream bypass weirs, 20 inches high (8 inches above the outlet invert). Grating was positioned over the channel to help displace the inflow turbulence and protect the captured sediment from scour. Openings were located upstream of each weir to allow the flow to be conveyed into the inner chamber and lower sump. The flow passed along the outside of a lower outlet disk and through an opening in the pretreatment disk, downstream of the bypass weirs, where it was conveyed into the outlet pipe. An annular secondary horizontal plate was located within the lower sump to protect the collected sediment from scour. Drawings of the HS 4 test unit are shown on Figure 1**.** A photograph showing the unit installed in the test loop is shown on Figure 2.

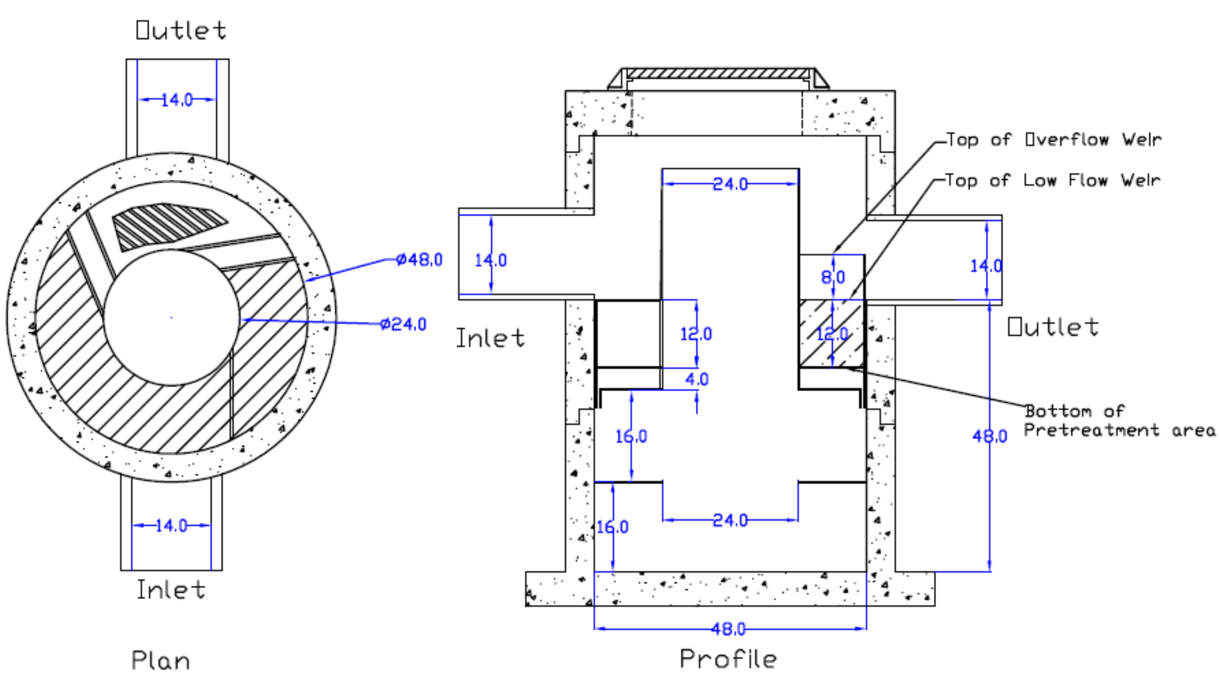

Figure 1: Drawing of the Hydroworks HS 4 Treatment Unit

Figure 2: HS 4 Test Unit Installed in Alden Flow Loop

3.0 Materials and Methods

3.1 Experimental Design

The HS 4 test unit was installed in the Alden test loop, shown on Figure 3**,** which is set up as a recirculation system. The loop is designed to provide metered flow up to approximately 17 cfs, using calibrated orifice plate and venturi differential-pressure meters. Flow was supplied to the unit using either a 20HP or 50HP laboratory pump (flow dependent), drawing water from a 50,000-gallon supply sump. 30 feet of straight 14-inch pipe conveyed the metered flow to the unit. 8 feet of 14-inch effluent piping returned the test flow back to the supply sump. The influent and effluent pipes were set at 0.25% slopes. A 14-inch tee was located 4 pipe-diameters upstream of the test unit for injecting sediment into the crown of the influent pipe.

Filtration of the test-loop flow, to reduce background concentration, was performed with an inline filter wall containing 1-micron filter bags.

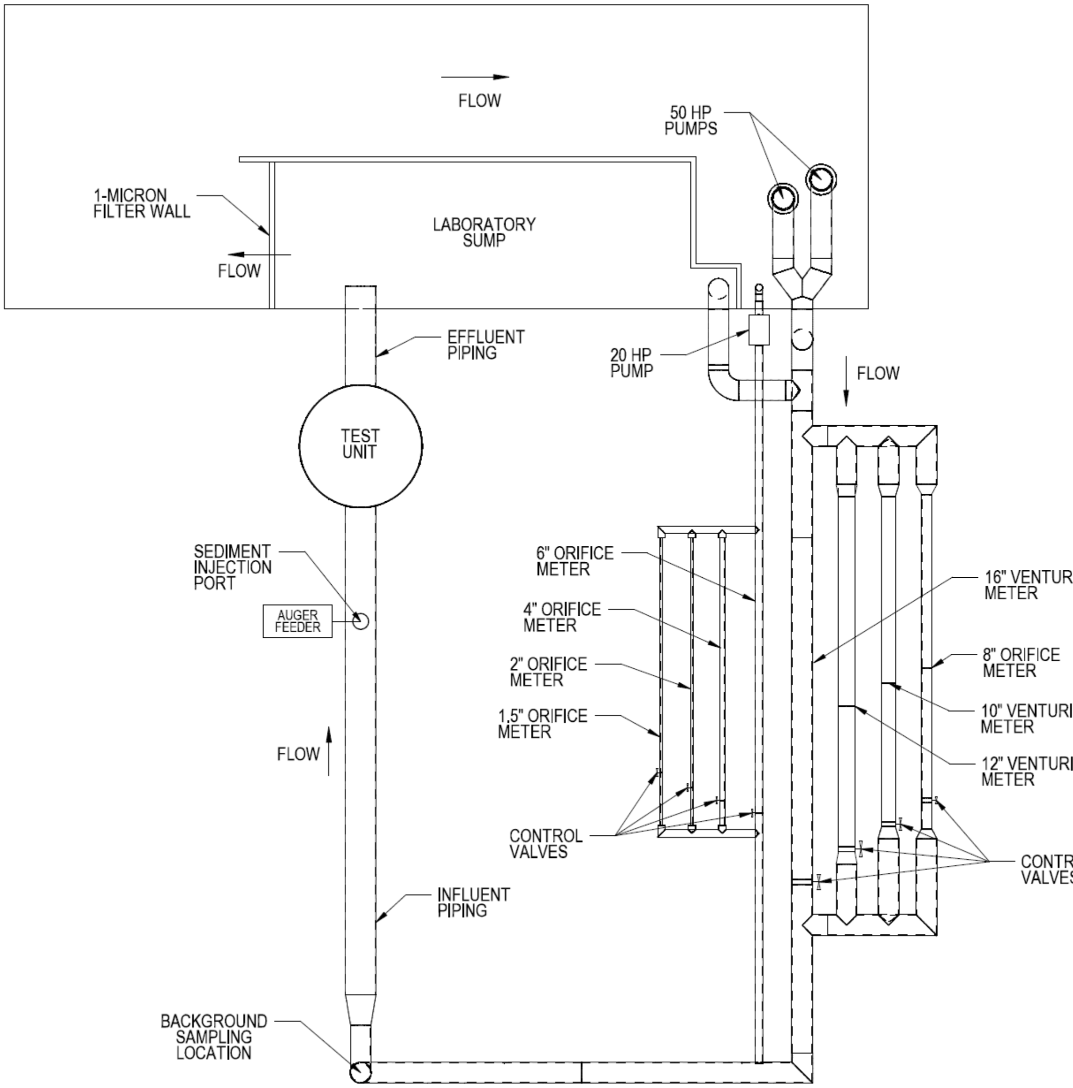

Figure 3: Plan View of Alden Flow Loop

3.2 Hydraulic Testing

The HS 4 unit was tested with clean water to determine its hydraulic characteristic curves, including loss coefficients (Cd's) and/or K factors, as well as the maximum flow prior to bypass. Flow and water level measurements were recorded for 15 steady-state flow conditions using a computer Data-Acquisition (DA) system, which included a data collect program, 0-250" Rosemount Differential Pressure (DP) cell, and Druck 0-2 psi Absolute Pressure (AP) cell. Flows were set and measured using calibrated differential-pressure flow meters and control valves. Each test flow was set and operated at steady state for approximately 10 minutes, after which time a minimum of 60 seconds of flow and pressure data were averaged and recorded for each pressure tap location. Water elevations were measured within the treatment unit in the pretreatment channel, inner chamber and upstream of the outlet area. Measurements within the influent and effluent pipes were taken one pipe-diameter upstream and downstream of the unit.

3.3 Removal Efficiency Testing

Removal testing was conducted on a clean unit utilizing the End-of-pipe sampling methodology. A false floor was installed at the 50% collection sump sediment storage depth of 6", as stated by Hydroworks. All tests were run with clean water containing a sediment solids concentration (SSC) of less than 20 mg/L.

Five sediment removal efficiency tests were conducted at flows corresponding to 25%, 50%, 75%, 100% and 125% Maximum Treatment Flow Rate (MTFR).

The test sediment was prepared by Alden to meet the PSD gradation of 1-1000 microns in accordance with the distribution shown in Table 1. The sediment is silica based, with a specific gravity of 2.65. Random samples of the test batch were analyzed for PSD compliance by GeoTesting Express, Inc., an independent certified analytical laboratory, using the ASTM D422-63 (2007)e1 analytical method. The average of all the samples was used for compliance with the protocol specification.

The target influent sediment concentration was 200 mg/L (+/-20 mg/L) for all tests. The concentration was verified by collecting a minimum of six timed dry samples at the injector and correlating the data with the measured flow rate. Each sample volume was a minimum of 0.1 liters, with the collection time not exceeding 1-minute. The allowed Coefficient of Variance (COV) for the measured samples is 0.10. The reported concentration was calculated based on the total mass injected during the test and total volume of water introduced during sediment dosing.

A minimum of 25 lbs of test sediment was introduced into the influent pipe for each test. The moisture content of the test sediment was determined using ASTM D4959-07 for each test conducted. In addition, the criterion of the supply water temperature below 80 degrees F was met for all tests conducted.

Eight (8) background samples of the supply water were collected using an iso-kinetic sampler at evenly-spaced intervals throughout each test. Collected samples were analyzed for Suspended Solids Concentration (SSC) using the ASTM D3977-97 (2013). A 3rd-order curve and corresponding equation was developed for calculating the adjusted effluent concentrations. A correction was made to each timestamp to account for the detention time between the background and effluent sampling locations. The sampler was allowed to flow for the duration of all tests except 25% MTFR, for which the sampler valve was closed after collection of each sample. The average recorded inflow was adjusted to account for the sampler flow.

Fifteen (15) effluent samples were collected from the end of the effluent pipe at evenly-spaced intervals, using 1-L wide-mouth bottles. Sampling was started after a minimum of three (3) detention times were allowed to pass after the initiation of sediment injection, as well as after the interruption of sediment feed for injection verification.

Table 1:
NJDEP Target Test Sediment Particle Size Distribution

	TSS Removal Test PSD	Scour Test Pre-load PSD
Particle Size (Microns)	**Target Minimum % Less Than[2]**	**Target Minimum % Less Than[3]**
1,000	100	100
500	95	90
250	90	55
150	75	40
100	60	25
75	50	10
50	45	0
20	35	0
8	20	0
5	10	0
2	5	0

1. The material shall be hard, firm, and inorganic with a specific gravity of 2.65. The various particle sizes shall be uniformly distributed throughout the material prior to use.
2. A measured value may be lower than a target minimum % less than value by up to two percentage points, provided the measured d_{50} value does not exceed 75 microns.
3. This distribution is to be used to pre-load the MTD's sedimentation chamber for off-line and on-line scour testing.

3.4 Sediment Scour Testing

A sediment scour test was conducted to evaluate the ability to retain captured material during high flows. The 50% capacity (6 inches) false floor was left installed in the collection sump and 4-inches of 50-1000 micron sediment was pre-loaded on the floor. This resulted in preloading to the 83% (10 inches) storage capacity level. All test sediment was evenly distributed and levelled prior to testing.

The unit was filled with clean water (< 20 mg/L background) to the invert of the outlet pipe prior to testing. Testing was conducted at a temperature not exceeding 80 degrees F. The test was initiated within 96 hours of filling the unit.

The test was conducted at 200% MTFR for on-line certification. Testing consisted of conveying the selected target flow through the unit and collecting 15 time-stamped effluent samples (every 2 minutes) for SSC analysis, and a minimum of 8 time-stamped background samples evenly spaced throughout the test. The target flow was reached within 5 minutes of commencement of the test. Flow data was continuously recorded every 5 seconds throughout the test and correlated with the samples.

Effluent samples for sediment concentration were collected from the end of the outlet pipe with the use of 1-L bottles.

3.5 Instrumentation and Measuring Techniques

3.5.1 Flow

The inflow to the test unit was measured using one of five (5) calibrated differential-pressure flow meters (2”, 4”, 6”, 8” or 12”). Each meter is fabricated per ASME guidelines and calibrated in Alden’s Calibration Department prior to the start of testing. Flows were set with a butterfly valve and the differential head from the meter was measured using a Rosemount® 0 to 250-inch Differential Pressure (DP) cell, also calibrated at Alden prior to testing. The test flow was averaged and recorded every 5-30 seconds (flow dependent) throughout the duration of the test using an in-house computerized data acquisition (DA) program. The accuracy of the flow measurement is ±2%. A photograph of the flow meters is shown on Figure 4.

Figure 4: Photograph Showing Laboratory Flow Meters

3.5.2 Temperature

Water temperature measurements within the supply sump were obtained using a calibrated Omega® DP25 temperature probe and readout device. The calibration was performed at the laboratory prior to testing. The temperature reading was documented at the start and end of each test, to assure an acceptable testing temperature of less than 80 degrees F.

3.5.3 Pressure Head

Pressure head measurements were recorded at multiple locations using piezometer taps and a Druck®, model PTX510, 0 - 2.0 psi cell. The pressure cell was calibrated at Alden prior to testing. Accuracy of the readings is ± 0.001 ft. The cell was installed at a known datum above the unit floor, allowing for elevation readings through the full range of flows. A minimum of 60 seconds of pressure data was averaged and recorded for each pressure tap, under steady-state flow conditions, using the computer DA program. A photograph of the pressure instrumentation is shown on Figure 5

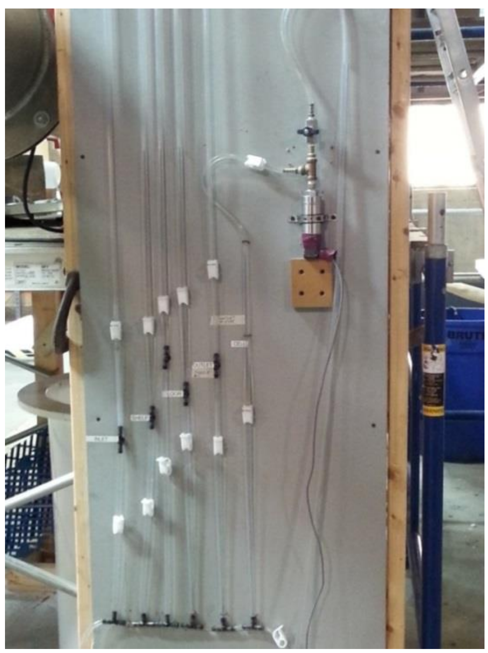

Figure 5: Pressure Measurement Instrumentation

3.5.4 Sediment Injection

The test sediment was injected into the crown of the influent pipe using an Auger® volumetric screw feeder, model VF-1, shown on Figure 6. The feed screws used in testing ranged in size from 0.5-inch to 1.0 inch, depending on the test flow. Each auger screw, driven with a variable-speed drive, was calibrated with the test sediment prior to testing, to establish a relationship between the auger speed (0-100%) and feed rate in mg/minute. The calibration, as well as test verification of the sediment feed was accomplished by collecting 1-minute timed dry samples and weighing them on an Ohaus® 4000g x 0.1g, model SCD-010 digital scale. The feeder has a hopper at the upper end of the auger to provide a constant supply of dry test sand.

Figure 6: Photograph Showing Variable-speed Auger Feeder

3.5.5 Sample Collection

Effluent samples were collected in 1-L bottles from the end of the pipe for sediment concentration analyses. Background concentration samples were collected from the center of the vertical pipe upstream of the test unit with the use of a 0.75-inch isokinetic sampler, shown on Figure 7.

Figure 7: Photograph Showing the Background Isokinetic Sampler

3.5.6 Sample Concentration Analyses

Effluent and background concentration samples were analyzed by Alden in accordance with Method B, as described in ASTM Designation: D 3977-97 (Re-approved 2013), "Standard Test Methods for Determining Sediment Concentration in Water Samples". The required silica sand used in the sediment testing did not result in any dissolved solids in the samples and therefore, simplified the ASTM testing methods for determining sediment concentration.

3.6 Data Management and Acquisition

A designated Laboratory Records Book was used to document the conditions and pertinent data entries for each test conducted. All entries are initialed and dated.

A personal computer running an Alden in-house Labview® Data Acquisition (DA) program was used to record all data related to instrument calibration and testing. A 16-bit National Instruments® NI6212 Analog to Digital (A/D) board was used to convert the signal from the pressure cells to a voltage. Alden's in-house data collection software, by default, collects one second averages of data collected at a raw rate of 250 Hz. The system allows very long contiguous data collection by continuously writing the collected 1 second averages and their RMS values to disk. The data output from the program is in tab delimited text format with a user-defined number of significant figures.

Test flow and pressure data was continuously collected at a frequency of 250 Hz. The flow data was averaged and recorded to file every 5 to 30 seconds, depending on the duration of the test. Steady-state pressure data was averaged and recorded over a duration of 60 seconds for each point. The recorded data files were imported into Excel for further analysis and plotting.

Excel based data sheets were used to record all sediment related data used for quantifying injection rate, effluent and background sample concentrations, captured mass and PSD data. The data was input to the designated spreadsheet for final processing.

3.7 Preparation of Test Sediment

The sediment particle size distribution (PSD) used for scour and removal efficiency testing was comprised of 50-1000 and 1-1000 micron (respectively) silica particles with a SG of 2.65. Commercially-available blends were provided by AGSCO Corp., a QAS International ISO-9001 certified company. The 1-1000 mix was found to be outside of the tolerance below approximately 50 microns. Test batches were adjusted by Alden as needed and a minimum of three random batch samples were analyzed in accordance with ASTM D422-63 (2007), by GeoTesting Express, an AALA ISO/IEC 17025 accredited independent laboratory, prior to testing. The specified less-than (%-finer) values of the 3-sample average were within the 2 percentage-point tolerance listed in the protocol.

3.8 Data Analysis

The following equations and procedures were used in analyzing the data collected on the Hydroworks HS 4 test unit:

3.8.1 Hydraulics

The pressure cell was mounted at an elevation of 0.067m below the outlet pipe invert. This datum value was added to all measurements taken to calculate the water height above the invert. The system energy loss across the unit was determined by adding the velocity head to the elevation measurements taken in the inlet and outlet pipes.

The velocity head is defined by:

$$\mathbf{H = V^2/2g} \tag{1}$$

where,

H = velocity head (ft), V = velocity (ft/sec), and g = gravity (32.17 ft/sec^2).

The velocity is defined by:

$$\mathbf{V = Q/A} \tag{2}$$

where,

V = velocity (ft/sec), Q = flow (ft^3/sec), and A = area (ft^2).

The area in the partial pipe flow was calculated using:

$$\boldsymbol{A = 0.125(\theta - Sin\theta)D^2} \tag{3}$$

where,

A = area (ft^2), θ = angle of inclusion (radians), and D = pipe diameter (ft).

The angle of inclusion of the water surface (θ) was calculated using:

$$\boldsymbol{\theta = 2\pi - 2(ACos\left(\frac{y - \frac{D}{2}}{\frac{D}{2}}\right))} \tag{4}$$

where,

Y = measured water depth (ft), and D = pipe diameter (ft).

The system and pipe loss coefficient (Cd) was calculated using:

$$\boldsymbol{Cd} = \frac{\boldsymbol{Q}}{\boldsymbol{A(2g\Delta H)^{0.5}}} \tag{5}$$

where,

Q = flow (ft^3/sec), A = area of insert outlet (0.75 ft^2), g = gravity (32.17 ft/s^2), and ΔH = energy loss across unit (ft).

3.8.2 Removal Efficiency

The injected mass was calculated by:

$$\mathbf{M_{inj} = \Delta M - (\Delta M \times w)} \tag{6}$$

where,

M_{inj} = final mass of injected sediment (lbs), ΔM = measured mass of injected sediment (lbs), w = moisture content of sediment (%).

The sediment removal efficiency was calculated by:

$$\%\ \boldsymbol{Removal} = \frac{(\boldsymbol{Average\ Influent\ Concentration - Average\ Effluent\ Concentration}*)}{\boldsymbol{Average\ Influent\ Concentration}}\ \boldsymbol{x\ 100} \tag{7}$$

*Effluent concentration adjusted for background

The background sample concentrations were calculated as follows:

$$\mathbf{BG\ (mg/L) = Sediment\ Wt\ (mg) / Sample\ Volume\ (L)} \tag{8}$$

The auger injector verification concentrations were determined by the following:

$$\mathbf{C_i = M_f / Q_{avg}} \tag{9}$$

where,

C_i = influent concentration (mg/L), M_f = sediment mass feed (mg/min), Q_{avg} = average flow (gpm)

3.9 Laboratory Analysis

The following Test Methods were used to analyze the various dry and aqueous sediment and plastic samples:

- **Sediment Concentration**

  ASTM Designation: D 3977-97 (Re-approved 2013), "Standard Test Methods for Determining Sediment Concentration in Water Samples"

- **Sediment Moisture Content**

  ASTM Designation: D4959-07, "Standard Test Method for Determination of Water (Moisture) Content of Soil by Direct Heating"

- **Dry Sediment Particle Size Distribution**

  ASTM D422-63 (2007), "Standard Test Method for Particle Size Analysis of Soils"

3.9.1 Independent Analytical Laboratories

All dry sediment PSD analyses were performed by GeoTesting Express, Inc., Acton, Massachusetts. GeoTesting is an AALA ISO/IEC 17025 accredited independent laboratory

3.10 Quality Assurance and Control

A Quality Assurance Project Plan (QAPP) was submitted and approved outlining the testing methodologies and procedures used for conducting the verification tests. The QAPP was followed throughout the testing.

All instruments were calibrated prior to testing and periodically checked throughout the test program. The instrumentation calibrations are included in Appendix B.

3.10.1 Flow

The flow meters and Pressure Cells were calibrated in Alden's Calibration Laboratory, which is ISO 17025 accredited. A standard water manometer board and Engineers Rule were used to verify the computer measurement of each flow meter.

3.10.2 Sediment Injection

The sediment feed in g/min was verified with the use of a digital stop watch and 4000g calibrated digital scale. The tare weight of the sample container was recorded prior to collection of each sample. The final sediment concentrations were adjusted for moisture.

3.10.3 Sediment Concentration Analysis

All sediment concentration samples were processed in accordance with the ASTM D3977-97 (2013) analytical method. Gross sample weights were measured using a 4000g x 0.1g calibrated digital scale. The dried sample weights were measured with a calibrated 0.0001g analytical balance. The change in filter weight due to processing was accounted for by including three control filters with each test set. The average of the three values, which was typically (+/- 0.1mg), was used in the final concentration calculations.

Analytical accuracy was verified by preparing two blind control samples and processing using the ASTM method. The final calculated values were within 0.26% and 0.87% of the theoretical sample concentrations, with an average of 0.57% accuracy.

4.0 Results and Discussion

4.1 Removal Efficiency Sediment

The commercially-available AGSCO NJDEP1-1000 sediment mix was procured for the sediment removal testing and adjusted by Alden to meet the NJDEP acceptance criteria shown in column 2 of Table 1. Test batches of approximately 30 lbs each, were prepared in individual 5-gallon buckets, which were arbitrarily selected for each removal test. A well-mixed sample was collected from 4 random test batches and analyzed for PSD by GeoTesting Express. The average of the samples was used for compliance to the protocol specifications. The PSD data of the samples are shown in Table 2 and the corresponding curves are shown on Figure 8

Table 2:
Removal Efficiency Test Sediment Particle Size Distribution

Particle size (µm)	NJDEP Target (percent-finer)	Test Sediment Particle Size Distribution (percent-finer)					QA / QC Compliant
		Bucket 1	Bucket 6	Bucket 10	Bucket 14	Average	
1000	**100**	100	100	100	100	**100**	Yes
500	**95**	96	95	95	96	**96**	Yes
250	**90**	91	90	90	92	**91**	Yes
150	**75**	75	74	76	77	**76**	Yes
100	**60**	61	60	60	61	**61**	Yes
75	**50**	52	51	51	52	**52**	Yes
50	**45**	46	45	46	47	**46**	Yes
20	**35**	35	35	36	36	**35**	Yes
8	**20**	21	20	22	22	**21**	Yes
5	**10**	14	14	16	16	**15**	Yes
2	**5**	6	7	7	7	**7**	Yes
D_{50}	**75**	65	71	68	63	**67**	Yes

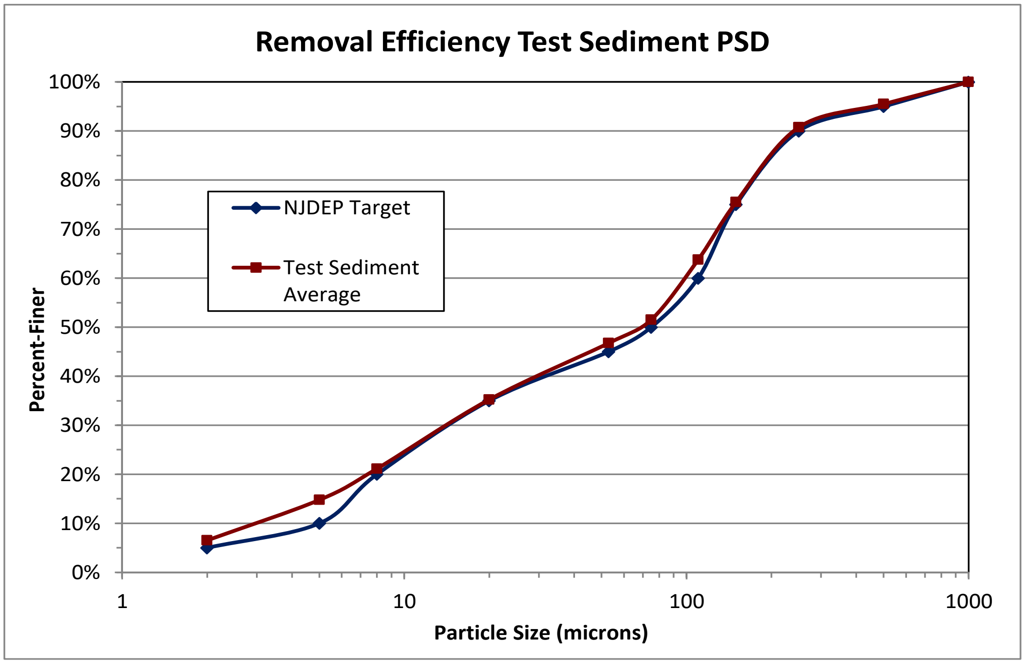

Figure 8: Average Removal Efficiency Test Sediment PSD

4.2 Sediment Removal Performance

Removal efficiency tests were conducted at the 5 required flows of 25%, 50%, 75%, 100% and 125% MTFR. The 100% MTFR was 0.88 cfs, resulting in target flows of 0.22, 0.44, 0.66, 0.88 and 1.10 cfs. The 25% MTFR test flow was greater than the 10% target allowance. However, the higher flow is conservative and therefore, included. The target influent sediment concentration was 200 mg/l.

The target and measured flow and temperature parameters are shown in Table 3 and the injected sediment and background data summary is shown in Table 4.

Table 3:
Test Flow and Temperature Summary

MTFR	Target Flow		Measured Flow		Deviation from Target	Flow Measurement COV	Maximum Temperature	QA / QC Compliant
	cfs	gpm	cfs	gpm			Deg. F	
25%	0.22	98.7	0.25	112.2	13.7%	0.001	62.5	No
50%	0.44	197.5	0.44	195.4	-1.1%	0.002	67.8	Yes
75%	0.66	296.2	0.67	298.7	0.8%	0.004	72.4	Yes
100%	0.88	395.0	0.84	378.4	-4.2%	0.003	76.1	Yes
125%	1.10	493.7	0.99	446.6	-9.5%	0.002	75.7	Yes

Table 4:
Injected Sediment Summary

Flow	Target Concentration	Average Injected Concentration	Injector Measurements COV	Mass/Volume Concentration	Injected Mass	Maximum Background Concentration	QA / QC Compliant
gpm	mg/L	mg/L		mg/L	lbs	mg/L	
112.2	200	202	0.01	188	27.28	4.42	Yes
195.4	200	199	0.00	188	26.81	3.54	Yes
298.7	200	209	0.00	209	28.10	8.09	Yes
378.4	200	206	0.00	191	25.92	6.82	Yes
446.6	200	199	0.00	198	26.99	8.91	Yes

At the end of each test run, the collected effluent and background samples were processed and quantified. The calculated removal efficiencies ranged from 42.8% to 58.5%, with a weighted removal of 50.1% for the 5 flows tested. The removal summary is shown Table 5 with the corresponding removal curve shown on Figure 9. All sampling data is presented in each testing sub-section.

Table 5:
Removal Efficiency Summary

Flow	Influent Concentration	Average Adjusted Effluent Concentration	Removal Efficiency	Weight Factor	Weighted Removal
gpm	mg/L	mg/L			
112.2	188.2	78.1	**58.5%**	0.25	**14.6%**
195.4	188.3	89.9	**52.3%**	0.30	**15.7%**
298.7	208.7	115.7	**44.6%**	0.20	**8.9%**
378.4	191.0	107.6	**43.7%**	0.15	**6.6%**
446.6	197.7	113.0	**42.8%**	0.10	**4.3%**
				1.00	**50.1%**

<u>**Repeat Tests**</u>

It was required to repeat the 50% and 100% MTFR tests due to the background concentrations exceeding the 20 mg/L acceptance limit.

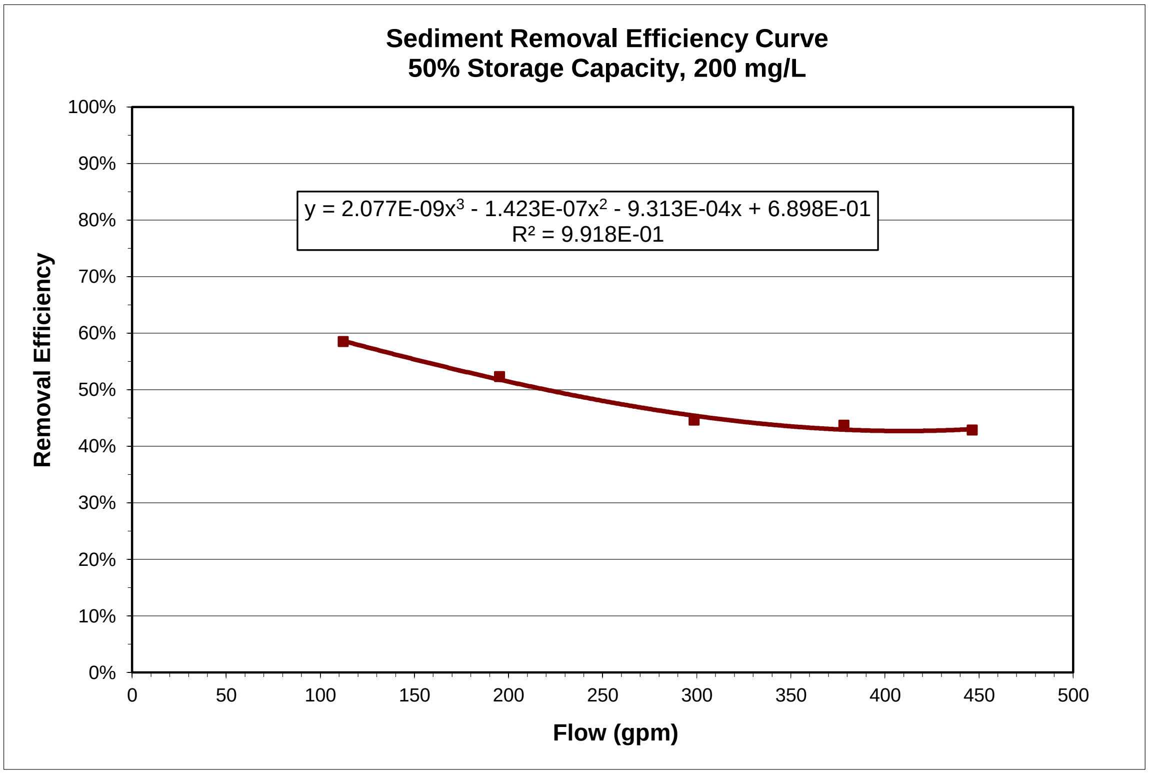

Figure 9: Hydroworks HS 4 Removal Efficiency Curve

4.2.1 25% MTFR (99 gpm, 0.22 cfs)

The test was conducted at 112 gpm (0.25 cfs) over a period of 160 minutes. This flow exceeds the 10% tolerance, but is considered conservative. The resulting removal efficiency was 58.5%. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 112 gpm, with a COV of 0.001. The recorded temperature for the full test ranged from 61.6 to 62.5 degrees F. The resulting data is shown in Table 6

The injection feed rate of 84.8 g/min was verified by collecting 1-minute weight samples from the injector. The measured influent injection concentrations for the full test ranged from 200 to 206 mg/L, with a mean of 202 mg/L and COV of 0.01. The total mass injected into the unit was 27.3 lbs. The calculated mass-flow concentration for the test was 188 mg/L.

The measured influent concentration and flow data for the complete test is shown on Figure 10.

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.3 to 4.4 mg/L. The background curve and equation are shown on Figure 11.

Table 6:
Background and Effluent Concentration Data

Sample ID	Time Stamp minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Eff 1	9	77.7	0.6	77.1
Eff 2	15	71.1	0.6	70.6
Eff 3	21	81.7	0.6	81.1
Eff 4	38	71.3	1.0	70.3
Eff 5	44	67.7	1.3	66.5
Eff 6	50	60.1	1.6	58.5
Eff 7	66	78.0	2.4	75.5
Eff 8	72	73.2	2.8	70.4
Eff 9	78	87.8	3.1	84.7
Eff 10	94	93.5	3.9	89.6
Eff 11	100	87.4	4.1	83.3
Eff 12	106	79.2	4.2	75.0
Eff 13	123	85.9	4.2	81.7
Eff 14	129	81.8	4.0	77.8
Eff 15	135	113.0	3.8	109.3
Mass-Volume Influent Concentration =	**188 mg/L**		**Average**	**78.1**
			StDev	**11.7**
			COV	**0.150**

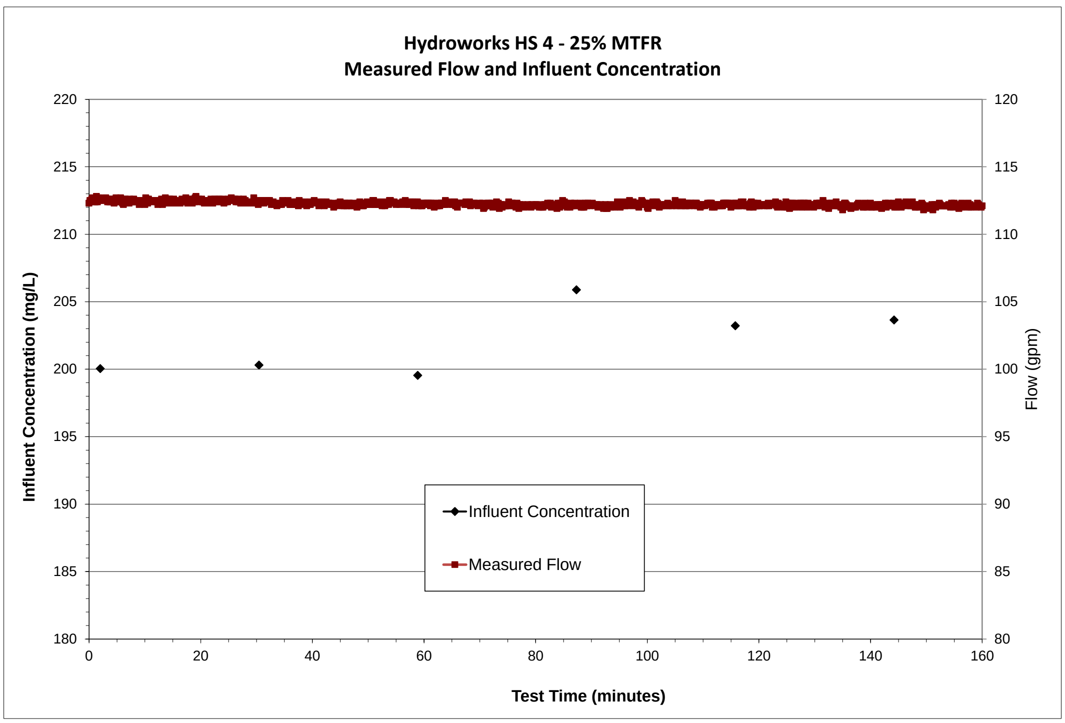

Figure 10: 25% MTFR Measured Flow and Influent Concentrations

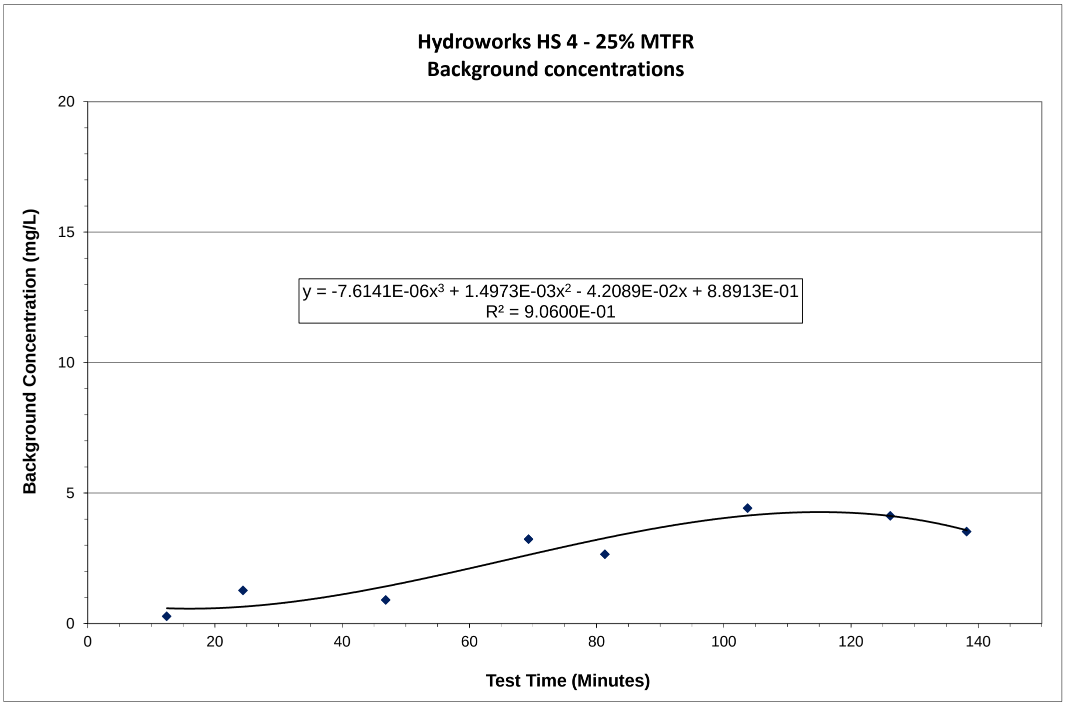

Figure 11: 25% MTFR Measured Background Concentrations

4.2.2 50% MTFR (197 gpm)

The test was conducted at 195 gpm over a period of 94 minutes. The resulting removal efficiency was 52.3%. The test flow was averaged and recorded every 10 seconds throughout the test. The adjusted average recorded test flow was 195 gpm, with a COV of 0.002. The recorded temperature for the full test ranged from 67.7 to 67.8 degrees F. The resulting data is shown in Table 7

The injection feed rate of 147.6 g/min was verified by collecting 1-minute weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 to 200 mg/L, with a mean of 199 mg/L and COV of 0.00. The total mass injected into the unit was 26.8 lbs. The calculated mass-flow concentration for the test was 188 mg/L.

The measured influent concentration and flow data for the complete test is shown on Figure 12.

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.0 to 3.5 mg/L. The background curve and equation are shown on Figure 13.

Table 7:
Background and Effluent Concentration Data

Sample ID	Time Stamp minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Eff 1	6	51.2	0.0	51.2
Eff 2	9	85.1	0.1	85.0
Eff 3	12	94.3	0.2	94.2
Eff 4	22	93.0	0.5	92.5
Eff 5	25	91.5	0.6	90.9
Eff 6	28	91.8	0.7	91.1
Eff 7	38	89.1	1.1	87.9
Eff 8	41	99.6	1.2	98.3
Eff 9	44	96.5	1.4	95.1
Eff 10	54	96.9	1.9	95.0
Eff 11	57	90.1	2.1	88.1
Eff 12	60	100.0	2.3	97.8
Eff 13	71	97.0	3.0	94.0
Eff 14	74	125.9	3.2	122.7
Eff 15	77	67.6	3.5	64.1
Mass-Volume Influent Concentration =	**188 mg/L**		**Average**	**89.9**
			StDev	**15.8**
			COV	**0.176**

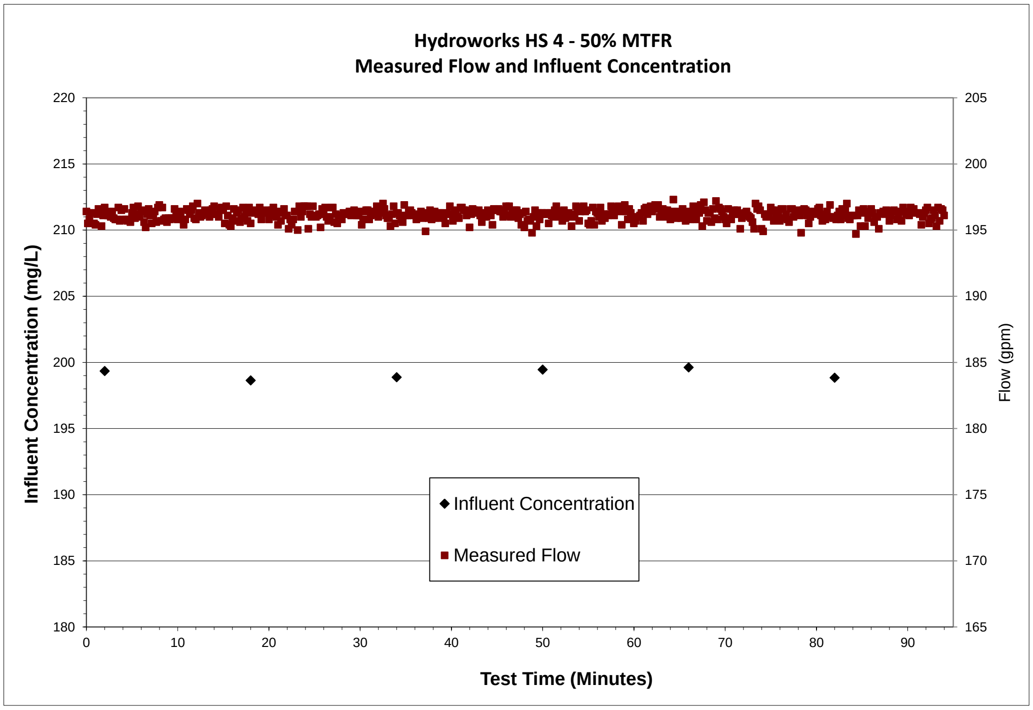

Figure 12: 50% MTFR Measured Flow and Influent Concentrations

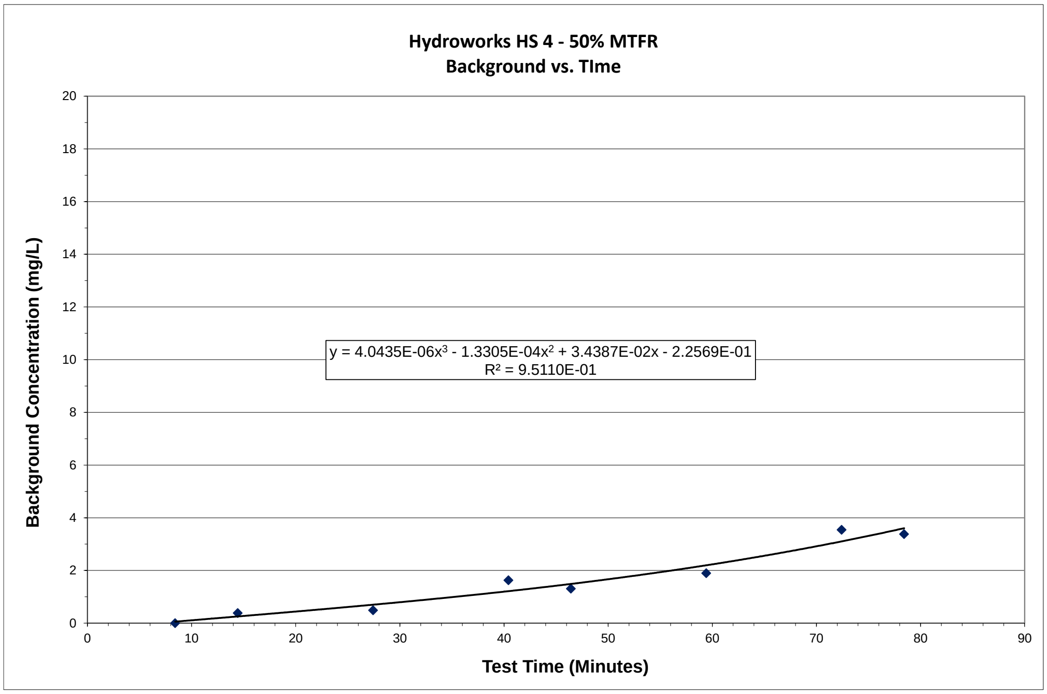

Figure 13: 50% MTFR Measured Background Concentrations

4.2.3 75% MTFR (296 gpm)

The test was conducted at 299 gpm over a period of 60 minutes. The resulting removal efficiency was 44.6%. The test flow was averaged and recorded every 10 seconds throughout the test. The adjusted average recorded test flow was 299 gpm, with a COV of 0.004. The recorded temperature for the full test ranged from 72.1 to 72.4 degrees F. The resulting data is shown in Table 8

The injection feed rate of 227.1 g/min was verified by collecting 1-minute weight samples from the injector. The measured influent injection concentrations for the full test ranged from 209 to 210 mg/L, with a mean of 209 mg/L and COV of 0.00. The total mass injected into the unit was 28.1 lbs. The calculated mass-flow concentration for the test was 209 mg/L.

The measured influent concentration and flow data for the complete test is shown on Figure 14

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.9 to 8.1 mg/L. The background curve and equation are shown on Figure 15.

Table 8:
Background and Effluent Concentration Data

Sample	Time Stamp minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Eff 1	4	107.1	1.2	105.8
Eff 2	6	109.7	1.0	108.7
Eff 3	8	110.3	0.9	109.4
Eff 4	15	125.1	0.8	124.3
Eff 5	17	120.7	0.9	119.9
Eff 6	19	139.0	1.0	138.1
Eff 7	26	108.9	1.7	107.2
Eff 8	28	114.8	2.0	112.8
Eff 9	30	117.0	2.3	114.7
Eff 10	37	120.3	3.5	116.7
Eff 11	39	128.7	4.0	124.8
Eff 12	41	128.9	4.4	124.5
Eff 13	48	85.4	6.0	79.4
Eff 14	50	137.1	6.5	130.7
Eff 15	52	124.8	7.0	117.8
Mass-Volume Influent Concentration =		**209 mg/L**	**Average**	**115.7**
			StDev	**13.5**
			COV	**0.117**

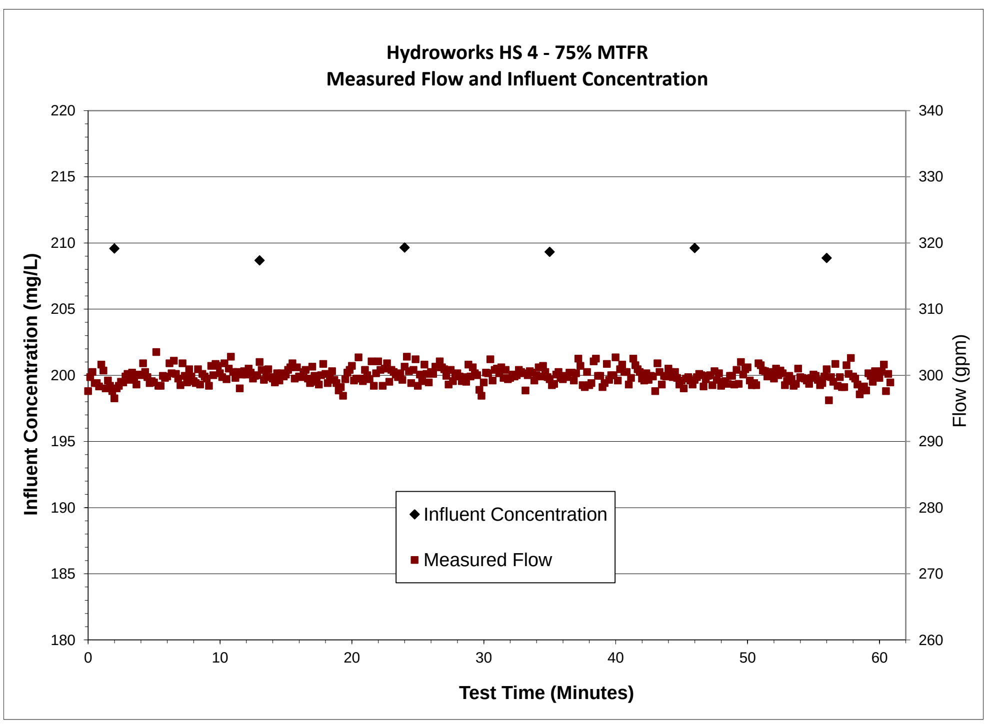

Figure 14: 75% MTFR Measured Flow and Influent Concentrations

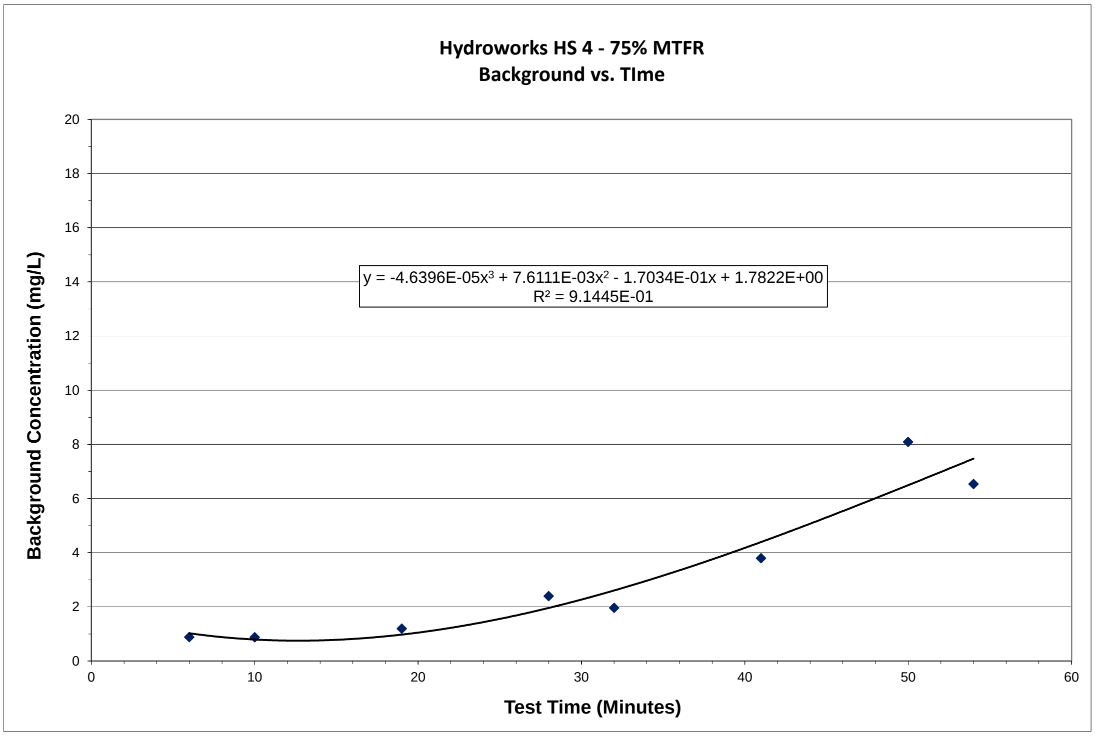

Figure 15: 75% MTFR Measured Background Concentrations

4.2.4 100% MTFR (395 gpm)

The test was conducted at 380 gpm over a period of 48 minutes. The resulting removal efficiency was 43.7%. The test flow was averaged and recorded every 10 seconds throughout the test. The adjusted average recorded test flow was 378 gpm, with a COV of 0.003. The recorded temperature for the full test ranged from 76.0 to 76.1 degrees F. The resulting data is shown in Table 9.

The injection feed rate of 288.8 g/min was verified by collecting 45-second weight samples from the injector. The measured influent injection concentrations for the full test ranged from 206 to 207 mg/L, with a mean of 206 mg/L and COV of 0.00. The total mass injected into the unit was 25.9 lbs. The calculated mass-flow concentration for the test was 191 mg/L.

The measured influent concentration and flow data for the complete test is shown on Figure 16.

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.0 to 6.8 mg/L. The background curve and equation are shown on Figure 17

Table 9: Background and Effluent Concentration Data

Sample	Time Stamp	Effluent Concentration	Background Concentration	Adjusted Effluent
	minutes	mg/L	mg/L	mg/L
Eff 1	4	89.2	0.2	89.0
Eff 2	6	104.4	0.1	104.2
Eff 3	8	107.5	0.1	107.4
Eff 4	13	99.9	0.2	99.7
Eff 5	15	97.1	0.3	96.8
Eff 6	17	107.7	0.4	107.3
Eff 7	22	104.9	0.9	104.0
Eff 8	24	128.2	1.1	127.1
Eff 9	26	113.3	1.4	111.9
Eff 10	31	137.8	2.3	135.5
Eff 11	33	121.6	2.7	118.9
Eff 12	35	126.9	3.2	123.7
Eff 13	40	109.0	4.5	104.5
Eff 14	42	124.6	5.1	119.5
Eff 15	44	69.8	5.7	64.1
Mass-Volume Influent Concentration =		191 mg/L	Average	107.6
			StDev	17.2
			COV	0.160

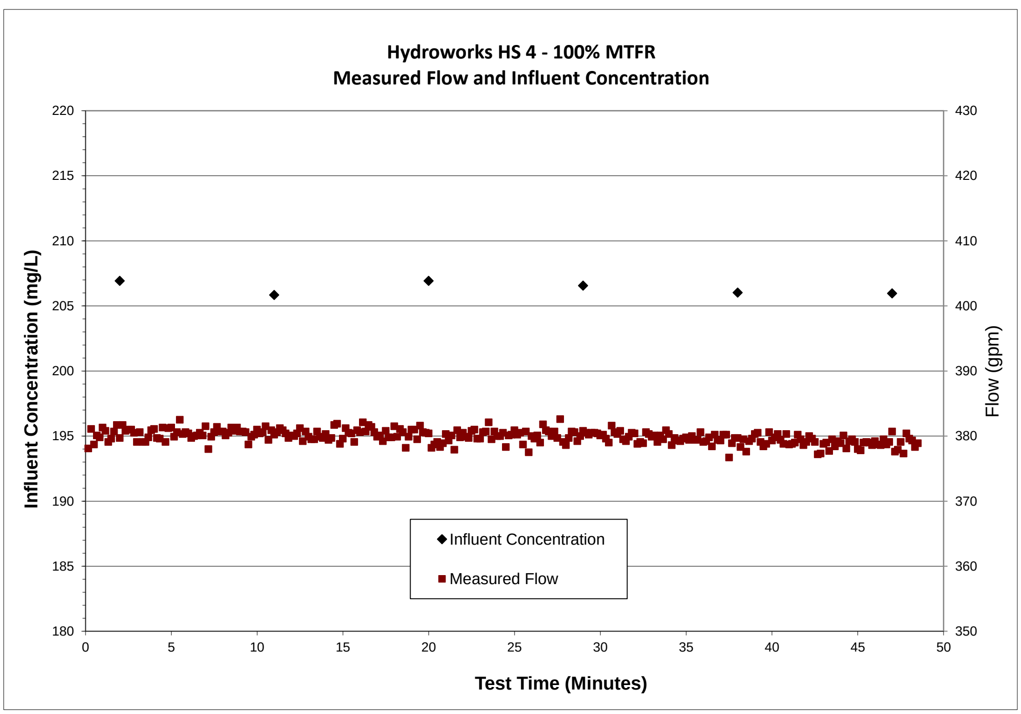

Figure 16: 100% MTFR Measured Flow and Influent Concentrations

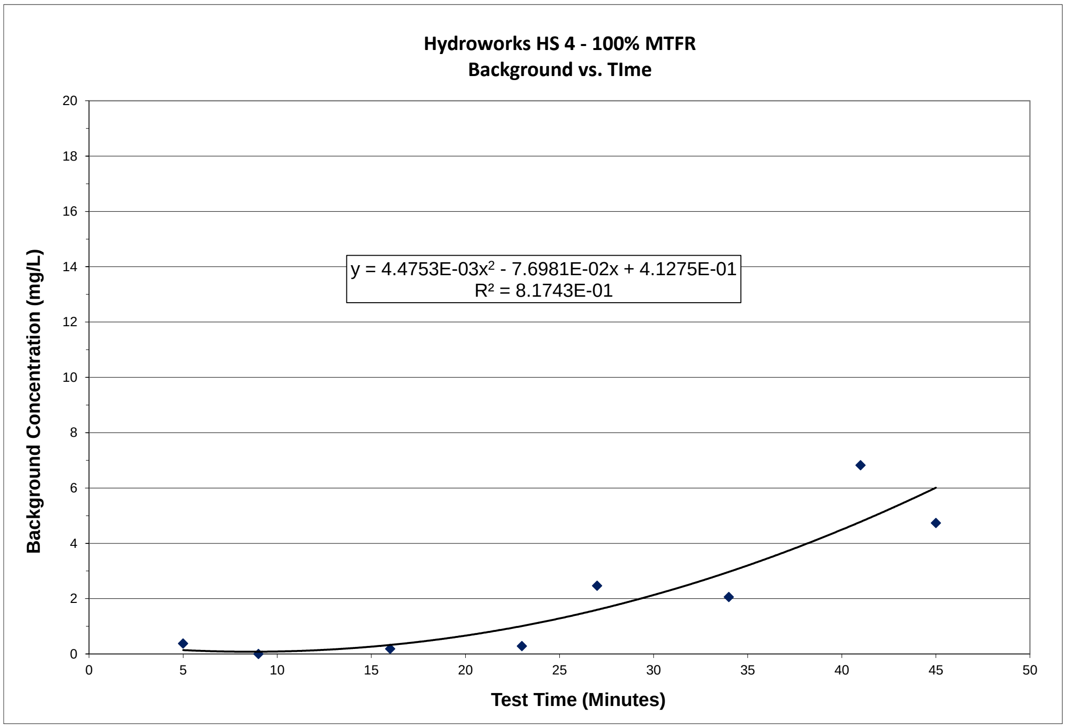

Figure 17: 100% MTFR Measured Background Concentrations

4.2.5 125% MTFR (494 gpm)

The test was conducted at 448 gpm over a period of 41 minutes. The resulting removal efficiency was 42.8%. The test flow was averaged and recorded every 10 seconds throughout the test. The adjusted average recorded test flow was 447 gpm, with a COV of 0.002. The recorded temperature for the full test was 75.7 degrees F. The resulting data is shown in Table 10

The injection feed rate of 339.8 g/min was verified by collecting 30-second weight samples from the injector. The measured influent injection concentrations for the full test ranged from 198 to 199 mg/L, with a mean of 199 mg/L and COV of 0.00. The total mass injected into the unit was 27.0 lbs. The calculated mass-flow concentration for the test was 198 mg/L.

The measured influent concentration and flow data for the complete test is shown on Figure 18

Eight (8) background concentrations samples were collected throughout the test and ranged from 1.5 to 8.9 mg/L. The background curve and equation are shown on Figure 19

Table 10: Background and Effluent Concentration Data

Sample	Time Stamp minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Eff 1	4	126.9	1.7	125.2
Eff 2	6	118.0	1.6	116.5
Eff 3	7	107.6	1.5	106.1
Eff 4	12	109.0	1.5	107.5
Eff 5	13	106.2	1.6	104.7
Eff 6	15	118.5	1.7	116.8
Eff 7	19	113.1	2.4	110.7
Eff 8	21	121.7	2.7	119.0
Eff 9	22	125.3	3.1	122.2
Eff 10	27	121.5	4.3	117.2
Eff 11	28	125.9	4.8	121.0
Eff 12	30	116.6	5.3	111.3
Eff 13	34	113.8	7.0	106.8
Eff 14	36	108.7	7.6	101.1
Eff 15	37	117.2	8.2	108.9
Mass-Volume Influent Concentration =	**198 mg/L**		**Average**	**113.0**
			StDev	**7.2**
			COV	**0.064**

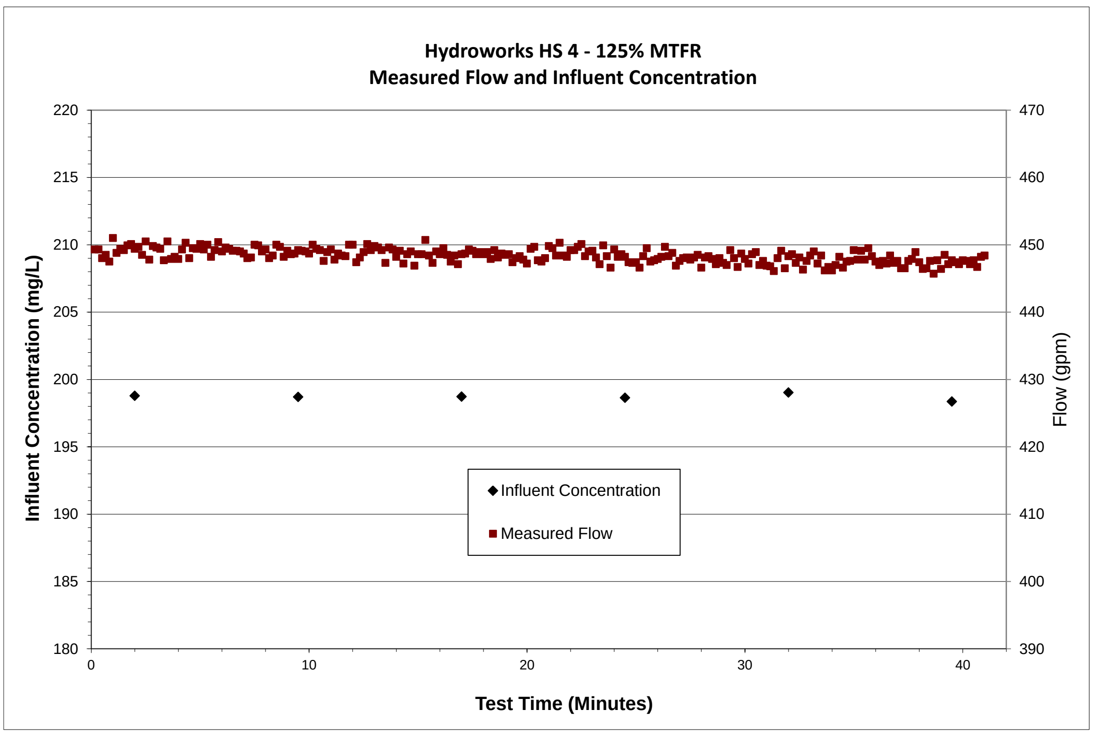

Figure 18: 125% MTFR Measured Flow and Influent Concentrations

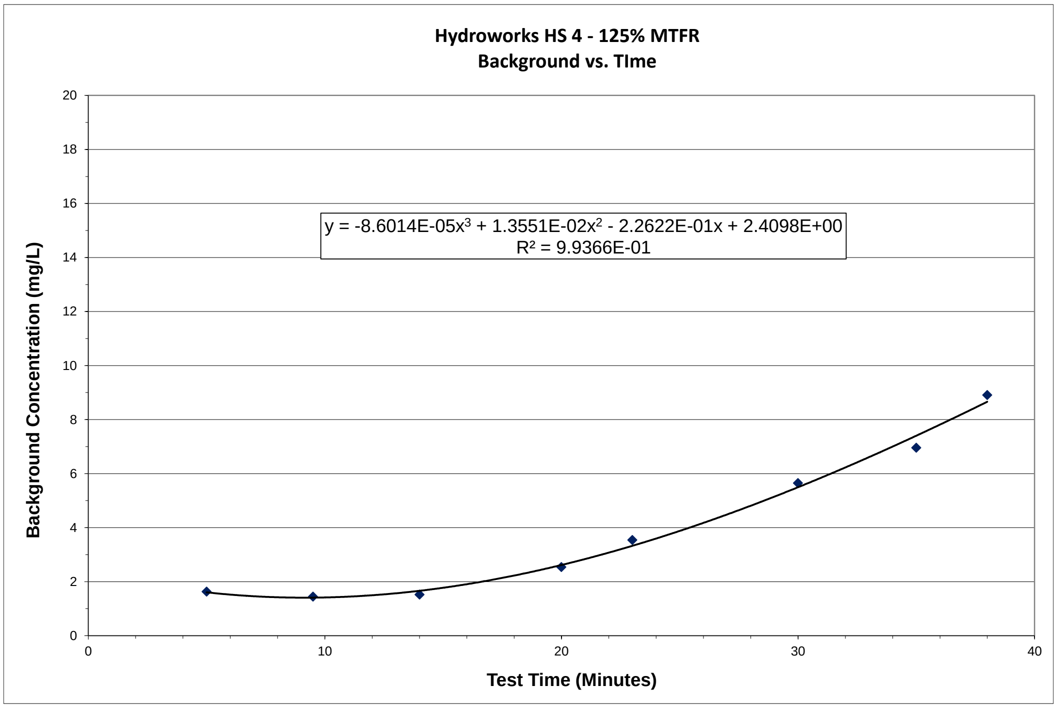

Figure 19: 125% MTFR Measured Background Concentrations

4.3 Sediment Scour Testing

The commercially-available AGSCO NJDEP50-1000 certified sediment mix was utilized for the scour test. Three random samples of the batch mix were analyzed in accordance with ASTM D422-63 (2007), by CTLGroup, an ISO/IEC 17025 accredited independent laboratory, prior to testing. The specified less-than (%-finer) values of the sample average were within the specifications listed in **Column 3** of Table 1, as defined by the protocol. The D_{50} of the 3-sample average was 202 microns. The PSD data of the samples are shown in Table 11 and the corresponding curves, including the initial AGSCO in-house analysis, are shown on Figure 20.

Table 11: PSD Analyses of AGSCO NJDEP50-1000 Batch Mix

Particle size (µm)	NJDEP %-Finer Specifications	Test Sediment Particle Size (%-Finer)			
		Sample 1	Sample 2	Sample 3	Average
1000	100	100	100	100	**100**
500	90	95	95	95	**95**
250	55	58	58	59	**58**
150	40	41	41	42	**41**
100	25	23	23	23	**23**
75	10	10	10	11	**10**
50	0	1	1	1	**1**

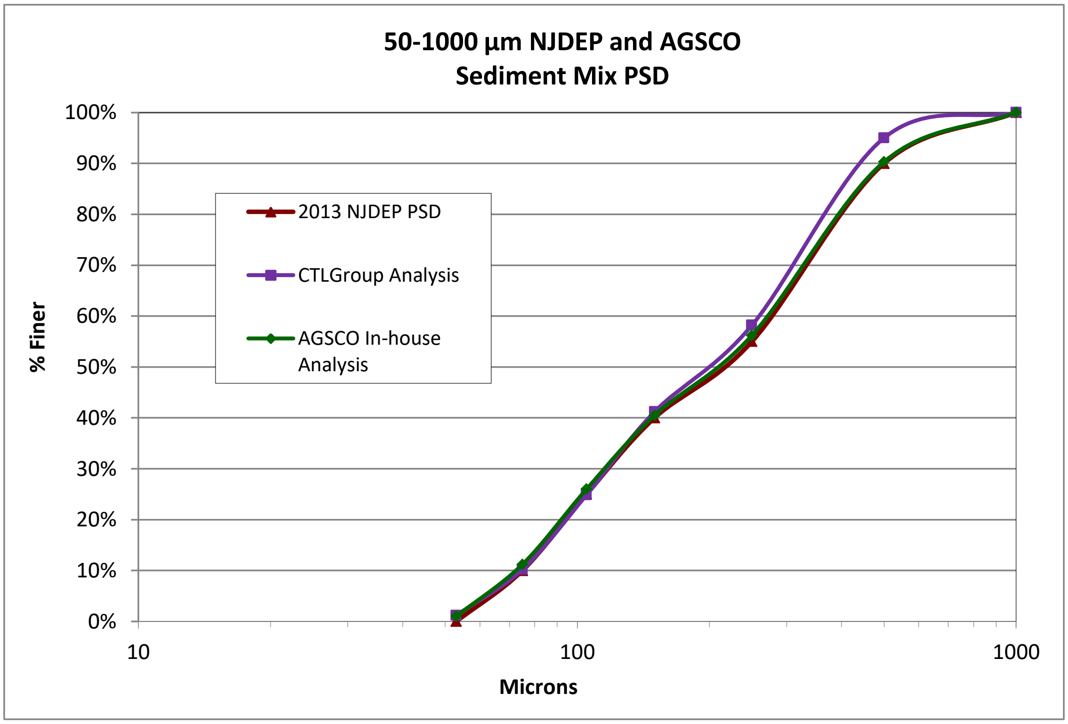

Figure 20: PSD Curves of AGSCO Batch Analysis and NJDEP Specifications

The scour test was conducted with the 50% capacity (6”) false floor installed. An additional 4” of the 50-1000 micron test sediment was preloaded on top of the false floor, resulting in the unit being preloaded to the 83% storage capacity of 10”.

The test was conducted at a target flow of 900 gpm, which is equal to 228% MTFR. The flow data was recorded every 5 seconds throughout the test and is shown on Figure 21**.** The target flow was reached within 5 minutes of initiating the test. The average recorded steady-state flow was 903 gpm, with a COV of 0.002. The recorded water temperature was 66.2 degrees F.

Eight background samples were collected throughout the duration of the test. The measured concentrations ranged from 1.2 to 3.1 mg/L, with an average concentration of 2.2 mg/L.

A total of 15 effluent samples were collected throughout the test. The measured concentrations ranged from 10.9 to 30.3 mg/L, with an average concentration of 16.8 mg/L. The average adjusted effluent concentration for the test was 14.6 mg/L. The effluent and background concentration data is shown in Table 12 and on Figure 22.

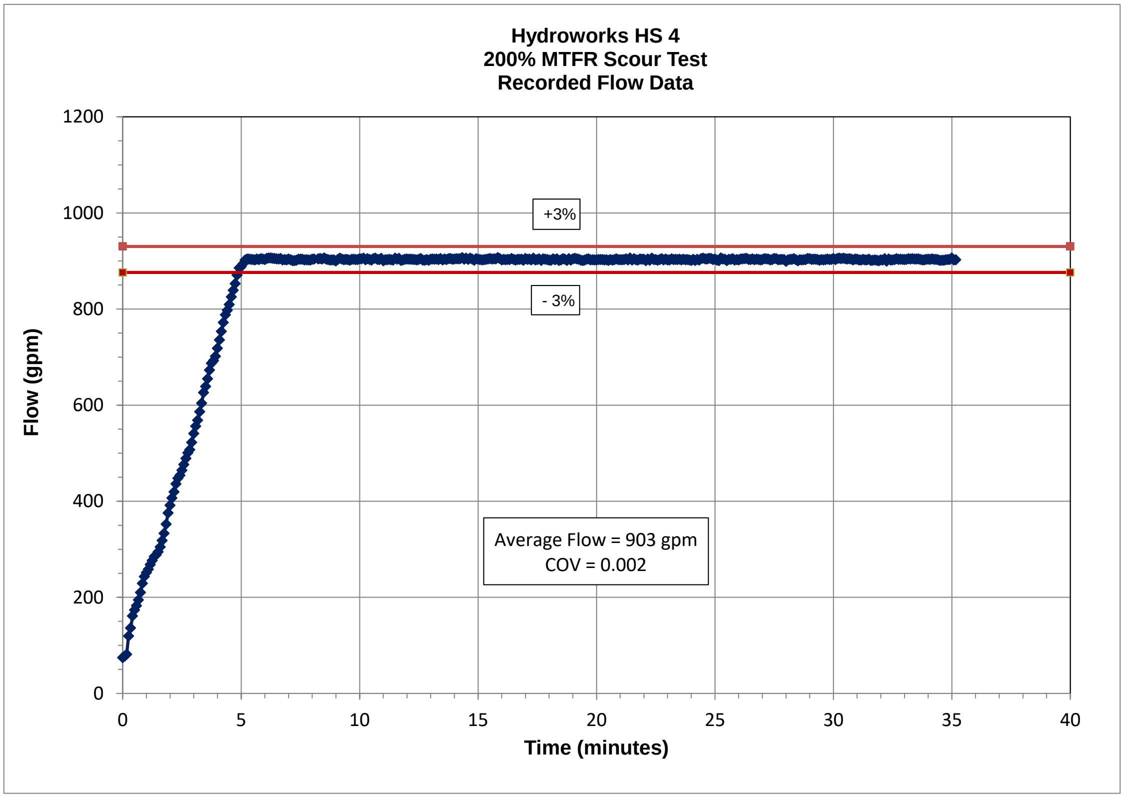

Figure 21: Scour Test Recorded Flow Data

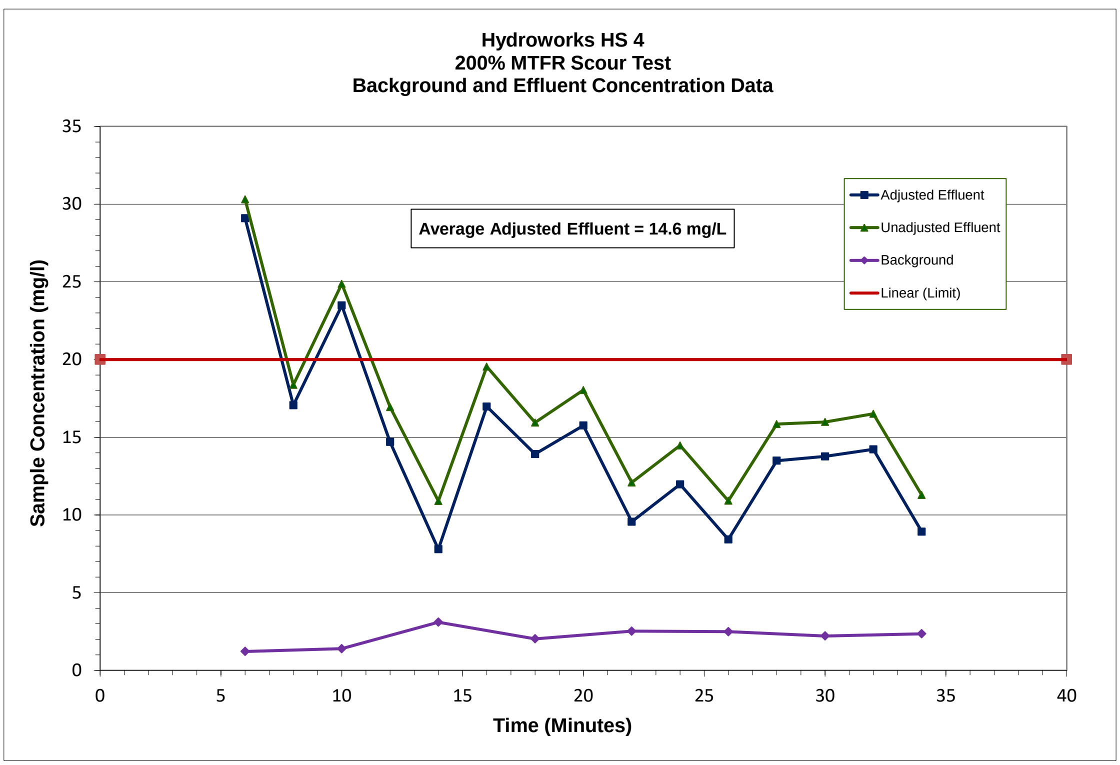

Figure 22: Measured Background and Effluent Concentrations

Table 12: Background and Effluent Concentration Data

Sample ID	Timestamp (minutes)	Effluent Concentration (mg/L)	Background Concentration (mg/L)	Adjusted Effluent Concentration (mg/L)
EFF 1	6	30.3	1.2	29.1
EFF 2	8	18.4	1.3	17.1
EFF 3	10	24.9	1.4	23.5
EFF 4	12	16.9	2.2	14.7
EFF 5	14	10.9	3.1	7.8
EFF 6	16	19.5	2.6	16.9
EFF 7	18	15.9	2.0	13.9
EFF 8	20	18.0	2.3	15.7
EFF 9	22	12.1	2.5	9.6
EFF 10	24	14.5	2.5	12.0
EFF 11	26	10.9	2.5	8.4
EFF 12	28	15.8	2.4	13.4
EFF 13	30	16.0	2.2	13.8
EFF 14	32	16.5	2.3	14.2
EFF 15	34	11.3	2.4	8.9
	Average	**16.8**	**2.2**	**14.6**

4.4 Hydraulic Characteristics

Piezometer taps were installed in the unit as described in **Section 3.2**. Flow (gpm) and water level (ft) within the unit were measured for 15 flows ranging from 0 to 1745 gpm (3.9 cfs). The influent pipe was flowing full at approximately 1500 gpm. The entrance to the effluent pipe was submerged at approximately 1745 gpm. The flow reached bypass at approximately 430 gpm. The recorded data and calculated losses are shown in Table 13**.** The Elevation Curves for each pressure tap location are shown on Figure 23. The pressure data for the inlet and outlet pipes were corrected for energy as discussed in **Section 3.8.1.**

Table 13:
Recorded Flow and Elevation Data

Measured Flow		Water Elevations (adjusted to outlet invert)						Losses			
		Inlet Pipe	Inlet Area	Pretreatment Channel	Inner Chamber	Outlet Shelf	Outlet Pipe	Inlet El. (A')	Outlet El. (E')	System Energy Loss	Loss Coeff.
		A		B	C	D	E	Corrected for Energy	Corrected for Energy	A'-E'	Outlet Area
gpm	cfs	ft	sq-ft	ft	ft	ft	ft	ft	ft	ft	Cd
0	0	0.170	0.000	0.000	0.000	0.000	-0.009	0.170	0.000	0.000	0.000
25.0	0.06	0.249	0.032	0.153	0.129	0.128	0.064	0.297	0.155	0.142	0.025
50.2	0.11	0.284	0.054	0.201	0.187	0.186	0.095	0.350	0.211	0.139	0.050
100.4	0.22	0.326	0.086	0.284	0.267	0.262	0.144	0.432	0.279	0.153	0.095
150.9	0.34	0.357	0.111	0.360	0.330	0.321	0.185	0.499	0.332	0.166	0.137
202.1	0.45	0.389	0.140	0.433	0.389	0.372	0.219	0.551	0.382	0.169	0.182
278.1	0.62	0.520	0.270	0.545	0.468	0.433	0.265	0.602	0.444	0.157	0.260
350.1	0.78	0.647	0.412	0.653	0.539	0.484	0.300	0.703	0.500	0.203	0.288
431.2	0.96	0.802	0.592	0.803	0.616	0.541	0.342	0.843	0.552	0.291	0.296
502.4	1.12	0.858	0.657	0.871	0.672	0.596	0.371	0.903	0.598	0.305	0.337
602.1	1.34	0.916	0.722	0.927	0.728	0.639	0.418	0.970	0.654	0.316	0.397
702.1	1.56	0.960	0.771	0.973	0.779	0.702	0.461	1.024	0.707	0.317	0.462
999.6	2.23	1.094	0.909	1.091	0.906	0.797	0.571	1.187	0.856	0.332	0.643
1514.0	3.37	1.289	1.054	1.295	1.141	1.024	0.724	1.448	1.088	0.360	0.934
1745.4	3.89	1.404	1.069	1.409	1.271	1.199	0.728	1.610	1.205	0.405	1.016

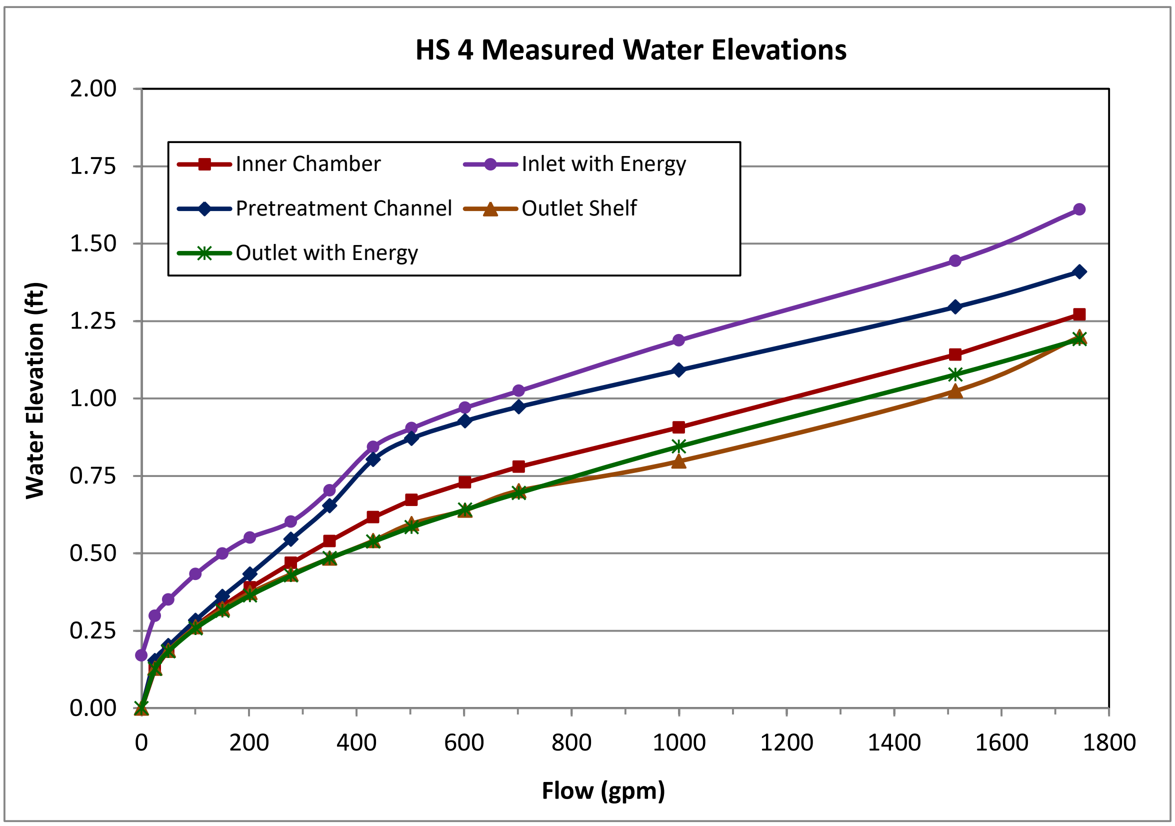

Figure 23: Measured Flow vs Water Elevations

As seen on Figure 24, the calculated system energy loss (influent to effluent) ranged from 0 to 0.089 m at the point of bypass. The loss decreased as expected due to bypass flow and started increasing once the water elevation reached the top of the outlet pipe. The loss coefficient (Cd) for the insert was based on the area of the insert outlet (0.75 ft^2). The Cd values prior to bypass ranged from 0.03 to 0.30.

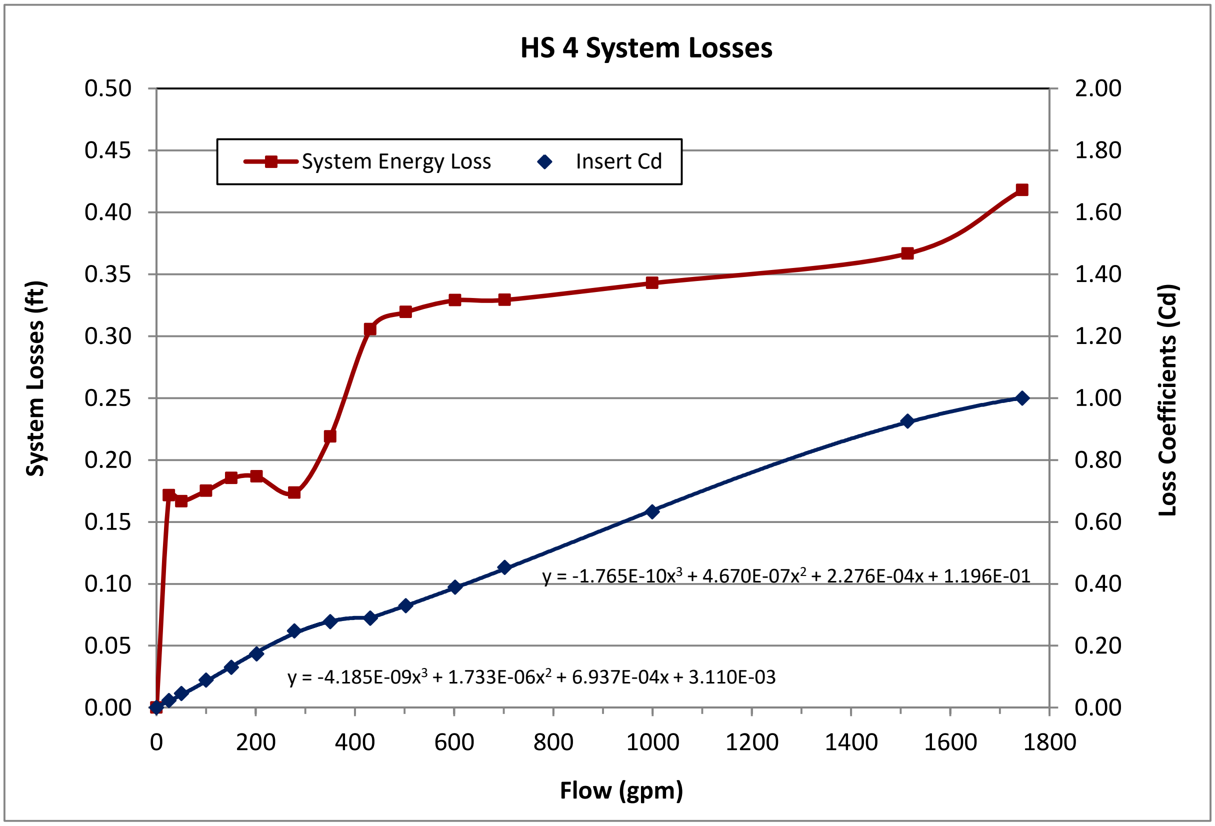

Figure 24: Calculated Losses and Insert Outlet Cd

5.0 Conclusions

The Hydroworks HS 4 Stormwater Treatment Unit achieved removal efficiencies ranging from 42.8% to 58.5%, using the NJDEP 1-1000 micron sediment PSD. The NJDEP weighted removal efficiency was 50.1%, which meets the 50% acceptance criterion.

A 200% MTFR on-line sediment scour test was performed with the collection sump preloaded to 83% of the capture capacity (10”), using the NJDEP 50-1000 micron sediment PSD. The test resulted in an average effluent concentration of 14.6 mg/L, which meets the on-line acceptance criterion.

Hydraulic testing was conducted at flows ranging from 0 to 1745 gpm. Bypass was reached at 431 gpm. The maximum calculated system loss at 1745 gpm was 0.41 ft.

6.0 Nomenclature and Abbreviations

A	= area	(L^2)
Cd	= coefficient of discharge	
Ci	= influent sediment concentration	(M/L^3)
Cfs	= cubic feet per second	(L^3/T)
COV	= coefficient of variance	
D	= diameter	(L)
D_{50}	= median particle size	(L)
DA	= data acquisition	
DP	= differential pressure	(ΔL)
°F	= degree Fahrenheit	(T)
ft.	= feet	(L)
ft^3	= cubic feet	(L^3)
g	= grams	(M)
g	= gravity	(L/T^2)
gpm	= gallons per minute	(L^3/T)
H	= head	(L)
Hz	= hertz	(T)
Kg	= kilogram	(M)
L	= liters	(L^3)
mg/L	= milligram per liter	(M/L^3)
min	= minute	(T)
PSD	= particle size distribution	
Q	= flow	(L^3/T)
sec	= seconds	(T)
SLR	= surface loading rate	($L^3/T/L^2$)
SSC	= suspended solids concentration	
V	= velocity	(L/T)
w	= moisture content (%)	

7.0 References

ASTM (2013), "Standard Test Methods for Determining Sediment Concentration in Water Samples", Annual Book of ASTM Standards, D3977-97, Vol. 11.02.

ASTM (2007), "Standard Test Method for Particle Size Analysis of Soils", Annual Book of ASTM Standards, D422-63, Vol. 04.08.

ASTM (2007), "Standard Test Methods for Determination of Water (Moisture) Content of Soil by Direct Heating", Annual Book of ASTM Standards, D4959-07, Vol. 04.08.

ASME (1971), "Fluid Meters Their Theory and Application- Sixth Edition".

NJDEP (2013), "Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device", The New Jersey Environmental Technology Verification Program.

APPENDIX A
ALDEN QUALIFICATIONS

Founded in 1894, Alden is the oldest continuously operating hydraulic laboratory in the United States and one of the oldest in the world. From the early days of hydropower development and aviation, through World Wars I and II, and into the modern world defined by environmental needs, Alden has been a recognized leader in the field of fluid dynamics consulting, research and development. In the 21st Century, Alden is a vibrant, growing organization consisting of engineers, scientists, biologists, and support staff in five specialty areas. Much of our work supports the power generating, environmental, manufacturing, and process industries.

Alden offers a scope of specialized services including: conceptual design, detailed design, verification testing, analytical modeling, Computational Fluid Dynamics (CFD), field measurements, physical modeling, precision flow meter calibrations, and field testing. Decades of combined experience in numerical simulation techniques, physical modeling, and field studies provide the broad knowledge that is essential for recognizing which method is best suited to solving a problem.

Unusually large facilities (more than 125,000 square feet of enclosed space) and sophisticated data acquisition systems are available for each study. Approximately twenty buildings, located on thirty acres at our headquarters in Holden, MA are equipped with flow supplies and control systems for conducting hydraulic modeling, verification and equipment testing, fish testing, air/gas flow modeling, and numerous other types of flow testing. Fixed facilities providing air and water flow and an inventory of movable flow related equipment such as pumps, valves, meter devices, fish screens, etc. are located on the premises at our Massachusetts laboratory. Fully equipped and staffed carpentry, machine, and instrumentation shops provide rapid and efficient project support.

Alden has performed verification testing on approximately twenty Hydrodynamic Separator and Filtration Manufactured Treatment Devices (MTDs) for multiple manufacturers under various state and federal testing protocols. Alden's senior stormwater engineer, James Mailloux, has served on the ASTM and SWEMA Stormwater Technical committees, providing guidance in the area of testing methodologies. He has a Master's Degree in Environmental Engineering from Worcester Polytechnic Institute and has been conducting testing at Alden for more than 25 years. Mr. Mailloux has contributed to articles related to laboratory testing in Stormwater Magazine, as well as presented on multiple testing and regulatory topics at various conferences, including StormCon, WefTec and the National Precast Concrete Association training seminars.