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ASSESSMENT OF VORTEX SOLIDS SEPARATORS FOR THE CONTROL AND TREATMENT OF WET-WEATHER FLOW

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NOTICE

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This manual is the product of the efforts of many individuals. Gratitude goes to each person involved in the preparation and review of the document.

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EXECUTIVE SUMMARY

ASSESSMENT OF VORTEX SOLIDS SEPARATORS FOR THE CONTROL AND TREATMENT OF WET WEATHER FLOW

BACKGROUND

This document presents results of a technical evaluation of vortex solids separators for the treatment of wet-weather flows (WWF). This evaluation provides information in support of the Municipal Technology Branch (MTB) and the National Risk Management Research Laboratory (NRMRL) of the U.S. Environmental Protection Agency (EPA) mission to collect, evaluate, and disseminate technical information on WWF control and treatment practices which achieve the goals of the Federal Clean Water Act.

These evaluations explore design-related issues, identify specific weaknesses or limitations, provide cost data and are beneficial in resolving operation and maintenance (O&M) problems. In addition, the results of these evaluations identify a specific range of conditions under which the processes or technologies demonstrate levels of performance efficiency. These evaluations are an essential first step in disseminating actual data on the selected processes or techniques. As such, this report is an assessment of vortex solids separators for the control and treatment of WWF from separate storm-sewer systems. Because the preponderance of data is from combined sewer overflow (CSO) application, CSO data was used.

APPROACH AND SCOPE

Originally the primary objective of this report was to assess vortex solids separators for the control and treatment of separate storm-sewer discharges. However, only a limited amount of effectiveness data for storm-sewer applications is currently available. Therefore, CSO (and other) data will be presented along with stormwater data. It should be understood that vortex treatability is principally a function of particle settling velocity; therefore, use of data from different types of flow, i.e., stormwater, CSO and river water, are justified and valid. This report is prepared for engineers and scientists who wish to obtain a basic understanding of vortex solids separators. It identifies current applications of this technology, presents limitations, describes certain types of units, provides general cost information, and evaluates performance using available information and data. This evaluation was derived from careful consideration of data from:

- Vendors, developers, and
- Demonstration studies.

This project focused on existing data from the three commercially available types of vortex solids separator units: the EPA swirl flow regulator/settleable-solids separator (swirl), the Storm King™, and the Fluidsep™. No direct data collection was conducted. Nevertheless, this evaluation represents a careful assessment of vortex solids separators. As additional vortex solids separators are installed and new data become available, periodic reevaluations of this technology are recommended.

FINDINGS AND CONCLUSIONS

Based on data from CSO applications, the mass suspended solids (SS) removal from vortex solids separators varied between an average of 38% at the Washington, DC full-scale swirl facility to 54% at the full-scale Fluidsep™ facility in Tengen, Germany. The mass SS net removal (defined as the mass SS removal less the percentage of the underflow:inflow ratio) was found to be lower. Average mass SS net removals varied between 7% at the Tengen, Germany full-scale CSO Fluidsep™ facility and 17% at the pilot-scale stormwater swirl facility at West Roxbury (Boston), MA. The average mass SS removal was 26% for separate stormwater treatment in West Roxbury.

It was concluded that mass SS net removal by concentration into the underflow (actual treatment) is approximately 30% or less. In CSO applications, most of the mass is removed by regulation (flow splitting of the underflow) not by concentration. However, the vortex may capture small storms that would otherwise result in overflows. This additional CSO management advantage may not be obvious by focusing on the net removal of mass SS. It was impossible to make any conclusions about the performance of one type of vortex unit relative to the other due to site-specific flow characteristics and treatment objectives and the limited available data.

Vortex solid separators performed better in terms of mass SS removal under lower hydraulic loading (HL). Lower HL did not improve mass SS net removal.

Based on available information, capital costs in 1994 (ENR 5450) dollars attributable to vortex solids separators were between \$3,900 and \$25,000/MGD of design flowrate (Q_d) depending on specific site requirements.

SECTION 1

INTRODUCTION TO VORTEX SOLIDS SEPARATORS

The degradation of our nation's water bodies can partly be attributed to pollution in stormwater runoff and combined sewer overflow (CSO). During the past two decades, significant research has been conducted to identify and test technologies to control wet-weather sources of pollution that contribute to the degradation of the water bodies. One technology that has shown promise for achieving pollution control while consuming minimal land space is the vortex solids separator.

This section will introduce the concept of vortex separation, describe available units and their application, and defines particles removed. Design criteria for the swirl and the commercially available vortex separators are provided in Section 2. A performance assessment of the technology for control of both CSO and separated stormwater is presented in Section 3. Section 4 presents the costs of various technologies. Section 5 summarizes the performance characteristics, process limitations and recommendations.

BACKGROUND INFORMATION

Vortex separators were initially studied in Bristol, England, in the early 1960s as dual purpose CSO regulator/suspended solids (SS)-liquid separator devices. Experiments were conducted to determine the hydraulic and performance characteristics of the vortex mechanism. Results of early studies indicated that vortex separation was effective at regulating CSO and concentrating SS into the underflow for further treatment while producing a significantly cleaner overflow for discharge to a receiving water.

In the 1970s, the U.S. Environmental Protection Agency (EPA) and the American Public Works Association (APWA) expanded vortex separation technology with their own tests relative to North American practice. The original purposes were to hydraulically regulate CSO as well as to provide concentration of the settleable SS. Through hydraulic modeling studies the EPA and the APWA developed design specifications for a triple-purpose (flow regulator/settleable-solids separator/floatables collector) vortex device or *swirl* to control CSOs. Thorough design information on swirls for CSO and stormwater control is available in an EPA *design manual* (Sullivan *et al.*, 1982). In the late 1970s the first full-scale swirl for CSO control was constructed in Lancaster, Pennsylvania (Pisano *et al.*, 1984). EPA also developed the swirl degritter (Sullivan *et al.*, 1974; Sullivan *et al.*, 1977; Shelley *et al.*, 1981; Sullivan *et al.*, 1982) for settleable solids separation without flow regulation.

CURRENT STATUS

In addition to the swirl, two other vortex separators developed by private companies will be emphasized in this report. One is the Fluidsep™ patented by a German firm, Umwelt-und

Fluid-Technik (UFT) and the other is the Storm King™ patented by Hydro International Limited (HIL), a British firm. Each of the three units will be described in Section 2.

Vortex units are most often used for CSO control although they have been used to treat stormwater runoff at two sites in the U.S. and one in England. There are at least 19 full-scale swirl units in the U.S. and four in Japan, as shown in Table 1-1. Of the 24 swirls listed, 23 are used to control CSOs. A swirl pilot unit was also tested for flow regulation and treatment of stormwater in a separate storm-sewer system in West Roxbury (Boston), Massachusetts (Pisano *et al.*, 1984) (in the late 1970's, but has since been disassembled). Swirls are also located in other countries, e.g., Holland, France, and Norway. As of this writing, there are 13 full-scale Fluidsep™ units in the U.S. and Europe, as shown in Table 1-2, with additional units planned for construction. The Fluidsep™ unit has only been applied to CSOs. There are no full-scale Storm King™ units in operation in the U.S. at this time, however, there are more than 100 Storm King™ units in operation in Europe and Canada, as shown in Table 1-3. Full-scale Storm King™ units are planned for the City of Columbus, Georgia, to treat CSOs. Stormwater treatment by the HIL's Storm King™ has only been demonstrated at pilot scale in Bradenton, Florida and by HIL's Grit King™, a full-scale degritting unit, in Surrey Heath, B.C., England.

TABLE 1-1 SWIRL CSO INSTALLATIONS

Location	Diameter (ft)	Number of Units	Design Flowrate Per Unit (MGD)	Hydraulic Loading* Per Unit (gpm/ft^2)
United States				
Auburn, IN	28.0	1	32.0	36
Brownsburg, IN	25.0	1	25.0	31
Brownsburg, IN	28.0	1	36.0	41
Decatur, IL	25.0	1	40.0	57
Decatur, IL	44.0	1	113.0	52
Decatur, IN	18.0	1	37.0	101
Lancaster, PA	24.0	1	26.0	40
Oswego, NY	36.0	1	60.0	41
Presque Isle, ME	18.5	1	14.0	36
Syracuse, NY	12.0	1	6.9	40
Toledo, OH	32.0	3	51.7	45
Washington, DC	57.0	3	133.0	36
West Roxbury (Boston), MA**	10.5	1	3.9	31
Yonkers, NY	19.0	3	25.7	63
Japan				
Nerima-Shiyakuji Prk	36.1	1	8.4	6
Chuo WWTP	97.1	1	78.1	7
Itabashi	30.2	1	NA	NA
Ouji	78.7	1	61.6	9

* Hydraulic Loading (HL) is the design flowrate divided by the vortex chamber plan area and it is a nominal value since it does not account for the reduction in area due to the overflow weir arrangement.
** Stormwater pilot-scale application.
Source: Sullivan *et al.*, 1982; H.I.L. Technology, 1993, and NKK Corporation, 1987.

TABLE 1-2 FLUIDSEP™ CSO INSTALLATIONS

Location	Diameter (ft)	Number of Units	Design Flowrate Per Unit (MGD)	Hydraulic Loading Per Unit* (gpm/ft^2)
UNITED STATES				
Burlington, VT	40.0	1	80.0	44
Decatur, IL	45.0	1	113.0	49
Decatur, IL	44.0	4	104.0	47
Decatur, IL	27.0	1	20.0	24
Saginaw, MI	36.0	3	64.6	44
Saginaw, MI	36.0	1	130.0	89
EUROPE				
Tengen, Germany	10.0	2	10.8	95

* See footnote for Table 1-1.

Source: Pisano, 1993.

TABLE 1-3 STORM KING™ CSO INSTALLATIONS

Location	Internal Diameter (ft)	Number of Units	Design Flow Per Unit (MGD)	Hydraulic Loading Per Unit* (gpm/ft²)
ENGLAND				
Abersychan	29.5	1	38.8	39
Armagh West (NI)	10.0	2	3.7	33
Ashington	19.7	1	17.3	39
Bank Parade	18.0	1	15.0	41
Bargoed	21.3	1	15.5	30
Bexhill	9.8	1	2.9	27
Bexhill	13.1	2	6.2	32
Bexhill	16.4	2	11.0	36
Blaenau Ffestinog	25.0	1	22.8	32
Bluther Burn	14.8	1	5.2	21
Bluther Burn	13.1	1	3.5	18
Bowerfield D	24.6	1	25.3	37
Burn Beach	14.8	1	10.3	42
Burnham	26.3	1	14.8	19
Caroline Street, Langholm	5.9	3	1.5	38
Castleford	21.3	1	26.8	52
Clyde Park	33.8	1	54.6	42
Coatbridge	24.0	1	42.7	66
Coatbridge	29.4	1	78.9	81
Cowes (IOW)	14.8	1	8.0	32
Crewkerne	13.1	1	9.0	46
Crossways Park, Caerphilly	16.4	1	12.5	41
Culcheth	21.3	1	16.0	31
Denmead	13.1	1	6.1	31
Dock road	17.2	2	18.2	54
Dosthill	16.4	1	11.4	37
Ely Valley	16.4	1	9.0	30
Exwick and Redhills	17.3	3	0.9	3
Fountain Road	18.0	1	17.3	47
Gelli	16.4	1	13.7	45
Grange Lane	21.3	2	28.5	56
Grove Lane	25.0	1	31.9	45

TABLE 1-3 (Continued)

Location	Internal Diameter (ft)	Number of Units	Design Flow Per Unit (MGD)	Hydraulic Loading Per Unit* (gpm/ft^2)
Haverfordwest	2.0	2	0.2	44
Invergowrie	21.3	1	10.9	21
James Bridge	17.1	2	8.6	26
Kirkby Stephen	12.0	1	4.6	28
Ladye Bay	19.7	1	18.2	41
Lamberhurst	5.9	1	2.3	58
Lanark	29.4	1	91.2	93
Langwith	5.9	3	1.9	48
Lochaline	5.9	1	1.0	25
Lochgelly	23.0	2	27.6	46
Manthorpe	29.5	2	29.1	30
Mayland	9.8	1	2.1	19
Middleton Cheney	6.9	1	1.4	26
Milborne St. Andrew	11.0	1	1.6	12
Moor Row (Cleater Moor)	10.0	1	4.2	37
Neath Link	5.9	1	1.6	41
New Road	14.8	1	10.7	43
Newport (IOW)	25.0	1	105.2	149
Old Tebay	5.9	1	0.5	13
Oxford St. Maerdy	16.4	1	11.8	39
Oxford STW	17.2	1	18.2	54
Porterbrook	16.4	1	12.3	40
Portsmouth Relief D	21.3	1	17.1	33
Portsmouth Relief D	23.0	1	26.2	44
Portsmouth Relief D	21.3	1	21.7	42
Queensway	16.4	2	19.7	65
Rivacre	16.4	1	11.4	37
RMA Lake**	19.7	1	16.0	36
Sealstrand Dalgety Bay	16.4	1	14.0	46
Shenfield	23.0	2	10.6	18
SK Research	4.8	1	1.4	54
Sneyd Lane	17.3	1	7.4	22
South Ballachulish STW	5.9	1	1.3	33
Southern Orbital	6.9	1	2.3	43

TABLE 1-3 (Continued)

Location	Internal Diameter (ft)	Number of Units	Design Flow Per Unit (MGD)	Hydraulic Loading Per Unit* (gpm/ft^2)
Spa Slaithwaite	23.0	1	31.6	53
Spodden Valley	21.3	1	22.8	44
Stoke Canon	9.8	1	1.0	9
Summerhill	8.9	1	2.6	29
Swansea Road	19.7	1	16.0	36
Tatlers Farm	12.0	1	5.7	35
Totnes	13.1	1	4.7	24
Treorchy	23.0	1	25.1	42
Upminster	14.9	1	5.0	20
Warley Road	16.4	3	19.4	64
Wellingborough	8.9	1	4.1	46
Wellingborough	5.9	1	1.7	43
Wellingborough	7.9	1	2.7	38
Wellingborough	8.9	1	3.7	41
Wellingborough	8.9	1	3.9	44
Wenvoe	5.9	1	2.0	51
Wenvoe	5.9	1	2.0	51
West Pontnewydd D	14.8	1	9.6	39
White Bridge	5.9	1	1.4	36
Whitecliffe	8.2	2	4.2	55
Wick	16.4	1	10.4	34
Wigton Bypass	10.0	1	5.7	50
CANADA				
Gander, Newfoundland	29.5	4	3	3

Note: All Storm Kings™ are used for SS removal.

* See footnote for Table 1-1.
** Stormwater application.

Source: H.I.L. Technology, 1993.

PROCESS DESCRIPTION

Vortex SS separators have no moving parts. The cylindrical chamber configuration induces rotational forces that cause the separation and removal of settleable solids. During storm-flow conditions, flow enters the unit tangentially and a vortex is induced which concentrates SS into the underflow and thereby reduces SS concentration in the clarified liquid overflow. Vortex separation occurs when settleable SS circulating in the stationary unit are directed tangentially outward from the fluid flowfield and downward by gravity. In CSO applications, the concentrated SS are removed from the bottom of the unit and conveyed via the intercepting sewer to a wastewater treatment plant (WWTP). In separate stormwater applications, the concentrated underflow may be routed to a holding tank or pond or can also be routed to the WWTP if capacity (including sewerlines) is available.

In the case of the swirl degritter or the Grit King™ (HIL's vortex degritter) there is no underflow. The grit collection zone is at the bottom of the vortex unit. The Surrey Heath Grit King™ in England treats separate stormwater runoff from roof and highway runoff. Periodic emptying of deposits is required from a bottom hopper.

For CSO applications, vortex separators may be used in-line or off-line. Dry-weather flow (DWF) passes unimpeded through an in-line unit. Off-line units receive flow only when storm flows are diverted to the unit. In both in-line and off-line modes, the units can be used in combination with other CSO control facilities (i.e., storage tanks or ponds). Figures 1-1 and 1-2 illustrates alternative arrangements that can be used with vortex flow regulators/separators for CSO and separately sewered stormwater applications, respectively.

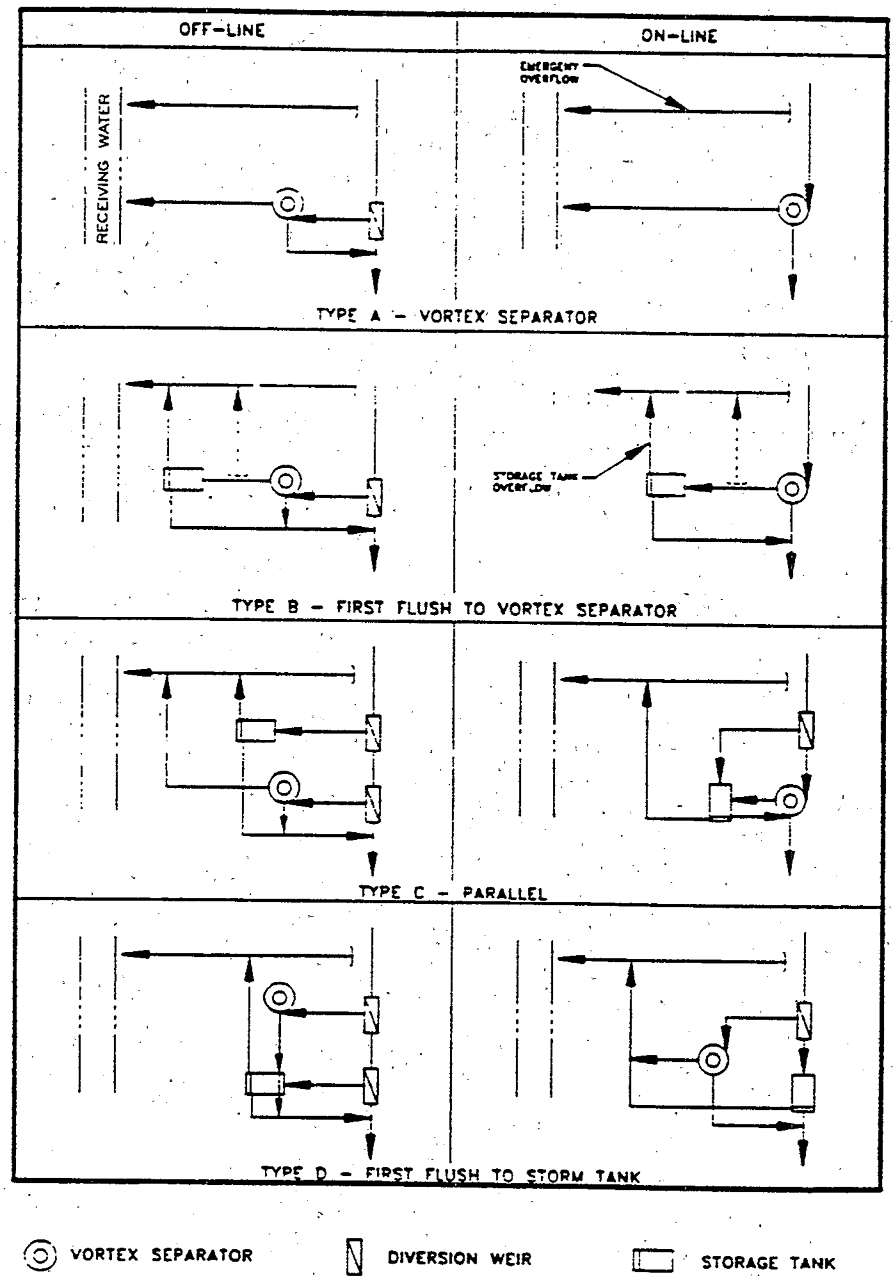
PARTICLES REMOVED BY VORTEX SEPARATORS

Vortex SS separators have been used for many CSO control applications, and for a few separate stormwater applications. As a result, the bulk of existing information on vortex units pertains to CSO applications. Although there are intrinsic differences between the two types of wet-weather overflows, the water quality characteristics of CSO and urban stormwater runoff are similar.

The design and performance of vortex-solids separators are based on solids' settling characteristics. This characterization aspect of WWF is at least as important as the actual concentration of solids for processes that depend on inertial separation. In the early 1970s EPA provided curves shown in Figure 1-3 that was the basis of design for the swirls.

FIGURE 1-1

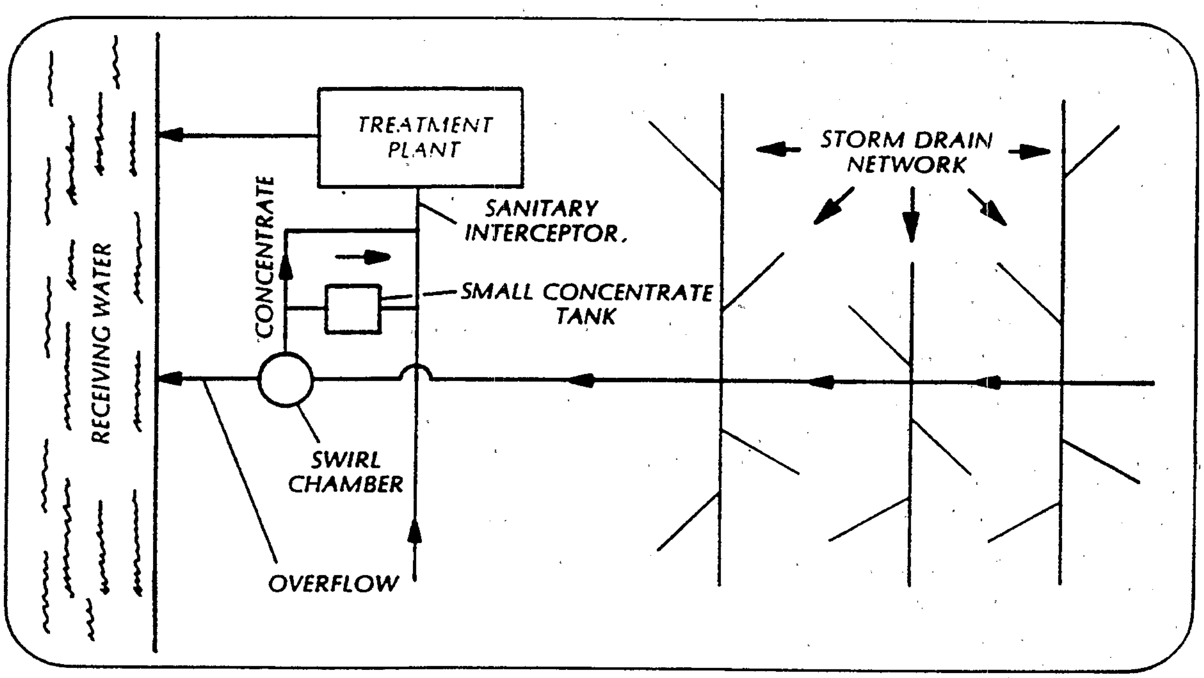
ALTERNATIVE PROCESS ARRANGEMENTS (CSO)



Source: Adapted from Pisano, 1993.

FIGURE 1-2

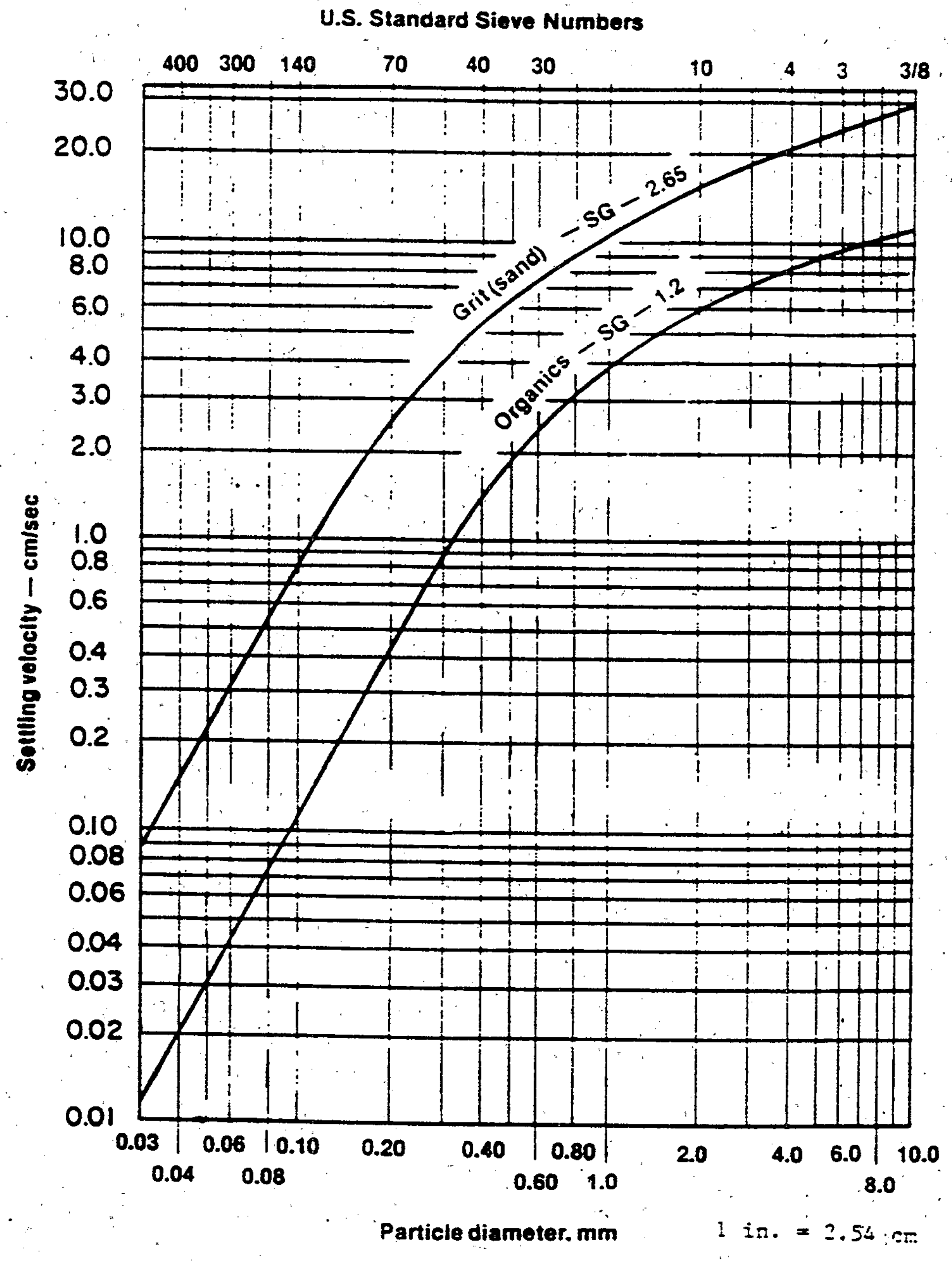
ALTERNATIVE PROCESS ARRANGEMENTS (STORMWATER)



Source: Field and Masters, 1977.

FIGURE 1-3

SETTLING CURVES



Source: Sullivan *et al.*, 1982.

Swirl SS separation efficiency also depends upon its design flowrate, Q_d and the fraction of settleable solids included in the total storm-flow influent SS. The swirl was developed through hydraulic modeling studies which used representative settleable model particles (based on the Froude Number and Stokes Law) to simulate grit [fine sand] (specific gravity (SG) equal to 2.65 and d_e from 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) (Sullivan *et al.*, 1982). Floatables were also simulated (SG range of 0.90 to 0.96 and d_e's from 5 to 50 mm). It is important to appreciate this aspect of the swirl's development and not expect significant removals of fine-grained and/or low-specific gravity particles.

The swirl *design manual* (Sullivan *et al.* 1982) stating removal values of 70%, 80%, 90%, and 100% are for the removal of synthetic *settleable solids* used for swirl development. A major portion of these simulated particles have settling velocitoies of 2.6 cm/sec or greater. The swirl will also concentrate 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.

SECTION 2

DESIGN CRITERIA

GENERAL

Prior to designing a vortex solids separator, regardless of the type or multi-purpose function, the mass and concentration of pollutants to be removed and the design flowrate, Q_d must be established. Other considerations include location and site structural limitations, operation and maintenance strategies, and regulatory requirements.

Vortex separators should be designed to achieve the desired level of SS removal for a statistical envelope of settling velocity distributions. Several other design parameters affect the performance of the vortex separator and must be considered so that the desired control is achieved. These parameters include the Q_d, which should be verified by long-term continuous modeling and the underflow rate. However, the SS settleability characteristics and dissolved solids fraction of the incoming flow is of primary importance. Since vortex separators are designed to remove grit-like solids and heavier organic particles, they will not concentrate the finer SS found in wet weather flows. The desired removal efficiency of SS and associated pollutants will dictate the Q_d allowable for the measured SS settling characteristics in conjunction with the underflow rate. Typically, the underflow is designed to capture between 5 and 10 percent of the Q_d.

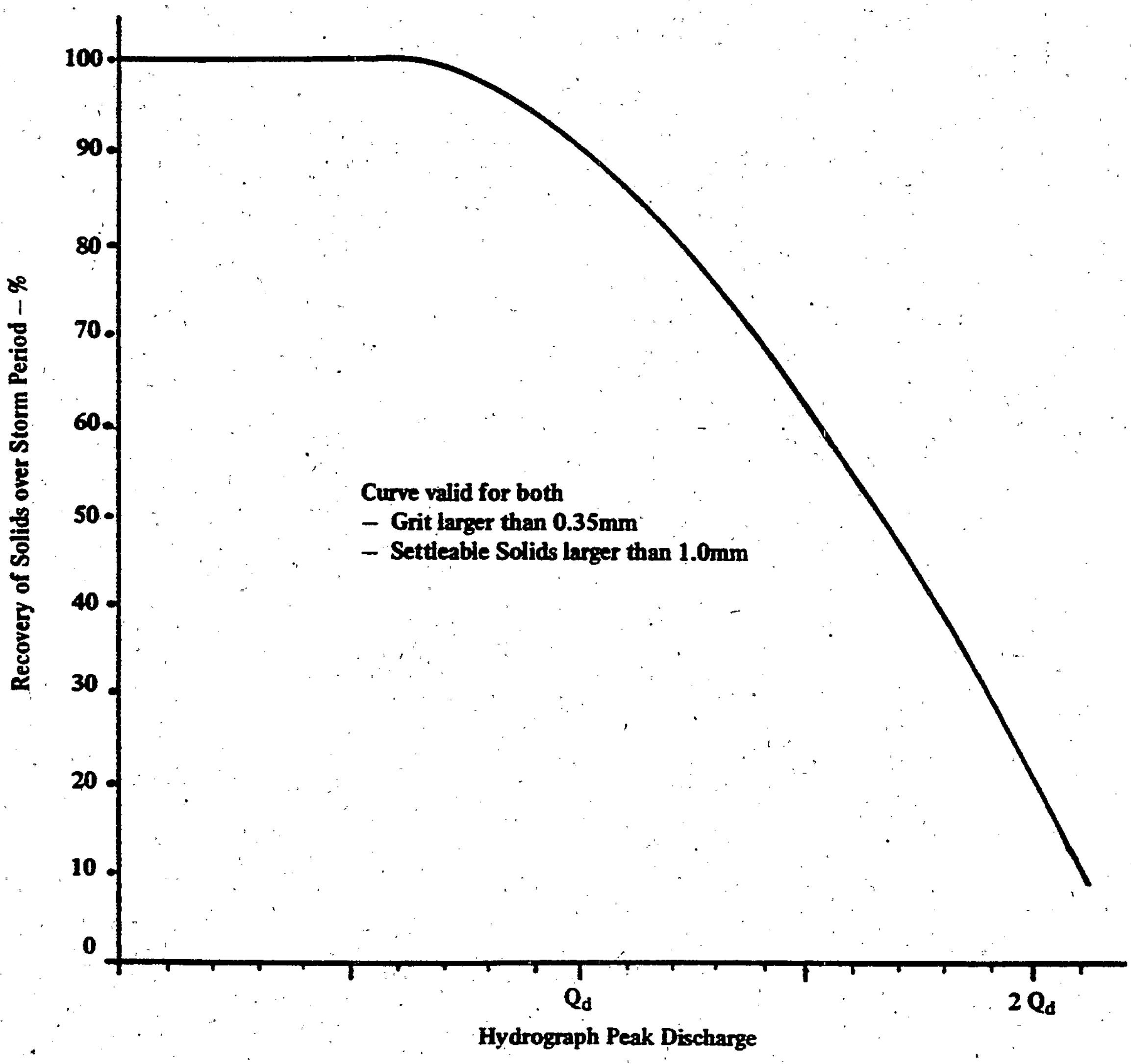
Flowrates less than the Q_d result in higher removals by way of gravity separation and flow reduction (a greater portion of the flow is diverted to the underflow). Figure 2-1 illustrates decreased settleable-solids removal as a function of increasing flowrate. A swirl is still capable of a reasonable degree of settleable solids concentration when its influent flowrate is below twice the Q_d. Flowrates that exceed twice Q_d convey the settleable solids through the unit too quickly and keep the particles suspended i.e., not removed by swirl concentration.

Small storm events may be fully captured in the underflow reducing the number or volumetric quantity of overflows. The underflow is drained to the sanitary intercepting sewer. In the absence of a sanitary sewer system or inadequate interceptor carrying capacity, a holding tank or compartment would need to be part of the swirl, Fluidsep™, or Storm King™ system and the tank would isolate the concentrated material for further treatment and disposal. Another option is the swirl degritter, Grit King™ or other vortex degritter design that does not have an underflow.

Although the performance of the three vortex units is based on a similar vortex SS separation mechanism, each has its own design criteria. Therefore, the background and design of the three types of vortex separators are discussed individually in the following text.

FIGURE 2-1

SWIRL SETTLEABLE SOLIDS REMOVAL



Source: Sullivan et al., 1972.

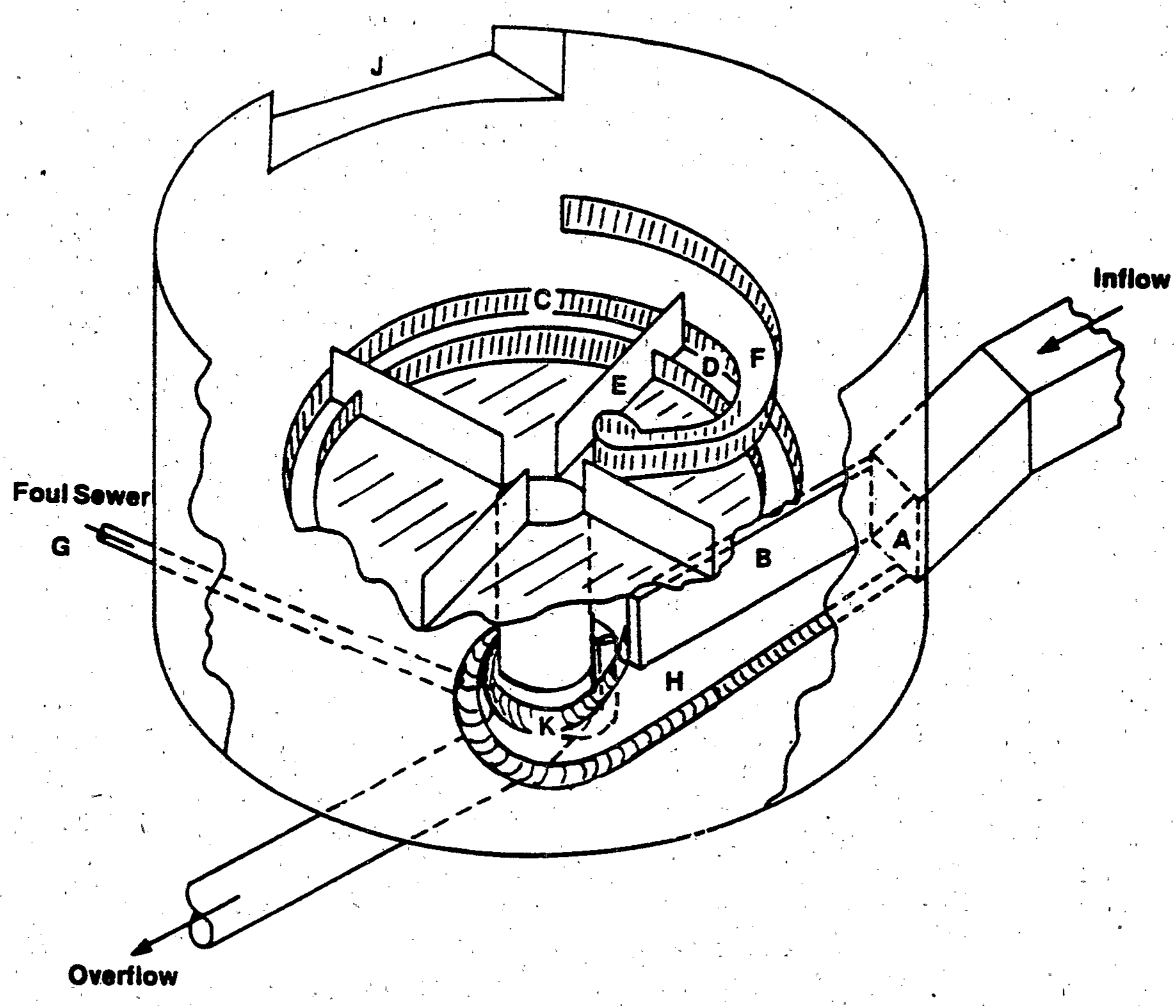
SWIRL

The swirl design, developed in the 1970s, is based on settleability studies and hydraulic modeling (Sullivan *et al.*, 1972). EPA derived settleability curves that were intended to represent CSO SS settling velocity distributions using the Froude Number and Soke's Law to scale-up the model for full-scale (prototype) results. The optimum design configuration was based on 90% removal of the SS based on specified settling velocity distributions. Various design curves are found in the EPA *design manual* (Sullivan *et al.*, 1982). This allows a unit to be designed for a desired removal and given particulate settling velocity distribution after determination of site-specific settling velocities and Q_d.

The swirl configuration is shown in Figure 2-2. Flow enters through a tangential inlet at the bottom of the unit. A flow deflector is located at the entrance ramp so that flow completing its first revolution is deflected off the wall and inward preventing short circuiting. The flow completes an additional revolution thereby following the longest path. SS and floatables separation occurs as the flow circulates within the unit. The foul-sewer outlet conveys DWF and storm flow having concentrated SS to the WWTP (for CSOs) or holding tank (typically for stormwater application for periods when the sanitary intercepting sewer/WWTP does not have enough capacity to accept the underflow). The original design for the swirl was for CSO application, therefore, a primary floor gutter was included in the design. The primary floor gutter conveys DWF from the inlet ramp to the foul-sewer outlet. This was done to provide confined DWF and thus prevent solids deposition on the floor of the unit.

FIGURE 2-2

SWIRL ISOMETRIC



A Inlet ramp
B Flow deflector
C Scum ring
D Overflow weir and weir plate
E Spoilers
F Floatables trap
G Foul sewer outlet
H Floor gutters
I Downshaft
J Secondary overflow weir
K Secondary gutter

Source: Sullivan *et al.*, 1982.

Buoyant materials quickly float to the top of the unit where they are directed to the floatables trap. The mini-vortex in the floatables trap draws the captured floatables under the weir plate where the floatables are contained by the weir skirt and weir plate arrangement. The floatables eventually exit into the foul-sewer outlet during DWF drawdown.

Treated flow exits over the overflow weir and onto the weir plate. Spoilers on the weir plate reduce rotational energy of the flow, thus increasing the overflow capacity of the downshaft and improving the separation efficiency (Field and Masters, 1977). Flow that exits through the downshaft is conveyed to further treatment, a holding tank, or the receiving water body (where permitted).

The swirls installed in the U.S. (see Table 1-1) represent a wide range of sizes and design criteria with diameters from 12 to 57 ft, nominal hydraulic loadings (HL) from 24 to 101 gpm/ft^2, and Q_d from 3.9 to 134 MGD. The swirls in Japan are designed with significantly lower HL, all being under 10 gpm/ft^2.

FLUIDSEP™

The basis of Fluidsep™ design is similar to the swirl in that SS settling velocity distribution curves are used to determine the most appropriate unit dimensions. The Fluidsep™ design requires that site-specific settling velocity distribution curves and modeling be performed by the proprietor. Once the settling characteristics are established, a unit is designed for that site. The settling characteristics may take from three months to one year to establish.

Flow enters the Fluidsep™ through a tangential inlet near the bottom of the unit. The inlet is designed to dampen the incoming flow velocities. Unlike the swirl, the Fluidsep™ does not have floor gutters, spoilers, or flow deflectors. This allows for an unimpeded vortex flow pattern.

The unit has a conical baffle as shown in Figure 2-3. The conical baffle stabilizes an inner vortex separation core where smaller particles have greater opportunity to be entrained in the core and swept toward the foul-sewer outlet that is in alignment with the vessels rotational axis. The unit is constructed with an angled floor (6% to 8%) that slopes toward the foul-sewer outlet in the center of the unit. The slope as well as the smooth finish, are intended to enhance the separated SS removal and facilitate washdown.

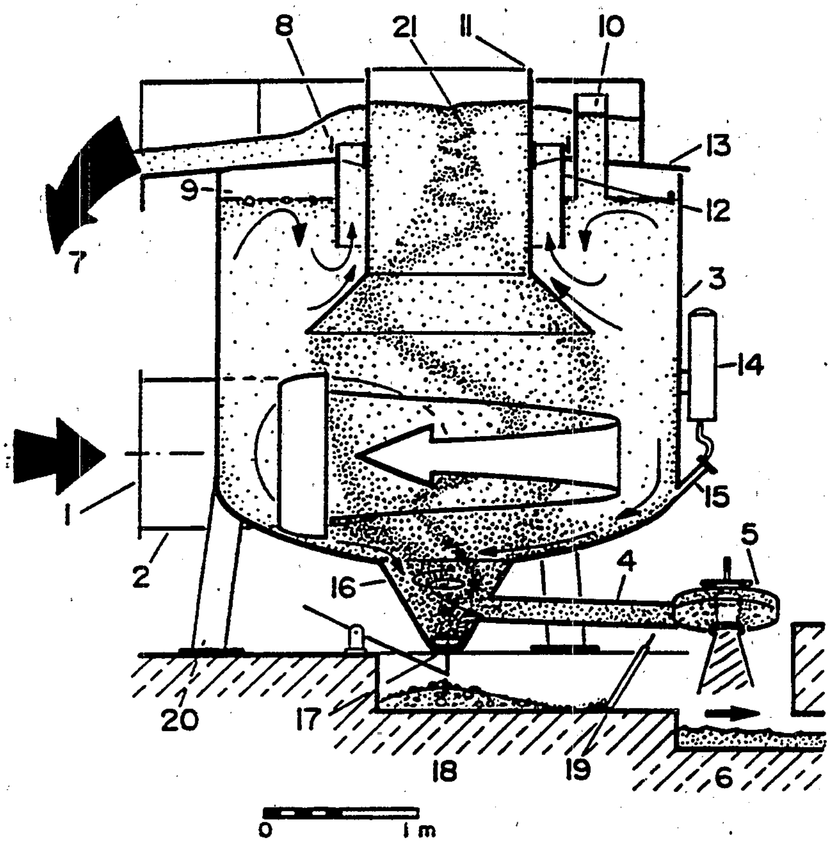
Clear flow exits the Fluidsep™ between the guiding, conical baffle, and the scumboard/weirboard, as shown in Figure 2-3. The discharge exits the unit on the opposite side it entered. An adjustable weirband allows the effluent flow to exit in a uniform peripheral fashion preventing short circuiting before the flow is collected in a trough.

Floatables are trapped in an air cushion that slowly rotates under the cover. The air cushion at the top of the vessel is created by the scumboard and the vent with the dip pipe.

FIGURE 2-3

FLUIDSEP™ ISOMETRIC

1 inflow from sewer
2 tangential inlet
3 vortex chamber
4 underflow
5 flow restrictor
6 interceptor to WWTP
7 overflow to receiving water
8 adjustable weir band
9 air cushion for floatables trap
10 vent with dip-pipe
11 guiding baffle
12 scum board
13 cover
14 electronic level monitor with data logger
15 pressure pick up
16 outlet cone
17 outlet plug with lever
18 depot for coarse sediments
19 screen
20 support leg
21 inner precessing vortex core



Source: Brombach *et al.*, 1993.

After a storm event the floatables are removed via the foul-sewer outlet and conveyed to the WWTP. Floatables trap capture effectiveness varies with the flowrates. During extremely highflowrates the floatables often escape the unit. The unit can be modified to include screening devices above the overflow outlet to trap any escaping floatables.

The Fluidsep™ units installed in the U.S., as shown in Table 1-2, also represent a wide range of sizes and design criteria. The diameters range from 27 and to 44 ft and are typically 2.5 times greater than the height, but vary between 0.5 and 3.0 times the height (Pisano, 1993). The HL range from 32 to 95 gpm/ft^2 with Q_d (per unit or group of units) from 25 to 416 MGD.

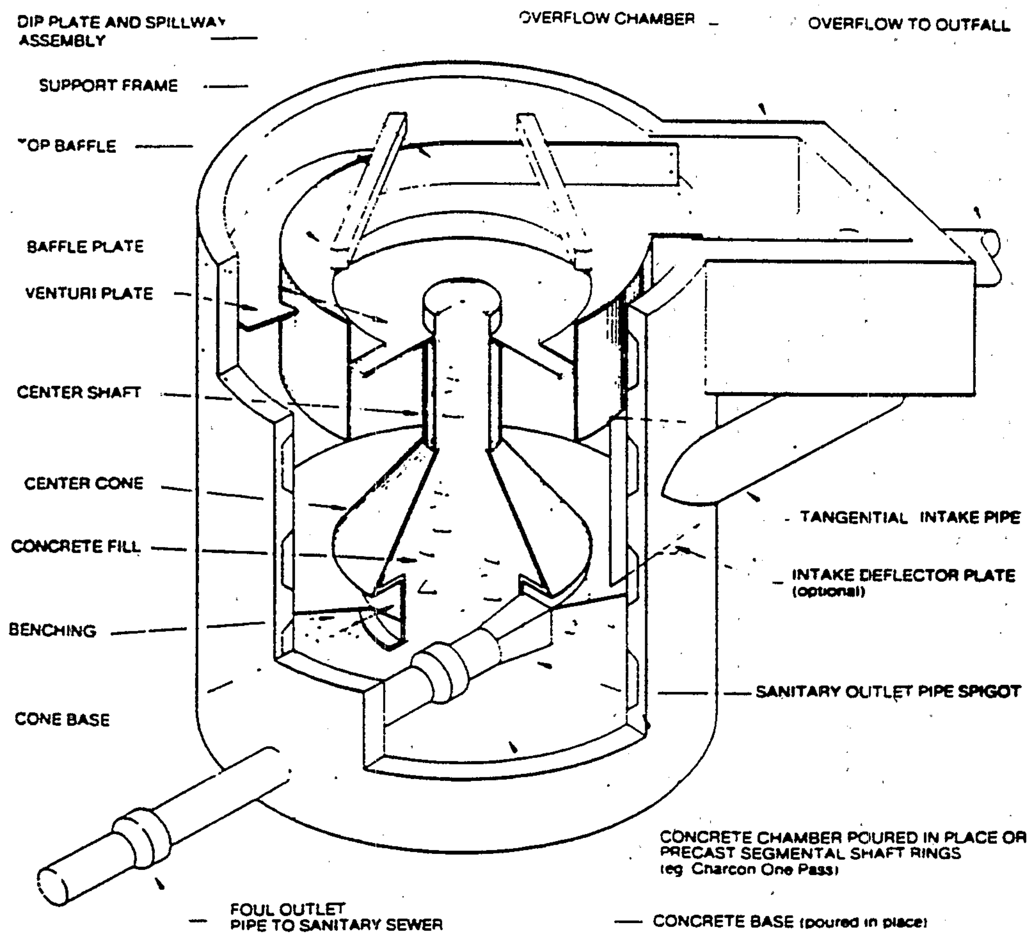
STORM KING™

Prior to installing a Storm King™ at a site, a pilot study should be performed to determine dimensions most appropriate for the site. It is not always necessary to perform a pilot study if the particle settling velocity distribution for the drainage area is known. Pilot studies, however, reduce the possibility of installing an incorrectly sized unit. Pilot units are usually 3 to 6 ft in diameter. Information required for the pilot study would include the desired SS (or pollutants) removal, Q_d, and the particle settling velocity distribution. The HL is varied during the pilot study to establish the HL at which optimum removal is achieved.

The Storm King™'s configuration consists of a cylindrical vessel with a solid central cone, a sloped floor, and a top assembly, as shown in Figure 2-4. A majority of the units in

FIGURE 2-4

STORM KING™ ISOMETRIC



Source: H.I.L. Technology, Inc., 1991.

England are prefabricated, however, cast-in-place units are available. Dimensions of the units will vary, but generally, the diameter is twice as large as the depth (Hedges *et al.*, 1992). Flow enters the unit tangentially through an entry port located halfway up the vessel wall. Similar to the swirl, a deflector plate can be constructed at the entrance that will prevent the heavily polluted storm flows from bypassing treatment and immediately exiting via the overflow. SS removal is also aided by the slope of the floor, which is between 10° and 30°. This slope provides an additional benefit of minimizing solids collecting on the benching during drawdown. The concentrated underflow exits via a helical channel, which is identified as benching in Figure 2-4, and is conveyed to the WWTP or holding tank. The benching is located midpoint between the outside and center axis of the unit, therefore decreasing the energy required to move the SS to the outlet. Furthermore, the outlet is located beneath the dip plate where the shear zone forms and the greatest vortex activity and separation occurs. This differs from the other two vortex designs that have exit points in or near the center of the unit.

The flow that was directed down the perimeter of the unit is then directed toward the center of the unit and up the center cone. The flow rotates at a slower velocity during this action than the velocity that occurred during the downward flow. The clear flow rises up toward the baffle plate and exits the chamber between the baffle plate and the dip plate and is then conveyed to the overflow chamber. The dip plate locates the shear zone, which is the interface between the outer, downward flows and the inner, upward flows.

Floatables are also removed by the Storm King™. The buoyant materials move upward and outward and become trapped behind the dip plate. When the storm flow ends and the unit drains down, the floatables exit out the foul-sewer outlet and are conveyed to the WWTP or storage tank.

The Storm King™ installed in England, as shown in Table 1-3, have diameters from 2 to 33.8 ft, HL from 3 to 149 gpm/ft^2 and Q_d from 0.2 to 105.2 MGD.

DEGRITTERS

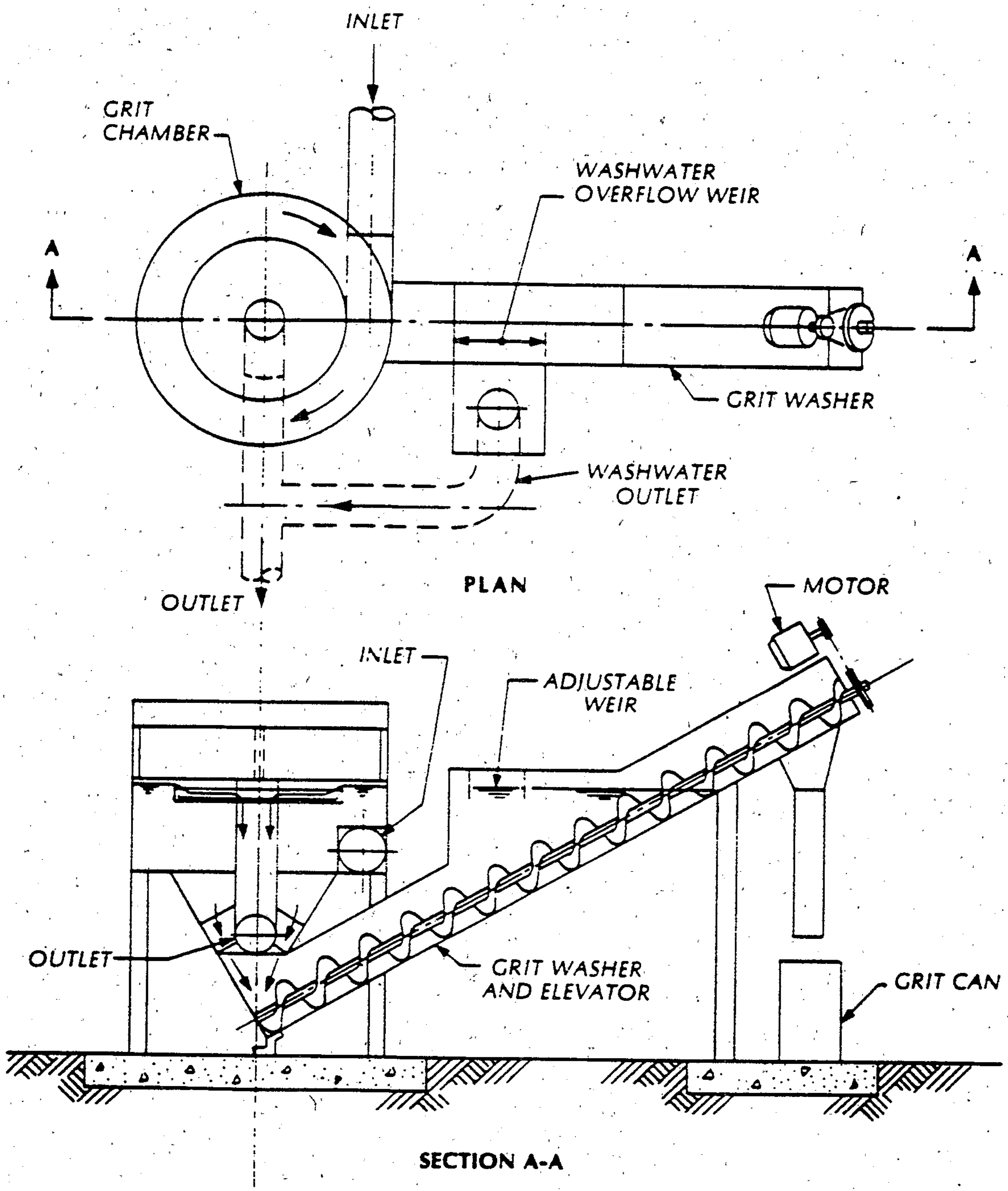
Vortex-type degritters come in various forms, two of which are:

- EPA swirl degritter, and
- HIL Grit King™

The swirl degritter does not have a continuous underflow to the WWTP or holding tank. Instead a relatively dry mass of settleable solids (grit/detritus) collects in a 60° conical-bottom hopper for intermittent removal. Degritters have been used in CSO, stormwater, potable water and river water intake applications. Figures 2-5 and 2-6 contain plan and elevation views of the swirl degritter and the Grit King™.

FIGURE 2-5

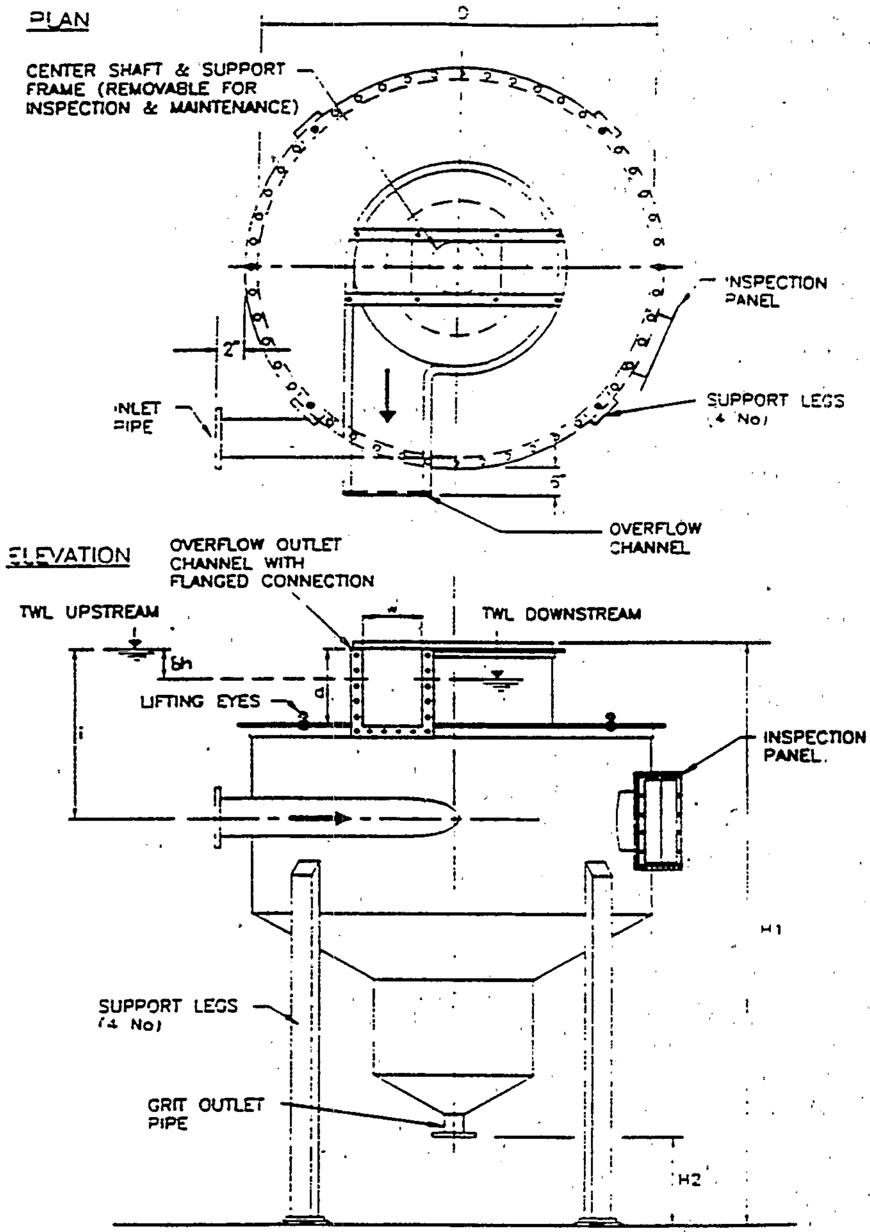
SWIRL DEGRITTER



Source: Sullivan *et al.*, 1982.

FIGURE 2-6

GRIT KING™



NOTES:

1. THE LAYOUT IS GENERAL AND INTENDED FOR GUIDANCE ONLY.
2. THE DIMENSIONS ARE NOMINAL AND SUBJECT TO CHANGE DEPENDENT UPON SITE SPECIFIC REQUIREMENTS.
3. THE ORIENTATION (ON PLAN) OF INTAKE, OVERFLOW, GRIT OUTLET PIPE & INSPECTION PANELS CAN BE ADJUSTED TO SUIT THE ENGINEERS' REQUIREMENTS.

Source: H.I.L. Technology, Inc., 1991.

MONITORING AND ANALYSES

Proper sampling, flow measuring, and analysis are a must for design and treatability evaluation. Prior to selecting the swirl or vortex separator 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 total solids and SS and associated pollutant content should then be determined. This analysis is essential for assessing the applicability of vortex separators. If the storm flow does not contain enough SS with grit-like particles ($SG \geq 2.65$ and d_e from 0.2 to 2 mm) and relatively-heavy-organic particles ($SG \geq 1.2$ and d_e from approximately 0.2 to 5.0 mm) then swirl and vortex technology may be inappropriate and alternative technologies should be used. As previously noted, the swirl will also concentrate particles with lower settling velocities down to 0.14 cm/sec but with decreasing effectiveness.

The variable nature of storm flow and sewer slope influence suspended-/settleable-solids concentration and particle-settling-velocity distribution. In addition, the build up 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. These 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 the swirl was developed to remove) and not manifest biassed results due to stratification. For an automatic sampling device, this means that its intake velocities and ports must be greater than the main stream velocity and must be placed at multiple levels, respectively, in order to capture the heavier particles 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 (gravimetric) and the other for settling-velocity distribution. These analyses will enable a site estimate of the percent of SS the swirl is capable of removing.

If particle-settling velocities indicate that swirl technology will remove an acceptable percentage of the particles in the storm flow, then hydrological and hydraulic studies should be conducted to determine the Q_d. This analysis of flow should be done on a long-term continuous basis using mathematical modeling and then directly measuring flowrates for calibration and verification to achieve the best Q_d and settleable-solids removal prediction.

DISINFECTION

Swirl/vortex separators used in CSO applications can be often modified to include disinfection. The mode of disinfection to be applied may require a higher solids removal than the mandated discharge requirements.

Swirl/vortex separators can be placed upstream and/or downstream of disinfectant addition. A benefit of disinfectant addition upstream of the swirl is that mixing by the swirling action will increase collisions between the disinfectant and the microorganisms, potentially resulting in a more effective kill per unit contact time. This was done using chlorination at Lancaster, PA (Pisano *et al.*, 1984) and Syracuse, NY (Drehwing *et al.*, 1979). However, additional laboratory analysis is necessary to determine the effectiveness of disinfection due to protective particles in the overflow. Microorganisms may survive in the interstices of the larger organic particles and in the micro-fractures of soil grains. The swirl/vortex units would not remove all these particles and therefore would allow a portion of the particles and their occluded microorganisms to overflow to the receiving waters.

SECTION 3

TECHNOLOGY ASSESSMENT

Data from performance tests were obtained on each of three types of vortex separators and a swirl degritter. The data discussed in this section are from a stormwater treatment demonstration project in West Roxbury (Boston), Massachusetts (swirl-pilot scale); three full-scale CSO control demonstrations in Washington, DC (swirl), Tengen, Germany (Fluidsep™), and James Bridge, England (Storm King™); and a full-scale demonstration in Tamworth, N.S.W., Australia (swirl degritter) of pretreatment of intake river water for potable supply.

PERFORMANCE EQUATIONS

The performance data available for evaluation in this report were presented so that similar comparisons could be made between each of the facilities except the previously mentioned degritting units which do not have an underflow. The fraction of the influent SS (and associated pollutants) that are concentrated by the vortex separators into the underflow indicates the portion of SS diverted from the effluent (overflow) to the WWTP. The three performance indicators for swirl and vortex treatment are:

- *Removal*
- *Net Removal*
- *Treatment Factor (TF)*

The aforementioned performance indicators are defined by the terms in these storm-flow-event summation equations:

$$M = \sum_{j=1}^{n} c(\xi_j)Q(\xi_j)\Delta_j t \qquad (1)$$

$$V = \sum_{j=1}^{n} c(\xi_j)\Delta_j t \qquad (2)$$

$$C = \frac{M}{V} \qquad (3)$$

where M = storm-flow-event pollutant mass loading (mass), V = storm-flow-event flow volume (volume), C = storm-flow-event flowrate-weighted-average pollutant concentration (flow-weighted-average concentration), $c(\xi_j)$ = average pollutant concentration between samples, $Q(\xi_j)$ = average flowrate between samples, and $\Delta_j t$ = time interval between samples.

These terms can be combined to form this equation for *Removal*:

$$Removal = \frac{C_i V_i - C_e V_e}{C_i V_i} x\ 100\% = \frac{M_i - M_e}{M_i} x\ 100\% \qquad (4)$$

where $M_i = C_i V_i$ = mass of untreated influent and $M_e = C_e V_e$ = mass of treated effluent.

For most treatment unit operations, e.g., settling, screening, and filtration, the volumes of the influent and effluent are equivalent and therefore may be canceled out of Equation 4. *Removal* (4) can then be rewritten in terms of concentration alone. However, this approach, using only concentration to measure performance, cannot be used for the swirl because the swirl treatability evaluation is complicated by the continuous and relatively dilute underflow. The volume of the underflow remains significant throughout the event and its percentage of the influent is highly variable (5% to 10% at Q_d and as high as 100% for the smaller storms which are completely captured in the swirl chamber without causing effluent). Therefore a different approach is necessary to evaluate the concentrating effect of the swirl and other vortex units.

Assuming there is no net concentrating effect by the swirl or vortex, i.e., SS concentration of the influent, effluent, and underflow are all equal, then C would cancel out of Equation 4. The equation would then only reflect the flow splitting nature of these devices and is termed the *Reduction*:

$$Reduction = \frac{V_i - V_e}{V_i} \times 100\% \qquad (5)$$

where: V_i = influent volume and V_e = effluent volume. This non-concentrating flow phenomenon is similar to what occurs during the operation of conventional CSO flow regulators. Accordingly this can further be thought of as the CSO pollution reduction resulting from a conventional flow regulator.

Removal (4) and *Reduction* (5) can now be combined to define the *Net Removal* and *TF* which represent the pollution *Removal* above and beyond the *Reduction* gained by conventional CSO flow regulation. The equation for *Net Removal* is:

$$Net\ Removal = Removal - Reduction \tag{6}$$

A positive *Net Removal* indicates that SS (and associated pollutant) concentration has taken place in the unit. The *TF* equation is :

$$TF = \frac{Removal}{Reduction} = \frac{(C_i V_i - C_e V_e)/C_i V_i}{(V_i - V_e)/V_i} = \frac{C_u}{C_i} \tag{7}$$

where C_i = influent flow-weighted-average concentration and C_u = underflow flow-weighted-average concentration. *TFs* greater than 1 indicate that the vortex separator is concentrating SS to the underflow. The higher the *TF* the better the vortex device concentrates pollutants. A negative *Net Removal* or a *TF* less than 1, indicates an anomaly or faulty sampling and monitoring techniques.

These equations define the terms used in the tables presented in the following subsections. In the case of the swirl degritter and Grit King™, as with most forms of treatment, the influent volume can be treated as equivalent to the effluent volume.

The volume of underflow, a function of the Q_d for the unit, is very significant in the calculation of performance. The *Net Removal* and *TF* for a storm-flow event that does not overflow in the swirl or vortex unit will be 0% and 1, respectively, while *Removal* is 100%. Events that barely overflow the unit will have high *Removals* with low *Net Removals* and *TFs* due to the proportionately larger volume in the underflow. As the storm flow increases towards the Q_d, *Removal* will begin to decrease while *Net Removal* and *TF* should increase due to significantly decreased volume (5 to 10% at Q_d) of the underflow.

Two important factors that will effect performance measurements are:

- sampling and flow measuring techniques
- variation of SS loading and influent flowrate

To provide a "true" measurement of performance, sampling devices must be able to capture the heavier influent SS that the swirl/vortex was designed to remove. As previously mentioned in Section 2, the intake ports of automatic sampling devices need intake velocities greater than the main stream velocity of the influent SS being sampled and must be placed at multiple levels in order to capture the heavier particles at the channel invert without reflecting bias due to stratification. Sampling of SS and other pollutants must also be synchronized with flow measurements.

The data presented in this report only represent averaged *Removals*, *Net Removals*, and *TFs* for specific events and the total average of these events. To gain a better understanding of the capture of pollutants and the most polluted segment of the storm flow please refer to the individually referenced reports which display the capture of pollutants through a storm event.

CSO CONTROL APPLICATIONS

Evaluation of the Swirl

Three swirls were evaluated as part of Washington DC's CSO abatement program. The abatement program was required because of a high sediment oxygen demand downstream and depletion of dissolved oxygen in the Anacostia River. These two factors resulted in frequent fish kills and the elimination of game fish. In addition, public health standards for coliform bacteria resulted in restriction of water contact recreation.

The swirls are in an enclosed facility. In addition to the swirls, an automated inflatable weir system was installed upstream to provide in-line storage at nine of the largest, overflows in the conveyance system. Flow from approximately 4,000 acres are treated by either the swirls and/or stored upstream of the weirs for subsequent treatment by the Blue Plains WWTP.

The automated inflatable weir system was designed to maximize the storage of wet-weather flows within the sewer system. During extreme high flows, the weirs are deflated when the level in the sewer becomes too high, thus preventing upstream flooding. The swirls and weir system operate automatically. A telemetry system allows for real-time control at the Bureau of Sewer Services and at the Blue Plains WWTP.

Dry-weather flows are conveyed from the Northeast Boundary (NEB) CSO Swirl Treatment Facility to the Blue Plains WWTP, which has a capacity for complete treatment of 740 MGD with an additional capacity of 336 MGD for primary treatment. However, when the flow exceeds 15 MGD during wet-weather events, the flow is diverted and gravity fed to the swirls. The swirls have a total Q_d of 400 MGD, although they have been operated at 500 MGD on occasion.

Minor modifications were made to the swirl design due to site constraints. For example, the depth of the swirl was decreased and the diameter was increased, while maintaining the same capacity in accordance with the design specifications (Sullivan *et al.*, 1982). The swirls were installed as part of a CSO abatement system, which includes the upstream inflatable weirs, an upstream bar screen which captures the larger debris (i.e., cans, bottles, leaves) and high-rate disinfection following the swirls.

The three swirls are identical in design. They are 57 ft in diameter, 6.5 ft deep, have a Q_d of 134 MGD for a combined total of 400 MGD, and have a per unit hydraulic loading (HL) of 36 gpm/ft^2 (O'Brien and Gere, 1992). Flow to the foul-sewer lines is controlled and approximately 8 MGD per unit (or 5% of the Q_d) are conveyed as underflow to a downstream pumping station. Each unit also is equipped with an automated washdown system.

During the first year of operation sampling and analyses were performed to determine the swirls' effectiveness. Samples were collected at the screening, the influent chamber, the downshaft, the overflow weir, and at the foul sewer (underflow). The monitoring was originally set up to be done automatically, but conditions, e.g., SS stratification, necessitated the monitoring to be performed manually.

Settleability tests were performed which indicated that the CSO contained a large fraction of SS with settling velocities lower than what the swirl was developed to remove. SS *Removals* based on HL were predicted for each storm event, as shown in Table 3-1. The SS *Removals* for all but one storm event exceeded the predicted removals.

TABLE 3-1 SWIRL CSO CONTROL PERFORMANCE, WASHINGTON, DC NORTHEAST BOUNDARY FACILITY

Storm Number	Date	Flow Range (MGD)	Avg Flow (MGD)	Avg Foul Flow (MGD)	Volume Reduction (%)	Influent Flow Wgtd Avg SS (mg/l)	Mass SS Removal (%)	Mass SS Predicted Removal (%)	Mass SS Net Removal (%)	TF
1	3/29/91	18 - 90	62	9.4	15	183	28.3	16.6	13.1	1.87
3	5/6/91	17 - 30	21	11.6	55	297	67.5	67.0	12.3	1.22
4	6/16/91	8 - 50	23			211	39.4			
5	6/18/91	15 - 103	50	7.7	15	250	27.9	22.2	12.5	1.81
7	8/27/91	10 - 60	35	9.2	26	180	42.0	26.0	15.7	1.60
8	9/24/91	63 - 100	72	8.4	12	365	35.6	10.5	23.9	3.05
9-SW2	10/6/91	11 - 68	27			510	48.9			
10	10/17/91	23 - 51	33						73	34.9
11	11/22/91	8 - 58	29	8.4	29	140	29.9	25.7	0.9	1.03
12	12/2/91	45 - 95	63	7.9	13	104	21.1	32.1	8.6	1.68
Average			42	8.9		231	37.6	28.6	12.4	1.75

Note: No settling characterization performed for storms 4, 9, and 10. Storm #3 contains data from relatively low flowrates. Design flowrate of 134 MGD with an HL 36 of gpm/ft². SS Mass Removals, Predicted Removals, and Net Removals are determined using mass loadings.

Source: O'Brien and Gere, 1992

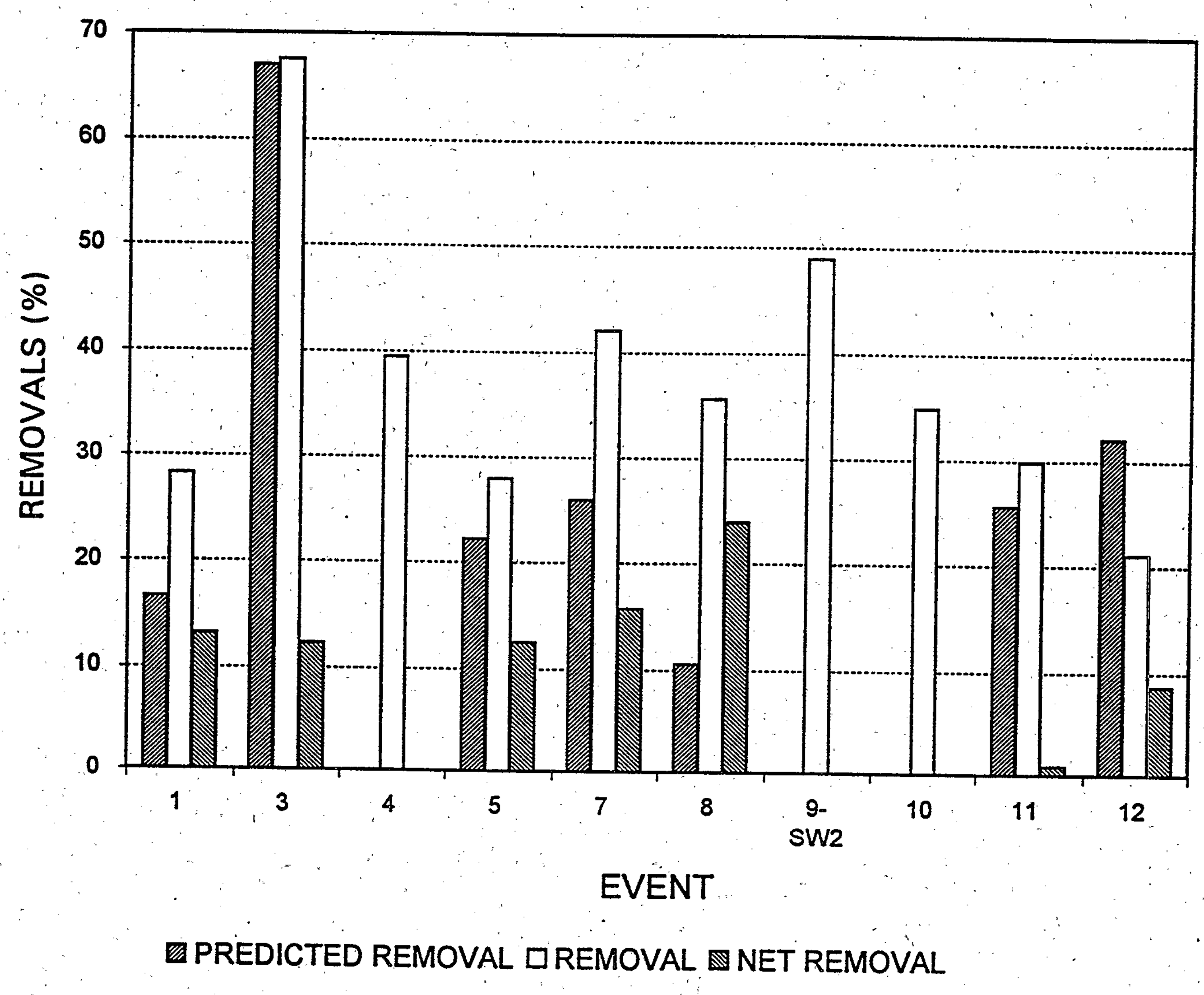
The average *Net Removal* for the storm events was 12.4%. This indicates that SS are being concentrated into the underflow and a portion of the *Removal* (*Net Removal*) is not simply due to flow splitting. Figure 3-1 illustrates *Removals*, *Net Removals* and predicted removals for several storm events sampled in 1991. Performance was also evaluated by determining *TF*. All *TFs* were greater than 1 with the average being 1.75, which indicates that the swirl is concentrating SS to the underflow.

Evaluation of the Fluidsep™

Only one thorough evaluation of a full-scale Fluidsep™ has been performed. This evaluation took place at the Tengen, Germany facility. This facility was constructed in 1987 to treat CSOs from a 25.3 acre drainage area and contains two Fluidsep™ units with a total design flowrate of 19 MGD. Dry-weather flowrate was 0.2 MGD, or approximately one hundredth of the design flowrate. Their chamber diameters are approximately 10 ft and have an overall specific volume of 254 ft^3/acre, which includes upstream wet-weather flow pipe storage. Underflow from the units, which peaks at a combined rate of 0.81 MGD, discharges to a trunk sewer and is then conveyed to a WWTP (Brombach *et al.*, 1993).

FIGURE 3-1

SWIRL CSO CONTROL PERFORMANCE, WASHINGTON, DC



The first phase (1987-1988) of the performance evaluation had 134 facility storm activations. Of these only 80 events, or 47.8%, resulted in overflow events with discharge to the receiving stream. The remainder of the events did not result in overflow events due to the upstream and Fluidsep™ storage (Brombach *et al.*, 1993).

During the second phase of the evaluation, samples from the underflow and overflow were collected during five storm events. Each of the samples were analyzed for SS, settleable solids, COD, and phosphorus. The SS settling velocities were also determined. *Removals*, as well as the HL for each event and other pertinent data, are presented in Table 3-2. Figure 3-2 illustrates *Removal* and *Net Removal* for the storm events sampled.

The average *Net Removal* and the *TF*, as shown in Table 3-2, for the storm events were 6.9% and 1.19, respectively, indicating limited treatment. The *TF* and *Net Removal* are low due to the high volume of underflow which ranged from 24% to 82% of the inflow.

Evaluation of the Storm King™

There are two 17.3 ft diameter Storm King™ units operating in parallel at the James Bridge facility in Walsall, England. This facility treats CSOs from a 39 acre drainage area at a design flowrate of 16.8 MGD. Due to a high drainage area perviability, runoff was

TABLE 3-2 FLUIDSEP™ CSO CONTROL PERFORMANCE, TENGEN, GERMANY

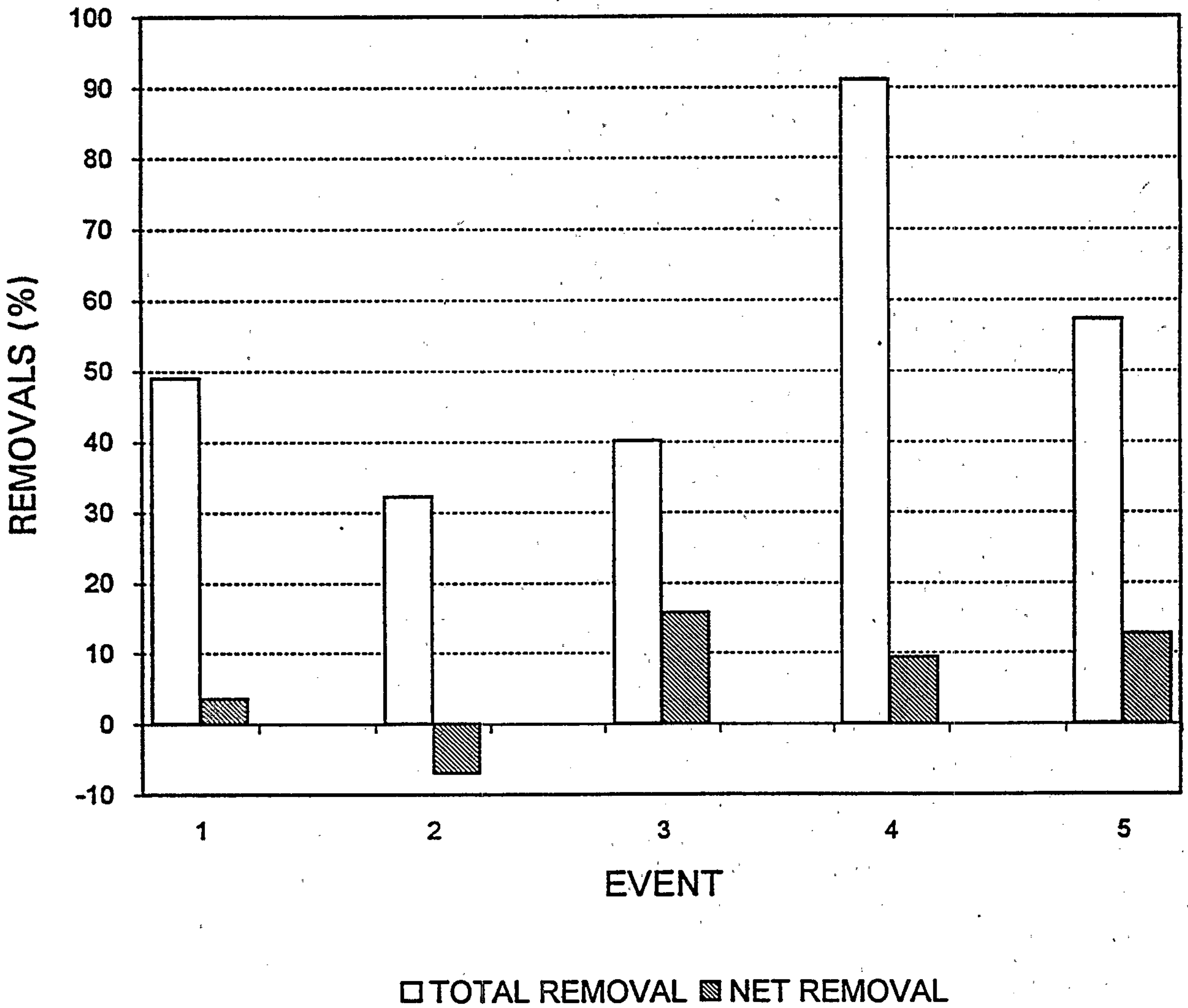
Storm Number	Antecedent Dry Period (days)	Rain Depth (in.)	Rain Duration (hr)	Overflow Duration (hr)	Foul Influent Volume (gal)	Sewer Volume (gal)	Volume Reduction (%)	Influent Mass SS (lb)	Effluent Mass SS (lb)	Mass SS Removal (%)	Mass SS Net Removal (%)	TF
1	7	0.3	2.6	0.9	73,000	33,000	45	481	246	49	3.6	1.08
2	14	0.3	2.3	0.6	77,000	30,000	39	696	472	32	-7.1	0.82
3	5	0.9	4.5	2.6	260,000	63,000	24	1610	965	40	15.8	1.65
4	1.1	0.2	3.3	0.9	52,000	42,000	82	179	16	91	9.3	1.11
5	0.2	0.7	5.5	3.3	200,000	90,000	44	738	316	57	12.7	1.29
Average		0.5	3.6	1.7	130,000	52,000	47	742	403	54	6.9	1.19

Note: Design flowrate of 10.8 MGD with a surface loading rate of 95 gpm/ft². Total and net TSS removals are determined using loadings.

Source: Brombach *et al.*, 1993.

FIGURE 3-2

FLUIDSEP™ CSO CONTROL PERFORMANCE, TENGEN, GERMANY



significantly reduced to the separators. During the study, one of the units had to be shut down to force an overflow in the operating unit.

The number of overflow events were infrequent as a result of an unusually dry year. Data from only three of the events were analyzed and are presented in Table 3-3. As shown, events 2 and 3 were so small that greater than 90% of the flow ended up in the underflow and this is reflected in the *TF* which indicate that significant SS concentration does not occur.

Due to the insufficient storm runoff, an additional six tests were conducted using river water. Sanitary sewage was added to the river water to simulate a CSO. The volume of the underflow for the six tests ranged between 9% and 36% of the inflow volume. Table 3-3 and Figure 3-3 show the results of the second phase.

Performance results using *Net Removals* and *TF* are shown in Table 3-3. The combined average *Net Removals* and the *TF* for the storm events and river water tests were 14.3% and 1.65, respectively, which shows concentration occurred. Bar graphs of *Removals* and *Net Removals* for the storm events and river water test are shown in Figure 3-3.

TABLE 3-3 STORM KING™ CSO CONTROL PERFORMANCE JAMES BRIDGE, ENGLAND

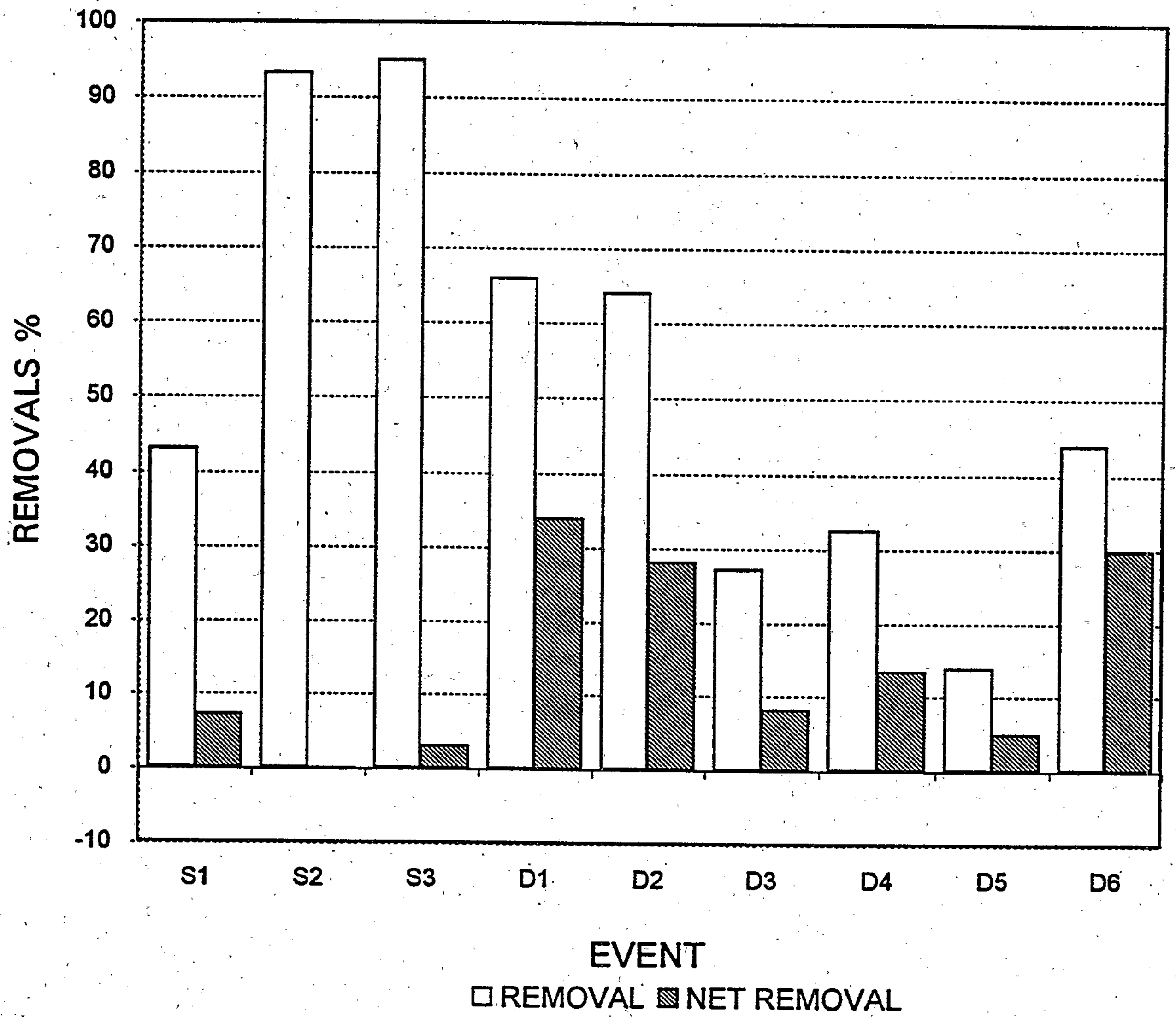
Test Number	Peak Flow (MGD)	Volume Reduction (%)	Hydraulic Loading (gpm/ft²)	Mass SS Removal (%)	Mass SS Net Removal (%)	TF
Storm Events						
S1	6.8	35.9	12.9	43.1	7.2	1.20
S2	5.7	93.6	1.0	93.4	-0.2	1.00
S3	3.7	91.9	0.9	95.0	3.1	1.03
River Water Tests						
D1	2.7	32	5.4	65.9	33.9	2.06
D2	2.0	36	3.7	64.1	28.1	1.78
D3	2.5	19	6.1	27.1	8.1	1.43
D4	5.0	19	11.9	32.4	13.4	1.71
D5	5.2	9	13.9	13.9	4.9	1.54
D6	4.6	14	11.6	43.8	29.8	3.13
Average	4.3	39	7.5	53.2	14.3	1.65

Note: Design flowrate of 8.6MGD with a hydraulic loading of 26 gpm/ft².

Source: Hedges *et al.*, 1992.

FIGURE 3-3

STORM KING™ SS REMOVALS FOR CSO CONTROL, JAMES BRIDGE, ENGLAND



STORMWATER CONTROL APPLICATIONS

Swirl

The West Roxbury (Boston), MA pilot study was conducted to demonstrate the effectiveness of swirls as a treatment technology for separate urban stormwater. The unit was tested between 1979 and 1981, and is no longer in existence. *Removals*, *Net Removals*, and *TF* were determined for each of the events.

The 160 acre drainage area served by the demonstration facility was located in a moderate income residential neighborhood served by a completely separate storm-sewer system. In addition, due to the gravity operation of the unit, considerations had to be made for the vertical elevation available. The project also evaluated the helical-bend regulator/concentrator (another concentrating unit that uses similar secondary-fluid motion solids separation principles as that of the swirl). The project layout is shown in Figure 3-4.

Rainfall records from two local rainfall gauging stations were analyzed for a period of 10 years to determine the appropriate Q_d for the units. Discrete storm events were identified, as well as the year, month, and day the storm began; the hour of day that the storm began; the length of the antecedent dry period; the total amount of rainfall in the storm event; the duration of the storm event; the maximum hourly rain in the storm; and the hour of the maximum rain in the storm.

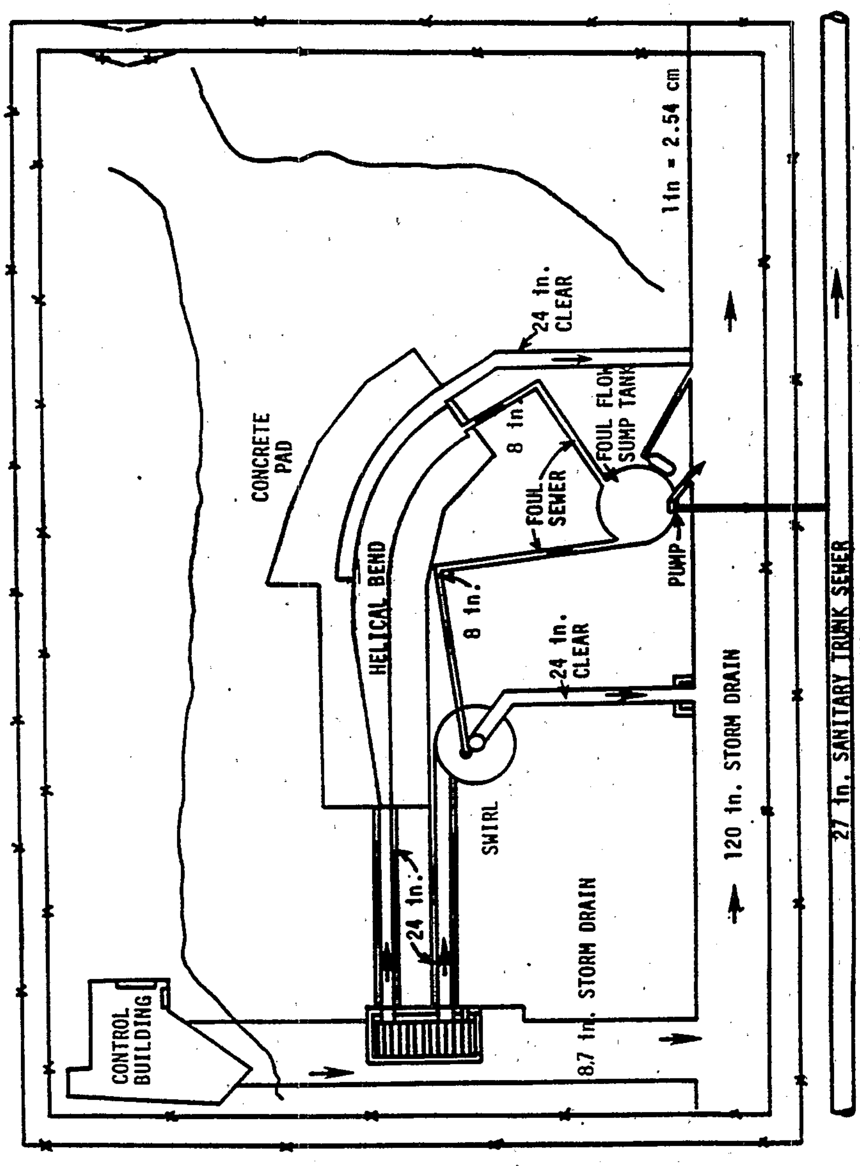
Hydrologic modeling of the catchment area was then performed using the EPA Storm Water Management Model (SWMM). This was done to determine an overall estimate of the runoff coefficient for the watershed. The runoff coefficient was required so that the swirls design flowrate frequencies could be estimated.

The Rational Formula (Q_d = CIA) was used to determine the design flowrate, Q_d, for the watershed. The runoff coefficient, C, was determined to be 0.41. A time series of maximum average hourly intensities for the observed rainfall events at one of the rainfall gauging stations and a drainage area, A, of 160 acres were used in the calculation. The resultant design flowrate was 3.9 MGD per unit (swirl and helical-bend regulator), with a maximum flowrate to each unit of 7.8 MGD.

The design of the swirl was based on the initial guidelines established by the EPA (Sullivan *et al.*, 1972). The unit was sized to provide 80% removal of settleable solids. The inlet and outlet pipes were 2 ft in diameter and the unit diameter was 10.5 ft. Flow entering the foul-sewer outlet was regulated by a Hydro Brake™, which only allowed up to 0.1 MGD to discharge. This is equivalent to 3% of the Q_d. SS from the a foul-sewer outlet were discharged

FIGURE 3-4

SITE PLAN FOR THE WEST ROXBURY, MA FACILITY



Source: Pisano *et al.*, 1984.

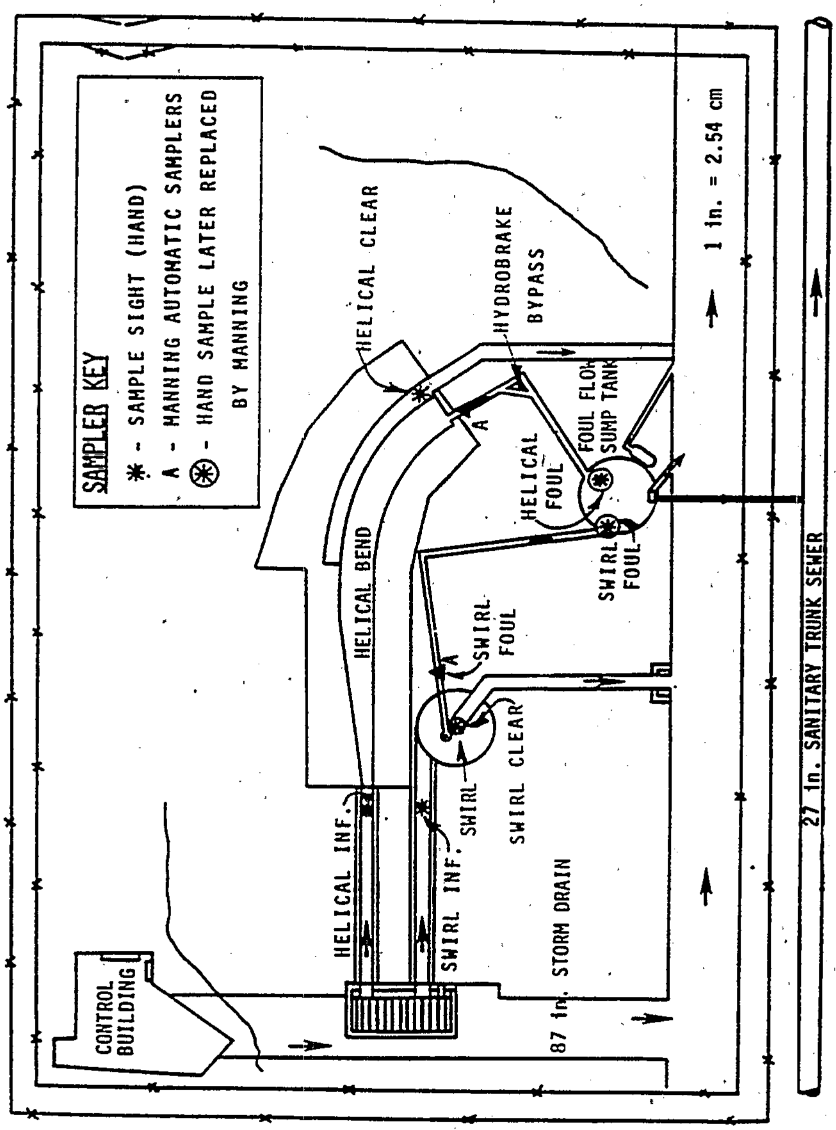
to a foul sewer tank 10.5 ft in diameter and 6 ft in depth that could be pumped to either a 120 in. diameter storm drain or into a 27 in. sanitary sewer.

Flow and quality measurements were performed at the West Roxbury facility. Monitoring and sampling was done at the influent, the effluent, and the foul-sewer discharge. The sampling locations are identified in Figure 3-5. Sampling consisted of both manual and automatic procedures. Samples were analyzed for SS, volatile SS, settleable solids, and volatile settleable solids.

Although additional monitoring occurred, only seven storm events were selected for detailed analysis. *Removals*, *Net Removals*, and *TF* were determined for each of the events and are shown in Table 3-4. The SS *Removals* varied between 6% and 36% and averaged 28.1%. The *Net Removal* and *TF* averaged 17.0% and 3.4, respectively which indicates that SS concentration had taken place. *Removal* and *Net Removals* for several storm events are shown in Figure 3-6.

FIGURE 3-5

SWIRL SAMPLING LOCATIONS FOR WEST ROXBURY, MA



Source: Pisano *et al.*, 1984.

TABLE 3-4 SWIRL STORMWATER CONTROL PERFORMANCE, WEST ROXBURY, MA

Storm Number	Date	Average Flowrate (MGD)	Volume Reduction (%)	Mass SS Removal (%)	Mass SS Net Removal (%)	TF
1	6/29/80	1.3	12.8	21.0	8.2	1.64
2	7/29/80	1.9	7.8	35.3	27.5	4.53
3	10/3/80	3.9	4.0	36.0	32.0	9.00
4	10/25/80	1.9	8.3	29.7	21.4	3.58
5	6/9/81	0.5	31.3	34.0	2.8	1.09
		1.9	8.0	27.0	19.0	3.38
6	6/22/81	1.4	11.0	27.0	16.0	2.45
		1.3	12.0	33.0	21.0	2.75
7	8/4/81	3.9	4.0	9.5	5.5	2.38
	*	7.8	0.0	5.8	5.7	58.00
Average		2.0	11.0	28.1	17.0	3.4

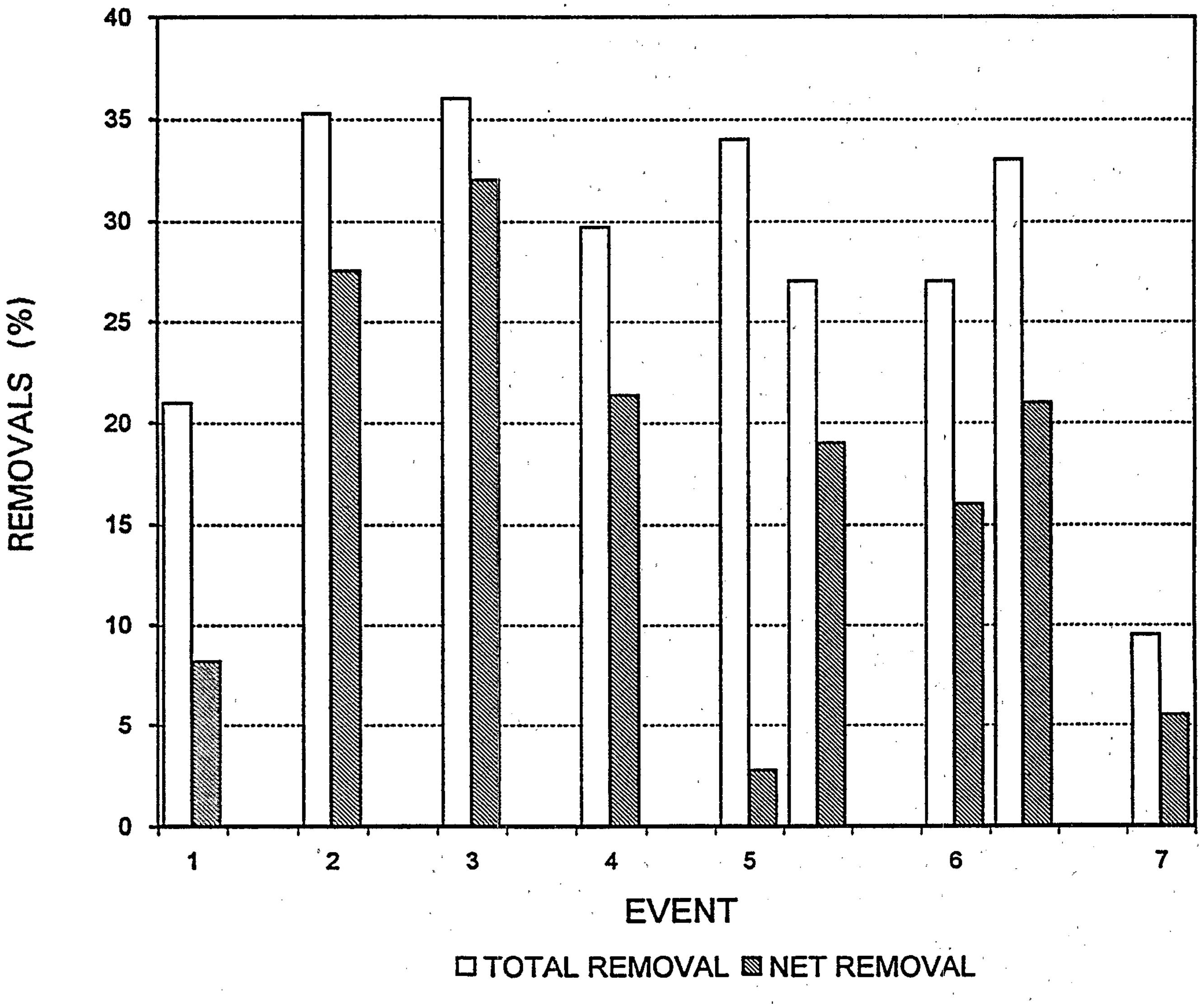
Note: Design flowrate of 3.9 MGD with a HL of 31 gpm/ft^2. SS mass Removals and Net Removals are determined using loadings. Reductions are estimated.

* Data is extreme and not included in the average.

Source: Pisano *et al.*, 1984.

FIGURE 3-6

SWIRL STORMWATER CONTROL PERFORMANCE, WEST ROXBURY, MA



SWIRL DEGRITTER

A full-scale 16.5 ft diameter swirl degritter was demonstrated in Tamworth, N.S.W., Australia as a cheaper alternative for pretreatment of river water as a way to reduce wear and tear on raw-water pumps. It was designed to operate between 3.4 MGD and 19.4 MGD. The swirl degritter efficiently removed the portion of SS for which it was designed (defined as inorganic material ≥ 0.2 mm in diameter with a specific gravity of 2.65), achieving an average of 95.5% (Shelley *et al.*, 1981).

OPERATION AND MAINTENANCE

Vortex separators do not have any moving parts and, accordingly, are not maintenance intensive. However, washdowns are required following every CSO event to prevent shoaling and foul odors from developing. Some of the units are designed to be self-cleansing or have automated washdown systems. Washdown may not be necessary after every storm event for separated stormwater treatment applications since the residual solids tend to be less putrescible.

The length of time that automated washdown operates varies with the time at which the washdown takes place following the overflow event. Typically, the washdown system for the Washington, DC swirl will run for approximately one-half of an hour if the washdown occurs immediately following an overflow. Longer washdowns will be required as the time increases between the end of the overflow and the washdown. For a CSO application, the washdown water and the residuals caught in the water flow are generally conveyed via the underflow to the sanitary sewer.

The amount of SS or floatables that reach the vortex separator vary due to several factors including the antecedent-dry period; sewer flowrate, volume and duration; drainage area and sewer length, topographic and sewer slopes; and season (e.g., autumn will generate added solids due to leaf fall). Any pretreatment (i.e., bar screens) that exists will decrease the quantity of coarse solids reaching the vortex separators. This may include street cleaning, to reduce those wastes that get flushed by the stormwater runoff. If bar screens are used, these require regular maintenance (i.e., cleaning and residuals disposal).

The Fluidsep™ in Tengen, Germany and the Storm King™ in Surrey Heath, England have not reported any malfunctions in their 4 years and 1.5 years of operation, respectively. Experience with the DC swirls has also indicated that the wash down system would be more effective with a few design modifications. The operators of the units have recommended that the floor be sloped toward the underflow. The original vortex unit in Bristol, England has been in operation for approximately 30 years w/o bar screen and has required very little maintenance.

OTHER POLLUTANT REMOVALS

Most available data on the performance of vortex solids separators focused on SS *Removal*. Limited information is available on other pollutants of concern. The Tengen, Germany CSO Fluidsep™ evaluation determined *TF* for COD averaged 1.8 with a range of 1.0 to 8.0. Again, it is indicated that a *TF* > 1 indicates some *Net Removal* of COD by vortex concentration. COD *Removal* in Tengen was lower than the SS *Removal* as indicated by the *TF* of 2.1 for SS.

SECTION 4

TECHNOLOGY COSTS

This section presents the costs associated with the design, construction, and operation of vortex solids separators. Each cost type is discussed in the following subsections. All costs have been converted to 1994 dollars (ENR 5450).

DESIGN COSTS

As discussed in Section 2, Design Criteria, each of the three different vortex solids separator units have varying design protocols. The swirl design is available in the public domain from an EPA design manual (Sullivan *et al.*, 1982). Additional design cost associated with this unit include settleability analysis and possibly a pilot-scale demonstration. The Storm King™ design is based on pilot-scale units that can be rented at $2,000 a month without including piping and treatability studies (HIL, 1995). The pilot-scale testing is performed on units 3 to 6 ft in diameter. Pilot testing is necessary to select the appropriate unit dimensions which best suits the intended application. A Storm King™ pilot-scale steel unit (3ft diameter) may be purchased for $12,000 as was done in the case of Columbus, Georgia (HIL, 1995). The Fluidsep™ design is based on site-specific settleability studies. The Fluidsep™ design study costs typically vary between $25,000 to $100,000, with actual study cost depending on the site and size of the facility. The study takes from three months to one year to complete. The swirl, Storm King™, and Fluidsep™ require hydrologic studies for proper Q_d selection.

Cost estimates were determined for the Bradenton, Florida pilot study using two 5 ft diameter Storm Kings™. The costs were calculated with pumping or for gravity feed. The costs for pumped and gravity fed units were $54,000 and $37,500 (1990 costs), respectively (Smith and Gillespie, 1990). Other costs include the pumps, maintenance on the pumps, electricity for the pumps, excavation, piping and valves. This amounts to $335 - $482 /acre of drainage area or $110,000 - $158,000 /mgd design flow (1990 costs).

CAPITAL COSTS

The capital cost for vortex solids separator facilities are very dependant on site-specific characteristics. Commonly, vortex solids separators are used with other treatment technologies e.g., disinfection. The adjusted capital costs (ENR 5450) for several vortex CSO control facilities are shown in Table 4-1 as a function of Q_d, diameter, and volume. The general range of capital costs for vortex facilities in the U.S. varies between $3,500 and $25,000/MGD.

The swirl CSO facility in Washington, DC had a capital cost of approximately $16,200,000 of which $9,100,000 were attributable to the swirl (O'Brien an Gere, 1992). The total facility contains three 57 ft diameter swirls, automated bar screens, and chlorinationdechlorination. The capital costs attributable to the swirl facility are $2,116/acre drainage area or $22,750/MGD Q_d. Earlier swirl demonstration projects in Syracuse, NY (Drehwing *et al.*, 1979) and Lancaster, PA (Pisano *et al.*, 1984) are also listed.

Capital cost data is available for several vortex separator installations. Fluidsep™ facility costs were between $3,500 and $14,600/MGD. Capital costs of the Fluidsep™ units are available for the Decatur, IL Oakland and 7th Ward projects (Pisano, 1994). The Fluidsep™ for the 7th Ward costs approximately $5,200/MGD for the separator alone as shown in Table 4-1. The Oakland unit at $14,600 reflects cost including foul-sewer pumping. The capital costs of the vortex units alone are approximately 10 to 12% of the total capital costs of the CSO abatement facilities including the vortex units. Additional costs are a result of the improvements made to the overall facility (e.g., grading, piping, bypass structures, outfalls, and mechanical screening). Capital costs for Storm King™ units are also provide in Table 4-1 (Boner, 1994). The costs include the conveyance systems, tanks, pumps, etc.

Generally, above-ground units will be less costly than the underground units do to excavation costs. However, pumping should also be avoided to reduce capital and operational costs. In a comparison of annual operation and present worth, respectively, the swirl degritter cost approximately 10% and 20% less than the conventional aerated grit chamber (Sullivan *et al.*, 1982). In its first application, swirl degritter construction costs in Australia were 30% less than that of an equivalent aerated grit chamber (Shelley *et al.*, 1981).

TABLE 4-1. COMPARATIVE UNIT COST

LOCATION	ENR/Year	COST		
		per MGD	per ϕ-ft★	per ft^3
SWIRL				
Syracuse, NY*	5450	$10,700	$5,900	
Lancaster, PA	5450	$5,900	$6,400	
Washington, DC†	5450	$22,900	$53,500	$170
FLUIDSEP™				
Saginaw, MI	5450	$4,600	$8,200	$20
Burlington, VT	5450	$3,500	$7,000	$14
Decatur, IL -- 7th Ward	5450	$5,200	$13,000	$20
Decatur, IL -- Oakland*	5450	$14,600	$10,800	$47
STORM KING™				
Hartford, CT*	1994	$27,000	$27,000	
Columbus, GA‡	1994	$20,000	$15,000	$29

★ $\phi \equiv$ diameter.
* Includes foul-sewer pumping.
† Reflects total cost attributable to swirl.
‡ Estimated cost, includes internal components and piping.

OPERATION AND MAINTENANCE (O&M) COSTS

Vortex solids separator units require minimal energy expenditures unless pumping or automated washdown systems are required. Fluidsep™ and Storm King™ units which are deeper than the swirl, are much more likely to require pumping. The units are designed to operate without moving parts which are less likely to require replacement. Operating expenses primarily include labor for washdown or minimal, intermittent energy to support an automated washdown system.

HIL's Grit King™ in Surrey Heath England, which treats separate stormwater runoff from roof and highway runoff, has a grit collection zone at the conical base of the vortex unit which requires periodic emptying once the level of the grit accumulates. Periodic maintenance to clean out the grit collection zone is estimated to cost between $300 and $450 per cleaning.

SECTION 5

SUMMARY OF FINDINGS

PERFORMANCE SUMMARY

Selected design information, *Removals*, *Net Removals*, and *TF* for the vortex solids separator units evaluated in this report are summarized in Table 5-1. The storm events were screened to eliminate data from storm events with appreciably less flow than the design flowrate. Net removal determinations from storm events that are significantly below design flowrate are misleading because the underflow component is disproportionately large relative to the overflow.

The performance data indicates that vortex separators can separate SS from the influent and concentrate them in the underflow. Average *Removals* varied from a low of 37.6% at the DC swirl to 54% at the Tengen, Germany Fluidsep™. Average *Net Removals* varied from 6.9% at the Tengen, Germany Fluidsep™ and to 17% at the West Roxbury, MA pilot-scale study.

The data on the performance of swirl and vortex separators was too specific to site and storm event and too limited in scope to assess the performance of one vortex separator design relative to the others. More evaluation is needed with a set of full-scale units to make a meaningful comparison. The stormwater application of swirl and vortex units exhibited *Removals* and *Net Removals* within the same range as for units treating CSO.

TABLE 5-1 - VORTEX SOLIDS SEPARATOR PERFORMANCE SUMMARY

Unit Type & Location	Design Hydraulic Loading (gpm/ft²)	Design Flow (MGD)	Storm Event*	Flow (MGD)	Mass SS Removal %	Net SS Removal %	Treatment Factor
Swirl							
Washington, DC	36	134	3/29/91	62	28.3	13.1	1.87
			9/24/91	72	35.6	23.9	3.05
			12/2/91	63	21.1	8.6	1.68
West Roxbury, MA**	31	3.9	10/3/80	3.9	36.0	32.0	9.00
			8/4/81	3.9	9.5	5.5	2.38
Fluidsep™							
Tengen,Germany	95	10.8	No. 2	3.2	32	-7.1	0.82
			No. 3	2.3	40	15.8	1.65
Storm King™							
James Bridge Walsall, UK	26	8.6	11/29/88	6.8	43.1	7.2	1.20

* Storm events selected because respective HL is closest to design HL out of sample storms.

** Evaluation based on separate stormwater flow.

All available data from sample storms is provided in Section 3.

Because vortex solids separation removes particles by concentrating SS by inertial separation, the settling velocity distribution of the SS affect the performance of the unit. SS in storm flow, whether stormwater or CSO, that exhibit settling velocities > 0.14 cm/sec, are more amenable to removal by vortex separation than SS with lower settling velocities. However, the design of vortex solids separator units are targeted for particle with high settling velocities (e.g., 2.65 cm/sec or greater for the swirl, as previously discussed). Vortex unit design should be based on site-specific settleability and pilot-scale testing.

The available data indicate that vortex solid separators had higher *Removals* under conditions with lower HL. Lower HL generally decrease *Net Removals* as a result of the large capture of underflow during storm events well below the design flowrates. A balance must be struck in choosing Q_d between determining the greater benefits of *Removal* or *Net Removal* for each particular installation.

FINDINGS

__Applications__

The selection of the best treatment or control technology for any wet-weather flow application must be based upon knowledge of these three components: pollutants of concern, pollutant characteristics (particle settling velocity or size distributions), and performance requirements (permitted discharge levels or removal efficiencies). General information on the potential of pollutant classes to be removed by settleability-based treatment such as vortex separators are presented in Table 5-2. Vortex separators are an attractive process where high-rate SS separation of gritty materials, heavy particles, or floatables is required. A significant portion of the pollutants of concern have settling velocities < 0.14 cm/sec, are dissolved or colloidal, or close to the density of water, vortex separators are not an appropriate technology.

The majority of vortex separator applications have been for CSO. There has only been limited testing for separated stormwater. Vortex separators provide similar SS *Removals* for separated stormwater and CSO. Vortex units have been used for CSO because they offer several advantages apart from the level of SS *Removal* provided. For example, swirls provide a secondary purpose of flow regulation. The vortex separator can capture smaller storms, providing storage for the polluted flow segment or entire flow volume, and then allow discharge of the stored volume to the underflow, thus eliminating the major portion of smaller CSO events. This latter concept has been successfully applied at the Washington, DC swirl facility where the numbers of CSO events have been reduced. By operating the three swirl units in parallel rather than providing limited treatment through one unit, smaller storms are completely captured. This advantage is not available from storm-flow controls that do not have an underflow to a treatment facility, or those which have limited underflow holding facilities.

TABLE 5-2

POTENTIAL POLLUTANTS AMENABLE
TO TREATMENT IN VORTEX SOLIDS SEPARATORS

Wet-Weather Water Quality Concerns	Potential Performance by Vortex Solid Separator*
Suspended solids and Sediment	Good removal of heavier particles. Fair to good removal can be expected for total suspended solids.
Floatables	Good floatables capture up to design flowrates can be expected.
Oil and grease	Fair removal
Oxygen demanding organics	Fair to good removal of heavy organic material. Poor or no removal for light particles and dissolved organics.
Nutrients	Fair removal of phosphorus associated with particles is possible. Poor removal of dissolved forms of nitrogen.
Metals	Fair to good removal of metals which sorb to particles or are in solid form. Poor removal of metals like zinc and nickel.
Toxic organics	Poor removal of dissolved organics. Toxic organics that bind to particulates may exhibit fair to good removals.

Source: Randall, *et al.*, 1983 and Whipple and Hunter, 1981.

* This table is based upon the pollutants general response to settlebality based treatment. Additional research is necessary to document actual vortex solids separator performance. Approximate range of pollutant removal is the following: excellent>90%; Good 60-80%; Fair 30-60%; poor<30%.

Vortex separators for stormwater control and treatment are most appropriate when used in conjunction with other controls. For example, a vortex separator can be used prior to a detention pond or wetland to lessen deposits and floatables and the associated operation and maintenance requirements.

Vortex separator units, when designed as satellite systems, are relatively compact units. They are often suitable for underground installation. Satellite units can be used over a broad expanse of the collection system, minimizing the high cost of conveyance systems needed for centralized treatment facilities.

The swirl degritter or HIL's Grit King™ can be used when coarse or preliminary treatment is the only objective and flow regulation or flow splitting is not required. Here detritus (grit and heavy organics) is collected in a bottom hopper for later removal. To decrease downstream wear, the swirl degritter can also be placed in series with a swirl to remove detritus from the foul-sewer underflow (especially in cases where the underflow has to be pumped back to the WWTP). This was done for CSO in the Lancaster, PA project (Pisano *et al.*, 1984).

Limitations

Characteristics of the pollutants of concern and the nature of SS carried in the storm flow should be identified in preliminary investigations to determine if a vortex separator is the appropriate control for each site. Vortex treatment effectiveness will be poor for storm flow having a relatively small percentage of particles with high settling velocities. Many water quality pollutants adhere to fine particles or are dissolved. The vortex unit will only provide minimal abatement of these pollutants.

Treatment objectives must match the capability of the vortex solids separator. If a specific application necessitates high-level SS removal (say 80%), vortex separators would not likely be an applicable control. However, if the vortex separator does not achieve the desired treatment level as a stand-alone unit, it can still be appropriate to use as part of the overall storage/treatment system.

Vortex units should be placed underground so that they are gravity fed. Inflow pumping is costly and breaks up particles rendering them less settleable and treatable. Therefore, site conditions may restrict the use of vortex units. Sites must have the appropriate depth and stability to structurally support the unit. Sites that require blasting will significantly increase construction costs. If the flows from the underflow must be pumped from the vortex unit, the capital and O&M cost associated with pumping increase the cost of using this technology.

Vortex separators are not maintenance intensive; however, washdown should be performed following every significant storm-flow event. Experience with vortex separators used for CSO treatment in Washington, DC indicates that if maintenance is not performed, odors occur. Manpower or automated washdown should be available, particularly for CSO applications.

RECOMMENDATIONS

- Additional studies on the effect of design variables (e.g., settling velocity, hydraulic loading, and underflow to influent ratio) on unit performance would ensure better design.
- More data is necessary to assess the ability of vortex separators to treat pollutants other than SS.
- Results from side-by-side studies of all three commercially available units will help to determine the effects of the design differences and comparative unit performance. A demonstration of this type is under development for CSO by the New York City Department of Environmental Protection.

SECTION 6
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