Hydro StormScape™ Phosphorus Removal

The performance of the StormScape system has been independently verified for TSS removal by the New Jersey Corporation for Advance Technology (NJCAT). NJCAT is considered one of the premier independent stormwater BMP performance verification agencies in the United States. New Jersey is a TARP member state, as is Massachusetts.

NJCAT testing protocols only evaluate BMP's for TSS removal. To evaluate other pollutants of concern, a StormScape system was installed in 2021 at the UNH Stormwater Center's field site, for evaluation under the Washington State TAPE field testing program. To date, not enough rain event samples have been gathered form the UNH site to make meaningful use of the data. Therefore, the performance of the StormScape system can be evaluated for phosphorus removal through other publicly available data.

The StormScape system is categorized as a High Rate Biofiltration device (HRBF) through the guidance of International Stormwater BMP Database. (See Table 1-2 in the attached excerpt from BMP Database.)

Findings of the International Stormwater BMP Database are summarized below, along with corresponding excerpts from the 2020 Summary Statistics report. The full report can be located here: https://www.waterrf.org/system/files/resource/2020-11/DRPT-4968_0.pdf

HRBF are considered among the best performing BMP's for TSS removal, as sited in excerpts 2.3 and 2.4. TSS removal efficiencies range from 84% to 89% and are classified as exhibiting significant reduction in TSS concentrations.

NJCAT testing of the StormScape system indicates strong correlation to BMP Database results. The enclosed NJCAT excerpts of Table 8 and Table 14 illustrate cumulative TSS removal efficiencies of over 90%.

Regarding phosphorus removal, sections 4.3 of the BMP Database indicates that approximately 70% of total phosphorus was removed through the removal of particles greater than 20 microns diameter. When particles as small as 5 microns are removed, approximately 80% of total phosphorus removal was achieved. For correlation to StormScape TSS removal data, Table 1a and Figure 6a from the NJCAT report illustrate the test sediment used for evaluation. These charts show that only 65% of the test sediment was larger than 20 microns. Recognizing that the StormScape system demonstrated 90% TSS removal, sediments finer than 20 microns would have been removed to achieve this result. And 86% of the test sediment was greater than 5 microns. Therefore, a strong portion of the sediment down to 5 microns in size would need to be removed to achieve 90% overall TSS removal. These combined results indicate that at least 70% phosphorus removal from the StormScape can be anticipated, with potential removal efficiencies as high as 80%.

Lastly, section 4.6 of the BMP Database documents that HRBF are among the best performing BMP's for total phosphorus removal.

THE Water Research FOUNDATION

PROJECT NO.

4968

International Stormwater BMP Database

2020 Summary Statistics

International Stormwater BMP Database: 2020 Summary Statistics

Prepared by:

Jane Clary
Jonathan Jones
Wright Water Engineers, Inc.

Marc Leisenring
Paul Hobson
Geosyntec Consultants, Inc.

Eric Strecker
Terraphase Engineering, Inc.

2020

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1.1 Performance Analysis Overview

Approximately every two years following upload of new data sets, the BMPDB team generates data analysis reports that include updates of summaries that characterize categories of BMPs and/or that involve advanced or targeted analyses. Updates of the BMP category-level statistical analysis reports focus on commonly monitored water quality analytes including of solids, bacteria, metals, and nutrients, as summarized in Table 1-1. The BMP categories included in the analysis are summarized in Table 1-2. This BMP category-level analysis includes summary statistics for various BMP category-analyte combinations, graphical representations of statistics and hypothesis testing comparing inflow versus outflow concentrations.

Table 1-1. Constituents Analyzed by Pollutant Category.

Solids	Bacteria	Nutrients	Metals
Total suspended solids (TSS) Total dissolved solids (TDS)	Fecal coliform *Escherichia coli* (*E. coli*) Enterococcus	Total phosphorus Orthophosphate Dissolved phosphorus Total nitrogen Total Kjeldahl nitrogen (TKN) Nitrate and nitrate plus nitrite (NOx) Ammonia as N	Arsenic (total and dissolved) Cadmium (total and dissolved) Chromium (total and dissolved) Copper (total and dissolved) Iron (total and dissolved) Lead (total and dissolved) Nickel (total and dissolved) Zinc (total and dissolved)

Table 1-2. BMP Categories Included in 2020 Performance Analysis.

BMP Category	Code	Description
Detention Basin	DB	Dry extended detention grass-lined and concrete lined basins that empty out after a storm.
Retention Pond	RP	Surface wet pond with a permanent pool of water, may include underground wet vaults.
Wetland Basin	WB	Similar to a retention pond (with a permanent pool of water), typically with more than 50 of its surface covered by emergent wetland vegetation.
Wetland Channel	WC	A continuously wet channel with wetland vegetation and slow velocities.
Grass Swale	BS	Shallow, vegetated channel, also called bioswale or vegetated swale.
Grass Strip	BI	Vegetated areas designed to accept laterally distributed sheet flow from adjacent impervious areas, also called buffer strips or vegetated buffers.
Bioretention	BR	Shallow, vegetated basins with a variety of planting/filtration media and often including underdrains. Also called rain gardens and biofiltration.
Media Filter	MF	Filter bed with granular media, typically sand.
High Rate Biofiltration	HRBF	Manufactured devices with high rate filtration media that support plants.
High Rate Media Filtration	HRMF	Manufactured devices with high rate filtration media consisting of a variety of inert and sorptive media types and configurations (e.g., cartridge filters, upflow filters, membrane filters, vertical bed filters).
Hydrodynamic Separation Devices	HDS	Manufactured devices providing gravitational settling using swirl concentrators, screens, and baffles.
Oil/Grit Separators and Baffle Boxes	OGS	Manufactured devices including oil/water separators and baffle chambers designed for removing floatables and coarse solids.
Permeable Friction Course (Overlay)	PF	Open-graded bituminous mixture placed over an impervious road base.
Porous Pavement	PP	Full-depth pervious concrete, porous asphalt, paving stones or bricks, reinforced turf rings, and other permeable surface designed to replace traditional pavement.

Note: Additional BMP types are included in the BMP Database. This table represents BMP types with sufficient data for inclusion in category-level, pollutant concentration focused statistical analysis.

2.3 Performance Data Summary for TSS and TDS

Analysis for solids focused on total suspended solids (TSS) and total dissolved solids (TDS). Other solids can also be retrieved and analyzed through the BMPDB. Tables 2-2 and 2-3 provide influent/effluent summary statistics for TSS and TDS, respectively. Figures 2-2 and 2-3 provide graphical representations of these data.

Table 2-2. Influent/Effluent Summary Statistics for TSS (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	44; 575 (0.7%)	46; 611 (0.7%)	24.4 - 131	10.0 - 49.0	65.1 (57.0, 74.0)	22.0 (17.1, 22.5)	▼▼▼
Retention Pond	72; 1199 (1.1%)	74; 1191 (3.0%)	15.0 - 150	5.00 - 32.9	49.0 (41.0, 54.0)	12.0 (11.0, 13.0)	▼▼▼
Wetland Basin	31; 601 (0.3%)	30; 563 (3.0%)	14.0 - 89.0	4.69 - 32.0	35.5 (29.7, 40.0)	14.0 (11.5, 15.2)	▼▼▼
Wetland Channel	15; 269 (0.0%)	13; 219 (0.0%)	14.0 - 81.0	10.0 - 70.5	25.7 (20.5, 32.0)	24.0 (17.0, 28.0)	◇◇▼
Grass Swale	35; 582 (0.2%)	40; 656 (0.3%)	10.4 - 62.0	6.00 - 34.7	26.0 (22.0, 28.1)	13.7 (12.0, 14.9)	▼▼▼
Grass Strip	52; 920 (0.1%)	52; 711 (2.8%)	24.0 - 95.0	10.0 - 49.0	48.0 (43.0, 50.0)	23.0 (20.0, 24.0)	▼▼▼
Bioretention	43; 840 (0.0%)	41; 685 (5.3%)	16.0 - 119	4.00 - 20.0	44.0 (38.0, 48.0)	10.0 (8.00, 10.0)	▼▼▼
Media Filter	35; 533 (0.6%)	39; 563 (8.7%)	19.6 - 105	2.82 - 18.6	44.0 (37.0, 49.1)	7.20 (6.00, 8.00)	▼▼▼
HRBF	6; 104 (0.0%)	6; 104 (1.0%)	15.8 - 55.2	2.5 - 6.0	30.8 (21.0; 35.2)	3.80 (3.00; 4.15)	▼▼▼
HRMF	18; 392 (0.5%)	18; 392 (3.8%)	20.0 - 100	8.15 - 32.6	44.0 (37.0, 53.5)	18.0 (15.0, 19.0)	▼▼▼
HDS	27; 488 (0.4%)	27; 452 (1.1%)	26.6 - 162	15.9 - 87.0	63.9 (56.6, 73.0)	39.0 (33.0, 43.8)	▼▼▼
OGS	16; 261 (0.4%)	16; 216 (1.9%)	11.0 - 88.0	4.38 - 44.2	36.0 (27.8, 42.0)	15.5 (11.2, 19.1)	▼▼▼
PFC	NA	6; 135 (0.0%)	NA	6.00 - 16.5	NA	9.00 (8.00, 10.0)	NA
Porous Pavement	16; 483 (0.8%)	24; 402 (2.2%)	23.0 - 226	10.1 - 43.9	77.0 (63.0; 90.0)	22.0 (18.0; 23.5)	▼▼▼

*Confidence interval about the median; computed using the BCa bootstrap method described by Efron and Tibishirani (1993).
** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant *increase* in concentrations

2.4 Summary of Findings for TSS and TDS

All of the BMPs included in the sediment analysis generally performed well with respect to TSS, both in terms of statistically significant pollutant removal and relatively low effluent concentrations. Conversely, no BMPs showed statistically significant removal of TDS, while filter strips, media filters and retention ponds showed increases in TDS effluent concentrations. Primary observations for TSS include:

- Median influent TSS concentrations generally range between 26 and 77 mg/L.
- All BMPs with sufficient data for analysis show statistically significant reductions.
- The best performing BMPs are bioretention, media filters, and high rate biofiltration with effluent TSS concentrations ranging from 4 to 10 mg/L.
- Retention ponds and wetland basins performed similarly with effluent TSS concentrations in the 12-14 mg/L range.
- Median influent concentrations for TSS varied considerably, with detention basins, porous pavement and hydrodynamic separators treating more elevated influent TSS relative to several other BMP categories. This observation is not a function of BMP type; it is simply an observation that some BMP categories had relatively clean influent, which may be related to land use or level of source control. This may affect interpretation of statistical tests. For example, out of the three statistical tests, only the Wilcoxon signed-rank test showed statistically significant reduction of TSS for wetland channels; however, the median inflow TSS was already relatively low at 26 mg/L.

Primary observations for TDS include:

- TDS data are more limited than TSS data for many BMP types.
- No BMP with sufficient data has statistically significant concentration reductions for TDS. Furthermore, retention ponds, wetland basins, grass strips, media filters, and hydrodynamic separators increase TDS.
- The HDS category had unusually high concentrations of TDS, which were also highly variable. Further review of the underlying studies in this category indicated the statistics are influenced by a USGS study at a city maintenance yard in Madison, WI. Waschbusch (1999) reports that the site may have unique conditions, particularly the presence of road sand and salt piles close to the system inlet. The Madison site's median inflow TDS was 3,858 mg/L, whereas median influent concentrations at the other three sites ranged from 44 to 118 mg/L.
- Without advanced treatment, volume reduction is likely the only effective method for reducing TDS loads to surface receiving waters, based on the BMP types currently analyzed in the BMPDB. Note that for mobile TDS fractions (i.e., road salt), volume reduction due to infiltration may cause groundwater or interflow issues; therefore, identification of potential source controls is particularly important for TDS.

As this analysis shows, stormwater managers have a broad range of options for reducing TSS concentrations in urban runoff. BMPs that provide sedimentation and filtration processes and are well designed, installed and maintained are expected to provide good removal of TSS. In general, these mechanisms are anticipated to be more effective if linked together in a treatment train (i.e., sedimentation followed by filtration) and as the hydraulic residence time increases for each. Hydraulic residence can be increased in wetlands and ponds by increasing flow paths through the use of berms, baffles, and dense vegetation, as well as multi-stage outlet structures, such as perforated risers. In media filters and bioretention, increasing bed thickness and evenly distributing flows would likely improve performance. Outlet control would also be expected to increase performance by minimizing short circuiting and increasing residence times. For infiltration-oriented BMPs, maintenance is critical to prevent clogging from sediment build-up. Designing BMPs to minimize scour and resuspension of

The two primary concerns with nitrogen in stormwater are eutrophication of receiving waters and toxicity. Nitrate is readily available for biological uptake and, when present with sufficient amounts of phosphorus, which is often the case for estuaries and coastal environments, can cause eutrophication. Ammonia is of concern due to its fairly rapid transformation to nitrate, but also because unionized ammonia (NH_3) can be toxic to some aquatic species at fairly low concentrations. Nitrate is a concern for drinking water.

4.3 Phosphorus Removal Mechanisms and Factors Affecting Removal

Treatability for phosphorus is a function of partitioning (dissolved vs. particulate). If dissolved, treatability is a function of concentration and speciation. If particulate-bound, treatability is a function of the association of phosphorus to particles across the particle size and density distribution. Phosphorus can readily undergo surface complexation reactions, be adsorbed or precipitated. Media or soils containing iron, aluminum, calcium, or hydrated Portland cement can be very effective at removing phosphorus species from solution through surface complexation or precipitation. However, complexation or partitioning to engineered media or particulate matter can be reversible; and particulate-bound phosphorus can be a chronic threat, especially in a cyclic redox environment (WERF 2005). In other words, phosphorus release from sediment or organic matter is a major concern with respect to long-term phosphorus removal. Thus, routine maintenance of BMPs to remove sequestered forms of phosphorus before they become bioavailable again is a critical factor in effective phosphorus removal. Depending on the BMP type, the maintenance activity may include removing accumulated sediment and debris, scraping off the top few inches of media, replacing adsorptive media, or harvesting vegetation. Overall, BMPs must be designed with multiple treatment mechanisms, avoid the use of phosphorus containing materials (e.g., compost), and be actively maintained to achieve consistent removal and meet low numeric targets for phosphorus. Table 4-1 provides a summary of the primary transformation and removal mechanisms of major phosphorus species along with the factors that may affect those mechanisms.

Table 4-1. Summary of Phosphorus Transformations, Removal Mechanisms, and Important Factors.

Species	Transformation and Removal Mechanisms	Important Factors
Particulate Phosphorus	Physical separation (inert filtration and sedimentation)	Partitioning of phosphorus between particulate and soluble forms. Oxidation-reduction potential, pH, and bacterial communities that may transform phosphorus into soluble forms thereby releasing previously captured phosphorus.
Orthophosphates	Adsorption/precipitation	Contact with reactive media/soils, pH, temperature.
	Plant and microbial uptake	Vegetation and root density, presence of nitrogen and other essential nutrients, bacterial communities. Periodic harvesting of vegetation.

Some of the key factors affecting dominant removal mechanisms for phosphorus include:

- **Particulate Association:** Particle size and density are important factors in determining particle settling velocity (or time required for particles to settle) and filtration effectiveness. Therefore, particle size distribution and densities of suspended solids in untreated stormwater are major factors that affect the overall fraction of particles that may be removed in a stormwater treatment system. The fraction of phosphorus that can be removed through sedimentation and filtration – two of the most common unit processes harnessed in stormwater treatment BMPs – is dependent on

two additional factors:

- The fraction of total phosphorus bound to particulates, and
- The fraction of particulate-bound phosphorus associated with each particle size bin.

  A study of stormwater treatability found that, on average, approximately 70% of total phosphorus and phosphate were removed from stormwater through removal of particles with diameter greater than 20 µm (WERF 2003). Unfiltered (i.e., starting) concentrations for these tests were 0.38 and 0.8 mg/L, respectively. Removing particulates down to 5 µm increased removal efficiency to approximately 80% and removing particles greater than 0.45 µm increased the removal efficiency to approximately 90% for both. Other studies on phosphorus fractionation (i.e., mass associated with various particle size ranges) in soils and sediment suggest that concentrations are typically greatest on fine particles (clays and silts); however, the particle size distribution also determines where most of the phosphorus mass resides. For example, if most of the suspended particles are sands, then most of the particulate-bound phosphorus mass in stormwater will be associated with sand (Dong et al. 2003; Vaze and Chiew 2004). More easily filterable larger solids such as leaves and other organic matter may also contribute significant fractions of phosphorus in stormwater (Washbush et al. 1999). For example, Selbig (2016) found that 56% of the annual total phosphorus yield in stormwater from two residential catchments in Madison, Wisconsin was due to leaf litter; with an aggressive leaf removal program, this yield could be reduced to 16% of the total annual phosphorus load.

- **pH:** Both pH and oxidation-reduction potential (ORP) have important and complex interrelated effects on partitioning and sorption. Solubility of phosphorus species in rainfall-runoff ranges from >80% at a pH of 6 to <1% at a pH of 8 (WERF 2005). As a result, phosphorus tends to adsorb onto particles at high pH. Additionally, at higher pH, metals tend to adsorb onto particulates, which creates more sorption sites for phosphorus (Holford and Patrick 1979). However, with increasing pH, the electrostatic potential at the surface of particles decreases and generally reduces the sorption capacity of particles (Barrow 1984). Phosphorus complexation with metals is also strongly influenced by pH. Phosphorus complexes with aluminum and iron in acidic conditions and with calcium in alkaline conditions (Minton 2005). These interactions and other factors suggest a complex, non-monotonic relationship between pH and sorption capacity.
- **Oxidation Reduction Potential (ORP):** ORP is especially important in interactions between phosphorus and iron in soils. Phosphorus may be removed from solution in oxidizing conditions (i.e., high ORP) as iron oxidizes from Fe^{+2} to Fe^{+3}, causing phosphorus to precipitate. However, this reaction is reversible, with phosphorus being released under reducing (i.e., low ORP) conditions. In fact, studies have shown that anaerobic conditions in BMPs can result in lower removal effectiveness for phosphorus (Minton 2005).
- **Cation Exchange Capacity**: Related to the above, the removal of dissolved phosphorus through sorption, precipitation, and complexation is dependent on the sorption capacity of media/soil. Two media/soil properties thought to be important factors in sorption are cation exchange capacity (CEC) and amount of phosphorus already present in the soil. Organic material with high CEC (such as hemic peat) has been shown to provide good phosphorus removal. Conversely, highly decomposed peat (sapric) and compost can be a source of phosphorus. As a result, some BMP design manuals have specified the use of partially decomposed fibric or hemic peat (e.g., NYSDEC 2010) and little to no compost. In addition, a variety of mineral substances such as zeolites, iron and aluminum oxide-coated sand, and similar filtration media have been found to promote the sorption of phosphorus (WERF 2005). Amendments that have been shown to be effective in increasing chemical sorption of dissolved P include iron filings (Erickson et al. 2012; Groenenberg et al. 2013), steel wool (Erickson et al. 2007), drinking water treatment residuals (O'Neill and Davis 2012a and 2012b; Hinman and

4.6 Performance Findings and Discussion

The analysis of BMP performance data for nutrients aligns relatively well with observed urban runoff concentration characteristics and theoretical background of unit treatment processes and transport mechanisms for phosphorus and nitrogen. Performance summaries of phosphorus and nitrogen are provided separately below.

4.6.1 Phosphorus

Effective phosphorus control is essential for protecting receiving waters from nutrient enrichment impacts because phosphorus is often the limiting nutrient in freshwater bodies. Findings for phosphorus include:

- Median influent total phosphorus concentrations generally range between 0.1 and 0.3 mg/L.
- Many BMPs show statistically significant reductions for total phosphorus, but grass swales, grass strips, and bioretention show phosphorus export. Bioretention had the highest phosphorus median effluent concentrations for all three forms of phosphorus analyzed, ranging from 0.24 to 0.35 mg/L, which exceeds water quality standards established by some states for total phosphorus. Although not evaluated in this analysis, it is possible that more recent bioretention designs with greater attention to the phosphorus content (e.g., P index, compost percentage) of media may have better results; conversely, some communities are also applying pressure for higher compost content to support better vegetative growth.
- Detention basins effectively remove total phosphorus, but not dissolved phosphorus or orthophosphate.
- The best performing BMPs for total phosphorus reduction are media filters, high rate biofiltration, and high rate media filtration with total phosphorus median effluent concentrations of 0.05 to 0.09 mg/L.
- The best performing BMPs for dissolved phosphorus and orthophosphate in the analysis data set are retention ponds, wetland basins, and media filters. High rate media filters and hydrodynamic separators also show reductions for dissolved phosphorus. Most practices do not show statistically significant reductions for dissolved phosphorus and orthophosphate.

In summary, because phosphorus in stormwater runoff is generally highly particulate-bound, BMPs with unit processes for removing particulates (i.e., sedimentation and filtration) will generally provide good removal for total phosphorus. In particular, BMPs with permanent pools appear to be effective at reducing the major forms of phosphorus. Leaching of phosphorus from soils/planting media and resuspension of captured particulate phosphorus may be a cause of phosphorus increases observed in vegetated BMPs such as bioretention, swales, and filter strips. Vegetated BMPs should be designed with adequate inlet protection, dense vegetation, and drop structures or check dams to minimize resuspension of particulates. The use of virgin compost or chemical fertilizers should be avoided and planting media within BMPs should be tested for phosphorus content prior to installation if phosphorus is a constituent of concern.

Filters capable of capturing fine particulates and containing adsorptive media may be very effective for phosphorus removal. Future analyses of the BMP Database could include comparison of various media amendments as more studies with media amendments are included in the database.

Infiltration can be an effective mechanism for reducing phosphorus loads, particularly since phosphorus presents very little risk to groundwater, even in the dissolved state, due to its affinity to adsorb to minerals and organics. Volume-related load reductions were not included in this analysis. However, in areas with naturally high phosphorus concentrations in soils or groundwater, infiltrating additional runoff might result in additional groundwater loadings to receiving waters.

NJCAT TECHNOLOGY VERIFICATION

StormScape™ Filter

Hydro International

June 2020

Table 8 Removal Efficiency Results

Run #	Inf. Conc. (mg/L)	Avg. Adj. Eff. Conc. (mg/L)	Test Vol. (L)	Mass Added (kg)	Test Mass Escaped (kg)	Drawdown Volume (L)	Drawdown Conc. (mg/L)	Drawdown Mass Escaped (kg)	Cumulative Mass Captured (kg)	Run Efficiency	Cumulative Removal Efficiency
1	193.63	17.33	6175.17	1.20	0.11	422.23	19.0	0.008	1.081	90.38%	90.38%
2	192.28	20.37	6148.50	1.18	0.13	401.01	29.0	0.012	2.126	88.42%	89.41%
3	192.32	19.93	6162.77	1.19	0.12	456.62	22.0	0.010	3.178	88.79%	89.20%
4	190.53	22.67	6129.65	1.17	0.14	456.62	24.0	0.011	4.196	87.17%	88.70%
5	198.25	18.83	6134.77	1.22	0.12	361.49	22.0	0.008	5.289	89.85%	88.93%
6	190.94	20.43	6146.33	1.17	0.13	354.17	21.0	0.007	6.330	88.66%	88.89%
7	185.98	12.30	6146.50	1.14	0.08	388.57	16.0	0.006	7.391	92.84%	89.44%
8	184.59	13.00	6187.44	1.14	0.08	384.18	17.0	0.007	8.446	92.39%	89.79%
9	191.12	10.53	6184.84	1.18	0.07	413.45	15.7	0.006	9.557	93.94%	90.26%
10	189.77	16.80	6192.18	1.18	0.10	399.54	16.5	0.007	10.621	90.59%	90.29%

Table 14 Mass Load Capacity Removal Efficiency Results

Run #	Inf. Conc. (mg/L)	Avg. Adj. Eff. Conc (mg/L)	Test Vol. (L)	Mass Added (kg)	Mass Escaped (kg)	Drawdown Volume (L)	Drawdown Conc. (mg/L)	Drawdown Mass Escaped (kg)	Cumulative Mass Captured (kg)	Run Eff.	Cumulative Removal Efficiency	Note
1-10				11.76	1.06			0.082	10.621		90.29%	
11	194.61	12.50	6187.27	1.20	0.08	399.54	21.5	0.009	11.739	92.86%	90.53%	
12	194.10	13.87	6223.12	1.21	0.09	437.59	19.5	0.009	12.852	92.15%	90.67%	
13	195.21	18.23	6218.69	1.21	0.11	409.79	21.0	0.009	13.944	89.95%	90.61%	
14	185.55	21.30	6235.01	1.16	0.13	367.35	19.5	0.007	14.961	87.90%	90.42%	1
15	180.16	20.27	6211.76	1.12	0.13	420.03	16.5	0.007	15.947	88.13%	90.28%	
16	183.53	18.73	6221.96	1.14	0.12	371.00	22.0	0.008	16.965	89.08%	90.20%	
17	190.34	17.78	5878.93	1.12	0.10	432.47	25.0	0.011	17.968	89.69%	90.17%	
18	193.98	18.87	6301.96	1.22	0.12	418.57	29.5	0.012	19.059	89.26%	90.12%	
19	199.58	17.53	6317.23	1.26	0.11	493.94	22.0	0.011	20.199	90.35%	90.13%	
20	195.76	7.98	6325.99	1.24	0.05	425.15	25.0	0.011	21.376	95.06%	90.39%	
21	181.23	17.13	6342.08	1.15	0.11	423.69	14.3	0.006	22.411	90.02%	90.38%	
22	174.50	16.10	6349.67	1.11	0.10	535.65	14.5	0.008	23.409	90.07%	90.38%	2
23	164.94	20.00	6222.98	1.03	0.12	535.65	29.5	0.016	24.295	86.33%	90.38%	2
24	204.06	15.33	6223.67	1.27	0.10	535.65	19.5	0.010	25.459	91.66%	90.44%	
25	196.35	20.73	6236.77	1.22	0.13	535.65	26.5	0.014	26.540	88.28%	90.34%	
26	196.95	19.23	6242.86	1.23	0.12	535.65	19.5	0.010	27.639	89.38%	90.30%	
27	194.98	21.90	6255.62	1.22	0.14	542.24	18.5	0.010	28.712	87.95%	90.20%	
28	202.84	19.93	6242.39	1.27	0.12	493.94	18.0	0.009	29.845	89.47%	90.17%	
29	190.97	17.10	6266.43	1.20	0.11	544.43	22.5	0.012	30.922	90.02%	90.17%	
30	198.48	18.50	6246.28	1.24	0.12	536.38	17.5	0.009	32.037	89.92%	90.16%	
31	192.60	12.97	6203.35	1.19	0.08	474.18	22.5	0.011	33.140	92.37%	90.24%	

Run #	Inf. Conc. (mg/L)	Avg. Adj. Eff. Conc (mg/L)	Test Vol. (L)	Mass Added (kg)	Mass Escaped (kg)	Drawdown Volume (L)	Drawdown Conc. (mg/L)	Drawdown Mass Escaped (kg)	Cumulative Mass Captured (kg)	Run Eff.	Cumulative Removal Efficiency	Note
32	207.88	18.60	6128.75	1.27	0.11	586.87	16.5	0.010	34.291	90.29%	90.24%	
33	203.43	15.97	6171.98	1.26	0.10	621.27	20.0	0.012	35.435	91.16%	90.27%	
34	197.44	15.47	6175.20	1.22	0.10	562.73	21.0	0.012	36.547	91.20%	90.30%	
35	198.46	17.67	6175.71	1.23	0.11	590.53	22.5	0.013	37.650	90.01%	90.29%	
36	205.62	19.10	6178.25	1.27	0.12	602.24	21.0	0.013	38.790	89.72%	90.27%	
37	199.40	17.07	6197.23	1.24	0.11	584.68	23.0	0.013	39.907	90.35%	90.27%	
38	197.12	18.83	6182.84	1.22	0.12	580.29	11.8	0.007	41.002	89.88%	90.26%	
39	205.71	19.03	6113.78	1.26	0.12	555.41	18.0	0.010	42.133	89.95%	90.25%	
40	199.53	19.13	6131.11	1.22	0.12	540.04	19.5	0.011	43.229	89.55%	90.24%	
41	199.40	18.70	6170.41	1.23	0.12	640.29	20.0	0.013	44.331	89.58%	90.24%	3
42	205.29	15.47	6031.11	1.24	0.09	490.28	11.8	0.006	45.470	92.00%	90.28%	
43	207.05	16.27	6057.83	1.25	0.10	552.48	18.5	0.010	46.616	91.33%	90.31%	
44	206.39	14.77	6056.97	1.25	0.09	529.80	20.0	0.011	47.766	92.00%	90.35%	
45	202.15	16.43	6091.81	1.23	0.10	535.65	13.0	0.007	48.890	91.31%	90.37%	
46	204.93	13.70	6079.05	1.25	0.08	742.01	15.5	0.012	50.041	92.39%	90.37%	3

Note 1 - Electrical failure caused test to be cut short. All effluent samples taken, but final auger sample missed. Mass counted towards both total cumulative mass captured and cumulative removal efficiency calculations.

Note 2 – Influent concentration out of specification. Mass counted towards total cumulative mass captured but not used in cumulative removal efficiency calculations.

Note 3 – Head level exceeded maximum allowed. Mass counted towards neither cumulative mass captured calculation nor for cumulative removal efficiency.

2.2 Test Sediment

The test sediment was a blend of commercially available silica sand grades. The sediment was blended by Hydro and the particle size distribution was independently confirmed by GeoTesting Express in Acton, Massachusetts certifying that the supplied silica meets the specification within tolerance using ASTM D-422 as described in Section 5B of the Protocol. Results of particle size gradation testing are shown in **Table 1a** and **Figure 6a** below. The D_{50} of this blend is 64 microns.

Table 1a Particle Size Distribution Results of Test Sediment Samples (July 2019)

Particle Size (µm)	% Finer				Test Sediment Average	Diff. from Protocol
	Protocol	Sample 1	Sample 2	Sample 3		
1000	100	100	100	100	100	0
500	95	99	99	99	99	-4
250	90	94	94	94	94	-4
150	75	84	84	84	84	-9
100	60	63	63	63	63	-3
75	50	53	53	53	53	-3
50	45	45	46	45	45	-0
20	35	35	36	35	35	-0
8	20	20	20	20	20	-0
5	10	14	14	14	14	-4
2	5	8	8	8	8	-3

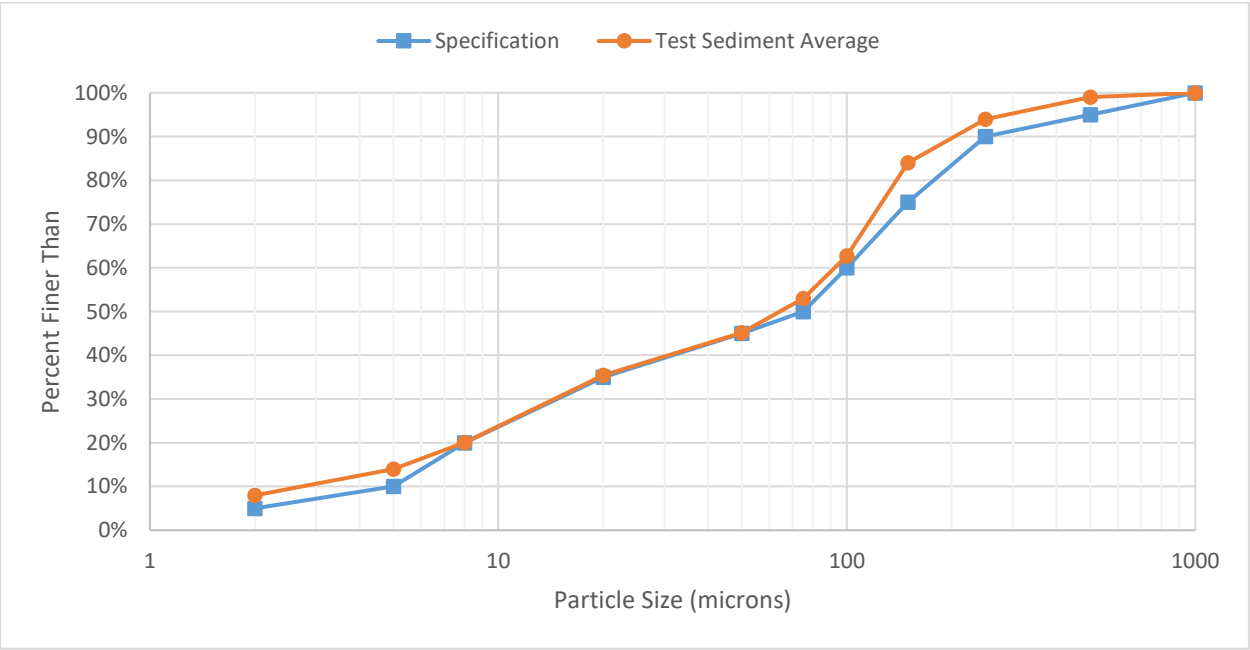

Figure 6a Avg. PSD of Test Sediment Compared to Protocol Specification (July 2019)