# Technology Assessment Report

# Vortechs™ Stormwater Treatment System
# Vortechnics Inc. Scarborough, ME

**Prepared for**
**The STrategic Envirotechnology Partnership**

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# EXECUTIVE SUMMARY

## Technology Description

The Vortechs™ system is a structural Best Management Practice (BMP) used to provide treatment of sediment, oil and grease in stormwater runoff. The Vortechs™ stormwater treatment system consists of a precast concrete box and structural inserts that form four treatment chambers: a grit chamber, oil chamber, flow control chamber, and outlet chamber. Suspended solids are removed from the flow by hydrodynamic separation in the grit chamber. The oil chamber is configured with a baffle to provide separation and retention of buoyant materials, including oils and grease. The flow control chamber is configured with a Cippoletti-shaped orifice that is sized to submerge in the inlet pipe when the system is operating at 20% of its treatment capacity. The system is also configured with a high-flow weir to allow the system to discharge the peak design flow. The units are designed to be installed below grade. Systems designed without a bypass are called “on-line” systems, and systems designed with a bypass are called “off-line” systems. All systems require inlet structures upstream and may include additional treatment structures downstream in a treatment train configuration.

## Sizing Criteria

The relationship between removal rates and flow is the basis for Vortechnics’ sizing criteria. Generally, at high flow rates solids removal efficiency will be low, and at low flow rates removal efficiencies will be high. Vortechs™ units are sized to remove a percentage of sediment on an annual average basis, typically 80%. Vortechnics developed regionally specific intensity-frequency plots of storm events, and using the rational method, flowrates for each intensity were estimated. By integrating the relative removal rates over the frequency plot of stormwater flow rates, a total annual average removal rate was predicted.

In 2002, Vortechnics updated their technical bulletins that describe their current sizing methodology for the Vortechs™ systems. They developed the following equation for customers to use to size the Vortechs™ unit based on the rational method. The equation incorporates information from area rainfall intensity plots, removal efficiencies observed in laboratory tests, and site-specific drainage basin characteristics into a relatively simple equation for estimating Vortechs System size that will achieve the targeted load reduction:

$$\text{Grit Chamber Area} \geq \frac{C*A*448.83\ \text{gpm/cfs}}{\text{Design Ratio}}$$

Where: A= Drainage area (acres)
C= Site runoff coefficient
Design Ratio = developed by Vortechnics
gpm = gallons per minute
cfs = cubic feet per second

The design ratio is the Vortechs™ operating rate (gpm/ft$^2$ of grit chamber area) divided by the local characteristic rainfall intensity. Vortechnics specifies the appropriate design ratio to use in the equation.

The same sizing equation is used for on-line and off-line Vortechs™ units. The sizing equation will indicate the appropriate size to meet the suspended solids removal requirements. The proposed sizing is also adjusted for hydraulic capacity based on a design peak storm, such as a 25-year event. If the hydraulic loading rate exceeds the design capacity of the unit, either a larger unit with adequate hydraulic capacity is selected for “on-line” systems, or a bypass is specified, making the unit an “off-line” system.

The Vortechs™ systems are available in nine standard sizes, but custom-sized units can also be manufactured. The table below summarizes the design criteria for the standard Vortechs™ system sizes:

**Vortechs™ Sizing Chart**

| Model Number | Approximate Size[1] L x W ft x ft | Grit Chamber Diameter / Surface Area ft / $ft^2$ | Peak Design Flow[2] cfs | Sediment Storage[3] $yd^3$ | Sediment Storage[3] $ft^3$ |
|---|---|---|---|---|---|
| 1000 | 9 x 3 | 3 / 7 | 1.6 | 0.75 | 20.25 |
| 2000 | 10 x 4 | 4 / 13 | 2.8 | 1.25 | 33.75 |
| 3000 | 11 x 5 | 5 / 20 | 4.5 | 1.75 | 47.25 |
| 4000 | 12 x 6 | 6 / 28 | 6.0 | 2.5 | 67.5 |
| 5000 | 13 x 7 | 7 / 38 | 8.5 | 3.25 | 87.75 |
| 7000 | 14 x 8 | 8 / 50 | 11.0 | 4.0 | 108.0 |
| 9000 | 15 x 9 | 9 / 64 | 14.0 | 4.75 | 128.25 |
| 11000 | 16 x 10 | 10 / 79 | 17.5 | 5.5 | 148.5 |
| 16000 | 18 x 12 | 12 / 113 | 25.0 | 7.0 | 189.0 |

Adapted from Vortechnics Website, June 2002.

1. The sizing information above is representative of typical Vortechs™ systems. Construction details may vary depending on the specific application.
2. For on-line Vortechs™ systems without a bypass. Sizing criteria is based on providing one square foot of grit chamber surface area for each 100 gpm of peak design storm flow rate (e.g., 10-year storm).
3. Sediment storage volumes assume a 3-foot sump and a 1-foot opening under baffle. The Vortechs™ systems can be provided with other sump sizes, which will change the sediment storage volume.

## Performance Data

Vortechnics has developed data from laboratory and field tests in support of its performance claims. In 1996-1997, Vortechnics undertook laboratory testing on a full-scale Vortechs™ Model 2000 unit located at Vortechnics research facility in Maine. Subsequently in 1998, Vortechnics initiated a study at the DeLorme Publishing Company in Yarmouth, Maine. A Vortechs™ Model 11000 was installed in a parking lot and monitored for suspended solids in two phases with a break for the winter months over the course of a year. The DeLorme unit was installed in an in-line configuration. The New York State Department of Environmental Conservation (NYDEC) undertook a field demonstration of an off-line Model 11000 Vortechs™ unit in Lake George, NY during 2000. The Lake George unit was monitored for total suspended solids, nitrogen, phosphorus, BOD, and total coliform over the course of a year.

The laboratory tests demonstrate the performance of the Vortechs™ unit under controlled conditions. Tests were run to assess total suspended solids (TSS) removal efficiency with varied particle sizes (ranging from 38 μm to 450 μm), flow rates, and sediment loads. The results indicate that removal efficiency decreases as particle size decreases and flow rate increases, and average removal efficiencies are positive for hydraulic loading rates up to 100 gpm per square foot of grit chamber area. Removal efficiencies exceeded 80% when the hydraulic loading rates were less than 20 gpm per square foot of grit chamber area for particles greater than 63 μm. Thus, Vortechnics' methodology for sizing the units is supported by these results. The results of the tests performed with sediment accumulated in the grit chamber indicate that removal efficiency decreases when sediment accumulates up to the design capacity, thus regular maintenance of the units is warranted.

Field-testing was performed in two phases at the DeLorme site to allow for snow removal during the winter months. Due to the deficiencies described in the detailed description of the field test, including deviations in the sampling and monitoring scheme, the Phase I data were not included in the efficiency ratings for the site. For all 20 storm events included Phase 2 of the DeLorme field tests, the estimated removal efficiency of the on-line Vortechs™ Model 11000 unit is 83% by efficiency ratio, 73% by summation of loads, 77% by regression of loads, and 60% by efficiency of individual storm events. Problems associated with flow measurement during the first 10 events suggest that the average removal efficiency may be more accurately calculated considering only events 11-20. Average removal efficiencies calculated by the four methods for events 11-20 are 57% by the efficiency ratio, 44% by summation of loads, 40% by regression of loads, and 60% by average of individual storms. The results of the removal efficiency calculations suggest a difference between the stated performance claim and the removal efficiency measured on this site. Deficiencies were identified in the DeLorme Phase 2 data set, including deviation from the sampling and analysis protocol and the flow meter calibration for the first ten storm events. A particle size distribution was not conducted on the sediment accumulated in the grit chamber.

Estimated removal efficiencies for the Lake George Vortechs™ unit are 87% by efficiency ratio, 88% by summation of loads, 90% by regression of loads, and 72% by efficiency of individual storm events. Based on the particle size distribution of the accumulated sediment in the unit, most of the removed material fell within the sand-sized range, 100 microns to 2 mm. The results suggest that the Vortechs™ system may be able to provide suspended solids treatment levels as claimed. However, the assessment of the data provided by NYDEC suggests that significant error may be associated with the results. Potential sources of error include: lack of sampling quality control, lack of equipment calibration, and the methodology used for calculating the influent and effluent event mean concentrations (EMC). The Vortechs™ system did not remove appreciable amounts of nitrogen, phosphorus, or BOD. Because of the quality assurance and control problems with the fecal coliform analysis, no conclusion about removal of the pathogen can be made.

In light of the challenges of quantifying treatment performance, review of the laboratory and field data suggests that the Vortechs™ system should be capable of providing removal of TSS in stormwater runoff at higher efficiencies than the water quality inlets described in the Stormwater Management Handbooks (DEP and CZM, 1997), which have a TSS removal rating of 25%. The Vortechs™ system is based on reasonable and accepted principles of design for water treatment and conveyance systems. However, deficiencies exist in the current data sets from the laboratory tests and the field tests at the DeLorme and Lake George sites. Based on the laboratory data and Lake George field data, the Vortechs™ unit may provide average annual TSS removal efficiencies of 80% under conditions similar to those reported herein. While these data represent a substantial effort in both time and resources, all the studies had problems with sampling and analysis procedures that may have introduced error into the results. These data suggest that sizing models for the Vortechs unit tested in the lab and demonstrated in the field may be appropriate. However, data available for this review did not contain sufficient data quality assurances suitable for unequivocal validation of performance claims.

## Applicability

The Vortechs™ system is suited for local or lateral stormwater lines within a conveyance system. The system is designed to follow an inlet, such as a catch basin. The system can be used on sites with a wide range of drainage areas provided it is sized correctly. On larger drainage area installations, multiple units may be located throughout the drainage area rather than in a central location, providing treatment of runoff closer to its source. The unit can be used as a component in a mixed structural control system, for example: inlet, Vortechs™, infiltration basin. The Vortechs™ system has a small area requirement in relation to its claimed performance capability, thus it is particularly well suited for constricted areas and redevelopment.

The applicability of this technology for suspended solids removal is similar to that of several other BMPs, including: sand and organic filters, catch basins, and water quality inlets, all of which are described in the Stormwater Management Handbooks (DEP and CZM, 1997). Use of the Vortechs™ system to meet the stormwater treatment Standards 1-9, as described in the Stormwater Management Handbooks (DEP and CZM, 1997), is summarized below:

- Standard 1. No Untreated Stormwater Outfalls/Discharges: The Vortechs™ system, in combination with other treatment measures required in Standards 2-9, can be used within a stormwater conveyance system for the treatment stormwater to meet the requirements for Standard 1.

- Standard 2. Post-Development Peak Discharge Rates: The Vortechs™ system is a flow-through system and cannot control discharge rates, thus it is not applicable to Standard 2. When properly designed and maintained, the system will not cause a hydraulic bottleneck within the conveyance system.

- Standard 3. Recharge to Groundwater: The Vortechs™ system is not designed as a recharge system, and is not applicable to Standard 3 unless combined with an approved recharge system. The system may be used as a pretreatment device for recharging systems to reduce the rate of clogging of the infiltrative surface.

- Standard 4. Removal of 80% TSS: The laboratory and field studies show that the Vortechs™ system may be capable of removing up to 80% of annual TSS load. The laboratory tests indicate higher removal efficiencies for larger particles. Average removal efficiencies varied depending on the method used for calculating efficiency, and all the studies had problems with sampling and analysis procedures that could have introduced error into the results. Therefore, the efficiencies cited in the study results should be considered an approximate indicator of predicted efficiencies for installations with similar topographic and hydrologic conditions.

- Standard 5. Land Uses with Higher Pollutants: The Vortechs™ system has the ability to trap sediment and spills of hydrocarbons, oils, and grease. This makes the system suitable for use on areas with higher potential pollutant loads, specified under Standard 5. However, oil and grease constituents were not included in any of the data analyzed for this report, thus removal effectiveness was not able to be determined. Additional information should be carefully reviewed before this technology is applied for oil and grease removal.

- Standard 6. Critical Areas: The Vortechs™ system is not included on the list of approved BMPs for critical areas. The system can be used as a sediment pretreatment device for BMPs that have been approved by DEP for use in critical areas.

- Standard 7. Redevelopment: The Vortechs™ system is suitable for retrofits and upgrades under Standard 7.

- Standard 8. Erosion and Sediment Controls: The Vortechs™ system can be used for the control of sediment loads on construction sites.

- Standard 9. Operation and Maintenance Plans: The Vortechs™ system requires regular maintenance, as described in report section *Technology Description*, and should be included in any Operation and Maintenance Plan.

## Maintenance Requirements

Accumulated sediment and oil can be removed from the unit by a vacuum truck. Vortechnics recommends that the units be cleaned when sediment has accumulated within six inches of the dry weather water level, or when an appreciable level of grease or oil is floating on the water surface. The frequency of cleaning depends upon the rate of accumulation of sediment and oil, which is site-dependent. Vortechnics recommends that the system be inspected quarterly during the first year of operation to determine the appropriate cleaning frequency. The risk of washout increases if the accumulated sediment in the system is not removed.

## Recommendations for Future Performance Testing

It is recommended that any future studies be undertaken with a higher level of quality control. The *Stormwater Best Management Practice Demonstration Tier II Protocol for Interstate Reciprocity* (TARP, 2001) is the current standard for stormwater technology demonstrations in Massachusetts and should be used as guidance for any subsequent field tests. Extensive field testing under the TARP protocol and other protocols which have high level of data quality assurance may be useful for understanding general technology performance under an array of conditions. However, extensive laboratory testing with targeted field validation may yield similarly valuable results at less cost. Vortechnics is recognized as having performed extensive laboratory validation of its Vortechs™ sizing model. Further, the results of Vortechnics' field performance tests reported herein fall within a reasonable range of performance given the expected variability of uncontrolled field conditions. Any future field tests should be targeted toward data that is not included within the current body of laboratory and field testing, such as further definition of removal efficiencies for sediments with different particle sizes, concentrations, and flow conditions.

## TECHNOLOGY PROPONENT

The technology described in this review is the Vortechs™ stormwater treatment system. The technology is currently owned and patented by Vortechnics, Inc. of Scarborough, Maine. The patent is titled "Method and Apparatus for Separating Floating and Non-Floating Particulate from Rainwater Drainage," number 5,759,415. The same corporation is commercializing the product.

## TECHNOLOGY DESCRIPTION

The Vortechs™ system is a structural Best Management Practice (BMP) used to provide treatment of stormwater runoff. The Vortechs™ system may be categorized as a "hydrodynamic structure", which is typically designed with baffles to reduce turbulence in the treatment chamber. The Vortechs™ system does not fall into any of the existing BMP categories listed in the Massachusetts Stormwater Management Handbooks (DEP and CZM, 1997), but it is often referred to as an innovative water quality inlet or a second-generation oil and grit separator. These systems typically have higher total suspended solids (TSS) removal efficiencies than the water quality inlets described in the Stormwater Management Handbooks, which have a TSS removal rating of 25% (DEP and CZM, 1997).

### System Configuration and Operation

The Vortechs™ stormwater treatment system consists of a precast concrete box and structural inserts that form four treatment chambers: a grit chamber, oil chamber, flow control chamber, and outlet chamber as shown in Figure 1.

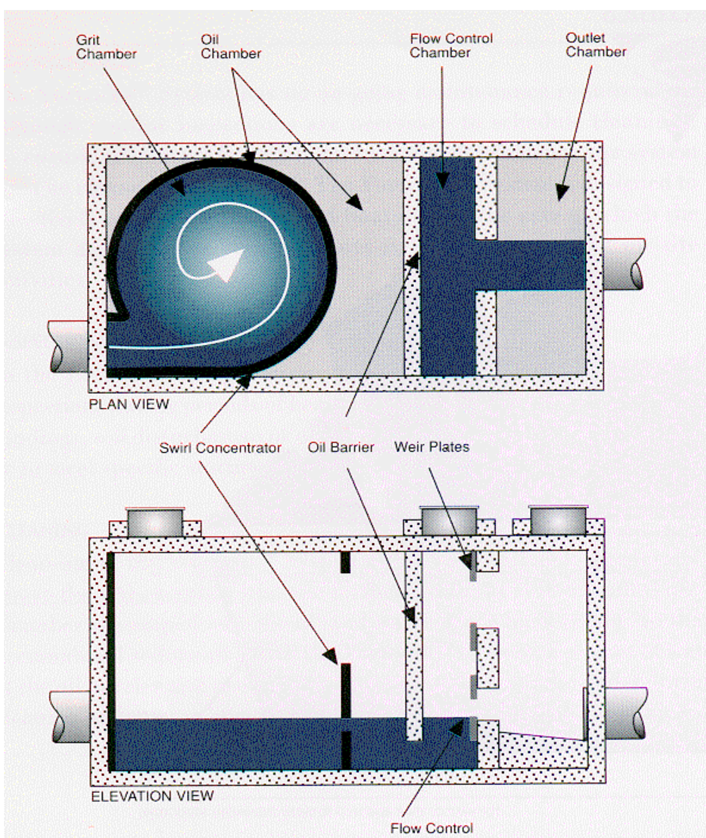


**Figure 1. Illustration of Vortechs™ System (Vortechnics, Inc., Scarborough, ME. 1997)**

Flow enters the Vortechs™ unit in the grit chamber. The curved-wall configuration of the grit chamber is called a "swirl concentrator" by Vortechnics. The "swirl concentrator" is designed to enhance solids removal by reducing particle energy and velocities more effectively than conventional sedimentation chambers. Suspended solids are removed from the flow by gravitational setting in the grit chamber. The oil chamber is configured with a baffle to provide separation and retention of buoyant materials, including oils and grease. The flow control chamber is configured with a Cippoletti-shaped orifice that is sized to submerge in the inlet pipe when the system is operating at 20% of its design flow. The system is also configured with a high-flow weir to allow the system to discharge the peak design flow.

The units are designed to be installed below grade. Access to the unit is obtained via three openings in the top sized for standard manholes covers. The openings are typically located over the grit chamber, the flow control chamber and outlet chamber. The Vortechs™ systems are currently manufactured in nine standard sizes, as shown in Table 1. Details about the development of the sizing criteria are discussed in the *Sizing Methodology* report section.

**Table 1. Vortechs™ Sizing Chart**

| Vortechs Model | Approximate Size[1] L x W ft x ft | Grit Chamber Diameter / Surface Area ft / $ft^2$ | Peak Design Flow[2] cfs | Sediment Storage[3] $yd^3$ | Sediment Storage[3] $ft^3$ |
|---|---|---|---|---|---|
| 1000 | 9 x 3 | 3 / 7 | 1.6 | 0.75 | 20.25 |
| 2000 | 10 x 4 | 4 / 13 | 2.8 | 1.25 | 33.75 |
| 3000 | 11 x 5 | 5 / 20 | 4.5 | 1.75 | 47.25 |
| 4000 | 12 x 6 | 6 / 28 | 6.0 | 2.5 | 67.5 |
| 5000 | 13 x 7 | 7 / 38 | 8.5 | 3.25 | 87.75 |
| 7000 | 14 x 8 | 8 / 50 | 11.0 | 4.0 | 108.0 |
| 9000 | 15 x 9 | 9 / 64 | 14.0 | 4.75 | 128.25 |
| 11000 | 16 x 10 | 10 / 79 | 17.5 | 5.5 | 148.5 |
| 16000 | 18 x 12 | 12 / 113 | 25.0 | 7.0 | 189.0 |

Adapted from Vortechnics Website, June 2002.

1. The sizing information above is representative of typical Vortechs™ systems. Construction details may vary depending on the specific application.
2. For on-line Vortechs™ systems without a bypass. Sizing criteria is based on providing one square foot of grit chamber surface area for each 100 gpm of peak design storm flow rate (e.g., 10-year storm).
3. Sediment storage volumes assume a 3-foot sump and a 1-foot opening under baffle. The Vortechs™ systems can be provided with other sump sizes, which will change the sediment storage volume.

Systems designed without a bypass are called "on-line" systems, and systems designed with a bypass are called "off-line" systems. Vortechnics' recommended sizes for on-line systems are larger than those for off-line systems because the on-line systems will have higher peak flows. Both on-line and off-line systems are designed to have a surface loading rate no greater than 100 gallons per minute per square foot of grit chamber area during peak storm events, which is based on the results of laboratory tests described in the *Data Supporting Claims* report section.

## Maintenance Requirements

Accumulated sediment and oil can be removed from the unit by a vacuum truck. Confined space entry into the unit is not required for regular cleaning. Vortechnics recommends that the units be cleaned when sediment has accumulated within six inches of the dry weather water level, or when an appreciable level of gas or oil is floating on the water surface. The frequency of cleaning depends upon the rate of accumulation of sediment and oil, which is site-dependent. Vortechnics recommends that the system be inspected quarterly during the first year of operation to determine the appropriate cleaning frequency. The risk of washout increases if the accumulated sediment in the system is not removed.

## TECHNICAL FEASIBILITY

The principle of operation of the Vortechs™ system for removing suspended solids is sedimentation. Stormwater runoff is directed tangentially into a cylindrical grit chamber called a "swirl concentrator", which creates a vortex flow pattern. In this chamber, solids are drawn to the center of the chamber by centrifugal forces and settle out of the water column due to gravity. Flow exits the swirl concentrator through an opening in the cylinder wall. Technical data describing the flow characteristic of the swirl concentrator are not available from Vortechnics. However, vortex separation has been utilized in wastewater grit removal applications and is a generally accepted treatment technology for grit removal (Metcalf & Eddy, 1991). Sedimentation may be greater in the Vortechs™ system than conventional gravity sedimentation technologies (such as oil/grit separators) under optimal flow conditions because of the enhanced settling environment created by the vortex.

Reduction of other pollutant parameters that are associated with the solids may occur as a function of sedimentation. Pollutants may be adsorbed to organic coatings on settled sediment or may be agglomerated in settleable sized particulates. Inorganic nitrogen, phosphorus, and metals may associate with settleable materials through adsorption to organic materials.

A barrier wall located between the oil chamber and the flow control chamber is used to retain oil and grease within the unit. The opening is located at the bottom of the wall and is submerged under both high- and low-flow conditions. This physical barrier traps floating materials in the oil chamber. The effectiveness depends upon adequate detention time to allow the floating materials to separate from the flow.

## SIZING METHODOLOGY

The Vortechs™ system sizing was first developed in the early 1990's from a study funded under the Maine Environmental Internships Program using a Model 2000 located in Vortechnics' Maine facility. A Vortechs™ Model 2000 was scaled down to 1/5th size and operated under various loading conditions. Water containing sand with uniform particle size characteristics and known mass was run through the system at various flow rates, and the retained mass was measured. The results indicated that the unit could provide up to 96% TSS removal at rates lower than 1 gpm/ft$^2$. At higher flow rates, TSS removal decreased. The results of the study demonstrated that removal efficiency varies based on flow through the unit and that the unit is capable of retaining sediment under a range of flow conditions.

The relationship between removal rates and flow is the basis for Vortechnics' sizing criteria. Vortechs™ units are sized to remove a percentage of sediment on an annual average basis, typically 80%. As demonstrated in the early tests of the unit, generally at high flow rates solids removal efficiency will be low, and at low flow rates removal efficiencies will be high. In order to calculate an annual average removal rate, Vortechnics developed an intensity-frequency plot of storm events, like the one for Portland, ME shown in Figure 2. Using the rational method, flowrates for each intensity are estimated. By integrating the relative removal rates over the frequency plot of stormwater flow rates, a total removal rate was predicted. Vortechnics has recently prepared similar intensity-frequency plots for several locations throughout the United States and Canada.

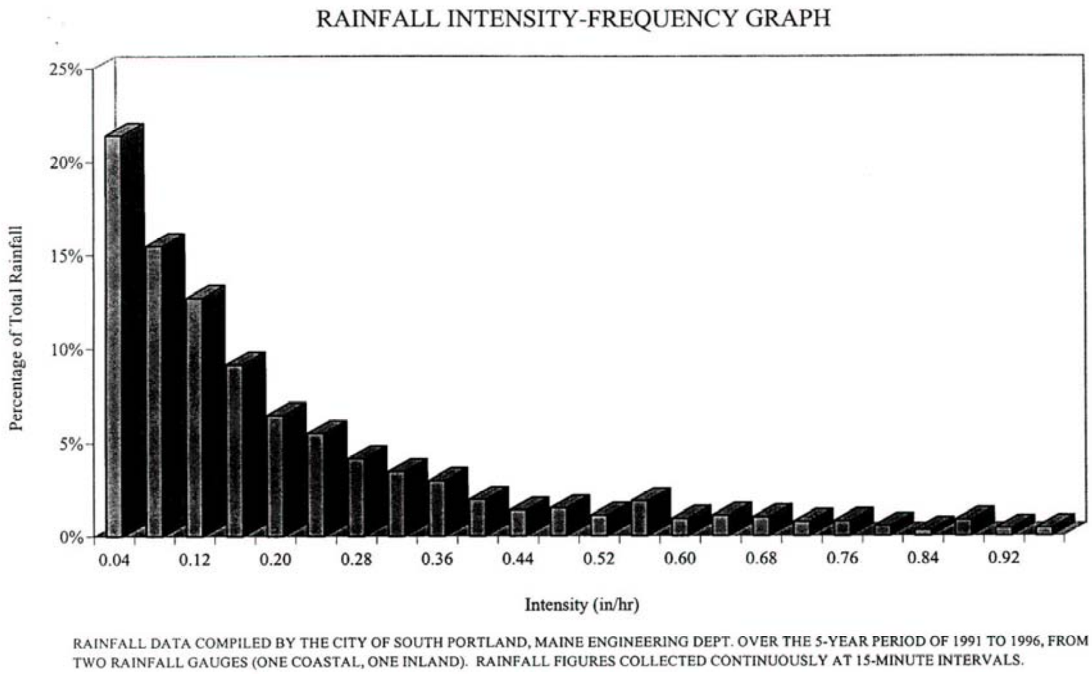


**Figure 2. Rainfall Intensity-Frequency Graph (Vortechnics, Inc., Scarborough, ME. 1997)**

In 1996-1997, Vortechnics updated the removal efficiency data with results from laboratory tests on a full-scale Vortechs™ Model 2000 unit located at Vortechnics research facility in Maine. Testing was performed by Vortechnics to assess TSS removal efficiency with various particle sizes, flow rates, and sediment loads, as described further in report section *Data Supporting Claims*. From that data, Vortechnics developed a "50 micron particle curve" that describes the relationship between flow and removal efficiency (Vortechnics, 2002, Technical Bulletin 1). The 50-micron curve is a combination of the laboratory results for 38 and 63-micron particles. According to Vortechnics, the 50-micron particle size was chosen as the representative particle size for design removal efficiencies because this particle size had lower removal efficiencies than the larger-sized particles. Use of the 50-micron curve does not mean that Vortechnics is claiming that the Vortechs™ units will achieve 80% removal for 50-micron particles, but that they are designed to remove 80% of the total suspended solids, which is composed of a range of particle sizes.

In 2002, Vortechnics updated their technical bulletins that describe this current sizing methodology. They developed the following equation for customers to use to size the Vortechs™ unit based on the rational method. The equation incorporates information from area rainfall intensity plots, removal efficiencies observed in laboratory tests, and site-specific drainage basin characteristics into a relatively simple equation for estimating a Vortechs System size that will achieve the targeted load reduction:

$$\text{Grit Chamber Area} \geq \frac{C*A*448.83\text{gpm/cfs}}{\text{Design Ratio}}$$

Where: A= the drainage area (acres)
C= Site runoff coefficient
Design Ratio = developed by Vortechnics
gpm = gallons per minute
cfs = cubic feet per second

The design ratio is the Vortechs™ operating rate (gpm/$ft^2$) divided by the local characteristic rainfall intensity. Based on the laboratory data and the rainfall intensity plots, Vortechnics has calculated regionally specific design ratios required to achieve an average annual removal efficiency of 80% (Vortechnics, Technical Bulletin 4, 2002). Vortechnics specifies the appropriate design ratio to use in the equation.

The same sizing equation is used for on-line and off-line Vortechs™ units. The sizing equation will indicate the appropriate size to meet the suspended solids removal requirements. The proposed sizing is also adjusted for hydraulic capacity based on a design peak storm, such as a 25-year event. If the hydraulic loading rate exceeds the design capacity of the unit, either a larger unit with adequate hydraulic capacity is selected for "on-line" systems, or a bypass is specified, making the unit an "off-line" system.

## PERFORMANCE CLAIM

Vortechnics, Inc. claims the Vortechs™ technology is capable of achieving an average of 80% TSS removal on an annual basis.

## DATA SUPPORTING CLAIMS

Vortechnics has developed data from laboratory and field tests in support of its performance claim. In 1996-1997, Vortechnics undertook laboratory testing on a full-scale Vortechs™ Model 2000 unit located at Vortechnics research facility in Maine. Subsequently in 1998, Vortechnics initiated a study at the DeLorme Publishing Company in Yarmouth, Maine. A Vortechs™ Model 11000 was installed in a parking lot and monitored for suspended solids in two phases over the course of a year with a break for the winter months. The DeLorme unit was installed in an in-line configuration. The New York State Department of Environmental Conservation (NYDEC) undertook a field demonstration of an off-line Model 11000 Vortechs™ unit in Lake George, NY during 2000. The Lake George unit was monitored for total suspended solids, nitrogen, phosphorus, BOD, and total coliform over the course of a year.

Although the sizing methodology for the Vortechs™ units has been updated since these tests were completed, according to Vortechnics (personal communication, July 2002), the recommended size of the units in the field demonstrations described below is the same.

### Laboratory Results

The sizing criteria for the Vortechs™ units is based on laboratory testing on a full-scale Vortechs™ Model 2000 unit located at Vortechnics research facility in Maine. Vortechnics performed testing over 15 months to assess TSS removal efficiency with various particle sizes, flow rates, and sediment loads. Tests were run with uniform particle sizes ranging from 38 μm to 450 μm and with a distribution of particle sizes shown in Table 2, simulating a "typical" stormwater sediment. Flows up to the design capacity of the Vortechs™ unit, 100 gpm/$ft^2$ of grit chamber surface area, were evaluated. The Vortechs™ Model 2000 has a rated maximum sediment load of 34 cubic feet. Tests were run with varying volumes of sediment accumulated in the grit chamber up to the maximum rated sediment accumulation. A list of the laboratory tests that were conducted by Vortechnics is presented in Table 3.

| Table 2. Particle Size Gradation for "Representative Stormwater Sediment" | | | |
|---|---|---|---|
| | **Size Fraction** | **Percent of Total Sediment (by weight)** | **Pounds** |
| 1 | (>250 μm) | 27% | 4.59 |
| 2 | (150-250 μm) | 11% | 1.87 |
| 3 | (100-150 μm) | 7% | 1.19 |
| 4 | (75-100 μm) | 9% | 1.53 |
| 5 | (63-75 μm) | 4% | 0.68 |
| 6 | (<63 μm) | 42% | 7.14 |
| **TOTAL** | | **100%** | **17** |

| Table 3. Laboratory Tests Conducted by Vortechnics (10/96 - 12/97) | | |
|---|---|---|
| **Sediment Size (μm / mesh size)** | **Sediment Volume Accumulated in Vortechs™ Grit Chamber ($ft^3$)** | **Flow Rate ($gpm/ft^2$ grit chamber)** |
| 450 / 40 | 0 | 21, 25, 33 |
| 250 / 60 | 0, 24.6 | 10, 20, 20.8, 28, 30, 33, 40, 50, 60, 70, 80, 90, 100 |
| 150 / 100 | 0, 1.5, 3, 14, 18.5, 24.6, 30, 34 | 10, 18.8, 20, 25, 30, 33, 40, 50, 60, 70, 80, 90, 100 |
| 100 / 150 | 14,18.5, 24.6, 30, 34 | 10, 18.8, 20, 30, 33, 40, 50, 60, 70, 80, 90, 100 |
| 75 / 200 | 18.5, 24.6, 30, 34 | 10, 18.8, 20, 30, 40, 50, 60, 70, 80, 90, 100 |
| 63 / 250 | 0 | 10, 20, 30, 40, 50, 70, 80, |
| 38 / 400 | 0 | 60, 70, 80, 90, 100 |
| Representative stormwater sediment distribution | 0 | 10, 20, 30, 40, 50, 70, 80, 90, 100 |

## Laboratory Results Discussion

Results from tests run without sediment loaded in the grit chamber demonstrate that removal efficiency tends to decrease as flow increases, as shown in the graphs included in Appendix A. Polynomial lines were fit to the data and $R^2$ values were reported to illustrate these trends in the data. However, some exceptions to the data are evident. The results for the first set of tests, tests 1-11, indicated that removal efficiencies were generally lower than later tests run with similar flow rates. The relationship between flow rate and removal efficiency is stronger when the data from these early tests are not included. Vortechnics reported that the laboratory did not follow the prescribed analytical methods for these early tests. Moreover, data quality assurance through replicates, blanks, and analytical quality control are not present in any of the data submitted for review.

Removal rates decrease with decreasing particle size, as shown in Figure 3. Again, polynomial lines were fit to the data and $R^2$ values were reported simply to illustrate trends in the data. Removal efficiencies tended to be greater than 80% for particle sizes larger than 75 microns at flow rates less than 30 $gpm/ft^2$ of swirl concentrator. Removal efficiencies for 63-micron particles were greater than 80% only at flow rates below 10 $gpm/ft^2$. Removal rates were measured for 38-micron particles at flow rates between 60 and 100 $gpm/ft^2$. Removal rates for this particle size range tended to be less than 40% at 50 $gpm/ft^2$ and 0% at 100 $gpm/ft^2$.

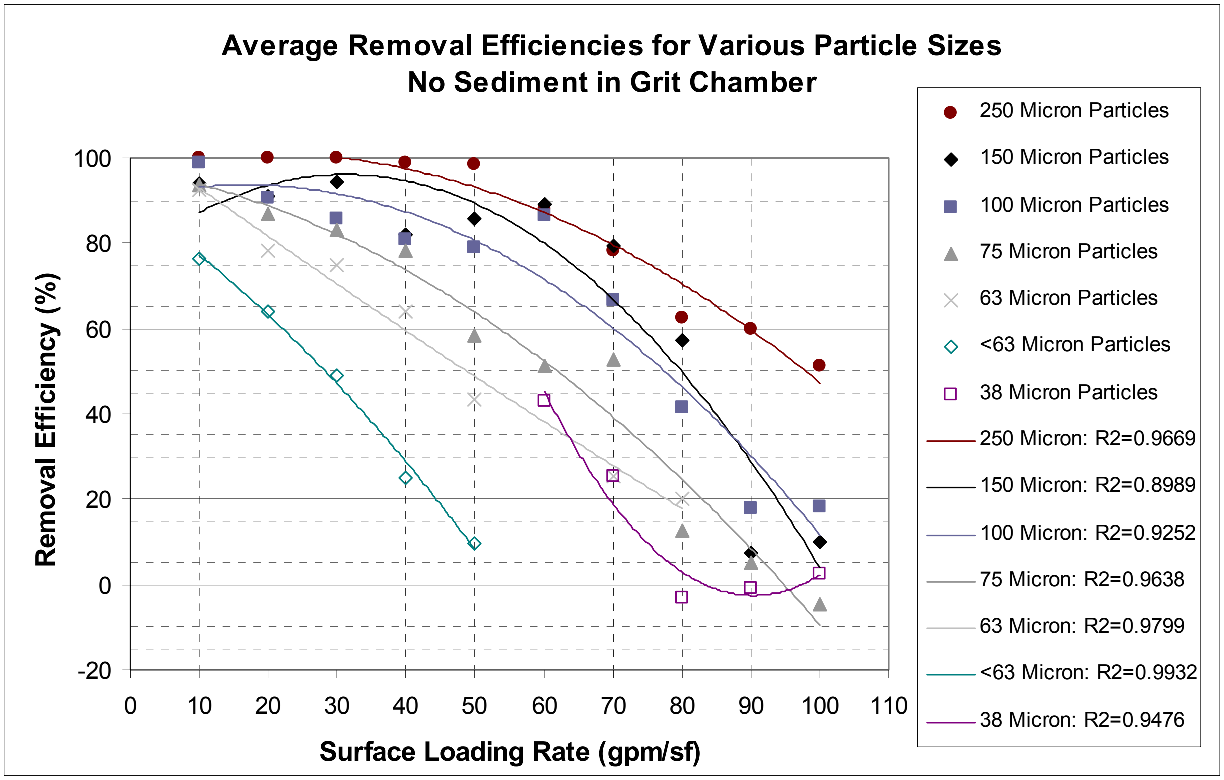


**Figure 3. Comparison of Removal Efficiencies for Various Particle Sizes (Not Including Results from Early Tests 1-11)**

Tests were also run with accumulated sediment in the Vortechs™ grit chamber for 75 to 250 micron particles. Results under these conditions demonstrated a decrease in removal efficiency as flow increased. This relationship is illustrated by polynomial lines that were fit to the data in the graphs included in Appendix B. The removal efficiencies with sediment in the unit were typically lower than the corresponding results without any sediment in the grit chamber. Suspended solids removal efficiency tended to be greater that 80% at lower flows, up to 20 gpm/ft$^2$, for 100 to 250 micron-sized particles and grit chamber sediment volumes up to 34 ft$^3$. Tests with 75-micron particles had greater than 80% TSS removal efficiencies at flow rates of 10 gpm/ft$^2$ for all sediment loads. However, removal rates decreased below 80% at flow rates greater than 10 gpm/ft$^2$. Sediment re-entrainment tests demonstrate the Vortechs™ unit may be capable of retaining stored sediment under various flow regimes, but sediment re-entrainment can occur. These data also indicate the importance of regular maintenance to minimize the potential for wash out of the sediment during future storm events.

## Data Analysis Conclusions

The laboratory tests demonstrate the performance of the Vortechs™ unit under controlled conditions. The lack of data quality assurance should be considered when reviewing these test results. Differences in removal efficiencies for similar flow rates were not explained by Vortechnics. Additionally, the design of the test apparatus may have allowed a significant variation in flowrates from those recorded for each test due to fluctuations in static head level in the flow storage tank. General trends in the data are consistent with expected changes in efficiencies as flow increases and particle size decreases. Results indicate that removal efficiency decreases as particle size decreases and flow rate increases, and average removal efficiencies are positive for hydraulic loading rates up to 100 gpm per square foot of grit chamber area.

For most particles sizes tested, removal efficiencies exceeded 80% when the hydraulic loading rates were 20 gpm per square foot of grit chamber area or less. Thus, Vortechnics' methodology for sizing the units is supported by these results. The results of the tests performed with sediment accumulated in the grit chamber indicate that removal efficiency decreases when sediment accumulates up to the design capacity, thus regular maintenance of the units is warranted.

## Field Demonstration – DeLorme Publishing Company, Yarmouth, Maine

In 1998, Vortechnics initiated a study at the DeLorme Publishing Company in Yarmouth, Maine. A Vortechs™ Model 11000 installed in a 4-acre, 300-car parking lot treats flow from the parking lot as well as flow from an off-site highway drainage pond/swale area. Effluent from the treatment system discharges to a detention pond and then to a stream. The site is primarily used for day parking, but also has motor home parking and a two-bay loading dock.

Field-testing was performed in two phases to allow for snow removal during the winter months. The first phase of field-testing was conducted between October 1998 and November 1998. The second phase of testing occurred between May 1999 and November 1999. The parking lot was mechanically swept prior to the second phase of sampling. Study results were prepared by Vortechnics (Vortechnics, 1999).

### Phase 1 Test Conditions

ISCO 6700 auto samplers were installed to sample the influent and effluent. Samples were taken using a standard 4 inch perforated ISCO sample strainer and transferred to the sampling device through ½" vinyl tubing. The influent sample strainer was positioned at the end of the influent pipe, in the grit chamber. The effluent sample strainer was positioned just below the inlet of the effluent pipe in the outlet chamber. The effluent strainer was allowed to float/tilt up as flow increased in the outlet pipe. An ISCO 674 Rain Gauge was mounted at the edge of the pond near the outfall of the Vortechs™ effluent pipe.

The rain gauge was configured to initiate the sampling sequence, and the auto samplers were programmed to provide flow-weighted composites. In order to capture first flush and high-intensity events, two sampling programs "A" and "B" were established based on local rainfall intensities. Program "A" was designed to activate the samplers for 15 minutes, during which 4 samples were collected every 5 minutes, each time the rain gauge registered 0.01 inches. Program "B" was operated when a rainfall rate of at least 0.03 inches/15 minutes was recorded. For some events, a combination of both sampling programs was used.

Sample bottles with a capacity of 500 mL were used to capture 450 mL samples. The auto sampler was replenished with empty bottles during each event, as needed. Samples were collected and returned to the Vortechnics laboratory for analysis. Samples were analyzed for TSS concentration within 72 hours of collection using Hach method 8271; an EPA approved gravimetric method for total non-filterable solids. Sample weights were measured using an Acculab V-1 analytical balance with a readability of 0.001g.

### Phase 1 Results and Discussion

Seven rainfall events were sampled during Phase 1 of the DeLorme study. Event removal efficiency was calculated based on flow-weighted composite influent and effluent concentrations. It was reported that the flow-paced sampling did not follow the protocol that prescribed flow weighting based on actual flows. Instead, a time-paced sample program was used. Event mean concentrations were calculated by weighting the time-paced sampling results by flow. Because flow into the Vortechs™ unit was not metered, the rational method was used to estimate flow. Use of the rational method to determine actual system flows can introduce large error into calculations. Thus, a removal efficiency value for Phase 1 of the study is not reported in this document.

Removal efficiencies for the Phase 1 paired influent and effluent samples versus influent concentration is illustrated in Figure 4. These results suggest a non-linear relationship between influent concentration and removal efficiency. The site generally had low influent concentrations relative to typical TSS concentrations in stormwater of 100 to 300 milligrams per liter (mg/L). The observed low removal rates at low concentrations may be consistent with treatment efficiency as described by Minton (personal communication, 1999).

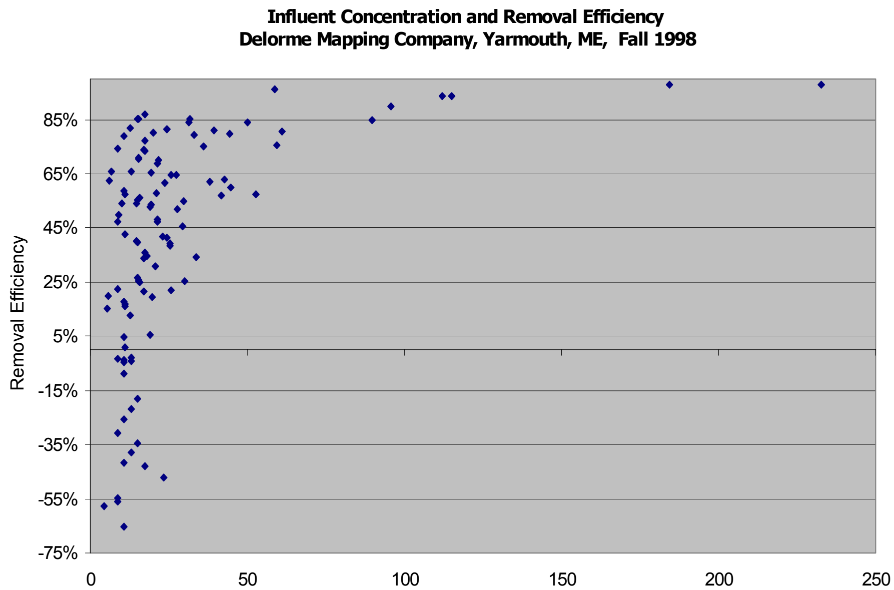


**Figure 4. Phase 1 Total Suspended Solids Removal Efficiencies for Paired Influent and Effluent Samples (Vortechnics, Inc., Scarborough, ME. 1998)**

Given the limitations of the data it may be appropriate to estimate the Phase 1 removal efficiencies as a range. Over the course of seven events the range of TSS removal efficiencies was reported as 19.8% to 91.6%. Comparing the average influent concentration for all events of 63.3 mg/L with a standard deviation of 322 to the average effluent concentration for all events of 10.4 mg/L with standard deviation of 6 demonstrates some uniformity to treatment. However, without accurate flow rate data, efficiency as a function of flow rate cannot be determined. Since this is key to the validation of design specifications it suggests that this data is non-supportive these data were not included in the efficiency ratings for the site per conversations with Vortechs technical staff.

## Phase 2 Test Conditions

During Phase 2 of the sampling program an ISCO 4250 area-velocity flow meter was installed to directly monitor flow through the unit. All other test equipment was installed identically to the configuration in Phase 1. Prior to Phase 2 testing, the DeLorme site was mechanically swept. Total suspended solids were analyzed using Standard Method 2540 D, rather than Hach method 8271, which was used during Phase 1.

## Phase 2 Results and Discussion

During the second season of testing, 20 events were monitored. Event removal efficiency was calculated based on flow-weighted composite influent and effluent sample concentrations. Flow measurements taken using the area velocity meter for the first 10 events did not correlate well with flow measurements for similar depth events measured in the second set of 10 rainfall events. According to Vortechs, this difference could not be explained with physical evidence, however the event depths and flow measures appeared to be consistently lower than later measure by a factor of 7.5. Accordingly, Vortechs modified the flow values for the first 10 events for the purpose of calculating sediment load. Based on the fact that the equipment malfunction could have an impact on loading values and efficiency ratings the data for all 20 events is treated both inclusively and exclusively without the suspect first 10 events. Efficiency values are calculated and presented for both conditions.

For the purpose of this review the average removal efficiency for all events was calculated by the following four methods (ASCE/EPA 1999):

1. *Efficiency Ratio (ER):*

$$\text{Removal efficiency} = \frac{\text{average inlet EMC} - \text{average outlet EMC}}{\text{average inlet EMC}}$$

2. *Summation of Loads (SOL):*

$$\text{Removal efficiency} = 1 - \frac{\text{sum of outlet loads}}{\text{sum of inlet loads}}$$

3. *Regression of Loads (ROL):*

$$\text{Removal efficiency} = 1-\beta$$

Where $\beta$ is the slope of the least squares linear regression line of the inlet and outlet loads with the intercept constrained to zero

4. *Efficiency of Individual Storm Events:*

$$\text{Removal efficiency} = \text{Average}\left(1 - \frac{\text{outlet load of individual storm}}{\text{inlet load of individual storm}}\right)$$

The efficiency ratio method is the preferred method for calculating removal efficiencies specified in the *Stormwater Best Management Practice Demonstration Tier II Protocol for Interstate Reciprocity* (TARP, 2001). The regression of loads approach may not be the best method for small data sets as the $R^2$ value is often very low, indicating a poor linear relationship in the data (ASCE/EPA, 1999). In this case the $R^2$ value was 0.26 for all events and 0.97 for events 11-20. Removal efficiencies calculated by the summation of loads and regression of loads approaches tend to be dominated by larger storm events. The summation of loads method uses a mass balance approach, while in the efficiency ratio method EMCs from all storms are weighted equally. All storm removal efficiencies are weighted equally in the efficiency of individual storm events approach.

It is important to note that the use of any of the above efficiency calculations for annual average removal efficiency is at best an approximation. For the purposes of quantifying annual average removal efficiency, a multi-year study would be required and would allow for statistical comparison of year-to-year variation based on precipitation and load characteristics.

Results of the event monitoring for Phase 2 of the DeLorme testing are summarized in Table 4. The average removal efficiencies for all 20 events, calculated by the four different methods, ranged from 60% to 83%. Given the problems with flow meter during the first 10 events, the average removal efficiency may be more accurately calculated considering only events 11-20. Removal efficiencies calculated by the four methods for events 11-20 ranged from 40% to 59%. Overall removal efficiencies for Phase 2 of the DeLorme study may be biased due to errors in flow measurements. And, inaccuracies may exist in estimates of EMCs calculated from the first ten events, especially where sum of loads and regression of loads is used to calculate efficiency.

**Table 4. Phase 2 - DeLorme Publishing Company TSS Results**

| Storm | Storm Date | Rainfall Depth (in) | Flow Volume Thru Vortechs™ ($ft^3$)[1] | Number of Sub samples | Influent EMC (mg/L) | Effluent EMC (mg/L) | Event Removal Efficiency[1] |
|---|---|---|---|---|---|---|---|
| 1 | 5/24/1999 | 0.3 | 21,600 *(2880)* | 28 | 65.9 | 50.3 | 24 % |
| 2 | 6/24/1999 | 0.52 | 12,051 *(1607)* | 17 | 1010.7 | 149.2 | 85 % |
| 3 | 6/28/1999 | 0.32 | 9,117 *(1216)* | 12 | 1364.9 | 63.6 | 95 % |
| 4 | 7/6/1999 | 0.32 | 13,203 *(1760)* | 13 | 857.6 | 49.4 | 94 % |
| 5 | 7/18/1999 | 0.53 | 9,630 (1284) | 11 | 367.6 | 145.9 | 60 % |
| 6 | 7/24/1999 | 0.46 | 6,831 *(911)* | 18 | 533.2 | 57.8 | 89 % |
| 7 | 8/7/1999 | 0.55 | 14,441 *(1925)* | 30 | 43 | 31 | 28 % |
| 8 | 8/14/1999 | 0.75 | 18,045 *(2406)* | 40 | 1088.8 | 52 | 95 % |
| 9 | 8/29/1999 | 0.10 | 2,183 *(291)* | 6 | 37.2 | 33.6 | 10 % |
| 10 | 9/7/1999 | 0.17 | 4,559 *(608)* | 12 | 61 | 38 | 38 % |
| 11 | 9/15/1999 | 5.45 | 147,586 | 123 | 88.8 | 59.1 | 33 % |
| 12 | 9/30/1999 | 0.48 | 1,284 | 40 | 111.6 | 47.3 | 58 % |
| 13 | 10/4/1999 | 0.53 | 13,210 | 70 | 46.2 | 19.8 | 57 % |
| 14 | 10/9/1999 | 0.13 | 2,908 | 12 | 69.2 | 14.7 | 79 % |
| 15 | 10/14/1999 | 0.43 | 9,543 | 40 | 33.1 | 12.6 | 62 % |
| 16 | 10/23/1999 | 1.91 | 71,607 | 40 | 164.1 | 93.2 | 43 % |
| 17 | 11/2/1999 | 1.02 | 29,378 | 80 | 233.6 | 102.4 | 56 % |
| 18 | 11/11/1999 | 0.27 | 6,858 | 33 | 93.3 | 25.5 | 73 % |
| 19 | 11/14/1999 | 0.25 | 6,614 | 32 | 57.4 | 21 | 63 % |
| 20 | 11/20/1999 | 0.30 | 7,753 | 37 | 188.4 | 70.3 | 63 % |

(after Vortechnics, 1999)[1] Values in italics are untransformed flow values in $ft^3$

**Table 4. Phase 2 - DeLorme Publishing Company TSS Results (cont.)**

| | |
|---|---|
| **Removal Efficiencies for all Events:** | |
| Removal Efficiency by *Efficiency Ratio*[2]: | 83% |
| Removal Efficiency by *Summation of Loads*[2]: | 73% |
| Removal Efficiency by *Regression of Loads*[2]: | 77% |
| Removal Efficiency by *Efficiency of Individual Storm Events*[2]: | 60% |
| **Removal Efficiencies for Events 11-20:** | |
| Removal Efficiency by *Efficiency Ratio*[2]: | 57% |
| Removal Efficiency by *Summation of Loads*[2]: | 44% |
| Removal Efficiency by *Regression of Loads*[2]: | 40% |
| Removal Efficiency by *Efficiency of Individual Storm Events*[2]: | 59% |

1. Results for Events 1-10 likely contain significant error due to calibration problems with the flow meter.
2. Methods taken from ASCE/EPA (1999).

### Data Analysis Conclusions

Removal efficiencies calculated by the four methods suggest a difference between the stated performance claim and the removal efficiency measured on this site. This is especially so when considering the ratios calculated without the first 10 events. Deficiencies in data quality were identified in the DeLorme Phase 2 data set, including deviation from the sampling and analysis protocol and the flow meter calibration for the first ten storm events. A particle size distribution was not conducted on the sediment accumulated in the grit chamber. However, when considering all the data, the preferred calculation method using *Efficiency Ratio* exceeded 80% removal for the twenty monitored events.

## Field Demonstration – Marine Village Watershed, Village of Lake George, New York

The New York State Department of Environmental Conservation undertook a field demonstration of a Model 11000 Vortechs™ unit in 2000 (West et. al. 2001). The stated objective of the study was to determine the performance of the Vortechs™ system under different storm conditions over the course of a year. Measured stormwater constituents included total suspended solids, total phosphorus, total nitrogen, and biological oxygen demand (BOD), fecal coliform, and conductivity. A particle size analysis of the accumulated sediment in the Vortechs™ system was also performed in June 2000.

### Marine Village Site Conditions

The Vortechs™ system receives stormwater runoff from 3.78 hectares (9.34 acres), in which 95% of the area is covered by impervious surface based on a visual land survey (West 2001). Stormwater is collected through several drop inlets and routed to the Vortechs™ system. The effluent from the Vortechs™ system is routed through a 24-inch high-density polyethylene (HDPE) pipe to a culvert for ultimate discharge to Lake George. The Vortechs™ system was installed per the manufacturer's recommended configuration with a bypass (West, 2001). Based on the locations of the sampling and flow monitoring equipment, only the flow and constituents received by the Vortechs™ system were monitored. The extent of bypassing cannot be quantified, and the total constituent removal for the entire system cannot be determined. While unconfirmed, it is reported by Vortechs that bypass flows were minimal and their effect on TSS efficiency for the system may be minimal.

## Sampling Methodology

The following equipment was used during the field test (West 2001):

- Flow monitoring: An 1830 series Druck 5.0 psi submersible transducer was mounted on the upstream wall opposite of the weir and orifice in the Vortechs™ system. The transducer was connected to a Telog Instruments Inc. Model WLS-2109e Level Tracker. Output from the level tracker was translated into flow rates using standard weir and orifice equations. Levels were measured every minute and averaged over 5-minute intervals.

- Precipitation: The precipitation data was collected at the Cedar Lane Atmospheric Deposition Station, which is located in another drainage basin, approximately 0.9 miles from the Vortechs™ system. Precipitation was collected using a Qualimetrics, Inc. Model 6021A tipping bucket rain-snow gauge that tips once for every 0.01 inches of wetfall. The precipitation levels were automatically recorded and stored in 5-minute intervals by a Telog Instruments, Inc. Model R-2107 event recorder.

- Water Quality Samples: Influent and effluent water quality samples were collected using two Manning Environmental, Inc. 4901 Portable Vacuum Priority Contaminant™ Samplers. The influent samples were collected from a drop manhole where the flow from two pipes was combined prior to entering the unit. The distance from the manhole to the unit could not be determined from the information provided in the Final Report. The sampler was located within the manhole approximately one inch above the invert of the outflow pipe. Effluent samples were collected in the effluent chamber of the Vortechs™ system, just below the invert of the outlet pipe.

  The influent sampler was connected to a Keller Psi 5.0 psi submersible transducer, which was mounted next to the Druck transducer. The sampler was programmed to allow collection based on either water level input from the transducer or a specified time interval. The samplers were connected together by a contact closure connection, which signaled the completion of the influent sampling collection and activated the collection of the effluent sample. In all cases, discrete samples were collected.

  The sample bottles were triple-rinsed with deionized water before they were installed. The collection lines attached to the automatic samplers were automatically flushed before the collection of each sample.

No discussion of equipment calibration was provided in the Final Report. The primary investigator for the study could not confirm that any of the equipment had been calibrated per the manufacturers' specifications (personal communication, West, 2002). The Vortechs™ system was not cleaned prior to the start of the study. However, it was cleaned in June 2000, at which time a grab sample was collected for particle size analysis.

The samplers were set up before precipitation began. Samples were taken throughout the event based on regular time intervals. For some of the storms, samplers were programmed to collect samples based on fluctuations in the water level. The sampling scheme (time or flow paced-sampling) used for each event was not reported. In all events, discrete, fixed volume samples were collected.

A subset of the samples was chosen for analysis based on the flow hydrograph developed from the water level data. Samples were not split or composited. Samples for the TSS and conductivity analysis were first selected from the entire set, and the samples to be analyzed for chemical species were selected from the remainder (personal communication, West, 2002). Samples from three events were analyzed for BOD and coliform.

Samples were retrieved and sent to the lab within 24 hours of collection. No information about sample handling and transport is provided in the Final Report. No discussion of field quality assurance/quality control measures was provided in the Final Report. Field blanks were collected and sent to the laboratory along with samples for total phosphorus and total nitrogen. However, no blanks or field duplicates were analyzed for TSS (personal communication, West, 2001).

## Laboratory Analysis

Samples were analyzed using the methods summarized in Table 5. The Darrin Fresh Water Institute in Bolton Landing, NY analyzed nitrogen, phosphorus and coliform samples. TSS and specific conductance samples and most of the BOD samples were analyzed at the New York State Department of Environmental Conservation (NYSDEC). One set of the BOD samples was sent to the NYS Department of Health, Wadsworth Center for Laboratories and Research for analysis to confirm results of NYDEC analysis. Proposed processing, preservation, and holding times for the samples were included in the Final Report Methodology, but no statement was made as to whether these guidelines were adhered to for the samples that were analyzed. Samples were analyzed in accordance with the specified analytical method and the QA/QC protocols for that laboratory. However, laboratory QA/QC reports for the data were not included in the Final Report.

**Table 5. Summary of Analytical Procedures Utilized in the Village of Lake George System Study**

| Parameter | Method | Processing | Preservation | Volume | Container | Holding Time |
|---|---|---|---|---|---|---|
| Total Phosphorus | Colorimetric – Persulfate Oxidation | Raw sample | Freeze | 100 mL | 125 mL PE | 28 days |
| Total Nitrogen | Colorimetric – Persulfate Oxidation | Raw sample | Freeze | 100 mL | 125 mL PE | 28 days |
| Total Suspended Solids | Total Suspended Solids Dried at 103-105$^o$ C (SM 2540 D) | Raw sample | Cool to 4$^o$C | 500-1000 mL | 1000 mL PE | 7 days |
| Fecal Coliform Bacteria | Membrane Filtration (SM 9222 D) | Raw sample | Cool to 4$^o$C | 1000 mL | 1000 mL PE | 48 hrs |
| Biological Oxygen Demand | NYSDOH Lab – 5-day BOD test (SM 5210) and Field Lab – 5-day BOD test (BOD Trak™ Instrument, Hach® Company) | Raw sample | Cool to 4$^o$C | 100 mL | 125 mL PE | 6 hrs |
| Specific Conductance | Instrumental (SM 2510 B) | — | — | — | — | — |

(After West, 2001)

## Results and Discussion

Precipitation, flow, and constituent monitoring began in February 2000 and continued through December 2000. Eighteen storm events were monitored. Eight of the storm events were combined into three "sampling events", as shown in Table 6. A total of 13 sampling events were used to determine TSS removal efficiencies. Nine of the thirteen sampling events were used to determine removal efficiencies for nitrogen and phosphorus.

**Table 6. Summary of Reported Precipitation and Sampling Events for Village of Lake George, New York**

| Event No. | Precipitation Events | | | | | Sampling Events | | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start Time | Stop Time | Duration (minutes) | Depth (in) | Time between Events (hr) | Start Date | Start Time | Stop Date | Stop Time | No. of TSS Samples Analyzed | Event Volume (gallons) | |
| 1 | 2/13/00 22:25 | 2/14/00 13:45 | 920 | 1.38 | 0.0 | 2/14/00 | 9:00 | 2/14/00 | 20:30 | 13 | 314,926 | |
| 2 | 2/24/00 13:40 | 2/25/00 17:40 | 1680 | 0.33 | 239.9 | 2/23/00 | 10:40 | | | | 75,297 | Events 2-5 were sampled as a single event - sampling began before the first precipitation was recorded for this event. Total volume of events 4 and 5 was less than 0.1 inches. |
| 3 | 2/27/00 23:35 | 2/28/00 7:20 | 465 | 0.39 | 53.9 | | | | | | 89,035 | |
| 4 | 2/28/00 13:55 | 2/28/00 14:00 | 5 | 0.01 | 6.6 | | | | | | 2,378 | |
| 5 | 3/1/00 18:55 | 3/1/00 22:30 | 215 | 0.03 | 52.9 | | | 3/2/00 | 20:55 | 62 | 6,869 | |
| 6 | 3/9/00 11:15 | 3/9/00 22:45 | 690 | 0.21 | 180.8 | 3/9/00 | 17:40 | | | | 47,820 | Events 6 and 7 were sampled as a single event. Sampling stopped prior to end of storm event. |
| 7 | 3/11/00 7:55 | 3/12/00 16:10 | 1935 | 0.94 | 33.2 | | | 3/12/00 | 13:45 | 22 | 214,530 | |
| 8 | 3/25/00 20:15 | 3/25/00 20:55 | 40 | 0.04 | 316.1 | 3/25/00 | 20:50 | 3/26/00 | 1:50 | 3 | 9,247 | 3 samples collected for storm event. The second sample was collected on 3/25/00 at 21:50. Total volume of this event was less than 0.1 inches. |
| 9 | 3/27/00 23:30 | 3/28/00 15:05 | 935 | 1.16 | 50.6 | 3/28/00 | 0:08 | 3/28/00 | 19:35 | 20 | 264,728 | |
| 10 | 4/3/00 8:50 | 4/3/00 14:25 | 335 | 0.20 | 137.8 | 4/3/00 | 11:20 | | | | 45,707 | Events 10 and 11 were sampled as a single event. |
| 11 | 4/3/00 21:45 | 4/4/00 14:20 | 995 | 1.41 | 7.3 | | | 4/4/00 | 14:15 | 19 | 321,796 | |
| 12 | 4/8/00 19:10 | 4/9/00 17:50 | 1360 | 0.72 | 100.8 | 4/8/00 | 19:50 | 4/10/00 | 20:05 | 10 | 164,332 | Sampling stops 26 hours after precipitation. |
| 13 | 4/20/00 20:10 | 4/21/00 16:30 | 1220 | 0.87 | 266.3 | 4/20/00 | 21:00 | 4/21/00 | 6:30 | 10 | 198,678 | Sampling stopped prior to end of storm event. |
| 14 | 6/5/00 20:00 | 6/6/00 23:55 | 1675 | 2.17 | 1083.5 | 6/5/00 | 20:10 | 6/6/00 | 10:25 | 6 | 470,540 | Sampling stopped prior to end of storm event. |
| 15 | 8/23/00 10:45 | 8/23/00 16:50 | 365 | 0.73 | 1858.8 | 8/23/00 | 11:10 | 8/23/00 | 21:05 | 10 | 158,256 | |
| 16 | 10/5/00 14:40 | 10/6/00 9:10 | 1110 | 1.14 | 1029.8 | 10/5/00 | 16:15 | 10/5/00 | 23:50 | 6 | 247,291 | Sampling stopped prior to end of storm event. |
| 17 | 11/9/00 22:40 | 11/10/00 16:40 | 1080 | 0.94 | 829.5 | 11/9/00 | 23:45 | 11/10/00 | 15:20 | 12 | 206,076 | Sampling stopped prior to end of storm event. |
| 18 | 12/11/00 21:55 | 12/12/00 9:45 | 710 | 0.70 | 749.3 | 12/11/00 | 3:00 | 12/12/00 | 8:00 | 11 | 159,841 | Sampling stopped prior to end of storm event. |

After West (2001)

Some of the storm events during the study period were not sampled because the equipment malfunctioned or the samples bottles were not installed prior to the beginning of the storm event. Antecedent dry conditions were not reported. TSS samples were collected during precipitation events that accounted for approximately 40% of the total annual runoff (West, 2001).

Precipitation hydrographs showing rainfall intensity were not reported. The precipitation data was used to compare the flow levels measured in the Vortechs™ system to the start and stop times of the precipitation event (personal communication, West, 2001). Because the rain gauge was located outside of the drainage basin, approximately 0.9 miles from the Vortechs™ system, the precipitation results could not be directly correlated with the Vortechs™ system site.

Because flow-weighted samples were not collected, the influent and effluent EMCs for TSS, total nitrogen, and total phosphorus for each storm event were calculated based on the following non-standard approach:

- The concentrations of chemical constituents from discrete samples collected during the storm event were linearly interpolated to develop a series of concentration estimates at 5-minute intervals. The last discrete sample was used to estimate the concentration for subsequent discharges.
- The interpolated concentrations were multiplied by the corresponding flowrate calculated from 5-minute water level readings using the weir and orifice equations.
- The product of the 5-minute concentrations and flows were then summed to produce the total mass loading for each event. The load was then divided by the total event volume to determine the EMC for the event.

This approach can reasonably approximate EMCs if the samples were collected over the entire hydrograph, including the rising limb, peak, and falling limb. For the Lake George study, this was not always the case. Based on the Vortechs™ water level data and the reported time/date of each sample (West, 2001), it appears that portions of the hydrograph are not represented in the sampling results for sampling events 4, 5, 8, 9, and 11. Sampling Event 4 consisted of only three samples, none of which were taken when water levels in the Vortechs™ system were near their peak. Additionally, only 0.04 inches of rainfall was measured during this event. The resulting EMCs are likely to have significant error due to unverified flow measurement and significant bias in discrete sample selection. EMCs for sampling events 2, 3, and 6 included samples collected during multiple precipitation events and where flow may represent base flow versus runoff. EMCs from these events may not be suitable for inclusion in the overall performance value. However, it was noted by Vortechs that some storm events were related to snow melt, hence no precipitation or limited precipitation would be recorded.

For all 13 "sampling events", the average removal efficiencies were calculated by the following methods: efficiency ratio, summation of loads, regression of loads, and efficiency of individual storm events, as described earlier in this document. Removal efficiencies for the individual events ranged from –68% to 99%, as shown in Table 7. Event 4 may be viewed as suspect. The *Efficiency Ratio* and *Efficiency of Individual Storm Events* calculated without event 4 increase from 87% to 90% and 72% to 84% respectively. Removal efficiencies for all events ranged from 72% to 90%.

At the end of the sampling period, a sample from the accumulated sediment in the grit chamber was analyzed for particle size distribution. The particle size distribution indicated that the majority of the particles removed from the flow by the Vortechs™ system are sand sized particles with the following grain size distribution by dry weight (West, 2001):

- 5% was less than 50 microns.
- 15% between 100 and 250 microns,
- 30% between 250 and 500 microns,
- 30% between 500 microns and 1 millimeter,
- 15% between 1 and 2 millimeters, and
- 10% was greater than 2 millimeters.

The results for nitrogen and phosphorus indicate that the difference between the influent EMCs and effluent EMCs is not statistically different from zero. Therefore, the Vortechs™ system did not remove appreciable amounts of either constituent.

Because so few BOD samples were collected (seven samples during two storm events), event removal concentrations were not calculated. The results suggest that the influent concentrations do not vary statistically from the effluent concentrations.

A limited number of samples were analyzed for fecal coliform. Most of the results for the fecal coliform analysis were flagged because samples were analyzed outside of their holding times, while others showed a high background count. Because of the quality assurance and control problems with the fecal coliform, no conclusion about removal of the constituent by the Vortechs™ system can be made.

**Table 7. Village of Lake George TSS Results**

| Sampling Event | Precipitation Event | Rainfall Depth (in) | Flow Volume Thru Vortechs™ ($ft^3$) | Number of TSS samples | Influent EMC (mg/L) | Effluent EMC (mg/L) | Event Removal Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1.38 | 42,090 | 13 | 987 | 263 | 73% |
| 2 | 2-5 | 0.76 | 23,199 | 62 | 129 | 59 | 54% |
| 3 | 6-7 | 1.15 | 35,063 | 22 | 1040 | 338 | 68% |
| 4 | 8 | 0.04 | 1,236 | 3 | 214 | 359 | -68% |
| 5 | 9 | 1.16 | 35,381 | 20 | 1674 | 71 | 96% |
| 6 | 10-11 | 1.61 | 49,116 | 19 | 535 | 70 | 87% |
| 7 | 12 | 0.72 | 21,963 | 10 | 181 | 30 | 84% |
| 8 | 13 | 0.87 | 26,553 | 10 | 2492 | 35 | 99% |
| 9 | 14 | 2.17 | 62,887 | 6 | 90 | 32 | 64% |
| 10 | 15 | 0.73 | 21,151 | 10 | 1047 | 37 | 96% |
| 11 | 16 | 1.14 | 33,050 | 6 | 439 | 17 | 96% |
| 12 | 17 | 0.94 | 27,542 | 12 | 445 | 17 | 96% |
| 13 | 18 | 0.70 | 21,363 | 11 | 1156 | 45 | 96% |

(After, West 2001)

| **Removal Efficiencies for all Events:** | |
|---|---|
| Removal Efficiency by *Efficiency Ratio*[1]: | 87% |
| Removal Efficiency by *Summation of Loads*[1]: | 88% |
| Removal Efficiency by *Regression of Loads*[1]: | 90% |
| Removal Efficiency by *Efficiency of Individual Storm Events*[1]: | 72% |

1. Methods taken from ASCE/EPA (1999).

### Data Analysis Conclusions

TSS removal efficiencies ranged between 72% and 90% for the four methods of calculating average annual removal, and the TSS removal efficiency as calculated by the efficiency ratio method was 87%. Based on the particle size distribution of the accumulated sediment in the unit, most of the removed material fell within the sand-sized range, 100 microns to 2 mm. The results suggest that the Vortechs™ system may be able to provide suspended solids treatment levels as claimed. However, the assessment of the data provided by NYDEC suggests that significant error may be associated with the results. Potential sources of error include: lack of sampling quality control, lack of equipment calibration, and the methodology used for calculating the influent and effluent event mean concentrations (EMC). The Vortechs™ system was installed with a bypass, and only the flow and constituents received by the unit were monitored. Therefore, the extent of bypassing cannot be quantified, and the total TSS removal for the entire flow cannot be determined. The Vortechs™ system did not remove appreciable amounts of nitrogen, phosphorus, or BOD. Because of the quality assurance and control problems with the fecal coliform analysis, no conclusion about removal of the pathogen can be made.

## TECHNOLOGY APPLICATION

The Vortechs™ system is suited for local or lateral stormwater lines within a conveyance system. The system is designed to follow an inlet, such as a catch basin. The system can be used on sites with a wide range of drainage areas provided it is sized correctly. On larger drainage area installations, multiple units may be located throughout the drainage area rather than in a central location, providing treatment of runoff closer to its source. The unit can be used as a component in a mixed structural control system, for example: inlet, Vortechs™, infiltration basin. The Vortechs™ system has a small area requirement in relation to its claimed performance capability, thus it is particularly well suited for constricted areas.

The applicability of this technology for suspended solids removal is similar to that of several other BMPs, including: sand and organic filters, catch basins, and water quality inlets, all of which are described in the Stormwater Management Handbooks (DEP and CZM, 1997). Use of the Vortechs™ system to meet the stormwater treatment Standards 1-9, as described in the Stormwater Management Handbooks (DEP and CZM, 1997), is summarized below:

- Standard 1. No Untreated Stormwater Outfalls/Discharges: The Vortechs™ system, in combination with other treatment measures required in Standards 2-9, can be used within a stormwater conveyance system for the treatment stormwater to meet the requirements for Standard 1.
- Standard 2. Post-Development Peak Discharge Rates: The Vortechs™ system is a flow-through system and cannot control discharge rates, thus it is not applicable to Standard 2. When properly designed and maintained, the system will not cause a hydraulic bottleneck within the conveyance system.
- Standard 3. Recharge to Groundwater: The Vortechs™ system is not designed as a recharge system, and is not applicable to Standard 3 unless combined with an approved recharge system. The system may be used as a pretreatment device for recharging systems to reduce the rate of clogging of the infiltrative surface.
- Standard 4. Removal of 80% TSS: The laboratory and field studies show that the Vortechs™ system may be capable of removing up to 80% of annual TSS load. The laboratory tests

indicate higher removal efficiencies for larger particles. Average removal efficiencies varied depending on the method used for calculating efficiency, and all the studies had problems with sampling and analysis procedures that could have introduced error into the results. Therefore, the efficiencies cited in the study results should be considered an approximate indicator of predicted efficiencies for installations with similar topographic and hydrologic conditions.

- Standard 5. Land Uses with Higher Pollutants: The Vortechs™ system has the ability to trap sediment and spills of hydrocarbons, oils, and grease. This makes the system suitable for use on areas with higher potential pollutant loads, specified under Standard 5. However, oil and grease constituents were not included in any of the data analyzed for this report, thus removal effectiveness was not able to be determined. Additional information should be carefully reviewed before this technology is applied for oil and grease removal.

- Standard 6. Critical Areas: The Vortechs™ system is not included on the list of approved BMPs for critical areas. The system can be used as a sediment pretreatment device for BMPs that have been approved by DEP for use in critical areas.

- Standard 7. Redevelopment: The Vortechs™ system is suitable for retrofits and upgrades under Standard 7.

- Standard 8. Erosion and Sediment Controls: The Vortechs™ system can be used for the control of sediment loads on construction sites.

- Standard 9. Operation and Maintenance Plans: The Vortechs™ system requires regular maintenance, as described in report section *Technology Description*, and should be included in any Operation and Maintenance Plan.

## COMPETING TECHNOLOGIES

Several direct competing technologies exist for Vortechs™, including other sedimentation chamber technologies like oil and grit separators and hydrodynamic structures. Information submitted by a competing technology suggests that Vortechs™ is cost competitive with other technologies that produce comparable removal efficiencies, if performance claims are valid. Conventional oil and grit separators are not likely to achieve the same level of treatment as the Vortechs™ system. Average TSS removal efficiencies for the oil and grit separators included a study conducted along the Southeast Expressway in Boston, MA were approximately 30% (Kirk, 2002). The Vortechs™ system has a smaller footprint than detention ponds and artificial wetlands, which is an advantage for many retrofit projects, and it usually will have lower capital costs.

## REGULATORY ISSUES

The performance requirements for stormwater treatment systems are established by the DEP Stormwater Management Standards listed in the Stormwater Management Handbook (DEP and CZM, 1997). Projects subject to the standards may be required to file a Notice of Intent when they are sited in wetland jurisdictional areas. Under the Wetlands Protection Act, Conservation Commissions must apply the standards to new or modified discharges. Permits for surface water discharges under the National Pollutant Discharge Elimination System (NPDES), issued by the Massachusetts DEP Bureau of Resource Protection Division of Watershed Management, are not required if the discharge is tied to a conveyance or system of conveyances operated primarily for the purpose of collecting and conveying uncontaminated stormwater runoff. Other regulations may apply.

## CROSS MEDIA IMPACTS

Disposal of sediment from stormwater treatment systems is permitted in lined or unlined permitted solid waste landfills. In the absence of written approval from DEP, sediments are considered non-hazardous solid waste and may be treated in accordance with all DEP regulations policies and guidelines. Typical removal of sediment can be performed with a vacuum truck. Grease and oils may accumulate in the sedimentation chambers and can be removed and disposed as non-hazardous solid waste. If the system has received influent from a hazardous materials spill, the system should be managed in accordance with an approved emergency response plan and appropriate state requirements. The Vortechs™ system does not present more restrictions for removal of wastes than would be associated with any other BMP.

## ENERGY ISSUES

There are no specific energy issues related to this technology, as it is not an energy consumer. There may be energy benefits when this "passive" system is compared to other technologies that may consume energy resources.

## RECOMMENDATIONS FOR FUTURE PERFORMANCE TESTING

It is recommended that any future studies be undertaken with a higher level of quality control. The *Stormwater Best Management Practice Demonstration Tier II Protocol for Interstate Reciprocity* (TARP, 2001) is the current standard for stormwater technology demonstrations in Massachusetts and should be used as guidance for any subsequent field tests. Extensive field testing under the TARP protocol and other protocols which have high level of data quality assurance may be useful for understanding general technology performance under an array of conditions. However, extensive laboratory testing with targeted field validation may yield similarly valuable results at less cost. Vortechnics is recognized as having performed extensive laboratory validation of its Vortechs™ sizing model. Further, the results of Vortechnics' field performance tests reported herein fall within a reasonable range of performance given the expected variability of uncontrolled field conditions. Any future field tests should be targeted toward data that is not included within the current body of laboratory and field testing, such as further definition of removal efficiencies for sediments with different particle sizes, concentrations, and flow conditions.

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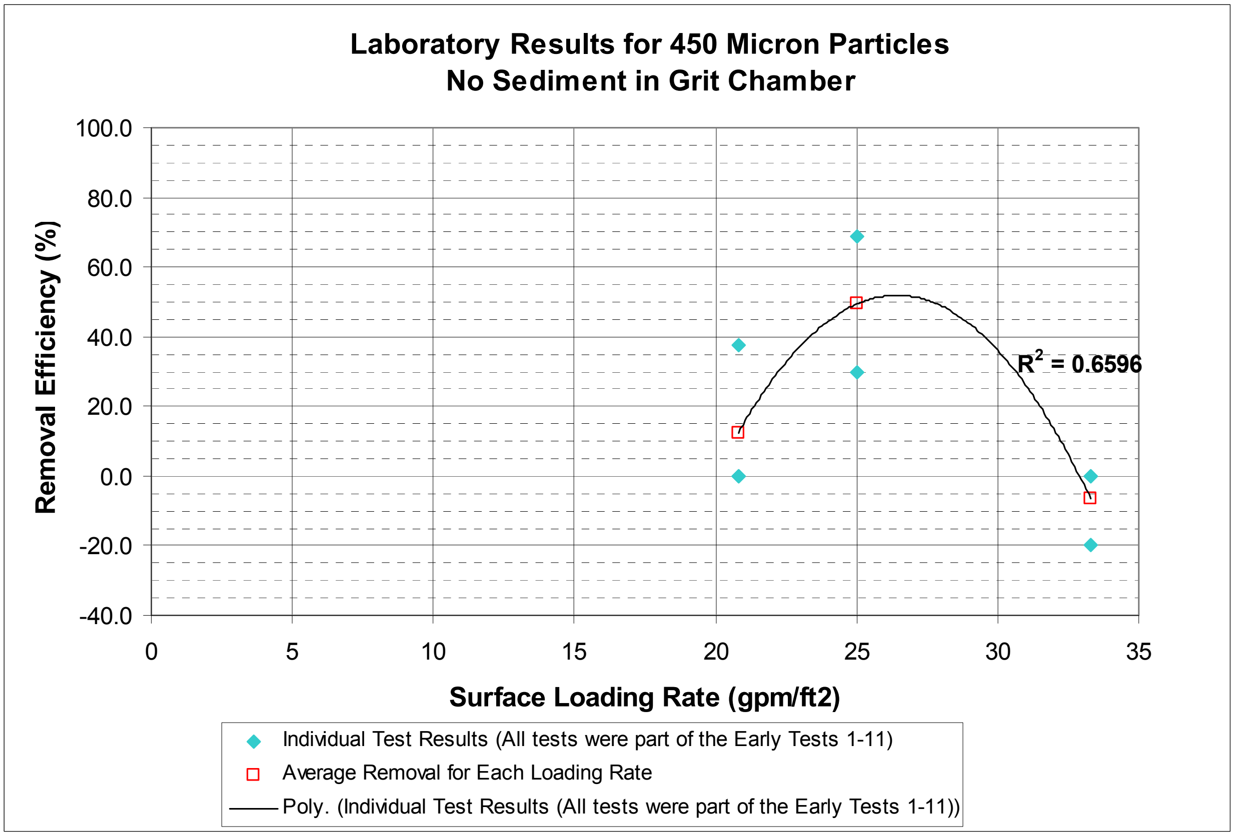
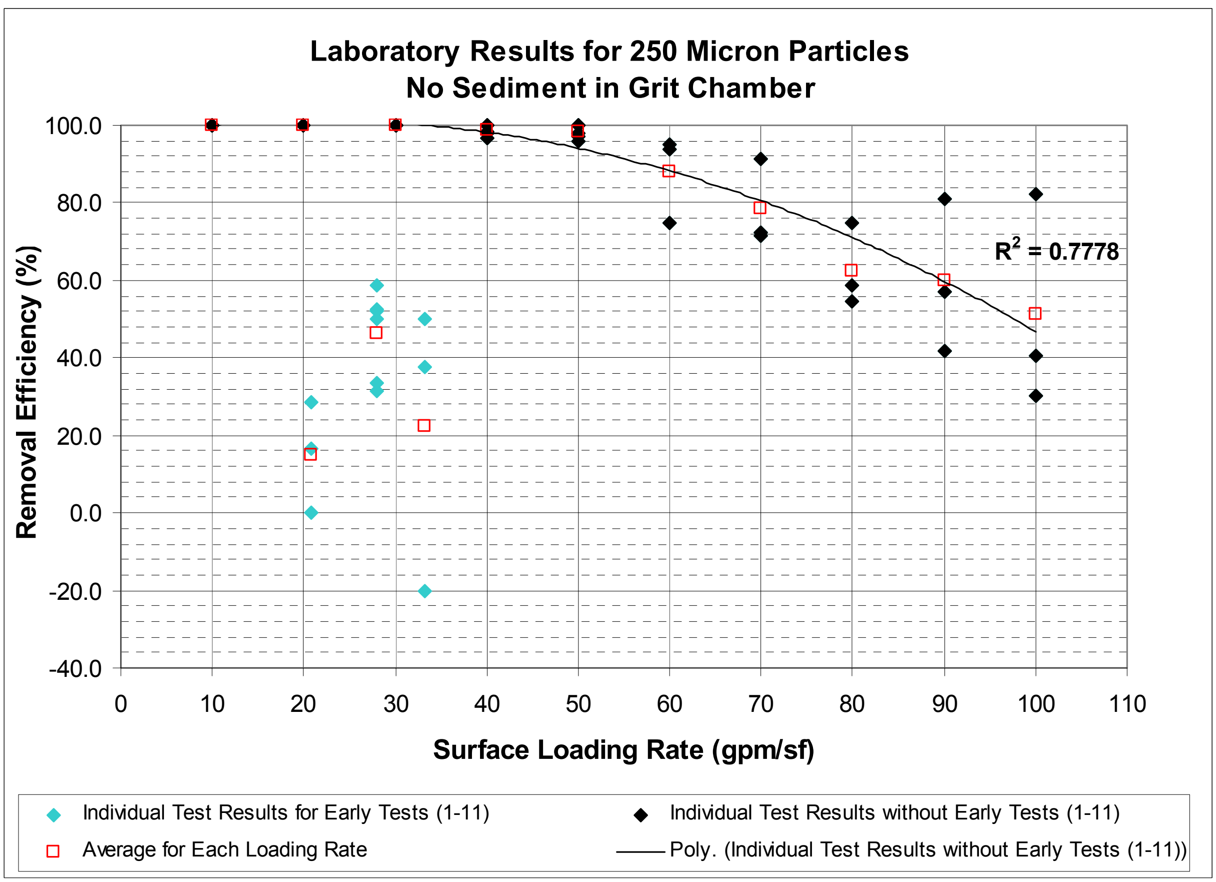
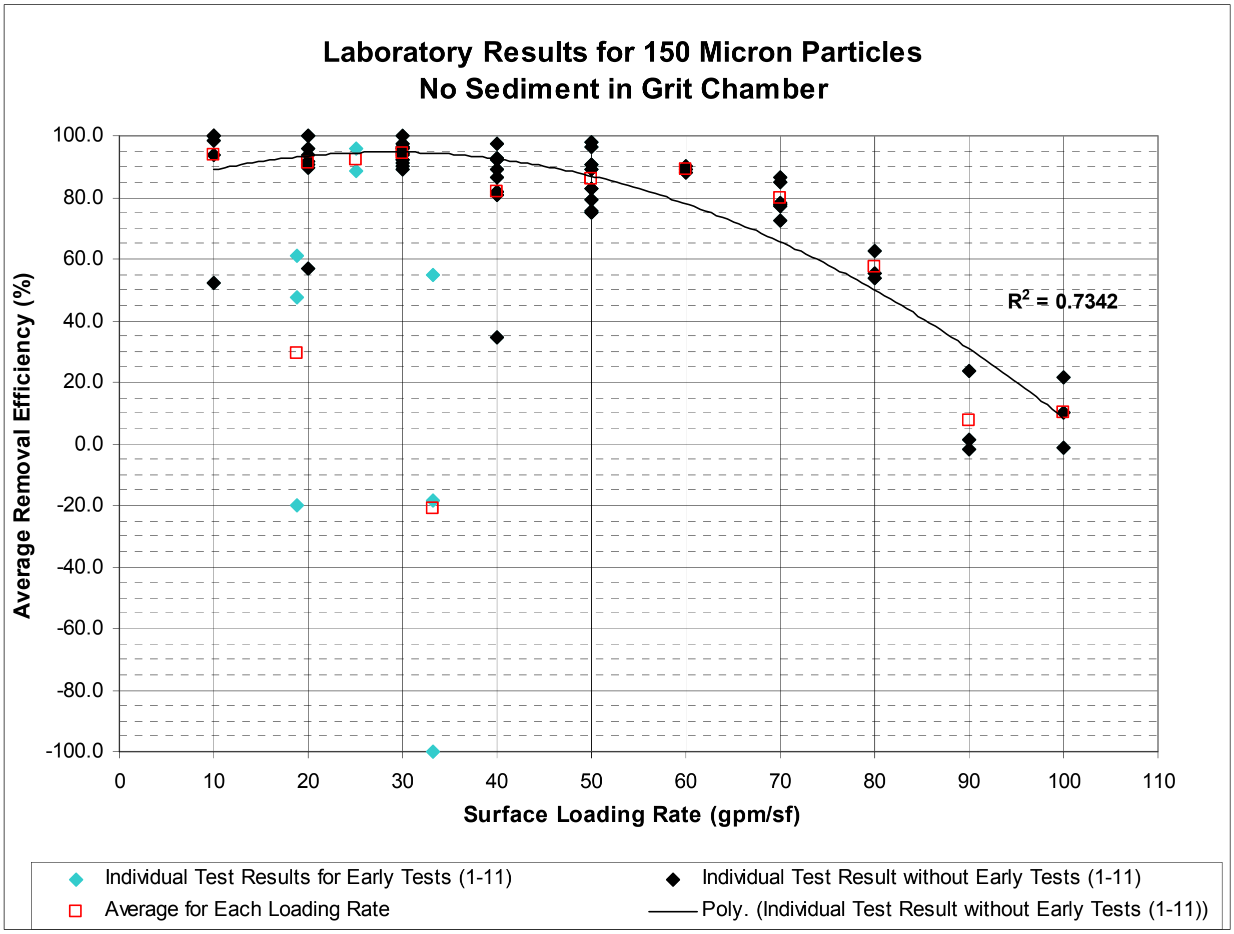
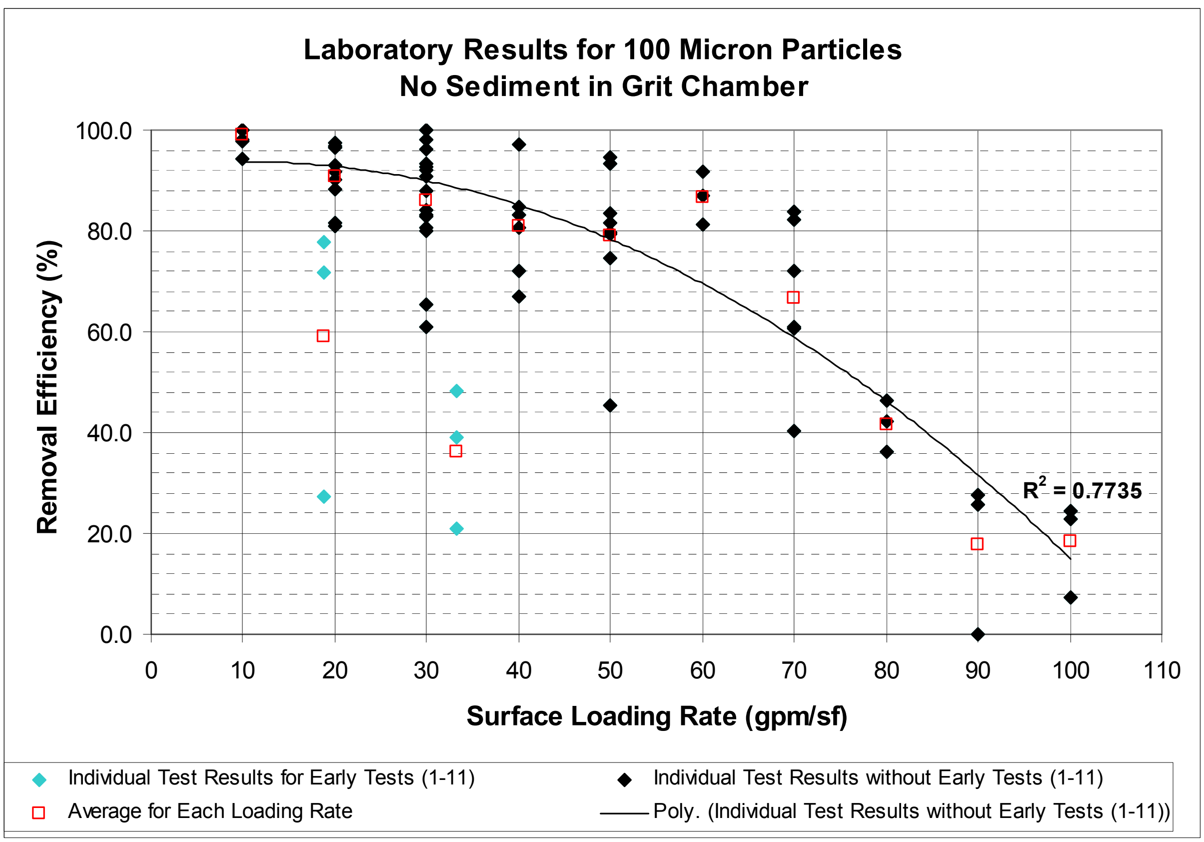
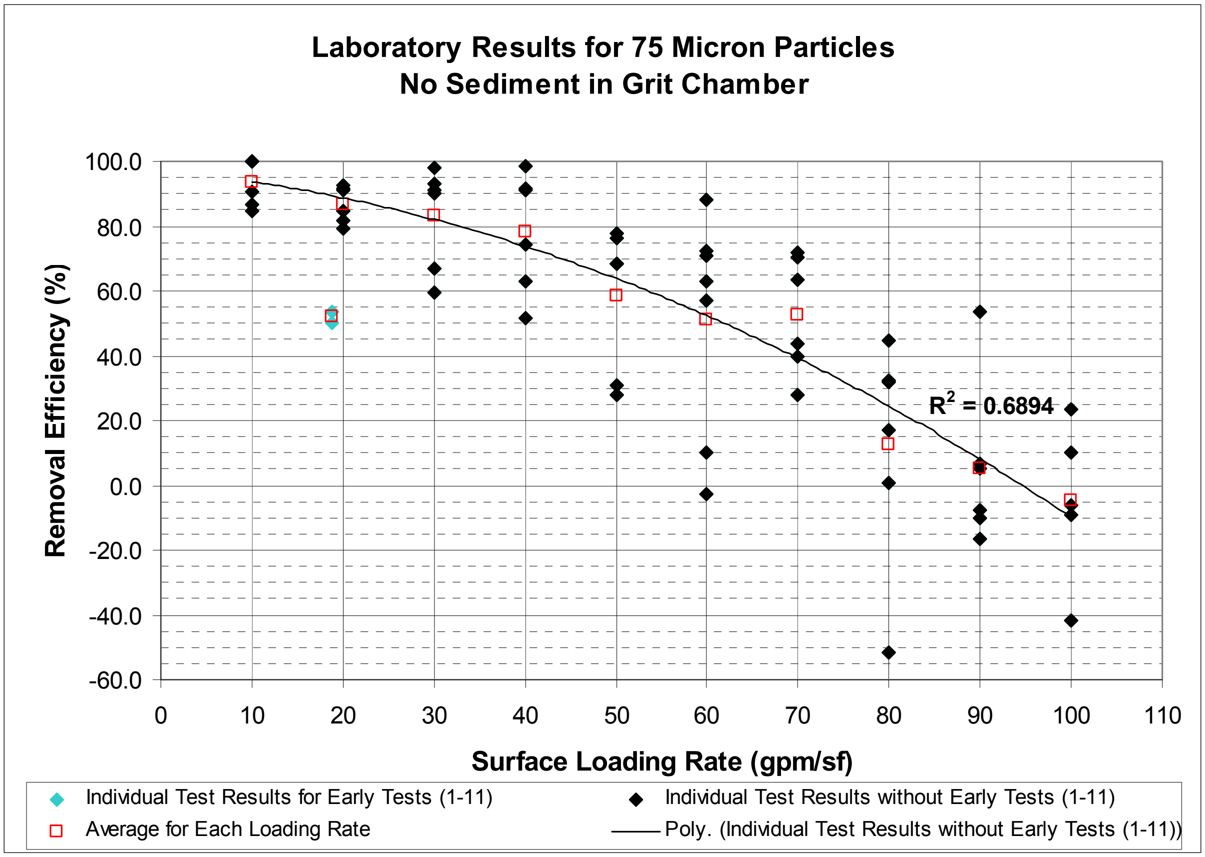
# APPENDIX A – LABORATORY TEST RESULTS WITH NO SEDIMENT IN GRIT CHAMBER

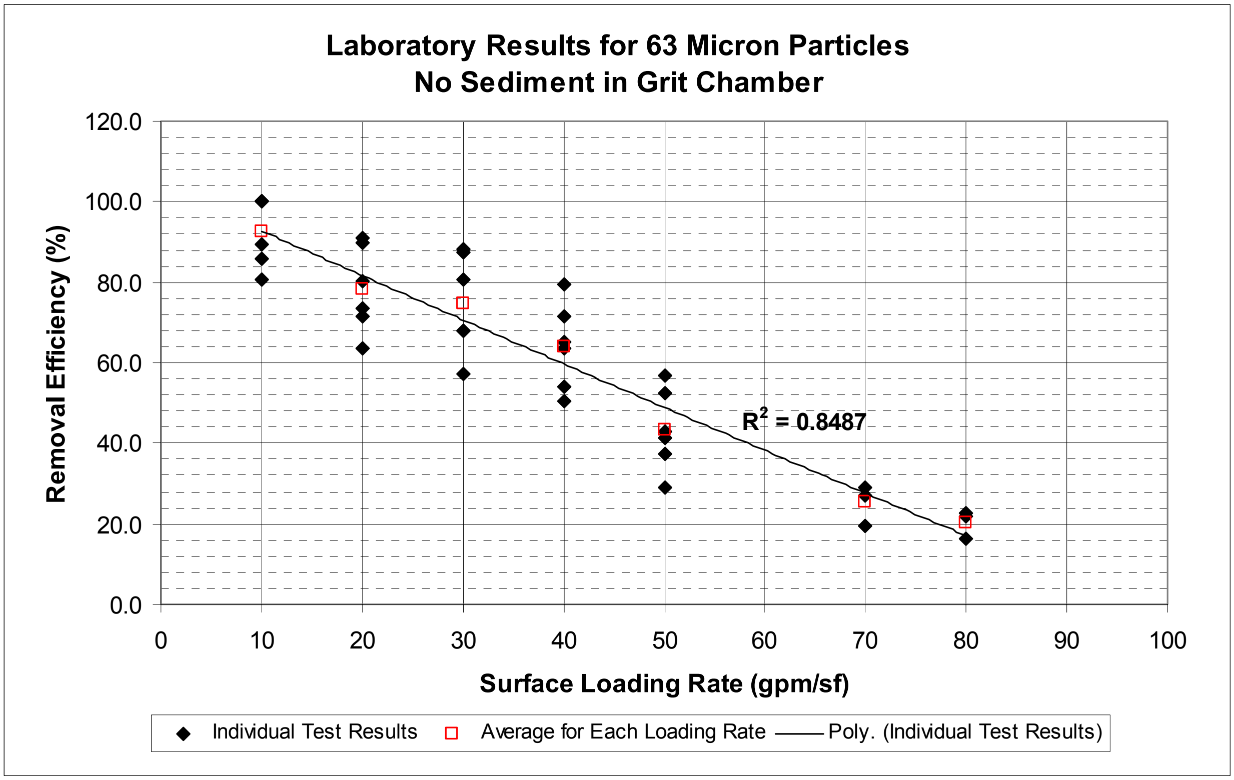

Laboratory Results for 450 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
0
5
10
15
20
25
30
35
Surface Loading Rate (gpm/ft2)
$R^2$ = 0.6596
Individual Test Results (All tests were part of the Early Tests 1-11)
Average Removal for Each Loading Rate
Poly. (Individual Test Results (All tests were part of the Early Tests 1-11))

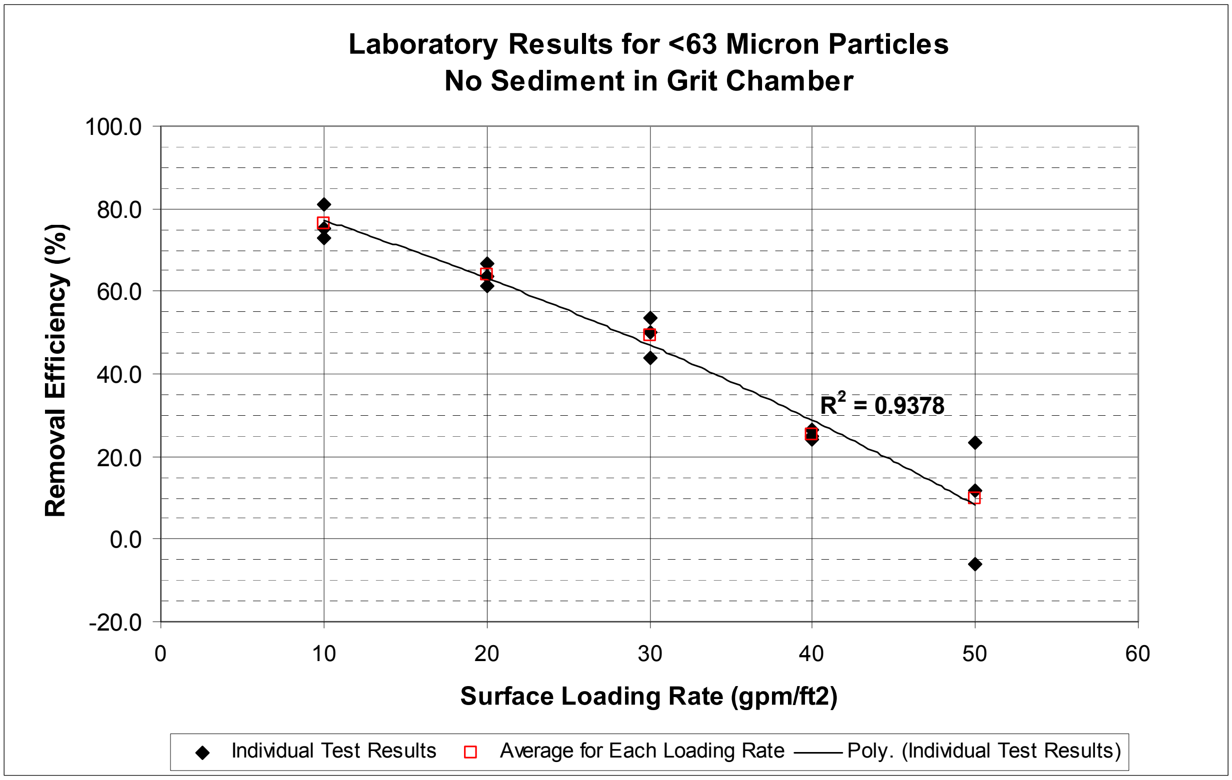

Laboratory Results for 250 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
0
10
20
30
40
50
60
70
80
90
100
110
Surface Loading Rate (gpm/sf)
$R^2$ = 0.7778
Individual Test Results for Early Tests (1-11)
Individual Test Results without Early Tests (1-11)
Average for Each Loading Rate
Poly. (Individual Test Results without Early Tests (1-11))

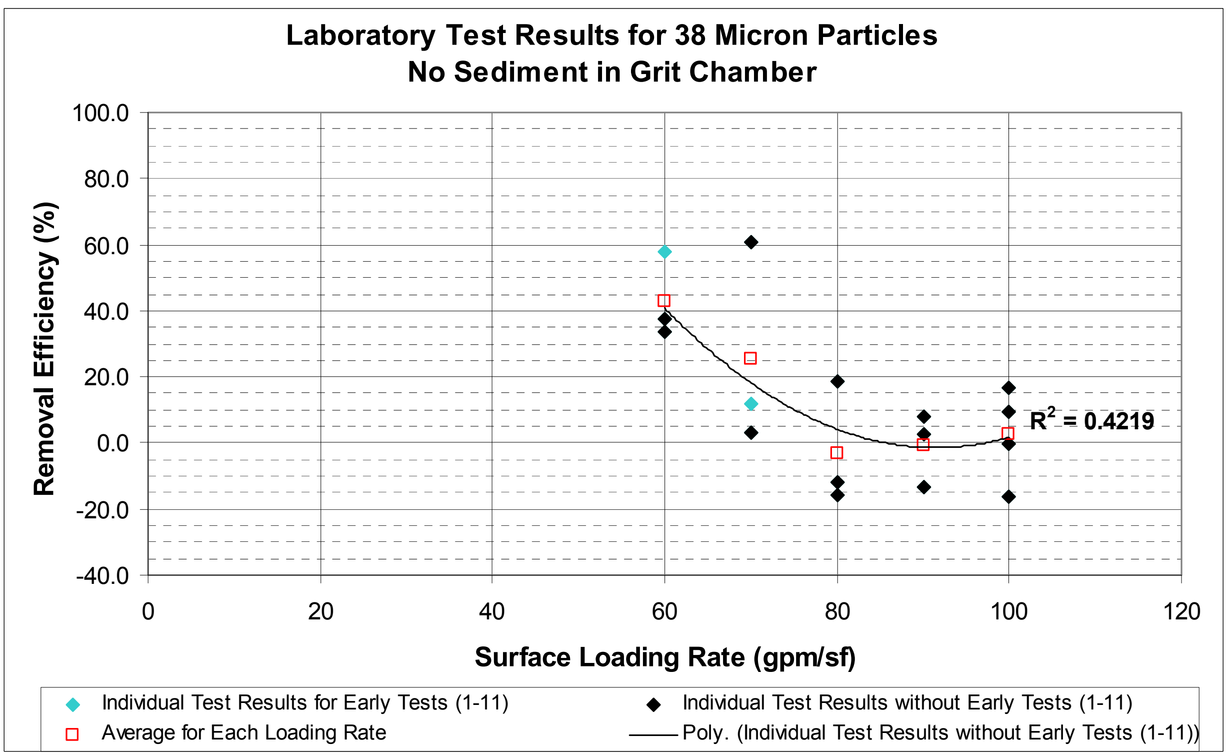

Laboratory Results for 150 Micron Particles
No Sediment in Grit Chamber
Average Removal Efficiency (%)
Surface Loading Rate (gpm/sf)
$R^2$ = 0.7342
Individual Test Results for Early Tests (1-11)
Individual Test Result without Early Tests (1-11)
Average for Each Loading Rate
Poly. (Individual Test Result without Early Tests (1-11))

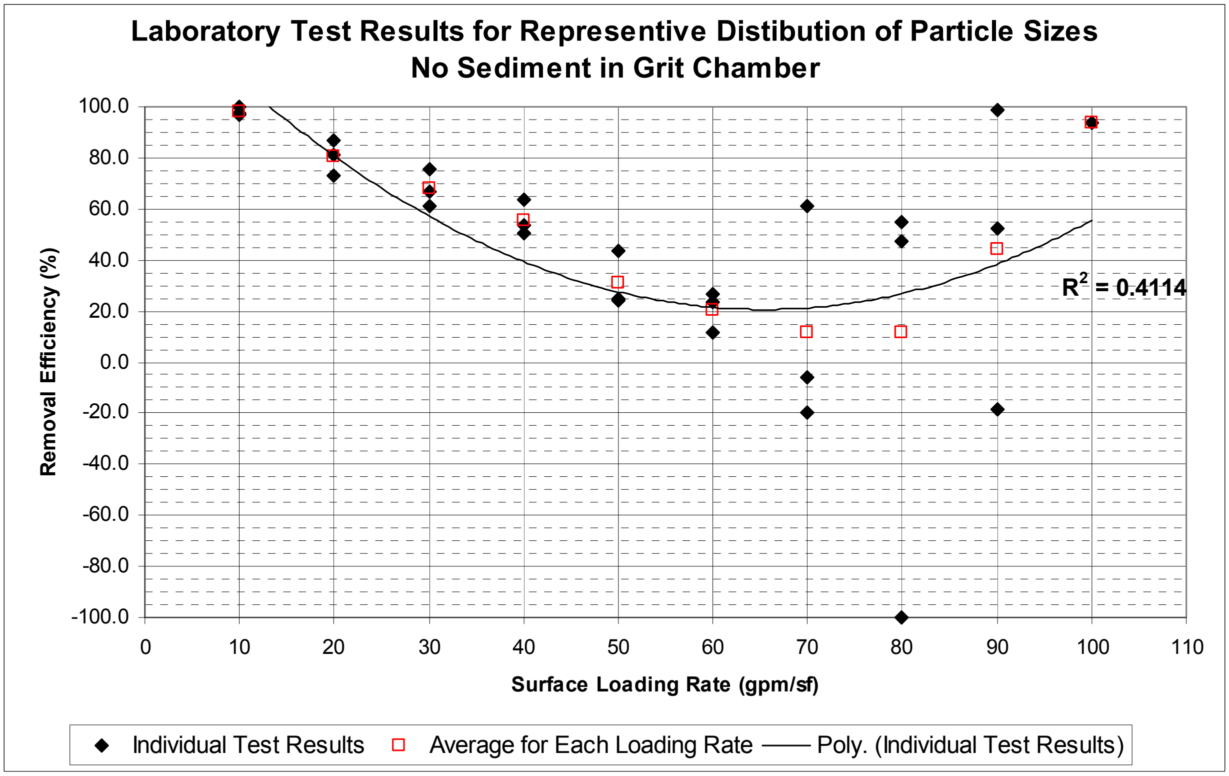

Laboratory Results for 100 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
Surface Loading Rate (gpm/sf)
$R^2$ = 0.7735
Individual Test Results for Early Tests (1-11)
Individual Test Results without Early Tests (1-11)
Average for Each Loading Rate
Poly. (Individual Test Results without Early Tests (1-11))


Laboratory Results for 75 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
0
10
20
30
40
50
60
70
80
90
100
110
Surface Loading Rate (gpm/sf)
$R^2$ = 0.6894
Individual Test Results for Early Tests (1-11)
Individual Test Results without Early Tests (1-11)
Average for Each Loading Rate
Poly. (Individual Test Results without Early Tests (1-11))

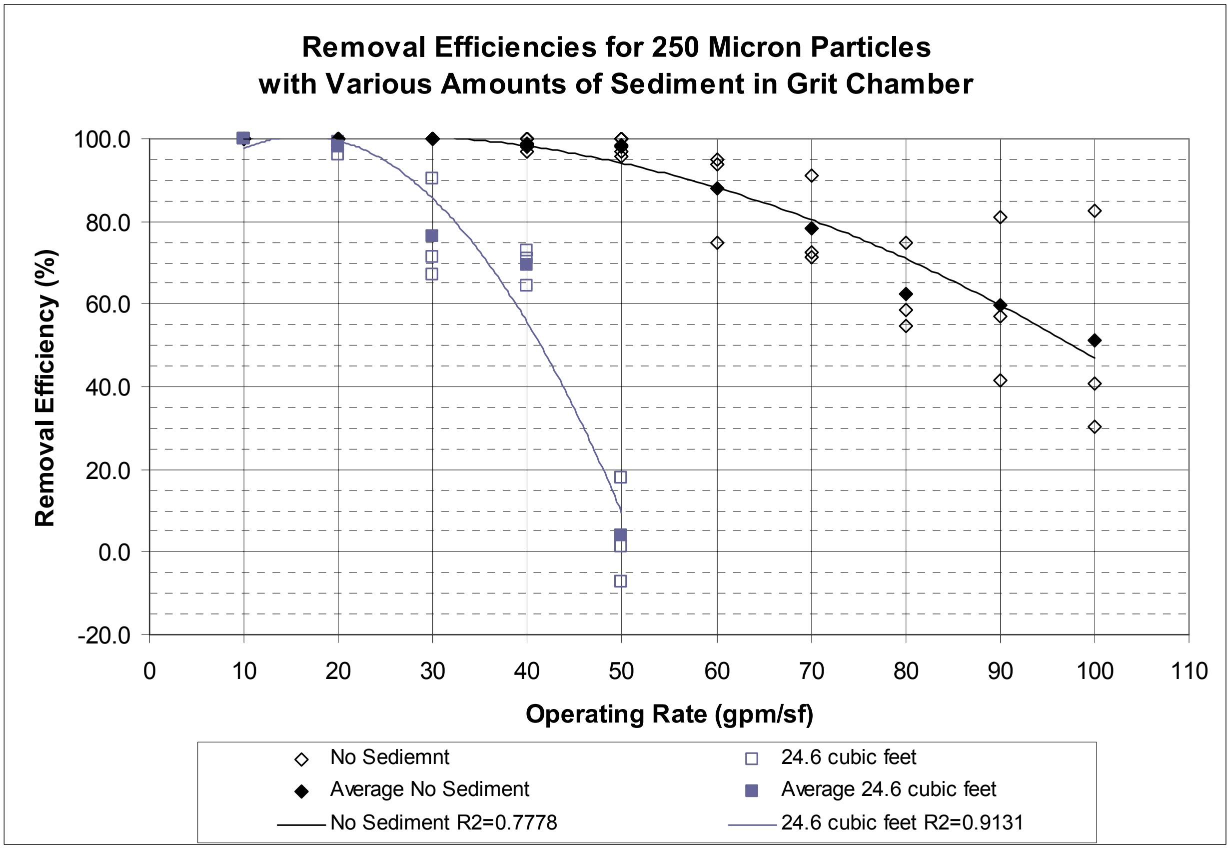

Laboratory Results for 63 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
10
20
30
40
50
60
70
80
90
100
Surface Loading Rate (gpm/sf)
$R^2$ = 0.8487
Individual Test Results
Average for Each Loading Rate
Poly. (Individual Test Results)

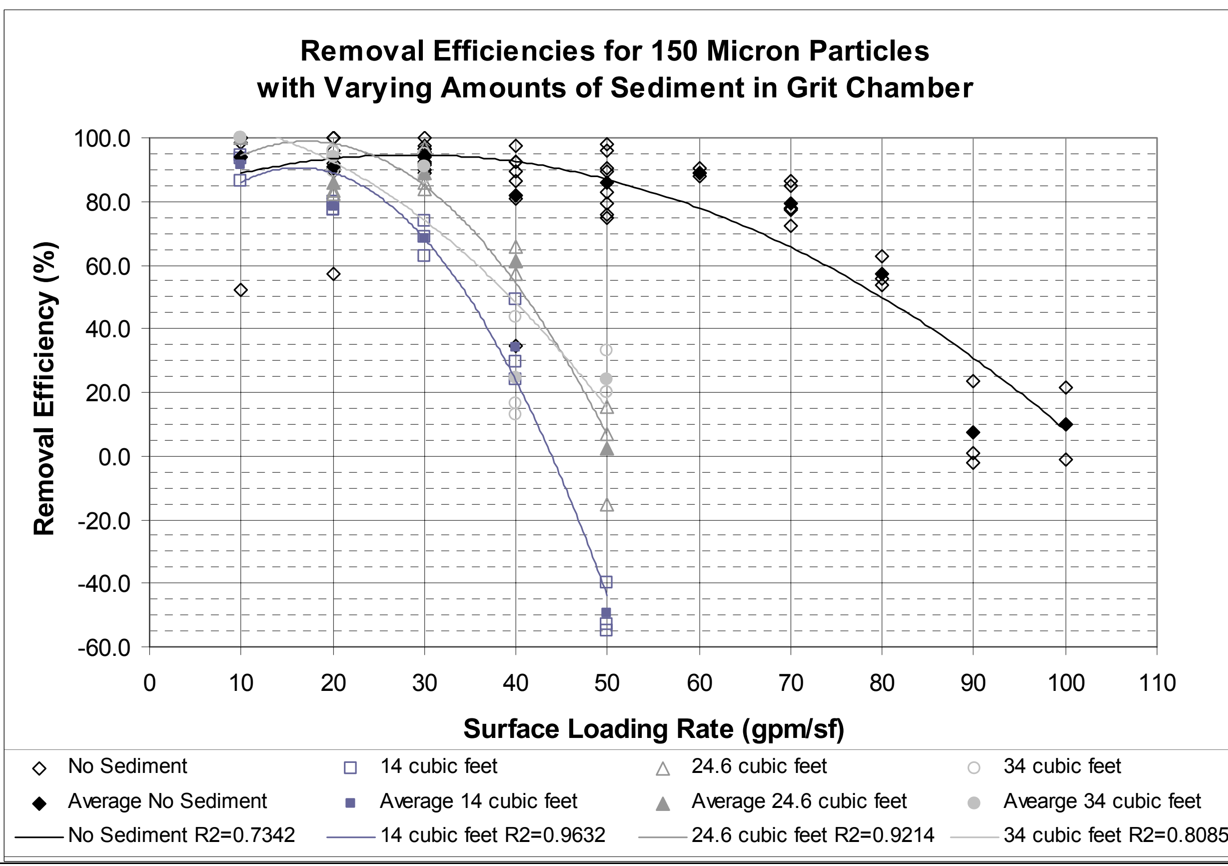

Laboratory Results for <63 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
0
10
20
30
40
50
60
$R^2$ = 0.9378
Surface Loading Rate (gpm/ft2)
Individual Test Results
Average for Each Loading Rate
Poly. (Individual Test Results)

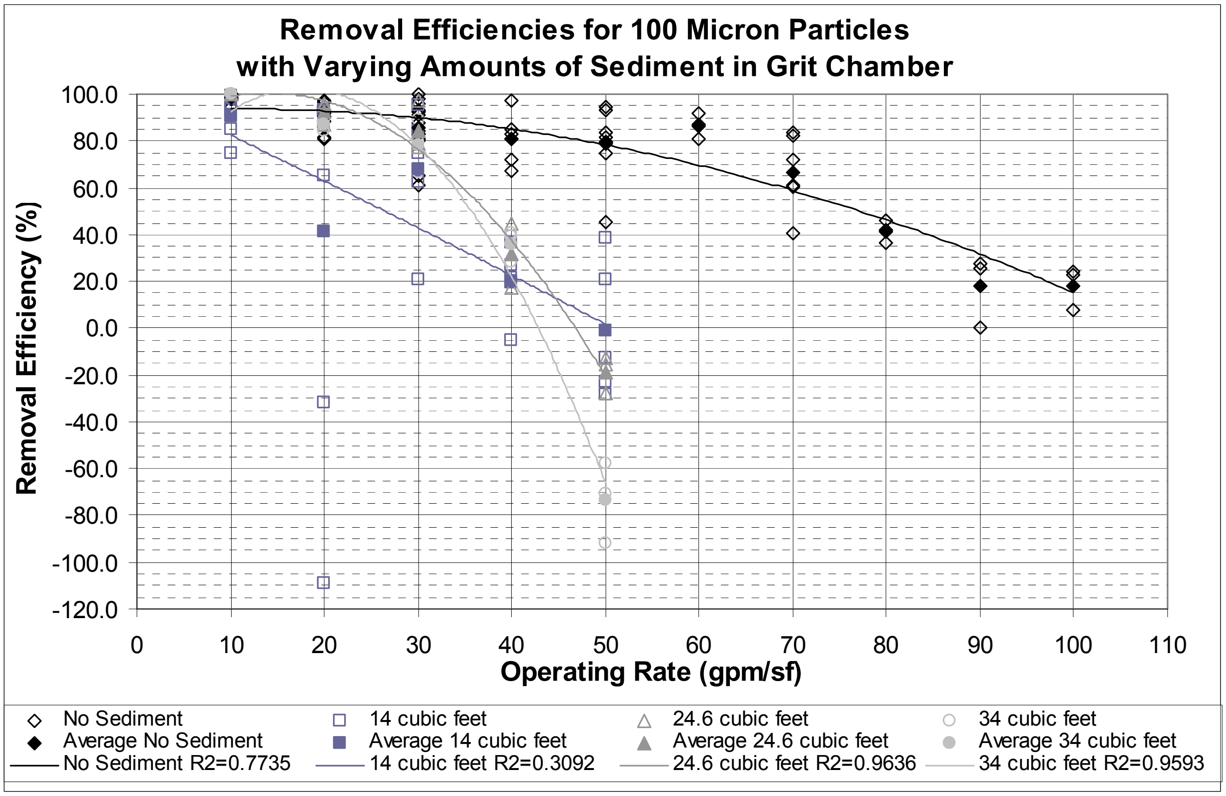

Laboratory Test Results for 38 Micron Particles
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
0
20
40
60
80
100
120
$R^2$ = 0.4219
Surface Loading Rate (gpm/sf)
Individual Test Results for Early Tests (1-11)
Individual Test Results without Early Tests (1-11)
Average for Each Loading Rate
Poly. (Individual Test Results without Early Tests (1-11))

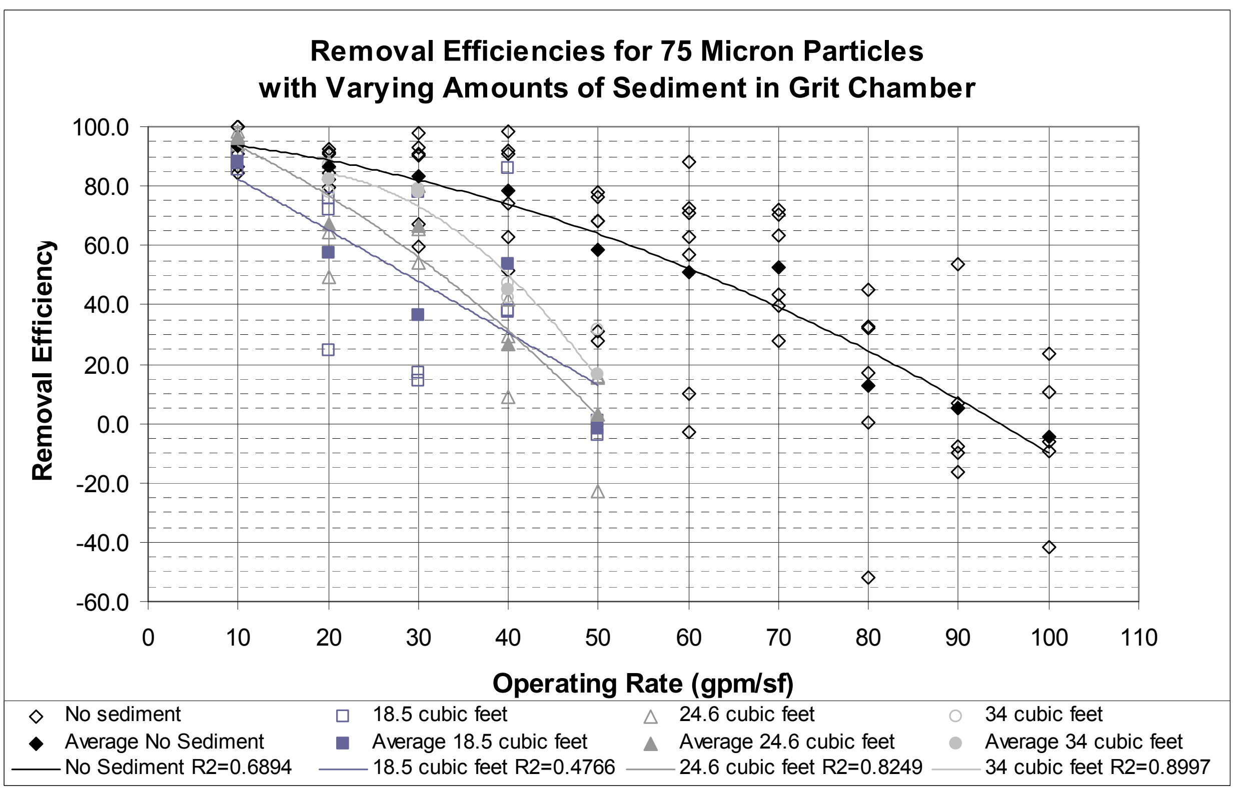

Laboratory Test Results for Representive Distibution of Particle Sizes
No Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
0
10
20
30
40
50
60
70
80
90
100
110
Surface Loading Rate (gpm/sf)
R2 = 0.4114
Individual Test Results
Average for Each Loading Rate
Poly. (Individual Test Results)

## APPENDIX B – LABORATORY TEST RESULTS FOR VARIOUS AMOUNTS OF SEDIMENT ACCUMULATED IN GRIT CHAMBER


Removal Efficiencies for 250 Micron Particles
with Various Amounts of Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
0
10
20
30
40
50
60
70
80
90
100
110
Operating Rate (gpm/sf)
No Sediemnt
24.6 cubic feet
Average No Sediment
Average 24.6 cubic feet
No Sediment R2=0.7778
24.6 cubic feet R2=0.9131


Removal Efficiencies for 150 Micron Particles
with Varying Amounts of Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
0
10
20
30
40
50
60
70
80
90
100
110
Surface Loading Rate (gpm/sf)
No Sediment
14 cubic feet
24.6 cubic feet
34 cubic feet
Average No Sediment
Average 14 cubic feet
Average 24.6 cubic feet
Avearge 34 cubic feet
No Sediment R2=0.7342
14 cubic feet R2=0.9632
24.6 cubic feet R2=0.9214
34 cubic feet R2=0.8085


Removal Efficiencies for 100 Micron Particles
with Varying Amounts of Sediment in Grit Chamber
Removal Efficiency (%)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
-120.0
0 10 20 30 40 50 60 70 80 90 100 110
Operating Rate (gpm/sf)
No Sediment
Average No Sediment
No Sediment R2=0.7735
14 cubic feet
Average 14 cubic feet
14 cubic feet R2=0.3092
24.6 cubic feet
Average 24.6 cubic feet
24.6 cubic feet R2=0.9636
34 cubic feet
Average 34 cubic feet
34 cubic feet R2=0.9593


Removal Efficiencies for 75 Micron Particles
with Varying Amounts of Sediment in Grit Chamber
Removal Efficiency
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
0 10 20 30 40 50 60 70 80 90 100 110
Operating Rate (gpm/sf)
No sediment
Average No Sediment
No Sediment R2=0.6894
18.5 cubic feet
Average 18.5 cubic feet
18.5 cubic feet R2=0.4766
24.6 cubic feet
Average 24.6 cubic feet
24.6 cubic feet R2=0.8249
34 cubic feet
Average 34 cubic feet
34 cubic feet R2=0.8997