Verification Testing of the Hydroworks HS 4 Stormwater Treatment System

In Accordance with the Canadian ETV Program

"Procedure for Laboratory Testing of Oil-Grit Separators", 2014

Technical Evaluation Report

Alden Report No. : 1152HS4SVT-CETV-R1

Submitted to:

Hydroworks, LLC
Clark, NJ

Prepared by

James Mailloux
Senior Engineer
Alden Research Laboratory

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1.0 Introduction

Under a contract from Hydroworks, LLC, verification testing of a Hydroworks HydroStorm 4-ft diameter Hydrodynamic Separator (HS 4), was conducted at Alden Research Laboratory, Inc. (Alden) in Holden, Massachusetts. The purpose of the testing was to define the performance characteristics of the HS 4 treatment unit under controlled laboratory conditions, utilizing established standard testing methodologies. The testing was conducted in accordance with the Canadian Environmental Technology Verification (CETV) Program "Procedure for Laboratory Testing of Oil-Grit Separators 2014", to establish the following parameters:

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

b) **Sediment Scour Testing:**
Quantify the sediment mass by particle size fractions that are washed out of the unit at defined flows.

c) **Sediment Removal Efficiency Curve:**
Quantify the sediment removal characteristics at various surface loading rates, including particle size fractions, using a mass balance methodology.

d) **Light liquid Re-entrainment:**
Perform testing to qualitatively assess the unit's ability to retain light liquid at defined flows using a plastic bead surrogate.

e) **Particle Size Distribution (PSD):**
At a minimum, the particle size distribution of the influent, effluent and/or captured material for all sediment test conditions.

2.0 Test Unit Description

The HS 4 test unit was a concrete cylindrical device measuring 1.22 m in diameter with a sump depth of 1.2 m and a collection sump area of 1.17 m^2. Aluminum inlet and outlet pipes, 0.35 m in diameter, were oriented along the centerline of the unit, with the inverts located 1.24 m and 1.19 m above the sump floor, respectively. The pipes were set with 0.25% slopes. The internal geometry was divided into an annular pretreatment channel, 0.61 m diameter inner chamber, and lower collection sump. The pretreatment channel extended 0.305 m below the outlet pipe invert and contained three (3) intermediate low-flow weirs, 0.305 m high (flush with the outlet invert), and two (2) downstream bypass weirs, 0.508 m high (0.203 m 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. Initial testing was performed using a solid plate. After the completion of testing, the plate was replaced with a perforated plate and a test was repeated to demonstrate that the treatment was not sensitive to the plate geometry. 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.**

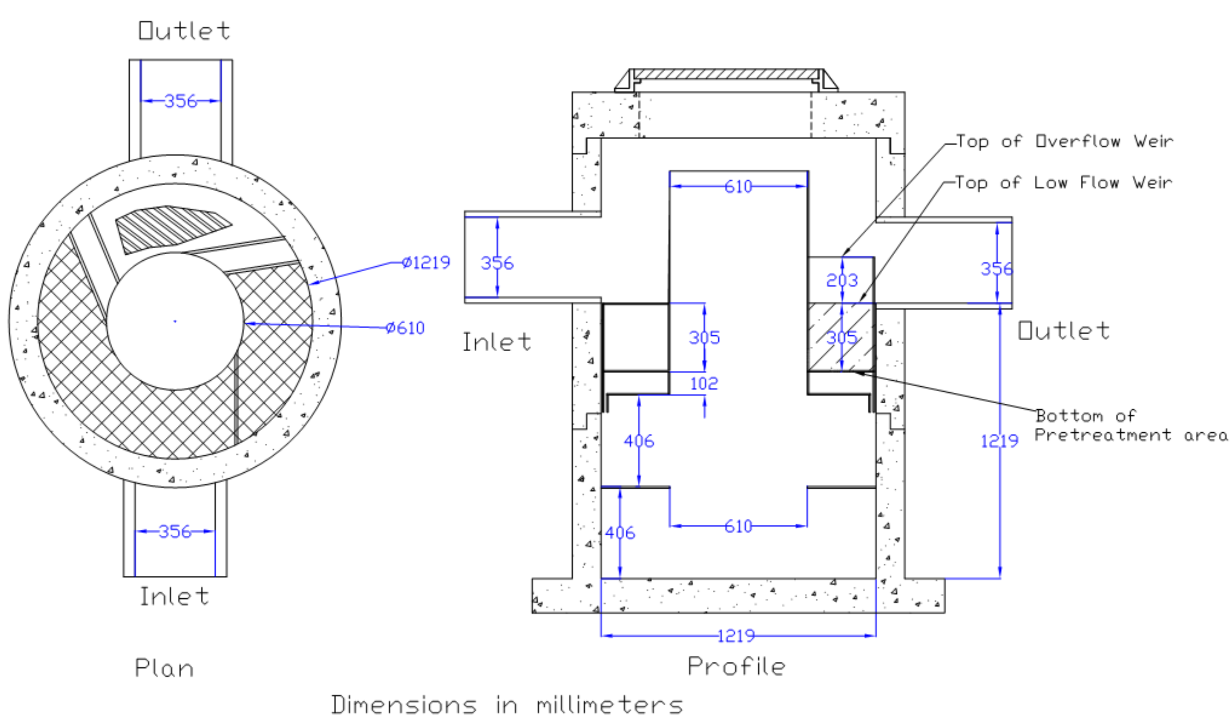

Figure 1: Drawing of the HS 4 Treatment Unit

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 was set up as a recirculation system. The loop was designed to provide metered flow up to approximately 17 cfs (481 L/s). Flow was supplied to the unit using either a 20HP or 50HP laboratory pump (flow dependent), drawing water from a 50,000-gallon (190,000 L) supply sump. Thirty feet (9.1m) of straight 14-inch (0.35m) pipe conveyed the metered flow to the unit. The influent and effluent pipes were set at 0.25% slopes. A 14-inch (0.35m) tee was located 4 pipe-diameters upstream of the test unit for injecting sediment into the crown of the influent pipe. This location deviated from the recommended distance of 5 pipe-diameters. However, the shorter distance was considered conservative for collecting sediment in the influent pipe and provided a better assessment of the unit's ability to capture sediment. Filtration of the test-loop flow, to reduce background concentration, was performed with an inline filter wall containing 1-micron filter bags.

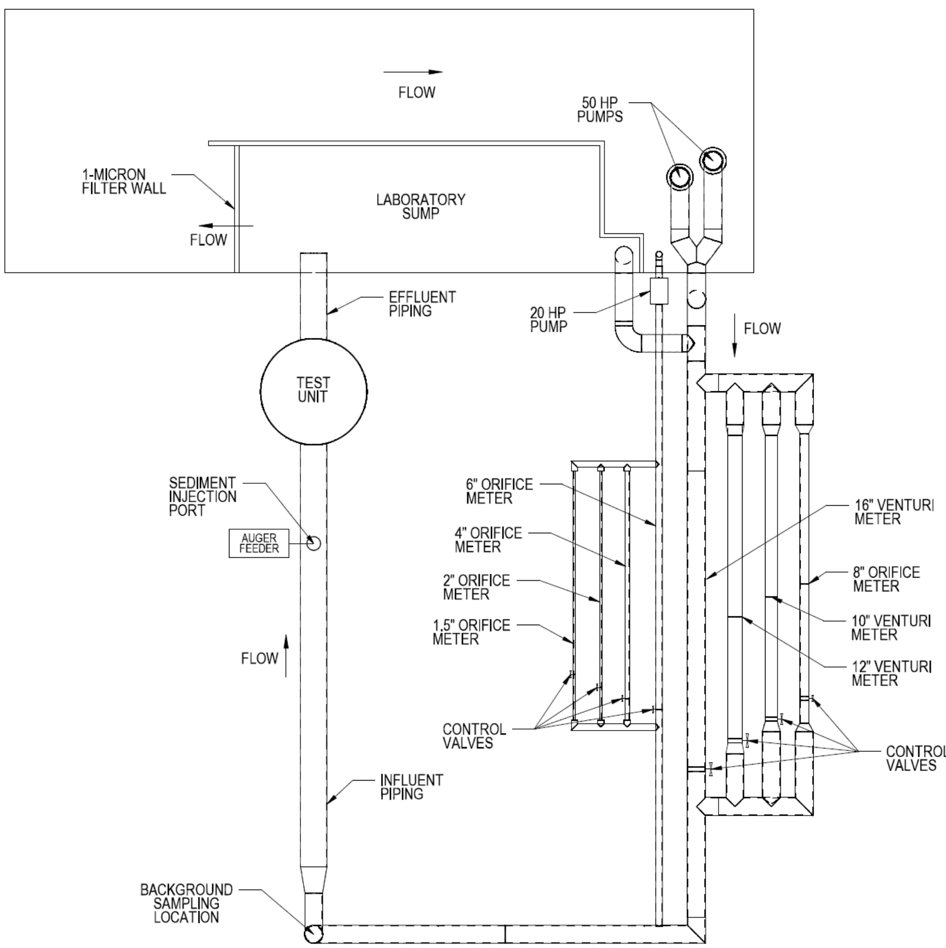

Figure 3: Plan View of Alden Flow Loop

3.2 Testing

3.2.1 Hydraulic Testing

The HS 4 unit was tested with clean water to determine its hydraulic characteristics, 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 fifteen steady-state flow conditions using a computer Data-Acquisition (DA) system, which included a data collect program, a 0-250" Rosemount Differential Pressure (DP) cell, and a 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.

3.2.2 Removal Efficiency Testing

Removal testing was conducted on a clean unit utilizing the mass balance methodology. A false floor was installed at the 50% collection sump sediment storage depth of 6" (0.15m), as stated by Hydroworks. All tests were run with clean water containing a sediment solids concentration (SSC) of less than 20 mg/L.

A minimum of seven sediment removal efficiency tests were conducted at loading rates corresponding to 40, 80, 200, 400, 600, 1000 and 1400 L/min/m^2 of effective treatment area. The HS 4 treatment area was 1.17 m^2, resulting in test flows of 47, 94, 234, 468, 702, 1170 and 1638 L/min.

The 600 L/min/m^2 test was repeated with a perforated secondary plate installed to determine the impact of the plate design on removal efficiency.

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. Samples of each 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 (+/-25 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 to produce the resulting influent concentration values for each test. The allowed Coefficient of Variance (COV) for the measured samples was 0.10.

A minimum of 11.3 kg of test sediment was introduced into the influent pipe for each test. In addition, the criteria of 25 minutes of test time, eight collection sump volume exchanges, and a supply water temperature below 25 degrees Celsius were met for all tests conducted. The moisture content of the test sediment was determined using ASTM D4959-07 for each test conducted.

A minimum of 5 background samples of the supply water were collected at evenly-spaced intervals throughout each test. Samples were collected every hour for any test that was greater than 5 hours in duration. Collected samples were analyzed for Suspended Solids Concentration (SSC) using the ASTM D3977-97 (2013).

After completion of a selected test, the unit was decanted over a period not exceeding 30 hours. The remaining water and sediment was collected from the treatment unit and dried in designated pre-weighed nonferrous trays in compliance with ASTM D4959-07.

Table 1:
Target CETV Test Sediment Particle Size Distribution

Particle Size (µm)	Percent Less Than	Particle Size Fraction (µm)	Percent
1000	100	500-1000	5
500	95	250-500	5
250	90	150-250	15
150	75	100-150	15
100	60	75-100	10
75	50	50-75	5
50	45	20-50	10
20	35	8-20	15
8	20	5-8	10
5	10	2-5	5
2	5	<2	5

3.2.3 Sediment Scour Testing

A sediment scour test was conducted on the test unit to evaluate the ability to retain captured material through a range of flows. The solids storage sump of the test unit was pre-loaded to the 50% storage capacity level of 15.2 cm with the 1-1000 micron sediment listed in **Table 1**. A false floor was installed in the sump to reduce the quantity of material required for the test. However, a minimum sediment depth of 10.2 cm was preloaded as per the protocol specification. The solid secondary plate, located just above the collection sump, was also preloaded to 10.2 cm with the 1-1000 sediment, as requested by Toronto Region Conservation Authority (TRCA). All test sediment was evenly distributed and levelled. The pretreatment channel was preloaded with a conservative blend consisting of all the material captured during the 40, 80 and 200 L/min/m^2 removal efficiency tests and an additional 30% of 1-1000 micron sediment. The material was preloaded in the areas of deposition observed during the removal 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 25 degrees C. The test was conducted within 96 hours of filling the unit.

The test was conducted sequentially at five surface loading rates equal to 200, 800, 1400, 2000 and 2600 L/min/m^2. Testing consisted of conveying the selected target flow through the unit and collecting 5 pairs of time-stamped effluent samples (every 1 minute) for SSC and PSD analysis, and a minimum of 5 time-stamped background samples evenly spaced throughout the test. Each target flow was reached within 1 minute of commencement of the flow change. Flow data was continuously recorded every 10 seconds throughout the test and correlated with the samples. The first target flow was reached within 1 minute of initiating the test.

It was necessary to change flow meters during the test, as the required flows exceeded the minimum and/or maximum range of any single meter, while maintaining the required COV of 0.04. When the flow capacity of the selected meter was reached, the flow was shut down over a period of approximately 10 seconds and all flow data saved. The next flow meter data-acquisition file was executed and the flow increased at a rate that corresponded to reaching each previous target flow after a period of 1-minute, thereby preventing artificially-induced scour due to flow surge.

Effluent samples for PSD and sediment concentration were collected in 1-L wide-mouth bottles from the end of the outlet pipe for all flows.

An additional scour test was conducted using the same methodology but with a perforated secondary plate installed in the sump. The lower sump was preloaded to the 50% capacity level with 1-1000 micron sediment. The pretreatment channel was preloaded with a sediment distribution that reflected the distribution captured during removal testing. This is considered a scientifically sound approach, as the channel is designed to capture the coarse particles prior to the flow entering the inner chamber.

3.2.4 Light-liquid Re-entrainment Testing

A test was conducted to assess the ability to retain light liquid within the unit. The unit was tested with a false floor installed at the 50% capture elevation, as in the sediment removal testing. The test flows were the same as in the sediment scour tests (200, 800, 1400, 2000 and 2600 L/min/m^2) and were conducted to the same time criteria (1-minute transition, 5-minute test).

The ETV protocol prescribes low-density polyethylene beads as a surrogate to represent floating liquid for a qualitative assessment of liquid behavior during operation. Dow Chemical Dowlex^{tm} 2517, with a density of 0.917 g/cm^2, has been specified as the acceptable surrogate material.

The pellets were preloaded within the inner-chamber area to a volume equal to a depth of 50.8 mm over the sedimentation area. The corresponding mass of the test material was measured and recorded prior to loading the unit.

The effluent was collected in flow-designated nets to allow for quantification of any re-entrained pellets for each flow rate. The collected pellets for each flow, as well as the interim periods, were dried and the volume and mass of collected pellets was quantified for each flow rate, as well as the overall test.

3.3 Instrumentation and Measuring Techniques

3.3.1 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”) [51mm, 102mm, 152mm, 203mm, 305mm]. Each meter is fabricated per ASME guidelines and calibrated in Alden’s Calibration Department. The 12” meter was used during hydraulic testing only. The high and low pressure lines from each meter were connected to manifolds containing isolation valves. Flows were set with a butterfly valve and the differential head from the meter was measured using a Rosemount® 0 to 250-inch (6.35m) 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 computer data acquisition (DA) program. The accuracy of the flow measurement is ±2%. A photograph of the flow meters is shown on **Figure 4** and the pumps on **Figure 5.**

Figure 4: Photograph Showing Laboratory Flow Meters

Figure 5: Photograph Showing Laboratory Pumps

3.3.2 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 and/or day (for multi-day tests), to assure an acceptable testing temperature of less than 25 degrees C.

3.3.3 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 ± 0.3 mm. 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 6**.

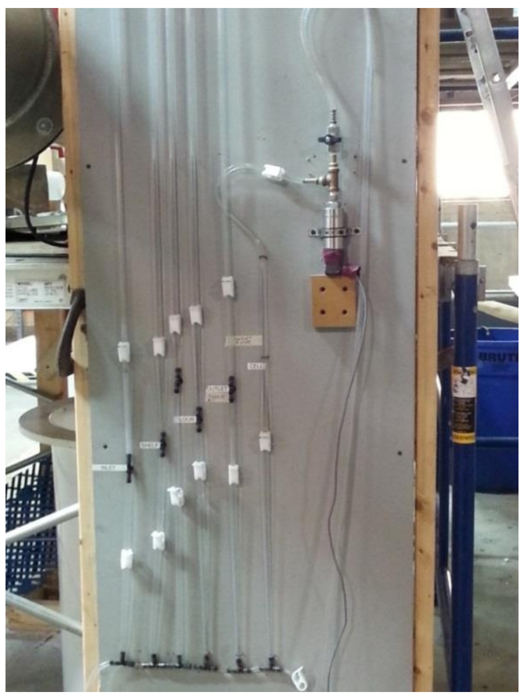

Figure 6: Pressure Measurement Instrumentation

3.3.4 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 7.** The feed screws used in testing ranged in size from 9.5mm to 25mm, 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 sediment.

Figure 7: Photograph Showing Variable-speed Auger Feeder

3.3.5 Sample Collection

Scour testing effluent samples were collected in 1-L bottles from the end of the pipe for sediment concentration and PSD analyses. Background concentration samples were collected from the center of the vertical pipe upstream of the test unit with the use of a 19mm diameter isokinetic sampler, shown on **Figure 8.**

Figure 8: Photograph Showing the Background Isokinetic Sampler

3.3.6 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 material 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.

3.3.7 Mass Balance Analysis

A modified mass balance method, in which the influent and captured sediment mass is quantified, was used to determine the sediment removal efficiency at each designated test flow. The mass of injected sediment was determined by weighing the prepared test batch prior to testing and subtracting the mass remaining in the injection hopper at the conclusion of the test. All captured material was collected in designated pre-weighed non-ferrous trays and dried in a Binder® laboratory oven; model ED-400, in accordance with ASTM Method D 4959-07, “Standard Test Method for Determination of Water (Moisture) Content of Soil By Direct Heating”. Depending on collected mass, each tray was weighed on either an Ohaus® 4000g x 0.1g; model SCD-010, or Ohaus® 30kg x 0.001kg; model RD-30LS digital scale.

3.4 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 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 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.

3.5 Preparation of Test Sediment

The sediment PSD used for scour and removal efficiency testing was comprised of 1-1000 micron silica particles with a SG of 2.65, as shown in Table 1. Sediment batches were prepared by Alden to meet the protocol specifications using commercially-available silica products. A random sample from each test batch was analyzed in accordance with ASTM D422-63 (2007)e1, 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 specifications listed in **Table 1**, as defined by the protocol. The D_{50} of the sample average was 69 microns. The PSD data of the samples are shown in **Table 2** and the corresponding curves are shown on **Figure 9**.

Table 2:
PSD Analyses of the 1-1000 micron Test Batches

Particle size	40 l/m/m^2	80 l/m/m^2	200 l/m/m^2	400 l/m/m^2	600 l/m/m^2	1000 l/m/m^2	1400 l/m/m^2	Average	CETV	QA / QC Compliant
(micron)	%-Finer	%-Finer	%-Finer	%-Finer	%-Finer	%-Finer	%-Finer	%-Finer	%-Finer	
1000	100	100	100	100	100	100	100	**100**	**100**	Y
500	95	97	95	95	96	96	95	**96**	**95**	Y
250	91	93	90	90	92	92	90	**91**	**90**	Y
150	77	74	76	74	79	73	74	**75**	**75**	Y
110	65	63	64	63	65	63	63	**64**	**60**	Y
75	53	51	51	51	54	51	50	**52**	**50**	Y
53	47	47	47	45	47	47	45	**46**	**45**	Y
20	35	36	36	35	36	37	35	**36**	**35**	Y
8	22	20	22	20	18	21	21	**21**	**20**	Y
5	16	14	16	14	13	15	15	**15**	**10**	Y
2	7	6	7	7	4	6	6	**6**	**5**	Y
D50	64	69	69	71	62	69	75	**69**	**75**	Y

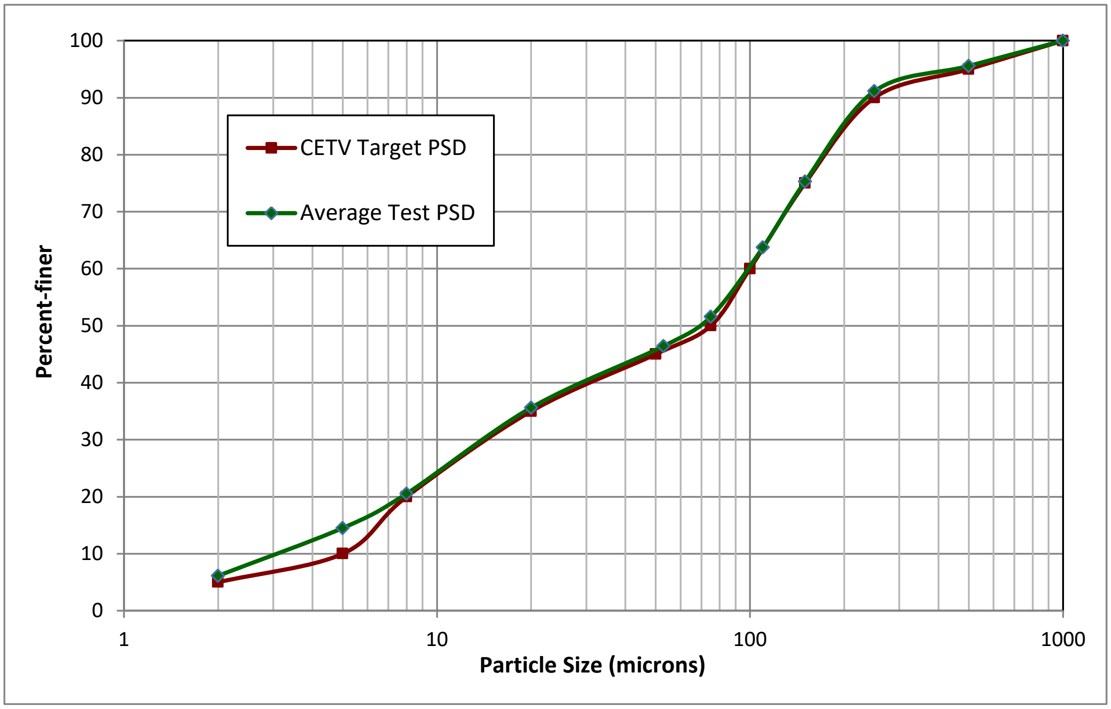

Figure 9: PSD Curves of Test Sediment Average and CETV Specifications

3.6 Data Analysis

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

3.6.1 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 (m), V = velocity (m/sec), and g = gravity (9.81 m/sec^2).

The velocity is defined by:

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

where,

V = velocity (m/sec), Q = flow (m^3/sec), and A = area (m^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 (m^2), θ = angle of inclusion (radians), and D = pipe diameter (m).

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 (m), and D = pipe diameter (m).

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

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

where,

Q = flow (m^3/sec), A = area of insert outlet opening (m^2), g = gravity (9.81 m/s^2), and ΔH = energy loss across unit (m).

3.6.2 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 (kg), ΔM = measured mass of injected sediment (kg), w = moisture content of sediment (%).

The sediment removal efficiency was calculated by:

$$\mathbf{\%\ Removal = (M_c / M_{inj}) \times 100} \tag{7}$$

where,

M_c = captured mass (g), M_{inj} = total mass of injected sediment (g)

The background sample concentrations were calculated as follows:

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

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 (L/min)

3.7 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”

- **Aqueous Sample Particle Size Distribution**

  ISO 13320-1 (2009) Particle Size Analysis – Laser Diffraction Methods

- **Light-Liquid Surrogate Plastic Density**

  ASTM D792-13 Method A “Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement”

3.7.1 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

All aqueous PSD samples were analyzed by Microtrac, Inc. Particle Analysis Laboratory, York, Pennsylvania. Microtrac is an ISO 9001, ISO 13320 and ISO/IEC 17021 accredited laboratory.

3.8 Quality Assurance and Control

A Test Plan was submitted and approved outlining the testing methodologies and procedures used for conducting the verification tests. The Test Plan was followed throughout the testing.

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

3.8.1 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.

3.8.2 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.

3.8.3 Sediment Concentration Analysis

All sediment concentration samples were processed at Alden 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 Sediment Removal Performance

Removal efficiency tests were conducted at the seven required flows of 40, 80, 200, 400, 600, 1000 and 1400 L/min/m^2. The target influent sediment concentration was 200 mg/l. The HS 4 treatment area was 1.17 m^2, resulting in target test flows of 47, 94, 234, 468, 702, 1170 and 1638 L/min, respectively. A summary of the calculated test parameters is shown in **Table 3**.

Table 3:
Calculated Test Parameter summary

TARGET FLOW	L/m/m^2	40	80	200	400	600	1000	1400
	L/min	47	94	234	468	702	1170	1638
	L/s	0.8	1.6	3.9	7.8	11.7	19.5	27.3
8X Treatment Unit Vol	cu.m.	10.0	10.2	10.8	11.1	11.4	12.2	13.1
Run Time	(min)	212.8	109.4	46.2	25.9	14.9	11.1	8.0
Sediment Quantity per Test	(Kg)	12.0	12.0	12.0	12.0	12.0	12.0	12.0
feed rate	(g/min)	9.4	18.7	46.8	93.6	140.4	234.0	327.6
Approx. Total Run Time	(min)	1282	641	256	128	85	51	37
	(hours)	21.4	10.7	4.3	2.1	1.4	0.9	0.6

The target and measured flow and temperature parameters are shown in **Table 4** and the injected sediment data is shown in **Table 5**.

Table 4:
Test Flow and Temperature Summary

Target Flow		Actual Flow	Deviation from Target	Flow Measurement	Maximum Temperature	QA / QC Compliant
L/min/m^2	L/min	L/min		COV	Deg. C	
40	47	46	-0.7%	0.004	22.6	Y
80	94	93	-0.3%	0.002	20.1	Y
200	234	233	-0.4%	0.002	22.1	Y
400	468	425	-9.2%	0.001	18.8	Y
600	702	736	4.9%	0.002	23.8	Y
1000	1170	1104	-5.7%	0.004	19.9	Y
1400	1638	1628	-0.6%	0.002	18.8	Y

Table 5:
Injected Sediment Summary

Target Flow L/min/m^2	Target Flow L/min	Target Concentration mg/L	Injector Wts. Concentration mg/L	Injector Measurements COV	Mass/Volume Concentration mg/L	Total Injected Mass kg	QA / QC Compliant
40	47	200	202	0.01	**203**	**11.7**	Y
80	94	200	203	0.02	**196**	**11.9**	Y
200	234	200	200	0.00	**201**	**11.9**	Y
400	468	200	201	0.01	**194**	**12.3**	Y
600	702	200	199	0.00	**199**	**12.2**	Y
1000	1170	200	200	0.00	**197**	**12.4**	Y
1400	1638	200	200	0.00	**194**	**12.6**	Y

At the end of each test run, the captured sediment was collected and quantified from the inlet pipe and treatment unit. The calculated removal efficiencies ranged from 35.7% to 68.6% for the seven flows tested. The %-removal summary is shown in **Table 6**, with the corresponding removal curve shown on **Figure 10**. The %-removal curves for the collected regions are shown on **Figure 11**.

Table 6:
Removal Efficiency Captured Mass Summary

Flow L/min/m^2	Tested Flow L/min	Removal Efficiency %	Inlet Pipe %	Pretreatment Channel %	Secondary Plate %	Outlet Dispersion Plate %	Collection Sump %
40	46	68.6	0.0	52.3	8.2	1.6	6.5
80	93	64.0	0.0	44.8	9.1	2.3	7.7
200	233	60.0	0.0	44.5	6.6	1.5	7.4
400	425	56.1	0.0	37.4	8.6	2.4	7.7
600	736	46.1	0.0	24.7	8.5	3.1	9.9
1000	1104	41.2	0.0	20.5	8.3	2.8	9.6
1400	1628	35.7	0.5	20.0	4.3	1.7	9.3

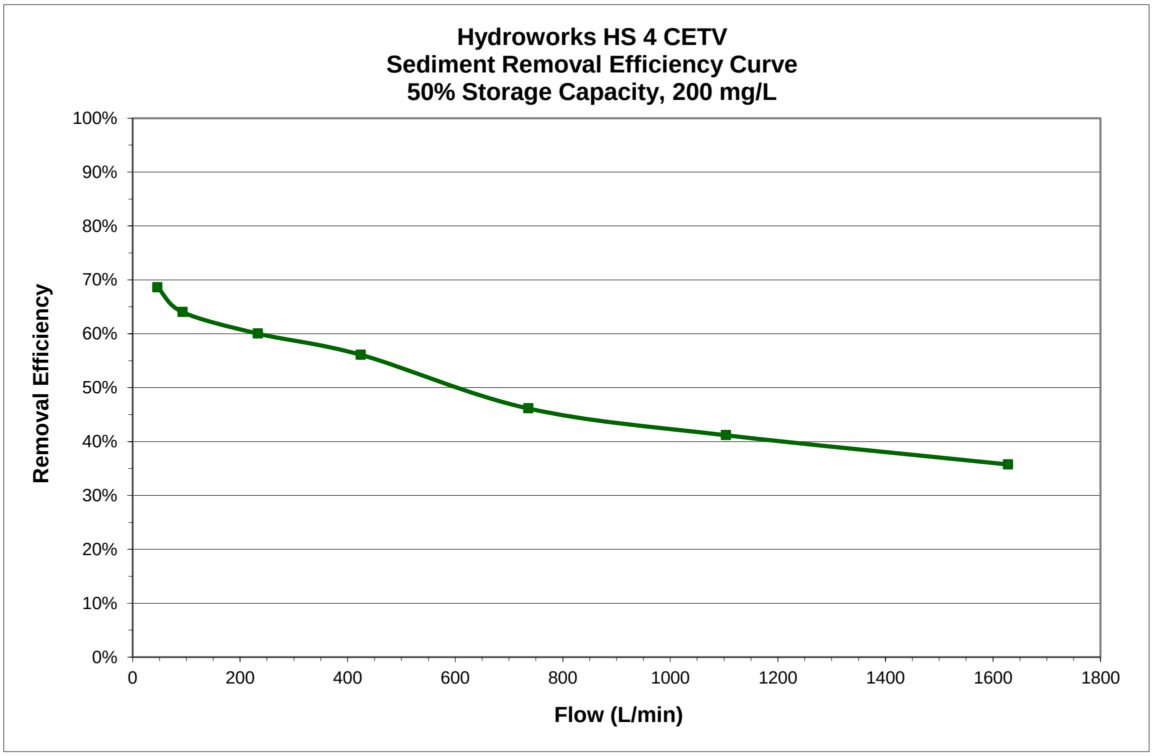

Figure 10: HS 4 Removal Efficiency Curve

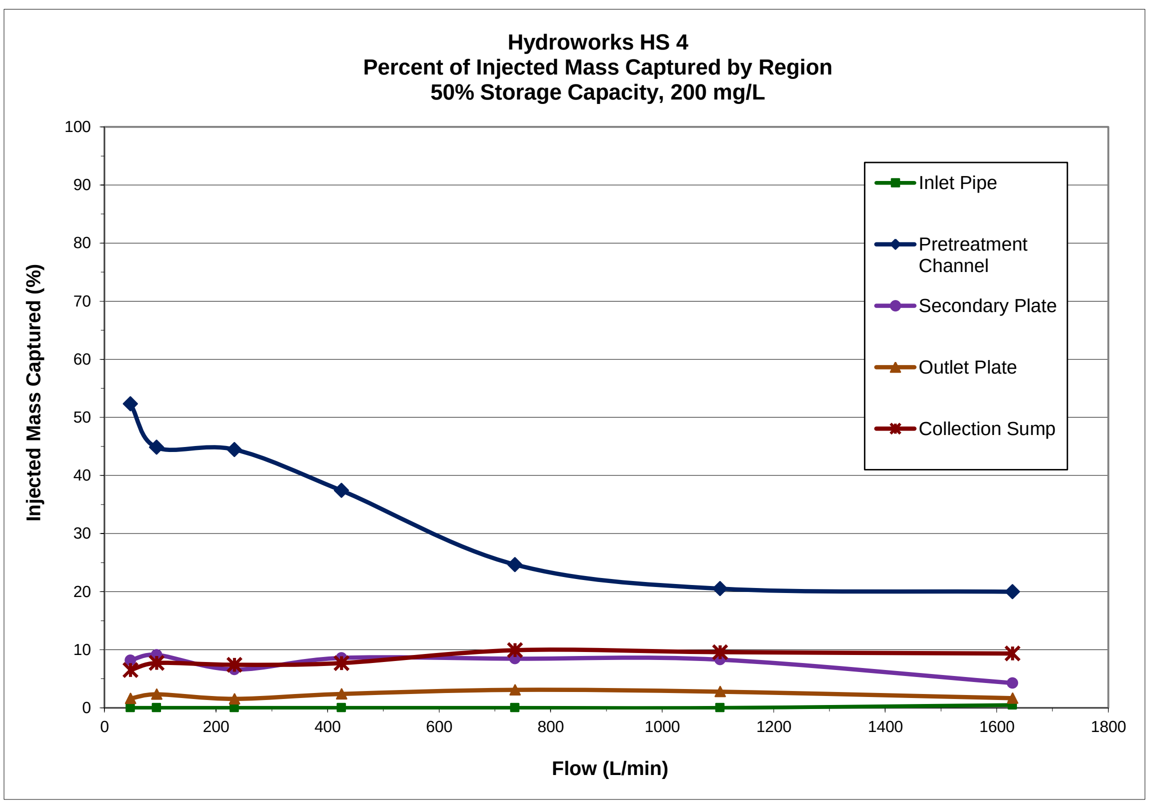

Figure 11: Captured Mass by Region

The particle size fractions of the captured sediment for all tests conducted are summarized in **Table 7.** The average test sediment data is included in column 2 as a benchmark. The percent of the size fractions of the injected sediment captured by the unit at each test flow is shown in **Table 8**. Some reported capture values are outside the absolute limit (+100%), or below the expected value. This is especially true at the larger size fractions (fewer particles) and those with small retained values. Factors that affect the accuracy of the data include how well the initial mix and collected sediment was blended and sampled, as well as accuracy and reporting of the PSD analyses. All sieve results were reported as whole numbers. Consequently, comparative values of 4.4% and 4.5% (2% difference) would be reported as 4% and 5% (25% difference).

PSD samples were analyzed for each deposition location only for the 40 L/min/m^2 test. For the remaining tests, the collected sediment from the sump, secondary plate and outlet plate were blended prior to taking a sample for analysis. A sample was collected from the pretreatment channel for each test. Details of the PSD data are presented in each removal test discussion section.

Table 7:
PSD Data Summary of Captured Sediment by Size Fraction

Particle Range (µm)	Average Test Sediment	40 L/min/m^2	80 L/min/m^2	200 L/min/m^2	400 L/min/m^2	600 L/min/m^2	1000 L/min/m^2	1400 L/min/m^2
>1000	0%	0%	0%	0%	0%	0%	0%	0%
500-1000	4%	4%	6%	5%	3%	4%	4%	1%
250-500	4%	4%	5%	5%	3%	5%	4%	2%
150-250	16%	15%	14%	12%	12%	12%	11%	11%
105-150	12%	11%	12%	13%	13%	11%	10%	10%
75-105	12%	12%	9%	10%	11%	7%	7%	6%
53-75	5%	5%	6%	7%	7%	4%	3%	3%
20-53	11%	8%	6%	5%	4%	2%	1%	1%
8-20	15%	5%	4%	2%	1%	0%	0%	0%
5-8	6%	1%	0%	0%	0%	0%	0%	0%
2-5	8%	1%	0%	0%	0%	0%	0%	0%

Table 8:
Injected Sediment Captured by Size Fraction at Each Flow

Particle Range (µm)	40 L/min/m²	80 L/min/m²	200 L/min/m²	400 L/min/m²	600 L/min/m²	1000 L/min/m²	1400 L/min/m²
>500	73%	194%	98%	67%	111%	103%	26%
250-500	100%	135%	92%	64%	115%	98%	48%
150-250	110%	75%	89%	72%	89%	60%	69%
105-150	94%	109%	107%	119%	78%	99%	91%
75-105	96%	76%	79%	95%	68%	54%	46%
53-75	87%	142%	170%	118%	56%	69%	65%
20-53	71%	54%	46%	44%	19%	14%	10%
8-20	38%	23%	15%	8%	2%	2%	2%
5-8	13%	6%	1%	1%	0%	0%	0%
2-5	8%	0%	0%	0%	0%	0%	0%

4.1.1 40 L/min/m² (46.7 L/min)

The test was conducted over a period of 3 days to meet the minimum 11.3 kg feed requirement. The total test duration was 21.4 hours. The test flow was averaged and recorded every 20 seconds throughout the test. The average recorded test flow for each day was 46.3, 46.5 and 46.6 L/min, respectively. The overall average was 46.5 L/min, with a COV of 0.004. The recorded temperature for the full test ranged from 22.1 to 22.6 degrees C.

The injection feed rate of 9.3 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 197 mg/L to 206 mg/L, with a mean of 202 mg/L and COV of 0.01. The total mass injected into the unit was 11.693 kg. The calculated mass-flow concentration for the test was 203 mg/L. The measured influent concentration data for the complete test is shown on **Figure 12**.

Twenty-four (24) background concentrations samples were collected throughout the test and ranged from 0.9 to 3.0 mg/L. The background curve is shown on **Figure 13**.

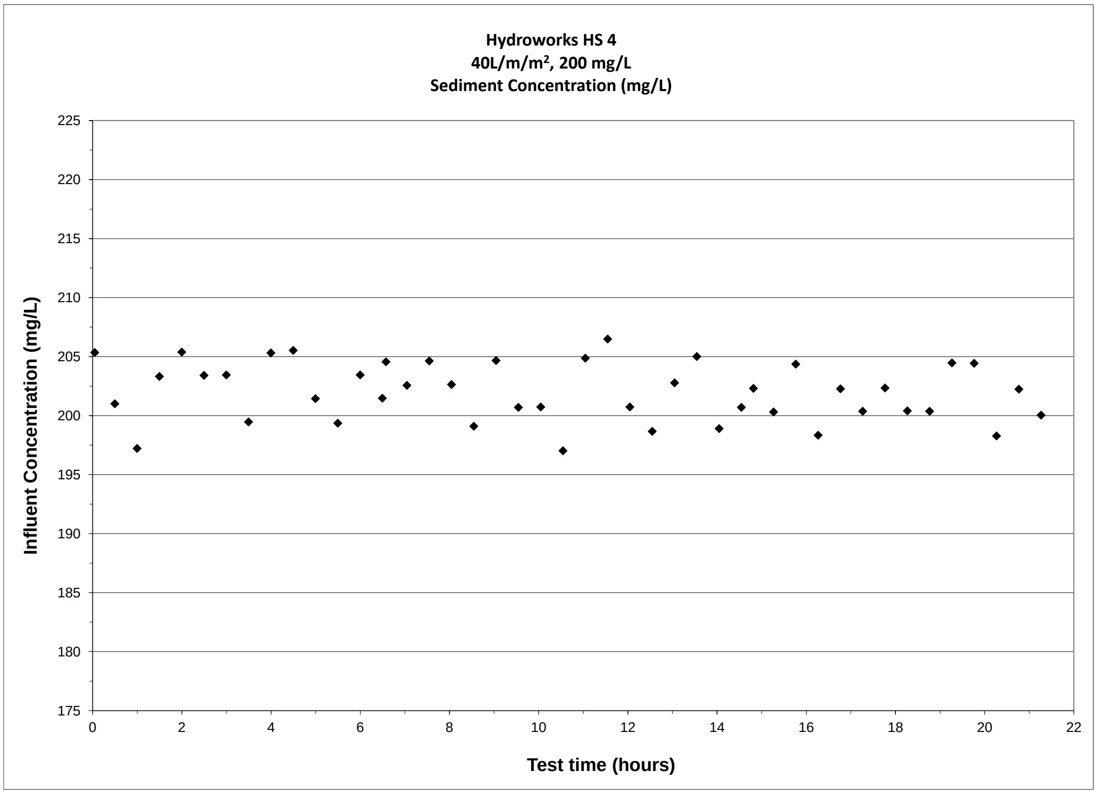

Figure 12: 40 L/min/m² Measured Influent Concentrations

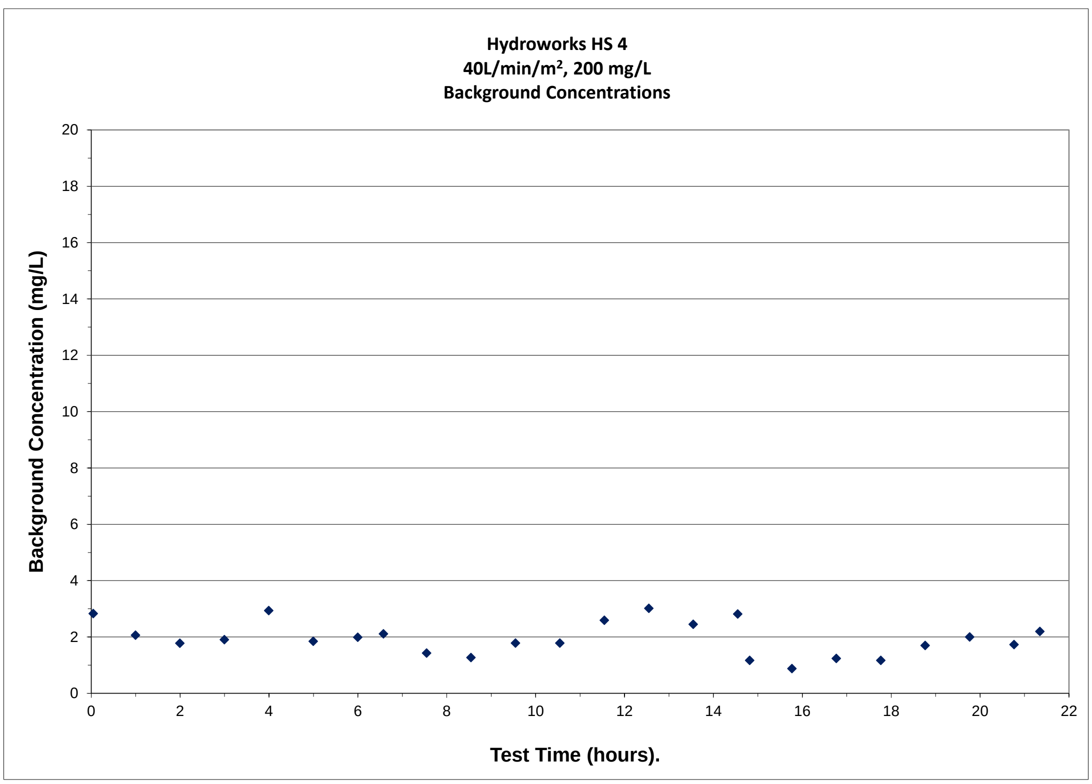

Figure 13: 40 L/min/m² Measured Background Concentrations

The total collected mass from the unit was 8.023 kg, resulting in a removal efficiency of 68.6%. The mass collected from each settling region was quantified based on the % of total captured mass, as well as % of total injected mass. The resulting data is shown in **Table 9**.

Table 9:
40 L/min/m^2 Breakdown of Captured Mass by Region

	Pretreatment Channel	Secondary Plate	Sump	Outlet Dispersion Plate	Total
mass (g)	6116.5	958.4	760.3	188.1	8023.3
% of captured	76.2%	11.9%	9.5%	2.3%	100.0%
% of Injected	52.3%	8.2%	6.5%	1.6%	68.6%

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 10** and the %-finer curves are shown on **Figure 14**.

Table 10:
40 L/min/m^2 PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	Test Sediment PSD	Pretreatment Channel	Secondary Plate	Collection Sump	Outlet Dispersion Plate	Total Retained
500-1000	5%	4%	0%	0%	0%	4%
250-500	4%	4%	0%	0%	0%	4%
150-250	14%	15%	0%	0%	0%	15%
100-150	12%	10%	1%	1%	0%	11%
75-100	12%	9%	2%	1%	0%	12%
50-75	6%	4%	1%	0%	0%	5%
20-50	12%	3%	2%	2%	1%	8%
8-20	14%	1%	2%	2%	1%	5%
5-8	6%	0%	0%	0%	0%	1%
2-5	9%	0%	0%	0%	0%	1%

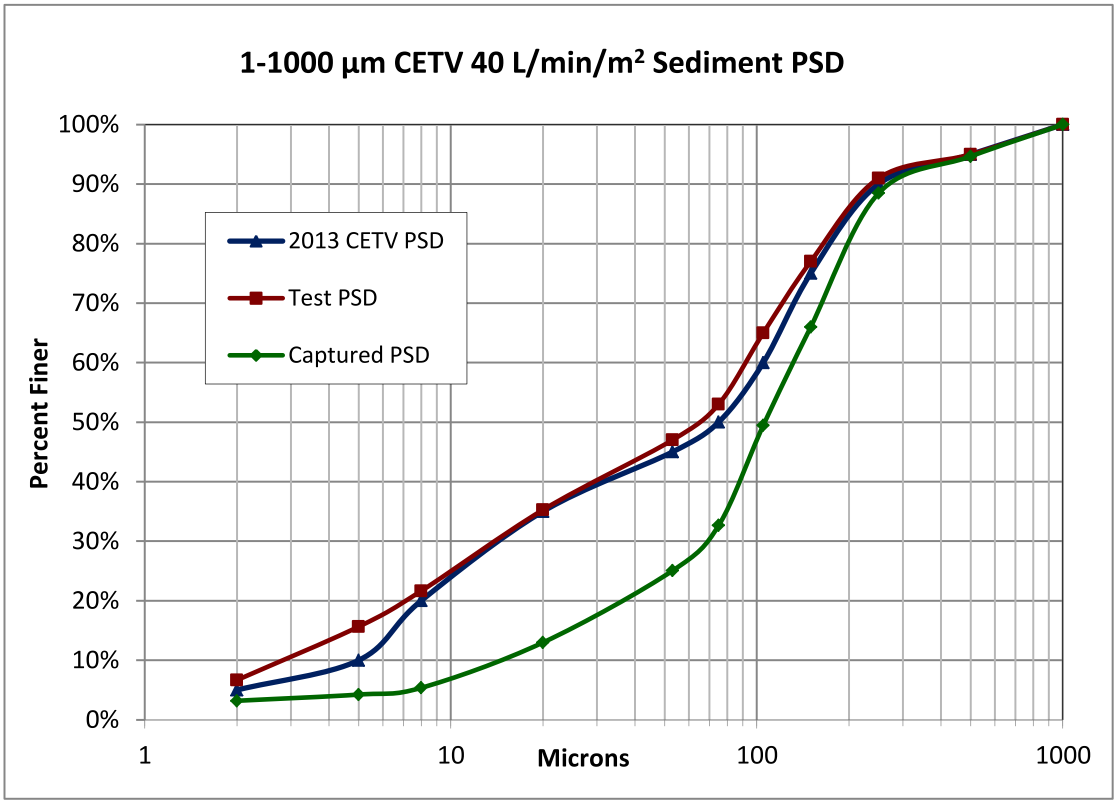

Figure 14: 40 L/min/m^2 %-Finer Curves of Test Sediment and Total Captured Mass

4.1.2 80 L/min/m^2 (93.4 L/min)

The test was conducted over a period of 2 days to meet the minimum 11.3 kg feed requirement. The total test duration was 11.1 hours. The test flow was averaged and recorded every 20 seconds throughout the test. The average recorded test flow for each day was 93.4 and 93.3 L/min, respectively. The overall average was 93.4 L/min, with a maximum COV of 0.002. The recorded temperature for the full test ranged from 19.6 to 20.1 degrees C.

The injection feed rate of 18.7 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 198 mg/L to 208 mg/L, with a mean of 203 mg/L and COV of 0.02. The total mass injected into the unit was 11.930 kg. The calculated mass-flow concentration for the test was 196 mg/L. The measured influent concentration data for the complete test is shown on **Figure 15**.

Thirteen (13) background concentrations samples were collected throughout the test and ranged from 1.3 to 5.0 mg/L. The background curve is shown on **Figure 16**.

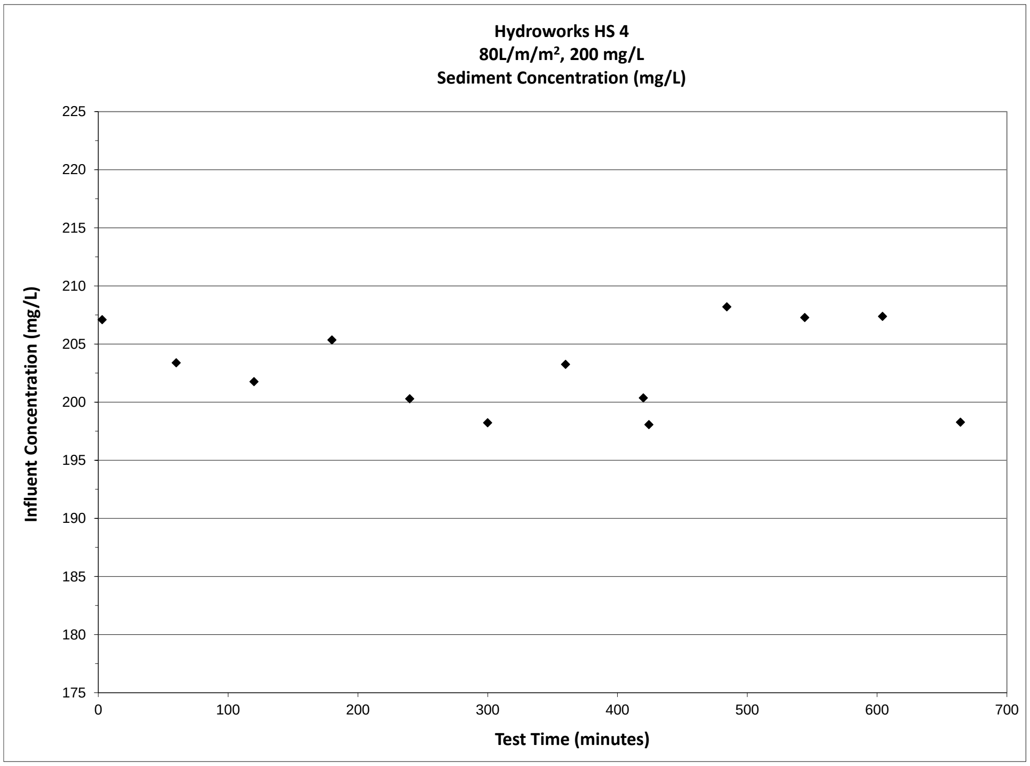

Figure 15: 80 L/min/m² Measured Influent Concentrations

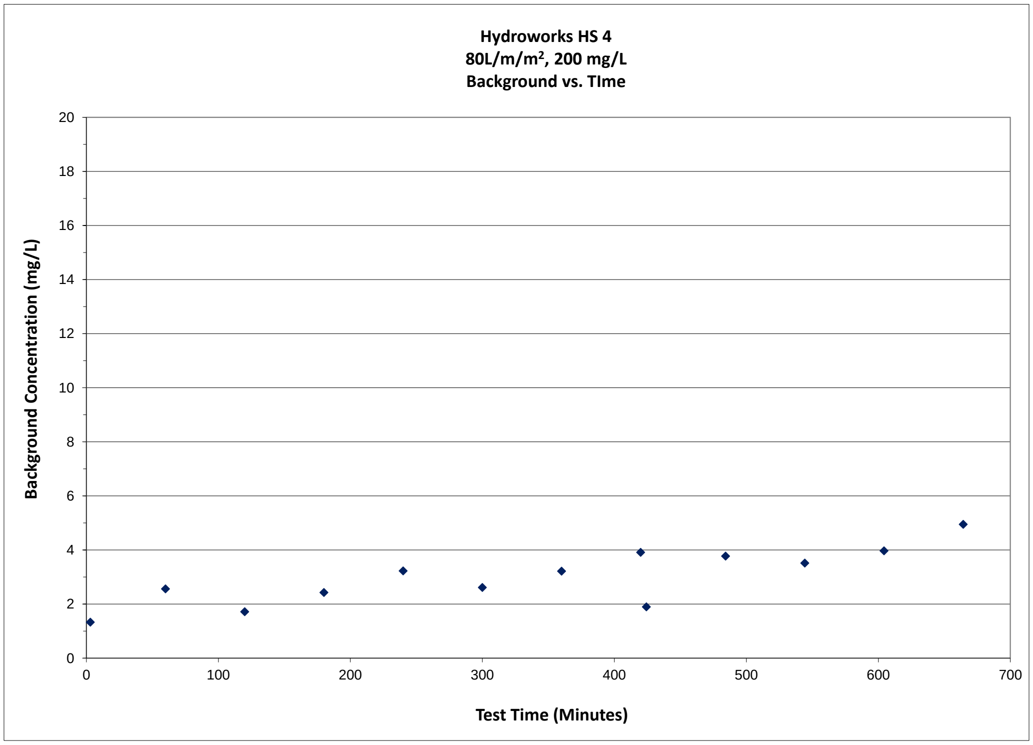

Figure 16: 80 L/min/m² Measured Background Concentrations

The total mass collected from the unit was 7.636 kg, resulting in a removal efficiency of 64.0

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 11** and the %-finer curves are shown on **Figure 17**.

Table 11:
80 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	**Test Sediment PSD**	**Total Retained**
500-1000	3%	6%
250-500	4%	5%
150-250	19%	14%
100-150	11%	12%
75-100	12%	9%
50-75	4%	6%
20-50	11%	6%
8-20	16%	4%
5-8	6%	0%
2-5	8%	0%

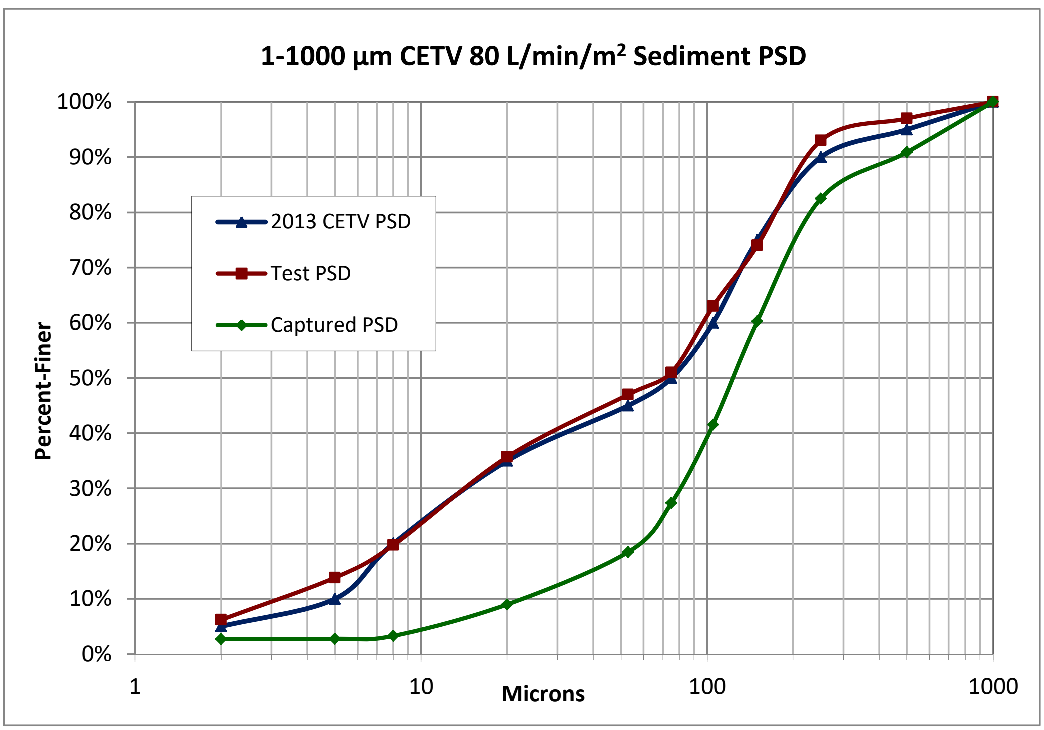

Figure 17: 80 L/min/m² Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.3 200 L/min/m² (233.4 L/min)

The test was conducted over a duration of 265 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 233.2 L/min, with a COV of 0.002. The maximum recorded temperature for the full test was 22.1 degrees C.

The injection feed rate of 46.8 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 202 mg/L, with a mean of 200 mg/L and COV of 0.00. The total mass injected into the unit was 11.946 kg. The calculated mass-flow concentration for the test was 201 mg/L. The measured influent concentration data for the complete test is shown on **Figure 18**.

Eight (8) background concentrations samples were collected throughout the test and ranged from 1.7 to8.1 mg/L. The background curve is shown on **Figure 19**.

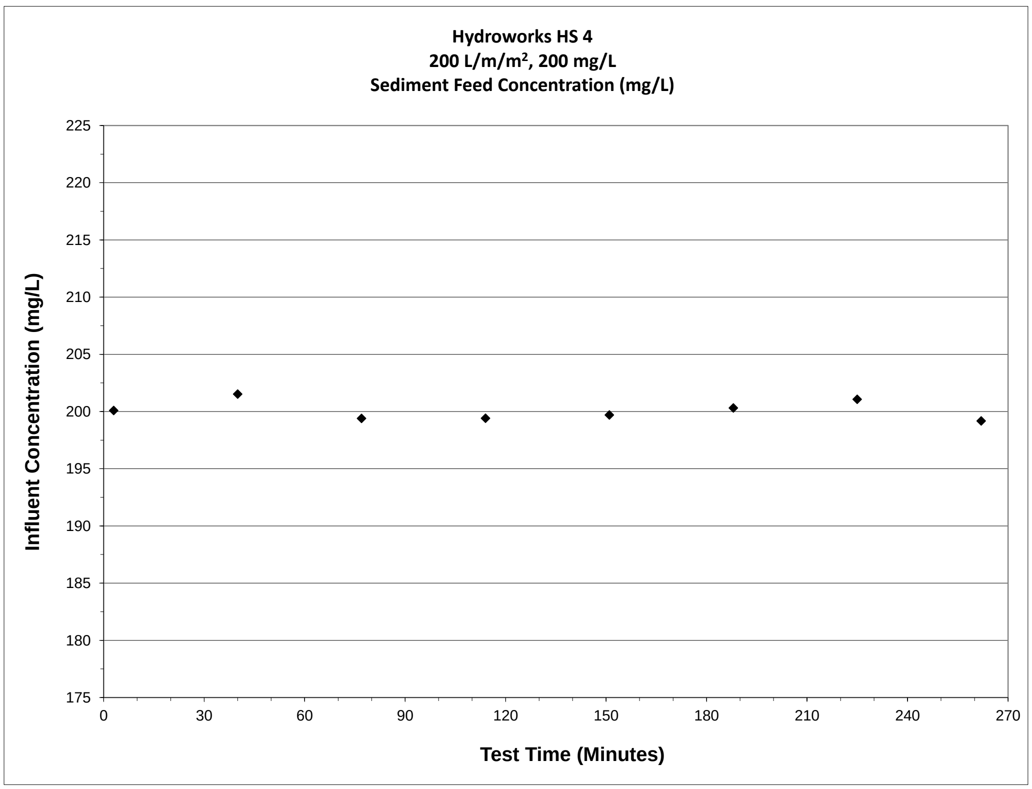

Figure 18: 200 L/min/m² Measured Influent Concentrations

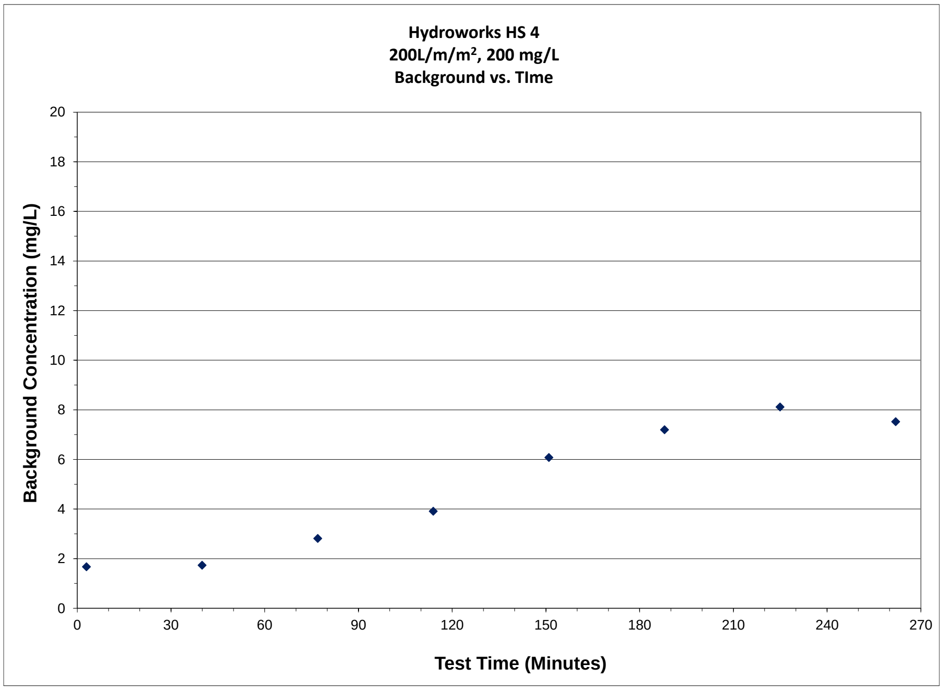

Figure 19: 200 L/min/m² Measured Background Concentrations

The total mass collected from the unit was 7.170 kg, resulting in a removal efficiency of 60.0%.

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 12** and the %-finer curves are shown on **Figure 20**.

Table 12:
200 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	**Test Sediment PSD**	**Total Retained**
500-1000	5%	5%
250-500	5%	5%
150-250	14%	12%
100-150	12%	13%
75-100	13%	10%
50-75	4%	7%
20-50	11%	5%
8-20	14%	2%
5-8	6%	0%
2-5	9%	0%

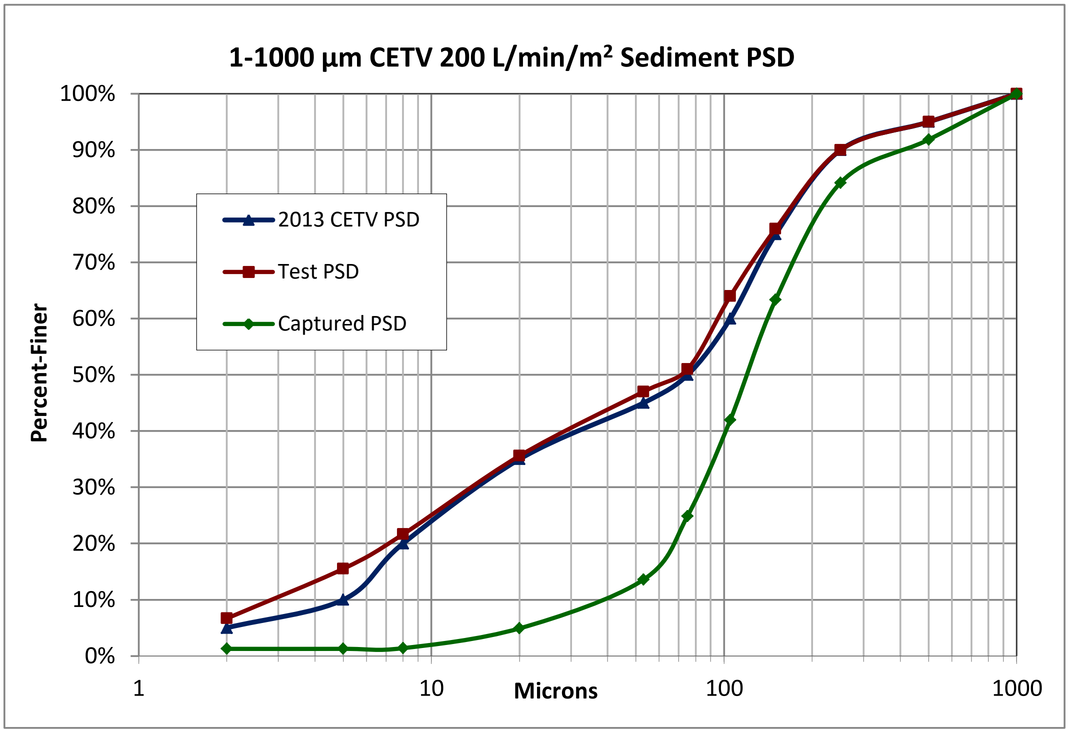

Figure 20: 200 L/min/m² Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.4 400 L/min/m² (466.8 L/min)

The test was conducted over a duration of 157 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 424.8 L/min, with a COV of 0.001. This flow is lower than the target of 467 L/min, but is within the 10% tolerance stated in the protocol. The maximum recorded temperature for the full test was 18.8 degrees C.

The injection feed rate of 84.8 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 202 mg/L, with a mean of 201 mg/L and COV of 0.01. The total mass injected into the unit was 12.345 kg. The calculated mass-flow concentration for the test was 194 mg/L. The measured influent concentration data for the complete test is shown on **Figure 21**.

Eight (8) background concentrations samples were collected throughout the test and ranged from 1.4 to8.9 mg/L. The background curve is shown on **Figure 22**.

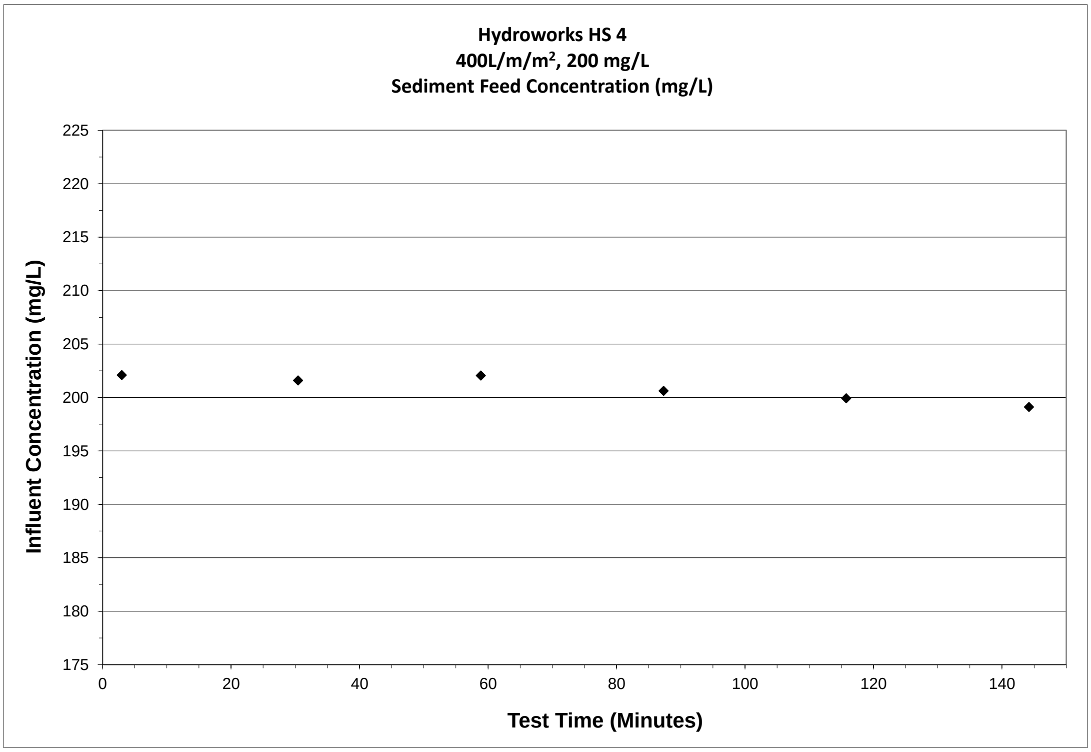

Figure 21: 400 L/min/m² Measured Influent Concentrations

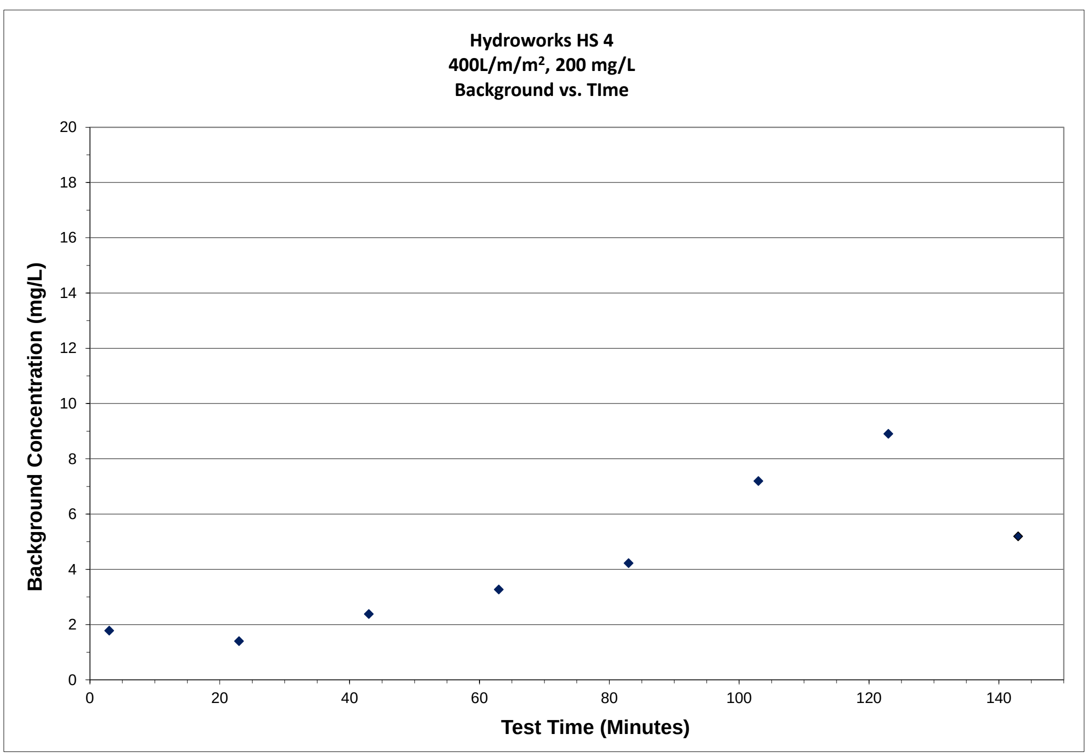

Figure 22: 400 L/min/m² Measured Background Concentrations

The total mass collected from the unit was 6.924 kg, resulting in a removal efficiency of 56.1%.

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 13** and the %-finer curves are shown on **Figure 23**.

Table 13:
400 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	**Test Sediment PSD**	**Total Retained**
500-1000	5%	3%
250-500	5%	3%
150-250	16%	12%
100-150	11%	13%
75-100	12%	11%
50-75	6%	7%
20-50	10%	4%
8-20	15%	1%
5-8	7%	0%
2-5	7%	0%

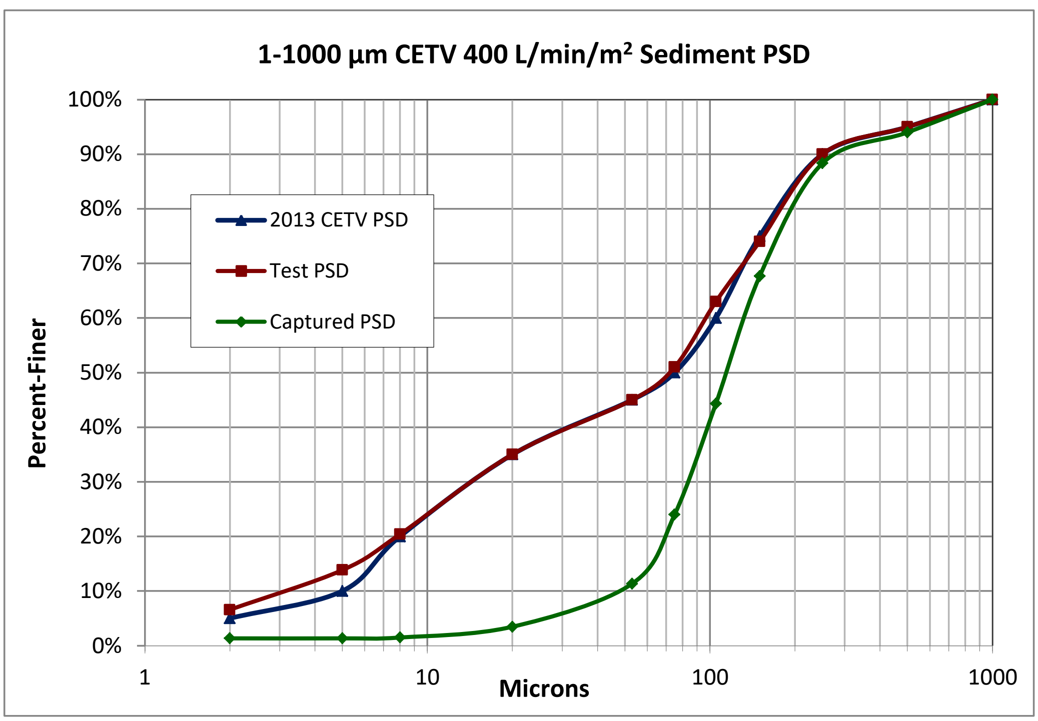

Figure 23: 400 L/min/m² Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.5 600 L/min/m^2 (700.1 L/min)

The test was conducted over a duration of 90 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 736.2 L/min, with a COV of 0.002. The maximum recorded temperature for the full test was 23.8 degrees C.

The injection feed rate of 147.6 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 200 mg/L, with a mean of 199 mg/L and COV of 0.00. The total mass injected into the unit was 12.177 kg. The calculated mass-flow concentration for the test was 199 mg/L. The measured influent concentration data for the complete test is shown on **Figure 24**.

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.1 to 2.6 mg/L. The background curve is shown on **Figure 25.**

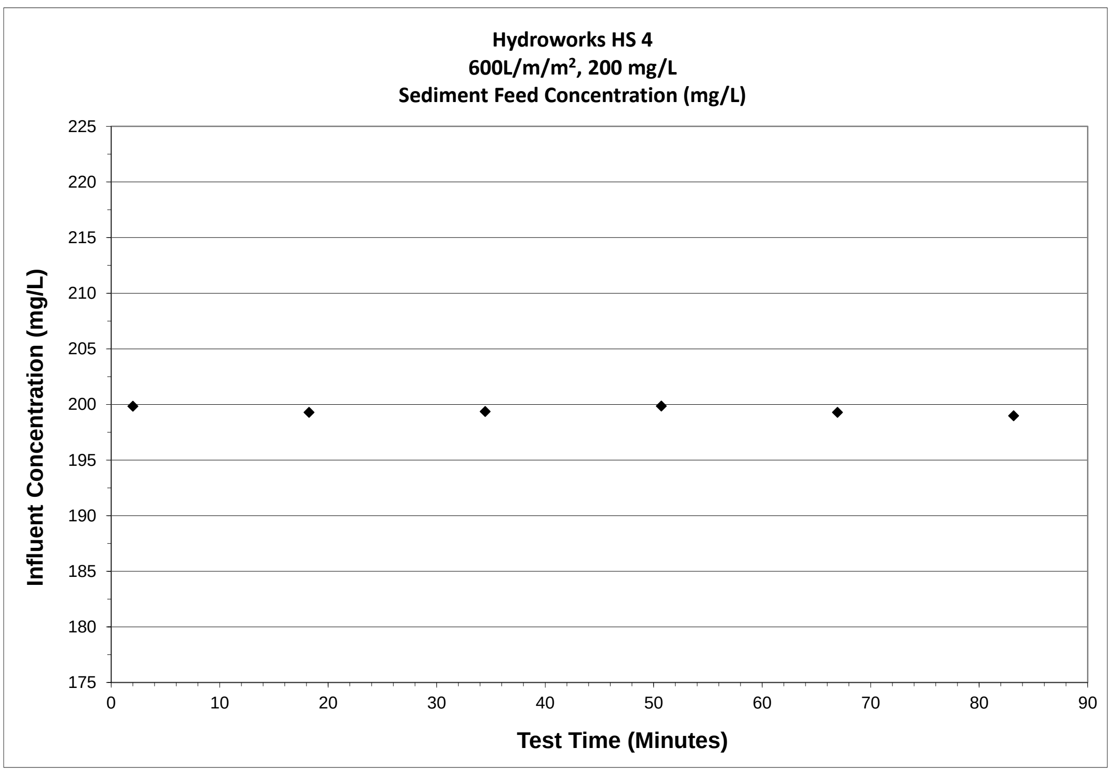

Figure 24: 600 L/min/m^2 Measured Influent Concentrations

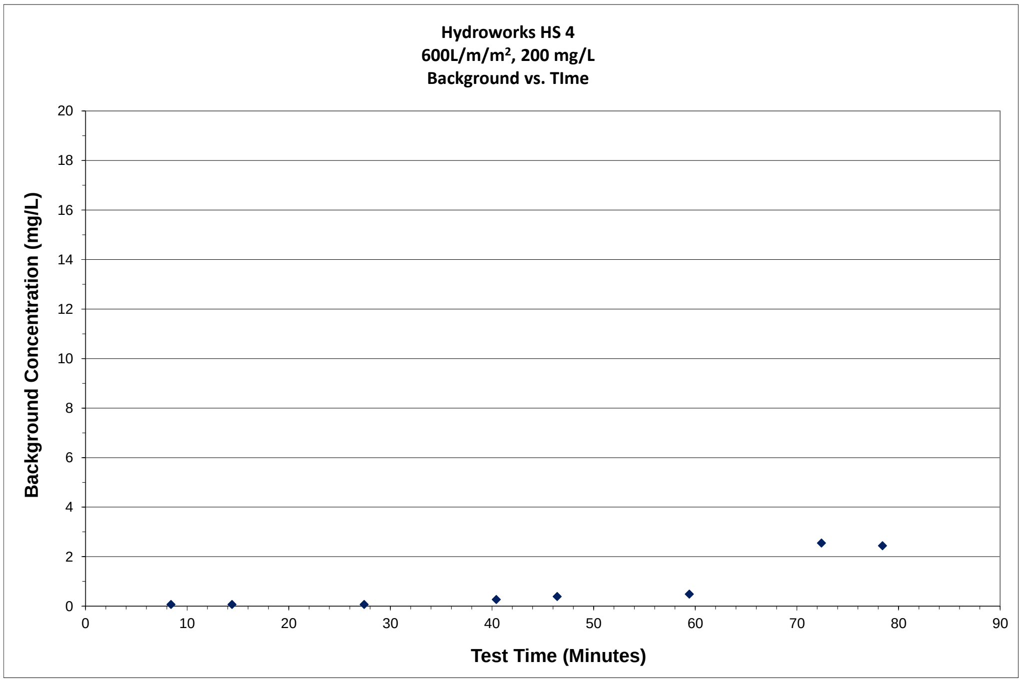

Figure 25: 600 L/min/m² Measured Background Concentrations

The total mass collected from the unit was 5.618 kg, resulting in a removal efficiency of 46.1%.

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 14** and the %-finer curves are shown on **Figure 26**.

Table 14:
600 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	Test Sediment PSD	Total Retained
500-1000	4%	4%
250-500	4%	5%
150-250	13%	12%
100-150	14%	11%
75-100	11%	7%
50-75	7%	4%
20-50	11%	2%
8-20	18%	0%
5-8	5%	0%
2-5	8%	0%

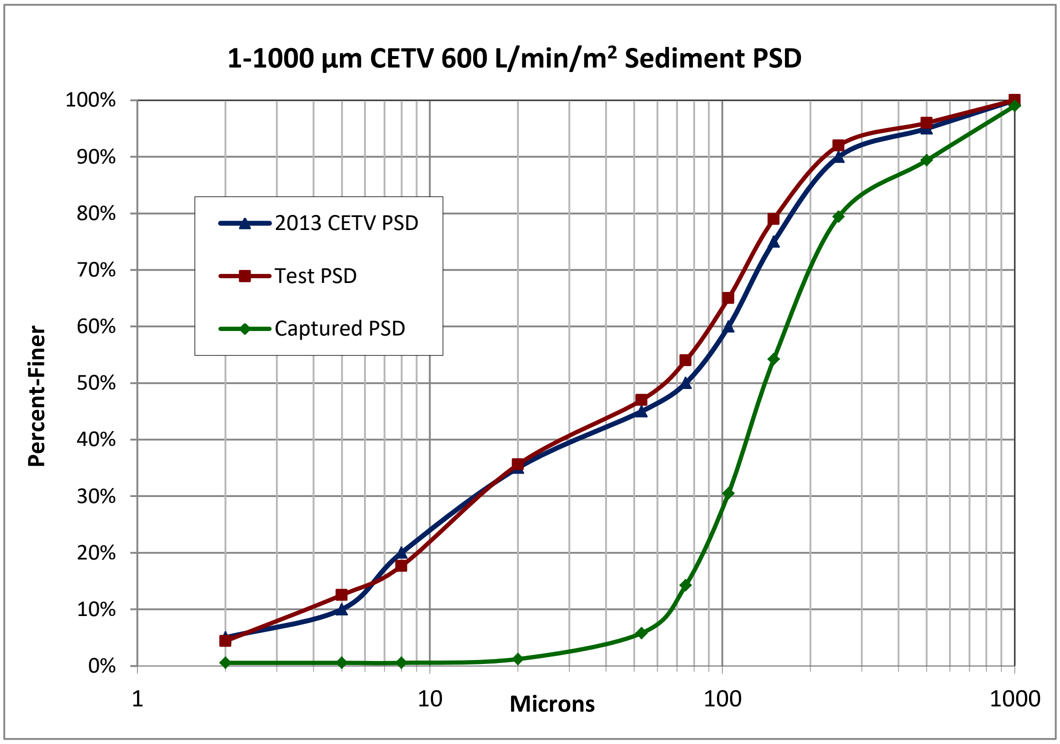

Figure 26: 600 L/min/m^2 Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.6 1000 L/min/m^2 (1167 L/min)

The test was conducted over a duration of 65 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 1104 L/min, with a COV of 0.004. The maximum recorded temperature for the full test was 19.9 degrees C.

The injection feed rate of 220.8 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 200 mg/L, with a mean of 200 mg/L and COV of 0.00. The total mass injected into the unit was 12.372 kg. The calculated mass-flow concentration for the test was 197 mg/L. The measured influent concentration data for the complete test is shown on **Figure 27**.

Eight (8) background concentrations samples were collected throughout the test and ranged from 1.2 to 7.6 mg/L. The background curve is shown on **Figure 28**.

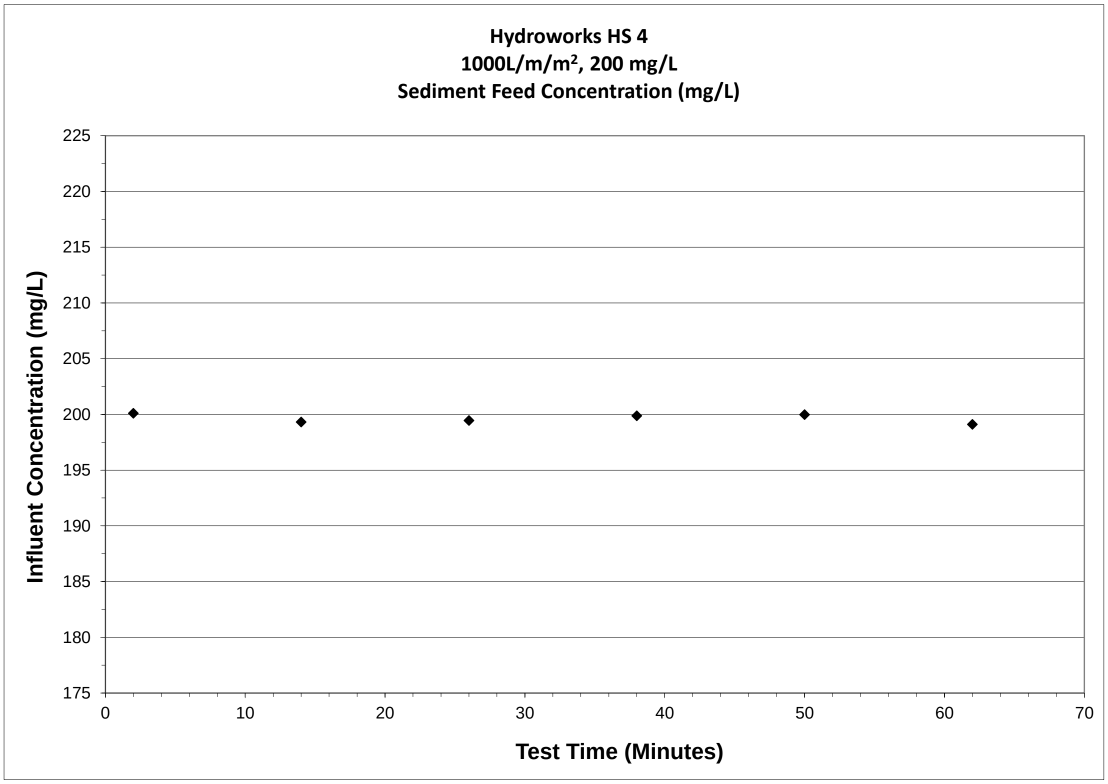

Figure 27: 1000 L/min/m^2 Measured Influent Concentrations

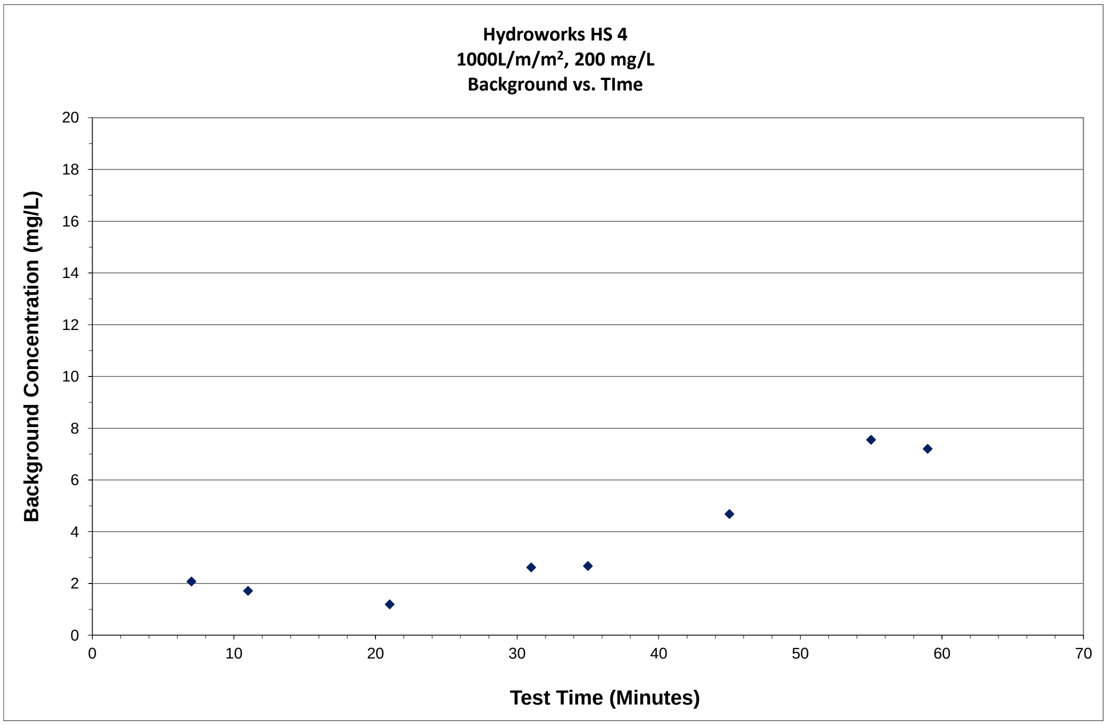

Figure 28: 1000 L/min/m^2 Measured Background Concentrations

The total mass collected from the unit was 5.093 kg, resulting in a removal efficiency of 41.2%.**4**

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 15** and the %-finer curves are shown on **Figure 29**.

Table 15:
1000 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	Test Sediment PSD	Total Retained
500-1000	4%	4%
250-500	4%	4%
150-250	19%	11%
100-150	10%	10%
75-100	12%	7%
50-75	4%	3%
20-50	10%	1%
8-20	16%	0%
5-8	6%	0%
2-5	9%	0%

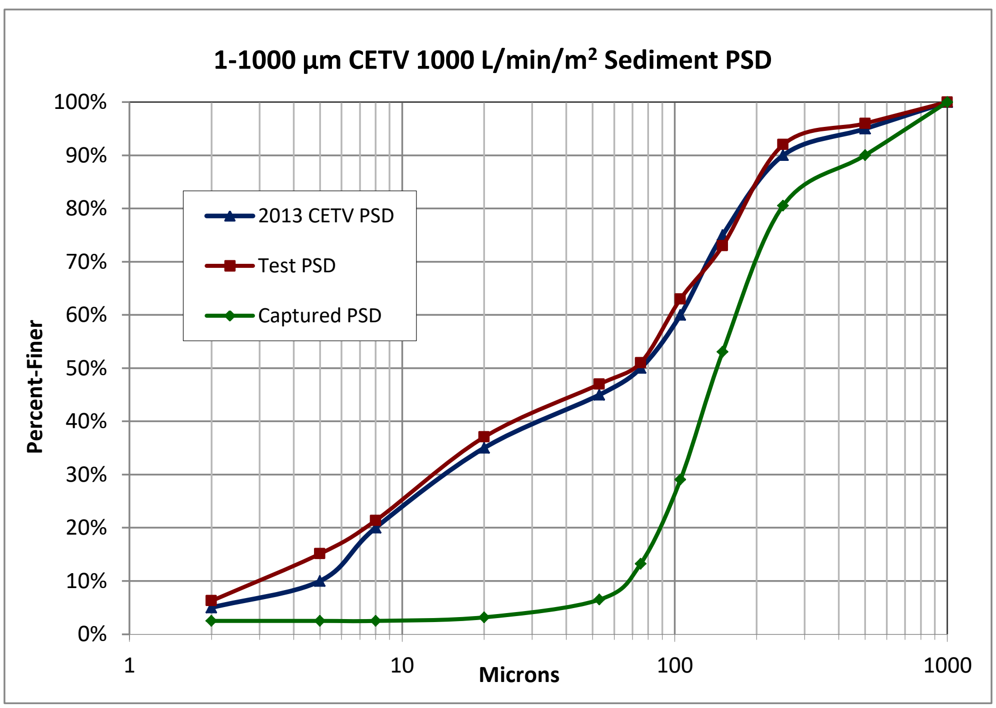

Figure 29: 1000 L/min/m² Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.7 1400 L/min/m² (1634 L/min)

The test was conducted over a duration of 45 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 5 seconds throughout the test. The average recorded test flow was 1628 L/min, with a COV of 0.002. The maximum recorded temperature for the full test was 18.8 degrees C.

The injection feed rate of 327.6 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 200 mg/L, with a mean of 200 mg/L and COV of 0.00. The total mass injected into the unit was 12.586 kg. The calculated mass-flow concentration for the test was 194 mg/L. The measured influent concentration data for the complete test is shown on **Figure 30.**

Eight (8) background concentrations samples were collected throughout the test and ranged from 0.3 to 4.0 mg/L. The background curve is shown on **Figure 31**.

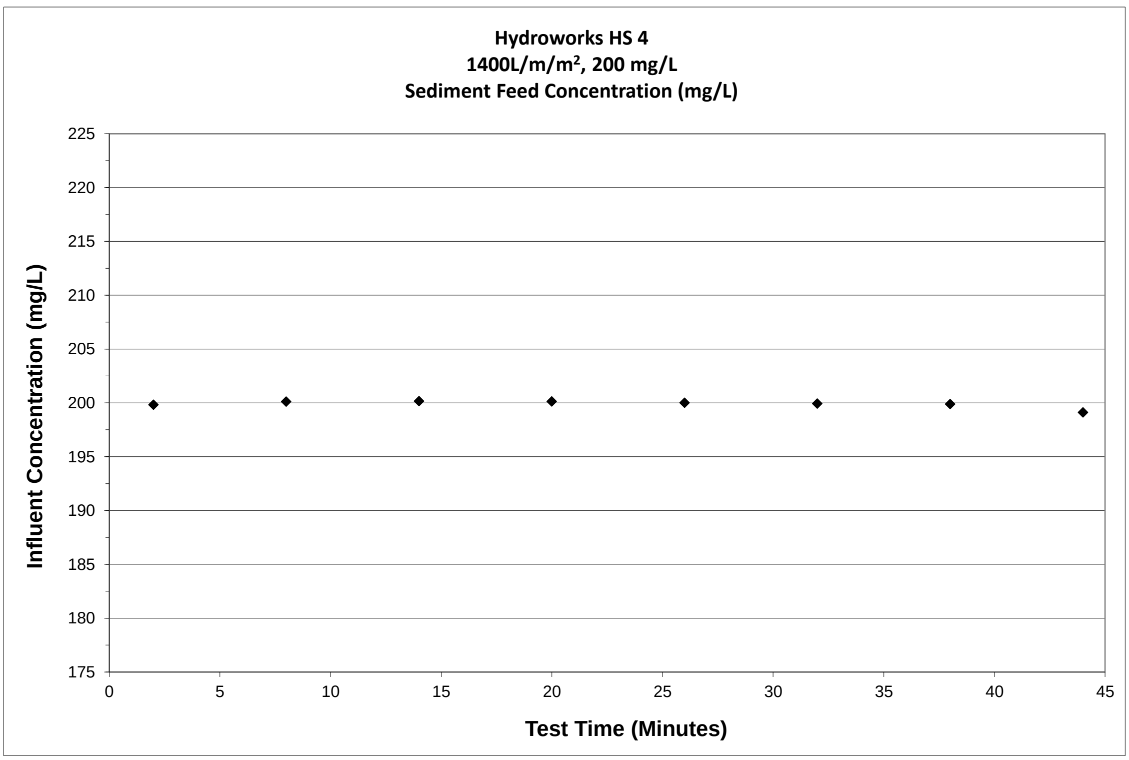

Figure 30: 1400 L/min/m² Measured Influent Concentrations

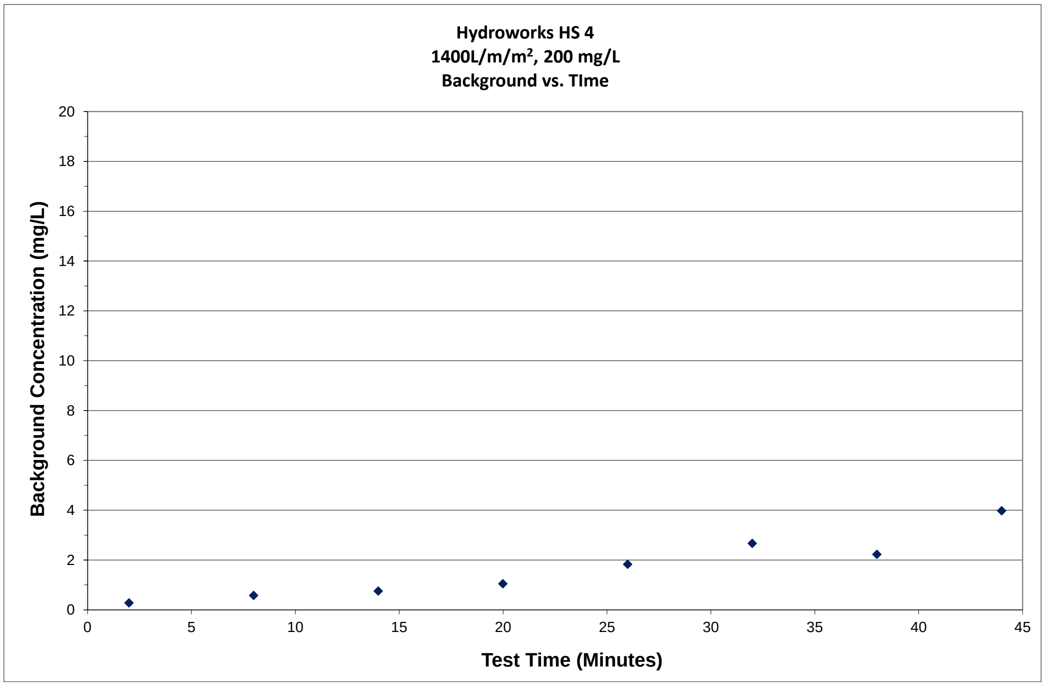

Figure 31: 1400 L/min/m² Measured Background Concentrations

The total mass collected from the unit was 4.498 kg, resulting in a removal efficiency of 35.7%.

Particle Size Distribution

A well-mixed random dry sample from the test batch was collected and analyzed for PSD by the independent analytical laboratory. A well-mixed dry sediment sample from each capture region was analyzed for PSD. The PSD breakdown of the percent of injected mass captured within each region is shown in **Table 16** and the %-finer curves are shown on **Figure 32**.

Table 16:
1400 L/min/m² PSD Breakdown of Injected Mass Captured

PSD Size Fraction microns	**Test Sediment PSD**	**Total Retained**
500-1000	5%	1%
250-500	5%	2%
150-250	16%	11%
100-150	11%	10%
75-100	13%	6%
50-75	5%	3%
20-50	10%	1%
8-20	14%	0%
5-8	6%	0%
2-5	9%	0%

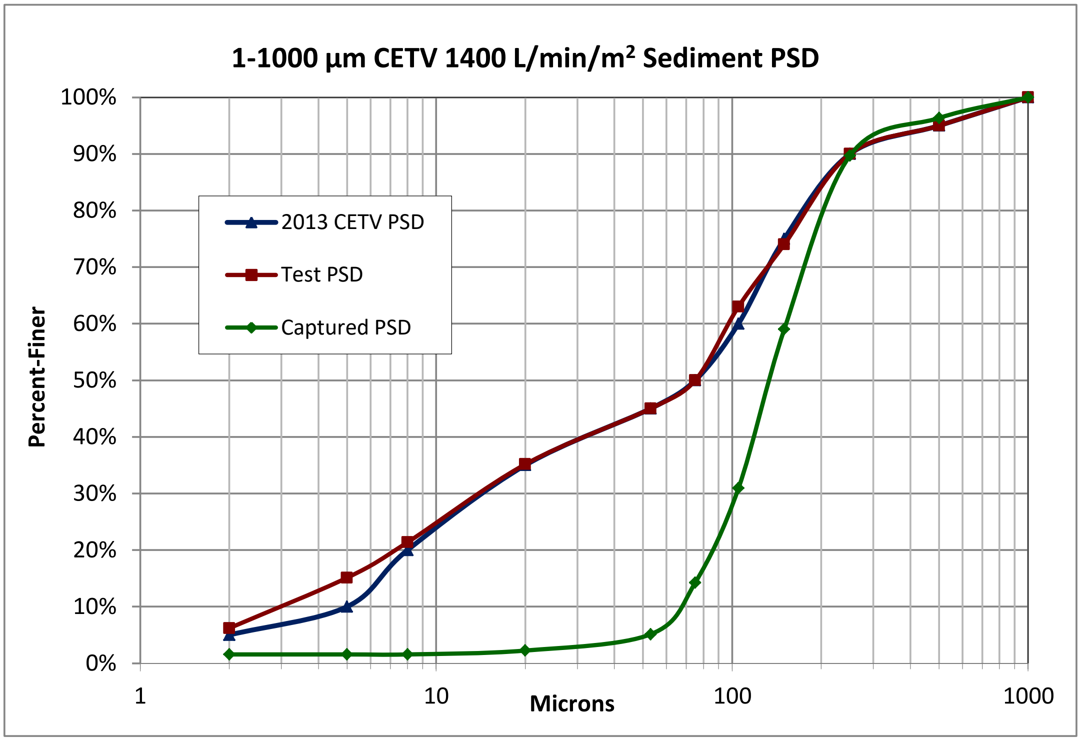

Figure 32: 1400 L/min/m^2 Percent-Finer Curves of Test Sediment and Total Captured Mass

4.1.8 Perforated Secondary Plate Test 600 L/min/m^2 (700.1 L/min)

The certification tests resulted in sediment deposition on the solid secondary plate, which consequently required the plate to be preloaded for scour testing. Taking into account the close proximity of the plate to the collection sump, as well as our knowledge of sediment transport, it is expected that the deposited sediment would have settled in the lower sump, with no impact on removal efficiency, if the plate was removed. Since the purpose of the plate is to protect the sump from potential scour, the plate was replaced with a 32% open-area perforated plate of the same geometry (size and orientation). The plate would provide a means for the sediment to deposit in the sump, while still providing a sufficient level of protection against scour. A repeat test was conducted at 600 L/min/m^2 to confirm that the new plate would produce the same flow and removal characteristics as the solid plate. PSD analyses were not conducted, being unnecessary to achieve the goal of the test.

The test was conducted over a duration of 90 minutes to meet the minimum 11.3 kg feed requirement. The test flow was averaged and recorded every 10 seconds throughout the test. The average recorded test flow was 740.9 L/min, with a COV of 0.003. The maximum recorded temperature for the full test was 16.1 degrees C.

The injection feed rate of 147.6 g/min was verified by collecting timed weight samples from the injector. The measured influent injection concentrations for the full test ranged from 199 mg/L to 200 mg/L, with a mean of 199 mg/L and COV of 0.00. The total mass injected into the unit was 12.035 kg. The calculated mass-flow concentration for the test was 194 mg/L. The measured influent concentration data for the complete test is shown on **Figure 24**.

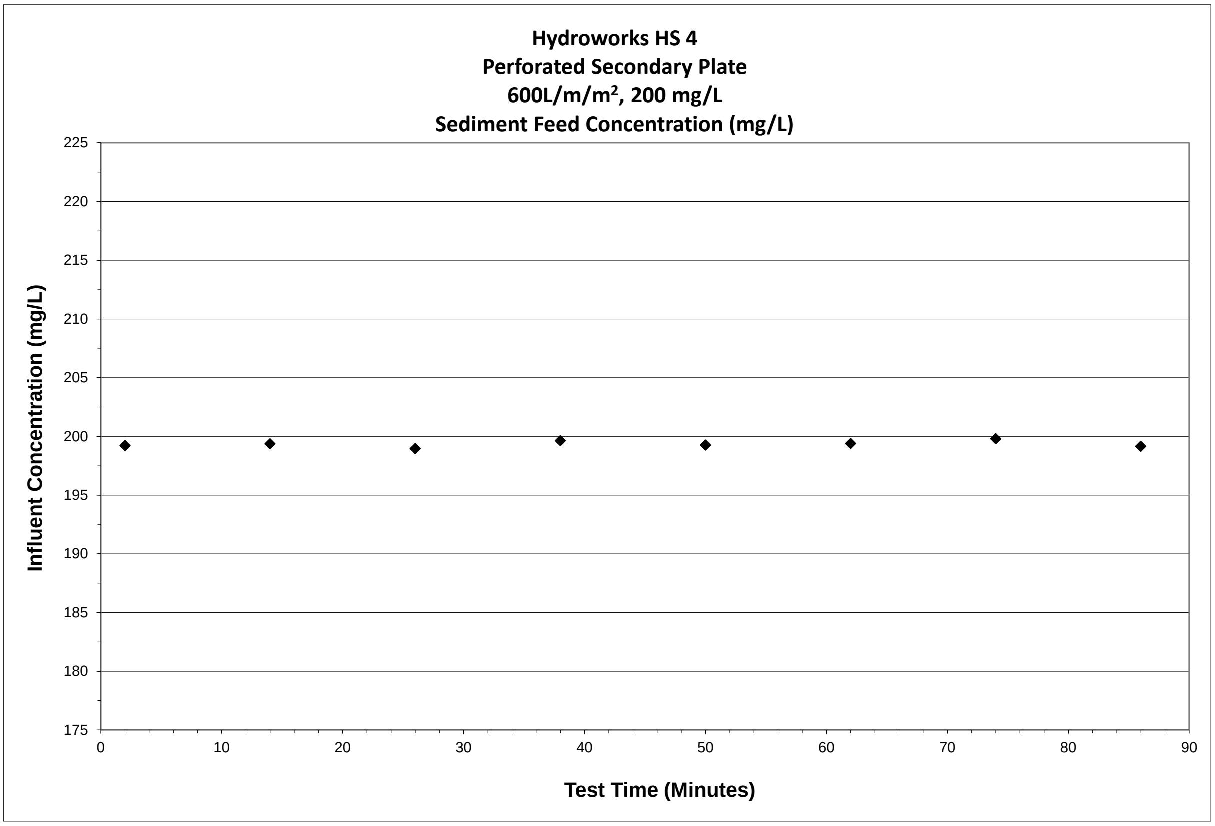

Figure 33: 600 L/min/m^2 Perforated Plate Measured Influent Concentrations

Eight (8) background concentrations samples were collected throughout the test. Approximately halfway through the test, it was observed that an internal sump wall had developed a crack, which allowed raw effluent to bypass the filtration wall. The testing was not terminated for the following reasons: 1) the impact of the breach on the background concentrations would not be known until the test was completed, and 2) being a closed-loop system, any increase in concentration is a result of the fine injected particles not being captured by the treatment system and therefore, will not skew the mass balance results. The concentration did exceed the 20 mg/L limit, with values ranging from 0.2 to 28.4 mg/L. The background curve is shown on **Figure 25.**

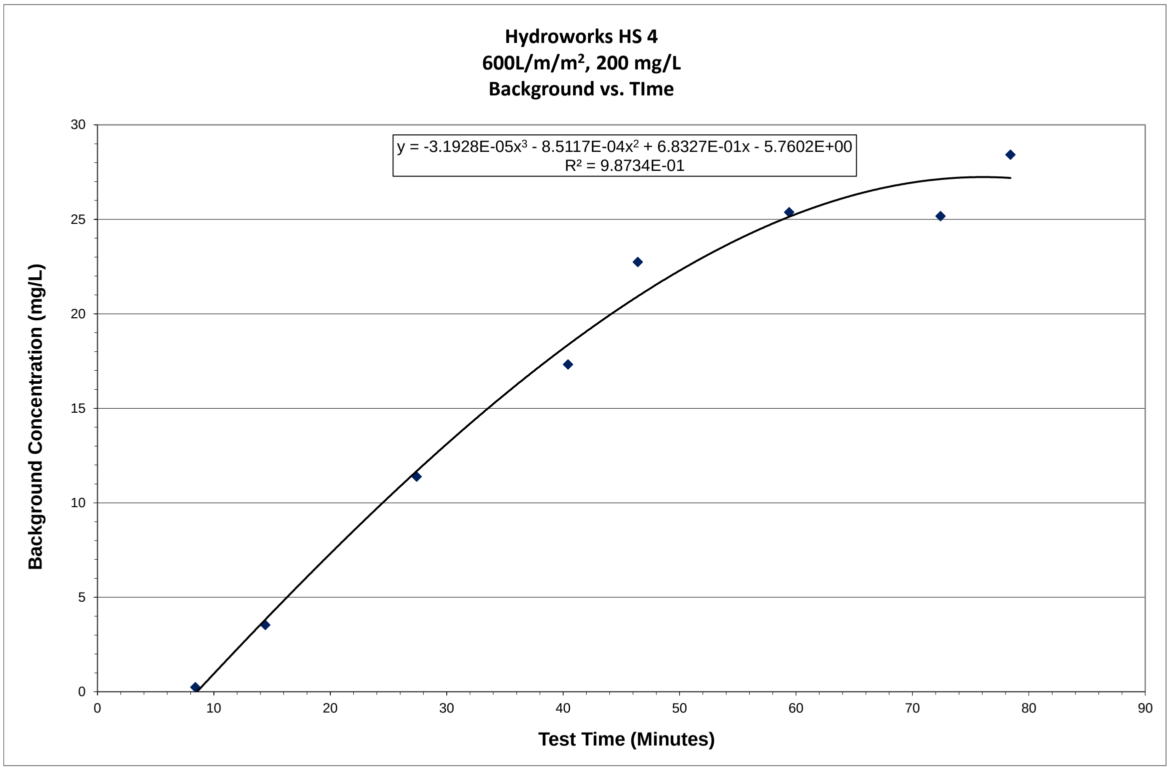

Figure 34: 600 L/min/m^2 Measured Background Concentrations

The total mass collected from the unit was 5.529 kg, resulting in a removal efficiency of 45.9%. This matches well with the previous test removal of 46.1%. The quantified deposition from the perforated plate was 2.7%, significantly lower than the 8.5% collected from the solid plate. This material was collected along the outer edge of the plate where it attaches to the mounting ring. The quantity of sediment collected from the sump increased by the same margin, validating the statement that the material from the solid plate would have been collected in the lower sump. The capture splits for the solid and perforated plate tests are summarized in **Table 17**.

Table 17:
600 L/min/m^2 Summary of Injected Mass Captured

	Flow	Tested Flow	Removal Efficiency	Pretreatment Channel	Secondary Plate	Outlet Dispersion Plate	Collection Sump
	L/min/m^2	L/min	%	%	%	%	%
Solid Plate	600	736.2	46.1	24.7	8.5	3.1	9.9
Perforated Plate	600	740.9	45.9	25.8	2.7	3.0	14.5

4.2 Sediment Re-Suspension and Washout

A false floor was installed in the collection sump to reduce the quantity of sediment required for the test. The sump was uniformly preloaded to the 50% sump capacity level (15.2 cm), with a minimum depth of 10.2 cm of 1-1000 micron sediment shown in **Table 1**.

Removal efficiency testing resulted in sediment deposition of <10% on the secondary plate at the lower flows (<5% at 1400 SLR). However, TRCA requested that the Secondary Plate surface be preloaded to a depth of 10.2 cm prior to conducting the re-suspension test. The leading edge was tapered at an angle of approximately 45 degrees to reduce slumping. The test was conducted as described in **Section 3.2.3** , with target surface loading rates of 200, 800, 1400, 2000 and 2600 L/min/m^2.

The average measured flow data recorded throughout the test is shown in Error! Reference source not found. and all recorded data on **Figure 35.** Seven (7) background samples were collected throughout the duration of the test. The measured concentrations ranged from 0.7 to 17.1 mg/L, as shown on **Figure 36**. A 3rd-order curve equation was established for adjusting the effluent concentrations.

Table 18:
Resuspension Flow Summary

Target SLR	Measured SLR	Deviation from Target	COV	QA / QC Compliant
200	204.8	2.4%	0.019	**Yes**
800	804.2	0.5%	0.004	**Yes**
1400	1407.8	0.6%	0.027	**Yes**
2000	2023.8	1.2%	0.002	**Yes**
2600	2622.7	0.9%	0.002	**Yes**

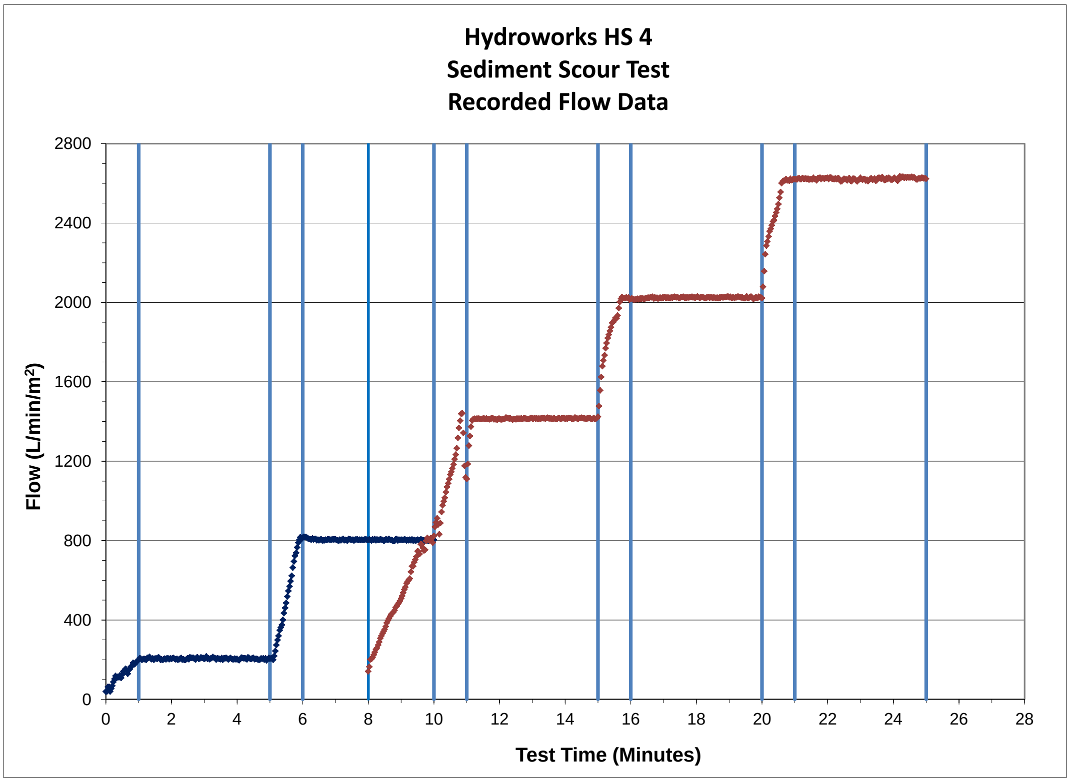

Figure 35: Scour Test Recorded Flow Data

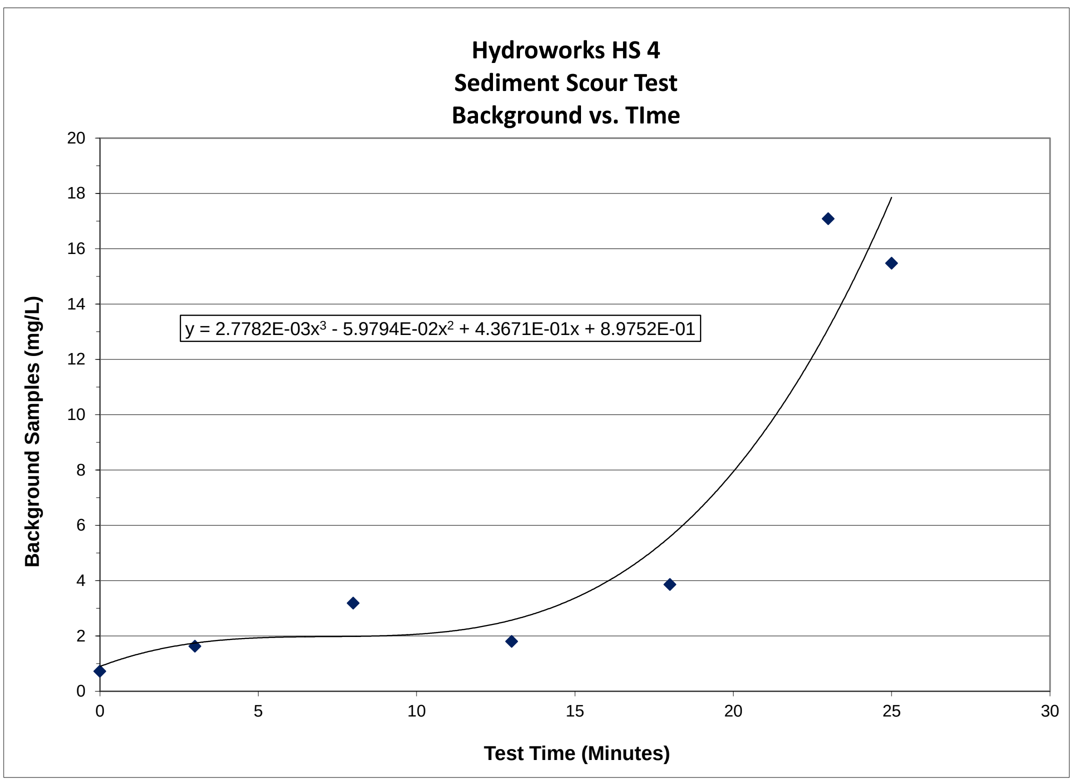

Figure 36: Measured Background Concentrations

Measured effluent sediment concentrations (adjusted for background) increased over the surface loading rates of 200, 800 and 1400 L/min/m^2, after which it decreased due to bypass flow. The average concentration for each tested SLR was 40.2, 71.0, 271.2, 227.1 and 128.5 mg/L, respectively. The concentrations were adjusted for particle size, based on a D_5 of 7.0 microns for the 40 L/min/m^2 removal efficiency test. The D_5 adjusted effluent concentrations were 11.3, 28.9, 196.7, 175.4 and 99.9 mg/L, respectively. The effluent data is shown in Error! Reference source not found. and the corresponding curves are shown on Error! Reference source not found..

The unit was slowly decanted after the completion of the test. It was observed that most of the Secondary Plate was devoid of sediment. A measurement of the sump depth revealed an increase of approximately 7 cm. This leads to a conclusion that most of the sediment from the Secondary Plate was carried into the lower sump. It can also be concluded that the fine material loaded on the Secondary Plate was re-suspended and conveyed out of the unit with the flow, as the velocity in the unit is higher than the fall velocity of the fine sediment.

Table 19
Measured Scour Effluent Concentrations (mg/L) Adjusted for Background

Measured Concentration at Each surface Loading Rate					
Effluent Sample No.	200 L/min/m^2	800 L/min/m^2	1400 L/min/m^2	2000 L/min/m^2	2600 L/min/m^2
1	32.4	58.0	68.5	255.7	138.5
2	38.8	120.7	188.1	254.8	128.6
3	37.4	75.5	329.0	238.0	113.6
4	40.1	55.8	417.5	216.7	144.7
5	52.1	44.9	352.9	170.3	117.1
Average	**40.2**	**71.0**	**271.2**	**227.1**	**128.5**
D_5 Correction	**11.3**	**28.9**	**196.7**	**175.4**	**99.9**

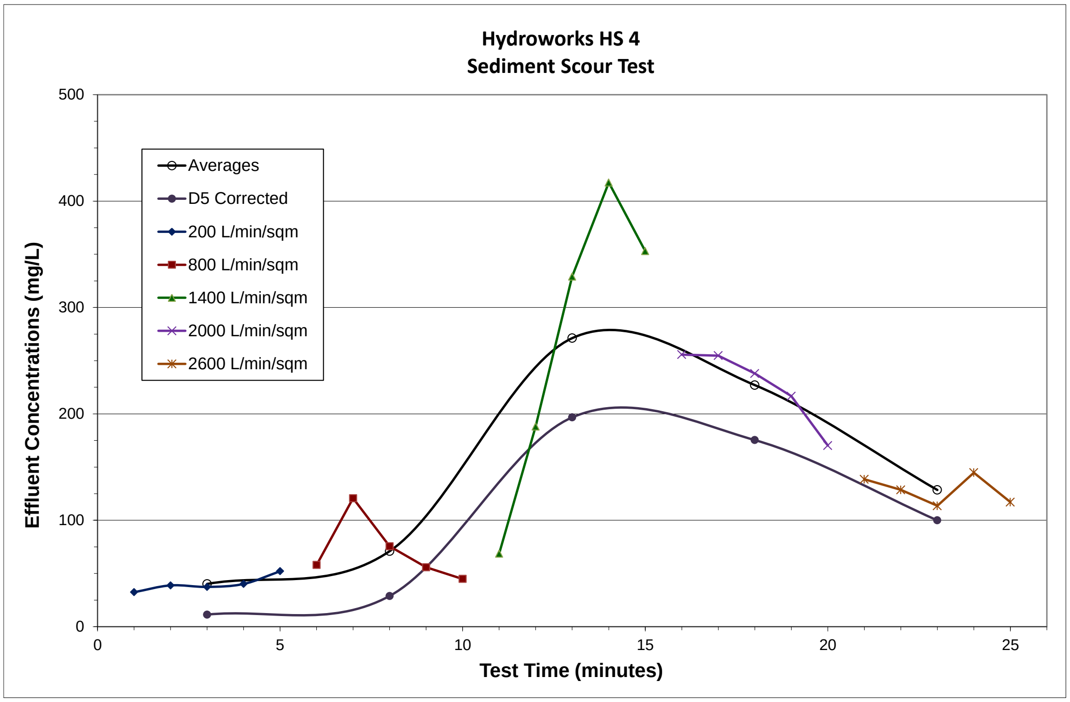

Figure 37: Scour Testing Effluent Concentrations Adjusted for Background

4.2.1 Perforated Plate Sediment Re-Suspension and Washout

A repeat scour test was conducted with the perforated secondary plate installed. The sump was uniformly preloaded to the 50% sump capacity level (15.2 cm), with a minimum depth of 10.2 cm of 1-1000 micron sediment shown in **Table 1**. The pretreatment channel was preloaded with 22 kg of sediment that was collected at the lower flows during removal testing, as shown on **Figure 38**. This is the scientifically correct approach, as the channel is designed to capture the coarse particles prior to the flow entering the inner chamber. A sieve analysis conducted on the material showed good correlation above 53 microns and a finer distribution below 53 microns. This indicates that there was still "flour" material (<53 microns) remaining from the previous adjusted scour test blend and is still conservative.

The average measured flow data recorded throughout the test is shown in Error! Reference source not found. and all recorded data on **Figure 35.** Seven (7) background samples were collected throughout the duration of the test. The measured concentrations ranged from 2.4 to 10.4 mg/L, as shown on **Figure 36**. A 3[rd]-order curve equation was established for adjusting the effluent concentrations.

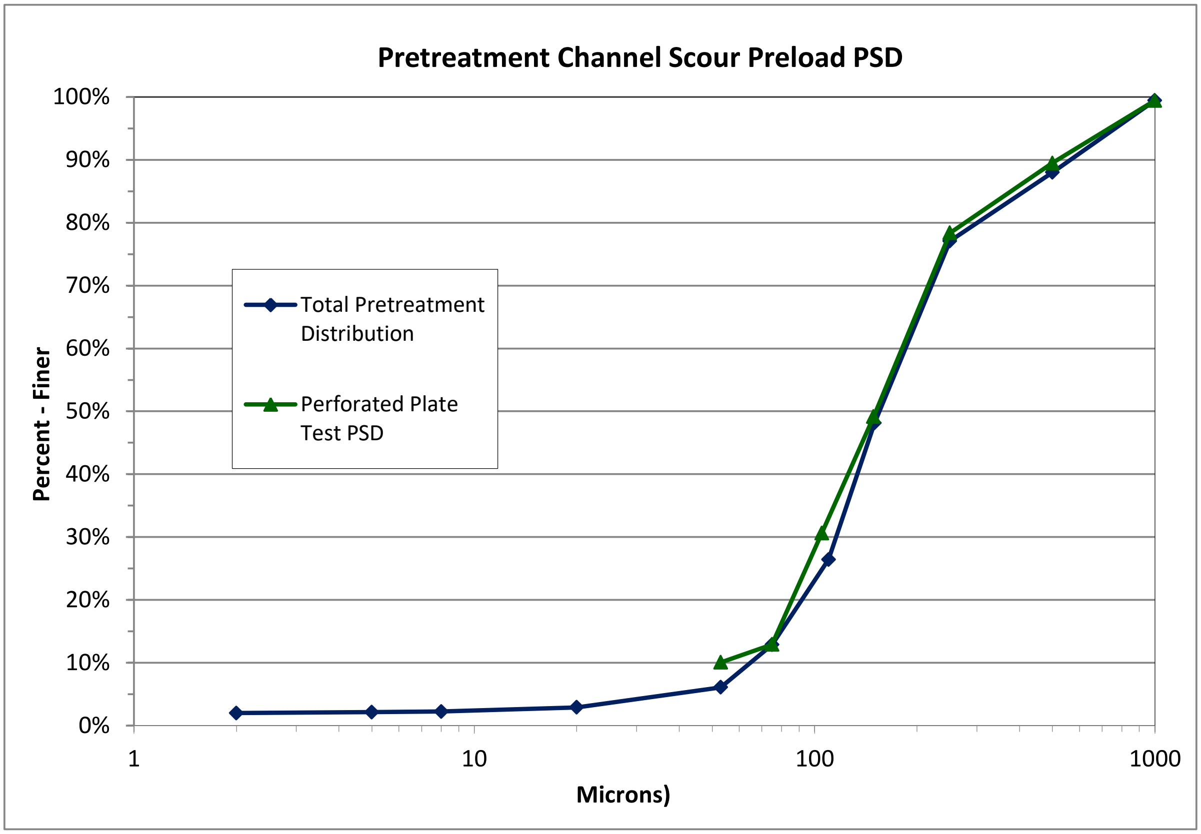

Figure 38: Repeat Scour Test Pretreatment Channel Preloaded PSD

Table 20
Repeat Scour Test Flow Summary

Target SLR	Measured SLR	Deviation from Target	COV	QA / QC Compliant
200	201.0	0.5%	0.020	**Yes**
800	805.9	0.7%	0.003	**Yes**
1400	1428.2	2.0%	0.006	**Yes**
2000	2009.9	0.5%	0.002	**Yes**
2600	2609.8	0.4%	0.002	**Yes**

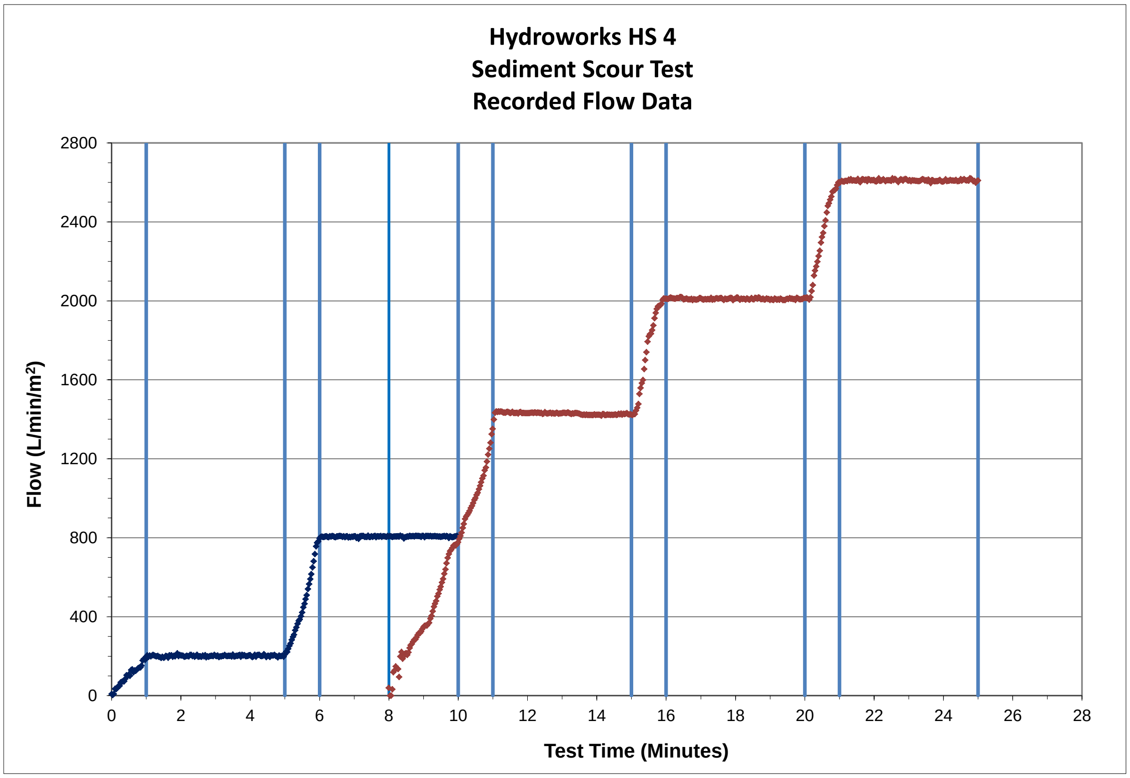

Figure 39: Repeat Scour Test Recorded Flow Data

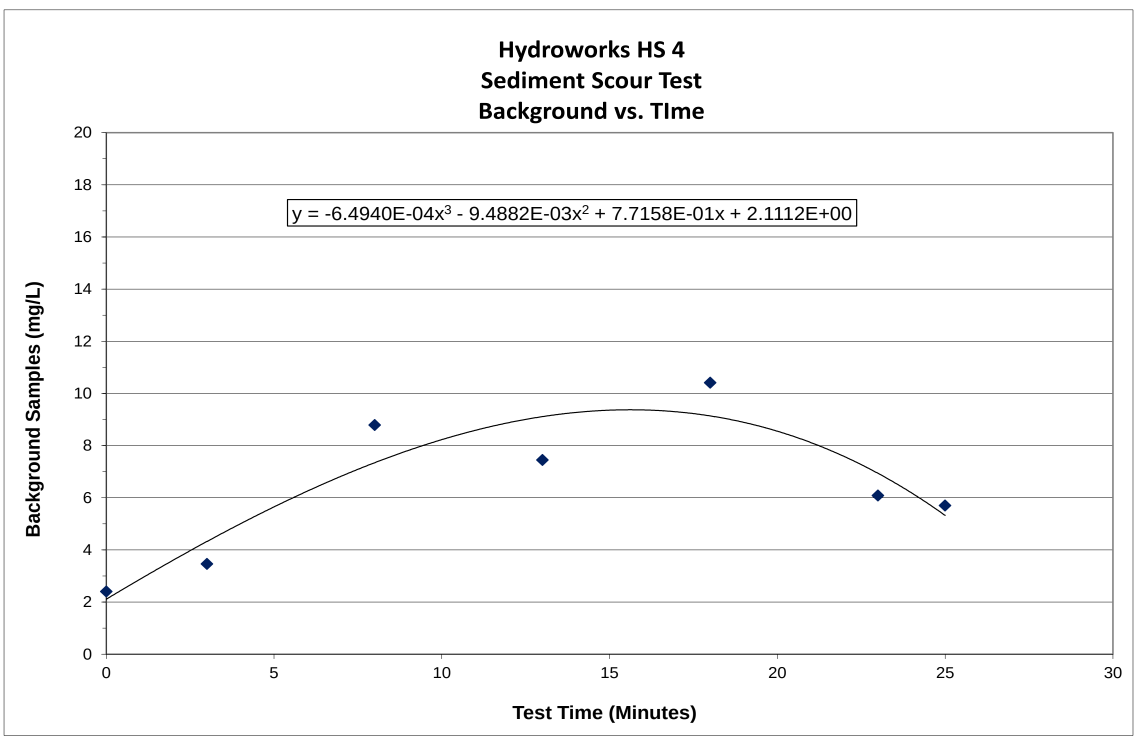

Figure 40: Measured Background Concentrations

The average concentration for each tested SLR was 37.2, 37.1, 24.1, 24.1 and 29.8 mg/L, respectively. The concentrations were adjusted for particle size, based on a D_5 of 7.0 microns for the 40 L/min/m^2 removal efficiency test. The D_5 adjusted effluent concentrations were 22.4, 28.5, 20.0, 19.1 and 24.4 mg/L, respectively. The effluent data is shown in Error! Reference source not found. and the corresponding curves are shown on Error! Reference source not found..

Table 21
Measured Scour Effluent Concentrations (mg/L) Adjusted for Background

Measured Concentration at Each surface Loading Rate					
Effluent Sample No.	200 L/min/m^2	800 L/min/m^2	1400 L/min/m^2	2000 L/min/m^2	2600 L/min/m^2
1	50.6	18.2	14.7	17.3	30.5
2	49.4	59.1	27.4	34.6	35.2
3	38.6	43.0	36.3	28.4	33.1
4	27.4	39.0	24.1	21.6	24.8
5	19.9	26.0	18.1	18.5	25.5
Average	**37.2**	**37.1**	**24.1**	**24.1**	**29.8**
D_5 Correction	**22.4**	**28.5**	**20.0**	**19.1**	**24.4**

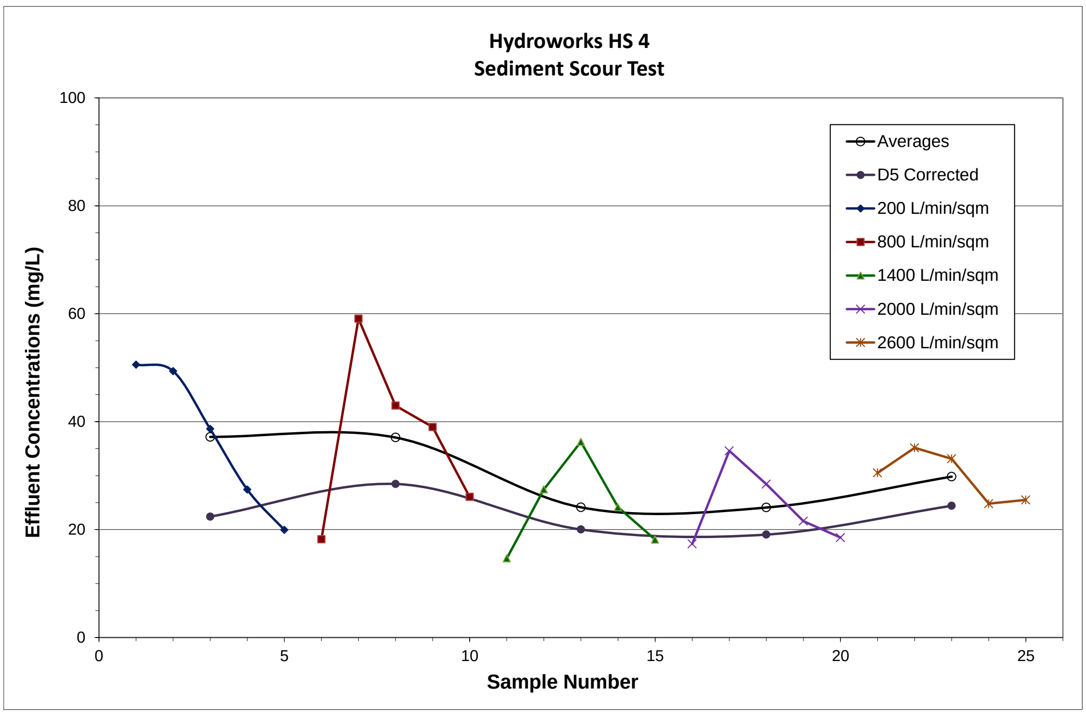

Figure 41: Scour Testing Effluent Concentrations Adjusted for Background

4.3 Light-Liquid Re-Entrainment Simulation

A light-liquid re-entrainment test was conducted using Dow Chemical Dowlex™ 2517 low-density polyethylene beads. The product density of 0.917 g/cm^2 was verified by an independent analytical laboratory using ASTM D1238 and ASTM D792 methods.

The inner chamber of the HS 4 unit was filled with 58.3 liters (33.4 kg) of pellets, which corresponded to a 5cm depth over the collection sump area of 1.17m^2. The test was conducted in accordance with the procedure described in **Section 3.2.4**, at the SLR of 200, 800, 1400, 2000 and 2600 L/min/m^2.

The recorded SLR flow data for the test is graphically shown on Error! Reference source not found.. All recorded flows were within 1% of the targets, with a maximum COV of 0.011. The recorded average flow data, as well as quantified volume and mass of collected pellets for each target SLR and overall test, is shown in Error! Reference source not found.. The maximum re-entrainment of 4.6% occurred at 1400 L/min/m^2, which is the 100% treatment flow and start of bypass. The re-entrainment diminished to 4.3% and 2.5% with each subsequent flow. The total volume re-entrained from the oil collection region for the entire test was 11.7%, for a retention rate of 88.3%.

Table 22:
Light-liquid Recorded Flow and Re-entrainment Data

Light-liquid Re-Suspension Data				Starting Volume	(Liters) 58.3	Starting Mass	(grams) 33399	Hydroworks HG4	
						Measured		Calculated Percentages	
Action	Time Stamp (minutes)	Meter	Target Flow (L/min/m^2)	Recorded Flow (L/min/m^2)	COV	Collected Volume (Liters)	Collected Mass (grams)	Collected Volume (Liters)	Collected Mass (grams)
Start D.A. Recording	0.0								
Flow set	1.0	4"	200	**199**	0.021	0	0	**0.0%**	**0.0%**
Stop Collection	6.0			-0.6%					
Flow set	7.0	4"	800	**807**	0.005	0.1	49	**0.1%**	**0.1%**
Stop Collection	12.0			0.9%					
Flow set	13.0	8"	1400	**1408**	0.002	2.7	1523	**4.6%**	**4.6%**
Stop Collection	18.0			0.6%					
Flow set	19.0	8"	2000	**2014**	0.002	2.5	1445	**4.3%**	**4.3%**
Stop Collection	24.0			0.7%					
Flow set	25.0	8"	2600	**2608**	0.002	1.5	847	**2.5%**	**2.5%**
Stop Collection	30.0			0.3%					
				Interim Collection Net		0.1	39	**0.1%**	**0.1%**
				Total		**6.8**	**3902**	**11.7%**	**11.7%**
						Pellets Retained		**88.3%**	**88.3%**

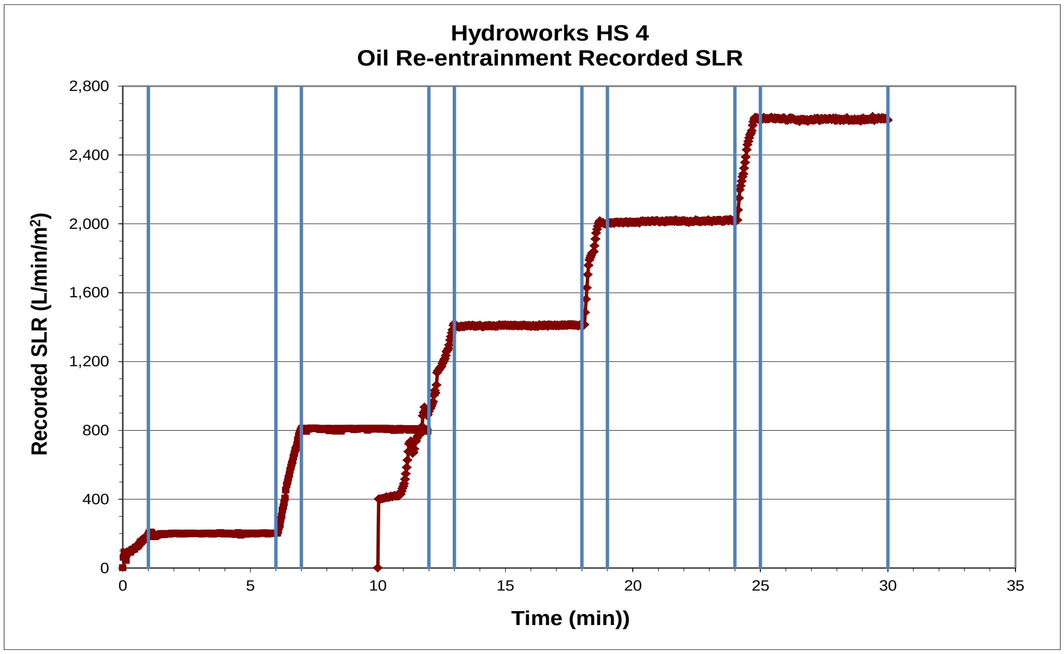

Figure 42: Recorded Light-liquid SLR Flow Data

4.4 Hydraulic Characteristics

Piezometer taps were installed in the unit as described in **Section 3.2.1**. Flow (L/min) and water level (meters) within the unit were measured for 15 flows ranging from 0 to 6606 L/min. The influent pipe was flowing full at approximately 5730 L/min. The entrance to the effluent pipe was submerged at approximately 6600 L/min. The flow reached bypass at 1630 L/min. The recorded data is shown in **Table 23** and the Elevation Curves for each pressure tap location are shown on Error! Reference source not found.. The pressure data for the inlet and outlet pipes were corrected for energy.

Table 23:
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
L/min	m	sq-m	m	m	m	m	m	m	m	Cd
0.0	0.052	0.000	0.000	0.000	0.000	-0.003	0.052	0.000	0.000	0.000
94.7	0.076	0.003	0.047	0.039	0.039	0.020	0.091	0.047	0.043	0.025
190.0	0.087	0.005	0.061	0.057	0.057	0.029	0.107	0.064	0.042	0.050
379.9	0.099	0.008	0.086	0.081	0.080	0.044	0.132	0.085	0.047	0.095
571.2	0.109	0.010	0.110	0.101	0.098	0.056	0.152	0.101	0.051	0.137
764.9	0.119	0.013	0.132	0.119	0.113	0.067	0.168	0.116	0.051	0.182
1052.7	0.158	0.025	0.166	0.143	0.132	0.081	0.183	0.135	0.048	0.260
1325.0	0.197	0.038	0.199	0.164	0.147	0.091	0.214	0.152	0.062	0.288
1631.9	0.244	0.055	0.245	0.188	0.165	0.104	0.257	0.168	0.089	0.296
1901.7	0.262	0.061	0.266	0.205	0.182	0.113	0.275	0.182	0.093	0.337
2278.9	0.279	0.067	0.283	0.222	0.195	0.127	0.296	0.199	0.096	0.397
2657.4	0.293	0.072	0.297	0.237	0.214	0.141	0.312	0.216	0.097	0.462
3783.6	0.333	0.084	0.333	0.276	0.243	0.174	0.362	0.261	0.101	0.643
5730.5	0.393	0.098	0.395	0.348	0.312	0.221	0.441	0.332	0.110	0.934
6606.4	0.428	0.099	0.429	0.387	0.365	0.222	0.491	0.367	0.123	1.016

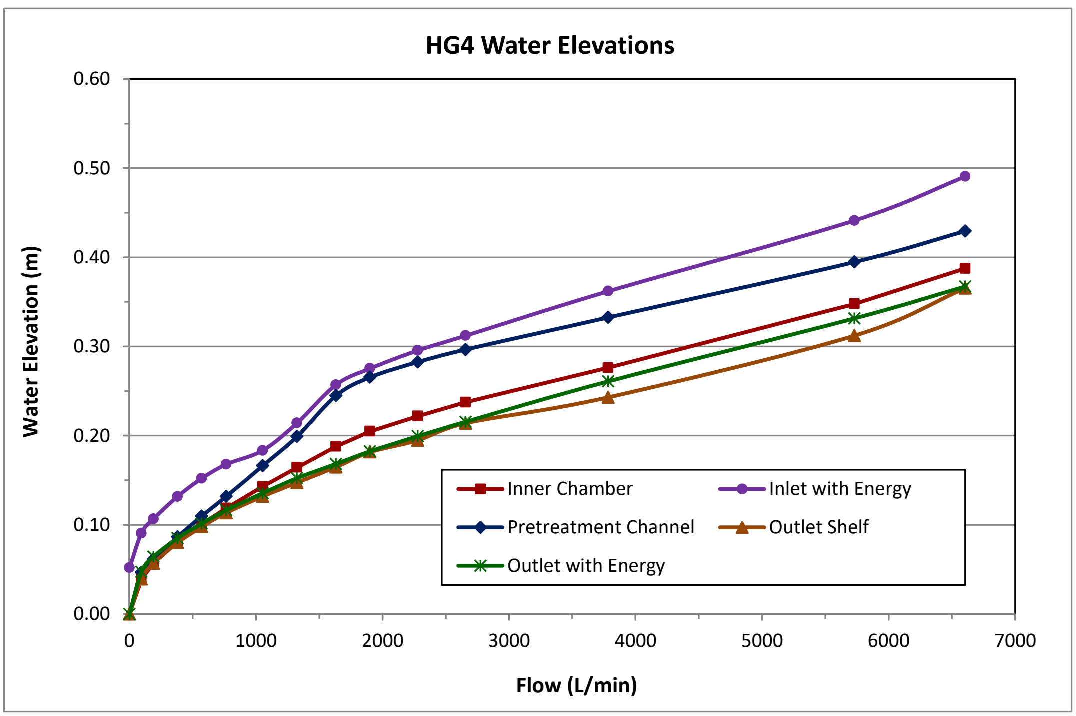

Figure 43: Measured Flow vs Water Elevations

As seen on Error! Reference source not found., 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 (0.07 m^2). The Cd values prior to bypass ranged from 0.03 to 0.30. The calculated losses are shown in **Table 233**.

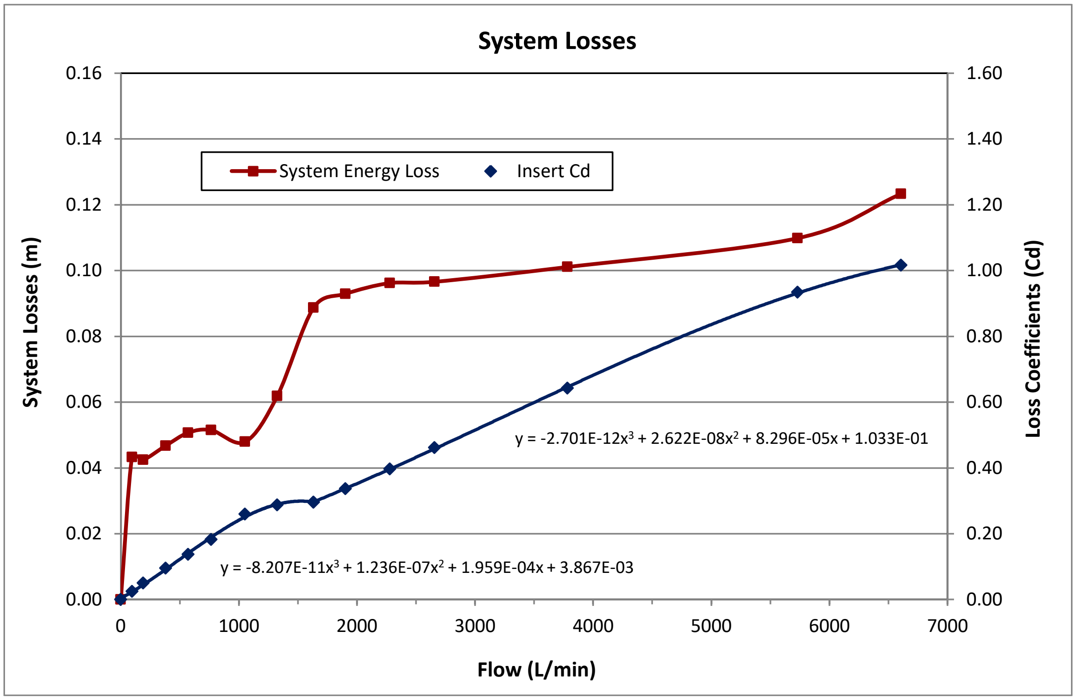

Figure 44: Calculated Losses and Insert Outlet Cd

5.0 Conclusions

The Hydroworks HS 4 Stormwater Treatment Unit achieved sediment removal efficiencies from 35.7% to 68.6% for surface loading rates ranging from 40 to 1400 L/min/m^2, respectively, using CETV specified 1-1000 micron PSD.

Light-liquid testing results showed that the unit was able to retain 88.3% of the pre-loaded pellets through the full range of SLRs from 200 to 2600 L/min/m^2.

Sediment scour testing resulted in average effluent concentrations ranging from 11 to 197 mg/L for loading rates up to 2600 L/min/m^2. This testing was conducted with the Secondary Plate preloaded to 10.2 cm.

Hydraulic testing was conducted at flows ranging from 0 to 6600 L/min. Bypass was reached at 1630 L/min. The maximum calculated system loss at 6600 L/min was 0.12 m.

The solid secondary plate was replaced with a 32% open-area plate and the 600 L/min/m2 test was repeated. The solid and perforated plate tests produced removal efficiencies of 46.1% and 45.9%, respectively. This indicates that the flow patterns and particle settling characteristics are not sensitive to the plate geometry.

A repeat scour test was conducted with the perforated plate installed. The calculated average effluent concentrations ranged from 19.1 to 28.5 mg/L. This is a significant drop from the solid plate maximum concentration of 197 mg/L and verifies that the perforated plate meets its intended purpose of protecting the sump from excessive scour.

6.0 Nomenclature and Abbreviations

A	= area	(L^2)
°C	= degree centigrade	(T)
Cd	= coefficient of discharge	
Ci	= influent sediment concentration	(M/L^3)
Cfs	= cubic feet per second	(L^3/T)
Cm^3	= cubic centimeters	(L^3)
COV	= coefficient of variance	
D	= diameter	(L)
D_{50}	= median particle size	(L)
DA	= data acquisition	
DP	= differential pressure	(ΔL)
g	= grams	(M)
g	= gravity	(L/T^2)
H	= head	(L)
Hz	= hertz	(T)
Kg	= kilogram	(M)
L	= liters	(L^3)
L/m	= liters per minute	(L^3/T)
L/s	= liters per second	(L^3/T)
m	= meter	(L)
mg/L	= milligram per liter	(M/L^3)
min	= minute	(T)
mm	= millimeters	(L)
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”.

CETV (2014), “Procedure for Laboratory Testing of Oil-Grit Separators”, The Canadian 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.

APPENDIX B
INSTRUMENTATION CALIBRATIONS