Verification Testing of the Hydroworks HD3 HydroDome Stormwater Treatment Unit In Accordance with the NJDEP Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Device, 2013

Technical Evaluation Report

Alden Report No. : 1202HD3-NJCAT-R0

Submitted to:

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1.0 Introduction

Under a contract from Hydroworks, LLC (Hydroworks), verification testing of a 3 ft diameter HydroDome stormwater treatment unit (HD3), was conducted at Alden Research Laboratory, Inc. (Alden), Holden, Massachusetts. The purpose of the testing was to define the performance characteristics of the HD3 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 (or greater).

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

Prior to starting the performance testing program, a quality assurance project plan (QAPP) was submitted to, and approved by, the New Jersey Corporation for Advanced Technology (NJCAT) as per the NJDEP certification process.

2.0 Test Unit Description

The HD3 test unit was a full scale 3 ft diameter by approximately 9-ft high stormwater treatment device with an internal outlet hood that facilitates the capture of floatables, oil, and sediment. The test tank was fabricated from plastic and included 18-inch diameter inlet and outlet pipes, oriented along the centerline of the tank. The pipe inverts were located 60 inches above the sump floor and were set with 1% slopes. The 100% and 50% sediment sump storage depths were 12 inches and 6 inches, respectively. The effective treatment sedimentation area was 7.07 ft^2.

Flow entering the unit is conveyed into the hood through openings in the side and perforations in a bottom plate. Flow is conveyed up two outer channels and down a center channel containing an outlet orifice by means of a siphon and then conveyed to the outlet pipe. Excessive flow is allowed to pass over an internal bypass weir. . Drawings of the HD3 test unit are shown on Figure 1. A photograph showing the unit installed in the test loop is shown on Figure 2.

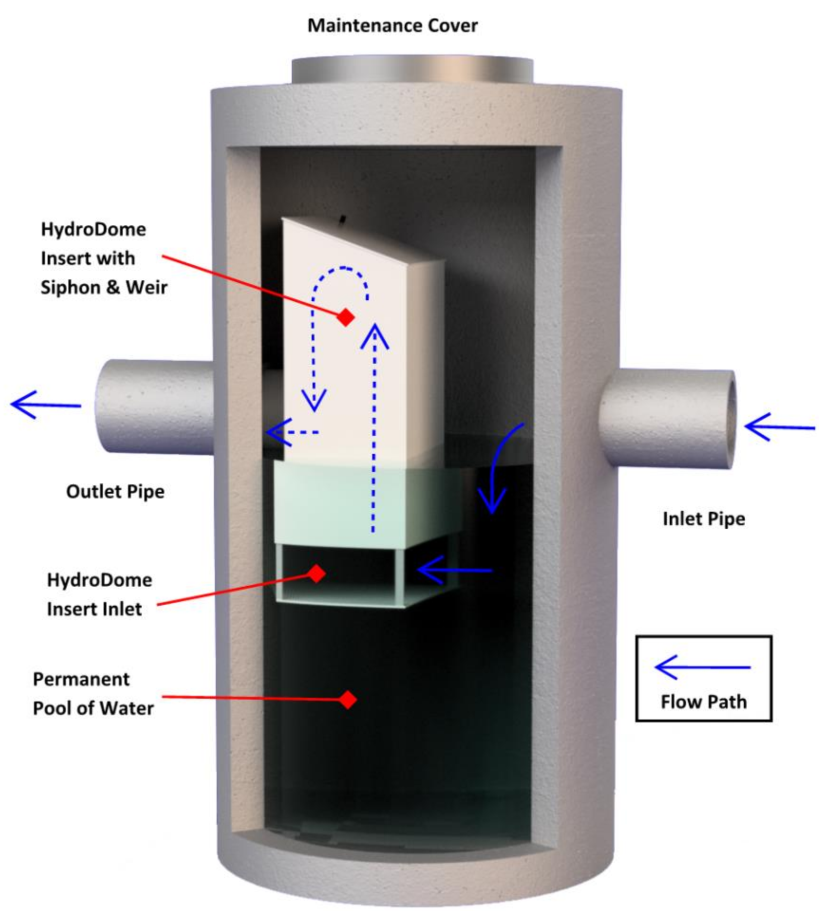

Figure 1: Drawing of the Hydroworks HD3 Treatment Unit

Figure 2: HD3 Test Unit Installed in Alden Flow Loop

3.0 Materials and Methods

3.1 Experimental Design

The HD3 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 9 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. Thirty (30) feet of straight 18-inch pipe conveyed the metered flow to the unit. Eight (8) feet of straight 18-inch effluent piping returned the test flow back to the supply sump as a free discharge. The influent and effluent pipes were set at 1% slopes. A 12-inch tee was located 5 pipe-diameters (7.5 ft) upstream of the test unit for injecting the test sediment into the crown of the influent pipe. Sediment injection was accomplished with the use of a volumetric screw feeder. The end-of-pipe grab sampling methodology was used for the scour and removal efficiency tests. An iso-kinetic sampler was installed in the upstream vertical riser pipe for collection of the background samples.

Filtration of the supply sump was performed with an inline filter wall containing 1-micron filter bags.

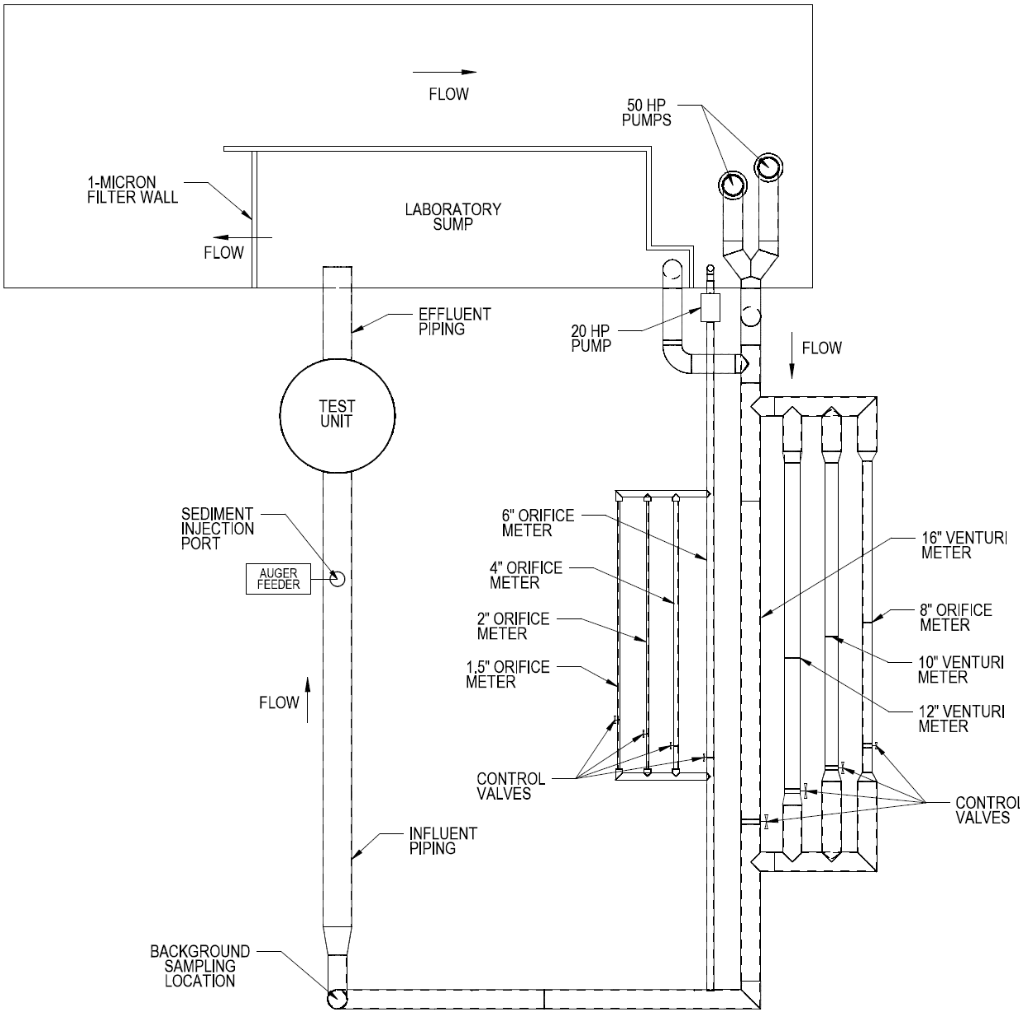

Figure 3: Plan View of Alden Flow Loop

3.2 Hydraulic Testing

The HD3 unit was tested with clean water to determine its hydraulic characteristic curves. Flow and water level measurements were recorded at 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 Omegadyne 0-2.5 psi Pressure Transducer (PT). 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 5 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 one pipe-diameter upstream and downstream of the unit, as well as within the treatment tank.

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 inches, as stated by Hydroworks. All tests were run with clean water containing a background sediment solids concentration (SSC) of ≤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 column 2 in Table 1. The sediment was silica based, with a specific gravity of 2.65. 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 was 0.10. The reported test 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 D4959-16 for each test conducted. The allowed supply water maximum temperature of 80 degrees F was met for all tests conducted.

A background sample of the supply water was collected with each odd-numbered effluent sample, using an iso-kinetic sampler. A 3rd-order background curve and corresponding equation was developed for calculating the adjusted effluent concentrations.

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 following the initiation of sediment injection. The three detention-time criterion was followed 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. A minimum of 4" of 50-1000 micron sediment was pre-loaded in the collection sump to the 50% 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 dry-weather condition 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 a minimum of 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.

Each effluent grab sample for sediment concentration analysis was collected from the end of the effluent pipe by sweeping a 1-liter large-mouth bottle through the effluent stream.

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 (1.5", 2", 4", 6" or, 8"). Each meter was fabricated per ASME guidelines and calibrated in Alden's Calibration Department. Flows were set with a control 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. The test flow was averaged and recorded every 5-20 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 ±1%. The maximum allowable Coefficient of Variance (COV) for flow documentation was 0.03. A photograph of the flow meter array 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 measurement was documented at the start and end of each test, to assure an acceptable testing temperature of ≤80 degrees F.

3.5.3 Pressure Head

Pressure head measurements were recorded at multiple locations using piezometer taps and an Omegadyne PX419, 0 - 2.5 psi pressure transducer (PT), 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. A photograph of the pressure instrumentation is shown on Figure 5.

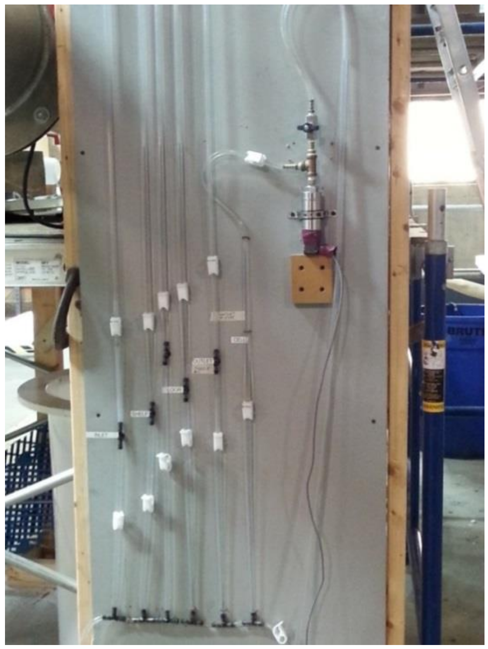

Figure 5: Pressure Measurement Instrumentation

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" to 1", depending on the test flow. Each auger screw, driven with a variable-speed drive, was calibrated with the test sediment prior to testing. The pre-test calibration, as well as test verification of the sediment feed was accomplished by collecting 1-minute (maximum) timed dry samples and weighing them on a calibrated Ohaus® 4000g x 0.1g, model SCD-010 digital scale. The allowable COV for sediment feed was 0.10.

Figure 6: Photograph Showing Variable-speed Auger Feeder

3.5.5 Sample Collection

Background concentration samples were collected from the center of the vertical riser pipe upstream of the test unit with the use of a 0.75” isokinetic sampler, shown on Figure 7. The sampler was calibrated for each test flow. All effluent grab samples were collected from the free-discharge at the end of the effluent pipe, using 1-L wide-mouth bottles. All collected samples were a minimum of 0.5L in volume.

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 2019), "Standard Test Methods for Determining Sediment Concentration in Water Samples". Alden has assigned a Non-Detection Limit (NDL) of 1.0 mg/L. To be conservative, all concentrations below the NDL were assigned a value of 0.5 mg/L.

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 voltage signal from the pressure cells. 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.

Excel based data sheets were used to record all sediment related data used for quantifying injection rate, effluent and background sample concentrations, flow, pressure, 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 micron test batches were prepared 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 sample average were within the 2 percentage-point tolerance listed in the protocol. The 50-1000 micron sediment was procured in bulk from AGSCO as certified material. The certification was performed by CTLGroup, an ISO/IEC 17025 accredited independent laboratory, and provided with the material shipment.

3.8 Data Analysis

The following equations and procedures were used in analyzing the data collected on the HD3 test unit:

3.8.1 Hydraulics

The pressure cell was mounted at an elevation of 1.016 ft below the inlet pipe invert. This datum value was subtracted from all recorded measurements to calculate the water height above the invert. The system energy loss across the unit was determined by adding the velocity head to the elevations at 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 = wetted 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).

3.8.2 Removal Efficiency

The injected mass was calculated by:

$$\mathbf{M_{inj} = \Delta M - (\Delta M \ x \ w)} \tag{5}$$

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:

$$\textbf{Removal Efficiency } (\%) = \frac{\left(\begin{array}{c}\textbf{Average Influent}\\ \textbf{Concentration}\end{array}\right) - \left(\begin{array}{c}\textbf{Average Adjusted}\\ \textbf{Effluent Concentration}\end{array}\right)}{\textbf{Average Influent Concentration}} \textbf{ x 100} \tag{6}$$

The background sample concentrations were calculated as follows:

$$\textbf{BG (mg/L) = Sediment Wt (mg) / Sample Volume (L)} \tag{7}$$

The auger injector verification concentrations were determined by the following:

$$\mathbf{C_i = M_f / Q_{avg}} \tag{8}$$

where,

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

The mass/volume influent concentration was calculated as follows:

$$\textbf{Average Influent Concentration} = \frac{(\textbf{Total mass injected})}{\left(\begin{array}{c}\textbf{Total volume of water conveyed into unit}\\ \textbf{during sediment dosing}\end{array}\right)} \textbf{ x 100} \tag{9}$$

3.9 Laboratory Analysis

The following Test Methods were used to analyze the various sediment samples:

- **Sediment Concentration**

  ASTM Designation: D 3977-97 (Re-approved 2019), "Standard Test Methods for Determining Sediment Concentration in Water Samples"

- **Sediment Moisture Content**

  ASTM Designation: D4959-16, "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 provided to NJCAT.

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

Verification of the sediment feed in g/min was performed with the use of a NIST traceable digital stopwatch and 4000g calibrated digital scale. The tare weight of the sample container was recorded prior to collection of each sample. The reported overall mass/volume 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 (2019) 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 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

Sediment test batches of approximately 35 lbs were prepared in individual 5-gallon buckets, which were arbitrarily selected for each removal efficiency test. A well-mixed sample was collected from each test batch 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	NJDEP Minimum Allowance	Test Sediment Particle Size Distribution (percent-finer)								QA / QC Compliant
			Bucket 2	Bucket 3	Bucket 8	Bucket 9	Bucket 10	Bucket 14	Bucket 15	Average	
1000	100%	98%	100%	100%	100%	100%	100%	100%	100%	**100%**	Yes
500	95%	93%	95%	95%	95%	96%	95%	95%	95%	**95%**	Yes
250	90%	88%	89%	89%	89%	89%	89%	89%	89%	**89%**	Yes
150	75%	73%	75%	75%	75%	76%	75%	75%	75%	**75%**	Yes
100	60%	58%	63%	62%	63%	63%	63%	63%	63%	**63%**	Yes
75	50%	50%	55%	54%	55%	55%	55%	55%	55%	**55%**	Yes
50	45%	43%	45%	44%	45%	45%	45%	45%	45%	**45%**	Yes
20	35%	33%	33%	33%	33%	34%	33%	33%	34%	**33%**	Yes
8	20%	18%	21%	21%	22%	22%	22%	21%	22%	**21%**	Yes
5	10%	8%	14%	15%	16%	15%	17%	15%	16%	**15%**	Yes
2	5%	3%	6%	7%	8%	7%	7%	8%	7%	**7%**	Yes
D_{50}	75	75	61	63	62	61	61	62	61	**62**	Yes

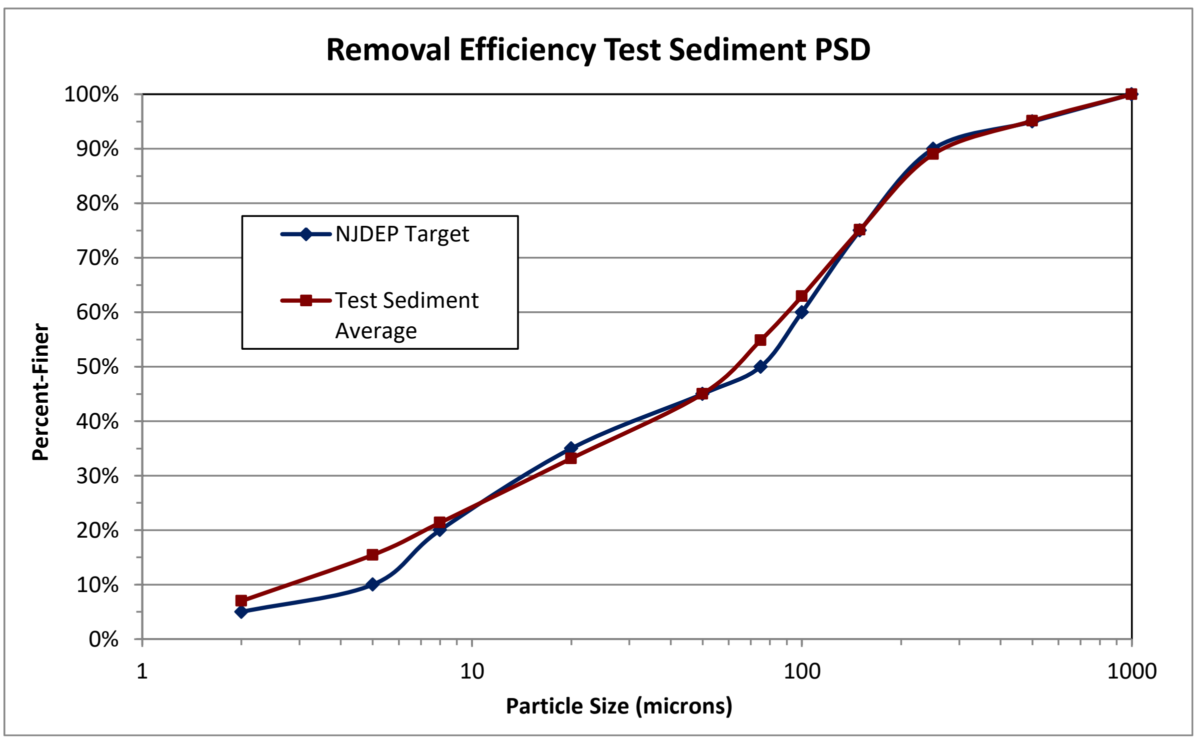

Figure 8: Average Removal Efficiency Test Sediment PSD

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 381.5 gpm, resulting in target flows of 95.4, 190.8, 286.1, 381.5 and 476.9 gpm. 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

Target Flow		Measured Flow		Deviation from Target	Flow Measurement COV	Maximum Temperature	QA / QC Compliant
cfs	gpm	cfs	gpm			Deg. F.	
0.21	95.4	0.21	94.4	-1.1%	0.001	65.4	Yes
0.43	190.8	0.39	173.9	-8.8%	0.002	64.9	Yes
0.64	286.1	0.64	286.3	0.0%	0.002	62.6	Yes
0.85	381.5	0.78	352.3	-7.7%	0.002	63.8	Yes
1.06	476.9	0.98	439.7	-7.8%	0.002	60.8	Yes

Table 4:
Injected Sediment Summary

Flow	Average Injected Concentration	Injector Measurement COV	Mass/Volume Concentration	Injected Mass	Maximum Background Concentration	QA / QC Compliant
gpm	mg/L		mg/L	Lbs	mg/L	
94.4	200	0.01	206	28.7	7.0	Yes
173.9	199	0.00	196	28.1	2.7	Yes
286.3	199	0.00	220	30.0	7.6	Yes
352.3	201	0.00	188	28.7	8.0	Yes
439.7	201	0.01	190	30.7	8.4	Yes

Additional Tests:

Two additional tests were conducted at 243 gpm and 538 gpm during the development of the removal curve. These tests fell outside of the allowable 10% of the target MTFR and were not used for calculating the weighted removal. All seven tests are included in the removal curve and corresponding equation.

The calculated removal efficiencies ranged from 41.8% to 69.9%, with a weighted removal of 58.5% for the 5 flows tested. The MTFR removal summary is shown Table 5. The removal curve and corresponding equation using all 7 tests are shown on Figure 9. The weighted removal at the target MTFR flows using the curve equation was 54.9%.

Table 5:
Removal Efficiency Summary

Flow	Influent Concentration	Average Effluent Concentration	Removal Efficiency	NJDEP Weight Factor	NJDEP Wt'd Removal Efficiency
gpm	mg/L	mg/L	%		%
94.4	206.2	70.6	65.8	0.25	**16.4**
173.9	196.3	59.1	69.9	0.30	**21.0**
286.3	219.9	106.3	51.7	0.20	**10.3**
352.3	188.4	106.4	43.6	0.15	**6.5**
439.7	190.2	110.7	41.8	0.10	**4.2**
				1.0	**58.5**

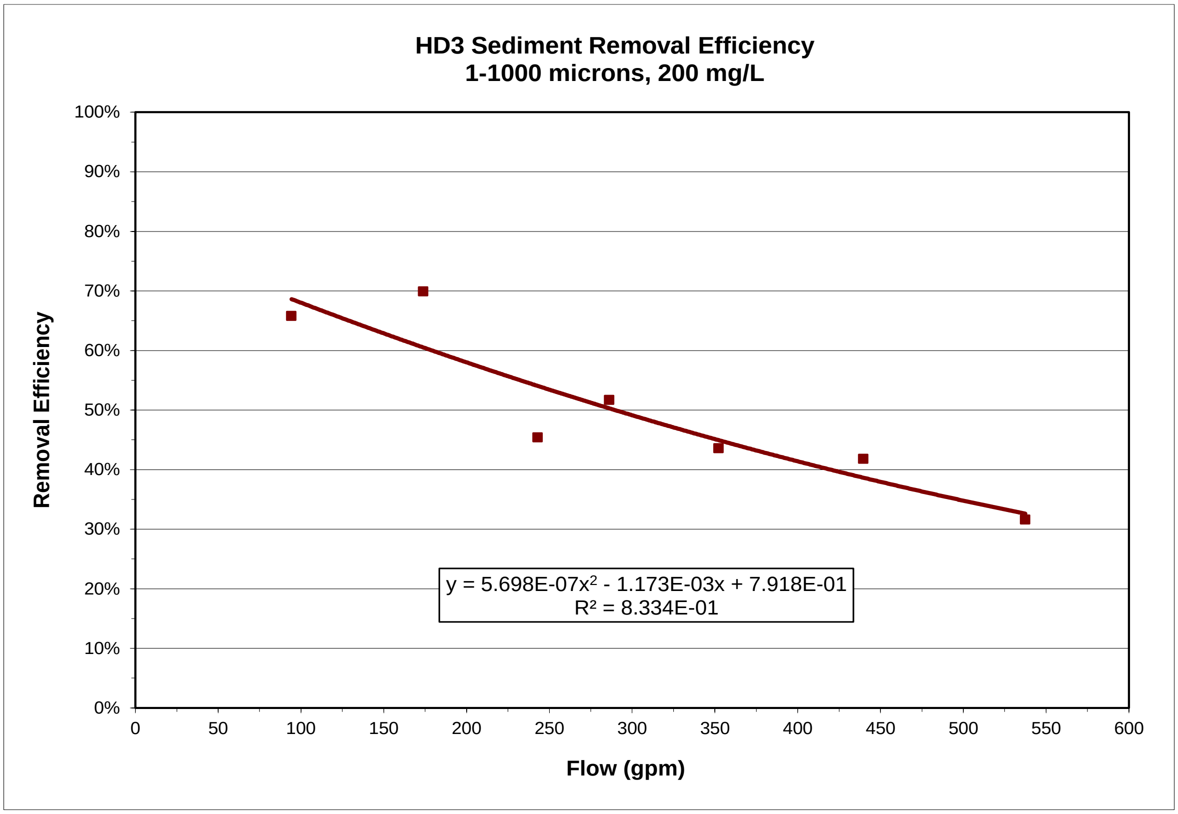

Figure 9: Hydroworks HD3 Removal Efficiency Curve

4.2.1 25% MTFR (95 gpm)

The test was conducted at 94 gpm over a period of 3 hours. The test parameters and sampling results are shown in Table 6.

Table 6:
25% MTFR Test Parameters and Collected Data

Injection Sample	Sample Time minutes	Sample ID	Sample Time minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Inj 1	1	**Eff 1, BG 1**	15	75.6	0.5	75.1
Inj 2	36	**Eff 2**	22	72.5	0.5	72.0
Inj 3	71	**Eff 3, BG 2**	29	67.9	0.5	67.4
Inj 4	106	**Eff 4**	50	73.6	1.7	71.9
Inj 5	141	**Eff 5, BG 3**	57	67.8	2.0	65.8
Inj 6	176	**Eff 6**	64	69.6	2.2	67.3
Injection Sampling Duration (seconds)	60	**Eff 7, BG 4**	85	73.1	3.0	70.2
		Eff 8	92	77.3	3.2	74.1
		Eff 9, BG 5	99	71.9	3.5	68.4
Detention Time (minutes)	3.7	**Eff 10**	120	79.3	4.3	75.0
		Eff 11, BG 6	127	78.1	4.6	73.6
		Eff 12	134	74.7	4.9	69.8
Total Run Time (minutes)	183.7	**Eff 13, BG 7**	155	77.9	6.0	71.9
		Eff 14	162	76.0	6.4	69.6
		Eff 15, BG 8	169	73.4	6.8	66.6
Mass/Volume Influent Concentration (mg/L)	206	**94 gpm**			**Average**	**70.6**
					Removal Efficiency	**65.8%**

The resulting removal efficiency was 65.8%. The test flow was averaged and recorded every 20 seconds throughout the test. The average recorded test flow was 94.4 gpm, with a COV of 0.001. The recorded temperature for the test did not exceed 66 degrees F.

The injection feed rate of 71.2 g/min was verified by collecting 1-minute weight samples from the injector. Six influent injection measurements were taken throughout the test duration. The calculated concentrations for the full test ranged from 199 to 203 mg/L, with a mean of 200 mg/L and COV of 0.01. The total mass injected into the unit was 28.7 lbs. The calculated mass-flow concentration for the test was 206 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 0.7 (NDL) to 7.0 mg/L.

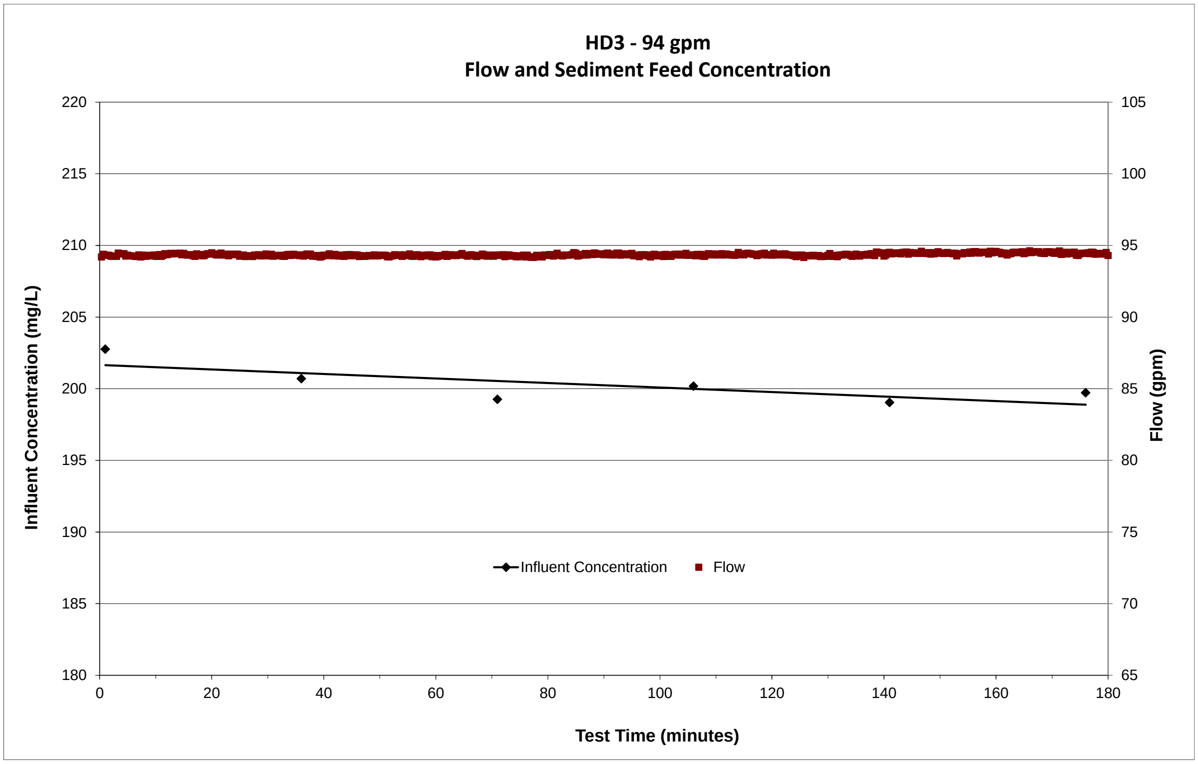

Figure 10: 25% MTFR Measured Flow and Influent Concentrations

4.2.2 50% MTFR (191 gpm)

The test was conducted at 174 gpm over a period of 1.75 hours. The test parameters and sampling results are shown in Table 7.

Table 7
50% MTFR Test Parameters and Collected Data

Injection Sample	Sample Time (minutes)	Sample ID	Sample Time (minutes)	Effluent Concentration (mg/L)	Background Concentration (mg/L)	Adjusted Effluent (mg/L)
Inj 1	1	**Eff 1, BG 1**	10	45.7	0.5	45.2
Inj 2	19	**Eff 2**	13	63.8	0.5	63.3
Inj 3	37	**Eff 3, BG 2**	16	45.1	0.5	44.6
Inj 4	55	**Eff 4**	28	41.0	0.5	40.5
Inj 5	73	**Eff 5, BG 3**	31	45.3	0.5	44.8
Inj 6	91	**Eff 6**	34	46.2	0.5	45.7
Injection Sampling Duration (seconds)	60	**Eff 7, BG 4**	46	60.3	0.5	59.8
		Eff 8	49	51.8	0.6	51.1
		Eff 9, BG 5	52	49.6	0.5	49.1
Detention Time (minutes)	1.98	**Eff 10**	64	66.7	1.2	65.5
		Eff 11, BG 6	67	53.7	1.4	52.3
		Eff 12	70	53.4	1.5	51.9
Total Run Time (minutes)	105	**Eff 13, BG 7**	82	94.1	2.3	91.7
		Eff 14	85	96.2	2.6	93.6
		Eff 15, BG 8	88	90.1	2.8	87.3
Mass/Volume Influent Concentration (mg/L)	196	**173 gpm**			**Average**	**59.1**
					Removal Efficiency	**69.9%**

The resulting removal efficiency was 69.9%. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 173.9 gpm, with a COV of 0.002. The recorded temperature for the test did not exceed 65 degrees F.

The injection feed rate of 131.6 g/min was verified by collecting 1-minute weight samples from the injector. Six influent injection measurements were taken throughout the test duration. The calculated concentrations for the full test ranged from 198 to 200 mg/L, with a mean of 199 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 196 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 0.0 (NDL) to 2.7 mg/L.

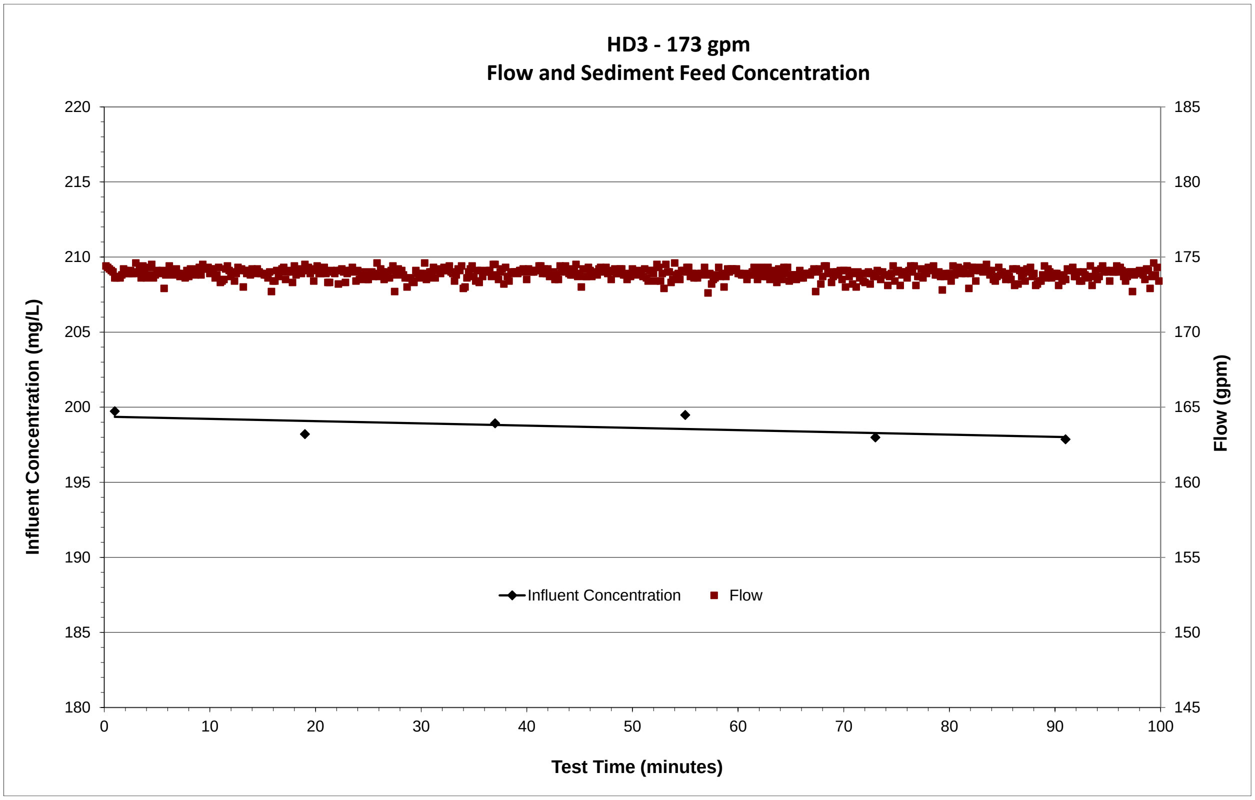

Figure 11: 50% MTFR Measured Flow and Influent Concentrations

4.2.3 75% MTFR (286 gpm)

The test was conducted at 286 gpm over a period of 1 hour. The test parameters and sampling results are shown in Table 8.

Table 8
75% MTFR Test Parameters and Collected Data

Injection Sample	Sample Time minutes	Sample ID	Sample Time minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Inj 1	1	**Eff 1, BG 1**	6	98.0	2.1	95.9
Inj 2	13	**Eff 2**	8	102.0	2.4	99.6
Inj 3	25	**Eff 3, BG 2**	10	105.8	2.6	103.2
Inj 4	37	**Eff 4**	18	119.2	3.1	116.1
Inj 5	49	**Eff 5, BG 3**	20	106.4	3.2	103.2
Inj 6	60	**Eff 6**	22	111.2	3.2	107.9
Injection Sampling Duration (seconds)	60	**Eff 7, BG 4**	30	120.2	3.5	116.7
		Eff 8	32	119.1	3.5	115.6
		Eff 9, BG 5	34	102.5	3.6	98.9
Detention Time (minutes)	1.20	**Eff 10**	42	100.5	4.2	96.3
		Eff 11, BG 6	44	105.8	4.5	101.3
		Eff 12	46	108.1	4.8	103.3
Total Run Time (minutes)	64	**Eff 13, BG 7**	54	116.7	6.6	110.0
		Eff 14	56	122.1	7.2	114.9
		Eff 15, BG 8	58	118.9	8.0	111.0
Mass/Volume Influent Concentration (mg/L)	220	**286 gpm**			**Average**	**106.3**
					Removal Efficiency	**51.7%**

The resulting removal efficiency was 51.7%. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 286.3 gpm, with a COV of 0.002. The recorded temperature for the test did not exceed 63 degrees F.

The injection feed rate of 216.6 g/min was verified by collecting 1-minute weight samples from the injector. Six influent injection measurements were taken throughout the test duration. The calculated 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 30.0 lbs. The calculated mass-flow concentration for the test was 220 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 2.3 to 7.6 mg/L.

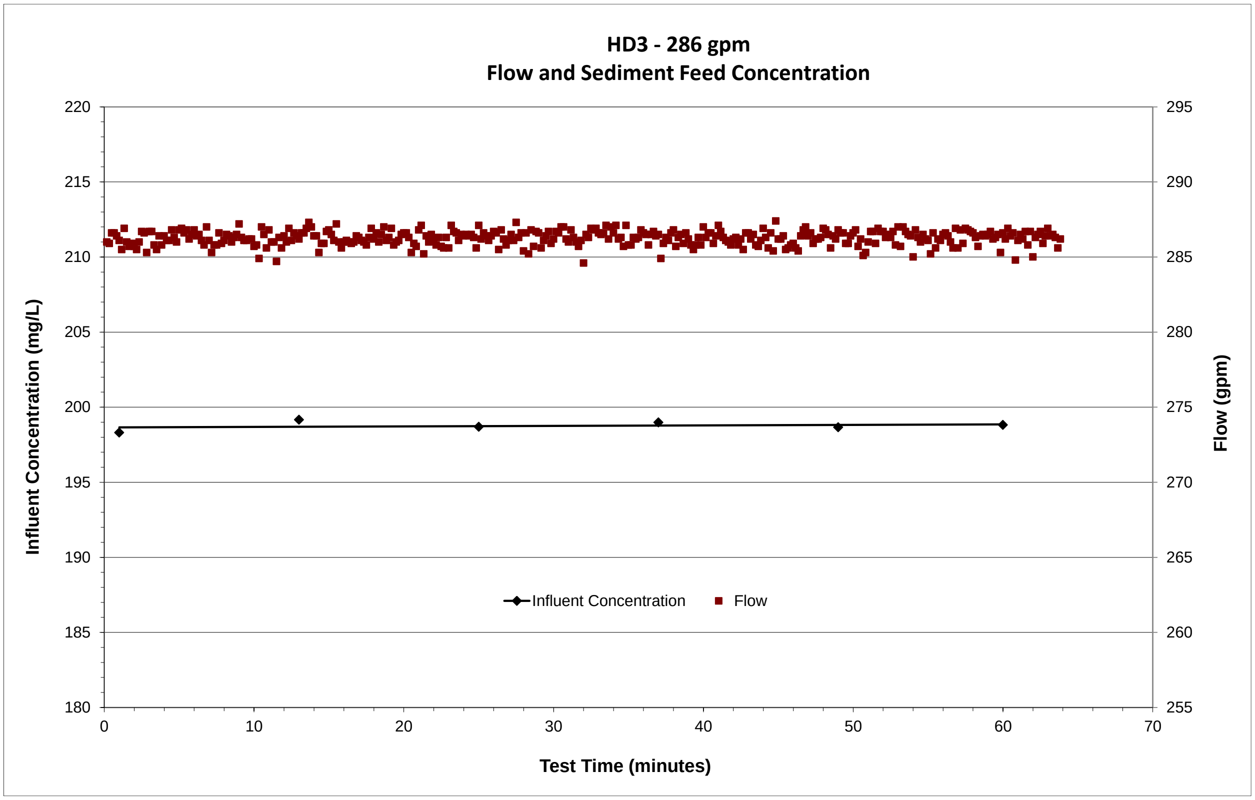

Figure 11: 75% MTFR Measured Flow and Influent Concentrations

4.2.4 100% MTFR (382 gpm)

The test was conducted at 352 gpm over a period of 1 hour. The test parameters and sampling results are shown in Table 9.

Table 9
100% MTFR Test Parameters and Collected Data

Injection Sample	Sample Time minutes	Sample ID	Sample Time minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Inj 1	1	**Eff 1, BG 1**	5	109.3	0.5	108.8
Inj 2	12	**Eff 2**	7	112.9	0.5	112.4
Inj 3	23	**Eff 3, BG 2**	9	119.4	0.5	118.9
Inj 4	34	**Eff 4**	16	120.2	0.7	119.5
Inj 5	45	**Eff 5, BG 3**	18	101.1	0.5	100.6
Inj 6	56	**Eff 6**	20	123.0	0.9	122.0
Injection Sampling Duration (seconds)	60	**Eff 7, BG 4**	27	104.6	1.7	102.8
		Eff 8	29	113.4	2.1	111.3
		Eff 9, BG 5	31	102.3	2.4	99.9
Detention Time (minutes)	0.97	**Eff 10**	38	128.0	3.8	124.2
		Eff 11, BG 6	40	121.0	4.3	116.7
		Eff 12	42	125.3	4.8	120.5
Total Run Time (minutes)	58.5	**Eff 13, BG 7**	49	82.3	6.5	75.8
		Eff 14	51	95.4	7.0	88.3
		Eff 15, BG 8	53	81.1	7.5	73.6
Mass/Volume Influent Concentration (mg/L)	188	**353 gpm**			**Average**	**106.4**
					Removal Efficiency	**43.6%**

The resulting removal efficiency was 43.6%. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 352.3 gpm, with a COV of 0.002. The recorded temperature for the test did not exceed 64 degrees F.

The injection feed rate of 267.5 g/min was verified by collecting 1-minute weight samples from the injector. Six influent injection measurements were taken throughout the test duration. The calculated concentrations for the full test ranged from 200 to 202 mg/L, with a mean of 201 mg/L and COV of 0.00. The total mass injected into the unit was 28.7 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 0.0 (NDL) to 8.0 mg/L.

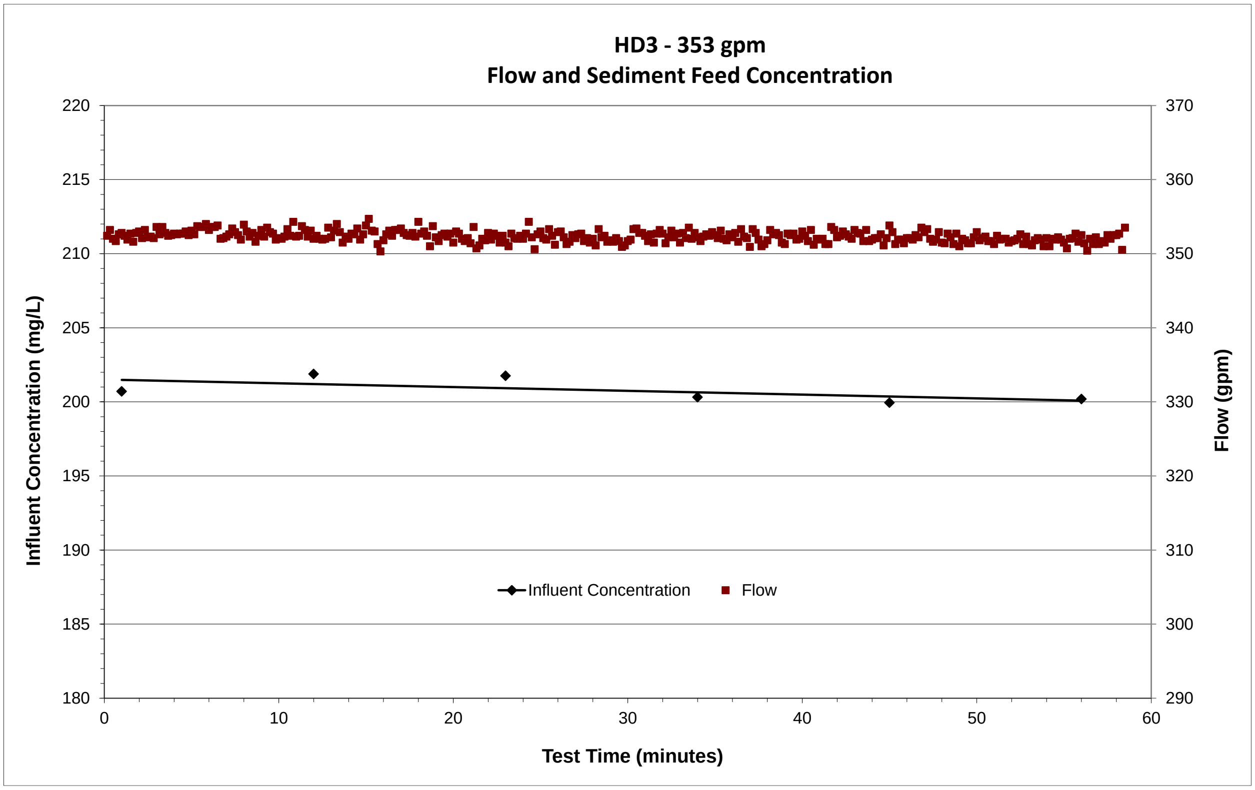

Figure 12: 100% MTFR Measured Flow and Influent Concentrations

4.2.5 125% MTFR (477 gpm)

The test was conducted at 442 gpm over a period of 48 minutes. The test parameters and sampling results are shown in Table 10.

Table 10
125% MTFR Test Parameters and Collected Data

Injection Sample	Sample Time minutes	Sample ID	Sample Time minutes	Effluent Concentration mg/L	Background Concentration mg/L	Adjusted Effluent mg/L
Inj 1	1	**Eff 1, BG 1**	5	108.8	1.2	107.6
Inj 2	10	**Eff 2**	6	105.3	1.2	104.1
Inj 3	19	**Eff 3, BG 2**	7	121.1	1.1	119.9
Inj 4	28	**Eff 4**	14	123.0	1.4	121.6
Inj 5	37	**Eff 5, BG 3**	15	128.3	1.5	126.9
Inj 6	45	**Eff 6**	16	127.1	1.6	125.5
Injection Sampling Duration (seconds)	30	**Eff 7, BG 4**	23	121.1	2.5	118.6
		Eff 8	24	122.6	2.7	119.9
		Eff 9, BG 5	25	119.2	2.9	116.3
Detention Time (minutes)	0.78	**Eff 10**	32	102.5	4.5	98.0
		Eff 11, BG 6	33	114.7	4.7	110.0
		Eff 12	34	118.1	5.0	113.1
Total Run Time (minutes)	48	**Eff 13, BG 7**	41	104.9	7.0	98.0
		Eff 14	42	111.7	7.3	104.4
		Eff 15, BG 8	43	84.0	7.6	76.4
Mass/Volume Influent Concentration (mg/L)	190	**442 gpm**			**Average**	**110.7**
					Removal Efficiency	**41.8%**

The resulting removal efficiency was 41.8%. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 439.7 gpm, with a COV of 0.002. The recorded temperature for the test did not exceed 61 degrees F.

The injection feed rate of 334.4 g/min was verified by collecting 30-second weight samples from the injector. Six influent injection measurements were taken throughout the test duration. The calculated concentrations for the full test ranged from 198 to 202 mg/L, with a mean of 201 mg/L and COV of 0.01. The total mass injected into the unit was 30.7 lbs. The calculated mass-flow concentration for the test was 190 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 1.1 to 8.4 mg/L.

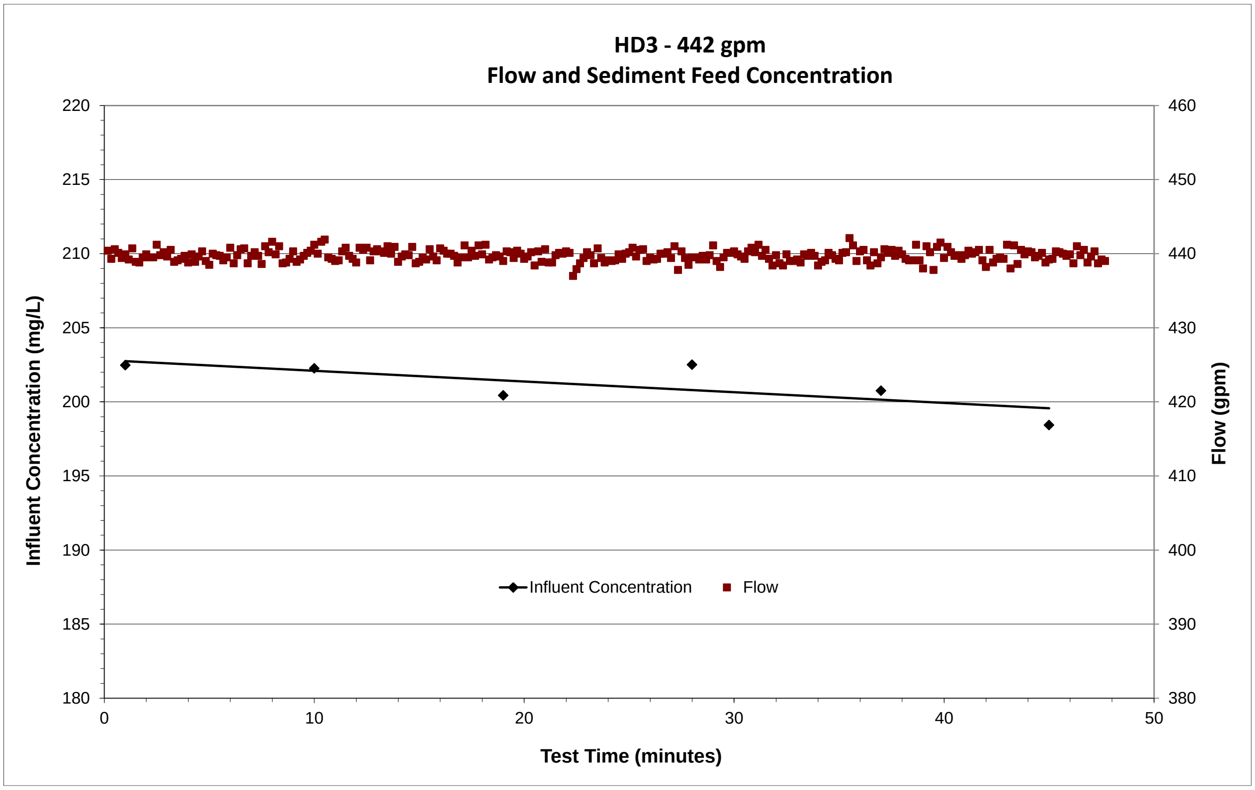

Figure 13: 125% MTFR Measured Flow and Influent Concentrations

4.3 Sediment Scour Testing

The commercially-available AGSCO NJDEP50-1000 certified sediment mix was utilized for the scour test. Three samples of the batch mix were analyzed in accordance with ASTM D422-63 (2007), by CTLGroup, an ISO/IEC 17025 accredited independent laboratory, and provided with the sediment shipment. 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 Error! Reference source not found. and the corresponding curves, including the initial AGSCO in-house analysis, are shown on Figure .

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**

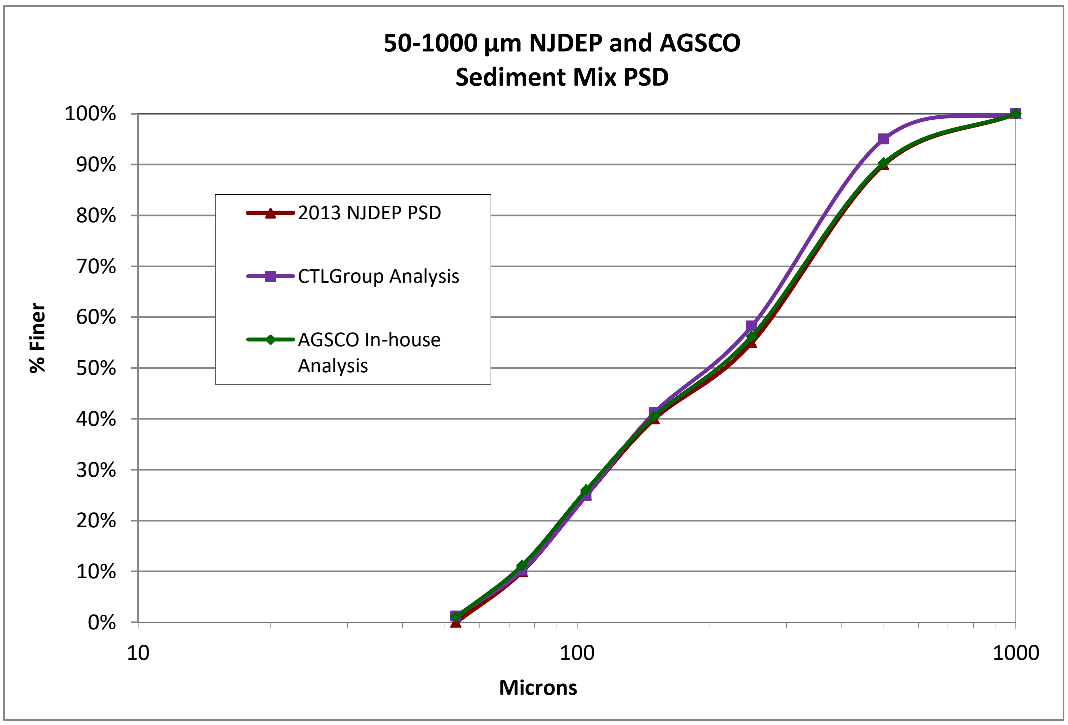

Figure 15: PSD Curves of AGSCO Batch Analysis and NJDEP Specifications

The scour test was conducted with the unit preloaded with 4” of sediment to the 50% capacity level (6”).

4.3.1 241% MTFR

The test was conducted at 919 gpm, which is equal to 241% MTFR. The flow data was recorded every 5 seconds throughout the test and is shown on Figure . The target flow was reached within 5 minutes of initiating the test. The average recorded steady-state flow was 919 gpm, with a COV of 0.011. The recorded water temperature was 64.8 degrees F.

Eight background samples were collected throughout the duration of the test. The measured concentrations ranged from 1.9 to 2.5 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 1.4 to 2.8 mg/L, with an average concentration of 2.2 mg/L. The effluent and background concentration data is shown in Table 12 and on Figure .

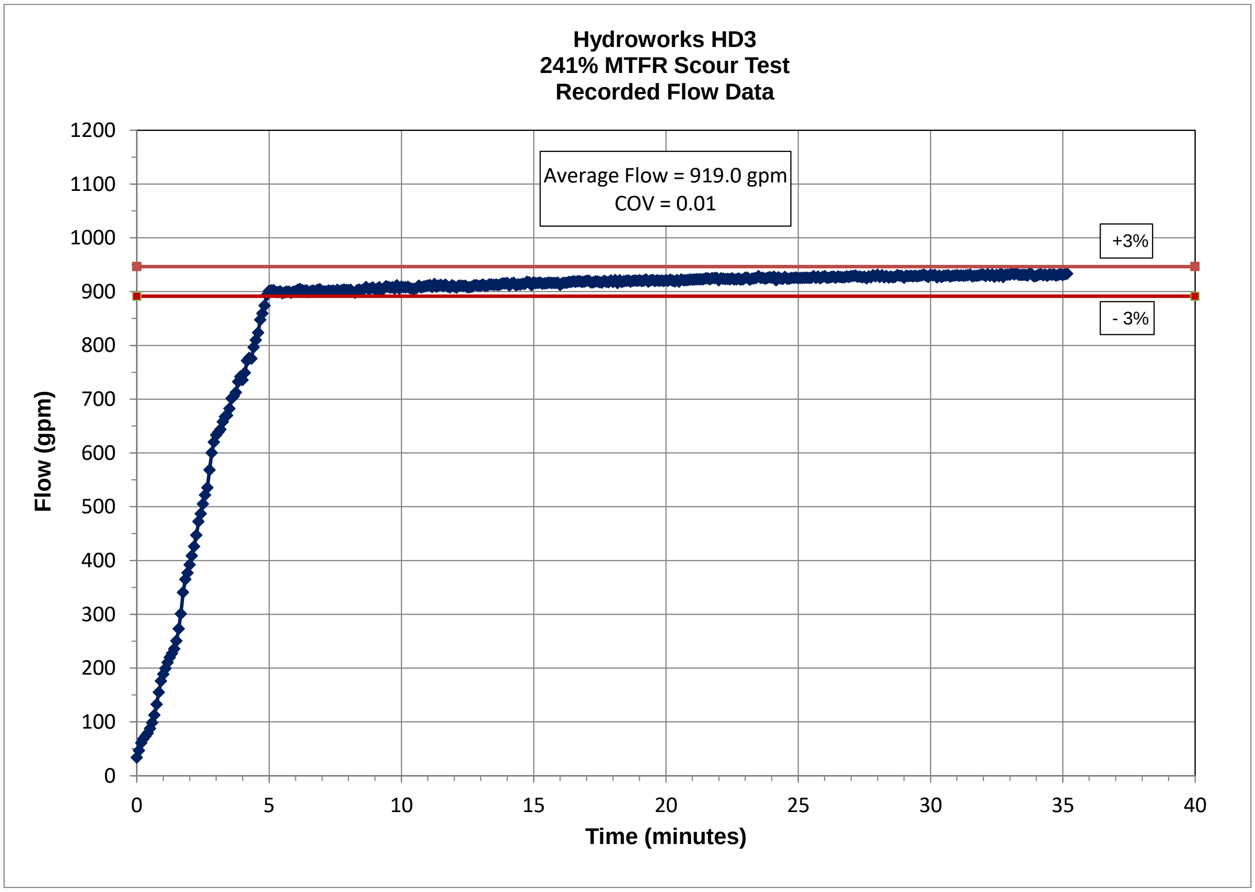

Figure 16: 241% MTFR Scour Test Recorded Flow Data

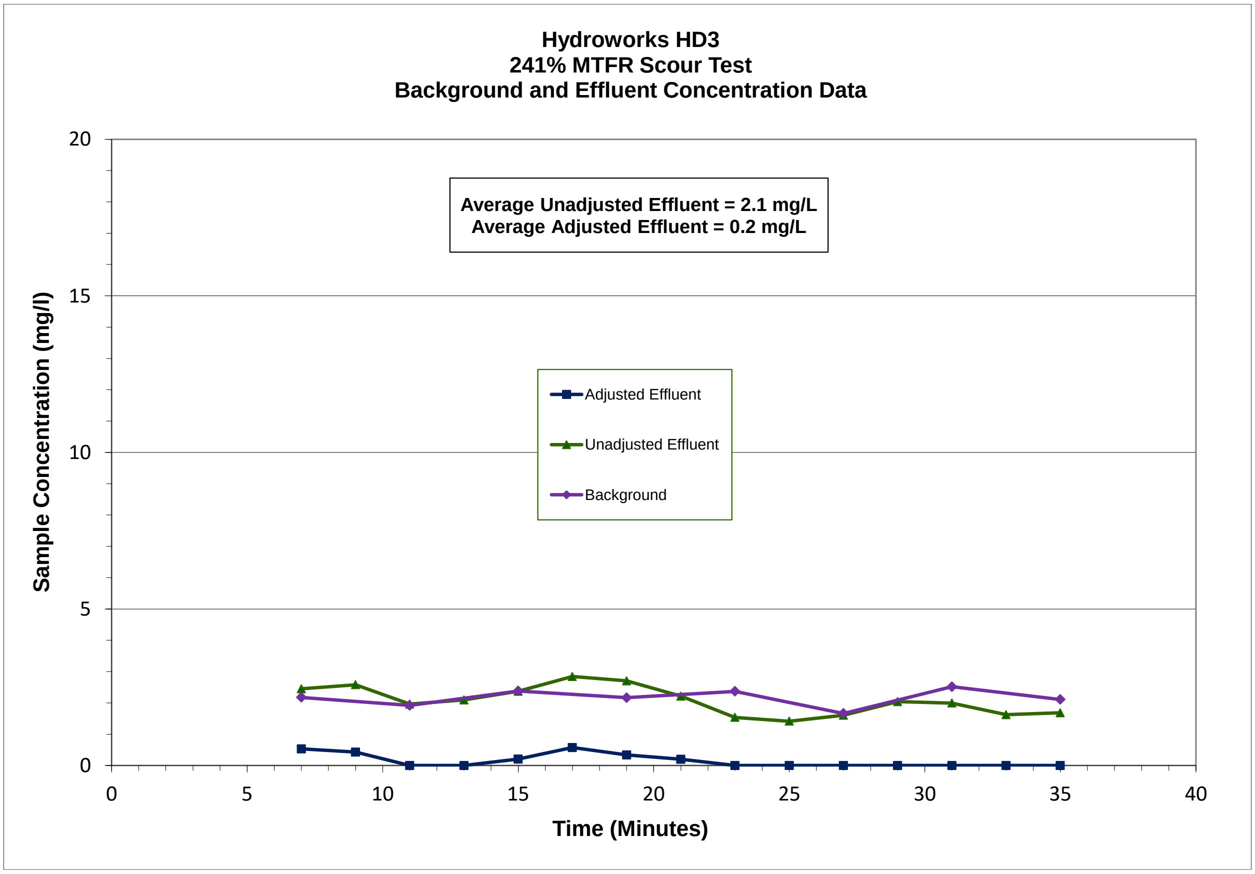

Figure 17: 200% MTFR Measured Background and Effluent Concentrations

Table 12:
241% MTFR Unadjusted Effluent Concentration Data

Sample ID	Timestamp (minutes)	Effluent Concentration (mg/L)	Background Concentration (mg/L)
EFF 1	7	2.45	2.18
EFF 2	9	2.58	2.05
EFF 3	11	1.96	1.92
EFF 4	13	2.09	2.15
EFF 5	15	2.37	2.38
EFF 6	17	2.84	2.27
EFF 7	19	2.70	2.17
EFF 8	21	2.21	2.27
EFF 9	23	1.53	2.37
EFF 10	25	1.42	2.01
EFF 11	27	1.60	1.66
EFF 12	29	2.04	2.09
EFF 13	31	1.99	2.52
EFF 14	33	1.62	2.31
EFF 15	35	1.68	2.11
	Average	**2.07**	**2.16**

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 system were measured for 12 flows ranging from 50 gpm to 1105 gpm (2.5 cfs). The recorded elevation data and system loss are shown in Table **.** The outlet flow oscillated within the pipe at low flows and consequently, it was necessary to interpolate the elevation at 100 gpm, as the measured depth was uncharacteristically low. The Elevation Curves for each pressure tap location are shown on Figure and the outlet velocity head vs system loss is shown on Figure . The pressure data for the inlet and outlet pipes were corrected for energy as discussed in **Section 3.8.1**. The greatest calculated loss was realized at the lowest flow, as the corrected inlet elevation was fairly constant, in comparison to the outlet elevation.

Table 13:
Recorded Flow and Elevation Data

Flow		Water Elevations (measured)			Water Elevations (adjusted to inlet)			Losses		
		Inlet Pipe	Tank	Outlet Pipe	Inlet Pipe	Tank	Outlet Pipe	Inlet El. (A')	Outlet El. (C')	System Energy Loss
gpm	cfs	A	B	C	A	B	C	Corrected for Energy	Corrected for Energy	A'-C'
		ft	ft	ft	ft	ft	ft	ft	ft	ft
0	0	1.016		0.973						
50.5	0.11	2.985	2.985	1.039	1.969	1.969	0.023	1.969	0.330	1.639
100.1	0.22	3.040	3.040	1.061	2.024	2.024	0.045	2.024	0.529	1.496
150.0	0.33	3.083	3.083	1.084	2.067	2.067	0.068	2.068	0.609	1.459
201.4	0.45	3.100	3.098	1.090	2.084	2.082	0.074	2.085	0.886	1.199
274.2	0.61	3.139	3.139	1.112	2.123	2.123	0.096	2.125	0.996	1.128
349.7	0.78	3.175	3.174	1.138	2.159	2.158	0.122	2.162	1.008	1.154
450.6	1.00	3.221	3.217	1.172	2.205	2.201	0.156	2.210	1.009	1.201
550.7	1.23	3.247	3.248	1.200	2.231	2.232	0.184	2.238	1.052	1.186
652.5	1.45	3.274	3.261	1.222	2.258	2.245	0.206	2.269	1.136	1.133
804.2	1.79	3.324	3.318	1.239	2.308	2.302	0.223	2.324	1.379	0.945
952.1	2.12	3.390	3.376	1.248	2.374	2.360	0.232	2.396	1.693	0.704
1105.0	2.46	3.398	3.402	1.272	2.382	2.386	0.256	2.412	1.801	0.611
				interpolated						

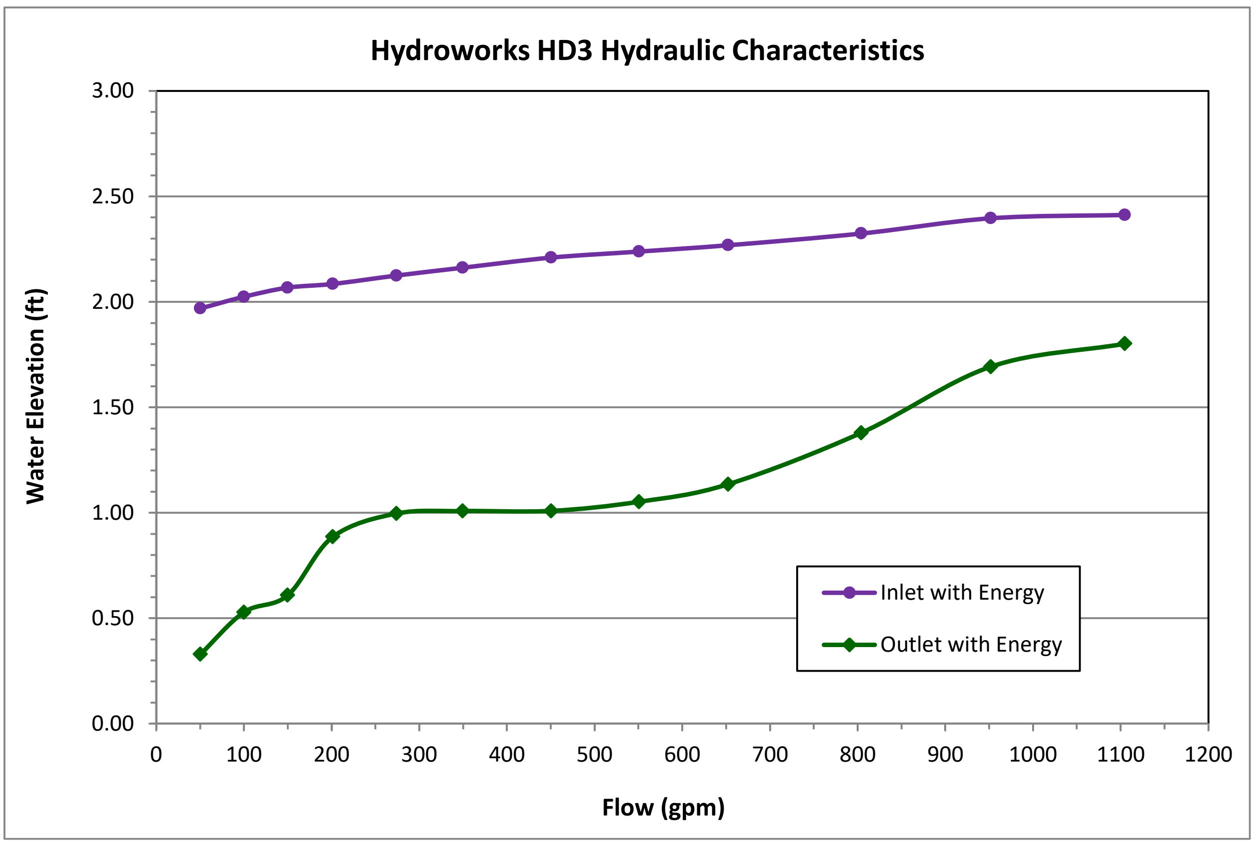

Figure 18: Measured Flow vs Water Elevations

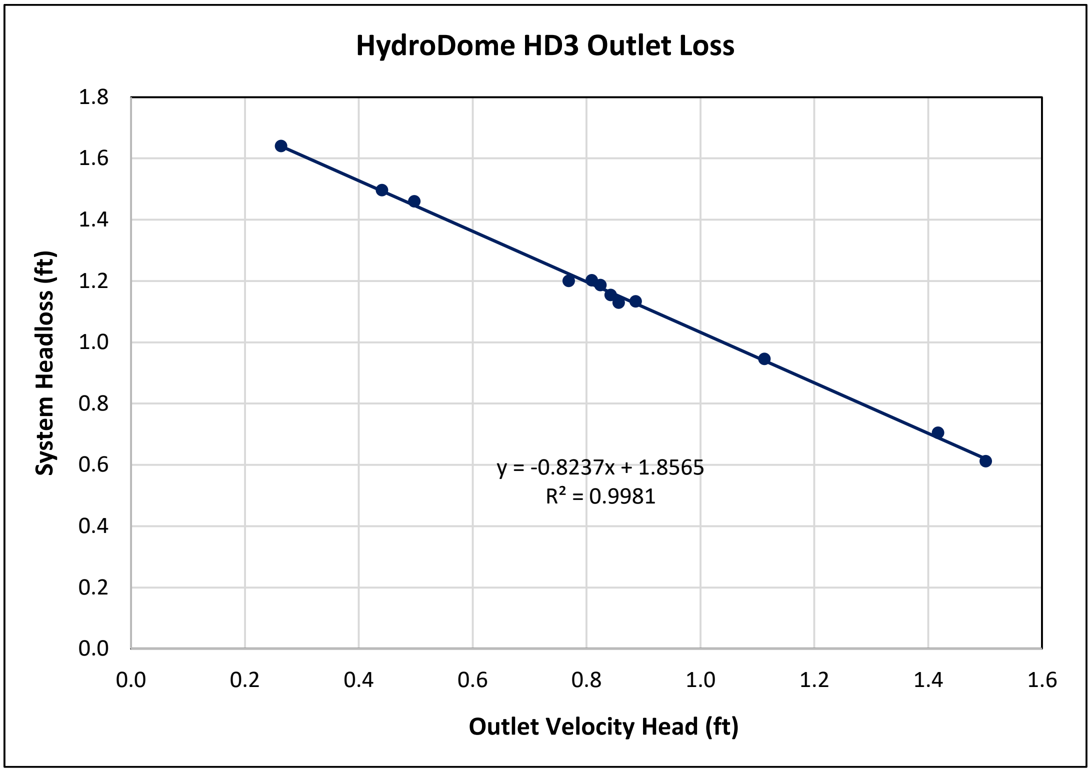

Figure 19: Calculated Outlet Losses

5.0 Performance Claims

The following performance claims for the Hydroworks HD3 are based on the independent laboratory testing conducted in accordance with the NJDEP testing protocol:

Total Suspended Solids (TSS) Removal Efficiency

The Hydroworks HD3 Stormwater Treatment Unit achieved removal efficiencies ranging from 41.8% to 69.9%, using the NJDEP 1-1000 micron sediment PSD. The NJDEP weighted removal efficiency based on an MTFR of 381.5 gpm, was 58.5%, which meets the 50% acceptance criterion.

Maximum Treatment Flow Rate (MTFR)

The effective treatment sedimentation area of the tested HD3 was 7.1 ft^2. The 100% MTFR is 381.5 gpm, with a corresponding surface loading rate of 53.7 gpm/ft^2.

Maximum Sediment Storage Depth and Volume

The maximum sediment storage depth of the test unit was 12”, which equates to a sediment storage volume of 7.1 ft^3. The 50% storage depth was 6”, corresponding to a volume of 3.5 ft^3.

Detention Time and Wet Volume

The wet volume of the tested HD3 was 344 gallons. The detention time at the MTFR of 382 gpm was approximately 1 minute.

Online / Offline Installation

A 241% MTFR on-line sediment scour test was performed with the collection sump preloaded to 50% of the capture capacity (6”), using the NJDEP 50-1000 micron sediment PSD. The test resulted in an average unadjusted effluent concentration of 2.1 mg/L, which meets the on-line installation acceptance criterion.

System Loss

Hydraulic testing was conducted at flows ranging from 0 to 1105 gpm. The maximum calculated system loss at 50 gpm was 1.64 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 (2019), “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 (2016), “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 Hydrodynamic Separator and Filtration Manufactured Treatment Devices (MTDs) for multiple manufacturers under various state and federal testing protocols. Alden's principal 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 years. Mr. Mailloux has contributed to articles related to laboratory testing in Stormwater Magazine and Water Innovations, as well as presented on multiple testing and regulatory topics at various conferences, including StormCon, WefTec and the National Precast Concrete Association training seminars.