NJCAT TECHNOLOGY VERIFICATION

Hydro International

February 2005

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1. Introduction

1.1 New Jersey Corporation for Advanced Technology (NJCAT) Program

NJCAT is a not-for-profit corporation to promote in New Jersey the retention and growth of technology-based businesses in emerging fields such as environmental and energy technologies. NJCAT provides innovators with the regulatory, commercial, technological and financial assistance required to bring their ideas to market successfully. Specifically, NJCAT functions to:

- Advance policy strategies and regulatory mechanisms to promote technology commercialization;
- Identify, evaluate, and recommend specific technologies for which the regulatory and commercialization process should be facilitated;
- Facilitate funding and commercial relationships/alliances to bring new technologies to market and new business to the state; and
- Assist in the identification of markets and applications for commercialized technologies.

The technology verification program specifically encourages collaboration between vendors and users of technology. Through this program, teams of academic and business professionals are formed to implement a comprehensive evaluation of vendor specific performance claims. Thus, suppliers have the competitive edge of an independent third party confirmation of claims.

Pursuant to N.J.S.A. 13:1D-134 et seq. (Energy and Environmental Technology Verification Program), the New Jersey Department of Environmental Protection (NJDEP) and NJCAT have established a Performance Partnership Agreement (PPA) whereby NJCAT performs the technology verification review and NJDEP certifies the net beneficial environmental effect of the technology. In addition, NJDEP/NJCAT work in conjunction to develop expedited or more efficient timeframes for review and decision-making of permits or approvals associated with the verified/certified technology.

The PPA also requires that:

- The NJDEP shall enter into reciprocal environmental technology agreements concerning the evaluation and verification protocols with the United States Environmental Protection Agency (USEPA), other local required or national environmental agencies, entities or groups in other states and New Jersey for the purpose of encouraging and permitting the reciprocal acceptance of technology data and information concerning the evaluation and verification of energy and environmental technologies; and

- The NJDEP shall work closely with the State Treasurer to include in State bid specifications, as deemed appropriate by the State Treasurer, any technology verified under the Energy and Environment Technology Verification Program.

1.2 Technology Verification Report

In August 2004, Hydro International (94 Hutchins Drive, Portland, Maine 04102) submitted a formal request for participation in the NJCAT Technology Verification Program. The request (after pre-screening by NJCAT staff personnel in accordance with the technology assessment guidelines) was accepted into the verification program. The technology proposed by Hydro International, the *Downstream Defender*®, is an Advanced Hydrodynamic Vortex Separator used for the control of sediments and their associated pollutants, oil and floatables in stormwater.

The *Downstream Defender*® has internal flow modifying members that ensure that stable flow regimes are maintained over a wide range of flows and that isolated storage zones are established for capturing material preventing the risk of re-entrainment / washout. The internal geometry, in conjunction with the flow modifying members, creates a three-dimensional flow field that is unique to the device and provides the basis for unit scaling.

This verification report covers the evaluation based upon the performance claim of the vendor, Hydro International (see Section 4). The verification report differs from typical NJCAT verification reports in that final verification of the *Downstream Defender*® (and subsequent NJDEP certification of the technology) awaits completed field testing that meets the full requirements of the Technology Acceptance and Reciprocity Partnership (TARP) – Stormwater Best Management Practice Tier II Protocol for Interstate Reciprocity for stormwater treatment technology. This verification report is intended to evaluate the *Downstream Defender*® initial performance claim for the technology based primarily on laboratory studies. This claim is expected to be modified and expanded following completion of the TARP required field-testing.

This verification project included the evaluation of assembled reports, company manuals, literature, computational fluid dynamic (CFD) modeling, and laboratory testing reports to verify that the *Downstream Defender*® meets the performance claim of Hydro International.

1.3 Technology Description

1.3.1 Technology Status

In 1990 Congress established deadlines and priorities for USEPA to require permits for discharges of stormwater that is not mixed or contaminated with household or industrial wastewater. Phase I regulations established that a NPDES (National Pollutant Discharge Elimination System) permit is required for stormwater discharge from municipalities with a separate storm sewer system that serves a population greater than 100,000 and certain defined industrial activities. To receive a NPDES permit, the municipality or specific industry has to develop a stormwater management plan and identify Best Management Practices (BMPs) for stormwater treatment and discharge. BMPs are measures, systems, processes or controls that reduce pollutants at the source to prevent the pollution of stormwater runoff discharge from the site. Phase II stormwater discharges include all discharges composed entirely of stormwater, except those specifically classified as Phase I discharge.

The nature of pollutants emanating from differing land uses is very diverse. Hydro International has developed a technology for separating and retaining floating and sinking pollutants including sediment, hydrocarbons and debris under rapid flow conditions using a hydrodynamic separator. Hydro's *Downstream Defender*® is a vertically oriented concrete cylindrical vessel with polypropylene internal components and a stainless steel support frame, designed to separate oil and sediment from stormwater. Between maintenance events, pollutants accumulate within the system and are therefore removed from the natural environment. Maintenance is performed from above by a vacuum truck and without interference from internal components.

General

Hydrodynamic Vortex Separators (HDVS) are characterized by tangential flow into a cylindrical vessel, which in turn creates a complex rotary flow regime. In comparison with conventional systems, which rely solely on 'gravity', HDVS utilize both gravity and inertial separation mechanisms to achieve higher rates of solids liquid separation and as such provide the performance equivalence of conventional systems in a considerably smaller footprint (Andoh and Smisson, 1994; and Andoh *et. al*., 2001).

The levels of pollutant removals achieved are very dependent on the nature and characteristics of the influent wastewater in terms of solids species and their settling properties. The general rule is that higher flow rates (short residence times) can be applied when the solids in the influent stream are readily settleable. For influent streams containing solids with poor settling characteristics longer residence times may be necessary to achieve the desired level of solids removals.

HDVS have been found to be generally more efficient than conventional chambers (Averill *et. al*., 1997; Arnett and Gurney, 1998). A vortex chamber tends to increase the time a particle stays in a confined space since the helical path from entrance to outlet is much longer than the straight distance between them.

High Efficiency HDVS

Although, in general, vortex separators belong to the same family of devices, different configurations have different separation efficiency characteristics (Saul *et. al*., 1993). Various configurations have evolved and are differentiated by the nature and type of internal flow modifying components and the location of inlets and outlets. The effectiveness of a given type of HDVS depends on the nature and characteristics of the rotary flow regime established and the degree to which complex swirls generated are structured and stabilized. This is a function of the internal geometry and the nature and placing of the internal components. Details of HDVS configurations and the role of internal flow modifying members are described elsewhere (Andoh and Smisson, 1994; and Andoh, 1998).

Hydro International's HDVS differ from other types of vortex separators in that the internal flow modifying components have been designed to ensure that the current generation of HDVS are highly efficient, relatively "low energy", rotary flow devices, with stable macro-flow fields over a wide range of flows and pressure drops (i.e. head loss) typically less than 4 inches at design flows. The HVDS (see Section 3) create an axial return flow above the cone region in the form of an inner helical vortex (see Figure 1). This increases the overall path-line between inlet and outlet and reduces the potential for short-circuiting. This flow regime in Hydro International's HDVS has also been found to be conducive to effective contacting for disinfection (Boner *et. al*., 1993; Alkhaddar *et. al*., 2000; and Turner *et. al*., 2000) as well as flocculation to enhance solids removals (Andoh *et. al*., 1996).

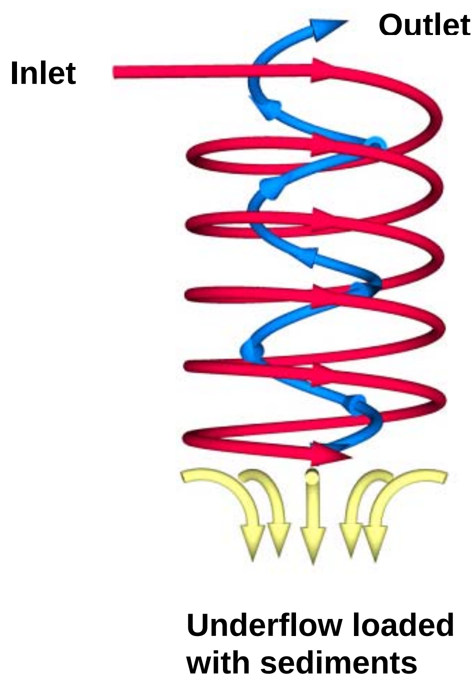

Figure 1. Simplified Flow Pattern Showing Outer and Inner Helical Flows

System Operation and Maintenance Features

The *Downstream Defender*® is unique in that the sediment and oil storage areas are outside the treatment flow path. As mentioned above, previously collected solids, oil and floatables are thereby protected from re-entrainment into the effluent during major storms or surcharge conditions. Furthermore, as sediment, floatables and oil are collected and stored over a period of several months, treatment capacities are not reduced as pollutants accumulate between clean-outs.

After a storm event, the water level in the *Downstream Defender*® drains down to the invert of the outlet pipe, keeping the unit wet. Maintaining a wet unit has two major advantages:

1. It keeps the oil and floatables stored on the water surface separate from sediment stored below the vortex chamber, providing the option for separate oil disposal, such as passive skimmers, if desired.
2. It prevents stored sediment from solidifying in the base of the unit. The clean-out procedure becomes much more difficult and labor intensive if the system allows fine sediment to dry-out and consolidate. When this occurs, clean-out crews must enter the chamber and manually remove the sediment; a labor intensive operation in a hazardous environment.

The *Downstream Defender*® has large clear openings and no internal restrictions or weirs, minimizing the risk of blockage and hydraulic losses

1.3.2 Specific Applicability

The *Downstream Defender*® is a water quality improvement device applicable for treatment of stormwater in a variety of development situations including:

- New developments and retrofits
- Construction sites
- Streets and roadways
- Parking lots
- Vehicle maintenance wash-down yards
- Industrial and commercial facilities
- Wetlands protection

1.3.3 Range of Contaminant Characteristics

The *Downstream Defender*® has been shown to capture a wide range of pollutants of concern. These include: trash and debris, TSS, sediments, and oil and grease.

1.3.4 Range of Site Characteristics

The *Downstream Defender*® is designed to accommodate a wide range of flows and volumes (Table 1). Four standard sizes are available, each designed to treat a range of flows to a specific solids removal efficiency. To meet specific performance criteria or for larger flow applications, Hydro International offers custom designed units up to forty (40) feet in diameter. The *Downstream Defender*® is a primary treatment device which requires no pretreatment. However, it can be used as a pretreatment device before detention systems, mitigating wetlands or other polishing systems.

Table 1. *Downstream Defender*® Standard Sizes

Model Number	Peak Treatment Flow[1] (cfs)	Maximum Inlet Pipe Diameter (inches)	Maximum Outlet Pipe Diameter (inches)	Head Loss at Peak Treatment Flow[2] (inches)	Continuous Oil Storage Capacity (gallons)	Spill Containment Capacity (gallons)	Sediment Storage Capacity (cubic yards)	Unit Diameter (feet)
4-FT	3.0	12	12	5	70	188	0.70	4
6-FT	8.0	18	18	8	230	634	2.10	6
8-FT	15.0	24	24	8	525	1,504	4.65	8
10-FT	25.0	30	30	10	1,025	2,937	8.70	10

NOTES:

1. Peak Treatment Flow rate is based on keeping headloss at a minimum and removal efficiencies within a desirable range. Higher flow rates are possible if lower removal efficiencies and higher headlosses are acceptable. Lower flow rates may be necessary if higher removal efficiencies and lower headlosses are desired. The Peak Treatment Flow rates listed in this table are not the flow rates verified for a specific removal efficiency in this report.
2. Headloss is defined as the difference between the top water level upstream and the top water level downstream of the unit.

1.3.5 Material Overview, Handling and Safety

A commercially or municipally owned sump-vac is used to remove captured sediment and floatables. Access ports are located in the top of the manhole. The floatables access port is above the outer annular space between the dip plate and the manhole wall, where floatables are retained. The sediment removal access port is located directly over the hollow center shaft which leads to the sediment storage facility below the vortex chamber. Floatables and oil should be removed prior to the removal of the sediment..

The frequency of the sump-vac procedure is determined in the field after installation. During the first year of operation, the unit should be inspected every six months to determine the rate of sediment and floatables accumulation. A probe can be used to determine the level of solids in the sediment storage facility. This information can then be used to establish a maintenance schedule. When sediment depth has accumulated to the specified depth, the contents should be removed by a sump-vac. In most situations, it is recommended that the units be cleaned annually. Maximum storage capacities are shown in Table 2

Table 2. *Downstream Defender*®'s Pollutant Storage Capacities and Maximum Clean-out Depths

Downstream Defender™ Pollutant Storage Capacities and Max. Clean-out Depths

Unit Diameter	Total Oil Storage	Oil Clean-out Depth	Total Sediment Storage	Sediment Clean-out Depth	Total Volume Removed
(feet)	(gal.)	(inches)	(gal.)	(inches)	(gal)
4	70	<16	141	<18	384
6	230	<23	424	<24	1239
8	525	<33	939	<30	2884
10	1050	<42	1,757	<36	5546

Notes:

1. Refer to Downstream Defender **Clean-out Detail** for measurement of depths.
2. Oil accumulation is typically much less than sediment, however, removal of oil and sediment during the same service is recommended.
2. Remove floatables first, then remove remaining volume.

Although a small portion of water is removed along with the pollutants during the clean-out process, the units are typically not completely dewatered - minimizing disposal costs. The sump vac procedure for a typical 6-ft diameter *Downstream Defender*® with one foot of sediment depth and two inches of oil and debris takes about 25 minutes and removes about 150-200 gallons of water in the process.

Solids recovered from the *Downstream Defender*® can typically be land filled or disposed of at a wastewater treatment plant. It is possible that there may be some specific land use activities that create contaminated solids, which will be captured in the system. Such material would have to be handled and disposed of in accordance with hazardous waste management requirements.

1.4 Project Description

This project included the evaluation of assembled reports, company manuals, literature, CFD simulations, and laboratory testing reports to verify that the *Downstream Defender*® meets the performance claims of Hydro International.

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2. Evaluation of the Applicant

2.1 Corporate History

The *Downstream Defender*® is part of a family of Hydrodynamic Vortex Separators designed, manufactured and supplied by Hydro International which have evolved over the last 40 years from pioneering work undertaken by Bernard Smisson. The history of Hydrodynamic Vortex Separators (HDVS) dates back to the early 1960s when Bernard Smisson built and tested the very first full-scale vortex type combined sewer overflow (CSO) unit at Bristol in the U.K. This first generation separator was found to be effective in retaining 70% of the pollution load (Smisson, 1967).

Smisson's pioneering work was followed by the development in the 1970s, of the USEPA Swirl Concentrator - a second generation HDVS, by the American Water Works Association and EPA, with Mr. Smisson acting as a consultant (Sullivan *et. al*., 1972, 1982). A third generation of HDVS was subsequently developed in the UK in the early 1980s, with Bernard Smisson's assistance, to overcome identified shortcomings with the EPA Swirl Concentrator, particularly to reduce shoaling of solids on the base, to reduce headloss at high flows and to further improve performance. This configuration was subsequently patented and commercialized with the trade name Storm King® Overflow.

It should be noted that CSO/SSO typically include sanitary solids, along with other pollutants, that cannot be stored for a length of time. Therefore, when used as a CSO/SSO treatment device the HDVS has an underflow component that returns concentrated solids to the sanitary collection system to be conveyed to a wastewater treatment plant for further processing.

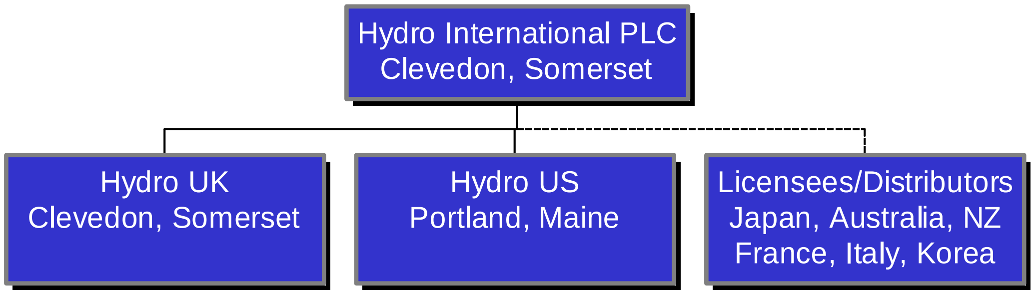
Further work in the 1990s in the USA, led to the adaptation of the third generation HDVS for stormwater treatment in the form of the *Downstream Defender*®. This new configuration (also patented) differs from the application of the HDVS as a CSO or SSO treatment device. Unlike CSO / SSO applications, pollutants removed from stormwater runoff are typically stored within a treatment device for several months to be removed periodically. The *Downstream Defender*® is configured with a sump to provide an isolated storage zone for the collection of separated sediments and their associated pollutants.

Since their development and subsequent commercialization in the 1980s and 1990s, Hydro International's HDVS have been the subject of numerous independent performance evaluations in Europe, North America and Japan (Hedges *et. al.*, 1992; Hedges, 1993; Boner *et. al*., 1992; Averill *et. al*., 1997; Arnett and Gurney, 1998; Turner, *et. al.*, 2000; Pratt, 2000 and Okamoto *et. al*., 2002). These evaluations have all confirmed the efficacy of the hydrodynamic separation phenomenon occurring in the separators.

A number of these included an assessment of influent solids and their settling characteristics, which in turn highlighted the relevance and importance of wastewater characterization (especially settling velocity distributions) in assessing device performance (Tyack *et. al*., 1992; Andoh and Smisson, 1994).

2.2 Organization and Management

An overview of the Company (Group) Structure is detailed below.



The Group has a relatively small employee base of approximately 60 employees. In addition, there is a strong network of independent agents (particularly in North America), distributorship agreements with key players in the market and selected licensing agreements.

2.3 Operating Experience with respect to the Proposed Technology

To date over 2,000 of Hydro International's HDVS have been installed worldwide for stormwater, combined sewage and wastewater treatment with device configurations adapted to the specific application area.

2.4 Patents

Hydro International holds the following international patents in reference to the *Downstream Defender®*:

Patent No. 5188238 - USA
Patent No. 2019390 - Canada
Patent No. 2233255 - UK

2.5 Technical Resources, Staff and Capital Equipment

For over 25 years, Hydro International has been working in partnership with their customers to ensure successful solutions throughout the design and installation process and has developed considerable expertise in the implementation of sustainable drainage systems. These systems include treatment, storage and flow controls.

Technical assistance is provided by an engineering staff at Hydro International's U.S. headquarters in Portland, Maine in addition to local Hydro International representatives in the State of New Jersey. Custom sizing and drawings are available for a given project.

Hydro International maintains a full-scale test facility in Portland, Maine as described in Section 5.2. To ensure results are accurate and unbiased, Hydro International utilizes full-scale, state-of-the-art testing technology both in-house and through independent centers of excellence including the following:

Academic Institutions
Federal and State Regulatory Agencies
Research Institutions
Consulting Engineers
Municipalities

In addition to field testing and external validation, Hydro International has developed considerable expertise in Computational Fluid Dynamics (CFD) simulation. This ability to mathematically model flow fields and assess device characteristics is enabling rapid prototyping, thereby shortening product development cycles and improving the quality of outputs.

Hydro International promote the benefits of sustainable strategies to the wider water environmental community. In addition to contributing to industry events, the company hosts educational conferences, which encourage knowledge sharing, dialogue and provides networking opportunities between Environmental Regulators, Municipalities, Engineers and Academic Institutions.

3. Treatment System Description

3.1 Components

The *Downstream Defender*® (Figures 2 and 3) has no moving parts and no external power requirements. It consists of a concrete cylindrical vessel with polypropylene internal components and a stainless steel support frame. The concrete vessel is a standard manhole, installed below grade, with a tangential inlet pipe and an overflow pipe which connect the treatment unit directly to the storm sewer. Two ports at ground level provide access for inspection and clean-out of stored floatables and sediment. The internal components consist of two concentric hollow cylinders (the dip plate and center shaft), an inverted cone (the center cone), a benching skirt and a floatables lid. The purpose of the internal components is two-fold:

- The components act as flow modifying members to effect a complex but stable flow regime through the device; which maximizes solids separation and prevents short circuiting.
- The components create isolated zones for pollutant capture and storage.

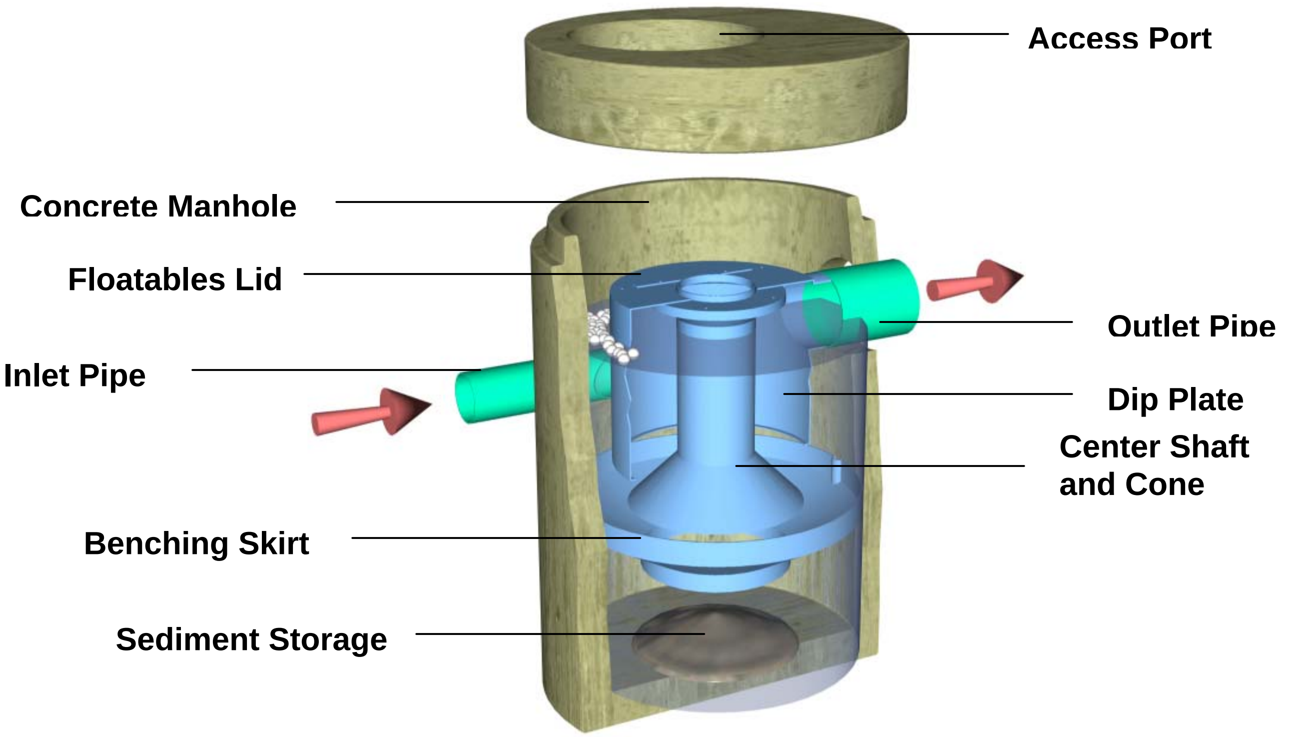


Figure 2. Cutaway View of the *Downstream Defender*®

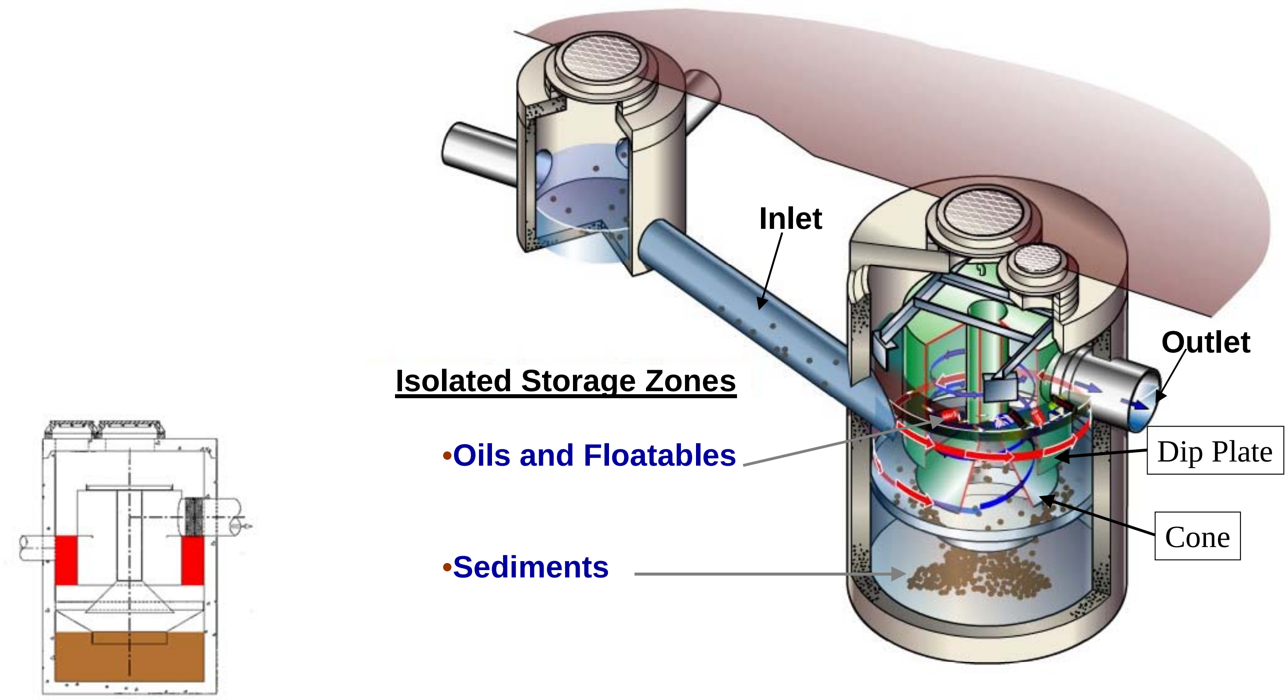


Figure 3. *Downstream Defender*® Pollutant Storage Zones

3.2 System Dynamics

The *Downstream Defender®* is self-activating and operates on simple fluid hydraulics. The geometry of the internal components and placement of the inlet and outlet pipes are designed to direct the flow in a pre-determined path through the vessel as described below.

Stormwater is introduced tangentially into the side of the vessel and initially spirals around the perimeter, in the outer annular space (between the dip plate cylinder and manhole wall), where oil and floatables rise to the water surface and are trapped. As the flow continues to rotate about the vertical axis, it travels down towards the bottom of the dip plate. Sediment is directed toward the center and base of the vessel where it is collected in the sediment storage facility, beneath the vortex chamber. The center cone protects stored sediment and redirects the main flow upwards and inwards. Flow passes under the dip plate and up through the inner annular space, inside the dip plate (between the dip plate and center shaft cylinders), as a narrower spiraling column rotating at a slower velocity than the outer downward flows. By the time the flow reaches the top of the vessel, it is virtually free of solids and is discharged from the inner annular space, through the outlet pipe.

The dip plate and center shaft cylinders are suspended from the underside of a component support frame. This dip plate serves two purposes:

- It locates the shear zone, the interface between the outer downward circulation and the inner upward circulation where a marked difference in velocity encourages solids separation, and
- It establishes a zone between it and the outer wall where floatables, oil and grease are captured and retained after a storm.

The floatables lid covers the inner annular space between the dip plate and center shaft. It separates oil and floatables stored in the outer annular space, between the dip plate and the manhole wall, from the treated effluent in the inner annular space.

3.3 Specifications

The *Downstream Defender®* can easily be custom sized to meet specific performance requirements. Headloss through the unit, at design flow, is typically less than 12 inches. At lower flows, the removal efficiencies are enhanced and headlosses decrease. To meet specific performance criteria or for larger flow applications, Hydro offers custom designed units up to forty (40) feet in diameter.

3.4 Installation

The unit should be installed in a location that is easily accessible for the maintenance vehicle, preferably in a flat area close to a roadway or parking area.

The *Downstream Defender*® is delivered to the site completely fabricated, ready to be installed into the excavated hole and connected to the inlet and outlet piping. It is compact and can fit within an excavation trench guard. Larger units are delivered to the site in component form for final assembly at the job site. Installation time for a 6 foot unit is typically 1½ hours.

4. Technical Performance Claim

Claim: The Hydro International *Downstream Defender*®, sized at a hydraulic loading rate of 20 gpm/ft^3 has been shown to have a 70% solids mass removal efficiency (as per NJDEP treatment efficiency calculation methodology) for F-95 sand with an average influent concentration of 240 mg/l, an average d_{50} particle size of 120 microns and zero initial sediment loading in laboratory studies using simulated storm water.

5. Technical System Performance

5.1 Indirect Testing vs. Direct Testing

5.1.1 Indirect Testing

Field-testing normally involves taking multiple samples from the influent and effluent streams to determine solids concentrations. The concentration of solids contained in the effluent is compared to the concentration of solids contained in the influent to indirectly determine the solids removal efficiency of the device. The actual mass of material captured by the unit is not measured. This method of indirect testing, while the only practical method available in the field, produces unreliable results due to the sampling method and the various assumptions made (see bullets below).

- Samples taken from a rapidly flowing influent and effluent stream may not be truly representative. The assumption made is that the solids content of the flow stream is consistent from one sample to the next. In reality, this assumption is not always valid.

- The sampling location can have a bearing on the results. Sampling sediment and sand particles is very difficult, as stratification tends to occur within the flow stream. Heavier particles tend to travel in the bottom of the pipe or channel while finer particles are carried higher in the water column.

- Statistically, small volume samples taken from a total flow, as when taking samples from the effluent stream, provide opportunity for compounding errors.

- Small-bore tubes used in automated samplers do not collect heavier sediments and large particles.

- In the case of laboratory testing, variations in background solids already in the feed water can impact the results.

5.1.2 Direct Testing

In contrast to the indirect testing method, Hydro International in its laboratory testing uses a direct method to determine the removal efficiency of the *Downstream Defender* ®. The mass of solids captured by the unit is collected and compared to the mass fed to the unit to directly measure the removal efficiency. Hydro International has set up a full-scale *Downstream Defender*® testing facility at its location in Portland, Maine. This comprehensive facility allows testing to be performed under controlled conditions and is equipped with an underflow collection tank. The whole of the underflow is collected to determine the quantity of solids captured which, when compared with the known quantity added to the influent, provides a direct method for measurement of removal efficiency. Experience has shown that direct testing allows easier closing of the solids mass balance. By capturing the whole of the underflow, any inaccuracies inherent in indirect testing (influent and effluent sampling) are avoided.

5.2 The *Downstream Defender*® Test Facility Description

The Hydro test facility (Figures 4, 5, 6) consists of a 23,300-gallon clean water storage reservoir equipped with a Flygt submersible pump to provide feed water. The test unit is a standard 4-ft diameter *Downstream Defender*® with an 8-inch diameter inlet and a 12-inch diameter outlet. The *Downstream Defender*® is connected to the pump delivery with 8-inch diameter PVC pipe-work that incorporates clear standpipes. For accurate flow control, the delivery line is fitted with a Hershey VP-820 gearbox butterfly valve and the pump is controlled by a variable frequency drive. A bypass line directs excess flow back to the reservoir. The overflow from the *Downstream Defender*® is returned to the reservoir for re-circulation via the 12-inch diameter PVC pipe.

An ISCO UniMag Magnetic Flowmeter is located in the 8-inch diameter inlet piping upstream from the inlet to the *Downstream Defender*® test unit for accurate flow readings.

A 3-inch diameter underflow pipe connects the sediment storage area of the *Downstream Defender*® test unit to an underflow collection tank. At the end of each test, the underflow valve is opened and the unit is drained down. Most of the captured material remains in the sediment storage area. A clean-out port at the base of the *Downstream Defender*® allows for rinsing and sediment collection. During drain down, some material is swept into the underflow collection tank equipped with a weir wall and two baffles for additional sediment collection.

A 6-inch diameter standpipe is provided in the delivery line approximately 15 feet from the *Downstream Defender*® inlet for introduction of the feed sediment. Alternatively, material may be introduced into the influent line through a stand pipe located approximately 2.5 feet from the *Downstream Defender*® inlet.

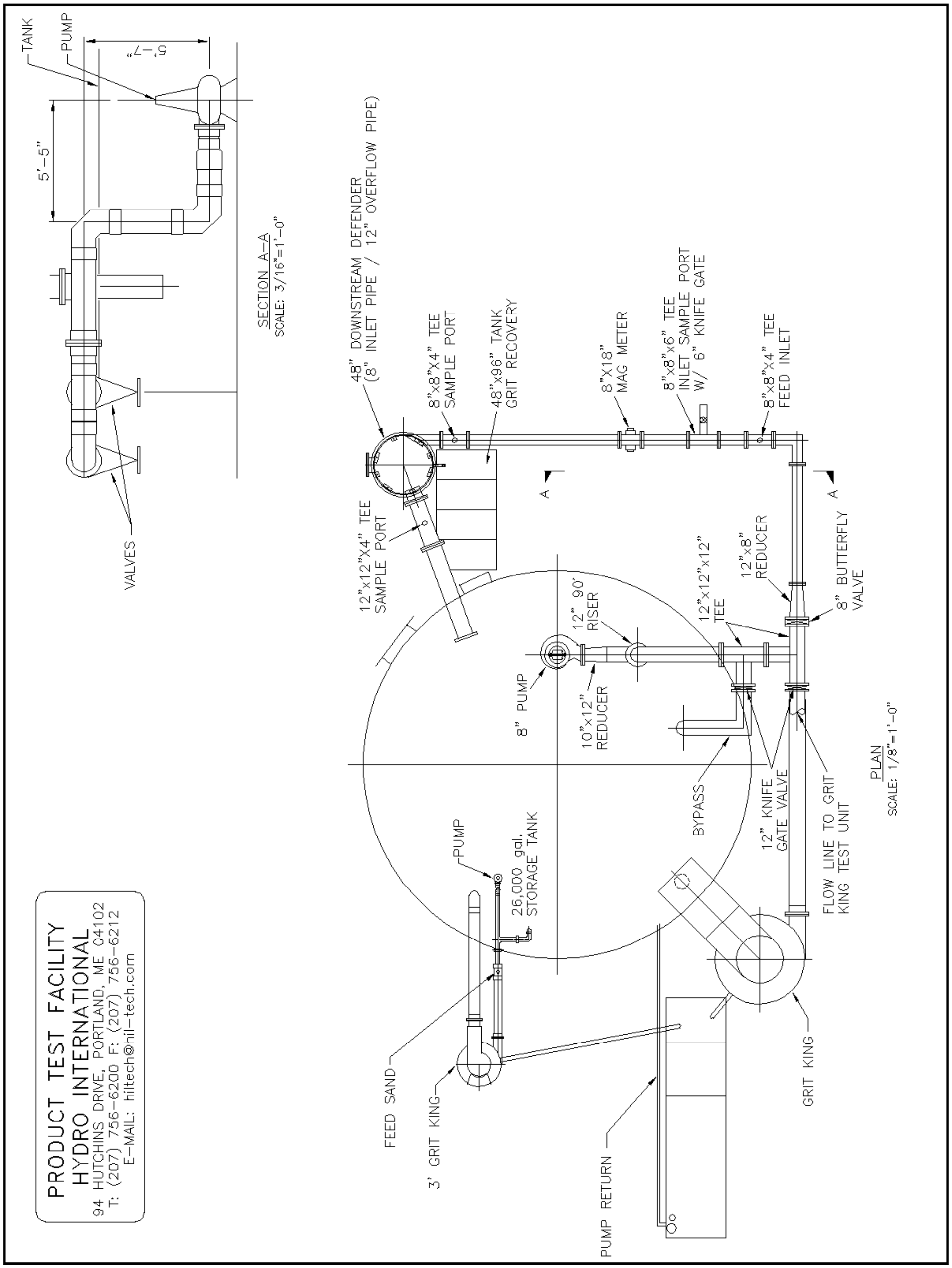


Figure 4. Test Facility General Arrangement

Figure 5. Photos of Test Facility

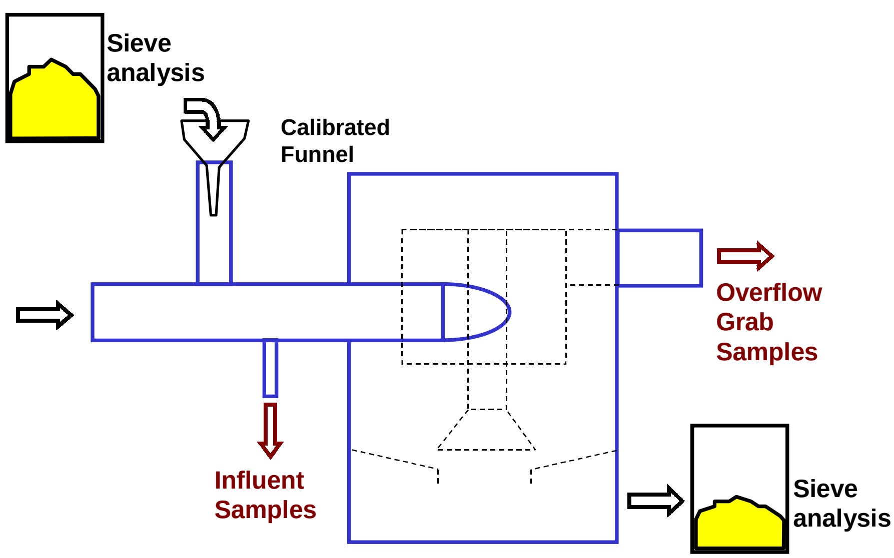


Figure 6. Schematic of Typical Test Set-up Highlighting both the "Direct" and "Indirect" Test Methods

5.3 Testing Criteria

5.3.1 Flow Rate

The flow rate to the 4.0-foot diameter *Downstream Defender*® can be adjusted from 0-1930 gpm (0.0-4.3 cfs).

5.3.2 Sediment Loading

Sediment (sand) loading for testing is typically based on an average target concentration of 300 mg/l. Ideally, the bulk influent feed weight should be between 30-50 pounds, although this may vary depending on the material being tested.

5.3.3 Influent Feed Sand Gradation

The feed sand is blended using clean, dry, industry standard silica sand. Feed sands of different grades are available and selected to best represent the sediment likely to be encountered at a project location.

5.4 Testing Procedure

5.4.1 Grain Size Distribution

Particle size analysis is performed on each blend to ensure that it conforms to the target gradation. Blends that are composed primarily of fine and medium sand are tested according to ASTM C136 (AASHTO T27) – Sieve Analysis of Fine and Coarse Aggregates. If a blend has significant quantities of material smaller than 75 microns (#200 sieve) a washed gradation is performed according to ASTM C117 (AASHTO T11). If fines dominate a blend, the particle size distribution is determined by performing a hydrometer analysis - ASTM D422 (AASHTO T88).

5.4.2 Performance Testing

The following procedure is used:

1. Accurately weigh out a bulk sample of the influent feed sand. Ideally, 30-50 lbs should be used for fine to medium sand.
2. Calculate the sediment feed rate necessary to deliver an average concentration of 300 mg/l to the treatment unit. The calculation is based on the mass of sediment fed per unit time (either dry feed or slurry feed) and the flow rate into the treatment unit.
3. Start the submersible pump and allow it to run until the *Downstream Defender*® overflows to the reservoir and the flow rate stabilizes. The flow rate can be adjusted using the inlet valve, valved bypass and the VFD pump controller. Allow the flow to stabilize.
4. Start the stopwatch as begin feeding the influent feed sand into the 6-inch diameter standpipe in the *Downstream Defender*® line at a constant rate. The method of feeding the material is

dependent on how well the material flows. Fine and medium sands may be fed with a calibrated funnel. Gradations dominated by fines, may not flow well and will have to be fed as a slurry using a peristaltic pump.

5. While the sand is being fed, record the flow rate at regular intervals (these records will be used to calculate an average flow rate).
6. Stop the stopwatch when all the sediment is delivered to the influent line.
7. Allow the flow to continue for five minutes after completion of sand addition.
8. Close the valve in the influent feed line.
9. Stop the pump.
10. Drain the *Downstream Defender*® unit through the underflow line into the underflow collection tank.
11. When the *Downstream Defender*® is completely empty, close the underflow valve and restart the submersible pump. Fill the *Downstream Defender*® with water up to the inlet to wash out any sand residue left in the system.
12. Let the sediment settle and drain the *Downstream Defender*® into the underflow collection tank again.
13. Repeat steps 11 and 12 for a total of three times.
14. Inspect the inside of the *Downstream Defender*® and collect any sand it may contain. Scoop sand into drying containers. Wet vacuum the remainder of the sediment from the sump and decant into drying containers.
15. Using a small submersible pump, decant the contents of the underflow tank and collect any sand with the wet vacuum.
16. Dry the sand in the oven at a temperature of 105°C until dry.
17. Weigh the collected sand for comparison with the influent sand weight to obtain a total solids removal efficiency.
18. By accepted methods, obtain a representative sample from collected sediment that is thoroughly blended. For fine to medium sand, usually 1 lb. is an acceptable sample size. Ensure that the sample is sized so that it will not overload the sieves.
19. Perform a sieve analysis on the collected sediment for comparison to the feed sand gradation.
20. When the underflow sample has been analyzed, the performance will be determined as follows:

Removal efficiency of total solids = $\dfrac{weight\ \ of\ \ captured\ \ sand}{weight\ \ of\ \ feed\ \ sand} x\,100$

Removal Efficiency in each particle size range = $\dfrac{weight\ of\ captured\ sand\ on\ each\ sieve}{weight\ of\ feed\ sand\ on\ each\ sieve} x\,100$

Removal Efficiency down to x microns = $\dfrac{weight\ of\ captured\ sand\ greater\ than\ x\ microns}{weight\ of\ feed\ sand\ greater\ than\ x\ microns} x\,100$

5.5 Verification Procedures

All the data provided to NJCAT were reviewed to fully understand the capabilities of the *Downstream Defender*®. To verify Hydro International's claim, the *Downstream Defender*® laboratory data were reviewed and compared to the draft NJDEP TSS laboratory testing procedure.

Claim: The Hydro International *Downstream Defender*®, sized at a hydraulic loading rate of 20 gpm/ft^3 has been shown to have a 70% solids mass removal efficiency (as per NJDEP treatment efficiency calculation methodology) for F-95 sand with an average influent concentration of 240 mg/l, an average d_{50} particle size of 120 microns and zero initial sediment loading in laboratory studies using simulated storm water.

5.5.1 NJDEP Recommended TSS Laboratory Testing Procedure

The NJDEP has prepared a draft TSS laboratory testing procedure (Patel 2003) to help guide vendors as they prepare to test their stormwater treatment systems prior to applying for NJCAT verification. The testing procedure has three components:

1. Particle size distribution
2. Full scale laboratory testing requirements
3. Measuring treatment efficiency

1. <u>Particle size distribution:</u>

The following particle size distribution will be utilized to evaluate a manufactured treatment system (See Table 3) using a natural/commercial soil representing United States Department of Agriculture (USDA) definition of a sandy loam material. This hypothetical distribution was selected as it represents the various particles that would be associated with typical stormwater runoff from a post construction site.

2. <u>Full Scale lab test requirements</u>
    A. At a minimum, complete a total of 15 test runs including three (3) tests each at a constant flow rate of 25, 50, 75, 100, and 125 percent of the treatment flow rate. These tests should be operated with initial sediment loading of 50% of the unit's capture capacity.
    B. The three tests for each treatment flow rate will be conducted for influent concentrations of 100, 200, and 300 mg/L.
    C. For an online system, complete two tests at the maximum hydraulic operating rate. Utilizing clean water, the tests will be operated with initial sediment loading at 50% and 100% of the unit's capture capacity. These tests will be utilized to check the potential for TSS re-suspension and washout.
    D. The test runs should be conducted at a temperature between 73-79 degrees Fahrenheit (°F) or colder.

3. Measuring treatment efficiency
    A. Calculate the individual removal efficiency for the 15 test runs.
    B. Average the three test runs for each operating rate.
    C. The average percent removal efficiency will then be multiplied by a specified weight factor (See Table 4) for that particular operating rate.
    D. The results of the 5 numbers will then be summed to obtain the theoretical annual TSS load removal efficiency of the system.

Table 3. NJDEP Particle Size Distribution

Particle Size (microns)	Sandy loam (percent by mass)
500-1,000 (coarse sand)	5.0
250-500 (medium sand)	5.0
100-250 (fine sand)	30.0
50-100 (very fine sand)	15.0
2-50 (silt)	(8-50 µm, 25%) (2-8 µm, 15%)*
1-2 (clay)	5.0

Notes:
1. Recommended density of particles ≤2.65 g/cm3

*The 8 µm diameter is the boundary between very fine silt and fine silt according to the definition of American Geophysical Union. The reference for this division/classification is: Lane, E. W., et al. (1947). "Report of the Subcommittee on Sediment Terminology," Transactions of the American Geophysical Union, Vol. 28, No. 6, pp. 936-938.

Table 4. NJDEP Weight Factors for different Treatment Operating Rates

Treatment operating rate	Weight factor
25%	.25
50%	.30
75%	.20
100%	.15
125%	.10

Notes:
Weight factors were based upon the average annual distribution of runoff volumes in New Jersey and the assumed similarity with the distribution of runoff peaks. This runoff volume distribution was based upon accepted computation methods for small storm hydrology and a statistical analysis of 52 years of daily rainfall data at 92 rainfall gages.

5.5.2 Laboratory Testing Results

Hydro International submitted laboratory data that had been obtained prior to the NJDEP test protocol development. While the data they submitted was not in accordance with the protocol it was still deemed to be sufficient to determine and verify a laboratory removal claim. The results of laboratory studies are shown in Table 5. The NJDEP weighted solids removal efficiency is shown in Table 6.

Table 5. Laboratory Testing Results for 4-ft Diameter *Downstream Defender*®

Run No.[1]	**Flow Rate** (gpm)	**Run Time** (secs)	**Feed Sand Mass**[2] (lbs)	**Surface Water Loading Rate**[3] (gpm/ft^2)	**Volumetric Water Loading Rate**[4] (gpm/ft^3)	**Sand Loading Rate**[5] (mg/L)	**Underflow Mass Recovered** (lbs)	**Total Removal Efficiency**[6] (%)
1	100	1369	4	7.96	3.98	210.1	3.918	97.95
2	200	821	6	15.92	7.96	262.7	5.583	93.05
3	400	527	8	31.83	15.92	272.9	4.221	52.76
4	500	541	8	39.79	19.89	212.7	3.304	41.30
5	600	488	10	47.75	23.87	245.6	3.652	36.52
6	800	606	12	63.66	31.83	178.0	3.382	28.18
7	900	399	14	71.62	35.81	280.3	3.588	25.63
8	1000	425	14	79.58	39.79	236.9	3.450	24.64

[1]Test Period: June 18 – 22, 2001
[2]Sand Type: F-95
[3]Unit Diameter = 4 ft, Surface Area = πr^2 = 12.6 ft^2, where r is the radius of the unit.
[4]Treatment Volume = $\pi r^2 h$ = 25.1 ft^3, where r is the radius of the unit, h is the distance between top of sloping part of the benching skirt and the invert of the outlet pipe and is equal to r.
[5]Calculated from the feed sand mass and the feed water volume.
[6]Calculated from the feed sand mass and the underflow mass recovered.

Table 6. Weighted Solids Removal Performance

Percent of Design Operating Rate	Loading Rate (gpm/ft^3)	Removal Efficiency[1] (%)	Weight Factor	Weighted Efficiency (%)
25%	5	96.55	.25	24.14
50%	10	82.72	.30	24.82
75%	15	57.42	.20	11.48
100%	20	41.17	.15	6.18
125%	25	35.34	.10	3.53
			Total	70.15%

[1]Linearly interpolated from the two adjacent laboratory data points in Table 5.

The F-95 sand with an average particle size (d_{50}) of 120 microns was used during the laboratory tests. The particle size distribution (PSD) of the F-95 sand is shown in Figure 7.

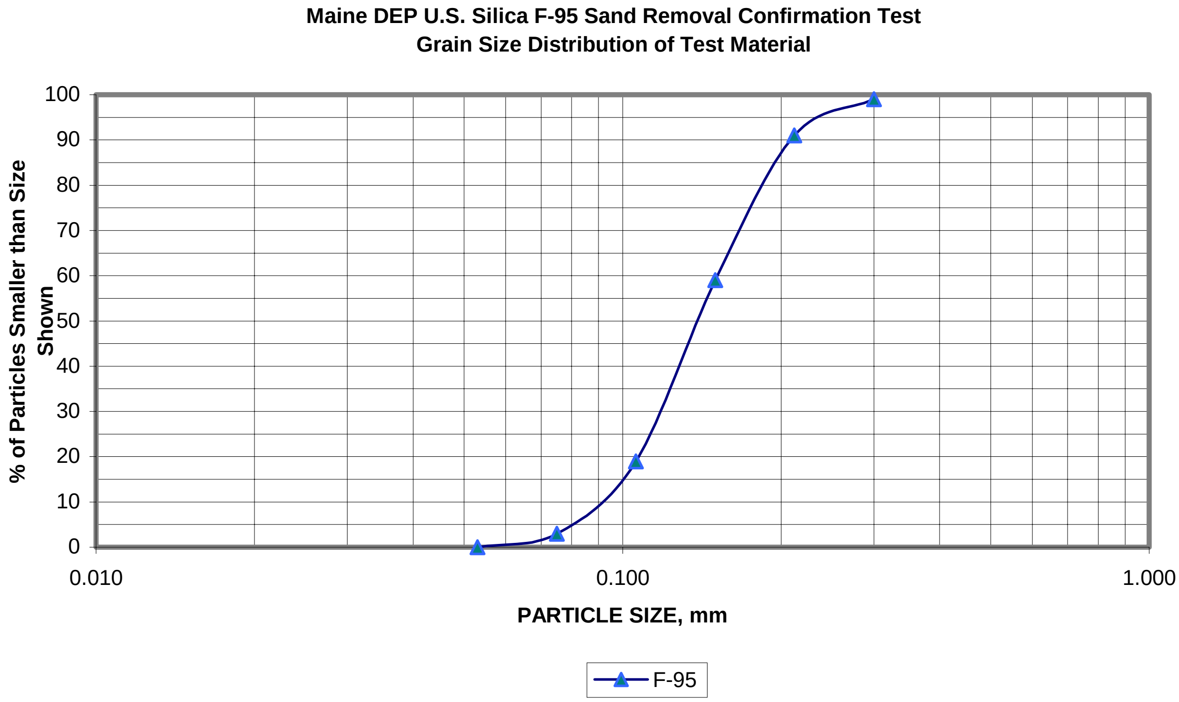


Figure 7. Particle Size Distribution of U.S. Silica F-95 Sand Used in the Laboratory Tests

The removal efficiency for a particular individual loading rate (Table 6) was linearly interpolated from the two adjacent points of data (Table 5) obtained from the laboratory tests. The fitting of all the data points with a pre-determined form of function, such as logarithmic or power function, did not yield a weighted removal efficiency significantly different from that obtained from the piece-wise linear interpolation (less than 5 % relative difference) and, more importantly, the fitted curves did not approach 100% solids removal at low flow rates.

A confirmation test was conducted and witnessed by the Maine Department of Environmental Protection on September 20, 2001(Dennis, 2001). Flow for the six runs varied from 611 gpm to 644 gpm with a mean of 628 gpm (25 gpm/ft^3). Solids contents in the water samples were analyzed using ASTM's Suspended Sediment Concentration method. Inflow concentrations ranged from 190 mg/l to 289.3 mg/l. Outflow concentrations ranged from 17.4 mg/L to 42.1 mg/L. Background concentration ranged between 5.3 and 9.3 mg/L. The removal efficiencies indicated by inflow/outflow pairs ranged from 82.1% up to 92.7%, with a mean 86.0%. When adjusted for recycled background concentrations, efficiencies were slightly higher, from 84.6% to 95.8% with a mean of 88.9%. It should be noted that the 88.9% removal efficiency at the flow rate of 628 gpm is much higher than the 35.35% removal efficiency interpolated from the data points in Table 5. The direct method (the mass balance method, described above) was used in producing data in Table 5, whereas the more commonly used indirect method (the influent and effluent sampling method, also described above) was employed in the Maine DEP confirmation test. The same size unit (4-ft), the same solids materials (F-95 sand), and the same laboratory setup were used in both tests. The use of different methods and procedures for evaluating the removal efficiency is expected to be the primary, if not the sole, reason for the large difference. Therefore, the NJDEP weighted removal efficiency most likely would have been higher than 70.15% (Table 6) if the indirect method and associated procedure were used.

5.5.3 Size Scaling

Only the smallest size (4-ft diameter) of the *Downstream Defender*® models was tested in the laboratory for performance. There is a need to scale the size up in order for the unit to take a higher treatment flow rate.

The commonly used scaling factor for design of solids settling basins (clarifiers, sedimentation tanks, etc.) is the surface area, i.e., the flow rate is scaled by length to the power of 2.0. This scaling factor of 2.0 was determined based on gravitational settling of discrete particles along the straight path (Peavy et al., 1985).

However, in the vortex/swirl hydrodynamic separator, solids settling/separation is enhanced by the flow pattern (Field and O'Connor, 1996). As the solids-laden flow swirls around the chamber, the difference in inertia between the settable solids and the water creates a tangential separation (spinoff) between the particle and fluid flow field. Gravity separation also occurs as particles follow the "long path" through the outer and inner swirl. Separation of solids is also assisted by the shear forces and friction losses between the inner and outer swirls and along the perimeter wall and the bottom.

For hydraulic structures, such as spillways and weirs, where there is a rapidly changing water-surface profile, the two dominant forces are inertia and gravity (Hickox, 1942). Therefore, to obtain similar paths of flow, the Froude numbers (the ratio of gravitational force over inertial force) of the model (the small size unit) and the prototype (the large size unit) are equated. Sullivan et al. (1972) did use the same Froude number in their physical model study of solids removal efficiency of the swirl separator, i.e., the treatment flow rate was scaled by length to the power of 2.5. Recently, a study of similarity based on the tracer residence time distribution indicated that scaling by length to the power of 2.85 was the most appropriate (Alkahaddar et al., 2001). Moreover, water detention time is typically calculated using volume of the water in the treatment chamber/tank/basin, i.e., the treatment flow rate is scaled by length to the power of 3.0.

Although it is not certain what exactly the scaling factor should be for particle removal in the vortex hydrodynamic separator, it appears the power of 3.0 is more appropriate than the power of 2.0 in the length scaling. Therefore, the scaling by length (radius) to the power of 3 was used to extrapolate performance of the tested size to other sizes of the unit for the *Downstream Defender*® (Table 7).

Alternatively, to be on the conservative side, the treatment flow rate could be scaled by the length to the power of 2.5. The formula for the treatment flow rate extrapolation would be $Q = 502\ (D/4)^{2.5}$, where Q is the flow rate in gpm and D is the diameter of the unit in ft. This alternative Froude Law-based scaling would give treatment flow rates that are smaller than the volume-based scaled treatment flow rates given in Table 7.

Table 7. *Downstream Defender®* Flow Rates for 70 Percent Solids Removal

Downstream Defender Diameter (ft)	Flow Rate = (20 gpm/ ft^3) x (πr^3)
4	502 gpm (1.1 cfs)
6	1696 gpm (3.8 cfs)
8	4020 gpm (9.0 cfs)
10	7860 gpm (17.5 cfs)

5.6 Re-entrainment Prevention

Another important performance issue is the retention efficiency characteristics of various separator configurations. Retention efficiency refers to the ability of the device to retain previously captured material. Preventing pollutant washout is particularly important for stormwater applications where pollutants are typically allowed to accumulate over several months between cleanouts. The internal components of the *Downstream Defender®* provide isolated storage zones for recovered material. In the configurations shown in Figures 2 & 3 the cone shields the separated solids in the sump region thereby reducing the risk of re-entrainment compared with configurations without this arrangement (Faram and Harwood, 2002). Floating material is held between the dip plate and the vessel wall preventing direct communication with the outlet. These features provide significant benefits with regards to the ability of the device to retain captured pollutants.

The *Downstream Defender®*'s ability to prevent re-entrainment of previously captured pollutants over its entire flow range was videotaped at Hydro's full-scale testing laboratory. For comparison purposes, the test was repeated with the internal components removed, resulting in pollutant washout. Liverpool John Moores University conducted similar tests on scale models of the *Downstream Defender®*, a Gravity Sedimentation Device (GSD) and a simple vortex separator (SVS). These tests were also videotaped and validate the in-house testing as well as CFD predictions. The *Downstream Defender®* had a superior ability to retain captured pollutants, preventing washout, compared to the GSD and SVS alternatives. This capability is critical to maintaining treatment levels as pollutants accumulate between cleanouts.

6. Technical Evaluation Analysis

6.1 Verification of Performance Claim

Based on the evaluation of the results from laboratory studies, sufficient data is available to support the Hydro International Claim: The *Downstream Defender®*, sized at a hydraulic loading rate of 20 gpm/ft^3 has been shown to have a 70% solids mass removal efficiency (as per NJDEP treatment efficiency calculation methodology) for F-95 sand with an average influent concentration of 240 mg/l, an average d_{50} particle size of 120 microns and zero initial sediment loading in laboratory studies using simulated storm water.

6.2 Limitations

6.2.1 Factors Causing Under-Performance

If the *Downstream Defender*® is designed and installed correctly, there is minimal possibility of failure. There are no moving parts to bind or break, nor are there parts that are particularly susceptible to wear or corrosion. Lack of maintenance may cause the system to operate at a reduced efficiency, and it is possible that eventually the system will become filled with sediment up to the dip plate.

6.2.2 Pollutant Transformation and Release

The *Downstream Defender*® will not increase the net pollutant load to the downstream environment. However, pollutants may be transformed within the unit. For example, organic matter may decompose and release nitrogen in the form of nitrogen gas or nitrate. These processes are similar to those in wetlands but probably occur at slower rates in the *Downstream Defender*® due to the absence of light and mixing by wind, thermal inputs and biological activity. Accumulated sediment should not be lost from the system at or under the design flow rate.

6.2.3 Sensitivity to Heavy Sediment Loading

Heavy loads of sediment will increase the needed maintenance frequency.

6.2.4 Mosquitoes

Although the *Downstream Defender*® is a self contained unit, the design does incorporate standing water in the lower chamber, which can be a breeding site for mosquitoes. No actual field tests were conducted regarding mosquitoes. However, it appears that the *Downstream Defender*® has advantages over other gravity separators and simple swirl concentrators. The *Downstream Defender*® has a submerged inlet. This will prevent access into the Defender's manhole from the upstream side. The Defender is supplied with frames and covers so there is no access to the Defender's manhole from above. The only access into the Defender is from a downstream catch basin inlet - up the storm drain into the "treated" area under the dip plate. If a mosquito were to make the flight, they would have access to surface water, but a much more reduced area compared to other treatment systems due to the floatables lid.

7. Net Environmental Benefit

The NJDEP encourages the development of innovative environmental technologies (IET) and has established a performance partnership between their verification/certification process and NJCAT's third party independent technology verification program. The NJDEP, in the IET data and technology verification/certification process, will work with any company that can demonstrate a net beneficial effect (NBE) irrespective of the operational status, class or stage of an IET. The NBE is calculated as a mass balance of the IET in terms of its inputs of raw materials, water and energy use and its outputs of air emissions, wastewater discharges, and solid waste residues. Overall the IET should demonstrate a significant reduction of the impacts to the environment when compared to baseline conditions for the same or equivalent inputs and outputs.

Once the *Downstream Defender*® has been verified and granted interim approval use within the State of New Jersey, Hydro International will then proceed to install and monitor systems in the field for the purpose of achieving goals set by the Tier II Protocol and final certification. At that time a net environmental benefit evaluation will be completed. However, it should be noted that the *Downstream Defender*® technology requires no input of raw material, has no moving parts, and therefore, uses no water or energy.

8. References and Bibliography

Andoh, R.Y.G., and Smisson, R.P.M. (1994). "High Rate Sedimentation in Hydrodynamic Separators." *Proc. of 2nd International Conf. On Hydraulic Modelling Development and Application of Physical and Mathematical Models*, Stratford, UK, pp. 341 – 358.

Andoh, R.Y.G., Harper, I., and Hipwell, P.M., (1996). "Meeting the EC Urban Wastewater Treatment Directive with Hydro Swirl-Flo™ Process." *Chemical Water and Wastewater Treatment IV, Proceedings of the 7th Gothenburg Symposium*, September 23 –25, Edinburgh, Scotland, pp 241 – 250.

Andoh, R.Y.G. (1998). "Improving Environmental Quality using Hydrodynamic Vortex Separators." *Water Quality International*, January/February.

Andoh, R. Y. G., and Saul, A.J. (2000). "Field Evaluation of Novel Wet-Weather Screening Systems." *Proc.WEF Speciality Conf., Collection Systems Wet Weather Pollution Control: Looking into Public, Private and Industrial Issues,* New York, USA, 7-10 May.

Andoh, R. Y. G., Faram, M. G., Stephenson, A. G. and Kane, A. (2001). "A Novel Integrated System for Stormwater Management." Novatech: 4th International Conference on Innovative Technologies in Urban Storm Drainage, Lyon, France, June 25-27.

Alkhaddar, R. M., Higgins, P. R. and Phipps, D. A. (2000). "Characterisation for in situ disinfection of a hydrodynamic vortex separator (HDVS)." *Proceedings of the 1st World Congress of the International Water Association*, Paris, 3-7 July.

Alkhaddar, R. M., Cheong, C. H., Phipps, D. A., Andoh, R., James, A., and Higgins, P. (2001). "The Development of a Mathematical Model for the Prediction of the Residence Time Distribution of a Vortex Hydrodynamic Separator." *Proceedings of Novatech 2001: 4th Int. Conf. on Innovative Technologies in Urban Drainage*, Lyon, France, June 25-27, pp. 835-842.

Alkhaddar, R. M., Higgins, P. R., Phipps, D. A., and Andoh, R.Y.G. (2002). "The Experimental and Residence Time Distribution Estimation of Decomposition of Hydrogen Peroxide within a Hydrodynamic Vortex Separator." 9ICUD Conference, Portland, Oregon, USA

Arnett, C. J. and Gurney, P. K. (1998). “High rate solids removal and chemical and non-chemical UV disinfection alternatives for treatment of CSO’s.” Innovation 2000, Conference on Treatment Innovation for the Next Century, Cambridge, UK.

Averill, D., Mack-Mumford, D., Marsalek, J., Andoh, R. and Weatherbe, D. (1997). “Field Facility for Research and Demonstration of CSO Treatment Technologies.” *Water Science & Technology*, 36 (8-9), 391 – 396.

Boner, M. C., Ghosh, D. R., and Hides, S. P. (1992). “High Rate Treatment of Combined Sewer Overflows in Columbus, Georgia.” Water Environment Federation, 69th Annual Conf. and Exposition, New Orleans, Louisiana, Sep., 20-24.

Boner M C , Ghosh D R, Hides S P and Turner B G (1993). “High Rate Treatment of Combined Sewer Overflows in Columbus, Georgia.” *Proceedings of the 6th International Conference on Urban Storm Drainage*, Niagara Falls, Ontario, Canada 1671-1676.

Deahl, P.J., and Faram, M. G., (2002). “Treatment, Storage and Control of Stormwater in Urban Developments.” 9ICUD conference, Portland, Oregon, USA.

Dennis, J. (2001). *Hydro International F-95 Sand SSC (TSS) Removal Confirmation Test, September 20, 2001*, Maine Department of Environmental Protection, Division of Watershed Management, Augusta, ME, November 16.

Dudley J (1994). “An Evaluation of a Pilot Lamella Settler and the Swirl-Flo™ Separator.” Report No. - UC 2356, Water Research Centre, Swindon, UK.

Dudley J, Mulhall, E and Solomon, S (1994). "Primary Treatment Processes to Reduce BOD and Suspended Solids – Final Report.” Report No. - UM 1458, Common Interest Research Programme Reference U-0816, Water Research Centre, Swindon, UK.

Faram, M.G. and Andoh, R.Y.G. (1999). “Evaluation and Optimisation of a Novel Self-Cleansing Combined Sewer Overflow Screening System using Computational Fluid Dynamics.” 8ICUSD Conference, Sydney, Australia, August-September.

Faram, M. G., Andoh, R. Y. G. and Smith, B. P. (2000). “Hydro-Jet Screen™: A Non-Powered Self-Cleansing Screening System for Storm Overflow Screening Applications.” *Wastewater Treatment: Standards and Technologies to Meet the Challenges of the 21st Century*, CIWEM/AETT Millennium Conf., Leeds, UK, 4-6 April, pp 205-212.

Faram, M. G. and Andoh, R. Y. G., (2000). “Application of Simulation and Predictive Techniques for the Evaluation of Hydrodynamic Separators.” *Wastewater Treatment: Standards and Technologies to Meet the Challenges of the 21st Century*, CIWEM/AETT Millennium Conf., Leeds, UK, 4-6 April, pp 223-230.

Faram, M. G. and Harwood, R., (2002). “A Method for the Numerical Assessment of Sediment Interceptors.” 3rd International Conference on Sewer Processes & Networks, Paris, France, 15-17 April.

Field, R. and O’Connor, T. P. (1996). “Swirl Technology: Enhancement of Design, Evaluation, and Application.” *Journal of Environmental Engineering*, Vol. 122, No. 8, pp. 741-748.

Harwood, R and Saul, A.J. (1996). “CFD and Novel Technology in Combined Sewer Overflow.” *Proc. 7th Int. Conf. On Urban Storm Drainage*, Hanover, Germany, pp 1025-1030.

Harwood, R., (1998). *Modelling Combined Sewer Overflow Chambers Using Computational Fluid Dynamics*. PhD Thesis, The University of Sheffield, UK.

Harwood, R. (1999). “The Influence of CSO Chamber Size on Particle Retention Efficiency Predictions.” 8ICUSD Conference, Sydney, Australia, August-September.

Harwood, R. (2002). “CSO Modelling Strategies using Computational Fluid Dynamics.” 9ICUD Conference, Portland, Oregon, USA.

Hedges, P.D., (1993). “The Relationship between Field and Model Studies of an Hydrodynamic Separator Combined Sewer Overflow.” *Proceedings of the 6th International Conference on Urban Storm Drainage*, Niagara Falls, Canada.

Hedges, P.D., Lockley P. E., and Martin J R, (1992). “A Field Study of an Hydrodynamic Separator Combined Sewer Overflow.” International Conference on Innovative Technologies in the Domain of Urban Storm Water Drainage, Novatech.

Hides, S.P., (1997). “Treatment of Wet Weather Discharges in Columbus, Georgia.” 69th Annual Meeting of the New York Water Environment Association, New York City, U.S.A, January 26-27.

Horowitz, A.J. (1991). *A Primer on Sediment-Trace Element Chemistry*, Second Edition, Lewis Publications, ISBN 0-87371-499-7, USA.

Hickox, G. H. (1942). “Hydraulic Models” in *Handbook of Applied Hydraulics*, C. V. Davis, Editor-in-Chief, McGraw-Hill Book Company, Inc., New York and London.

Okamoto, Y., Konugi, M. and Tsuchiya, H., (2002). “Numerical Simulation of the Performance of a Hydrodynamic Separator.” 9ICUD conference, Portland, Oregon, USA.

Patel, M. (2003). *Draft Total Suspended Solids Laboratory Testing Procedures*, dated December 23, 2003, New Jersey Department of Environmental Protection, Office of Innovative Technology and Market Development, Trenton, New Jersey.

Peavy, H. S., Rowe, D. R., and Tchobanoglous, G. (1985). *Environmental Engineering*, McGraw-Hill, Inc., New York, NY.

Pratt, C. (2000). *Laboratory Tests on Downstream Defender™ for Hydro International plc*, Clevedon, BS21 7RD, May-June, Coventry University, UK.

Saul, A.J., Ruff, S.J., Walsh, A.M., and Green, M.J. (1993). *Laboratory Studies of CSO Performance*. WRc Report No. UM 1421, October, UK.

Saul, A. J. (1998). "CSO state of the art review: a UK perspective." *UDM'98*, Fourth Int. Conf. on Developments in Urban Drainage Modelling, September, London, UK.

Smith, B. P., and Andoh, R. Y. G. (1997). "New generation of hydrodynamic separators for CSO treatment." *Proc. 2nd Int. Conf. on the Sewer as a Physical, Chemical and Biological Reactor*, Aalborg, Denmark, 25-28 May.

Smisson, B. (1967). "Design, Construction and Performance of Vortex Overflows." Institute of Civil Engineers. Symposium on Storm Sewage Overflows, London, pp 99 –110.

Southern Water Authority (1989). *Egerton Park Stream, An Ecological Study of the Long Term Effects of Stormwater from Hydrodynamic Separators on the Egerton Stream*. Sussex Division, UK.

Sullivan, R. H., Cohn, M. M., Coomes, J. P., and Smission, B. S. (1972). *The Swirl Concentrator as a Combined Sewer Overflow Regulator Facility*. USEPA-R2-72-008.

Sullivan R H , Ure J E, Parkinson F and Zielinski P (1982). *Swirl and Helical Bend Pollution Control Devices - Design Manual.* EPA - 600/8-82-013.

Tyack, J.N., Hedges, P.D., and Smisson, R.P.M. (1992). "The Use of Sewage Settling Velocity Grading in Combined Sewer Overflow Design." NOVATECH 92, International Conference on Innovative Technologies in the Domain of Urban Water Drainage, Lyon (France), November 3-5.

Turner B. G. and Boner M. (1998). "Economics of Wet Weather Water Quality Controls." *Proceedings and Workshop Session, Treatment Innovation for the Next Century, INNOVATION 2000*, by the European Water Pollution Control Association, Water Environment Federation, Chartered Institution of Water and Environmental Management and Anglian Water, Cambridge, July, UK.

Turner B. G., Arnett, C.J., and Boner M. (2000). "Performance Testing of Combined Sewer Overflow Control Technologies Demonstrates Chemical and Non-Chemical Disinfection Alternatives and Satisfies EPA CSO Policy." *Disinfection 2000: Disinfection of Wastes in the New Millennium*, WEF, March 2000, USA.

Turner B. G., Arnett, C.J., and Boner M. (2001). "Columbus, Georgia Water Quality Programs." *Conference Proceedings*, WEFTEC 2001, October, Atlanta, Georgia, USA.