Technology Review:
Ultra-Urban Stormwater Treatment Technologies

Prepared by:
Christopher C. Brueske
Department of Civil and Environmental Engineering
University of Washington
Seattle, WA

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Section 1: Introduction

The following document was compiled to provide a review of "ultra-urban" stormwater treatment technologies. "Ultra-urban" technologies are designed to remove pollutants from wet weather runoff in highly developed areas where land values are high and available space is limited. These technologies differ from traditional stormwater treatment methods (e.g., water quality ponds and grass swales) in that they are extremely compact and can be retrofitted into existing stormwater collection systems.

The technologies included in this review were developed primarily to remove suspended solids from urban runoff. Several of the units also include design features to remove oils and other floatable contaminants. Generally speaking, these technologies remove metals, nutrients, and other contaminants only to the extent that these contaminants are adsorbed to suspended solids. A notable exception to this is certain filtration systems, which can be operated with an adsorptive media specific to dissolved metals, organics, and nutrients.

1.1 Scope and Organization

This document examines stormwater treatment units similar to those that will be tested as part of the Environmental Technology Evaluation Center (EvTEC)/Washington State Department of Transportation (WSDOT) Technology Evaluation Project in Seattle, Washington. The units examined are designed to operate "in-line" with the stormwater collection system and provide treatment of stormwater flow on a continuous basis during a storm event. Generally speaking, the units are compact and do not require pumping or other energy input. This document examines in detail the following four types of treatment technologies, categorized according to their underlying solids removal mechanism:

- Gravity separation (Section 2)
- Swirl concentration (Section 3)
- Screening (Section 4)
- Filtration, combined in some cases with dissolved contaminant removal by an adsorptive media (Section 5)

For each of these categories, the following information is provided:

- Detailed examination of one or two representative trademark units to illustrate the treatment mechanism
- Summary of hydraulic principles involved in the treatment mechanism
- Literature review, including a summary of reported treatment performance data

Section 6 of this document examines issues associated with monitoring stormwater treatment units, including the following:

- Examination of both “storm event mass-based” and “hydrology-based” methodologies for calculating removal efficiency
- Summary of a proposed protocol for evaluating new stormwater treatment technologies, developed specifically for the Puget Sound region by the Stormwater Managers Committee of the Washington Chapter of the American Public Works Association (APWA)

Section 7 applies the findings of the technology review to develop a design protocol for selecting and installing an “ultra-urban” treatment technology. The purpose of the design protocol is to illustrate the factors that must be considered and the data limitations that add uncertainty to the design process.

Section 8 provides conclusions and highlights research needs applicable to “ultra-urban” stormwater treatment technologies.

Appendix A provides a list of contact information for manufacturers and vendors of stormwater treatment units similar to those examined in this paper.

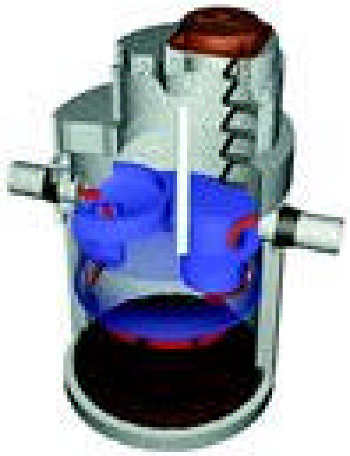
Section 2: Gravity Separation Technologies

Gravity separation is a common approach to stormwater treatment, although traditional gravity separation technology has relied on the use of detention basins and water quality ponds to achieve solids removal. “Ultra-urban” gravity separation units are designed to achieve solids removal without the land requirement associated with traditional technologies. Two representative gravity separation technologies selected for examination in this review are the Stormceptor® System, manufactured by CSR, Kansas City, Missouri, and the BaySaver® System, manufactured by BaySaver®, Inc., Mount Airy, Maryland.

2.1 Stormceptor® System

A schematic of the Stormceptor® System is provided in Figure 2-1. The system comprises a lower treatment chamber and an upper bypass chamber, separated by a fiberglass disc insert. The lower chamber is always full of water. Stormwater enters the treatment unit, and normal design flows are diverted into the lower treatment chamber by a weir and drop pipe. The drop pipe diverts flow along the wall of the lower treatment chamber to reduce turbulent eddies and the associated potential for sediment re-entrainment. As water flows through the lower chamber, sediment is removed by gravity separation, and floating oil is retained under the fiberglass disc insert. Water exits the treatment chamber through a submerged outlet pipe and exits the unit. Flow in excess of the weir capacity bypasses the treatment chamber and flows through the bypass chamber directly to the unit outlet. This bypass reduces the potential for scouring of sediment from the lower chamber during high flow conditions. The unit requires periodic clean out by a vacuum truck to remove oil and sediment. CSR manufactures nine model sizes of the conventional in-line Stormceptor®, ranging in maximum treatment capacity from 0.18 – 2.5 cfs and with diameters between 4 – 12 ft. These dimensions correspond to a hydraulic application rate (HAR) of 6.3 – 9.8 gpm/ft^2 of treatment chamber. Sediment and oil storage capacities range from 1.7 – 30.7 yd^3 and 85 – 1096 gal, respectively.

CSR has developed a computer model that incorporates the U.S. Environmental Protection Agency’s (EPA) surface water management model (SWMM) to select appropriately-sized Stormceptor® units for individual applications. Build-up and wash-off calculations for particles in urban runoff were incorporated into SWMM; the distribution of solids build-up is a function of antecedent dry days. The model uses a database of historical rainfall data for stations across the United States; fifteen-minute data are used to simulate rainfall over a period of several years. Settling calculations, based on Stokes Law (see Section 2.3 for a discussion of Stokes Law) determine the particle removal efficiency that will be achieved for several different sizes of Stormceptor® units, based on the detention time in the units. A uniform distribution of influent particles is assumed so that the mass of particles that bypasses the treatment chamber is proportional to the bypass flow. The model output is an overall estimated solids removal efficiency for various Stormceptor® unit sizes, allowing the designer to decide which unit is most appropriate. The Stormceptor® System Technical Manual provides model calibration data that suggests the model provides reasonable estimates of



Normal Flow Conditions

Bypass Conditions

Figure 2-1: Schematic of Stormceptor® System during normal flow conditions and bypass conditions (Source: Stormceptor® Internet Page: www.csra.com/csrstormceptor/products/inline.htm) actual field performance. Values of SWMM parameters used in the CSR model are provided in Table 2-1. The model user is able to select between two particle size distributions, shown in Table 2-2.

The settling velocities in Table 2-2 are based on Stokes Law (see Section 2.3). To account for the potential for coagulation of smaller particles, CSR uses an empirical coagulation equation to determine the settling velocity of 20-µm particles:

$$V_s = 0.35 + 1.77\ P_s \qquad (2\text{-}1)$$

where
V_s = settling velocity, mm/s
P_s = particle size, mm

Table 2-1: SWMM Parameters used in CSR's Stormceptor® Design Model

Area (acre)	Variable-entered by user
Imperviousness	99 %
Slope	2 %
Impervious depression storage (inches)	0.19
Pervious depression storage (inches)	0.02
Impervious Mannings n	0.015
Pervious Mannings n	0.25
Maximum infiltration rate (inches/hour)	2.46
Minimum infiltration rate (inches/hour)	0.39
Decay rate of infiltration (seconds $^{-1}$)	0.00055

Source: CSR, The Stormceptor® System Technical Manual

Table 2-2: Particle Size Distribution Options for CSR's Stormceptor® Design Model

Particle size (µm)	Percent by mass (%)	Specific gravity	Settling velocity (cm/sec) [a]
Option 1: "Typical" Particle Size Distribution			
20	20	[b]	0.035
60	20	1.8	0.158
150	20	2.2	1.07
400	20	2.65	6.50
2000	20	2.65	28.7
Option 2: "Coarse" Particle Size Distribution			
150	60	2.65	1.44
400	20	2.65	6.50
2000	20	2.65	28.7

Notes:
[a] Settling velocity based on Stokes Law
[b] Flocculated settling velocity based on $V_s = 0.35 + 1.77\ P_s$, where V_s = settling velocity (mm/sec) and P_s = particle size (mm)
Source: CSR, The Stormceptor® System Technical Manual

2.2 BaySaver® Separation System

A schematic of the BaySaver® System is provided in Figure 2-2. The system comprises two precast manholes (referred to as the primary manhole and the storage manhole) and a high-density polyethylene (HDPE) separator unit. The primary manhole is placed in-line with the storm drain, and the storage manhole is placed off-line. The system has three operational phases:

- Low flow operation: Stormwater enters the primary manhole, where coarse sediments settle out. Water leaves the primary manhole by flowing over a trapezoidal weir in the HDPE separator unit into the storage manhole, where finer sediments and floatable oils are removed. Water exits the storage manhole by a submerged effluent pipe and is returned to the storm drain.

- Moderate flow operation: Stormwater enters the primary manhole, and a portion of the flow is routed through the storage chamber; flow in excess of the storage chamber's capacity is treated only in the primary manhole. As with low operation, water flows over the weir and into the storage chamber. However, during moderate flow, a pair of submerged elbow pipes draws water in excess of the storage manhole's capacity from the center of the primary manhole. This water, having been treated for coarse sediment removal in the primary manhole, bypasses the storage manhole and is returned to the storm drain. By not diverting high flows through the storage manhole, the potential for re-entrainment of sediment from the storage manhole is reduced. In addition, by routing water from the top of the primary manhole to the storage manhole, removal of floatable contaminants such as oil and grease can continue during moderate flow operations.

- Bypass operation: During high flows, the treatment unit operates in a bypass mode. Stormwater exits the primary manhole by flowing over the HDPE separation unit; in addition, water enters the submerged elbow pipes from both the top and bottom, thus reducing the potential for resuspension of sediments from the primary manhole. During bypass operation, pollutant removal efficiency is effectively zero (BaySaver®, Inc., 1999).

Periodic cleaning by a vacuum truck is required to removed sediments and oils from the primary and storage manholes. BaySaver® Inc. manufactures HDPE separation units in three different sizes, and the size of the primary and storage manholes are varied depending on the design treatment flow. The storage manhole is typically the same size or larger than the primary manhole. Increasing the size of the storage manhole increases the overall system HAR and allows additional time to achieve solids settling. The capacity of the HDPE separation units ranges from 1.0 – 3.8 cfs for low flow operation, 2.4 – 11.1 for moderate flow operation, and 10 – 50 cfs for bypass operation. The diameters of the primary and storage manholes range from 4 – 8 ft, with a total system volume of 1,475 – 5,950 gal and a sediment storage capacity of 1.86 – 7.44 yd^3. HAR (in terms of flow per total manhole area) varies depending on the diameter of the primary

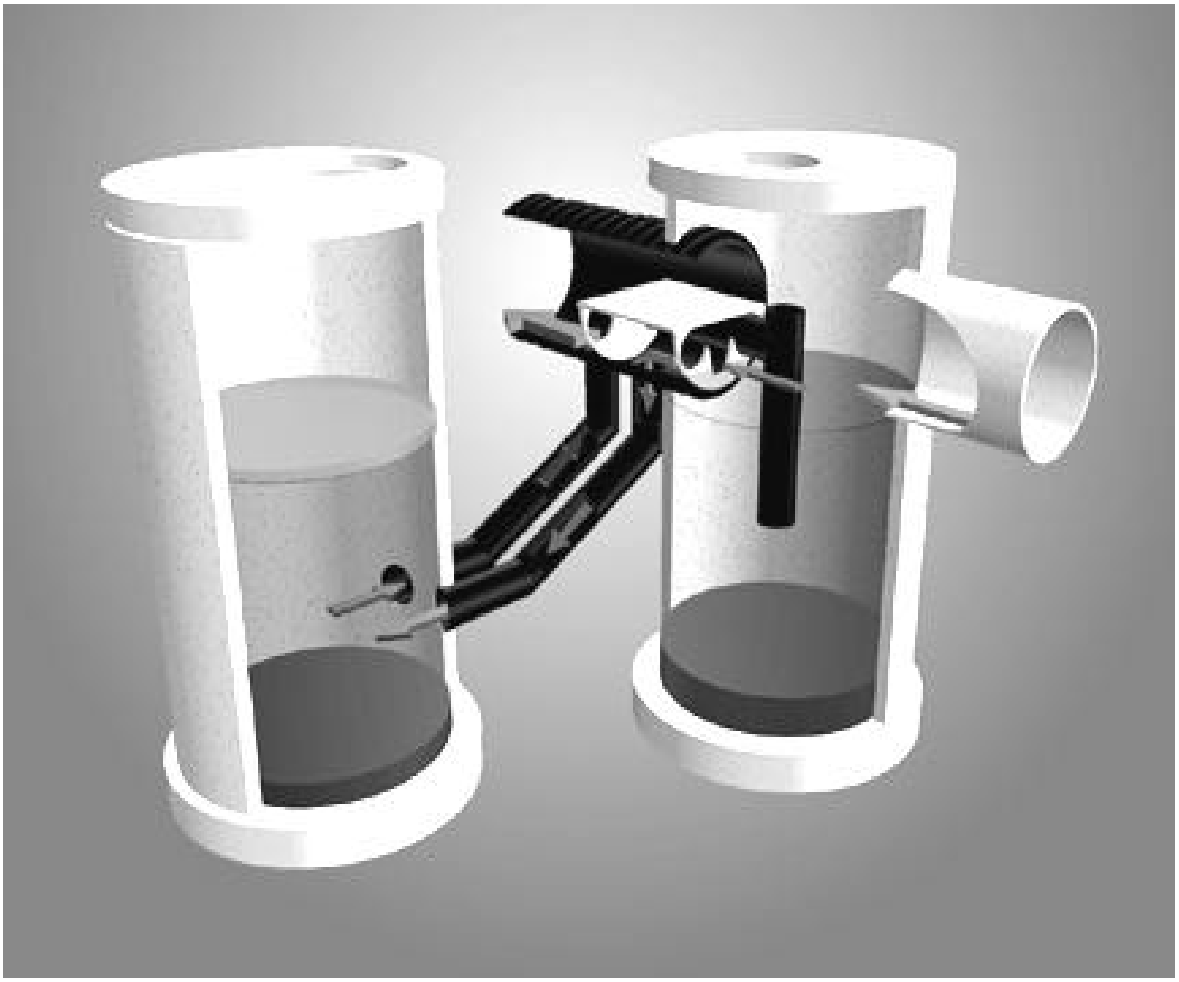


Figure 2-2: Schematic of BaySaver® Separation System during low flow operations (Source: BaySaver® Internet Page: www.baysaver.com/bss/oper/mf02.html)

and storage manholes, but based on standard BaySaver® manhole sizing guidelines (BaySaver®, Inc., 1999) a general range of low flow operation HAR is 11 –18 gpm/ft^2 for the smallest HDPE separation unit, 19 – 29 gpm/ft^2 for the middle unit, and 17 – 30 gpm/ft^2 for the largest unit. Oil storage capacity in the storage manhole ranges from 280 – 1,110 gal.

BaySaver® Inc. recommends that HDPE separation units be sized to convey the two year, one hour storm under moderate flow operations. The intent of this specification is to allow the unit to operate under low flow conditions during smaller, more common storms. The size of the primary and storage manholes can also be modified if additional detention time is required. For example, a site with a high concentration of fine particles may require additional detention capacity to achieve gravity separation of these particles.

2.3 Treatment Mechanism

The solids removal efficiency of a gravity separation treatment unit is a function of the detention time of the unit and the settling velocity of particles in the influent. The detention time (t_d, sec) is calculated from the volume of a treatment unit (V, m^3) and the flow rate to the system (Q, m^3/sec):

$$t_d = V / Q \qquad (2\text{-}2)$$

A design settling velocity (v_o, m/s) for a gravity separation process is described by Wanielista and Yousef (1993) in terms of the height of settling (h_o, m) and the detention time (t_d, sec):

$$v_o = h_o / t_d \qquad (2\text{-}3)$$

This equation is typically used in the design of gravity separation systems such as wet ponds. Stokes Law is used to calculate the settling velocity of a particle under gravitational effects:

$$v_o^2 = (4gd_s/3C_d)(SG-1) \qquad (2\text{-}4)$$

where:
v_o = terminal settling velocity, m/sec
g = acceleration due to gravity, m/sec^2
d_s= particle diameter, m
C_d = drag coefficient, unitless
SG = specific gravity of particle, unitless (SG = density of particle, kg/m^3 / density of water, kg/m^3)

Stokes Law, as originally derived, describes laminar flow around discrete spherical particles. In this form, the drag coefficient, C_d, is defined as:

$$C_d = 24/Re \qquad (2\text{-}5)$$

Where Re is the Reynolds number defined in terms of the fluid density (ρ, kg/m^3), the fall velocity (v_o, m/s), the particle diameter (d_s, m/s), and the dynamic viscosity of the fluid (μ, Pa sec):

$$Re = \rho v_o d_s/\mu \qquad (2\text{-}6)$$

This definition of C_d is generally applicable for fine particles (e.g., clay and silt) that settle in a laminar flow. In order to apply Stokes Law to larger sediment particles (e.g., sand and gravel) that settle in a turbulent flow, empirical formulas to define C_d have been derived. For example, Engelund and Hansen (1967) measured fall velocity of sand and gravel particles and derived the following best fit for the observed data:

$$C_d = (24/Re) + 1.5 \qquad (2\text{-}7)$$

As shown in Stokes Law, the settling velocity of a particle is a function of both the particle size and the particle density, expressed in terms of specific gravity. It is possible for two particles of different size to settle at the same rate, based on a difference in specific gravity. For example, a 100-µm sand particle (SG = 2.65) and a 280-µm organic particle (SG = 1.2) settle at approximately the same rate (0.8 cm/sec).

As the concentration of particles in a fluid increases, the probability of interaction between particles increases. This interaction can result in two phenomena that affect the settling velocity of a particle:

1) "Hindered settling," in which the settling of a high concentration of particles causes an upward flow of displaced water and reduces settling velocity.
2) Flocculation, in which particles agglomerate to form larger and heavier particles with higher settling velocities.

Hindered settling is not expected at solids concentrations less than 1,000 mg/L (EPA, 1978), and therefore should not affect the operation of stormwater treatment units. However, flocculation has been observed to influence the removal of particles in gravity separation processes by increasing settling velocities (EPA, 1978). In practice, it is common to use empirical equations to describe the effect of flocculation on the settling velocity of fine particles, as discussed previously for the Stormceptor® System.

2.4 Reported Performance and Design Methods

The Massachusetts Strategic Envirotechnology Partnership (STEP) conducted a review of performance data submitted by CSR for the Stormceptor® treatment system (STEP, 1998). A Stormceptor® unit in Westwood, Massachusetts demonstrated an average TSS removal efficiency of 77% for 6 storm events, with removal efficiencies for individual storms ranging between 28% and 99%. Average total petroleum hydrocarbon (TPH) removal efficiency for 5 storms during the same study period was 80%. A Stormceptor® unit in Edmonton, Canada demonstrated an average TSS removal efficiency of 52% over 4 storms. Removal efficiencies for individual metals (Fe, Pb, Zn, Cr, and Cu) ranged from 39% - 53%, and average oil and grease removal efficiency was 43%. The Edmonton unit was estimated to be undersized by a factor of 3 based on Stormceptor® sizing guidelines, which specified that the unit was intended to receive runoff from an impervious drainage area of 3.35 acre. The Edmonton unit was treating runoff from an impervious drainage are of 9.8 acres.

A laboratory study reported by Marcalek et al. (1994) demonstrated a decline in solids removal efficiency with increased flow rate for a 1:4 model-scale Stormceptor® unit. Froude similarity was used to calculate appropriate flow rates for the models, and ABS resin pellets were used to simulate medium sand (80 – 230 μm) in the stormwater. Reported solids removal efficiencies were 95% at 3.4 gpm/ft^2, 77% at 7.3 gpm/ft^2, 68% at 10.1 gpm/ft^2, and 6% at 22.4 gpm/ft^2. Bypass flow through the upper chamber occurred above 10.1 gpm/ft^2. A laboratory study by Pratt (1996) and reviewed by STEP (1998) evaluated a full-scale Stormceptor® unit receiving approximately one-half of its maximum treatment flow rate during a simulated 20-minute storm event. Sand and oil were used to create an influent with a TSS concentration of 210 mg/L and an oil concentration of 4,100 mg/L. HAR was approximately 5 gpm/ft^2. Removal efficiencies of 83% and 98% were reported for sand and oil, respectively.

Section 3: Swirl Concentration Technologies

Swirl concentration technologies have been used since the early 1960s, when a cylindrical vortex unit was used for the treatment of combined sewer overflow (CSO) in Bristol, England. The EPA Municipal Environmental Research Laboratory in Cincinnati, Ohio, in conjunction with the LaSalle Hydraulics Laboratory in Montreal, Quebec and the General Electric Company in Philadelphia, Pennsylvania, conducted a series of hydraulic and mathematical modeling studies in the 1970s to develop and demonstrate swirl concentration technology. This work resulted in the design of the EPA swirl CSO flow regulator/settleable-solids concentrator. The original CSO treatment units were designed with a "foul-water" outlet in the bottom center of the unit and a circular weir at the top of the unit, similar to a clarifier. During dry weather, all flow entering the unit was diverted through the "foul-water" outlet and conveyed to the wastewater treatment plant. During high flows, the unit served to concentrate solids in a portion of the flow, which exited the unit through the "foul-water" outlet and was conveyed to the wastewater treatment plant; the clearer supernatant overflowed the weir and was discharged to the receiving waters.

During the 1980s, swirl concentration technology was advanced and marketed by a growing number of private companies. A notable change to the original design is that commercially available swirl concentrators for stormwater treatment do not have a separate "foul-water" outlet; rather, accumulated sediments are stored in the unit and require periodic removal. Numerous swirl concentration units are commercially available. Of these, two representative technologies were selected for detailed examination in this paper. These are the Vortechs ™ Stormwater Treatment System manufactured by Vortechnics, Inc., Portland, Maine and the Downstream Defender ™ manufactured by H.I.L. Technology, Inc., Portland, Maine.

3.1 Vortechs ™ Stormwater Treatment System

A schematic of a Vortechs ™ Stormwater Treatment System is shown in Figure 3-1. The Vortechs ™ unit is designed to remove sediment and oil from stormwater and to prevent re-entrainment of these contaminants. Water enters the grit chamber through a tangential inlet and initiates the swirling fluid field. Settleable solids are concentrated at the center of the chamber, and the effluent exits through an orifice on the outside of the grit chamber. As flows through the unit increase, the effluent also exits over the top of the grit chamber wall. Oil and floatable contaminants collect at the water surface and are prevented from exiting by the underflow baffle in the flow control chamber. Accumulated sediment and floatable contaminants are periodically removed by a vacuum truck.

Vortechnics™ manufactures pre-cast units with a design treatment flow of 0.4 – 6.25 cfs and a corresponding peak flow capacity from 1.6 – 25.0 cfs. The grit chambers range from 3 – 12 ft in diameter and have sediment storage capacities of 0.75 – 7.0 yds^3. The permanent wet pool in the grit chamber is approximately 3-4 ft deep for all units. Cast-in-place designs are available for larger applications.

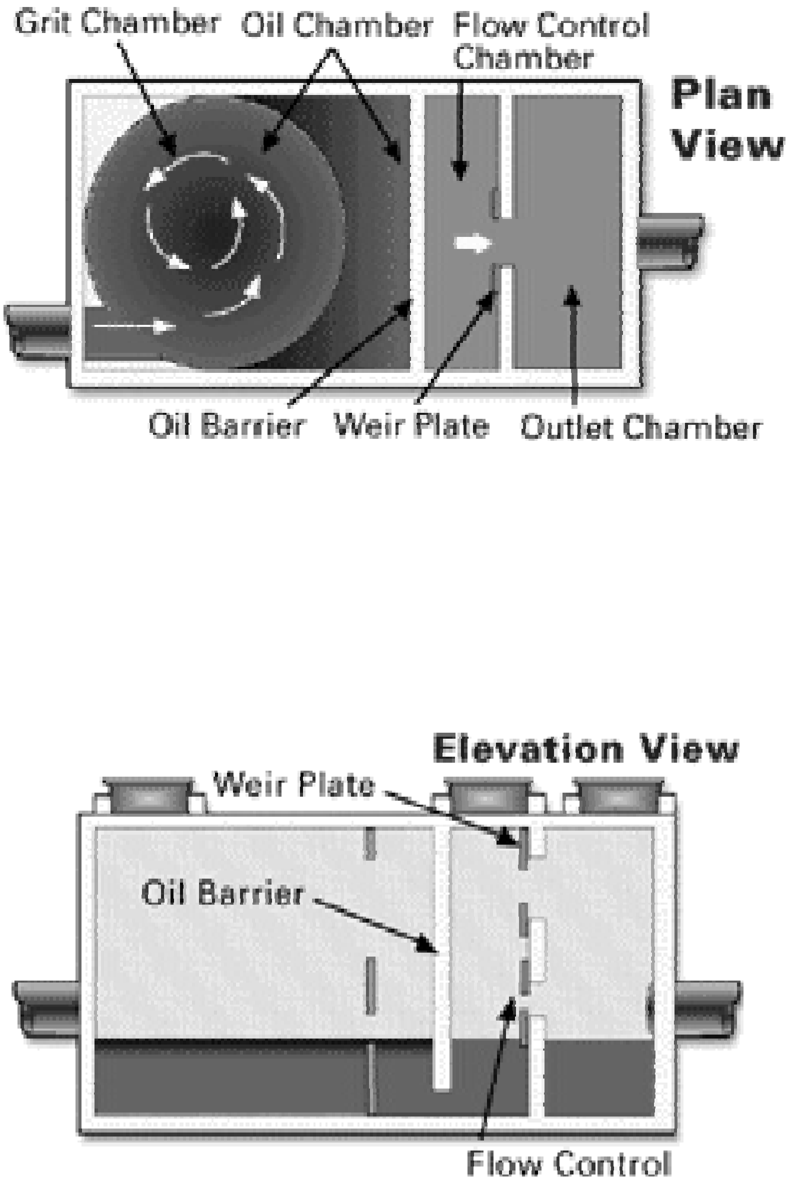


Figure 3-1: Schematic of a Vortechs™ Stormwater Treatment System (Source: Vortechnics™ Internet Page: www.vortechnics.com/vortechs/vorfeat.html)

Vortechs™ units can be installed either on-line, where all flow in a stormwater conveyance system passes through the unit, or off-line, where a portion of the flow in a stormwater conveyance system, up to a design flow, is diverted into the unit. In the case of an off-line installation, flow in excess of the unit's design flow continues in the conveyance system without treatment. Design of a Vortechs™ unit is based on HAR, expressed in terms of gpm / ft^2 of grit chamber area. Vortechnics™ (1999a) recommends the following design guidelines for sizing a unit, depending on the type of installation:

1) For on-line installations, size the system such that the maximum HAR during the design storm will be 100 gpm/ft^2.
2) For off-line installations, size the system such that it will operate at a maximum HAR of 24 gpm/ft^2 during a 2-month storm.

On-line installations are intended to provide treatment for all storms up to the design storm, including large, infrequent storms. The upper HAR limit of 100 gpm/ft^2 for on-line installations is based on laboratory tests conducted by Vortechnics™ that showed this to be the maximum HAR for which *some degree of treatment* (5-10% solids removal efficiency) was achieved. Off-line installations are intended to provide treatment only for smaller, more frequent storms and typically allow the use of smaller, less expensive treatment units. The HAR limit of 24 gpm/ft^2 for off-line installations corresponded to a much higher treatment efficiency in the same laboratory tests (65-98% solids removal efficiency). Additional discussion of these results is provided in Section 3.4.

3.2 Downstream Defender™

A schematic of the Downstream Defender™ is shown in Figure 3-2. The general operation of this unit is similar to the Vortechs™ unit; water enters the treatment chamber through a tangential inlet and induces a rotating fluid field. Water initially flows around the outer annular space between the manhole wall and the dip plate. Oil and floatable contaminants accumulate on the water surface in the outer annular space. Water continues to flow downward, depositing sediment in the bottom center of the unit. Water exits the unit by passing under the dip plate and spiraling upward through the inner annular space to the outlet pipe. The center cone serves to direct flow to the inner annular space and to protect accumulated sediment from re-entrainment. As with the Vortechs™ unit, accumulated sediments and floatable contaminants are periodically removed by a vacuum truck.

H.I.L. Technology manufactures pre-cast units for design flows of 0.75 – 13.0 cfs and corresponding peak flow capacities from 3.0 – 25 cfs. The units range in diameter from 4 – 10 ft, with sediment storage capacities of 0.7 – 8.7 yds^3. HAR for the units ranges from 26 – 74 gpm/ft^2 at the design flows. Cast-in-place units are available for larger applications. The specified design flows are based on a 90% removal efficiency for solids larger than 150-µm with a specific gravity of 2.65 for all flows up to the design flow (H.I.L. Technology, 2000).

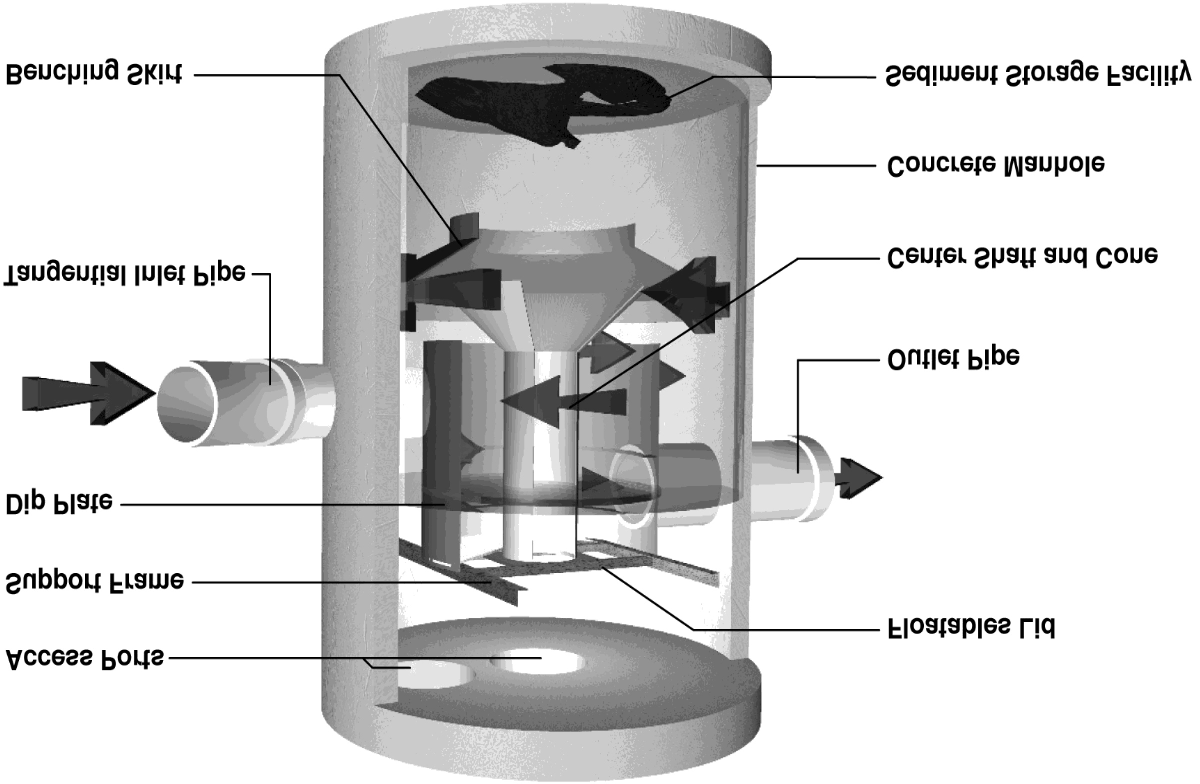


Figure 3-2: Schematic of a Downstream Defender™ unit (Source: H.I.L Technology, 2000)

3.3 Treatment Mechanism

Solids are removed from stormwater in a swirl concentrator by two distinct treatment mechanisms:

1) Gravity settling, which draws solids toward to floor of the treatment unit
2) Secondary currents, which concentrate settling solids in the center of the treatment unit

Gravity settling processes are discussed in Section 2 of this report. Secondary currents are the primary mechanism by which solids are removed by a vortex unit (Wong, 1997; Andoh and Smisson, 1994). Secondary currents are commonly known for their effect on river meandering, where they scour sediment from the outside of a river bend and deposit it on the inside of the bend. To examine the origin of secondary flows, it is necessary to understand vorticity. Mathematically, vorticity (ω) is defined as the curl of the velocity vector (V):

$$\omega = \nabla \times V \qquad (3\text{-}1)$$

In 2-dimensional flow, vorticity is the sum of the angular velocities of any pair of mutually-perpendicular, infinitesimal fluid lines that pass through a single fluid particle (Shapiro, 1969). Figure 3-3 illustrates the origin of vorticity in a viscous boundary layer. As shown in Figure 3-3, the non-uniform velocity distribution in the boundary layer imparts angular velocity perpendicular to the boundary; using the definition that vorticity is the sum of angular velocities of perpendicular fluid lines, this results in a component of vorticity in a vector transverse to the boundary.

In a vortex separator, secondary currents develop as a result of the vorticity caused by the boundary layer at the bottom of the treatment unit. Figure 3-4 illustrates the origin of secondary flows in a curved flow path (Shapiro, 1969). As fluid approaches a curve, there is no vertical component of vorticity (C, normal to page) and no streamwise component of vorticity (B). However, there does exist a transverse component of vorticity (A), which is generated by the viscous boundary layer at the bottom of the channel. As the fluid element moves through the curve, the vertical component of vorticity (C’) remains zero, but the streamwise vector (B’) rotates counterclockwise. To maintain the net vertical vorticity (C’) as zero, the existing transverse vorticity must rotate an equal amount clockwise. In so doing, the transverse vector develops a streamwise component of vorticity. This vorticity manifests itself as a clockwise circulation (looking downstream). In a bend of a river channel, this streamwise component of vorticity acts to scour sediment from the outside of the bend and deposit it on the inside of the bend.

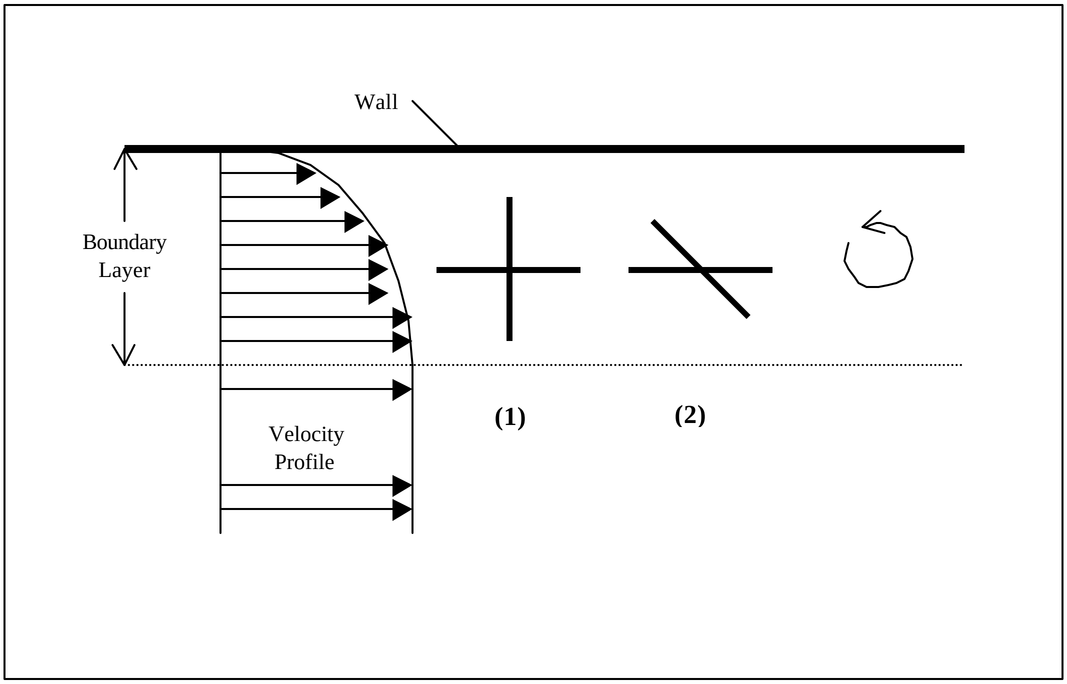


Figure 3-3: Generation of a transverse component of vorticity by shear forces in the boundary layer. As a pair of mutually perpendicular, infinitesimal fluid lines move from position 1 to position 2, frictional effects in the boundary layer impart an element of vorticity in a direction transverse to the boundary (normal to the page) (Adapted from Shapiro, 1969).

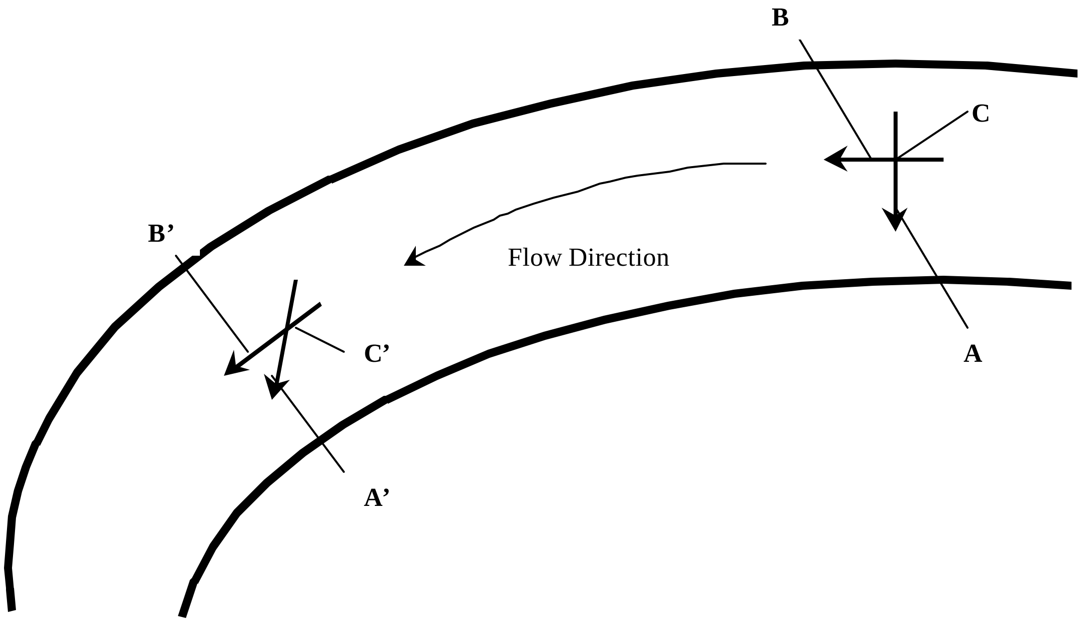


Figure 3-4: Generation of a streamwise component of vorticity in a curved channel. As a fluid element approaches a curve, there is no vertical component of vorticity (C, normal to page) and no streamwise component of vorticity (B). There does exist a transverse component of vorticity (A), which is generated by the viscous boundary layer at the bottom of the channel. As the fluid element moves through the curve, the vertical component of vorticity (C') remains zero, but the streamwise vector (B') rotates counterclockwise. To maintain the net vertical vorticity (C') as zero, the existing transverse vorticity must rotate an equal amount clockwise. In so doing, the transverse vector develops a streamwise component of vorticity. (Source: Shapiro, 1969)

In a swirl concentrator, the primary current is the visible swirl generated by the flow of stormwater through the tangential inlet. Because this primary current is a continuous circular flow field, secondary currents are maintained in the treatment unit. A conceptual representation of the effect of secondary currents in a vortex treatment unit is shown in Figure 3-5. Sediment settles to the bottom of the unit by gravity and is then concentrated in the center of the unit by secondary currents.

3.4 Reported Performance and Design Methods

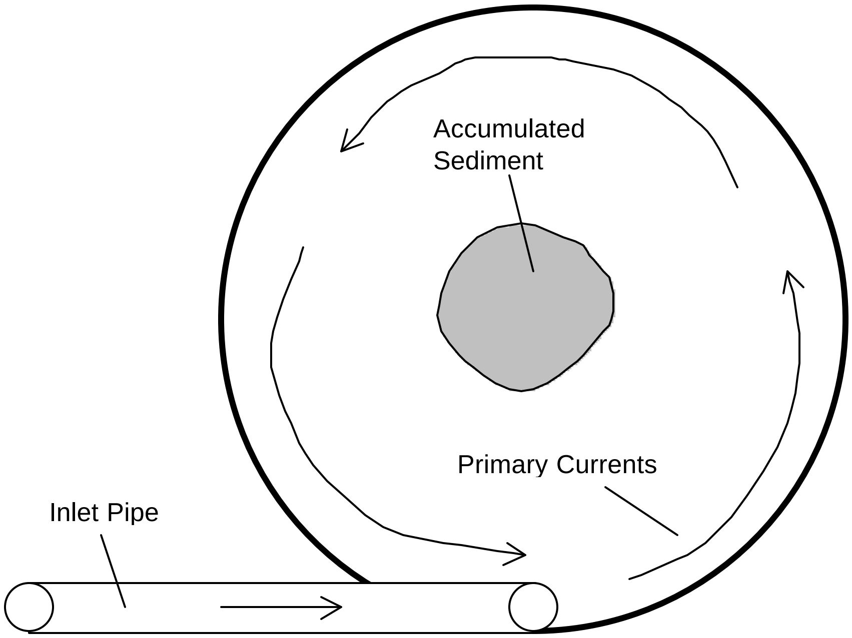
As stated previously, gravity separation is a necessary component of the treatment mechanism of a swirl concentrator. Particles with a slow settling velocity and non-settleable particles (i.e., particles on which gravitational forces and buoyant forces of approximately the same magnitude act) may escape treatment for the following reasons:

1) The particles do not settle into the zone of influence of the secondary currents
2) The particles do not remain in the accumulated sediment pile

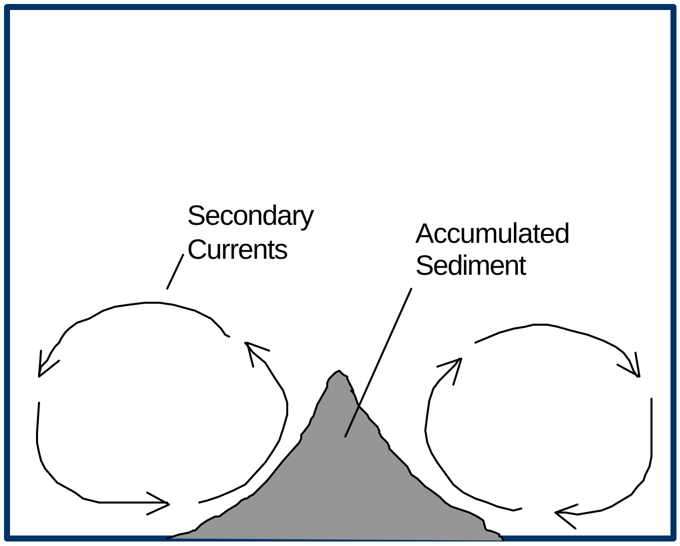
It has been reported (Vortechnics TM, 1998; Deamer et. al., 1994; H.I.L Technology, 2000) that removal efficiencies decrease with particle size in swirl concentrators. H.I.L. Technology (2000) states that vortex separation technology is not expected to achieve removal of non-settleable solids. Generally defined, non-settleable solids are those that remain in suspension after a specified settling time of 1 hour (APHA, 1987). These are generally particles less than 10-20 µm. Based on a review of existing performance data, Field and O'Connor (1996) report the limit of suspended solids removal effectiveness in a vortex separator is for particles with a settling velocity of 0.10 – 0.14 cm/sec (3.6 – 5.0 m/hr). Particles with a settling velocity lower than this are not expected to be effectively removed in a swirl concentrator. Based on Stokes Law, this minimum settling velocity is associated with a particle with spherical diameter of approximately 40-µm and a specific gravity of 2.65 at 20^{o}C (Wanielista and Yousef, 1993).

Figures 3-6 and 3-7 illustrate the effect of decreasing particle size and increasing flow rate on solids removal efficiency for a Vortechs™ unit and a Downstream Defender™ unit, respectively. These results, obtained by the respective manufacturers under laboratory conditions, illustrate that solids removal efficiency declines with decreasing particle size and increasing flow rate. In both cases, a decline in removal efficiency is not observed at very low flow rates. These data indicate that there is not a minimum flow rate necessary to establish secondary currents and achieve treatment in a swirl concentrator. Rather, gravity separation remains the primary removal mechanism at low flow rates.

The following section provides an overview of modeling efforts, laboratory tests, and field evaluations conducted on swirl concentrators. The modeling efforts are important design tools for the development and testing of swirl concentrators. Designs of swirl concentrators are frequently based on data derived from the testing of model-scale units and on the use of dimensionless parameters to scale-up the design to larger units.



Plan View



Cross Section View

Figure 3-5: Conceptual representation of primary and secondary currents in a swirl concentrator. Secondary currents, generated by circular flow path of the primary currents, act to concentrate solids in the center of the treatment unit.

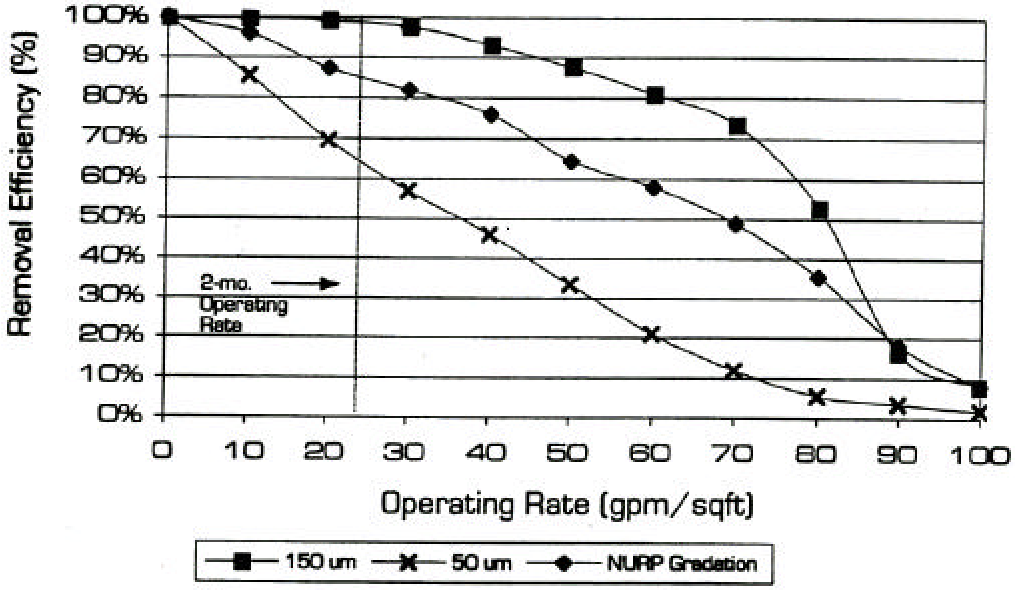


Figure 3-6: Effect of hydraulic application rate (gpm/ft^2 of grit chamber area) on solids (SG = 2.65) removal efficiency for a Vortechs™ Treatment System. Removal efficiency curves are shown for water with three particle size gradations: one comprised of particles 100-150 µm (labeled 150 µm), one comprised of particles 38 – 75 µm (labeled 50 µm), and one comprised of particles 20 – 2,000 µm, as specified by the National Urban Runoff Program (labeled NURP). The "2-mo operating rate" refers to the recommended HAR of 24 gpm/ft^2 for a 2-month return period storm. (Source: Vortechnics™, 1998).

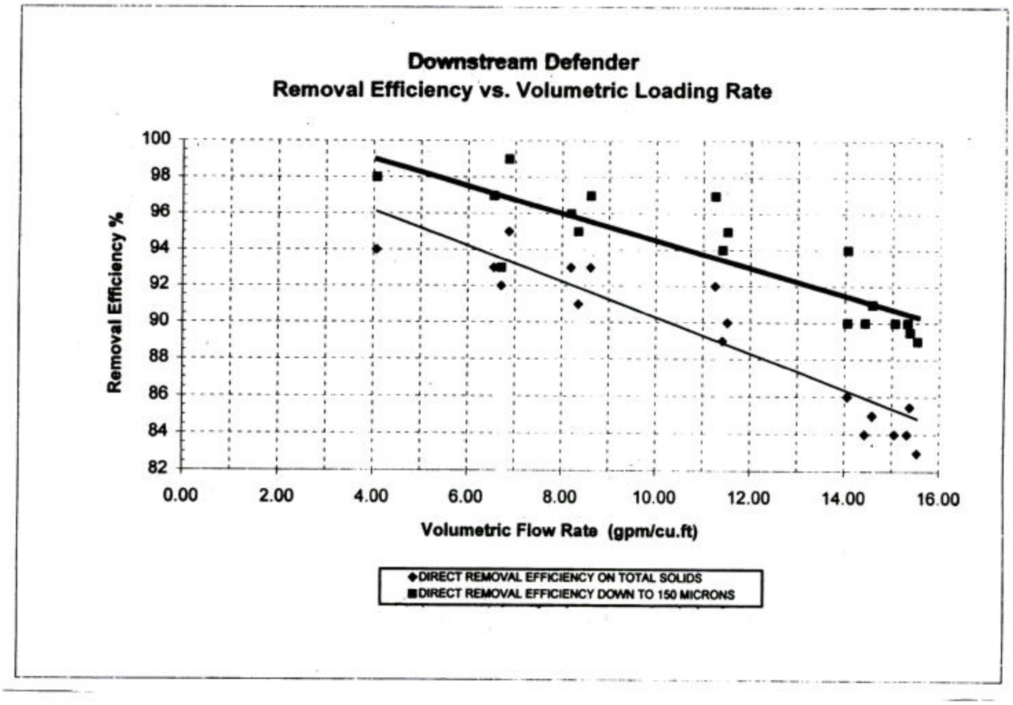


Figure 3-7: Effect of hydraulic application rate (gpm/ft^3 of treatment unit volume) on removal efficiency of a Downstream Defender™ for total suspended solids and for particles greater than 150 µm (Source: H.I.L. Technology, 2000).

In the original design of the CSO flow regulator/settleable-solids concentrator, EPA (1978) conducted hydraulic and mathematical modeling to develop an optimum design configuration. Results of the modeling were then tested at a large pilot facility receiving untreated sewage in Toronto, Canada. Pilot testing indicated that the 12-ft diameter swirl concentrator achieved 60% and 42% removal of settleable solids for an HAR of 1.8 gpm/ft^2 and 2.8 gpm/ft^2, respectively. Further, TSS removal efficiencies of 43% and 25% were observed for the same two HARs. Analysis of the settling velocity of influent solids to the pilot facility indicated that 60-80% of the solids had a settling velocity of 0.2 cm/sec or greater. The study concluded that the primary advantages of swirl concentrators over traditional primary settling tanks were a higher HAR and a lower detention time to achieve comparable solids removal. However, it was also concluded that the swirl concentrator was less economical than conventional settling tanks for applications where greater than 60% removal of suspended solids is required.

Based on the results of the modeling and pilot evaluations, EPA (1978) developed a design procedure based on empirical design charts relating solids removal efficiency to wastewater flow rate for units of varying diameters. Once the desired removal efficiency is picked, the corresponding diameter can be chosen, the remaining unit dimensions (e.g., inflow pipe diameter, weir height, etc.) are given in proportion to the unit diameter. As stated previously, however, these design procedures and performance estimates were based on the analysis of swirl concentrators receiving untreated sewage and therefore may not be applicable to the evaluation of “ultra-urban” technologies. Solids in sewage are lighter, more organic, and have different settling characteristics than those in stormwater. This is believed to be the main factor that allows “ultra-urban” units such as the Vortechs™ and Downstream Defender™ to achieve higher solids removal efficiencies at higher HARs than the original EPA swirl concentrator.

Andoh and Smisson (1994) reported results comparing removal efficiencies based on a semi-empirical design model to observed removal efficiencies at several wastewater treatment sites. The model was developed for the Storm King ™ unit, a precursor to H.I.L. Technology’s Downstream Defender ™, but with a separate underdrain for solids removal (similar to the original EPA CSO swirl concentrator). The general form of the model is as follows:

$$D^2S_v/Q = K_a^{K_b}[(N/R)(1-P/P)]^{0.5} \qquad (3\text{-}2)$$

where:
D = diameter of separator, ft
S_v = settling velocity of particle, ft/sec
Q = flow rate, ft^3/sec
N = ratio between solids concentration in the underflow to that in the overflow
R = ratio of overflow to underflow flow rates
P = underflow proportion (underflow flow rate / Q)
K_a = empirical coefficient, unitless
K_b = empirical coefficient, unitless

The empirical coefficients K_a and K_b were derived for several tank arrangements and geometries based on calibration of separator units. The reported comparisons between model predictions agreed closely with observed removal efficiencies for several operating units. Both this study and the EPA (1978) design guidelines discussed earlier illustrate the practical value of empirical design models to describe the complex flow field and solids removal mechanism of swirl concentrators.

Deamer et. al. (1994) conducted a detailed dimensional analysis, involving 13 parameters and 3 dimensions, to model the hydrodynamics of vortex separators. The relationship between the Froude number and removal efficiency was examined for three differently sized units and two particle size ranges. The relationship was found to be similar for the differently sized separators for particles with settling velocities in the range of 0.26 – 0.57 cm/sec; however, the relationship did not hold between different separators for larger particles (settling velocity range of 0.79 – 1.97 cm/sec). The authors speculated that the relationship did not hold because of different inlet Reynolds numbers between units. This illustrates conflicting design requirements between Froude similarity and Reynolds similarity.

Vortechnics Inc. (2000) reported results for 7 months of monitoring a Vortechs™ unit receiving runoff from a building and parking lot in Yarmouth, Maine. An overall removal efficiency of 80% was reported based on flow-weighed influent and effluent samples for 20 storms.

Brombach et al. (1993) monitored a pair of vortex separators receiving CSO in Tengen, Germany during 6 storms over a four-month period. The units were equipped with separate “foul-water” underflows to remove concentrated solids. Based on mass removal, efficiencies were reported for TSS (32% - 91%), settleable solids (29 – 97 %), chemical oxygen demand (30% - 92%), and phosphorous (46%; one storm only). Comparison of particle size distributions between underflow and overflow samples indicated that separation was achieved only for particles with a diameter greater than 30 microns.

Pisano et. al. (1984) reported results for a pilot-scale swirl concentrator (10.5-ft diameter) with solids underflow receiving stormwater from a separate storm sewer. A non-flow weighted average TSS mass removal of 28% was reported. This low removal efficiency was attributed to the silty nature of the stormwater and the associated low settling velocities (Field and O’Connor, 1996).

A large swirl concentrator facility in Washington D.C. (Pisano et al., 1984) exhibited a net TSS removal efficiency of 12%. This was attributed to low settling velocities of particles in the influent (Field and O’Connor, 1996). Fifty percent of the influent TSS had settling velocities less that 0.1 cm/sec (3.6 m/hr).

Vortechnics Inc. (1999b) conducted laboratory tests on a full-scale (2.8 cfs) Vortechs™ unit to evaluate oil and grease removal. 10w40 motor oil was added to the influent to produce concentrations between 15 – 90 mg/L. Removal efficiency was observed to decline with HAR; for example, 90% removal was observed at HAR = 24 gpm/ft^2, and 10% removal was observed at HAR = 100 gpm/ft^2.

Section 4: Screening Technologies

For the purposes of this review, screening technologies are considered separately from filtration technologies. This distinction is based fundamentally on the size of individual particles removed by each technology. Screening refers to the removal of larger particles, gross debris, and trash via flow through a permanent separation element (i.e., screen). Filtration (Section 5) refers to removal of finer particles by a replaceable filter media. The application of direct screening processes is common in stormwater and combined sewer systems. Direct screening refers to the alignment of screen apertures directly into the flow path. "Trash racks" are the most commonly used direct screening process; other direct screening systems, with bar spacings as fine as 6mm, are also used (Wong, 1997). However, direct screening mechanisms are susceptible to blocking and associated discharge reduction and potential for flooding. Continuous Deflective Separation (CDS®), manufactured by CDS Technologies®, Morgan Hill, California, was selected for detailed evaluation in this review because of an innovative design approach to prevent blocking of a screen system.

4.1 Continuous Deflective Separation (CDS®)

CDS® involves the removal of solids from stormwater by an indirect, non-blocking, and non-mechanical screening mechanism. A schematic of a CDS® unit is shown in Figure 4-1. Stormwater is diverted from the conveyance system by a weir, enters the treatment unit through a tangential inlet, and flows in a circular path across a stainless steel screen. Available screen apertures range from 0.6 - 4.7 mm. Selection of the appropriate screen size is based on site-specific characterization of particles and debris in the stormwater to be treated. A screen aperture of 4.7 mm is typically used for CSO applications or for runoff with large amounts of gross trash and debris. A screen aperture of 1.2 mm is more commonly used for stormwater applications. Settleable solids that do not pass through the screen accumulate in the catchment sump, and floatable contaminants, trash, and debris remain on the water surface. Oil can be removed in the unit if optional sorbents are added to the treatment chamber. Stormwater flow in excess of the design flow bypasses the unit over the diversion weir and continues in the conveyance system. The unit is periodically cleaned out with a vacuum truck to remove accumulated contaminants. CDS Technologies® manufactures pre-cast units with treatment capacity between 1.1 – 50 cfs, ranging in diameter from 6 – 17.5 ft, with a sump capacity of 5.3 – 14.1 yd^3. The corresponding HARs range from 17 – 93 gpm/ft^2. Cast-in-place units with peak treatment capacity up to 300 cfs are also available.

CDS Technologies® recommends sizing the unit to treat smaller, frequent storms, such as the 3- or 6-month storm events. This recommendation is based on hydraulic modeling reported by Wong (1997), in which 100 years of recorded rainfall data for Melbourne, Australia were used to assess the "diversion efficiency" of a stormwater treatment device as a function of the diversion weir height. Diversion efficiency is defined as the percentage of total runoff that is diverted from the conveyance system to the treatment unit. Results indicated that a weir height set to bypass flow in excess of a 3-month event achieved a diversion efficiency of 93% (i.e., 93% of the volume of stormwater over a

Figure 4-1: Schematic of CDS® unit (Source: CDS Technologies® Internet Page: www.cdstech.com.au/usa/index.html)

100-year period was diverted into the treatment unit). These results indicate that the majority of stormwater flow over a 100-year period will receive treatment even if the weir is set to bypass the unit as frequently as four times per year. As will be shown in the discussion of the CDS® treatment mechanism (Section 4.2), inlet velocity to the treatment chamber is an important factor in preventing screen blockage. Sizing a CDS® unit to treat only smaller, more frequent storms helps to prevent long periods during which the unit receives a flow much lower than its design flow (i.e., long periods during which the inlet velocity is very low).

4.2 Treatment Mechanism

In contrast to vortex separators, the CDS® unit does not rely on secondary currents to concentrate solids in the center of the treatment unit. Rather, trash, debris, and particles in the influent are removed by a non-blocking stainless steel screening mechanism. The screen apertures are elliptical and are aligned with the longer ellipse axis in the vertical direction. The width of the shorter ellipse axis is a design specification that depends on site-specific needs and stormwater characteristics. The available width range of screen apertures is 0.6 - 4.7 mm.

The screen surface area is large relative to the inlet pipe area, resulting in a radial flow velocity through the screen that is an order of magnitude lower than the inlet pipe velocity (Wong, 1997). A surface velocity distribution for a CDS® unit from Wong (1997) is provided in Figure 4-2. As shown in Figure 4-2, the highest tangential velocities are observed on the outer unit wall, adjacent to the separation screen. This velocity distribution maintains a constant shear force across the screen when water is flowing into the unit. Because of the slow radial velocity of water through the screen, the pressure differential force acting on particles in a direction perpendicular to the screen is small relative to the tangential shear force. Particles are prevented from being held against the screen by this significantly higher tangential shear force compared to low pressure differential force perpendicular to the screen (Wong, 1997). This mechanism allows the unit to achieve removal of particles and debris without blocking the screen.

The mechanism by which particles smaller than the screen aperture size are removed by a CDS® unit is not well understood (Wong, 1997). Particles with a higher settling velocity will tend to settle to the collection sump more quickly and will thus have less “exposure time” near the screen; consequently, there is a lower probability of these particles passing through the screen. Conversely, particles with a low settling velocity will not settle to the collection sump as quickly and will therefore be exposed to the screen for a longer period of time. This will increase the probability that these particles will pass through the screen and not be removed by the unit.

Wong (1997) states that the relationships between inlet pipe velocity and tangential velocity are “near-linear” relationships, and that the ratio of tangential velocity to radial velocity is consistent for a wide range of discharges. Further, Wong (1997) reports that tracer studies have indicated that flow rates through the screen are highest near the inlet

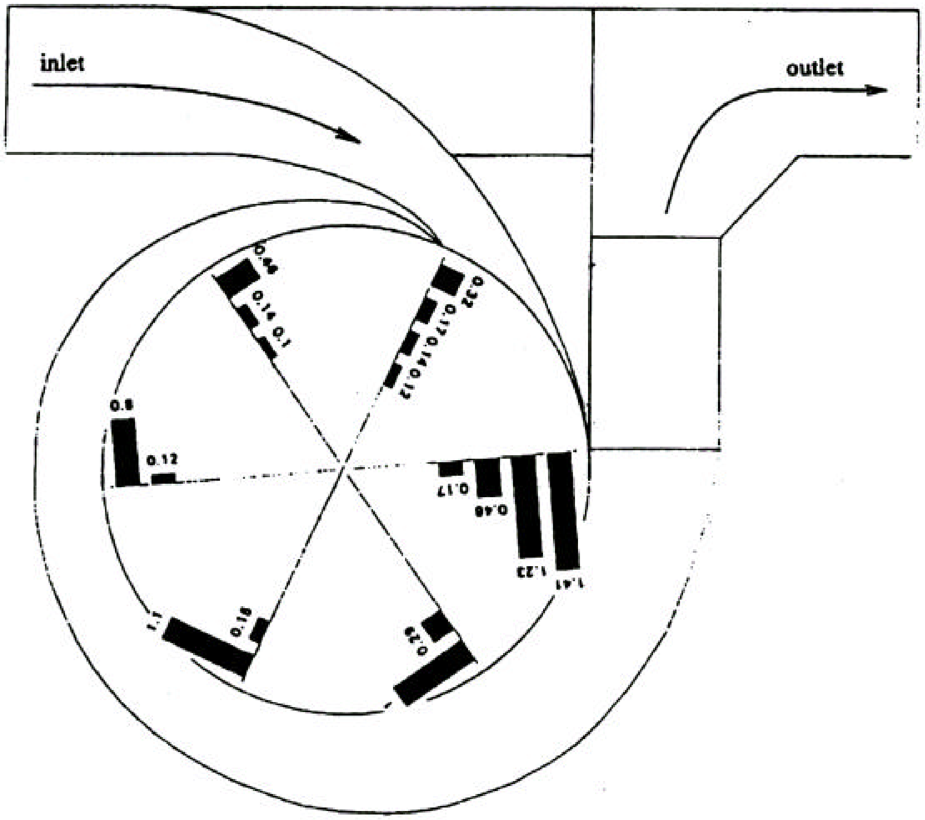


Figure 4-2: Surface velocity profile for a CDS® unit, showing that the highest tangential velocities are maintained adjacent to the screen. The units of velocity are m/sec (Source: Wong, 1997).

and decrease with increasing distance along the screen from the inlet. However, further details on this work are not available.

4.3 Reported Performance and Design Methods

Wong (1997) and researchers at UCLA and Portland State University (Stein, 1999) have reported removal efficiencies for CDS® units as a function of particle size and screen aperture size. Results of both studies are summarized in Table 4-1 (from Stein, 1999). The tests were conducted under laboratory conditions using graded sand and coarse sediment particles (SG = 2.65). For the 4.7 mm screen evaluation, the particle size reported in Table 4-1 is the average size of the particles in a particular gradation. For the 1.2 mm screen evaluation, the range of particle sizes in each gradation is reported.

Table 4-1: Screening Efficiencies as a Function of Particle Size (S.G. = 2.65) for 1.2 mm and 4.7 mm Screen Apertures for a CDS® Unit

4.7 mm Screen		1.2 mm Screen	
Average Particle Size (µm)	Particle Removal Efficiency (%)	Particle Size Range (µm)	Particle Removal Efficiency (%)
>4,700	100	>1,200	100
2,350	100	420-600	93
1,567	93	300-420	85
940	50	144-300	30
		84-144	22

Source: Stein, 1999

The data in Table 4-1 illustrate that the CDS® unit is capable, under laboratory conditions, of removing particles that are smaller than the aperture size. Further, removal efficiency is observed to decline with decreasing particle size. Wong (1997) conducted a similar laboratory evaluation to determine the effect of inlet pipe velocity on sand trapping efficiency for a CDS® unit with screen apertures of 2.4 mm. The removal efficiency for six sand gradations, with mean diameters ranging from 200-780 µm, was calculated at inlet pipe velocities of 0.5, 1.0, and 1.4 m/sec. The results of this evaluation are provided in Figure 4-3 and indicate that the unit removed particles smaller than the screen aperture size. Further, removal efficiency was observed to decline with decreasing particle size, and removal efficiency was observed to be largely independent of inflow velocities for the range tested (Wong, 1997).

Jago (1997) conducted an analysis of litter and sediments captured from a CDS® unit receiving runoff from a 50-hectare mixed commercial/residential suburb of Melbourne, Australia. Litter and sediment that accumulated in the unit over a 97-day period were collected during a routine cleanout and sampled for laboratory analysis. The accumulation rate of litter and sediment in the unit was calculated as 0.1m^3/ha/year, based on an assumed bulk density of litter and sediment of 1,500 kg/m^3. Dry-weight percent compositions of gross litter (26%), vegetative matter (39%), and inorganic sediments (35%) were reported. Particle size analysis of the captured sediments, conducted after combustion at 700 ^{o}C, indicated that 85% of the particles (by weight) was

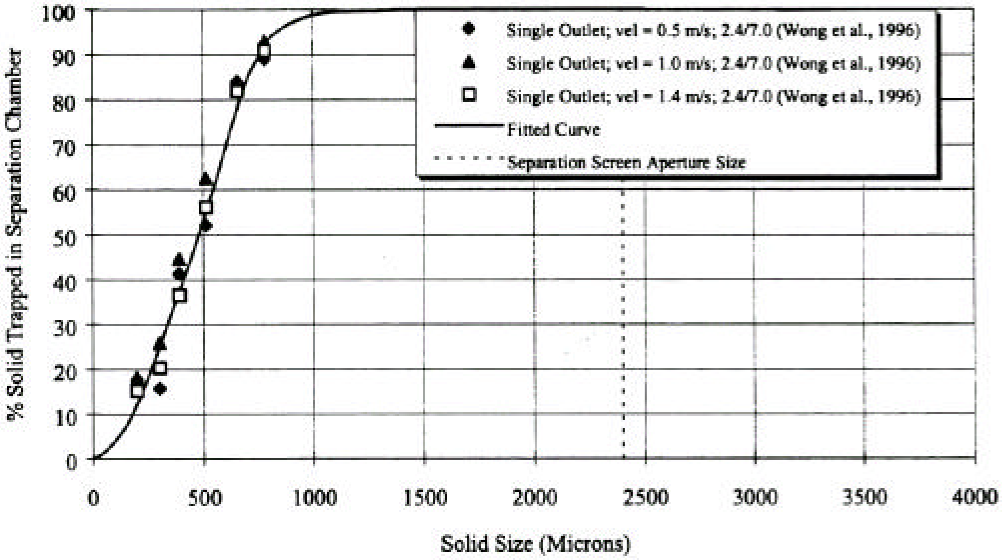


Figure 4-3: Relationship between pipe inlet velocity and solids removal efficiency for a CDS® unit with screen apertures of dimension 2.4 mm by 7.0 mm. Results for 6 sand grain (SG = 2.65) size ranges and 3 inlet pipe velocities are shown, indicating that removal efficiency declines with decreasing particle size, and that removal efficiency is largely independent of inflow velocities for the range tested (Source: Wong, 1997).

smaller than the screen aperture size of 4.7 mm, with 50% of the material being smaller than 200-µm and 11% being smaller than 50 µm.

Jago (1998) conducted an analysis of sediments collected in a CDS® unit with receiving runoff from a 217-hectare catchment at the Melbourne Airport in Australia. Sediment that accumulated over a 33-day period, during which 1.5 cm of rain fell, was collected and sampled for laboratory analysis. Particle size distribution of the sediment, conducted after combustion at 600 ^{o}C, indicated that a wide range of particle sizes were captured in the unit, from less than 50 µm up to 10 mm. Approximately 90% of the particles (by weight) were larger than 0.5 mm, and 50% were larger than 2 mm. The unit was equipped with a 4.7-mm aperture screen.

Allison et al. (1998) monitored a CDS® unit in Australia for a period of 12 months and concluded that it achieved a 99% removal efficiency for gross pollutants larger than the screen aperture size (the remaining 1% that was not removed was contained in water that bypassed the unit during high flows). Water quality monitoring was also conducted by collecting influent and effluent samples for 7 storms during the evaluation. The samples, collected during the initial phase of the storms, indicated that the CDS® unit reduced TSS concentrations from above 200 mg/L to a range of 150 – 200 mg/L. When influent TSS concentrations were below 150 mg/L, the CDS® unit did not appear to achieve any further reduction in TSS. This limited removal efficiency may be a function of the screen aperture size in the unit, which was 4.7 mm, and the concentration of fine particles in the stormwater. The data in Table 4-1 for a 4.7 mm screen indicate that removal efficiency declines with decreasing particle size, with only a 50% removal efficiency observed for particles with an average diameter of 940 µm. Therefore, the reduction in TSS from above 200 mg/L to 150 mg/L observed by Allison et. al (1998) may have been related to the removal of larger particles in the stormwater. However, particle size distribution results for the stormwater were not reported, so this cannot be confirmed.

An evaluation at UCLA (reported in Stein, 1999) found that 80% of free oil and grease was removed by a CDS® unit under laboratory conditions by adding polypropylene and co-polymer sorbent material to the separation chamber.

Section 5: Filtration Technologies

As discussed in Section 4, filtration technologies are distinguished from screening mechanisms in two regards:

- Filtration technologies are typically capable of removing finer particles than screening
- Filtration is accomplished by a replaceable filter media

Effective removal of TSS and other parameters from stormwater has been achieved has been achieved with sand filters; however, these systems are expensive to construct and require frequent maintenance to ensure proper hydraulic performance (e.g., Keblin et al., 1997). "Ultra-urban" filtration systems are designed to required less space and require less maintenance than traditional filters. The Stormfilter™ system, manufactured by Stormwater Management, Portland, Oregon, was selected for detailed examination in this review because of the innovative filter cartridge design and the range of available filter medias.

5.1 Stormfilter™ System

A schematic of the Stormfilter™ system is shown in Figure 5-1. Influent first enters a pretreatment bay, where heavy sediments settle out and floatable contaminants are trapped. Water exits the pretreatment bay via a flow spreader into the main filtration vault and gravity flows through filter cartridge units. The effluent from each filter cartridge is collected in an underdrain system and flows to the outlet bay. Flow in excess of the filtration capacity bypasses the filter cartridges and flows directly to the outlet bay. The treatment capacity of pre-cast units is variable and depends on the number of cartridges in the treatment unit. Each filter cartridge is approximately 19" in height and 19" in diameter (corresponding to an approximate cartridge surface area of 7.9 ft^2), and has a design hydraulic capacity of 15 gpm. This corresponds to a HAR of approximately 1.9 gpm/ft^2 of cartridge surface area. Maintenance for the units involves minor pump-out of water from the unit and replacement of the filter cartridges. Stormwater Management estimates that maintenance for an 8' x 16' unit with 30 cartridges (treatment capacity approximately 1 cfs) is typically required once per year (depending on contaminant loads) and takes approximately 2.5 hours.

The primary operational feature of the Stormfilter™ unit is the filter cartridge (Figure 5-2). During a storm, the float system in the center of the filter cartridge primes a siphon that draws stormwater through the filter media to the central drainage tube. As the treatment vault fills with water, trapped air is purged from the beneath the cartridge hood through the air relief valve. No filtration occurs until the water level rises to near the top of the cartridge; at this point, buoyant forces lift the float and allow water to exit through the underdrain. The air relief valve closes simultaneously and creates the siphon effect, which increases flow potential across the media and helps to distribute contaminants along the entire height of the filter media. The siphon effect continues until the water level drops to the bottom lip of the cartridge hood. At this point, the siphon is broken and

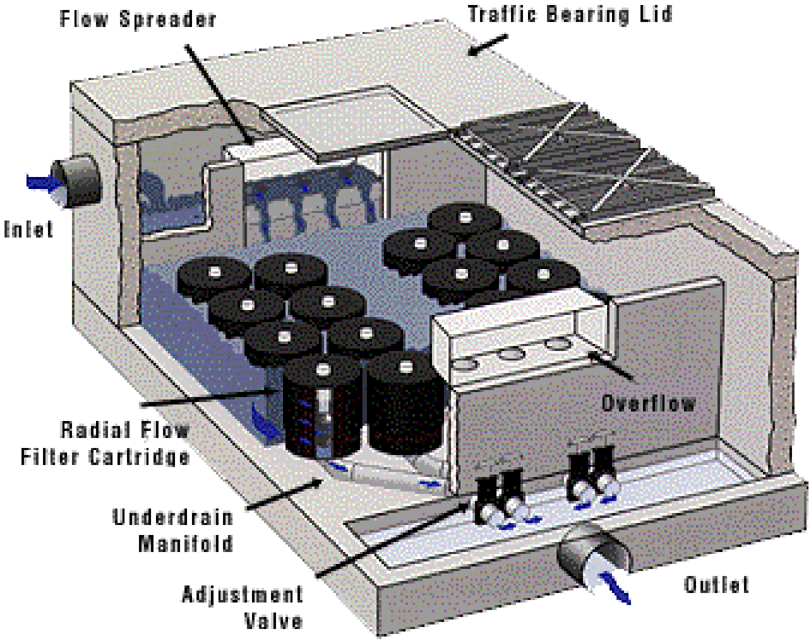


Figure 5-1: Schematic of Stormfilter™ System (Source: Stormwater Management, Inc. Internet page: www.stormwatermgt.com/products.html)

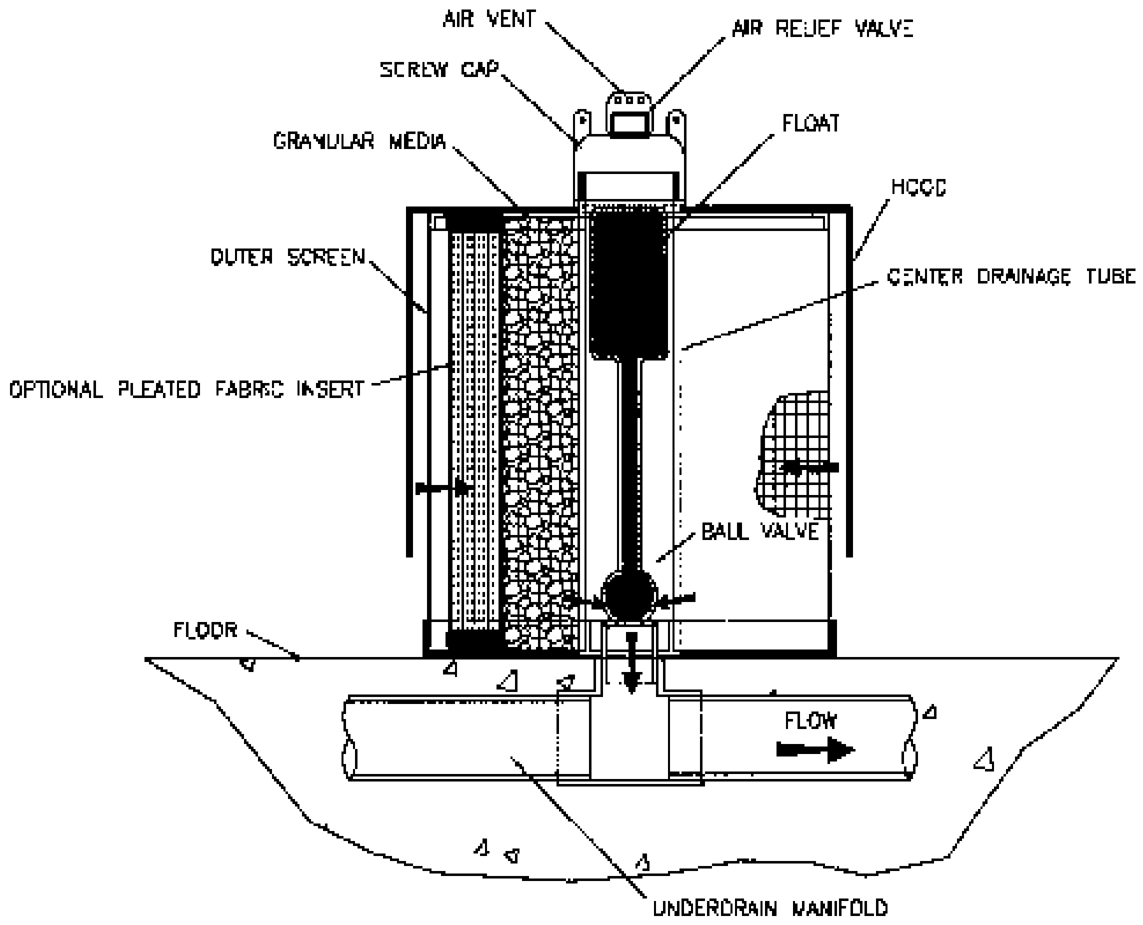


Figure 5-2: Cross Section of Stormfilter™ filter cartridge (Source: Stormwater Management, Inc. Internet page: www.stormwatermgt.com/engin.html)

air bubbles are forced under the hood, agitating the surface of the filter media. This creates a self-cleaning mechanism that causes a portion of the accumulated sediment to drop to the floor of the vault.

5.2 Treatment Mechanism

The mechanism by which contaminants are removed by a Stormfilter™ system depends on the type of media being used. Stormwater Technology manufactures several types of filter media that can be placed interchangeably in the filter cartridges. The appropriate filter media depends on site-specific discharge requirements and stormwater characteristics. Available media and the associated treatment mechanisms are summarized as follows:

- Perlite, or aluminum silicate, a naturally occurring volcanic ash; used for TSS and oil/grease removal. Suspended particles are trapped in angular projections on the media.
- CSF® Leaf Media, made of deciduous leaves that are composted and granulated; used for TSS, oil/grease, and soluble metals. Suspended particles are trapped on projections on the media, and soluble metals and oil/grease adsorb to the media. A disadvantage of this media is that it can increase phosphorous and nitrate concentrations in treated water.
- Zeolite, a naturally-occurring mineral; used to remove soluble metals, ammonium, and some organics. A modified zeolite, termed surface modified zeolite (SMZ), has a positive charge on the surface that attracts and captures anions such as ortho-phosphorous and nitrate.
- Pleated fabric insert, for removal of finer TSS. Two pore sizes are available: 30 μm and 70 μm. The fabric insert fits inside the standard filter cartridge, leaving a space between the insert and the central drainage tube where granular media can be placed.
- GAC, granular activated carbon. Organics and oil/grease adsorb to the surface of the media.
- Iron-Infused Media, an open-cell media infused with small bit of iron; this media carries a 3^+ surface charge and is used to remove phosphorous, soluble copper and zinc.

5.3 Reported Performance and Design Methods

Many reports exist in engineering trade journals regarding the Stormfilter™ system (e.g., ENR, 1997; Water, Environment, and Technology, 1997; Pollution Engineering, 1997). However, these reports do not typically contain water quality monitoring data. One study, conducted by the Unified Sewerage Agency of Washington County, Oregon, was reported in ENR (1997). This study, conducted over a three-year period, concluded that a

Stormfilter™ system using CSF® media exhibited removal efficiencies up to 90% for TSS, 85% for oils and grease, and 82-98% for metals.

Wigginton and de Ridder (1999) reported and overall TSS removal efficiency of 73.8% (mass basis) for a single Perlite-filled Stormfilter™ cartridge under laboratory conditions. The influent particle gradation was comprised of 3.5% clay, 60% silt, 30% fine to medium sand, and 6.5% coarse sand, with 82% of the particles smaller than 106 microns. TSS removal efficiency did not decline as sediment accumulated in the unit. The filtration rate through the cartridge was initially14.1 gpm (1.79 gpm/ft^2) and dropped by only 3.5% after 13 lbs (dry wt) of sediment had been removed. A 44% decrease in filtration rate was observed after 20 lbs of sediment were removed, and the filtration rate approached zero after 23.6 lbs of sediment had been removed. Of the total mass of sediment removed (23.6 lbs), 65% (15.4 lbs) were removed by the filter cartridge and 35% (8.3 lbs) settled out on the floor of the treatment tank. It was estimated that the majority of particles removed were greater than 30 microns.

Stormwater Management (2000) conducted laboratory tests to evaluate equilibrium adsorption of phosphorous to iron-infused media. Adsorption is typically modeled by the study of isotherms, or equilibrium relationships between contaminant concentration in the fluid phase and concentration in the adsorbent particles. Isotherms that are convex upward are considered favorable, because a relatively high contaminant loading on the media can be obtained at low contaminant concentrations in the fluid. Conversely, isotherms that are concave upward are unfavorable because relatively low contaminant loadings on the media are obtained. Isotherm data collected by Stormwater Management (2000) are shown in Figure 5-3. A near linear adsorption isotherm was observed up to a media loading of 779 mg P / kg media and a fluid concentration 42 mg ortho-P / L.

Stormfilter™ (2000) also conducted laboratory tests to assess removal efficiencies for TSS and dissolved phosphorous on a horizontal flow column containing 4 inches of Perlite media surrounding 3 inches of iron-infused media. The particle size distribution of the test water was similar to that of Wigginton and de Ridder (1999), with 82% of the particles being smaller than 106 μm. Ten trials were conducted, each involving the filtration of 12 L of water at a flow rate set to simulate the design flow rate of 15 gpm. TSS removal efficiencies increased from 23% to 60% over the first 5 filtration cycles, indicating that the filter media matured and stabilized. Removal efficiency then ranged between 60 – 76% for 5 subsequent filtration cycles, with an overall efficiency of 58%. Average dissolved phosphorus removal was 47% for 10 experiments with an influent concentration range of 0.02 – 0.32 mg ortho-P/L.

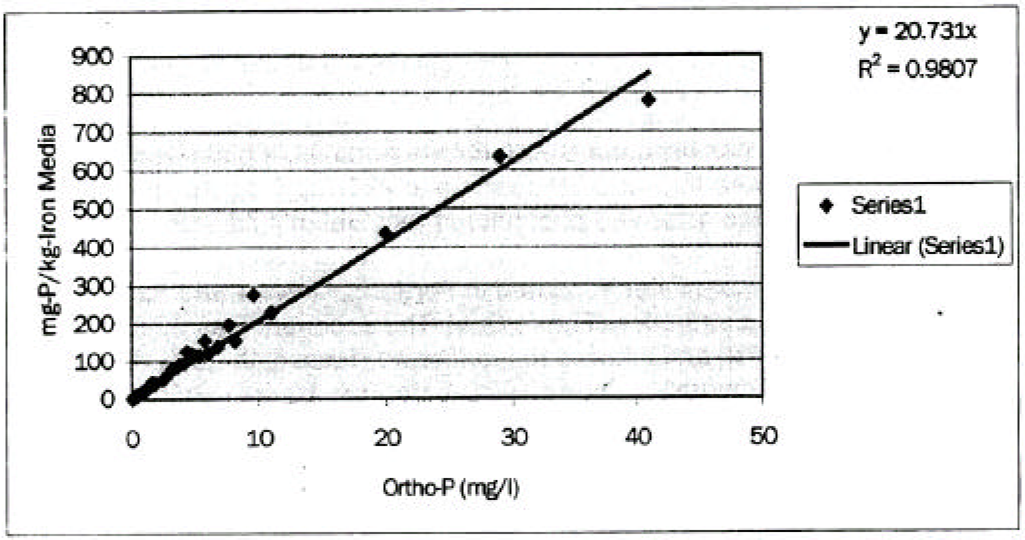


Figure 5-3: Ortho-phosphorus equilibrium adsorption isotherm for iron-infused media (Source: Stormwater Management, Inc., 2000).

Section 6: Performance Evaluation

The following section provides an overview of procedures used to evaluate the performance of stormwater treatment technologies. A discussion of "storm event mass-based" and "hydrology-based" performance monitoring methodologies is provided, and a proposed procedure for demonstrating the effectiveness of new stormwater treatment technologies is summarized.

6.1 Storm Event Mass-Based Calculation of Removal Efficiency

A number of publications (Minton, 2000; APWA, 1999; Field and O'Connor, 1996; Brombach et. al., 1993) have recommended that the performance evaluation of stormwater treatment technologies be based on the mass of contaminants removed by a treatment unit during an entire storm event. Performance results for several of the technologies discussed in this paper indicate that contaminant removal efficiency is affected by both the hydraulic load to the unit and the concentration and nature of suspended solids in the influent. Efficiency declines with increasing flow rate through the unit and increases as the influent contaminant concentration increases (Minton, 2000). Thus, storm event mass-based removal efficiency has three main limitations:

1) For each monitored parameter, only one removal efficiency calculation is obtained per storm event.
2) The calculated removal efficiency represents not only the treatment efficiency of the unit, but also the characteristics of the storm event with possibly varying flow rate and influent contaminant concentrations.
3) Because regional storm hydrographs vary widely, the ability to use mass-based performance data from one site to predict performance at another site is limited.

Storm event mass-based evaluation requires that both concentration and flow rate be measured for the duration of each monitored storm. Field and O'Connor (1996) summarize a mass-based performance monitoring approach to calculate a flow-weighted, average pollutant concentration, or event mean concentration (EMC), for a storm:

$$M = \sum_j [\ c_j\ Q_j\ \Delta t_j\ ] \qquad (3\text{-}1)$$

$$V = \sum_j [\ Q_j\ \Delta t_j\ ] \qquad (3\text{-}2)$$

$$EMC = M / V \qquad (3\text{-}3)$$

where:
M = storm-flow-event pollutant mass loading, kg
V = storm-flow-event volume, m^3
EMC = storm-flow-event flow-weighted average concentration, kg/m^3
c_j = average pollutant concentration between samples, kg/m^3
Q_j = average flow rate between samples, m^3/sec
Δt_j = time interval between samples, sec

Removal efficiency for a given storm event is then calculated as:

$$\text{Removal Efficiency} = [\ (M_i - M_e)/M_i\ ] * 100\% \qquad (3\text{-}4)$$

where:
M_i = storm event mass loading for influent, kg
M_e = storm event mass loading for effluent, kg

6.2 Hydrology-Based Calculation of Removal Efficiency

The Environmental Technology Evaluation Center (EvTEC), in conjunction with the Washington State Department of Transportation (WSDOT) has developed a hydrology-based performance monitoring procedure to mitigate the limitations of storm event mass-based performance monitoring in the upcoming “Ultra-Urban” Stormwater Treatment Technology Evaluation in Seattle, WA.

The hydrology-based performance monitoring methodology to be used for the EvTEC/WSDOT evaluation is described fully by EvTEC (2000). As with the storm event mass-based evaluation, the hydrology-based evaluation methodology requires that both concentration and flow rate be measured for the duration of each monitored storm. An automated time-paced sampling strategy will be used to monitor the concentrations of TSS, metals, and other pollutants in the influent and effluent of multiple treatment units. The basic premise of the method is to monitor changes in contaminant concentration for individual parcels of water that pass through the treatment unit. Influent and effluent samples will be collected from treatment units at regular time intervals during the course of a storm, and the influent hydrograph will be used to pair influent and effluent samples for individual “storm sampling periods.” The procedure for pairing influent and effluent samples is as follows:

- Within the storm sampling period, inflow to the unit will vary by less than 20% of the peak flow for that storm sampling period.
- The storm sampling period will be at least 8 times the estimated detention time of the unit.

Once the hydrograph has been used to identify the storm sampling periods, samples collected during each storm sampling period will be flow-weight composited into a single influent sample and a single effluent sample for each storm sampling period. These composite samples will then be analyzed for individual pollutants. Removal efficiency for each storm sampling period will be calculated as:

$$\text{Removal Efficiency (\%)} = [\ (C_i - C_o) / C_i\ ] * 100 \qquad (3\text{-}5)$$

where:
C_i = Flow-weighted influent concentration for the storm sampling period, mg/L
C_o = Flow-weighted effluent concentration for the storm sampling period, mg/L

To evaluate the data, removal efficiency will be correlated with the mean flow rate for each storm sampling period. Because removal efficiency is affected by both the operating flow rate and the influent concentration, results from the entire evaluation will be grouped into multiple concentration ranges for each pollutant, and removal efficiency as a function of operating flow rate will be determined for each concentration range. As a hypothetical example, three separate graphs of removal efficiency versus operating flow rate may be generated for TSS data: one for samples with influent concentration less than 50 mg/L, one for samples with influent concentration in the range 50 – 100 mg/L, and one for samples with influent concentration greater than 100 mg/L.

The intent of the EvTEC data evaluation procedure is to provide relationships between the reduction of contaminant concentrations and the flow rate through a given treatment unit for multiple influent concentration ranges. It is expected that these relationships can then be applied for different stormwater flows and contaminant concentrations at other locations.

6.3 Proposed Protocol for Evaluating New Technologies

The Stormwater Managers Committee of the Washington Chapter of the American Public Works Association (APWA) developed a proposed protocol for local jurisdictions in the Puget Sound region to use for evaluation of new stormwater treatment technologies (APWA, 1999; the protocol is available at www.mrsc.org/environment/water/water-s/apwa/protocol.htm). This protocol was developed to provide a tool by which regulators can compare alternatives and select the most appropriate treatment technology for a given application. Traditionally, reliance has been placed on the application of "Best Management Practices (BMP)," whereby a specific technology is required for an application, but a treatment standard is not associated with the BMP. This practice is employed because there is not currently a well-defined or enforceable performance standard for stormwater treatment technologies. One existing informal standard is "an aggregate removal of 80% total suspended solids (TSS) over all storms" (APWA, 1999). The origin of this standard is obscure (APWA, 1999), but the 80% removal standard was adopted in the Coastal Zone Act Reauthorization Amendments of 1990 and has also been informally adopted by some jurisdictions around the United States. However, this standard does not provide adequate guidance, such as sampling methodologies and data evaluation procedures, to assess compliance.

Rather than attempting to establish formal performance criteria, the basic premise of the APWA protocol is that in order to be acceptable, any new technology must perform as well as an existing technology that has been approved by the Washington Department of Ecology (DOE) for stormwater treatment. These technologies are detailed in DOE (1992) and generally include infiltration systems, wet ponds, sand filtration systems, swales, and wetlands. However, performance data on these "approved" systems are sparse, including only 3 studies on grass swales, 2 studies on wet ponds, and 3 studies on sand filters (Minton, 2000). AWPA used these data to generate performance curves relating removal efficiency to influent concentration for TSS, phosphorus, and zinc (a surrogate measurement for other metals and contaminants). The performance curves (referred to as the "line of comparative performance") are not based on a statistical relationship; rather, the line was manually drawn so that the majority of data from approved systems falls above the line (Minton, 2000).

The procedure to determine the performance of a new technology is to plot removal efficiency points as a function of influent concentration on the performance curves that were generated for grass swales, wet ponds, and sand filters. The data point to be plotted for each storm is calculated as follows:

$$\text{Storm Removal Efficiency} = [\ (EMC_i - EMC_e) / EMC_i\ ] * 100\% \qquad (3\text{-}6)$$

where:
EMC_i = event mean concentration for influent, kg/m^3
EMC_e = event mean concentration for effluent, kg/m^3

The APWA protocol recommends that if 90% of the data points (80% for phosphorous) fall above the "line of comparative performance," then the technology should be considered equivalent to an approved technology. The APWA protocol outlines data requirements to be used in the comparison. These requirements are briefly summarized as follows:

- One to three test sites, including medium density residential, retail commercial, and non-retail commercial areas
- A minimum of 10 storms per site, or 30 storms if only one site is studied
- Storm depth between 0.25 – 1.00 in; larger storms permitted if the technology's design flow is not exceeded
- Storm runoff duration between 7.5 – 30 hr
- Average rainfall intensity between 0.02 – 0.08 in/hr; higher intensities permitted if the technology's design flow is not exceeded
- A minimum of 10 sub-samples per storm; flow-weighted composite of these sub-samples to determine the EMC
- At least 75% of the volume of each storm must be sampled
- Analyses for TSS, pH, zinc, copper, cadmium, total phosphorus, bioavailable phosphorus, and total nitrogen

To calculate an overall efficiency based on all storms that were monitored for a given unit, Minton (2000) and APWA (1999) recommend that the following formula be applied:

$$\text{Overall Efficiency} = [\,(A-B) / A] * 100\% \qquad (3\text{-}7)$$

where:
A = geometric mean of all influent EMCs, kg/m^3
B = geometric mean of all effluent EMCs, kg/m^3

It is evident that this evaluation methodology requires an extensive investment of time and money to establish the equivalency of a technology. As of May 2000, no “unapproved” technology had completed the comparison procedure.

Section 7: Application of Technology Review Findings

The following section applies the findings of the technology review to develop an example design protocol. This protocol is intended to illustrate the factors that must be considered when selecting and sizing an "ultra-urban" stormwater treatment unit. It also illustrates data limitations that complicate and add uncertainty to the selection and design of a treatment unit. In addition to the design steps presented below, individual technology vendors may have additional data requirements and design steps that should be considered.

The following design protocol does not address the motivation for providing treatment to a specific stormwater source. There are numerous reasons why stormwater treatment may be required, primarily related to compliance with local, state, or federal water quality regulations. Full consideration of these factors is beyond the scope of this paper; therefore, the protocol outlined below assumes that a decision has been reached that improvement of the water quality of a specific stormwater source is necessary.

Design Step 1: Characterize the Source

It is necessary to understand both the hydrology and the pollutant loads of the stormwater source. When selecting an "ultra-urban" treatment unit, the peak flow rate, rather than the total runoff volume, is the most important hydrologic parameter. The peak flow rate can be determined by a standard hydrological evaluation such as the rational method, in which runoff flow rate is calculated based on the intensity of rainfall, the size of the drainage basin, and the basin land use (for example, the amount of impervious surface). Runoff flow rates should be calculated for rainfall intensities associated with various design storms, such as the 3- and 6-month and the 1-, 2-, 5-, 10-, and 100- year return period storms. To check the hydrology calculations, flows should be monitored at the point in the stormwater conveyance system where the treatment unit will be installed. A comparison of flow in the system to rainfall intensity for several storms will allow calibration of the hydrology evaluation. The end product of the hydrology evaluation is a table of peak runoff flow rates associated with several different design storms.

Water quality evaluations are necessary to characterize the type, concentration, and variability of pollutants in the stormwater source. Analyses that may be conducted, depending on water quality and regulatory issues, include TSS, metals (dissolved and total), and nutrients. In addition, the results of this technology review suggest that settleable solids and particle size distribution analyses should be conducted. Water quality samples should be collected during different portions of the storm hydrograph; specifically, samples should be collected during the onset of runoff, during the rising limb of the hydrograph, and during the period of peak runoff. This will determine how contaminant concentrations vary during the course of a storm. Sampled storms should be preceded by an antecedent dry period of 2-3 days to allow for pollutant build-up in the drainage basin.

Design Step 2: Determine Treatment Goals

Specific treatment goals will depend on the regulations motivating the installation of the stormwater treatment unit. Two types of treatment goals are possible. The first is based on achieving a specific water quality goal, such as an 80% reduction in TSS. This type of requirement for mass reduction based on a percent of the influent contaminant load is typical for stormwater applications. As discussed in Section 6, stormwater BMPs have been required to achieve 80% removal of TSS, but specific methods to measure this removal efficiency have not been formalized.

A second type of treatment goal is to achieve *some degree of treatment* for a specific design storm. For example, the *Stormwater Management Manual for the Puget Sound Basin* (DOE, 1992) requires that a BMP be used to provide treatment for flow up to the 6-month, 24-hr return period. However, there is not an associated water quality treatment goal for this requirement. It is important to note that these two types of treatment goals are not necessarily mutually exclusive. For example, it is possible to have a requirement to achieve 80% TSS reduction for all storms up to a design storm. In addition, if source characterization (Design Step 1) indicated that the majority of pollutants are carried during the initial stages of a storm, it may not be necessary for a treatment unit to treat the peak flow of a design storm to achieve a significant mass-reduction in pollutants. The research conducted for this technology review indicated that there is currently no clear consensus on what appropriate treatment goals should be applied to stormwater treatment units.

Design Step 3: Identify Site-Specific Constraints

Several site-specific factors must be considered for the location in the stormwater conveyance system where a treatment unit is to be installed. First, it is necessary to determine whether the unit can be installed in a parallel arrangement with the main stormwater conveyance system so that only flows up to the unit’s design flow are diverted into the unit. Flows in excess of the unit’s design flow remain in the conveyance system and bypass the treatment unit. Vortechnics™ Inc. refers to this type of installation as “off-line.” As discussed in Section 4, hydraulic modeling indicated that diverting flows only up to the 3-month storm event to a treatment unit still resulted in treatment of 93% of the total volume of stormwater over a 100-year period. The recommendation to treat smaller, more frequent storm events and bypass larger, infrequent events, was noted in this technology review several times. This type of installation allows better control of HAR and an increased ability to achieve consistent treatment. It also permits the use of smaller, less expensive treatment units.

If site conditions are such that the unit must be installed directly in the conveyance system, it must be sized to convey the maximum design storm for the stormwater conveyance system (for example, the 100-yr return period storm). It is important to note that all of the units reviewed include an internal bypass, whereby peak flows are routed through the unit with minimal treatment. In some cases, however, internal bypasses have the potential to allow resuspension and export of sediments from a treatment unit.

Another site-specific constraint that must be considered is the available hydraulic head at the point in the stormwater conveyance system where the treatment unit will be installed. “Ultra-urban” treatment units are designed to minimize head requirements; however, it is necessary to contact a technology manufacturer in order to ensure that sufficient head is available for each application. Finally, the availability of electricity at the installation site should be considered. Although none of the units reviewed require electricity to operate, electrical power may allow process modifications or the installation of automated monitoring equipment.

Design Step 4: Select Treatment Unit

Selecting a specific treatment unit is perhaps the most difficult step in this design protocol, due primarily to a lack of performance data that can be compared between units. Based on research included in this technology review, all of the units are capable of achieving some degree of water quality improvement; however, it is not possible to determine which units are most effective. Of the data that have been reported for these units, much of it was collected under laboratory conditions with synthetic stormwater. Data from field applications do exist, as reported in this technology review, but tests of various units under standardized conditions of flow and pollutant concentration have not been conducted. Without sound comparative data, only a few general observations can be made to compare the performance of the treatment units included in this technology review:

- Only the Stormfilter™ system addresses the removal of dissolved metals, nutrients, and organics.

- Stormfilter™ cartridges equipped with a 30-µm pleated fabric insert may be most effective at capturing fine and non-settleable solids, although specific data on this was not located.

- All units except CDS® include hydraulic controls to trap floatable debris and oil. CDS® has a physical control that captures floatable debris larger than the screen aperture size, and sorbents can be added to capture floatable oils.

- Due to the presence of secondary flows that augment gravity separation, swirl concentration technologies are conceptually capable of achieving a higher degree of treatment than technologies that are based strictly on gravity separation; however, no comparative data was located to verify this.

- A CDS® unit may be better suited for a stormwater source that carries excessive amounts of gross trash and debris than for a stormwater source with a high concentration of fine particles.

In the event that a CDS® unit is selected, it is necessary to select the screen aperture size, based on the particle size distribution of the stormwater. Also, if a Stormfilter™ unit is selected, the appropriate media must be chosen to obtain the treatment goals. In the absence of comparative performance data, the final selection of a treatment unit may be based more on cost (capital and maintenance) and other site-specific factors such as available space and hydraulic head.

Design Step 5: Size the Unit

Once a specific treatment unit is selected, correct sizing of the unit is essential to obtain reliable water quality improvement. The data from Design Steps 1-3 must be evaluated to address the following specific design issues and to properly size a treatment unit:

- What is maximum flow rate to be treated? This flow rate may correspond to the peak flow rate from a design storm, or to a “first-flush” flow rate (i.e., the flow rate from the rising limb of a storm hydrograph that carries the majority of pollutants for that storm).

- What HAR should be used to achieve the treatment goals? Relationships between removal efficiency and HAR were reported in this technology review for Vortechs™ and Downstream Defender™, and the Stormceptor® model can produce similar data for different sized units. Data similar to these are needed for other units to determine what size unit will achieve the treatment goals for the design flow rate. In addition, the effect of influent concentration on removal efficiency must be considered. For swales and wet ponds, removal efficiency is observed to increase with increasing influent concentration (Section 6); however, no similar relationships were located for “ultra-urban” technologies. This data limitation adds uncertainty to the process of sizing a unit to achieve a specific treatment goal.

Well-documented relationships between HAR and removal efficiency for various influent concentrations would provide a designer with valuable tools to size an “ultra-urban” unit; however, in lieu of such data, the designer and the technology manufacturer must work together to select an appropriately-sized unit. Technology manufacturers have specific procedures that are employed in sizing a unit, many of which were discussed in this review. However, it is necessary for the designer to be aware of those factors outlined above when working with a manufacturer to ensure that the project goals are met.

Section 8: Summary and Conclusion

Based on the technology review of "ultra-urban" stormwater treatment technologies presented in this paper, the following conclusions are drawn:

1) Solids removal efficiency for several treatment units was observed to decline with increasing hydraulic application rate (HAR) and with decreasing particle size. No studies were found that reported substantial removal of particles smaller than 30 microns. Particle size distribution and settleable solids analyses should be undertaken as part of an analysis of the capability of an "ultra-urban" treatment process. For stormwater with high concentrations of fine or non-settleable particles (i.e., < 30 μm), "ultra-urban" technologies may not achieve acceptable performance.
2) There is insufficient performance data for "ultra-urban" treatment processes to develop a rational design approach that can be used for all treatment units. HAR is a fundamental mechanistic design parameter, but is currently used only on a limited basis. Well-documented relationships between removal efficiency and HAR are needed to guide the selection and sizing of treatment units.
3) A design methodology that uses a peak flow rate based on a design storm event and HAR versus treatment efficiency relationships would provide a rational design basis for "ultra-urban" treatment technologies.
4) There is a lack of data relating the effect of influent concentration on removal efficiency for "ultra-urban" treatment units. This adds uncertainty to the sizing of a unit to achieve a specific treatment goal.
5) There is a need for a streamlined process by which "ultra-urban" technologies can be evaluated for their equivalency to existing BMPs. The time and expense associated with the proposed APWA protocol may deter technology manufacturers from attempting to demonstrate BMP equivalency. Further, treatment performance should not be the only factor considered when comparing "ultra-urban" technologies to traditional stormwater treatment technologies such as wet ponds and swales. "Ultra-urban" units can provide treatment in locations where the installation of traditional technologies may not be possible due to a lack of available space. This advantage should be recognized in any protocol designed to assess the equivalency of "ultra-urban" units.

7.1 Research Needs

Currently, there are a limited number of independent evaluations of "ultra-urban" stormwater treatment technologies. The upcoming EvTEC/WSDOT project has the potential to fill a large gap in stormwater treatment research under controlled field conditions. In addition to the data limitations described in the above conclusions, research is needed to evaluate removal efficiencies for various particle sizes. It is commonly reported (e.g., Characklis and Wiesner, 1997; Sansalone and Buchberger, 1997) that certain stormwater pollutants such as metals and nutrients are associated with finer particles. If the goal of stormwater treatment is to removed metals and nutrients, in addition to TSS, then it is critical to identify technologies capable of removing small particles.

Finally, expanded use of stormwater models is needed to evaluate the large-scale effectiveness of treatment units such as those discussed in this review. Urban wet-weather flow models, such as SWMM, are widely used to generate hydrographs and contaminant distributions for urban runoff (Heaney et. al., 1999). However, the application of these models to “ultra-urban” stormwater treatment technologies has been limited. It appears, based on the research presented in this paper, that the limited application of stormwater models is dictated by the lack of performance data for treatment units. Without a thorough understanding of how these treatment units operate under a range of flow rates and influent concentrations, model evaluations are potentially subject to a high level of uncertainty.

References

Allison, R., T. Walker, F. Chiew, I. O'Neill, and T. McMahon. 1998. From Roads to Rivers: Gross Pollutant Removal from Urban Waterways. Cooperative Research Center for Catchment Hydrology, Department of Civil Engineering, Monash University, Clayton, Australia.

American Public Works Association. 1999. Protocol for the Acceptance of Unapproved Stormwater Treatment Technologies for Use in the Puget Sound Watershed. Washington Chapter, APWA, Stormwater Managers Committee.

American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1987. Standard Methods for the Examination of Water and Wastewater, 17th ed., American Public Health Association, Inc., New York.

Andoh, R.Y.G. and R.P.M. Smisson. 1994. High rate sedimentation in hydrodynamic separators. In: A.J. Saul, ed., *2nd International Conference on Hydraulic Modeling*, Mechanical Engineering Publications Limited, London, United Kingdom.

BaySaver®, Inc. 1999. BaySaver® Separation System Technical and Design Manual. Mount Airy, Maryland.

Brombach, H., C. Xanthopoulos, H.H., Hahn, and W.C. Pisano. 1993. Experience with vortex separators for combined sewer overflow control. *Water Science and Technology*, 27: 93-104.

Characklis, G.W., and M.R. Wiesner. 1997. Particles, metals, and water quality in runoff from large urban watershed. *Journal of Environmental Engineering*, 123: 753-759.

CSR, Inc. The Stormceptor® System Technical Manual, Kansas City, Missouri.

Deamer, A.P., R.A. Fenner, S. Edwards. 1994. Hydrodynamic separators, dimensional analysis, and scaling laws. In: A.J. Saul, ed., *2nd International Conference on Hydraulic Modeling*, Mechanical Engineering Publications Limited, London, United Kingdom.

DOE. 1992. *Stormwater Management Manual for the Puget Sound Basin*. Washington Department of Ecology.

Engelund, F. and E. Hansen. 1967. *A Monograph on Sediment Transport in Alluvial Streams.* Teknisk Forlag, Copenhagen, Denmark.

Environmental Protection Agency (EPA). 1978. *The Swirl Primary Separator: Development and Pilot Demonstration*. Municipal Environmental Research Laboratory, Cincinnati, Ohio. EPA-600/2-78-122.

EPA. 1978. *The Swirl Primary Separator: Development and Pilot Demonstration*. Municipal Environmental Research Laboratory, Cincinnati, Ohio. EPA-600/2-78-122.

ENR. 1997. Low-tech filtration system uses leaves to remove solids. September 1, 1997, p. 12.

EPA. 1982. *Swirl and Helical Bend Pollution Control Devices*. Municipal Environmental Research Laboratory, Cincinnati, Ohio. EPA-600/8-82-013.

EvTEC. 2000. EvTEC Draft Evaluation Plan for Ultra-Urban Storm Water Technologies. Prepared by the Environmental Technology Evaluation Center, Washington, D.C. and David Evans and Associates, Bellevue, Washington.

Field, R. and T.P. O’Connor. 1996. Swirl technology: Enhancement of design, evaluation, and application. *Journal of Environmental Engineering*, 122: 741-748.

Heaney, J.P., L. Wright, and D. Sample. 1999. Research needs in urban wet weather flows. *Water Environment Research*, 71: 241-250.

H.I.L. Technology, Inc., 2000. Proceedings of the short course, *“New Technologies and Concepts in Stormwater Treatment ©*”, May 11-12, 2000, Lynwood, Washington.

Jago, R. 1997. Litter analysis from suburban CDS unit. Report on CDS web page: www.cdstech.com.au/articles/coburg/coburgan.htm .

Jago, R. 1998. Litter analysis case study-Melbourne Airport CDS unit. Report on CDS web page: www.cdstech.com.au/articles/MelbAirport/Melb_Airport.html.

Keblin, V., M. Barrett, J. Malina, and R. Charbeneau. 1997. The effectiveness of permanent highway runoff controls: sedimentation/filtration systems. CRWR Online Report 97-4. University of Texas at Austin: www.ce.utexas.edu/centers/crwr/reports/online.html .

Marsalek, J., R. Long, and D. Doede. 1994. Laboratory development of Stormceptor. National Waster Research Institute (Environment Canada), In: Stormceptor Study Manual. CSR, Kansas City, MO.

Minton, G. 2000. Lecture notes for the short course, *“New Technologies and Concepts in Stormwater Treatment ©*”, May 11-12, 2000, Lynwood, Washington.

McCabe, W.L., J.C. Smith, and P. Harriot. 1985. *Unit Operations of Chemical Engineering*, 4th ed., McGraw-Hill, Inc., New York. 960 pp.

Pisano, W. C., D.J. Connick, and G.L. Aronson. 1984. Swirl and helical bend regulator/concentrator for storm and combined sewer overflow control. *Rep. No. EPA-600/2-84/151 (NTIS PB 85-102 523),* USEPA, Edison, New Jersey.

Pollution Engineering. 1997. Space-saving filters handle high-volume storm runoff. August 1997, p. 39.

Pratt, C. 1996. Laboratory tests on X-Ceptor concrete bypass interceptor. Conventry University, Coventry, United Kingdom.

Sansalone, J.J. and S.G. Buchberger. 1997. Characterization of solid and metal element distributions in urban highway stormwater. *Water Science and Technology,* 36: 155-160.

Shapiro, A.H. 1969. Film Notes for *Vorticity.* Encyclopedia Britannica Educational Corporation, Chicago, Illinois.

Stein, W. 1999. CDS® General Information and Discussion: Continuous Deflective Separation (CDS®) – Treatment of Storm Water Runoff. CDS® Technologies, Inc., Morgan Hill, California.

STEP. 1998. Technology Assessment for Stormceptor®. The Massachusetts Strategic Envirotechnology Partnership, 13 pp.

Stormceptor® Design Manual. CSR, Kansas City, MO (www.csra.com/csrstormceptor)

Stormwater Management, Inc. 2000. Preliminary testing of iron-infused filtration media for the removal of dissolved phosphorus. Portland, Oregon.

Vortechnics TM, 1998. Technical Bulletin No. 1: Vortechs TM stormwater treatment system performance: Removal efficiencies for selected particle gradations. Portland, ME.

Vortechnics TM, 1999a. Technical Bulletin No. 3: Sizing Vortechs TM systems. Portland, Maine.

Vortechnics TM, 1999b. Technical Bulletin No. 5: Vortechs™ System Oil Removal Efficiencies. Portland, Maine.

Wanielista, M.P. and Y.A. Yousef. 1993. *Stormwater Management*. John Wiley and Sons, Inc., New York. 579pp.

Water Environment and Technology. 1997. Compost media capture pollutants from stormwater runoff. July 1997, p. 21.

Wigginton, B.O. and S. de Ridder. 1999. Sediment loading on a Perlite filled Stormfilter™ cartridge. Stormwater Management, Portland, Oregon.

Wong, T.H.F. 1997. Continuous deflective separation: Its mechanism and applications. Water Environment Federation 70th Annual Conference and Exposition, Chicago, Illinois.

Appendix: "Ultra-Urban" Stormwater Treatment Technology Manufacturer List

Note: The following table contains information on all manufacturers whose stormwater treatment technologies were reviewed in this document; in addition, information is provided on a few other manufacturers. This list does not necessarily contain all manufacturers of "ultra-urban" technologies.

Product	Treatment Mechanism	Contact Information
BaySaver® Separation System	Gravity Separation	BaySaver®, Inc 1010 Deer Hollow Drive Mt. Airy, MD 21771 (800) 229-7283 www.BaySaver.com
Stormceptor ® System	Gravity Separation	CSR, Inc. P.O. Box 9187 Kansas City, MO 64168 (816) 741-5557 www.csrstormceptor.com
Vortechs™ Stormwater Treatment System	Swirl Concentration	Vortechnics, Inc. 41 Evergreen Dr. Portland, ME 04103 (207) 878-3662 www.vortechnics.com
Downstream Defender™	Swirl Concentration	H.I.L. Technology, Inc. 94 Hutchins Dr. Portland, ME 04102 (800) 848-2706 hiltech@hil-tech.com
Continuous Deflective Separation®	Screening	CDS Technologies, Inc. 16360 S. Monterey Rd. Suite 250 Morgan Hill, CA 95037 (888) 535-7559 www.cdstech.com
Stormfilter™	Filtration and Adsorption	Stormwater Management, Inc. 2035 NE Columbia Blvd. Portland, OR 97211 (800) 548-4667 www.stormwatermgt.com
Aqua-Filter™ Stormwater Filtration System	Swirl Concentration and Filtration	AquaShield™ Inc. 2733 Kanasita Dr. Suite A Hixson, TN 37343 (423) 870-8888 http://www.aquashieldinc.com/
V2B1 Stormwater Treatment System	Swirl Concentration	Environment XXI™ 8713 Read Rd. PO Box 218 East Pembroke, NY 14056 (800) 809-2801 www.kistner.com