Vortex Separation Technology

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Several types of vortex separators have been developed during the last 30 years. Their major function has been to provide both flow regulation and settleable solids concentration for the control of combined sewer overflows (CSOs). A variety of opinions have developed regarding the application of these technologies, ranging from overwhelming support to reservations of their effectiveness. The performance of vortex devices depends on the settling velocity distribution of the particles in the wastewater. When correctly installed with other controls in combined sewer or separate stormwater systems, vortex devices can play an important role in the control of pollution from CSO and stormwater discharge. Reliable determination of performance depends principally upon accurate sampling techniques, suspended solids and other pollutant analyses, and the settling velocity distributions of the influent and effluent. Simultaneous flow rate measurement, synchronized to sampling time, is also necessary. This paper discusses design, application and evaluation of swirl/vortex technologies as part of CSO and stormwater pollution control systems.

Key words: combined sewers, stormwater, swirl, vortex separator, Storm King®, Fluidsep™

Introduction

Several solid/liquid separators use circular flow patterns to create inertial separation. One general classification of these devices includes swirl and vortex separators which have been in use for over 30 years for the control of combined sewer overflows (CSOs). Bernard Smisson first incorporated a cylindrical vortex-type CSO regulator and settleable solids concentrator into the Bristol, England, sewerage system in the early 1960s (Smisson 1967). Hydro Research and Development Ltd. of Great Britain continued research into vortex separators during the 1970s and produced the Storm King® dynamic separator or the Hydro-Dynamic Separator. This unit reportedly improved headloss and solids transport characteristics. The current Storm King® configuration was first used in Great Britain in 1983.

In the early 1970s, the U.S. Environmental Protection Agency (EPA) completed a series of projects to develop and demonstrate swirl settleable solids removal technology for North American applications. The projects
resulted in the EPA swirl CSO regulator and settleable solids concentrator (hereafter referred to as swirl) and other concentrator devices, including the EPA swirl degritter, a variation that effects settleable-solids (or detritus) separation but is not used to regulate flow.

German research conducted by Dr. Hans Brombach in the mid-1980s resulted in the development of a vortex separator which is marketed as the Fluidsep™. The objective was to develop a vortex vessel that could operate at high hydraulic loads and provide substantial removal of settleable and floatable solids (Water Pollution Control Federation 1989). In addition, the German researchers wanted to maximize the detention storage of the vessel for small storms and allow the vessel to act as a solids separator for larger storms.

Other versions of vortex technology have emerged, including the Japanese NKK Swirl (Nippon Kokan K.K. 1987). The swirl/vortex devices are similar in general operating principle although there are design and application differences. The main intent of these technologies is the same, i.e., to separate settleable solids from the storm flow by a vortex or swirling flow field.

To effectively apply swirl and vortex capabilities in a combined sewerage or stormwater drainage system, the control functions, applicability, and idiosyncrasies of their individual designs must be clearly understood. Factors which are essential to the successful application of swirl/vortex devices are (1) consistent and appropriate flow measurement, wastewater sampling and characterization protocols; (2) appropriate data management techniques, particularly the calculation of efficiency; (3) an understanding of swirl/vortex mechanisms, with realistic performance expectations; and (4) appropriate application or placement in the sewerage system.

**Vortex Technology Characteristics**

The original vortex separator devices provide three functions: flow regulation, settleable solids concentration and floatables capture.

Flow regulation was Smisson's original intent and is a prime function of the swirl. Flow regulation is achieved by installation of the device in-line in the sewer system. Dry-weather flows (DWF) pass through the unit. The volume of the device, if large enough, provides storage of wet-weather flow (WWF) to attenuate flow to a downstream treatment plant. Excess WWF is discharged in the overflow.

Settleable solids concentration is achieved by a combination of gravity settling and inertial separation due to the circular flow pattern. The concentrated stream is discharged in the underflow. Floatable materials are influenced by the same forces and are generally trapped at the surface of the devices.

Advantages of the swirl and vortex technologies include the lack of moving parts and the ability to operate at high hydraulic loads, resulting
in a small footprint and low cost. The relatively small volume of these devices makes them much less expensive than sedimentation tanks. However, when operating at the higher surface loading rates, vortex devices cannot offer the same suspended solids removal efficiency as conventional sedimentation tanks. In many cases, the swirl/vortex units are designed for continuous discharge of the underflow, thereby requiring no sludge handling facilities. The underflow (foul-orifice) diameter is usually large enough to avoid blockage (approximately 0.3-m diameter) such that pretreatment is not required.

A disadvantage of the swirl is the potential need for post-storm cleaning due to shoaling of solids. However, the Storm King® and Fluidsep™ designs with relatively steep floor slopes are reported to minimize or eliminate cleaning requirements. Underflow pumping, which increases operation and maintenance costs, may be required depending upon the local gradient and the depth of the unit (especially for the Storm King® and Fluidsep™ designs which have greater depth-to-width ratios than the swirl). Compared to more conventional treatment operations, e.g., sedimentation, swirl/vortex units produce a relatively dilute underflow rather than concentrated grit/sludge residuals. If the underflow is not returned to the sewerage system, the relatively large volumes of underflow require storage and possibly further treatment.

Swirl

The swirl was designed as a flow regulator and settleable solids concentrator, to be installed in-line with the sewer system. As illustrated in Fig. 1, flow enters the swirl tangentially and follows the outer wall of the cylindrical swirl chamber creating a swirling, vortex-like flow pattern. Gravity and the swirling action cause settleable solids to be concentrated at the bottom of the unit. These solids are then routed into the underflow which exits through a foul-sewer outlet in the bottom of the unit. This underflow ranges from 6 to 10% of the influent at the design flow.

The clarified effluent exits the top of the vessel via a circular overflow weir and horizontal weir-plate into the central downshaft. The weir-plate contains radial baffles to impede the free vortex-flow pattern. A circular baffle outside the weir plate captures floatables in the supernatant by directing them under the weir plate for containment during the storm-flow event. The floatables are then carried out in the underflow as the storm flow subsides and the water level in the swirl falls. During low- and dry-weather flow conditions, all flow passes out via the bottom foul-sewer outlet.

Separation of suspended solids (SS) in the swirl is enhanced by the flow patterns. The influent is deflected into a slower moving inner swirl pattern after one revolution around the perimeter. As the solids-laden flow swirls around the chamber, the difference in inertia between the settleable solids and the water creates a tangential separation (spin-off) between the particle and fluid flow field. Gravity separation also occurs as particles follow this “long path” through the outer and inner swirl.
Suspended solids separation efficiency depends upon the hydraulic load and the settleability (settleable fraction and settling velocity distribution) of the solids in the CSO or stormwater influent. The swirl was developed through hydraulic modeling studies on a 0.9-m diameter model with representative synthetic particles consisting primarily of gilsonite with a specific gravity (SG) of 1.06 and effective diameters ($d_e$) of approximately 0.5 to 3 mm (Sullivan et al. 1974). Using the Froude and Stokes laws, the synthetic particles and swirl model were scaled (1:12) to predict the removal of actual grit (fine sand, SG equal to 2.65 and $d_e$ from approximately 0.2 to 2 mm) and relatively heavy organics (SG equal to 1.2 and $d_e$ from approximately 0.2 to 5.0 mm) for an 11-m diameter prototype swirl (Sullivan et al. 1972). The swirl flow patterns are effective for the separation of only the relatively large $d_e$ and high SG particles. Separation effectiveness decreases as particle $d_e$ and SG decrease. Coarse floatable matter was also simulated for hydraulic model development (Sullivan et al. 1972).

**Fluidsep™**

The Fluidsep™ vortex separator was designed by Umwelt und Fluid-Technik (UFT), a German firm. The Fluidsep™ vortex vessel (Fig. 2) encourages free vortex flow since it has no centrally located baffles or
The Fluidsep™ vessel is rotationally symmetric with a conical bottom which slopes to the centre. The inlet to the vessel is tangential and located near the bottom of the unit. The overflow leaves through an annulus between the scum board and the guiding baffle and flows over the cover to the discharge. The guiding baffle prevents entrained particles from passing into the effluent. The settled solids are collected in a conical sump located on the rotational axis. The underflow is throttled to allow flow control during wet weather (Water Pollution Control Federation 1989).

The Fluidsep™ was developed, optimized and flow gauged using artificial tracers under laboratory conditions to ensure reproducible results. Systematic variations of flows and the resulting efficiencies were recorded using nine tracers (with settling rates from 0.1 to 15 cm/sec) and two floaters (Pisano 1990). These tracers were used to represent various sizes of particles. The efficiency of the removal of these 11 tracers
was correlated to aspect ratios (diameter to height) of 0.5, 1, 2 and 3 of the vessel.

The initial step in the design of a Fluidsep™ vessel is to produce a solids settling curve for the particular site. This is accomplished by collecting CSO samples and scrapings from overflow chambers. These solids settling curves are then compared to the settling curves of the 11 tracers using a similarity analysis for determination of appropriate vessel dimensions (Water Pollution Control Federation 1989).

**Storm King®**

The Storm King® was designed by the British firm Hydro Research and Development. The vortex separators were originally designed on the basis of pilot-scale testing at the site (Water Pollution Control Federation 1989). Currently, Storm King® design specifications are derived from a proprietary, semi-empirical model that predicts removal efficiency based on site-specific influent characteristics and hydraulic loading data. Pilot-scale Storm King® units are also available, by rental or purchase, for use in treatability studies.

![Diagram of Storm King™](image)

**Fig. 3.** Storm King™ (based on a drawing by H.I.L. Technology Inc.).
The Storm King® Dynamic Separator is a cylindrical vessel with a sloping bottom (Fig. 3). It contains a number of internal baffles designed to control the flow patterns. The raw liquid is fed tangentially into the side of the vessel at about mid-height, creating a flow pattern, which rotates about the vertical axis of the unit. The wastewater initially rotates around the outer annular space, which is separated from the rest of the vessel by a cylindrical baffle called the dip plate. Here, the floating material migrates to the top of the vessel where it is trapped. The settleable material is influenced by gravity and inertial forces and tends to move down and outward. The heavier material may move in density currents along the wall and bottom surfaces of the vessel.

The flow spirals downward in the outer annular space and is divided into two streams. Between 5 and 20% of the flow continues to move downward and inward, under a cone which is supported above the bottom of the vessel. This flow, and the settled particles which collect at the bottom of the vessel, become the underflow of the separator. The second stream, consisting of 80 to 95% of the influent, reverses its vertical direction and spirals up in the central zone of the vessel at a slower rotational velocity. The transition or “shear zone” between the outer, downward movement, and the inner, upward movement, is controlled by the position of the dip plate. The sudden change in velocity at this location may enhance the inertial separation of the particles.

When the flow approaches the top of the vessel, it passes through an annular space created by two concentric, horizontal baffle plates. The flow changes direction abruptly in negotiating this structure. At the top of the vessel, the fluid continues to spiral around the inner annular space and is discharged tangentially into the overflow chamber.

Discussion

Table 1 provides a comparison of the properties of the swirl, Fluidsep® and Storm King®. The principal differences between the designs consist of the internal configurations and appurtenances, and the aspect (height to diameter) ratios. The swirl and Storm King® designs include inlet baffles and central structures, which impede free vortex formation. The Fluidsep® design has no inlet baffle or centrally located obstructions to the flow.

The original design hydraulic loads of the swirl, Storm King® and Fluidsep® typically ranged from 1.2 to 2.4 m/min (approximately 70 to 140 m/h) (Boner et al. 1994). Design hydraulic loads can vary as a function of particle settling velocity distributions and associated SS removal objectives (Sullivan et al. 1982). Comparisons of loading rates should be made with the understanding that the hydraulic load may be defined in different ways. The surface area of the unit may be defined as the total area of the cylindrical vessel, or allowances may be made for portions of the surface which are not employed for solid/liquid separation. The hydraulic load may also be calculated on the basis of the influent flow or the overflow.
<table>
<thead>
<tr>
<th>Design element</th>
<th>Swirl concentrator</th>
<th>Storm King®</th>
<th>Fluidsep™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>Small diameter tangential inlet located on floor of unit; flow deflector diverts flow, minimizing turbulence and creating interior rotating water mass</td>
<td>Tangential inlet at mid-height, with deflector</td>
<td>Tangential inlet near floor; large diameter; low inlet velocity; no flow deflector</td>
</tr>
<tr>
<td>Baffles</td>
<td>Central downshaft; weir plate and vertical baffles at the surface dampen free vortex formation; scum baffle and floatables direct and trap floatables under the weir plate</td>
<td>Central shaft and cone control flow patterns; a cylindrical &quot;dip plate&quot; and three horizontal plates contain floatables</td>
<td>No central baffles to dampen vortex flow; cone-shaped baffle, cylindrical scum board and cover plate divert floatables from the effluent</td>
</tr>
<tr>
<td>Floor</td>
<td>Flat or &lt; 2% slope; curved gutters to direct solids and DWF to foul sewer outlet</td>
<td>Sloped floor; annular gutter under the centre cone,</td>
<td>Sloped floor; 4-6%; no gutters; conical sump on central axis</td>
</tr>
<tr>
<td>Foul sewer outlet</td>
<td>Tangential outlet, offset from the central axis at the base of the downshaft</td>
<td>Tangential outlet, offset from the central axis under the centre cone</td>
<td>Outlet from sump, in alignment with center of rotation</td>
</tr>
<tr>
<td>Underflow control</td>
<td>Due to difficulty in sizing underflow piping to act as throttle suggest using gate or vortex valve to control</td>
<td>Use vortex valve</td>
<td>Vortex action throttles underflow or use vortex valve</td>
</tr>
<tr>
<td>Overflow</td>
<td>Clarified water overflows a circular weir, flows across a horizontal plate toward a central dropshaft; dropshaft extends through floor of vessel and exits to the side</td>
<td>Clarified water flows up through the annular space between the horizontal, circular baffle plate and the cylindrical, vertical dip plate; flow passes over the circular baffle to the overflow chamber at the perimeter</td>
<td>Clarified water passes up through the annular space between vertical, cylindrical scum baffle and the cone shaped; flow passes over roof of vessel to the outlet</td>
</tr>
</tbody>
</table>

1 Based on a summary by Walker et al. 1993.
Use and Placement

A swirl/vortex device, when properly placed and applied in a combined sewerage or storm drainage system, will be an effective tool for pollution abatement. The placement of swirl/vortex units affects their pollutant removal effectiveness. Because swirl/vortex units were developed to remove the relatively heavy particles, they should not be placed downstream of storage/sedimentation basins or grit chambers. While most applications of swirl/vortex devices to date have used off-line configurations, swirls are recommended as in-line devices which operate as flow regulators. The developers of the Storm King® and Fluidsep™ design units for both in-line and off-line placement. Effective placement includes:

- **In-line installation as a stand-alone unit.** The swirl/vortex unit acts as a flow regulator and settleable solids concentrator. After removal of the readily settleable and floatable material, the wastewater is discharged directly to the receiving water. This application should be used only in cases where the receiving water can assimilate a partially treated effluent.

- **In-line placement upstream of a storage/treatment facility.** The swirl/vortex effluent is stored for eventual treatment at the main wastewater treatment plant (WWTP) or is treated on site in a satellite treatment facility before being discharged. Storage vessels also provide treatment by sedimentation before discharging excess flows to the receiving water. The swirl/vortex unit removes the majority of grit and floatable material from the wastewater, reducing the requirement for cleaning the downstream storage facility and protecting satellite treatment units from damage or fouling. The use of swirl/vortex units upstream of deep tunnels and created or natural wetlands are two specific examples of this type of application.

- **In-line placement downstream of in-sewer storage (if available).** This arrangement makes use of the flow regulation capacity of the swirl/vortex units, attenuating the flow to downstream facilities where the upstream sewer system has reserve capacity. In this configuration, a swirl regulator may be loaded at up to twice the design flow before a washout condition occurs.

- **Placement downstream of an existing flow regulator.** Swirl units are not recommended for this application because they are flow regulators. However, a suitably sized vortex separator can be used in place of a more conventional sedimentation/clarification unit. Because the vortex separator utilizes rotational and gravity forces, it is more efficient than a conventional sedimentation unit at an equal hydraulic load. Thus, the vortex separator can save space or improve effluent quality relative to a conventional unit. However, the aspect ratio and underflow ratio of the vortex separator must be taken into consideration with respect to available gradients and underflow storage or pumping requirements.

- **Swirl/vortex units may be used in conjunction with chemical disinfection.** Addition of a disinfectant upstream of the swirl/vortex unit makes use of mixing in the spiral flow field to increase contact between the disinfectant
and the microorganisms, potentially resulting in more effective kill per unit contact time. This method was employed with chlorination at Lancaster, Penn. (Pisano et al. 1984), and Syracuse, N.Y. (Drehwing et al. 1979). Alternatively, the swirl/vortex unit may be used to remove the more settleable material from the wastewater prior to chemical addition. Disinfectant demand and byproduct formation would be reduced in a downstream disinfection scenario.

- **Swirl/vortex treatment of stormwater from separate sewer systems.** The underflow can be diverted to a storage tank or the main WWTP. This method is much cheaper than constructing large traditional storage basins for stormwater collection.

### Intermittent Operation

The application of swirl/vortex separators to CSO and stormwater treatment results in an intermittent mode of operation. This condition effectively applies to both in-line and side-stream installations. Intermittent treatment vessel operation consists of several distinct stages which must be recognized when considering the dynamics of the system and when computing removal efficiencies. In most treatment processes, the underflow and storage in the vessel are often assumed to be negligible for continuously operated vessels. However, for intermittent vessel operation, the underflow and storage components play an important role in the removal of pollutants. Five stages of intermittent vessel operation are outlined below and illustrated in Fig. 4. In this figure, shaded areas on the hydrograph illustrate the volumes of wastewater associated with each of the five operating stages. The relative capacity of the underflow has been exaggerated for clarity. Vessel schematics illustrate the liquid levels. The five stages may be described as follows:

- **At the beginning of a storm event the vortex vessel is essentially empty.** A unit installed in-line with the sewer system will have flow entering the vessel and exiting only through the underflow, leaving most of the vessel volume unused. As the storm flow reaches the swirl/vortex vessel, the influent rate becomes greater than the low-head, flowthrough capacity and the vessel begins to fill (Fig. 4a). The shading on the hydrograph of Fig. 4a represents the volume of wet-weather flow entering the vessel prior to the onset of overflow. This volume is subdivided into underflow and storage components.

- **Overflow begins when the vessel is full.** The underflow rate attains its maximum value at this time. The rising liquid level in the previous stage can cause some floating material to bypass baffles which would otherwise retain them. Furthermore, turbulence during the filling period can contribute to the formation of foam. Depending on the design of the unit

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1Because bacteria can survive within suspended solids masses, homogenization of the overflow sample to break apart the relatively large-diameter protective particles is recommended prior to analysis to determine the true effectiveness of the disinfection operation.
and the characteristics of the wastewater, the initial overflow (Fig. 4b) may contain significant quantities of foam and floatables.

- The third stage (Fig. 4c) represents normal operation of the swirl/vortex unit as an overflow control device. Inflow, overflow and underflow are
continuous. The shading on the hydrograph of Fig. 4c indicates the volumes of overflow and underflow which occur during this stage.

- Drain-down begins to occur once the inflow rate decreases to less than the underflow capacity (Fig. 4d). For an in-line installation, the inflow returns to the dry-weather condition and continues to pass through the unit. In a side-stream installation, the inflow will eventually go to zero. Depending on the shape of the storm hydrograph and the underflow capacity, underflow may continue for a period of time after the storm event.

- A washdown stage (Fig. 4e) may be required to remove residual solids from the vessel. During a washdown stage, a gravity or pressure driven wash apparatus may be employed to remove retained solids. The requirement for washing may depend on the characteristics of the retained solids and the bottom slope of the vessel. Washing is apparently not required in many full-scale operations. The shading shown on the hydrograph of Fig. 4e represents the volume of washwater.

Where gravity discharge is feasible, underflow pipes are typically designed for flow rates of 5 to 20% of the design flow of the swirl/vortex unit. Underflow ratios as low as 2.5% have been used in some installations where the underflow was pumped to storage. The volume of the underflow remains significant throughout the event. The actual percentage of the total influent volume which is discharged as underflow is highly variable because of the storage capacity of the vessels and the duration of the storms; for smaller storms, as much as 100% may be captured without causing an overflow. The wide variation in the volume treated means a certain amount of caution is necessary in evaluating the performance of swirl and vortex units.

**Performance Equations**

Intermittent operation necessitates careful examination of the methods used to report process efficiency. The following discussion examines various definitions of treatment efficiency\(^2\) for an intermittent operation using the material balance diagram and operating cycle illustrated in Fig. 5. Material balance calculations across the system will reveal appropriate definitions of removal efficiency. For simplicity, the efficiencies are presented as fractions rather than percentages.

Ideally, flow and concentration data would consist of instantaneous values such that volumes and masses may be determined by integration. In practice, concentration values must be measured over finite time periods. Flows may be monitored continuously and averaged over the same sampling interval used for pollutant concentration measurement (\(\Delta t\)). Hence, in the following equations, concentration (\(C\)) and flow rate (\(Q\)) are understood to represent average values over a finite sampling period.

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\(^2\) Nomenclature varies between researchers and practitioners working in this area. An attempt has been made to use the more common definitions where practical.
Fig. 5. Material balance diagram and operating cycle for an intermittent operation.

Full Operating Cycle

The total volume and total pollutant mass found in the influent, overflow or underflow may be determined by summation over the appropriate time intervals. For example, with reference to Fig. 5, the influent wastewater volume \( V_i \) and influent pollutant mass \( M_i \) are calculated as

\[
V_i = \sum_{k=TI}^{T4} Q_{ik} \Delta t_k
\]

\[
M_i = \sum_{k=TI}^{T4} C_{ik} Q_{ik} \Delta t_k
\]

The flow-weighted average influent pollutant concentration \( \overline{C_i} \) may be determined from the total influent mass and the total influent volume

\[
\overline{C_i} = \frac{M_i}{V_i}
\]

The initial expression for the efficiency of the separation device is written for the entire operating cycle, exclusive of the washdown stage. Conceptually, the total efficiency \( (TE) \) would be determined by considering the operating cycle from the start of the stormwater flow to the end of the draindown stage. Since the underflow is considered only as the difference between the influent and overflow, the summation limits are between \( TI \) and \( T4 \) for the influent and between \( T2 \) and \( T3 \) for the overflow.

\[
TE = \frac{\sum_{k=TI}^{T4} Q_{ik} C_{ik} \Delta t_k - \sum_{k=T2}^{T3} Q_{ik} C_{ik} \Delta t_k}{\sum_{k=TI}^{T4} Q_{ik} C_{ik} \Delta t_k}
\]
This mass balance equation may be modified by the imposition of one or more simplifying assumptions. The results of making these assumptions are presented in the following sections.

**Negligible Fill Time**

One simplification allows the influent duration to equal the overflow duration ($t_i = t_o$). This time compromise calculation assumes the fill time is negligible. In other words, it includes the underflow contribution to removal but ignores storage or the flow attenuation component. This equation, which defines the *pollution separation efficiency* (PSE), has been used widely because there are often no data available until overflow occurs, or because the fill time of a flow regulator is considered to be negligible.

\[
PSE = \frac{\sum_{k=T^2}^{T^3} Q_{ik} C_{ik} \Delta t_k - \sum_{k=T^2}^{T^3} Q_{0k} C_{0k} \Delta t_k}{\sum_{k=T^2}^{T^3} Q_{ik} C_{ik} \Delta t_k}
\]

**Negligible Underflow**

An alternative simplification assumes that the influent flow equals the quantity of overflow ($Q_i = Q_o$). However, since $Q_o$ is not defined for $t < T^2$, the relevant portion of the inflow is written as $(Q_i - Q_{iu})$. This flow compromise calculation ignores the contribution of underflow to the removal of pollutants. This determination of *net efficiency* (NE) calculates the removal efficiency for only the flow which is treated and discharged but, by summing the influent flow over the total influent period, it also includes the storage contribution to removal.

\[
NE = \frac{\sum_{k=T^1}^{T^4} (Q_i - Q_{iu}) C_{ik} \Delta t_k - \sum_{k=T^2}^{T^3} Q_{0k} C_{0k} \Delta t_k}{\sum_{k=T^1}^{T^4} (Q_i - Q_{iu}) C_{ik} \Delta t_k}
\]

This definition is appropriate for storage/sedimentation systems in which there is no underflow, but storage and the solid/liquid separation effect are contributors to the removal of pollutants. Although it has no direct relevance to swirl/vortex units, this definition is an intermediate step to the following definition.

**Concentration Efficiency**

If both of the above simplifications are applied together ($Q_i = Q_o$ and $t_i = t_o$), the result is the *concentration-based efficiency* (CE) more commonly used for continuous-flow clarifiers with negligible underflow. Both
underflow and storage contributions to removal are ignored, leaving a measure of the solid/liquid separation efficiency of the unit.

\[
CE = \frac{\sum_{k=T2}^{T3} Q_{ik} C_{ik} \Delta t_k - \sum_{k=T2}^{T3} Q_{0k} C_{0k} \Delta t_k}{\sum_{k=T1}^{T3} Q_{ik} C_{ik} \Delta t_k}
\]  

(7)

Equation 7 may be simplified to the familiar form of efficiency equation, using the flow-weighted average concentrations

\[
CE = \frac{\overline{C}_e - \overline{C}_o}{\overline{C}_i}
\]

(8)

**Volumetric Material Balance**

A material balance may also be applied to the volume of wastewater. The volumetric removal efficiency calculated over the total cycle is called the *flow split* (FS).

\[
FS = \frac{\sum_{k=T1}^{T4} Q_{ik} \Delta t_k - \sum_{k=T2}^{T3} Q_{0k} \Delta t_k}{\sum_{k=T1}^{T4} Q_{ik} \Delta t_k}
\]

(9)

The ratio of solids removal efficiency to volumetric removal efficiency is an indication of the solids separation efficiency of the treatment device. This ratio, when applied to the total operating cycle, is called the *treatment factor* (TF).

\[
TF = \frac{TE}{FS}
\]

(10)

A *treatment factor* of 1.0 indicates that the wastewater flow is being separated into two streams without any effective treatment. If the value of TF is greater than unity, the suspended matter is being concentrated in the underflow. If TF is less than unity, the concentration in the effluent is being increased relative to that in the influent. An increase in concentration across the unit is unlikely but may result from certain combinations of coagulant addition, excessive foaming and short overflow events. A TF value less than 1.0 may also indicate a data anomaly or faulty monitoring techniques.

Alternatively, the volumetric material balance may be determined over the overflow period, resulting in the *effective flow split* (EFS) and the
effective treatment factor (ETF).

\[
EFS = \frac{\sum_{k=T2}^{T3} \frac{Q_{ik}}{C_{ik}} \Delta t_k - \sum_{k=T2}^{T3} \frac{Q_{0k}}{C_{0k}} \Delta t_k}{\sum_{k=T2}^{T3} \frac{Q_{ik}}{C_{ik}} \Delta t_k}
\]  

(11)

\[
ETF = \frac{PSE}{EFS}
\]  

(12)

Expansion of the effective treatment factor equation reveals that it may also be expressed as the ratio of the flow-weighted average concentration in the underflow (\(\bar{C}_u\)) to that in the influent.

\[
ETF = \frac{(\bar{C}_i V_i - \bar{C}_0 V_0)}{C_i V_i} = \frac{\bar{C}_u}{C_i}
\]  

(13)

Other Definitions

Several definitions of efficiency have been reported in the literature. Many can be derived from the material balance method described above. Some definitions result from volumetric balances on both the liquid and solid fractions of the wastewater; these methods require a value for the solids density. Other methods appear to be arbitrary constructs obtained through ratios or differences.

Net Removal is defined as the difference between the mass removal efficiency and the volumetric removal efficiency, exclusive of storage:

\[
Net \text{ Removal} = PSE - EFS
\]  

(14)

Conceptually, the Net Removal represents the pollution removal above and beyond the removal gained by installing a conventional, e.g., side weir, CSO flow regulator. This expression indicates the relative importance of pollutant removal and flow diversion. Greater values of Net Removal indicate greater efficiency for solid/liquid separation. Expansion of the equation reveals that the change in mass based on the throughput volume (overflow) is divided by the total influent mass.

\[
Net \text{ Removal} = \frac{\sum_{k=T2}^{T3} \frac{Q_{0k}}{C_{0k}} \bar{C}_i \Delta t_k - \sum_{k=T2}^{T3} \frac{Q_{0k}}{C_{0k}} \bar{C}_0 \Delta t_k}{\sum_{k=T2}^{T3} \frac{Q_{ik}}{C_{ik}} \Delta t_k}
\]  

(15)
Monitoring and Analysis

Appropriate methods of sampling, analysis and flow measurement are necessary for proper treatability evaluation, swirl/vortex design and performance assessment. These procedures are expensive and complex; however, reliable data collection can result in savings of construction and maintenance costs by ensuring that appropriate control measures are implemented.

Prior to selecting a swirl/vortex unit for a combined sewerage or separately sewered stormwater system, adequate volumes of representative samples of the storm flow should be collected by use of appropriate sampling techniques. The particle settling velocity distributions of these samples, as related to SS and associated pollutant content, should then be determined. This analysis is essential for proper assessment of the unit's applicability. If the storm flow does not contain enough grit-like particles (SG >2.65) and settleable organic particles (SG >1.2), then swirl/vortex units will leave substantial residual concentrations, and alternative or additional technologies should be used. A study in Quebec showed that the swirl was not effective at removing fine and low settling velocity particles which made up the majority of the particles in the flow (Villeneuve and Guame 1994). This limitation was also inadvertently demonstrated at a swirl installation in West Roxbury (Boston), Mass., to be discussed later.

The swirl design manual (Sullivan et al. 1982) reports removal values of 70, 80, 90 and 100% for the synthetic settleable solids used for swirl development. These synthetic particles simulated grit or fine sand (SG equal to 2.65 and d_e from 0.2 to 2 mm) and settleable organics (SG equal to 1.2 and d_e from approximately 0.2 to 5.0 mm). A major portion of these simulated particles had settling velocities of 2.6 cm/sec or greater. As previously noted, the swirl will also remove particles with lower settling velocities but with decreasing effectiveness. The design manual (Sullivan et al. 1982) indicates the limit of SS removal effectiveness is for particles with a settling velocity of 0.14 cm/sec. Pisano (1990) places this effective lower limit for vortex separators at a similar settling velocity of 0.10 cm/sec.

Wastewater Characterization

The variable nature of storm flow and collection system geometry influence suspended/settleable solids concentration and particle settling velocity distribution. The buildup of these settleable solids in the sewer system is usually a function of the length of the antecedent dry-weather period. Furthermore, suspended/settleable solids concentrations will vary with time during the storm event. “First flush” refers to a segment of flow with a high SS concentration resulting from the flushing of accumulated sediment and sewer slimes. The first flush is not a consistent phenomenon and should not be used as a principal design parameter. It is highly dependent upon collection system geometry, rainfall intensity and the time interval between storms. Storm flow variations require that sampling be done for the duration of the storm event and for several storms...
in order to develop a long-term average of the settleable solids concentration and particle settling velocity distribution.

Sampling devices must be able to capture the heavier SS or settleable solids (i.e., that fraction of the SS that swirl/vortex devices were developed to remove) and not manifest biased results due to stratification. For automatic sampling devices, the velocities must be greater than the main stream velocity, and the intake ports must be placed at multiple levels to include the heavier particles found near the channel invert.

After samples have been collected and analyzed for SS, two particle settling characteristic analyses should be conducted: one for settleable solids and the other for settling-velocity distribution. These analyses will enable a site-specific estimate of the percent of SS the swirl/vortex is capable of removing.

The settleable solids analysis should be the gravimetric type with data presented in mg/L (American Public Health Association et al. 1992) to determine the fraction of settleable solids in the storm flow. The method uses a column of at least 20 cm in depth. A sample is siphoned from the centre of the column after 1 h of quiescent settling to determine the non-settleable solids. The equivalent critical settling rate (for a 10-cm depth) is 0.003 cm/s or 0.1 m/h. Settlemens solids are equal to the initial SS concentration minus the non-settleable solids concentration. A crude method of estimating the fraction of SS that the swirl can concentrate (i.e., SS with a settling velocity greater than 0.10 cm/sec) is to siphon a sample at mid-depth after 100 sec. The SS that settle during the first 8 sec of the test (visual observation) are the major portion of the SS that the swirl was developed to remove (based on a settling velocity of 2.6 cm/sec or greater for a 20-cm column).

A review of the technical literature indicates that a variety of methods are being used to determine the settling rates of suspended particles. Ideally, settling tests should be conducted with representative samples of wastewater collected using non-destructive methods which preserve the in situ settling properties. The tests should be conducted under the original suspension conditions, including the wastewater temperature, suspended solids concentration, and factors which affect surface conditions (i.e., surfactants, ionic strength). Compromises are often made to simplify the procedure and reduce costs. Those methods which include pre-concentration of the suspended material risk changing the settling properties through the agglomeration which will occur in the naturally flocculant suspensions. Those methods which settle the particulates through non-representative fluids, e.g., tap water, invite errors associated with concentration and surface property effects. One problem generated by the lack of standard procedures is that the results of different studies can not be compared to each other. Considerable caution must be exercised in comparing published test results.

Two particle settling velocity distribution methods which use small sample volumes are the Brombach or German procedure (Michelbach and Wohrel 1993; Pisano and Brombach 1996) and the Norwegian Institute for
Water Research (NIVA) method (Lygren and Damhaug 1986; Walker et al. 1993). These methods were specifically designed for the high settling velocity particles that swirl/vortex units were developed to remove and may not reflect the settling behavior of finer material. The methods offer several benefits relative to the classical (large) settling column method. They require fewer analyses (one sample from the bottom as opposed to several simultaneous samples from multiple ports) and smaller testing volumes (approximately 4 to 12 L as compared to approximately 38 to 57 L). Each method uses a smaller apparatus which is more amenable to field use (less than 1 m deep and 5 cm wide as compared to approximately 2 m or deeper and 20 to 30 cm wide). These methods provide a truer representation of high-velocity discrete settling because the particles are allowed to settle over a known distance for a known time. In the classical settling column method, the larger particles form a small portion of the total mass, may not be uniformly distributed at time zero, may not be sampled adequately by side-mounted ports, and may have settled to the bottom before sufficient samples have been collected.

A study of CSO treatment options being conducted in the Province of Ontario (Averill et al. 1995) is directed toward attaining primary treatment equivalency with satellite treatment systems. This effluent quality objective necessitates consideration of the wastewater as a flocculant suspension because the removal of relatively fine organic material will be required. A modified long column settling procedure is being developed to respect the flocculant regime while providing additional information about floatable material and the faster settling particles. In this case, for comparison to a vortex separator, the long column data are being aggregated to derive the settling rate distribution rather than averaged over depth as would be required for a conventional horizontal-flow clarifier.

If particle-settling velocities indicate that swirl/vortex technology will remove an acceptable percentage of the particles in the storm flow, hydrological and hydraulic studies should then be conducted to determine the design flow. This analysis of flow should be done on a long-term continuous basis using mathematical modelling, in conjunction with direct measurements of flow rates for calibration and verification, to achieve the best design flow and settleable solids removal prediction. The use of the design-storm concept to establish the design flow and the “first flush” for the settleable solids load will not enable a proper design.

Design Enhancement Information

The detailed design procedures for commercial vortex units are proprietary information. Sizing is understood to be based on design flow and the settleability of the solids to be treated. The following discussion pertains to the swirl, for which a design manual has been published.

The size of the swirl, specifically the inlet and chamber diameters (all other dimensions are geometrically proportional to these components), is based on design flow and the desired removal efficiency for the settleable solids. Detailed design information for the swirl is contained in the EPA
publication *Design Manual: Swirl and Helical Bend Pollution Control Devices* (Sullivan et al. 1982).

While under-designing the swirl may lead to poor treatability, over-designing leads to a costly and ineffective facility. In one case, where design flow was based on a one in ten-year storm frequency, the swirl operated more like an underground storage system that required pumping rather than a CSO regulator (Field 1978). The *Design Manual* (Sullivan et al. 1982) states: “In general, if a pollution-control facility is designed for the maximum storm that occurs two or more times annually, the length of time that this rate will be exceeded on an annual basis is measured in minutes for the year... Thus, a careful analysis rather than an arbitrary rule of thumb will dictate the use of smaller, less costly units.”

The design flow selection should also consider the use and advantage of the secondary overflow weir (emergency spillway) located on the peripheral-cylindrical wall of the swirl and illustrated in Fig. 1. The secondary overflow weir provides flow relief to maintain an effective swirl flow field for settleable solids separation by decreasing what would have otherwise been flow velocities in the swirl chamber that are too high for settleable solids separation. This is accomplished by establishing the secondary weir elevation to limit the flow rate to the central downshaft to approximately twice design flow. Fig. 6 illustrates decreased settleable solids removal as a function of increasing flow rate. The elevation of the secondary overflow weir must not cause upstream flooding. The design should allow swirl secondary weir overflows to occur up to six times a year.

Pilot-scale testing is the optimal way of determining whether the swirl is suited for a particular site. While this increases preliminary design costs, it represents only a fraction of the overall construction costs. A pilot-scale swirl can be set up by diverting a side stream from the storm flow mainstream.

The swirl affords some flexibility in its sizing where site constraints are encountered. The aspect ratio may be adjusted (Sullivan et al. 1974; Sullivan et al. 1982), for example, to suit the site plan area and the difference in elevation between the inlet and outlet sewers. There is also design flexibility for settleable solids removal as a function of swirl size (Sullivan et al. 1982), i.e., the higher SS removal sought, the larger the required size. A swirl at Presque Isle, Maine (Pisano 1994), was doubled in volume based on settling column work which showed a relatively small fraction of SS that settled at greater than 0.5 cm/sec. A post-installation evaluation validated the Presque Isle design.

A careful assessment of additional cost requirements should be made before applying the swirl when underflow pumping is required. Swirls are even less likely to be cost effective if effluent pumping is required.

**Performance Assessment**

The same settleability analysis conducted for swirl/vortex site-selection assessment and design purposes (as previously discussed under “Wastewater Characterization”) should be conducted after installation to
quantify the performance of the unit. Sampling should at least be conducted for the influent and effluent; representative sampling of the underflow may prove to be too difficult. Short time intervals (of 10 minutes or less) are preferable; however, limitations in the budget (or by the sampling equipment) may require longer intervals. In addition to SS and settleable solids, other analyses, e.g., BOD, COD, nitrogen, phosphorus and metals, should also be conducted to categorize pollutant loads and removals.

Continuous flow rate measurements should at least be made for the influent and underflow. Accurate and reliable flow rate measurements must be carefully synchronized with sampling times in order to determine the fluid volumes and pollutant mass loads that are required for performance evaluation. While representative monitoring is complex and costly, without it, reliable data and performance evaluation cannot be developed.

As previously mentioned, representative samples of the influent and effluent SS (and associated pollutants) must be taken across the entire cross-section or water column of the flow. The sampling system must have intake velocities greater than the mainstream velocity in order to be
able to draw up the heavier particles and multiple leveled ports in order to capture the stratified heavy particles. This is essential for determining SS removals. An alternative sampling method is a "slice-sampler" for the influent conduit, which was used at the Lancaster, Penn., demonstration project (Pisano et al. 1984) and will be discussed later.

Another recommended method for measuring settleable solids treatment effectiveness is taking grab samples or using 0.2 mm aperture screening (intermittently, at short intervals) of the treated overflow effluent. These samples should not contain a significant amount of grit-like particles or organic settleable solids and floatables. SS, which settle during the first 8 seconds of the settleable solids analysis, should not appear based on the swirl's development (90% or better removal at design hydraulic load or less) and would indicate a design anomaly.

The removal of buoyant material (floatables) from CSO flows is a prime concern at many locations. Previous laboratory investigations have used small buoyant beads to simulate the fate of floatables in vortex vessels. In real flows, however, floatables are often larger objects, sometimes called "gross solids". Pilot- and full-scale demonstration projects using real CSO flows have provided only qualitative results on the performance of vortex separators for removing floatables. There is a need to produce quantitative data on the performance of vortex technologies in removing real floatables. Recommended methods for the assessment of floatables capture are: (1) visual assessment of floatables capture, (2) capture of the influent floatables with a coarse screen, and (3) capture of the effluent floatables (and coarse solids) with a coarse screen.

Coarse screening of the clarified effluent can be accomplished by dropping a "crab-net" type device intermittently and for short periods of time over the outlet to see if floatables are escaping the unit. In Syracuse, N.Y. (Drehwing et al. 1979), a coarse screen blocked floatables from going under the weir plate of the swirl and aided visual confirmation of capture efficiency. Coarse screening could also be done downstream of the swirl in the effluent outlet pipe. An abundance of floatables in the net or screen indicates that the floatables capture system is not meeting its developmental criteria. The downstream screen can have a smaller aperture and longer collection times than the "crab-nets" since backing up the flow temporarily will not cause flow inundation problems. If the screen aperture is small enough, e.g., 3.0 mm or less, capture of relatively large SS will indicate that the swirl is not performing according to its developmental criteria.

Case Studies

Little information has been published concerning the application and performance of swirl and vortex separation devices. Full-scale performance evaluations have tended to be meagre and results have been mixed. Furthermore, a comparison of the performance of different de-
signs is difficult because of differences in monitoring and data analysis techniques. The following discussion briefly summarizes studies done with swirl/vortex separators.

At West Roxbury (Boston), Maine (Pisano et al. 1984), a 3.2-m diameter pilot-scale swirl was evaluated for its ability to treat stormwater from a separate storm sewer. The swirl SS treatment effectiveness was low for this application. The non-flow-weighted average SS mass total efficiency (TE), Net Removal and treatment factor (TF) were 28.1, 17.0, and 3.4%, respectively, excluding one extreme data point. The incoming SS were of a silty nature with low settling velocities and did not readily separate from the storm flow in the swirl.

The Northeast Boundary, Washington, D.C., facility is comprised of three 17.4-m diameter swirls, each having a design flow of 503,000 m³/day with a hydraulic load of 1.4 m/min (84 m/h). Samples were obtained with samplers having proper intake velocities and evaluated. The TE averaged 38% for all the storm events; however, most of this removal (i.e., 26%) was accomplished by flow splitting and not by the swirl concentration effect. Table 2 shows that Net Removal was less than expected, averaging 12%, with a TF of only 1.46. The primary cause of low Net Removal appears to have been the relatively low settling velocities of

<table>
<thead>
<tr>
<th>Storm</th>
<th>TE (%)</th>
<th>FS (%)</th>
<th>Net Removal (%)</th>
<th>TF</th>
<th>Predicted TEb (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.3</td>
<td>14.6</td>
<td>13.7</td>
<td>1.94</td>
<td>16.6</td>
</tr>
<tr>
<td>3</td>
<td>67.5</td>
<td>64.4</td>
<td>3.1</td>
<td>1.05</td>
<td>67.0</td>
</tr>
<tr>
<td>4</td>
<td>39.4</td>
<td>33.9</td>
<td>5.6</td>
<td>1.16</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>27.9</td>
<td>14.9</td>
<td>13.0</td>
<td>1.87</td>
<td>22.2</td>
</tr>
<tr>
<td>7</td>
<td>42.0</td>
<td>24.3</td>
<td>17.8</td>
<td>1.73</td>
<td>26.0</td>
</tr>
<tr>
<td>8</td>
<td>35.6</td>
<td>10.8</td>
<td>24.8</td>
<td>3.30</td>
<td>10.5</td>
</tr>
<tr>
<td>9-SW2</td>
<td>48.9</td>
<td>27.1</td>
<td>21.8</td>
<td>1.83</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>34.9</td>
<td>23.9</td>
<td>11.0</td>
<td>1.46</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>30.0</td>
<td>30.0</td>
<td>0.0</td>
<td>1.00</td>
<td>25.7</td>
</tr>
<tr>
<td>12</td>
<td>21.1</td>
<td>12.6</td>
<td>8.5</td>
<td>1.67</td>
<td>32.1</td>
</tr>
<tr>
<td>Averagec</td>
<td>37.6</td>
<td>25.7</td>
<td>11.9</td>
<td>1.46</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Note: Design flow = 503,000 m³/day, diameter = 17.4 m, and hydraulic load = 1.4 m/min. Performance based on SS analyses.


Based on settling-velocity analyses.

Average of storm events.
particles in the influent CSO. However, an important observation of this swirl's performance is that the theoretical (predicted) average TE, estimated to be 29% based on measured SS settling velocities (averaged for seven storm events) and removal curves derived from hydraulic modeling (Sullivan et al. 1982), were lower than the actual measured TE of 38% (averaged for all ten storm events). The facility floatables traps were reported to be effective.

The Northeast Boundary, Washington, D.C. facility also shows that the swirl is capable of removing particles lighter than the particles used for swirl development. For one storm (#5 in Table 2), 50% of the influent SS had settling velocities greater than 0.1 cm/sec, and only 10% had settling velocities of 1.0 cm/sec or greater (O'Brien and Gere 1992). Therefore, although less than 10% of the influent SS mass had settling velocities in the range used for swirl development, a TE of 27.9%, a Net Removal of 13%, and a TF of 1.87 were achieved for this event.

Evaluation of the 7.3-m swirl in Lancaster, Penn. (Pisano et al. 1984), showed that proper sampling will result in higher SS TE and Net Removals. The Lancaster, Penn., demonstration project used a specially constructed cross-sectional sampler capable of automatically taking a vertical slice or segment of the whole influent conduit cross-section. Prior to using the slice-sampler, the Lancaster swirl had shown "...negligible to negative solids treatment efficiency..." and further that "...samples taken manually for settleability analyses typically contained SS concentrations much lower than concentrations of samples..." taken by the slice sampler (Pisano et al. 1984). As compared to a Manning model 6000( sequential sampler, the slice sampler collected samples having one-and-a-half to seven times the SS concentration. The non-flow weighted average SS mass TE and Net Removal were 55 and 37%, respectively, with a TF of 3.1.

A swirl evaluation project conducted in Holland (NWRW 1989) used a sampling system containing intake orifices at multiple levels with high intake velocities capable of sucking in the heavier particles. This sampling system was expensive, costing approximately US $50,000 in 1987. Table 3 contains results for this project. This is one of the few projects that evaluated the treatability of several pollutants. The project also partitioned swirl performance based on total, suspended and settleable solids, resulting in an evaluation across the full range of solids, i.e., from the dissolved, nonsettleable, suspended, through settleable solids fractions. This study showed that while representative sampling may be complex and costly, without proper and comparative sampling techniques, reliable data and efficiencies cannot be developed.

A 3.7-m diameter swirl with a design flow of 26,000 m³/day and a corresponding hydraulic load of 1.4 m/min (84 m/h) was demonstrated in Syracuse, N.Y. (Drehwing et al. 1979; Field and Masters 1977). Samples were obtained by sampling devices with adequate intake velocities. The swirl was used to treat actual combined sewer overflows from a 22-ha drainage area. Eleven storm events, monitored over a 2-year period, generated hydraulic loads spanning 8 to 43 m/h on an event-averaged basis.
Table 3. Swirl performance, CSO facility, Goes, Netherlands

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Solids fraction</th>
<th>Influent mass (kg)</th>
<th>Effluent mass (kg)</th>
<th>TE (%</th>
<th>Net removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>total</td>
<td>7993</td>
<td>3744</td>
<td>53</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>settleable</td>
<td>4673</td>
<td>1694</td>
<td>64</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>6518</td>
<td>2767</td>
<td>58</td>
<td>46</td>
</tr>
<tr>
<td>BOD</td>
<td>total</td>
<td>2552</td>
<td>1308</td>
<td>49</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>settleable</td>
<td>1339</td>
<td>550</td>
<td>59</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>2050</td>
<td>976</td>
<td>52</td>
<td>41</td>
</tr>
<tr>
<td>Kjeldahl nitrogen</td>
<td>total</td>
<td>351</td>
<td>211</td>
<td>40</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>settleable</td>
<td>102</td>
<td>47</td>
<td>54</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>137</td>
<td>68</td>
<td>50</td>
<td>48</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>total</td>
<td>100</td>
<td>60</td>
<td>39</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>settleable</td>
<td>37</td>
<td>19</td>
<td>49</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>69</td>
<td>40</td>
<td>41</td>
<td>22</td>
</tr>
</tbody>
</table>

Note: Design flow = 100,000 m³/day, diameter = 8.0 m, and hydraulic load = 1.4 m/min.

After NWRW 1989.

Observed TE fluctuated between 33 and 82%. SS TE and Net Removal for this project averaged 52 and 18%, respectively, with a TF of 1.53.

Tests with and without coagulants (and weighting agents) were undertaken at the Countess Wear STP in Exeter, England, using 1- and 2-m diameter Storm King® units (Hydro Research and Development 1986). With chemicals, the vortex separator achieved equivalent performance at more than six times the corresponding clarifier or lagoon hydraulic loading rate. Without chemicals, the vortex separator produced primary quality effluent at more than five times the conventional surface loading rate. Total retention time in the chemically aided vortex system was 40 to 80 minutes; removals were 90% for SS, 70% for BOD and 98%+ for phosphorus. However, influent concentrations were high by North American standards, and effluent concentrations were 50 to 70 mg/L for SS and 80 to 150 mg/L for BOD. The forecast uses were for small plants, plants with variable and intermittent loading conditions, standby mode operation, rapid pretreatment of industrial wastes or for partial treatment where sea outfalls are used. The maximum hydraulic load was 2.9 m/h. Ferric chloride appeared to be the most effective coagulant but dosages were not reported.

A 3-m diameter Storm King® unit was used as a CSO treatment device at the Stoke Cannon pumping station. The objective was to remove gross solids, grits and aesthetically offensive materials. The results indicated an average of 60% reduction in SS and 35% reduction in BOD. The objectives were 100 mg/L BOD and 60 mg/L SS, but the actual overflow
concentrations were not provided (Fagan 1993).

A pair of 3-m diameter Fluidsep™ vessels were tested in Tengen, Germany (Brombach et al. 1993). Phase I of the evaluation investigated the operational reliability and long-term hydraulic mass balances. Phase II investigated the separator removal. The average ratio of underflow to overflow concentrations of total solids and COD varied from 1.7 to 2.1, while the average hydraulic load varied from 14.4 to 50.5 m/h. Mass balances on the Fluidsep™ system revealed that the settleable solids removal efficiencies ranged from 29 to 97% (Pisano and Brombach 1993).

Muhs (1995) described the early evaluation of the Lincoln Park CSO facility in Decatur, Ill. This facility contains four Fluidsep(s)™ and is designed to handle a flow of 1,570,000 m³/d. A full report on this project is available from the Decatur, Ill., Sanitary District.

A pilot-scale study of CSO satellite treatment options is being conducted in Metropolitan Toronto. The majority of the experimental work has been conducted with a 3-m diameter Storm King® Dynamic Separator. The proposed CSO control policy for the province of Ontario includes the achievement of primary treatment equivalency, which is defined as at least 50% removal of suspended solids. Results from 2 years of experimental work in the field have generated an appreciable performance database. Based on dry-weather sewage tests, the vortex separator was found to be approximately 2.6 times more efficient (concentration-based definition) than a 2.3-m diameter circular clarifier which was tested in parallel at the same surface loading rate. Since wet-weather sewage was found, on average, to be more readily settleable, and would contain a larger fraction of particles amenable to inertial separation, the vortex separator would be expected to have a somewhat greater advantage under wet-weather conditions. Using TE as a measure of the reduction in pollutant load to the environment, the vortex separator achieved 50% SS removal at a hydraulic load³ of approximately 5 m/h without chemical aids. With an optimized coagulant dosage — typically ferric chloride at 20 mg Fe³+/L and an anionic polymer at 1 mg/L — the separator achieved 50% SS removal at approximately 8 to 9 m/h. The efficiencies quoted were based on data obtained over several months of operation treating a relatively slow-settling sewage; variability between events was appreciable. This study is described in two papers in this journal issue (Schmidt et al. 1997; Gall et al. 1997).

Discussion

Published case histories indicate that vortex technologies do remove solids. However, due to the limited performance and operating data, no quantitative conclusions about removal performance can be made.

³ The net surface load was calculated using the overflow rate and the total surface area of the cylindrical vessel.
The published results of studies done to date on the performance of vortex separators do not clearly distinguish between the solid/liquid separation efficiency of the units and the overall performance (including storage and flow splitting) of the technology. There is no discussion of the relative sizing importance of the underflow rate as a fraction of the total inflow. The rational sizing of individual vortex separators and the optimal operation of a battery of units during flow variations will require a basic understanding of the performance characteristics of vortex separation technology with respect to the design flow, hydraulic load and the underflow/inflow ratio.

Conclusions

Cost-effective pollution abatement solutions are inevitably unique to each CSO or stormwater collection and treatment system. Designers need to select from the range of technologies available to build a system of remediation solutions. Swirl/vortex devices are one of the techniques which should be considered. They are relatively simple, cost-effective devices which remove the larger and more readily settleable suspended pollutants. Although the performance database is sparse, swirl/vortex devices are proven tools which are used as components in sewerage system optimization programs.

Sound procedure should be followed to optimize swirl/vortex application, including (a) capture of the heavy, and sometimes stratified, particles for treatability assessment; (b) predetermination of the particle settling velocity distribution from representative samples and/or a pilot study to assess treatment suitability; (c) proper selection of design flow or hydraulic load based on a long-term hydrological/hydraulic study; and (d) proper placement of the swirl/vortex unit as part of the storage-treatment system, e.g., not downstream of a storage/sedimentation basin, grit chamber or flow regulator.

Acknowledgments

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**Notation**

\[ Q \quad = \quad \text{wastewater flow (m}^3/\text{s)} \]
\[ SG \quad = \quad \text{specific gravity} \]
\[ de \quad = \quad \text{effective particle diameter} \]
\[ T1 \ldots T6 \quad = \quad \text{specific start/end times (see figure 5)} \]
\[ M \quad = \quad \text{pollutant mass (kg)} \]
\[ V \quad = \quad \text{wastewater volume (m}^3) \]
\[ \bar{C} \quad = \quad \text{flow-weighted average pollutant concentration (kg/m}^3) \]
\[ C \quad = \quad \text{pollutant concentration of sample (kg/m}^3) \]
\[ Q \quad = \quad \text{average flow rate between samples (m}^3/\text{s)} \]
\[ t \quad = \quad \text{time interval between samples (s)} \]
\[ TE \quad = \quad \text{total efficiency (see equation 4)} \]
\[ PSE \quad = \quad \text{pollution separation efficiency (see equation 5)} \]
\[ NE \quad = \quad \text{net efficiency (see equation 6)} \]
\[ CE \quad = \quad \text{concentration-based efficiency (see equation 7)} \]
\[ FS \quad = \quad \text{flow split (see equation 9)} \]
\[ TF \quad = \quad \text{treatment factor (see equation 10)} \]
\[ EFS \quad = \quad \text{effective flow split (see equation 11)} \]
\[ ETF \quad = \quad \text{effective treatment factor (see equation 12)} \]
\[ Net \text{ Removal} \quad = \quad \text{(see equation 14)} \]

**Subscripts**

\[ i \quad = \quad \text{influent} \]
\[ o \quad = \quad \text{overflow (effluent)} \]
\[ u \quad = \quad \text{underflow} \]
\[ k \quad = \quad \text{positive integer index} \]
\[ v \quad = \quad \text{vessel} \]

**References**


Urban Storm Drainage. IAHR/IAWQ, Niagara Falls, Ont.


as a combined sewer over-flow regulator. EPA-670/2-74-039, U.S. EPA, Edison, N.J.


