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Combined Sewer Overflow Control

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Combined Sewer Overflow Control

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Office of Research and Development
Center for Environmental Research Information
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Notice

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Chapter 1
Introduction

Overflows from combined sewers during storm events result in the discharge to receiving waters of untreated sanitary sewage, which also may contain pre-treated industrial wastewaters and untreated stormwater. Combined sewer overflows (CSOs) contain pollutants that are present in the domestic and industrial wastewaters, as well as those in the urban stormwater runoff that enters the combined sewer system.

In many cases, these discharges have an adverse effect on receiving water quality and attainment of designated uses. In addition, since CSOs are point source discharges of untreated sanitary sewage, they require National Pollutant Discharge Elimination System (NPDES) discharge permits. In recent years, there has been an enhanced regulatory focus on CSOs and their control, and communities with combined sewer systems are being called upon to develop and implement programs for control of CSOs.

Control technology applicable to CSOs has many aspects in common with treatment of domestic wastewaters in publicly owned treatment works (POTWs). However, a number of unique aspects of CSOs must be considered both for overall control program design and for effective design and operation of treatment units.

Purpose

This manual provides information to assist in selecting and designing control measures for reducing pollutant discharges from CSOs. The manual will be useful for municipal public works staff, design engineers, and regulatory agency staff tasked with the development and review of facility plans and long-term CSO control programs.

Scope and Organization

The manual provides design information for six CSO control technologies that were selected because they represent the most commonly employed techniques used in programs developed to date. Additional control techniques are identified and described, but detailed design guidance for these techniques is beyond the scope of this manual.

Chapter 2 discusses the characteristics of CSOs and the special considerations these features impose on the development of effective designs for control systems and unit processes. It describes the technologies for which design guidance is provided, and the basis for technology selection. Finally, Chapter 2 identifies and discusses other potential CSO control techniques that are not addressed by the manual.

Chapter 3 presents process selection considerations, and describes how the six control technologies for which design details are provided relate to each other and to potential control programs for an overall system. The first section discusses a variety of alternative design goals that may be imposed by a regulatory agency or otherwise adopted for design, and describes how to convert such general requirements to a specific design for a control system or treatment unit. Factors that influence the performance of each selected control technology are identified, and the advantages and disadvantages associated with each technology are discussed.

Combined sewer systems with their associated overflow points are relatively complex. Hydraulic conditions are highly variable due to the intermittent and variable characteristics of rainfall. The quality characteristics of CSO flows, and hence their treatability, also can vary significantly from location to location and from storm to storm at a given location. As a result, effective design programs usually require application of computer models, appropriate analysis and interpretation of rain gage records, and quality and treatability characterizations of the CSOs. The second section of Chapter Three describes the data requirements for addressing these elements and for developing the information that forms the basis for the design details presented in Chapter 4.

Chapter 4 provides design details, rules of thumb, and examples of practice for the following control technologies:

- In-System Controls/In-Line Storage
- Off-Line Near-Surface Storage/Sedimentation
- Deep Tunnel Storage

- Coarse Screening
- Swirl/Vortex Technologies
- Disinfection

For each of these technologies, Chapter 4 summarizes process theory, design parameters, operational requirements, and important related aspects (e.g., solids handling, odor control). Examples of design and/or operational features from reported operating units also are provided.

Chapter 5 summarizes currently available capital and operation and maintenance (O&M) cost information relating to the selected control technologies. The information provided is suitable for preliminary indications of the general order of costs associated with the control measures, and the need for site-specific estimates for developing accurate local costs.

Chapter 2
Introduction to CSO Control Technologies

Unique Aspects of CSOs

The design criteria and performance capabilities for most unit operations at POTWs generally are well established, based on the existing wealth of knowledge regarding municipal wastewater flow and load characteristics, and decades of operating experience at thousands of treatment facilities. This same municipal sewage is an important component of the overflows from combined sewers during storms. Although mixed with surface stormwater runoff in varying degrees during CSO events, both the quality and treatability characteristics of CSO discharges and municipal sewage are relatively similar. Differences are more in degree than in kind. As a result, experience with the treatment of municipal wastewater provides an important and useful basis for the design and operation of CSO treatment technologies.

A number of important differences must be recognized, however, because they have a significant influence on the effort needed to develop effective designs for CSO control units. The differences derive from several unique aspects of CSOs; the influences they have on the design of CSO control programs and individual control units are discussed briefly below. Specific considerations are addressed in greater detail in other sections of the manual, where appropriate.

Performance Goals Are Not Uniform

CSO control goals may be governed by receiving water quality-based and/or technology-based requirements, depending on the policies of state and federal permitting authorities. A considerably wider range of potential performance requirements may be applied for a CSO area compared to the standard "secondary" or "advanced" treatment objectives that apply in the case of most POTWs. Chapter 3 provides examples of commonly encountered CSO performance goals. In addition, while the technology and design basis for providing secondary treatment at a POTW is well established, CSO control concepts and design details are influenced by the specific performance goal that is applied. Additional data and system analysis is required, in relation to POTW design, because the development of controls that meet a selected performance goal must consider the variability of CSO flows and the frequency of extreme events.

System Characteristics Are Site Specific

The characteristics of combined sewer systems are site specific, and have an important influence on the elements of an overall control program, the control technologies that are most appropriate, and design features of individual control units.

Many CSO control programs include clever modifications or adaptations of features of the existing combined sewer collection/conveyance system. For example, relatively minor piping changes or regulator modifications can significantly affect design of end-of-pipe control units. The design, maintenance, and operation of regulators can have an important effect on the CSO flows delivered to a control technology.

Typically, a combination of management practices and CSO control technologies is required to meet the CSO program goal for a given community. Simply applying a control technology at a particular overflow point usually is not appropriate; effective control programs require consideration of the system as a whole.

An important factor contributing to the complexity of CSO control is the existence of multiple overflow locations, which may discharge to different receiving water bodies. Multiple overflows may be consolidated for treatment or they may be addressed separately. In some cases, the most effective design approach may completely eliminate a particular CSO that discharges at a sensitive location, by means of piping system modifications to reroute the affected flows.

Often a number of possible alternatives exist for a given community. The design of cost-effective CSO control programs thus may involve modifications to the collection system to relocate or consolidate overflows, or to reduce overflows by expanding hydraulic conveyance capacity at critical locations. Such modifications will influence the number and design capacity of any end-of-pipe CSO treatment technologies that may be required to meet performance goals. As a result, site-specific features of a local combined sewer system impose an additional level of design considerations than the typical POTW design program.

Design Basis Selection Is Not Standardized

Rainfall, which produces flows in the combined sewer system, is the factor that determines when and where overflows will occur, and the rates, volumes, and durations of the episodes. Rainfall amounts vary from year to year, storm event to storm event, and hour to hour during individual events.

Effective CSO control requires that an appropriate design condition be selected from among the wide array of naturally occurring conditions. In some cases, a predetermined "design storm" may have been designated. While this can be used to provide a design basis for a particular CSO treatment unit, it leaves a number of design issues unanswered. First, there is some ambiguity in converting a designated design storm to CSO control system design, depending on whether the control technology design is keyed to volume or to flow rate. In cases where only a return period is used in the definition (e.g., 10-year storm, 1-year storm), a wide variation in the volumes and rates will occur depending on the arbitrarily selected duration associated with the recurrence interval. Even in the case of a more complete designation, as in the 1-year, 6-hour design storm, ambiguity exists. While this defines a volume, it does not represent a volume for a complete storm event, so inferences on performance of storage units will be uncertain. A rate of flow can be extracted from this design condition in a number of ways, none of which provide a confident basis for design of a technology unit based on flow rates and peak flows.

The principal issue to address in selecting an appropriate design basis for a treatment technology can be stated as follows. While an arbitrarily selected design storm condition provides a convenient starting point to size an individual control unit and develop design details, it provides no information on the overall level of performance that will be provided. This approach tacitly assumes that the designated design storm is, in fact, the appropriate basis for meeting control objectives, and that control units based on it will provide acceptable levels of performance. Consider situations where control performance goals are stated in other terms (see Chapter 3). If a CSO control program is to be designed to capture or treat some percentage of the total combined sewer flow, or to limit untreated overflows to some specified number per year, then the designer is required to develop, by appropriate analyses of local rainfall and collection system characteristics, a site-specific determination of the appropriate design condition to apply. Rainfall characteristics and analysis issues are discussed further in Chapter 3.

In summary, the design storm approach comes from flood control and urban drainage planning, where peak flow is of concern for flood damage risk control. Smaller storms are not an issue. For pollution control, even small storms can result in standards violations and environmental harm, especially due to bacterial contamination. As a consequence, the effect of control measures on the annual frequency and volume of all CSO events is more important than conditions associated with a particular peak flow.

CSO Flows Are Intermittent and Highly Variable

While analysis and interpretation of rainfall records can provide useful information for identifying an appropriate design basis, drainage area and conveyance system characteristics impose site-specific influences on the flow rates and volumes that will occur during any storm event at locations in the system where control technologies will be applied. Each combined sewer system is unique, and most will be of sufficient extent and complexity that deriving the necessary information on combined sewer flows and CSOs usually requires the application of simulation models such as EPA's Storm Water Management Model (SWMM).

Data requirements for the proper application of such models can be substantial, and are discussed in further detail in Chapter 3. Data requirements include information on physical features of the sewershed and combined sewer system, such as areas, pipe sizes, slopes, regulator and pump station design, and operating parameters. In addition, accurate information on the characteristics of a number of individual storms and the flows they produce at various locations in the system is required to calibrate the model. This, in turn, requires flow monitoring, usually at multiple locations and for an adequate number of storm events to permit an acceptable model calibration to be made.

Thus, a considerable study effort often is required simply to identify the flow regime that will prevail at the point of application of a control technology. The characteristics of the variable flows at one or more control locations must be developed by applying the calibrated model to a sufficiently long sequence of rainfall events to provide representative results. Additional analysis then is required to derive appropriate design parameters for the treatment technology to be evaluated or applied, based on the pattern of variable flows projected to be the inflows to the unit.

Facilities for the control of CSOs must be capable of performing under a wide range of flow and load conditions. CSO facilities have influent hydrographs that often are sharply peaked along with periods of no flow, so that the concept of an "average flow" often used in POTW design has little physical meaning to CSO facilities. Peak flow rate is an important design parameter for a number of technologies, and the designer must select an appropriate value from the range of extreme values that will apply at the control location. The range in actual flow values must be developed by the simulation model, however, insight to the inherent variability and recurrence frequency of extreme values is provided by the rainfall characteristics summarized in Table 3-2 of Chapter 3.

CSO Quality and Treatability Are Site Specific

Pollutant concentration levels in CSOs are site specific and influenced by the strength of dry weather flows, the age and condition of the collection system, and the amount of infiltration/inflow relative to the sanitary flow.

The fact that CSO quality characteristics are site specific limits the confidence with which data from other sites can be applied. A number of the quality features also influences treatability parameters. For example, the settling characteristics of solids in CSOs to be treated by sedimentation technology are influenced by local system features, so monitoring and treatability testing is advisable to develop control unit design parameters.

Higher pollutant concentrations may be associated with the initial peak flows, depending on factors such as the size and slope of the piping system, the time interval between storms, the drainage area characteristics and response, and the solids accumulation in the collection system. The existence and/or magnitude of high initial loadings can influence the design of a control unit, as discussed in Chapter 3.

Performance Data on CSO Controls Is Limited

Due to the highly variable nature of CSO flows, the relationships between pollutant removals and design parameters, such as hydraulic loading rates and detention times, can be difficult to establish with reliability. Thus, while many studies on pilot-scale or one-of-a-kind installations have been published in the past, a comprehensive data base covering performance and design criteria for the most commonly employed CSO control measures remains incomplete.

Contributing to this limitation is the cost and difficulty of implementing effective monitoring programs to develop operating data on existing CSO facilities. Unlike at dry-weather POTWs, where operating data generally can be collected at the operator's convenience, collecting useful data at CSO facilities requires a concerted effort by personnel to be available on short notice and at the odd hours during which storm events often occur. In addition, because of the substantial variability in applied flows and pollutant loads, monitoring programs to characterize performance must extend over a sufficiently long period of time to reliably determine performance level.

Because of the variability in flow and quality at any site, the differences between sites, and the technical difficulty and cost of developing comprehensive performance monitoring data, CSO control technologies represent a situation where theoretical prediction of flow and quality (based on models calibrated against limited data sets) may provide a more accurate basis for determining design parameters and performance characteristics.

Major Technologies To Be Addressed

This section identifies six CSO control technologies for which detailed design guidance is provided in Chapter 4. The technologies were selected based on the fact that they are currently in wide use and have been demonstrated to be effective in reducing CSO flows and/or pollutant loads.

Separately, these control technologies will almost never be sufficient to satisfy the needs of a comprehensive CSO control program. For example, coarse screening is rarely considered the only technology to be applied at an overflow point; its more common use is in providing pretreatment for any or all of the other control technologies. In cases where bacterial levels produced by CSOs cause designated use impairment, disinfection is a necessary component of a CSO control system that may include any of the other technologies. In fact, disinfection of CSOs often requires some level of solids reduction by one of the other technologies for maximum effectiveness and reliability. System-wide CSO control may well require application of different basic control technologies or combinations at different overflow locations.

A comprehensive control plan addressing the characteristics of the combined sewer system and overflows, which identifies the impact of CSOs on receiving water uses and establishes performance goals for the CSO control program, will provide the basis for selecting and locating appropriate technologies (or technology combinations) in the system.

A comprehensive control program design also should consider other control methods, such as those discussed below. Any methods that apply should be incorporated because some will affect the design basis of a control technology, and many will be necessary to assure continuing effective operation of a selected treatment technology.

A comprehensive CSO control program is likely to incorporate one or more of the following technologies, for which design details are provided in Chapter 4.

In-System Controls/In-Line Storage

This technology seeks to optimize the use of existing storage capacity in the collection system, and maximize the conveyance of combined flows to the POTW. In-system controls typically are less costly than other, more capital-intensive technologies such as off-line storage/sedimentation, and are attractive because they utilize the existing facilities most efficiently. However, they are not normally sufficient to provide the complete degree of control required. The application of in-system controls, and the feasibility of in-system storage is very site specific. A variety of common regulator types, along with control strategies and operational issues pertaining to in-system controls, are addressed below.

Near-Surface Off-Line Storage/Sedimentation

This technology reduces overflow quantity and frequency by storing all or a portion of the CSO that occurs during storm events. In designs providing sedimentation, flow in excess of the tank volume passes through the units, receiving some measure of solids separation. For smaller storms, the tanks may provide 100-percent capture. Stored flows are returned to the interceptor for conveyance to the POTW once system capacity is available. In some cases, flows may be conveyed to a CSO treatment facility. This manual reviews basic sedimentation theory as applied to CSO control facilities, and presents design criteria, examples of design details, and control strategies for storage/sedimentation facilities.

Deep Tunnel Storage

This technology provides storage and conveyance of storm flows in large tunnels constructed well below the surface. Tunnels can provide large storage volumes with relatively minimal disturbance to the ground surface, which can be very beneficial in congested urban areas. The components of tunnel systems as they relate to CSO control are described below. Geotechnical aspects of tunnel construction are noted, but are not addressed in detail in this manual.

Coarse Screening

This technology provides coarse solids removal, as well as a degree of floatables removal. Coarse screening typically is provided upstream of other control technologies, such as storage facilities or vortex units that are applied as off-line treatment units (rather than as in-line regulator/degritter units). Aspects of coarse screening as they relate to CSO applications and design are presented below.

Swirl/Vortex Technologies

These devices provide flow regulation and solids separation by inducing a swirling motion within a vessel. Solids are concentrated and removed through an underdrain, while clarified effluent passes over a weir at the top of the vessel. The swirl/vortex devices described in this manual include the U.S. Environmental Protection Agency (EPA) swirl concentrator and commercial vortex separators.

Conceptually, the EPA swirl concentrator is designed to act as an in-line regulator device. In addition to flow routing or diversion, it removes heavy solids and floatables from the overflow. The commercial vortex separators are based on the same concept as the EPA swirl concentrator, but include a number of design modifications intended to improve solids separation. Two commercial designs, the Fluidsep vortex separator and the Storm King hydrodynamic separator have been applied as off-line treatment units. Each type of swirl/vortex unit has a different configuration of depth/diameter ratio, baffles, pipe arrangements, and other details designed to maximize performance. The basis of design for each type of swirl/vortex unit, and examples of design details and control strategies, are reviewed in this manual.

Disinfection

This process inactivates or destroys microorganisms in overflows, most commonly through contact with chlorine, although a variety of disinfection technologies are available without chlorine. Some of the more common technologies include gaseous chlorine, liquid sodium hypochlorite, chlorine dioxide, ultraviolet radiation, and ozone. For disinfection of CSOs, liquid sodium hypochlorite is the most common technology. This manual focuses on the design of liquid sodium hypochlorite disinfection systems.

Other Control Methods

A variety of practices and control techniques can be utilized to supplement the application of a control technology at a CSO discharge location. An overall control program should consider all possibilities and utilize any that apply for the local situation. Implementing a locally appropriate combination of the practices discussed below can enhance performance of the control technology applied and, in some cases, may reduce the design size and cost of the basic control unit, while maintaining the targeted performance level.

Control "practices" fall into one of three categories:

- Practices that restrict the rate and/or volume of stormwater runoff that enters the combined sewer system.

- Pollution prevention practices that reduce the quantity of pollutants that enter the system.
- Operation and maintenance practices for the combined sewer system that improve its ability to contain wet weather flows and deliver them to the POTW.

Examples of such control practices are described below.

A number of treatment technologies available for control of CSOs are not addressed in this manual. Examples include dissolved air floatation, fine screens and microstrainers, high rate filtration, and biological treatment. These technologies have been tested on a demonstration scale and found to be capable of effective CSO control. Detailed discussion of these technologies is outside the scope of this manual; however, a brief discussion of each is provided later in this section.

Flow Control Practices

Both *infiltration* of ground water into a combined sewer system, and direct *inflow* of surface stormwater runoff to the system can significantly influence the magnitude and frequency of CSOs, and the size and cost of control technologies. Reducing the quantity of infiltration and inflow (I&I) will make additional system capacity available to contain wet weather flows and reduce the magnitude of the CSOs reaching the control technology application points.

Two examples of flow control practices are infiltration and inflow control, described below:

- *Infiltration control:* Sources of infiltration include ground water entering the collection system through defective pipe joints, cracked or broken pipes, and manholes as well as footing drains and springs. Infiltration flow rates tend to be relatively constant and result in lower volumes than inflow contributions. Infiltration problems usually are not isolated, and often reflect a more general sewer system deterioration. Extensive sewer rehabilitation typically is required to effectively remove infiltration. The rehabilitation effort often must include house laterals, which are normally a significant source. Infiltration control will generally have a much smaller impact on CSO reduction than will control applied to inflow.
- *Inflow control:* Combined sewer systems were designed to drain stormwater effectively and to convey sanitary sewage. For a large percentage of storm events, the surface runoff flows are much greater than the sanitary sewage flows in the combined system. CSO control efforts can be assisted either by diverting some of the surface runoff inflows from the combined sewer system to an alternate surface drainage system or to ground water via infiltration devices, or by retarding the rate at which these flows are permitted to enter the system.

  Inflow of surface runoff can be retarded by using special gratings or restricted outlet pipes to modify catch basin inlets to restrict the rate at which surface runoff is permitted to enter the conveyance system. Inlet flow restrictions may be designed to produce acceptable levels of temporary ponding on streets or parking lot surfaces, allowing all runoff to eventually enter the system at the inflow point, but reducing the peak flow rates that the combined sewer system experiences. Flow detention to delay the entry of runoff into the collection system by storing it temporarily and releasing it at a controlled rate also can be accomplished by roof-top storage under appropriate site conditions.

Peak flow rates in downstream segments of the collection system and at overflow points also may be regulated by the installation of flow-restricting devices at suitable locations in upstream portions of the combined sewer system. A variety of commercial flow-restricting devices are available, such as the vortex valves described in Chapter 4.

Eliminating the direct connection of roof drains to the CSO collection system and causing this runoff to reach the system inlets by overland flow patterns (preferably via unpaved or vegetated areas) also can retard inflows.

When site conditions permit, some surface runoff flows may be prevented from entering the combined system by diverting them via overland flow to pervious areas or to separate storm drains. When these outlets are not available, excess surface runoff flows may be diverted to more favorable locations in the combined system, a technique referred to as flow-slipping (WPCF, 1989). Also, depending on site conditions, it may be possible to intercept some of the surface runoff flows by using infiltration devices, and divert them to ground water. In coastal communities, repair and adequate maintenance of tide gates may prevent flow intrusion caused by diurnal tide cycles.

The implementation ("retrofit") of I&I controls in developed areas on a scale necessary to substantially control CSOs is difficult and may be impractical. Flow control techniques, however, may be useful and practical in selected problem areas for addressing specific segments of an overall system. Control measures that address I&I to avoid increasing stormwater flows in a combined system are most effectively implemented in areas currently being developed, where their use can be required as a condition for development or reconstruction.

Pollution Prevention Practices

Pollution prevention measures include source controls and other actions within a drainage basin that reduce the amount of stormwater-related pollution entering the combined sewer system. Source controls usually do not require large capital expenditures, but they are generally labor intensive, and ongoing operation and maintenance costs can be high.

Controlling the use of problem materials such as de-icing salt, fertilizers, and pesticides can reduce pollutants entering the system. Product bans or substitutions (e.g., for plastic fast-food packaging) can prevent particular problem pollutants from being generated. Pollution prevention also can include increased frequency of solid waste collection, and programs that enhance the environmentally responsive disposal of bulk refuse, home renovation debris, and household hazardous wastes.

Other control measures in this category are designed to minimize accumulation of pollutants on streets and other tributary land areas and in catchbasins. Implementing these measures decreases pollutant loadings to combined sewers by preventing or reducing their entry.

Examples of pollution prevention practices applicable to comprehensive control programs for reducing pollutant discharges from CSOs are discussed below.

Street Cleaning

Street litter can be a significant source of certain pollutants (e.g., floatables) entering receiving waters via CSOs. An extensive monitoring program conducted by the City of New York (NYC DEP, 1993) concluded that the major portion (perhaps 95 percent or more) of the floatables in CSOs originate as street litter. Litter on streets can be removed by mechanical or manual street cleaning. Street sweeping often is considered a practical best management practice (BMP) for CSO pollution control. The effectiveness of street sweeping depends on the rainfall frequency, sweeping frequency, and other factors such as street density and the prevalence of curbside parking. A major impediment to street cleaning in densely populated cities is cars parked adjacent to the curb; therefore, enforced parking regulations are an essential component of a street cleaning program.

Public Education Programs

Education methods may consist of developing public announcements, advertising, stenciling street drain inlets, and distributing information with water/sewer bills. An important aspect of a public education program for CSO control is to encourage the proper disposal of sanitary and personal hygiene items disposed of through household toilets. The New York City floatables study (NYC DEP, 1993) determined that although these items accounted for only about 5 percent of floatable materials discharged by CSOs, they include the more objectionable items which cause the greatest public concerns and result in beach closings.

Anti-litter campaigns can reduce the amount of street litter and floatables that originate from CSO. Since it is unrealistic to anticipate widespread enforcement of anti-litter ordinances, the effectiveness of such programs depends on public education. Citizen action or education programs instituted to focus on specific issues such as those identified above, also will raise public awareness of the problems associated with CSOs and the justification for the broader control programs.

Recycle Programs

Crankcase oil, paints, cleaning agents, chemicals and other household wastes, as well as leaves and grass clippings sometimes are disposed of in catchbasins or street inlets. Proper disposal of these materials should be addressed in public education programs, but an essential element of an effective program is the availability of suitable disposal mechanisms. Recycle programs that establish disposal locations and/or collection schedules must be organized by the municipal agency, though they may utilize commercial establishments to implement components of such programs (e.g., acceptance of waste oil by service stations).

Fertilizer and Pesticide Control

Fertilizers and pesticides washed off the ground during storms contribute to runoff pollutant levels. Controlling use of these chemicals on municipal lands can help reduce the pollutant load. For example, in urban areas an important source of fertilizer and pesticide runoff that can readily be controlled is the park systems. Individual homeowner use of these chemicals is not likely to be a major source of pollution in urban areas served by combined sewers. Where homeowners do use fertilizers and/or pesticides, a public education program is required to address this issue.

Soil Erosion Control

Controlling soil erosion is important because soil particles carry nutrients and metals as well as contribute sediment. The principal areas of potential concern in urban areas served by combined sewers are public parks and construction sites. Problems in public parks may require limitations on the type of use, regrading, and/or revegetation of eroding areas.

Commercial/Industrial Runoff Control

Certain commercial and industrial sites can be responsible for disproportionate contributions of some pollutants (e.g., grit, oils, grease, and toxic materials) to the combined sewers. Sources of potential concern include gasoline stations, railroad yards, freight loading areas, and parking lots. In specific cases where significant pollutant loadings to the combined sewer system are contributed by well-defined locations of limited area, pretreatment of runoff from these areas may be a practical and effective control measure. Pretreatment measures can be required as part of a community's sewer use regulations. Examples of pretreatment measures include oil/water separators for problem service stations, or use of modified catch-basin designs to enhance retention of oil and grease or solids.

Procedures for detecting and locating illicit connections to separate storm drains by testing for specific chemical tracers (U.S. EPA, 1993) can be applied to CSOs to identify commercial or industrial sources contributing substantial levels of problem pollutants.

Operation and Maintenance Practices

Operation and maintenance (O&M) program activities that focus on combined sewer system components (regulators, tide gates, pump stations, sewer lines, and catchbasins), can significantly influence the level of control applied to CSOs.

Regulator/Tide Gate Maintenance

Because of the debris normally present in combined sewage, especially at times of storm flows, regulators continually accumulate materials that cause clogging and blockages. This is a particular problem with static-passive regulators.

The majority of unnecessary overflows in passive regulators are caused by trash blocking the entrance orifice to the interceptor. Other causes of unnecessary diversions at regulators include weir plates or dams that are improperly set, damaged, or broken off. Improperly operating tide gates allow receiving water to enter the combined sewer system, and reduce the storage and flow capacity of downstream interceptors that otherwise would be available during wet weather. Trash in combined sewer flows and/or trash and timber in the receiving water body can cause a tide gate to remain partially open. Corroded or warped gates, or deteriorated gate gaskets are also common causes of improper operation.

Frequent inspection of CSO regulators and tide gates will assure that as much of the wet weather flow as system capacity permits is retained in the system. The size and characteristics of the combined sewer system will influence the schedule, but where practical, an inspection several times per month, and after every storm, will ensure that necessary repairs and maintenance to clear debris and obstructions are performed in a timely manner.

Sensors to detect the presence of water in overflow lines during dry weather periods (resulting from faulty regulator or tide gate operation) are used to signal the need for maintenance action.

Maintenance programs that prevent the systematic overflow of unnecessary quantities of wet weather flows can influence the required design size and cost of treatment technologies. Furthermore, effective O&M for collection system elements is necessary to ensure that CSO controls operate in accordance with conditions for which the design is based.

Pump Station Maintenance

Proper operation and maintenance will ensure that pump stations transfer the design flows. Inadequate pumping capacity may result from changes in the upstream area that cause flows to exceed the original design basis, or from mechanical defects that cause substandard performance. Inadequate capacity results in back-up of dry weather flow in the sewer system, possibly contributing to dry weather overflows and resulting in reduced storage and hydraulic flow capacity for wet weather flows. This contributes to CSO at overflow points upstream of the pump station, and also prevents the wastewater treatment facility from maximizing treatment of wet weather flows.

Removal of Sewer Line Obstructions

Blockages in interceptor sewers can cause back-ups that create excess CSO overflows upstream of the blockage. A common cause of sewer line obstruction is the deposition of solids, which deplete the in-system storage capacity otherwise available for wet weather flow and reduce the flow-carrying capacity of the sewers (U.S. EPA, 1984a). Other system obstructions may result from roots growing into pipes and from collapsed pipes.

Removal of flow obstructions may include maintenance activities to remove and prevent accumulations of debris in parts of the system that experience flow restrictions. Where flow obstruction is the result of sediment accumulations, sewer flushing may be an effective control measure. A maintenance program of periodically flushing sewers during dry weather to convey settled materials to dry weather treatment facilities minimizes the buildup of such sediments. In cases where a section of the conveyance system routinely accumulates sediment deposits at a substantial rate, design and installation of a permanent flushing station or an in-line grit chamber may be a cost-effective approach.

Severe situations may require the application of sewer cleaning measures to physically clean a segment of the conveyance system. Hydraulic, mechanical, or manual devices may be required to remove solids or resuspend solids into the waste flow and carry them out of the collection system (U.S. EPA, 1984b).

Knowledge of the area and collection system assists in determining the parts of the system where particular problems can occur, and guides development of an effective inspection program. For example, collapsed pipes occur most frequently in areas with old sewer lines or with current or recent construction activity. Excessive infiltration also is most likely to be a problem in these areas, as well as where water tables are high. The potential for obstructions caused by solids deposition is greatest where velocities are low during dry weather and for small- and average-sized storms. These conditions exist where lines are oversized for the flows they normally convey and/or where gradients are flat. As a result, solids deposition obstructions likely will recur where they are present. Lines with a history for acquiring sediment deposits should be scheduled for cleaning on a regular basis.

Catchbasin Cleaning

In many communities, catchbasin cleaning is performed infrequently and is targeted towards maintaining proper drainage system performance rather than pollution control. Regular cleaning of catchbasins (once or twice per year) can remove accumulated sediment and debris that ultimately could be discharged from CSOs, thus providing some degree of pollution control. This technique applies for true catchbasins, that is inlet chambers that provide a sump for retention of sediment and debris. The technique does not apply for simple drain inlets.

Other Control Technologies

Physical treatment technologies other than those identified earlier in this chapter and that have been applied to CSOs include dissolved air floatation, fine screens and microstrainers, dual-media high rate filtration, and biological treatment. Sewer separation also is considered a control technology here and is included in the discussion that follows. Although the technologies have not been widely applied in CSO control applications, they have been tested on a demonstration scale and are effective in CSO control. A brief synopsis of these technologies as they apply to CSO control is presented below.

Sewer Separation

Separation is the conversion of a combined sewer system into separate stormwater and sanitary sewage collection systems. This alternative, historically considered the ultimate answer to CSO pollution control, has been reconsidered in recent years because of cost and the major disruptions to traffic and other daily community activities associated with separation. Separate stormwater runoff also contains pollutants (sediments, organic matter, bacteria, metals, oils, floatables, etc.), which continue to be discharged to the receiving waters.

Several potential benefits of sewer separation might warrant its consideration in specific cases. These include:

- Eliminating CSOs and preventing untreated sanitary sewage from entering the receiving waters during wet weather periods. Sanitary sewage is a more objectionable source of some pollutants, such as TSS, sanitary floatables, and bacteria.
- Reduced volume of flow to be treated at the POTW, thus reducing O&M costs, by eliminating surface runoff inflows during wet weather periods.
- Reduced infiltration and excess flow to a POTW if new sanitary sewers are constructed to replace old combined sewers.
- Reducing upstream flooding as well as overflows in cases where the existing combined sewers are undersized and back up frequently during storm events.
- Being more effective and economical than treatment facilities for remote segments of a combined sewer system serving relatively small areas.

Dissolved Air Floatation

Dissolved air floatation (DAF) removes solids by introducing fine air bubbles to wastewater. Air bubbles attach to solid particles suspended in the liquid, causing the solids to float to the surface where they can be skimmed off. This technology has been tested in CSO applications (U.S. EPA, 1972a, 1975a, 1977, 1979a). A major advantage of DAF is its relatively high overflow rate and short detention time, which results in reduced facility size compared to conventional sedimentation. Oil and grease also are more readily removed by DAF. Operating costs for DAFs are high due to a large energy demand, and skilled operators are required for its operation.

Fine Screens and Microstrainers

These devices remove solids through capture on screen media. They have been tested for use in CSO control (U.S. EPA, 1970, 1971, 1973, 1974a). The most common fine screening devices are rotary drum and rotary disk devices. In the rotary drum screen, media is mounted on a rotating drum. Flow enters the end of the drum and passes out through the filter media. Drum rotational speed usually is adjustable. Solids retained on the inside of the drum are backwashed to a collection trough. Filter media aperture size typically ranges from 15 to 600 microns. The rotary disk screen media is mounted on a circular frame placed perpendicular to the flow. Flow passes through the bottom half of the rotating disk, which is submerged. Solids retained on the disk are directed to a discharge launder using spray water.

One form of static screens features wedge-shaped steel bars, with the flat part of the wedge facing the flow. These "wedge-wire" screens typically have openings ranging from 0.01 to 0.05 in. These screens require daily maintenance to prevent clogging (Metcalf & Eddy, Inc., 1991).

Screens are subject to blinding from grease and "first flush" solids loads. A means for providing high-pressure backwash, and collecting and conveying backwash solids typically is required. Effective cleaning of screens after storm events using high-pressure steam or cleaning agents is required to maintain performance.

Removal efficiencies may be increased by decreasing media aperture size, but smaller apertures are more likely to blind. Coarse screening and disinfection facilities often are provided in conjunction with microstrainers.

Filtration

Dual-media high-rate filtration has been piloted for treatment of CSO flows (U.S. EPA, 1972b, 1979b). A two-layer bed, consisting of coarse anthracite particles on top of less coarse sand, was used. After backwash, the less dense anthracite remains on top of the sand. Filtration rates of 16 gal/ft^2/min or more were utilized resulting in substantially smaller area requirements compared with sedimentation. Demonstration test systems included pretreatment by fine-mesh screens. The use of chemical coagulants improved performance considerably. Filtration is more appropriately applied after pretreatment provided by fine screening. Operation may be automated, but tends to be O&M intensive.

Biological Treatment

Biological treatment processes have been tested in CSO control applications (U.S. EPA, 1974b, 1975b, 1981a,b). Although they have potential to provide a high quality effluent, disadvantages of biological treatment of CSOs include:

- The biomass used to break down the organic material and assimilate nutrients in the combined sewage must be kept alive during dry weather, which can be difficult except at an existing treatment plant.
- The land requirements for these types of processes can preclude their consideration in an urban area.
- Operation and maintenance can be costly and facilities require highly skilled operators.

Some biological treatment technologies are utilized in CSO control as elements of a wastewater treatment plant. Pump-back or bleed-back flows from CSO storage facilities commonly receive secondary treatment at the treatment plant, once wet weather flows have subsided. In a treatment plant that has maximized the wet weather flows that are accepted, flows are sometimes split, with only a portion of the primary treated flows receiving secondary treatment, to avoid process upset. The split flows are blended and disinfected for discharge.

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Springfield, VA 22161
703-487-4650

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Chapter 3
Process Selection

Performance Goals

While the overall objective of CSO control programs is to protect or improve water quality and designated uses of water bodies that receive CSO discharges, selecting a treatment process and determining size or capacity involves a focus on a more specific performance target.

Individual technologies are more effective for controlling some pollutants or pollutant classes than others. Depending on the designated use of the receiving water, the specific pollutant classes that directly affect that use assume primary importance in developing control plans. Therefore, the first criterion in selecting the most appropriate technology to apply in a specific situation is its control effectiveness for pollutants that directly affect the protected use. Some overlap exists, but the following list of uses, CSO pollutants, and control technologies generally indicates the basic type of control technology to consider.

Considerations in Technology Selection

Use	Pollutants	Technologies
Swimming	Pathogens, bacteria	Disinfection, storage/sedimentation, fine screens
Shellfish	Pathogens, bacteria	Disinfection, storage/ sedimentation, fine screens
Aquatic life/fin fish	Solids, BOD, COD, metals, toxic organics	Storage/sedimentation, fine screens
Aesthetics	Solids, floatables	Screens, swirl/vortex, storage/sedimentation

Where the objective of CSO control is to mitigate a specific water quality problem in an area immediately influenced by a CSO, the foregoing considerations should have a major influence on treatment process selection. However, in many cases CSO control requirements are addressed in a more general manner.

Cause and effect relationships between CSO and water quality impacts often are difficult to establish. The intermittent and highly variable nature of CSO and the complexities of many receiving waters impose significant demands on monitoring data requirements. In addition, impacts on aquatic life resulting from long-term sediment pollutant buildup and/or an already degraded receiving water may not be obvious, or able to be related to CSO in a definitive way. In such cases, performance goals for CSO control may be governed by state or other regulations, and expressed as one of a number of alternative technology-based goals.

Examples of commonly used technology-based performance goals are:

- *Percent capture:* That a specified percentage of flow be captured and/or treated.
- *Overflow frequency:* Reducing the number of untreated CSOs per year to a specified number.
- *Treatment level:* Specifying the pollutant removal efficiency of the CSO controls; often specified as the equivalent of primary treatment.
- *First flush:* Providing capture and/or treatment of some portion of a total overflow, determined to contain a major fraction of the pollutant load.
- *Knee-of-the-curve:* Basing the size of a control unit on cost effectiveness (i.e., where significant increases in cost produce marginal improvements in performance).

Selection of the general control strategy and specific performance goals may depend on local, state, or federal regulations, a community's long-term CSO control plan, or requirements of a permitting authority. In practice, a combination of technology and water quality considerations may be used in developing a CSO control plan. Water quality considerations may be used to guide the general approach, identify the pollutant types of major concern at a particular location (and hence the appropriate technologies), address spatial issues such as consolidation and/or relocation of outfalls, and similar issues. Specific performance goals, such as those listed above, then would be used to develop the design basis for individual treatment units or systems.

Implementing any strategy requires an estimate of the CSO flows or volumes that must be used as a design condition in order to meet the selected performance goal. These estimates require information on local rainfall characteristics and an appropriate engineering analysis of the system layout and hydraulic characteristics. In most cases, an appropriate analysis may require development of a monitoring program and application of computer models, in order to adequately assess the operation of the collection system and/or the water quality impacts in the receiving water body. Computer models such as EPA's Storm Water Management Model (SWMM) (U.S. EPA, 1988) are commonly applied to simulate the hydraulic behavior of a combined sewer system, and develop the information necessary to design CSO controls.

All strategies require an estimate of the design flow to use in developing the design details discussed in Chapter 4. If a design storm has been specified (for example, the 1-year, 6-hour event), then an analysis would be made to determine the CSO flows that would be delivered to a planned control unit by that rainfall condition. However, if the performance goal specifies a desired result (e.g., four overflows per year), then the system analysis to be performed must, in effect, develop both the appropriate "design storm" to apply, and the CSO flows and volumes to be used for detailed design.

Data requirements for system modeling analysis and process selection and design are presented later in this chapter. General design considerations that relate to each of the possible performance goals for a CSO control are presented below.

Design for Percent Capture

This goal is properly defined as capture for subsequent treatment. It is used to define performance goals for storage technology. When applied to off-line storage for CSO, this performance goal is used to define the additional storage volume required to capture a specified percentage of either the volume of current CSOs or the volume of wet weather flows in the combined sewer system, usually considered on a system-wide annual average basis. This assumes that all captured flow is returned to the collection system during dry weather for treatment at a POTW. The required storage used for design considers the storage provided by both the collection system and additional storage devices.

This performance goal could also be applied to treatment units or combination storage-treatment systems located at individual outfall points (e.g., sedimentation, swirl/vortex, screens) if the specified percentage is considered to be the percentage of the total combined sewage volume treated by the unit at flow rates consistent with design criteria.

The percent capture by a storage unit could be expressed in an individual case as the percentage of current discharges from an overflow point. In the general case, however, it is usually and more appropriately considered to be a percentage of the total wet weather combined sewage flows. This definition imposes more uniform requirements for different CSO systems, and allows the designer flexibility to optimize the use of both in-line and off-line storage. Percent capture is most appropriately considered as a long-term average (or in a year of average rainfall).

An indication of the approximate total storage requirements for different capture efficiencies can be developed by extracting from the rainfall record the percentage of total rainfall volume resulting from storm events that are equal or smaller than a selected design storm volume. Figure 3-1 shows the relationship between design storm size used as a basis for storage design and the percentage of the combined sewage flows that will be captured, based on 42-year rainfall records at six locations. The performance pattern is similar for all locations. As the size of the design storm increases, the effect of regional differences in rainfall on percent capture become progressively smaller. Since a design storm (for example, the 1-year, 6-hour storm) can be expressed as a volume, the approximate performance of a storage control using it as a design basis can be estimated from the rainfall record.

A critical assumption for this estimate relates to the ability to physically place the storage at the locations where it is required. The results apply directly for the analysis of a single overflow point. If applied for a system with multiple overflows, the tacit assumption is that the required storage capacity is appropriately distributed among the overflow locations. Existing systems with portions that are undersized, or otherwise sensitive to "kicking-off" an overflow at particular locations during very small storms would generate more overflow events than the screening analysis suggests. However, where these situations are associated with relatively small drainage areas, the number of overflow occurrences may be disproportionately high, but the effect on the estimate of the overall percent captured may be minor.

The tacit assumption is that the aggregate of all storm events equal to or smaller than a selected storm size that accounts for a particular percentage of total rain volume also estimates the corresponding percentage of the total wet weather flow volumes. For example, if 75 percent of the total amount of rainfall is delivered by storms equal to or smaller than 1 inch, then about 74 percent of the total wet weather flow volume will be provided by the runoff from storms of this size. Thus, storage capacity sufficient to contain the runoff from a 1-inch storm would retain, in such a case, about 75

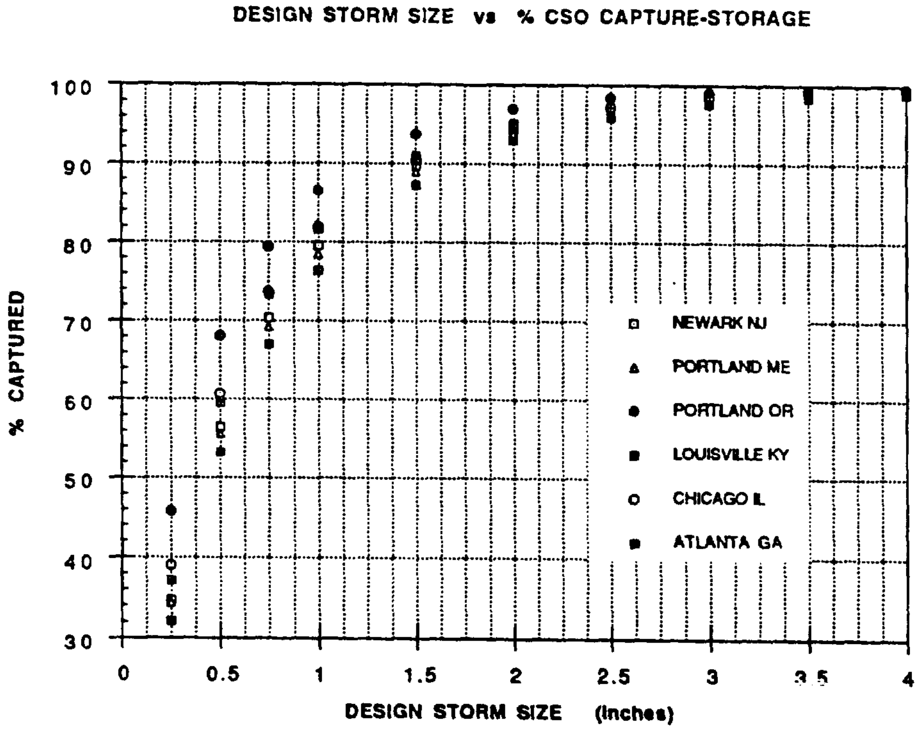


Figure 3-1. Approximate relationship between performance of CSO storage and storm size used as design basis—percent capture.

percent of the wet weather flows. The absolute amount will vary with the physical size and other features of the drainage area and collection system, and will be site specific. Details must be developed by an appropriate model or other analysis, but the required storage capacity inferred from the area rainfall characteristics would include all forms of storage that may be provided by the overall system. This would include capacity resulting from both in-system storage and off-line basins at the overflow points (as well as any natural depression storage that attenuates the rainfall reaching the combined sewers).

Maximization of in-system storage accordingly would reduce off-line storage capacity required to produce a desired capture percentage, because the required storage volume also would be accounted for, in part, by the wet weather flows that the conveyance system retains and delivers to the POTW as wet weather flows. An off-line storage basin is required to provide capacity only for the excess over capacity provided by other features of the overall system.

The captured volume usually is sent to the POTW where it is treated before ultimate discharge. At this point it is a wet weather-related component of the treatment plant flow. The ability of the POTW to process captured flows that are returned to the system, and the treatment for those flows, are important elements of the overall control program. An important influence on the performance of CSO storage units is the rate at which they can be emptied following a storm. A very large storage volume may be provided, but if it cannot be substantially emptied during the interval between most storms, it has the practical effect of providing a much smaller "effective" volume.

Two factors may restrict the emptying rate. One is the hydraulic capacity of the interceptors to which captured flows are returned for conveyance to the POTW. If infiltration into the combined sewer system is great enough that flows in the line remain high for extended periods following a storm, the ability to remove captured CSOs may be significantly restricted. The other factor relates to the capacity of the POTW and its ability to accept increased flows on a relatively consistent basis. If a large storage volume is provided, and a substantial percentage of wet weather flow is captured and then returned to the system over extended periods during dry weather, the result will be an increase in the average dry weather flow to the POTW. This flow could be significant.

The approximate ratio between annual volumes of sanitary sewage and stormwater in a combined sewer area is site specific. The sanitary flow from the area is determined by the wastewater generated (gallons per capita), and by the population density (persons per acre). Stormwater runoff depends principally on the amount of rainfall and how impervious the area is. In areas such as San Francisco with annual precipitation in the order of 15 or 20 inches, the annual sanitary volume generated is perhaps 3 to 5 times greater than the stormwater volume. In areas with 60 inches of annual precipitation (e.g., the Gulf Coast), the ratio is about 1 and the annual volumes generated are about equal. A large percentage of CSO areas are in regions with about 30 to 40 inches of annual precipitation, and annual sanitary volumes may be about 2 times the stormwater volume generated. Storage controls that provide a high percentage of CSO capture and distribute the returned flow to the system over much of the dry weather periods can significantly increase the "average" dry weather flow delivered to the POTW for treatment. There also will be additional sludge and grit generated by CSO control. This is an element of CSO control planning that should be properly considered.

Design To Reduce Overflow Frequency

Overflow frequency usually is defined as the number of overflows per year as a long-term average. Overflow frequency is higher in wet years and lower in dry years. This performance goal may be applied to a specific discharge, or treated as a value applied to the combined sewer system as a whole.

A preliminary indication of the design storm size used as a basis for CSO storage design can be developed by analyzing the rainfall record to determine the number of storm events that have larger volumes than the design storm. CSO storage units normally are not emptied until after the end of a storm because available system capacity is utilized by wet weather flows, so event volumes that exceed the design storm produce an overflow. Figure 3-2 illustrates the approximate relationship between the number of overflows (expressed as an annual average), and the design storm size for which storage is provided, based on analysis of rainfall records. Results are plotted using a log scale to assist in reading the low values.

A relationship exists between percent capture and number of overflows for any site using storage as the basic approach to control. Figure 3-3 illustrates the "equivalence" between performance goals that specify percent capture and number of overflows. The plot combines the results for all six locations shown separately on Figures 3-1 and 3-2. Of particular interest is the indication that very large storage volumes and capture efficiencies are required to reduce the number of overflows to 4 or 6 per year. Independent support for the relationship indicated is provided by results from a CSO study for the city of Windsor, Ontario (Mahood and Zukovs, 1993). A model analysis performed using the complete simulation model, STORM, was used to define the relationship between CSO capture and overflow frequency, and the results compare quite well with the general relationship indicated by Figure 3-3.

Design to comply with this performance goal would require continuous rainfall-flow modeling to verify and refine the above approximations. Parts of the collection system with marginal excess capacity produce a disproportionate number of overflows compared with the system as a whole.

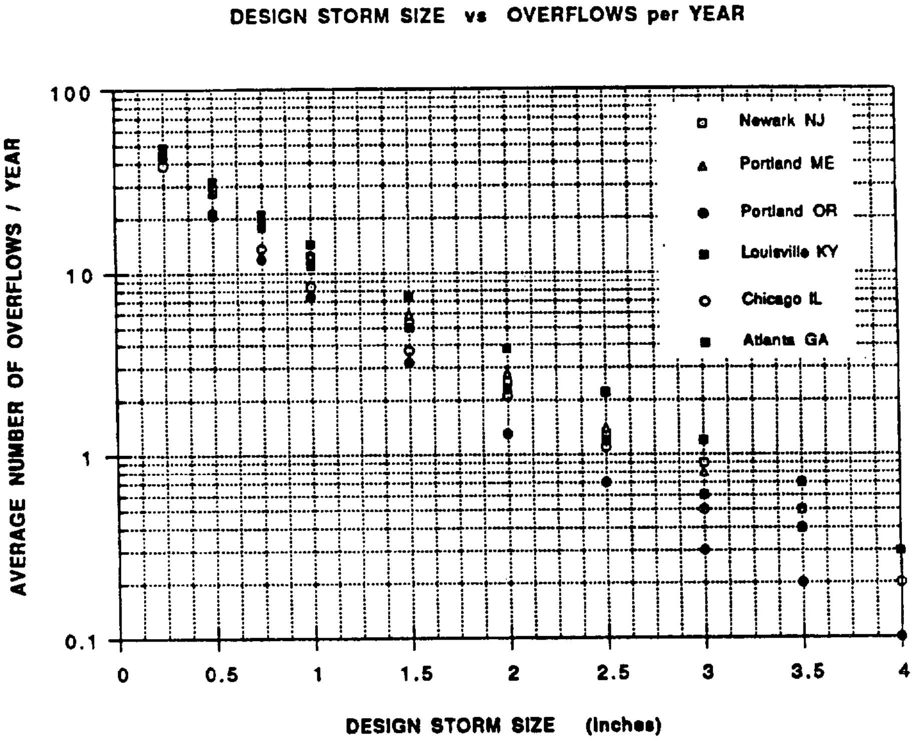


Figure 3-2. Approximate relationship between performance of CSO storage and storm size used as design basis—number of overflows.

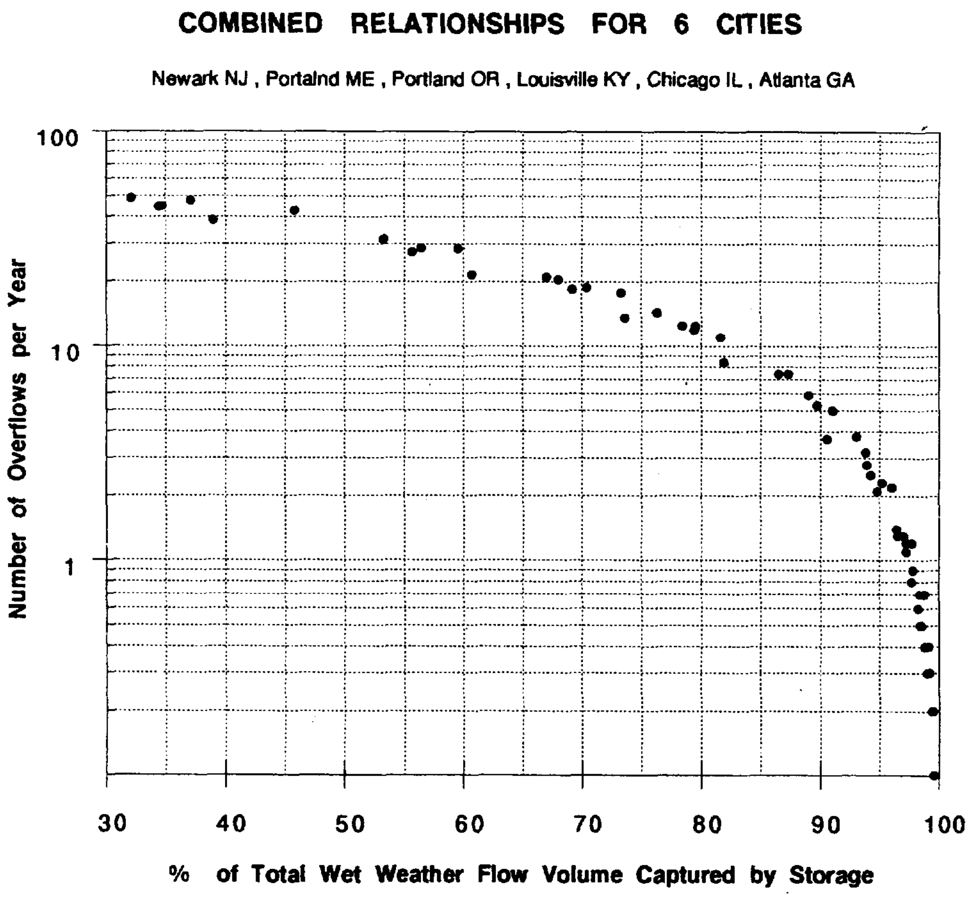


Figure 3-3. Relationship between percent capture and number of overflows for CSO storage control.

This performance goal could be applied to CSO control systems that provide treatment to CSOs, but continue to discharge them at the overflow point. In such a case, it would be necessary to establish that an "overflow" referred to an untreated discharge. In addition, for treatment units that operate as flow-through devices, the variable inflows produce short duration peaks, some amount of which may be bypassed. Since these peaks, at times, occur at more than one period during the same storm event, agreement as to what constitutes an "overflow event" is important to develop an appropriate design.

Design To Provide a Specified Treatment Level

Treatment technologies such as screens, sedimentation, and swirl/vortex designs are applied at individual discharge locations to remove pollutants from all or a portion of the combined sewer overflows, without modifying the overflow volume discharged at that point. Combination surface storage/sedimentation units are an exception because they return captured flow to the POTW for additional treatment. Also, the underflow (foul sewer discharge) from swirl/vortex units is retained in the conveyance system. However, for pure treatment technologies, essentially all flows are discharged at the overflow point in question, but pollutants are reduced or removed from these flows in accordance with the design size and treatment efficiency of the unit or process selected.

Any treatment device has an inherent performance capability dictated by its design principles and the removal mechanisms it employs. The pollutant mass removal efficiency it can apply to the flows delivered to it, even under optimum operating conditions, will vary for different pollutants. For example, removals by a particular unit could be nearly 100 percent for floatables, essentially zero for soluble nutrients, and anywhere between 5 and 50 percent for total suspended solids (TSS). Partitioning between dissolved/particulate fractions, particle sizes and settling velocity distributions, and settleable solids characteristics are all site specific and extremely important for design. Selection of the treatment technology to be adopted should consider the pollutants of concern for the outfall location and the average removal the type of unit is capable of providing.

A receiving water impact analysis can determine a specific treatment level, which is used to define a treatment level performance goal. An alternate application of this performance goal is to specify a technology-based treatment level. A common requirement is that

CSO control provide the equivalent of primary treatment. Because of the variability of CSO discharge flows, when this performance goal is applied a design storm flow rate also is specified and treatment units are designed for flows up to those produced by the design storm. Reduced performance is accepted for extreme events.

Estimates of performance characteristics for many types of treatment units can be based on experience with their performance as unit processes in a POTW. The relationship is not absolute because of differences between CSOs and sanitary sewage. The major factor for CSOs is the intermittent and highly variable nature of the influent flows and pollutant concentrations. Other factors, such as the reported tendency for CSO solids to have higher settling velocities and proportionally greater quantities of floatables, also may have an important bearing on design details.

Design/performance relationships could also be based on units that treat CSOs. The difficulty is that performance data on CSO treatment units is limited, and because the characteristics of CSOs vary substantially, the results for one site may not apply very well for other CSO sites. Table 3-1 summarizes the range in reported performance for CSO treatment units. Also, effectively monitoring intermittent, short-duration events, with variable and usually high flow rates and heavy particles, is difficult and the number of separate events monitored often is quite limited. Further, results from individual studies often are reported in such a way as to make it difficult or questionable to generalize sufficiently for transfer to other situations. Because of these considerations, the Table 3-1 results are best used as a general indication of approximate performance capabilities.

Treatment units that employ sedimentation are designed on the basis of overflow rates and detention times, which in turn are derived from particle settling velocities. A study of the relationship between solids removal performance and overflow rates for POTWs suggests that the performance expected from a given design overflow rate may also be affected by other factors (WEF, 1992). Since CSO quality and treatability tend to be highly site specific, the design of treatment units for CSO control should consider local analysis, including bench- and pilot-scale tests where reliable determination of performance is required. Determining the actual settling velocity distribution of the solids in the CSO will provide a more accurate assessment of the appropriate design overflow rate. Procedures to consider for local sampling and testing programs are further discussed later in this chapter.

Design of a CSO treatment-type control to meet a mass removal performance goal must consider two elements in combination. One is the efficiency of pollutant

Table 3-1. Reported Performance of CSO Treatment Technologies

	Percent Reduction			
Technology	**TSS**	**BOD**	**Remarks**	**Source**
Sedimentation				
Without chemicals	20-60	30	General characteristics	U.S. EPA, 1977a
Chemical assisted	68	68	General characteristics	U.S. EPA, 1977a
Storage/Sedimentation				
Cottage Farm site	45	erratic	General characteristics	U.S. EPA, 1974
Cottage Farm site—later data	46	28	Average data for 1988-1992	MWRA, 1993
Prison Point site	34	14	Average data for 1988-1992	MWRA, 1993
Chippewa Falls	18-70	22-24	General characteristics	U.S. EPA, 1974
Columbus, OH—Whittier St.	15-45	15-35	General characteristics	U.S. EPA, 1974
Swirl Concentrator/Regulator				
Washington, DC	33	83	Test data[a]	Washington, DC, 1992
Decatur, IL	(0-87) avg 37	(0-72) avg 34	Test data[b,c]	BGMA and CMT, 1987
General data	40-60	25-60	General characteristics[b]	U.S. EPA, 1977a
Screens				
Microstrainers	50-95	10-50		U.S. EPA, 1977a
Drum Screens	30-55	10-40		U.S. EPA, 1977a
Disc Screens	10-45	5-20		U.S. EPA, 1977a
Static Screens	5-25	0-20		U.S. EPA, 1977a

[a] 18% attributed to flow diversion, 15% to treatment by unit. Average flow was 32% of design peak; observed peak was 70% of design peak.

[b] No information was provided on removal by diversion or by treatment. Removals stated are presumed to be due to combination of treatment and diversion.

[c] 49 observations during four storm events. Individual range 0-87% TSS and 0-72% BOD reduction.

removal applied to the flows that are delivered to a unit for treatment, as discussed above. The other is the percentage of total flow delivered to and processed by the unit. When the performance goal is defined as the equivalent of primary treatment and a design storm size is specified, both of the required design conditions are defined. However, when a treatment level goal is defined only in terms of an overall pollutant mass removal percentage, then the design analysis also must determine the equivalent of the design storm size to be used as a basis for the treatment unit hydraulic design.

A trial and error assessment of alternative design sizes using a SWMM analysis may be required to make this determination. However, since treatment unit sizing is significantly influenced by peak flow rates, a summary of the frequency pattern of hourly rainfall intensities, extracted by analysis of rain gage data, can be helpful in identifying the most appropriate range of conditions to explore by the model analysis. Table 3-2 summarizes rainfall intensity characteristics for six locations in the United States. For each of a range of hourly intensities (inches/hour) the table lists the following information derived from a 42-year record and converted to an average annual basis:

- The upper segment indicates the average number of storm events per year that include one or more hours in which the intensity is greater than the intensity shown at the end of each row.
- The middle segment breaks down this total, and indicates that as the reference intensity increases, the number of "peak" hours in any event becomes increasingly restricted to only one or two individual hours.
- The lower segment lists the percentage of the total rainfall volume contained in all the hours of rainfall that have intensities equal to or lower than the reference value.

Practical considerations usually restrict SWMM model runs to limited time spans. Multi-year simulations rarely are feasible, and for complex systems practical simulation periods may be several months. Reliable estimates of the annual average number of untreated overflows or the percentage of total volume treated may not, therefore, be provided by the model simulation and limit its ability to suitably evaluate alternate design sizes. However, the model output can be analyzed/interpreted to identify the magnitude of the flow rates (and rainfall intensity) that will produce an overflow, or a peak condition at which the unit will be bypassed. The information on the overall pattern of rainfall characteristics listed in Table 3-2, can be used to determine the frequency at which the flagged condition (an overflow or a bypass) would occur as a long-term average, and the fraction of the total volume associated with that condition. In cases where the initial design selection either was inadequate or excessive in terms of the applicable performance goal, the rainfall relationships indicated in the table, coupled with the information derived from the model simulation, can be used to provide guidance on appropriate adjustments to the initially selected design parameters.

Design To Capture First Flush

The concept indicated by the term "first flush," is that in the early stages of a storm runoff or combined sewer overflow event, a relatively small percentage of the total flow contains a disproportionately large percentage of the total pollutant mass associated with the overall storm event.

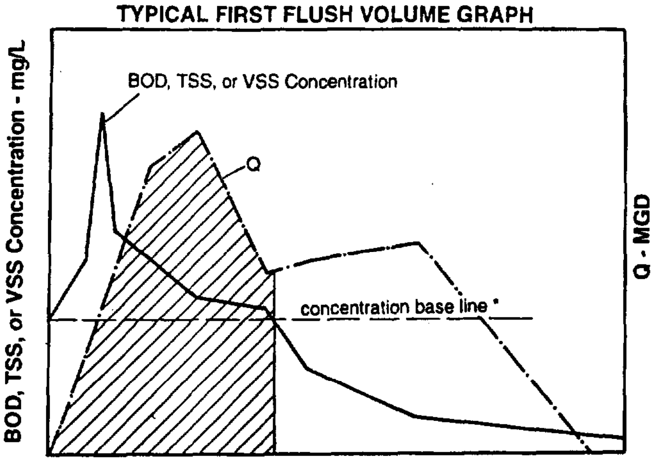
Significant first flush effects are most likely to be present with small catchments, flat slopes, low impervious fractions, relatively simple conveyance system networks, and lines with low dry weather flow velocities that permit solids to accumulate in-line. For larger drainage areas, and complex piping networks, an array of separate first flush conditions, may occur but reach the downstream location at which control is to be applied at staggered intervals that substantially attenuate and blend the small-scale effects. In addition, the design and capacity of the conveyance and treatment system may effectively retain that portion of many of the storms in which the first flush effect is present. Regulator configuration also may influence first flush solids loadings in CSO flows. If the regulator that diverts flow to the CSO control facility is a side weir or high-level outlet, much of the heavy bed-load of grit associated with the first flush may not be carried over to the CSO facility.

Monitoring data can be used to characterize the first flush. One method of estimating first flush volumes was employed in the design of first-flush tanks in Decatur, Illinois (BGMA and CMT, 1987). A sampling program established "baseline" average dry weather flow (DWF) concentrations for biochemical oxygen demand (BOD), TSS, and volatile suspended solids (VSS). The first flush was defined to start when the CSO facility influent concentrations rose above the baseline level, and continued until the concentrations returned to the baseline level. The first flush volume was then estimated by plotting flow on the same axis as the pollutant concentration. A sample plot is illustrated in Figure 3-4. The shaded area indicates the volume of the first flush. The limits of the shaded area under the flow curve (Q) correspond to the duration in which the pollutant concentration was greater than the baseline concentration.

A reasonably large event sampling program is desirable to characterize the potential significance of first flush effects at the point in the system where a control measure will be located. Various intensities/durations or

Table 3-2. Summary of Peak Hourly Rainfall Characteristics

<table>
<tr><th>Intensity for bypass (in/hr)</th><th colspan="3">Atlanta, GA</th><th colspan="3">Louisville, KY</th><th colspan="3">Chicago, IL</th><th colspan="3">Portland, ME</th><th colspan="3">Newark, NJ</th><th colspan="3">Portland, OR</th><th>Intensity for by-pass (in/hr)</th></tr>
<tr><td colspan="20">Average Number of Storms Per Year Having 1 or More Hours With a Greater Intensity</td></tr>
<tr><td>0.05</td><td colspan="3">63.8</td><td colspan="3">63.6</td><td colspan="3">51.2</td><td colspan="3">53.9</td><td colspan="3">57.2</td><td colspan="3">57.3</td><td>0.05</td></tr>
<tr><td>0.10</td><td colspan="3">52.8</td><td colspan="3">49.1</td><td colspan="3">35.5</td><td colspan="3">37.5</td><td colspan="3">42.1</td><td colspan="3">28.0</td><td>0.10</td></tr>
<tr><td>0.20</td><td colspan="3">34.2</td><td colspan="3">27.3</td><td colspan="3">18.9</td><td colspan="3">17.7</td><td colspan="3">22.1</td><td colspan="3">5.8</td><td>0.20</td></tr>
<tr><td>0.30</td><td colspan="3">22.9</td><td colspan="3">17.0</td><td colspan="3">11.8</td><td colspan="3">9.2</td><td colspan="3">12.3</td><td colspan="3">1.4</td><td>0.30</td></tr>
<tr><td>0.40</td><td colspan="3">15.8</td><td colspan="3">10.9</td><td colspan="3">8.1</td><td colspan="3">5.2</td><td colspan="3">8.0</td><td colspan="3">0.3</td><td>0.40</td></tr>
<tr><td>0.50</td><td colspan="3">10.8</td><td colspan="3">6.9</td><td colspan="3">6.0</td><td colspan="3">2.9</td><td colspan="3">5.3</td><td colspan="3">0.1</td><td>0.50</td></tr>
<tr><td>0.60</td><td colspan="3">7.0</td><td colspan="3">4.9</td><td colspan="3">3.9</td><td colspan="3">1.6</td><td colspan="3">3.2</td><td colspan="3">0.1</td><td>0.60</td></tr>
<tr><td>0.70</td><td colspan="3">4.8</td><td colspan="3">3.1</td><td colspan="3">2.9</td><td colspan="3">0.8</td><td colspan="3">2.1</td><td colspan="3">0.0</td><td>0.70</td></tr>
<tr><td>0.85</td><td colspan="3">2.8</td><td colspan="3">1.6</td><td colspan="3">1.9</td><td colspan="3">0.5</td><td colspan="3">1.2</td><td colspan="3">0.0</td><td>0.85</td></tr>
<tr><td>1.00</td><td colspan="3">2.0</td><td colspan="3">0.9</td><td colspan="3">1.3</td><td colspan="3">0.3</td><td colspan="3">0.5</td><td colspan="3">0.7</td><td>1.00</td></tr>
<tr><td>1.15</td><td colspan="3">1.4</td><td colspan="3">0.6</td><td colspan="3">0.9</td><td colspan="3">0.2</td><td colspan="3">0.3</td><td colspan="3">0.5</td><td>1.15</td></tr>
<tr><td>1.25</td><td colspan="3">1.0</td><td colspan="3">0.5</td><td colspan="3">0.8</td><td colspan="3">0.1</td><td colspan="3">0.2</td><td colspan="3">0.4</td><td>1.25</td></tr>
<tr><td colspan="20">Average Number of Storms Per Year With Indicated Number of Hours of Greater Intensity</td></tr>
<tr><td></td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td>1 hr</td><td>2 hr</td><td>>2 hr</td><td></td></tr>
<tr><td>0.05</td><td>20.5</td><td>14.6</td><td>28.2</td><td>20.0</td><td>15.1</td><td>28.2</td><td>13.7</td><td>13.3</td><td>24.0</td><td>13.6</td><td>10.2</td><td>29.6</td><td>15.3</td><td>11.4</td><td>30.1</td><td>19.7</td><td>12.9</td><td>24.1</td><td>0.05</td></tr>
<tr><td>0.10</td><td>24.0</td><td>12.1</td><td>16.7</td><td>23.4</td><td>11.9</td><td>13.8</td><td>17.9</td><td>8.4</td><td>9.2</td><td>14.1</td><td>7.8</td><td>15.4</td><td>17.5</td><td>90</td><td>15.6</td><td>15.3</td><td>5.9</td><td>6.8</td><td>0.10</td></tr>
<tr><td>0.20</td><td>20.9</td><td>7.8</td><td>5.5</td><td>17.9</td><td>5.5</td><td>3.9</td><td>12.0</td><td>4.5</td><td>2.4</td><td>10.1</td><td>3.7</td><td>4.0</td><td>13.3</td><td>4.8</td><td>4.0</td><td>4.6</td><td>0.7</td><td>0.5</td><td>0.20</td></tr>
<tr><td>0.30</td><td>16.6</td><td>4.5</td><td>1.8</td><td>12.9</td><td>2.9</td><td>1.2</td><td>8.7</td><td>2.2</td><td>0.9</td><td>6.3</td><td>1.7</td><td>1.2</td><td>8.6</td><td>2.6</td><td>1.1</td><td>1.3</td><td></td><td></td><td>0.30</td></tr>
<tr><td>0.40</td><td>13.0</td><td>2.0</td><td>0.8</td><td>8.5</td><td>1.8</td><td>0.6</td><td>6.5</td><td>1.2</td><td>0.5</td><td>3.9</td><td>1.0</td><td>0.4</td><td>6.2</td><td>1.3</td><td>0.5</td><td>0.3</td><td></td><td></td><td>0.40</td></tr>
<tr><td>0.50</td><td>9.2</td><td>1.4</td><td>0.2</td><td>5.9</td><td>0.9</td><td>0.2</td><td>4.9</td><td>0.9</td><td>0.3</td><td>2.3</td><td>0.4</td><td>0.1</td><td>4.5</td><td>0.6</td><td>0.3</td><td>0.1</td><td></td><td></td><td>0.50</td></tr>
<tr><td>0.60</td><td>6.4</td><td>0.6</td><td></td><td>4.4</td><td>0.5</td><td>0.1</td><td>3.1</td><td>0.6</td><td>0.2</td><td>1.5</td><td>0.1</td><td>0.1</td><td>2.8</td><td>0.3</td><td>0.2</td><td>0.1</td><td></td><td></td><td>0.60</td></tr>
<tr><td>0.70</td><td>4.5</td><td>0.3</td><td></td><td>2.8</td><td>0.3</td><td></td><td>2.4</td><td>0.4</td><td>0.1</td><td>0.7</td><td></td><td></td><td>1.9</td><td>0.2</td><td>0.1</td><td>0.0</td><td></td><td></td><td>0.70</td></tr>
<tr><td>0.85</td><td>2.6</td><td>0.1</td><td></td><td>1.5</td><td>0.1</td><td></td><td>1.6</td><td>0.3</td><td></td><td>0.5</td><td></td><td></td><td>1.1</td><td></td><td></td><td>0.0</td><td></td><td></td><td>0.85</td></tr>
<tr><td>1.00</td><td>2.0</td><td></td><td></td><td>0.8</td><td>0.1</td><td></td><td>1.1</td><td>0.2</td><td></td><td>0.3</td><td></td><td></td><td>0.4</td><td></td><td></td><td>0.6</td><td></td><td></td><td>1.00</td></tr>
<tr><td>1.15</td><td>1.4</td><td></td><td></td><td>0.6</td><td></td><td></td><td>0.8</td><td>0.1</td><td></td><td>0.1</td><td></td><td></td><td>0.3</td><td></td><td></td><td>0.5</td><td></td><td></td><td>1.15</td></tr>
<tr><td>1.25</td><td>0.9</td><td></td><td></td><td>0.4</td><td></td><td></td><td>0.7</td><td>0.1</td><td></td><td>0.1</td><td></td><td></td><td>0.2</td><td></td><td></td><td>0.4</td><td></td><td></td><td>1.25</td></tr>
<tr><td colspan="20">Percent of Total Rainfall Volume Associated With Hours Having Equal or Lower Intensity</td></tr>
<tr><td>0.05</td><td colspan="3">37.7</td><td colspan="3">44.8</td><td colspan="3">43.3</td><td colspan="3">53.9</td><td colspan="3">48.8</td><td colspan="3">73.2</td><td>0.05</td></tr>
<tr><td>0.10</td><td colspan="3">56.2</td><td colspan="3">63.7</td><td colspan="3">64.3</td><td colspan="3">73.7</td><td colspan="3">68.4</td><td colspan="3">91.0</td><td>0.10</td></tr>
<tr><td>0.20</td><td colspan="3">75.1</td><td colspan="3">80.9</td><td colspan="3">79.8</td><td colspan="3">89.2</td><td colspan="3">84.8</td><td colspan="3">98.5</td><td>0.20</td></tr>
<tr><td>0.30</td><td colspan="3">84.5</td><td colspan="3">88.4</td><td colspan="3">86.6</td><td colspan="3">94.6</td><td colspan="3">91.3</td><td colspan="3">99.8</td><td>0.30</td></tr>
<tr><td>0.40</td><td colspan="3">89.8</td><td colspan="3">92.6</td><td colspan="3">90.5</td><td colspan="3">97.1</td><td colspan="3">94.6</td><td colspan="3">99.9</td><td>0.40</td></tr>
<tr><td>0.50</td><td colspan="3">93.1</td><td colspan="3">95.2</td><td colspan="3">93.1</td><td colspan="3">98.3</td><td colspan="3">96.5</td><td colspan="3">99.9</td><td>0.50</td></tr>
<tr><td>0.60</td><td colspan="3">95.3</td><td colspan="3">96.8</td><td colspan="3">94.9</td><td colspan="3">99.0</td><td colspan="3">97.7</td><td colspan="3">99.9</td><td>0.60</td></tr>
<tr><td>0.70</td><td colspan="3">96.6</td><td colspan="3">97.8</td><td colspan="3">96.1</td><td colspan="3">99.3</td><td colspan="3">98.6</td><td colspan="3">99.9</td><td>0.70</td></tr>
<tr><td>0.85</td><td colspan="3">97.8</td><td colspan="3">98.7</td><td colspan="3">97.3</td><td colspan="3">99.6</td><td colspan="3">99.2</td><td colspan="3">100.0</td><td>0.85</td></tr>
<tr><td>1.00</td><td colspan="3">98.6</td><td colspan="3">99.2</td><td colspan="3">98.1</td><td colspan="3">99.8</td><td colspan="3">99.6</td><td colspan="3">100.0</td><td>1.00</td></tr>
<tr><td>1.15</td><td colspan="3">99.1</td><td colspan="3">99.5</td><td colspan="3">98.7</td><td colspan="3">99.9</td><td colspan="3">99.8</td><td colspan="3">100.0</td><td>1.15</td></tr>
<tr><td>1.25</td><td colspan="3">99.4</td><td colspan="3">99.7</td><td colspan="3">99.0</td><td colspan="3">99.9</td><td colspan="3">99.8</td><td colspan="3">100.0</td><td>1.25</td></tr>
</table>



* 188 mg/L for BOD
291 mg/L for TSS
203 mg/L for VSS

Figure 3-4. Illustration of use of monitoring data to characterize first flush.

more events should be sampled, because variations from event to event are expected. In addition, when such monitoring may be associated with reduced-scale pilot testing, an effort should be made to ensure that the influent samples used to characterize a first flush represent conditions at the location where the full-scale controls will be installed.

Whether a consistent and significant first flush effect exists at the point in the system at which control measures are to be applied is highly site specific, and only by appropriate monitoring can its presence and magnitude be determined. However, where appropriate monitoring can demonstrate and adequately characterize a first flush, then more cost-effective design of CSO controls may be possible. Where the first flush effect is significant and occurs reasonably consistently, some control units may have smaller design sizes for a given level of mass removal performance than otherwise would be the case. The design capacity of storage units would have a direct relationship to the presence of a first flush; however, the design of treatment-type units cannot be related to first flush in any practical manner, unless applied in relation to integral equalization storage that may be incorporated in the design.

A number of existing CSO facilities are designed to capture the more concentrated combined flows that may occur during the initial stages of a storm event. The key to designing such a facility is to define the limits of the first flush. First flush effects vary substantially from storm to storm, and sampling of combined flows resulting from a range of storm durations and intensities is required to indicate the duration of the first flush. For example, at the Massachusetts Water Resources Authority (MWRA) Cottage Farm facility, sampling indicated that the concentration of pollutants dropped off after 2 hours following activation of the facility (U.S. EPA, 1977b). At Bannockburn, Scotland, sampling indicated that BOD concentrations dropped to 65 percent of peak in 30 minutes, and 50 percent of peak in 60 minutes (Henderson et al., 1981).

Sizing for the first flush is complicated by the fact that, depending on the system configurations, part of the first flush may not even enter the CSO facility. Sampling at the Bannockburn facility indicated that the initial flow into the facility had the highest pollutant concentrations. The "rising leg" of the first flush, therefore, must have been carried down the interceptor. At the MWRA Cottage Farm facility, the downstream interceptor was sized for 2.1 times the mean dry weather flow. Depending on the timing of the storm, the interceptor may have available capacity to carry part of the first flush.

Design Based on Knee-of-the-Curve

The term "knee-of-the-curve" reflects the fact that as control units become larger, the incremental improvements in performance become progressively smaller in relation to incremental increases in design size and cost. This pattern is generally true, but often is intensified in the case of CSO control because the size of increasingly rare events (volumes and flows) grows logarithmically, and these rare events have an important influence at the high end of the performance scale.

The knee-of-the-curve technique is widely used to establish the design size of a specific control measure or an overall CSO control system, by identifying the point at which costs increase disproportionately for only a marginal improvement in performance. For any site, cost will be directly related to design size, and cost estimates, developed for units with a range of design capacities, can be developed and plotted against the corresponding performance levels for a formal knee-of-the curve assessment. Usually some degree of subjectivity involving best professional judgment is used to select the "knee," and it may be influenced by a variety of legitimate non-technical factors.

The knee-of-the-curve concept may be applied to the assessment of alternative design sizes for a particular control, when a particular type of control measure has been identified as the preferred approach. In a case where a CSO control assessment is made on a system-wide basis and includes consideration of alternate technologies as well as design sizes, a cost performance relationship developed to examine the knee of the curve may result in a pattern with discontinuities, rather than the smooth curves that usually apply for the assessment of a selected technology.

For a simple illustration, consider a case where storage technology has been selected for CSO control. For either surface storage or tunnel storage, the cost generally will increase relatively uniformly as performance level increases. However, space availability or other site constraints may place an upper limit on the maximum size and hence performance level (percent capture) that surface storage could provide, so that performance levels greater than this would require the use of tunnel storage. Examples of site constraints other than space availability that have been found to influence the placement of CSO control structures include:

- Ownership (including multiple ownership) of site.
- The presence of other utilities on site.
- Historic landmarks.
- Traffic concerns.
- Ground-water conditions.
- Zoning and other land use issues.
- Neighborhood resident concerns with visual impact of proposed structures and/or odor problems.

For situations where the maximum size of one control technology is constrained, a display of the overall cost curve showing the relationship over a broad range of performance levels shows a discontinuous step at the technology break point, when unit storage costs for tunnels are significantly greater than for surface storage units. Figure 3-5 illustrates the cost-performance relationships for a knee-of-the-curve design assessment.

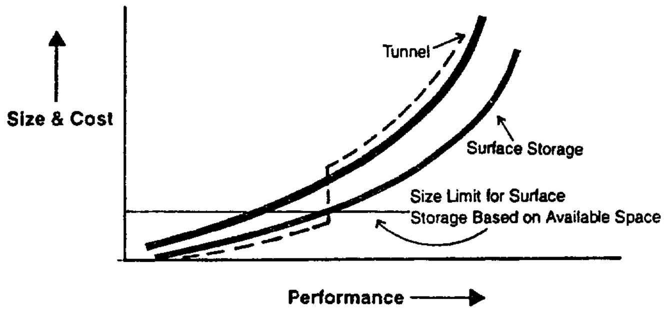


Figure 3-5. Illustration of knee-of-the-curve analysis.

Data Requirements for Design of CSO Controls

Several classes of data are important for designing CSO control systems or individual treatment units so that they achieve a specified performance goal.

- Information on the combined sewage and CSO volumes and flow rates used to design control units normally is developed using a simulation model such as SWMM. Data requirements for this model are discussed below in the section on modeling analysis.
- Although the model can accept all available hourly sequences of rainfall contained in a rain gage record, it is rarely practical to utilize the entire record. An appropriate year, season, month, or storm event must be selected. Analyzing a rainfall record for the study area can provide information to guide this selection. Rainfall data sources and analysis techniques are discussed below in the section on rainfall analysis.
- Most combined sewer systems are unique. Quality characteristics, including pollutant particle size and settling velocity distributions, tend to be site specific. Appropriate CSO monitoring and bench-scale treatability tests to establish treatability parameters can be important for the design of effective CSO controls. This issue is discussed below in the section on treatability analysis.

Modeling Analysis

Design of CSO control systems and individual units requires a determination of the combined sewage flow rates and volumes produced by rainfall on the drainage area. Most collection and conveyance systems are sufficiently large and/or complex that computations using a computer model are necessary. EPA's Storm Water Management Model (SWMM) is a common choice to simulate the behavior of a combined sewer system and approximate the characteristics of the associated CSOs. SWMM simulates the complex time-varying physical process of rainfall onto land of varying characteristics, the conversion of rainfall to runoff, and the collection and transport of mixed stormwater runoff and sanitary sewage through the collection system. It can develop hydrographs for selected nodes within a combined sewer system. Both hydraulic and pollutant routing are performed, and the model can be used for both single storm and long-term (continuous) simulation.

Single storm simulation provides a detailed assessment of the sewer system and overflow characteristics during individual storm events. This analysis mode can provide detailed predictions of flow and pollutant concentrations and can illustrate the manner in which control strategies or design alternatives affect these flows and concentrations. The continuous simulation mode performs a long-term analysis based on an annual or seasonal rainfall record, and is used to develop CSO flow and load statistics for an existing system as well as to simulate the effects of different control options. It provides information to assess the CSO problem and the cost effectiveness of abatement options. Both types of simulation are key to understanding the behavior of a combined sewer system, designing controls, and projecting CSO impacts on the receiving waters.

Detailed guidance on applying SWMM or other simulation models is provided in separate documents or by contacting EPA's Center for Exposure Assessment Modeling (CEAM), Athens, GA. The data required to perform an analysis using the SWMM model are discussed below.

Structure and Input Data

For convenience and computational manageability, SWMM is constructed in modules or "blocks." Included are modules that manage information and data, and modules that perform modeling and evaluation tasks. The Runoff and Transport Block modules determine the combined sewer system data requirements and relate to the design of CSO controls.

The Runoff Block is designed to simulate the quantity and quality of runoff from a drainage area. It utilizes a rainfall input file to produce hydrographs and pollutographs at selected locations in the system. These serve as inputs to the Transport Block, which routes them through the combined sewer system. Input data for this block includes:

- *Meteorological data:* Consists of rainfall and snowfall amounts, wind speeds, and air temperatures. All data should be local to the drainage area since storm variations throughout the drainage area can affect the patterns of runoff.
- *Surface quantity data:* Consists of characteristics that define the drainage area, which includes information on subcatchment areas, land slope, sewer inlet locations, infiltration, evaporation, depression storage, width of overland flow, and the land surface roughness. The model uses these factors (which may be developed through evaluating aerial photographs, topographic maps, field testing, or literature) to determine the amount and rate of runoff flow.
- *Surface quality data:* Includes information for calculating the amount and type of pollutants carried by the overland runoff flows. For a fully implemented Runoff Block, surface quality data relating to erosion, street dirt build-up and rain water washoff, street cleaning, snowplowing, and catch basin cleaning are needed. This information can be provided by literature, field data, and/or through calibration of observed pollutant loading data.

The Runoff Block is based on segmentation of the drainage area into an appropriate number of subcatchments. The number is determined by the features of the drainage area and by the layout and characteristics of the collection system. Manning's equation is used to calculate the maximum rate of runoff from each subcatchment area. The maximum subcatchment runoff is reduced by an infiltration and evaporation factor to produce a volumetric loading rate for use as input to the Transport Block.

The Transport Block routes inputs from the array of locations where flows enter the collection system, and simulates the quantity and quality of flow at locations of interest. Inputs, generated by the Runoff Block or by other means, are entered into the network at designated inlet manholes. The calculated flows and concentrations define the characteristics of specific overflows, or may be applied as input for another SWMM block, such as Storage/Treatment, or for a separate receiving water quality model. Information required by this block includes:

- *Transport data:* Describes the physical characteristics of the sewer system, which is conceptualized as a network of conduits connected by non-conduit nodes representing manholes or regulators. Conduits are described by shape or element type, dimensions, length, slope, roughness, and number of adjacent lines (barrels). Transport data are acquired from as-built drawings and field inspections of the sewer system.
- *Quality data:* Describes pertinent characteristics of pollutants the model routes through the sewer system. The required data for each pollutant simulated includes first-order decay rate, specific gravity, and solids particle size distributions. These parameters allow the Transport Block to determine pollutant concentrations after decay, scour, and deposition processes are accounted for in the model.
- *Internal storage data:* Input as an individual element of the drainage system. Geometry, depth-discharge relationships, and initial pollutant concentrations of a storage unit are all required data. A storage unit may be used to simulate processes such as sedimentation or chlorination.
- *Infiltration data:* Used to assess the amount of flow and pollutants entering the sewer system from leaking pipes and joints. Infiltration flow may come from ground water, rain water, residual moisture, and base dry weather infiltration. Monthly degree day data is used to determine infiltration from residual moisture. These data are most useful when obtained directly from the study area. Historical data from a near-by study area, estimates by local professionals, and estimates based on country-wide observations are useful alternatives when direct data are not available.

Additional Transport Block data requirements include subarea identification parameters, observed flow data, and flow estimating data. Subareas are subdivisions of the drainage area identified according to zoning classifications. Subareas may not correspond to subcatchments defined in the Runoff module. Land use, subarea acreage, water usage, population density, dwelling unit density, housing values, average income, and process flows are data required by the Transport Block to estimate average daily sewage flow and pollutant concentrations. This average sewage flow also is corrected for hourly and daily fluctuations in dry weather flows and concentrations. The Transport Block includes a dry-weather flow model that may be used to estimate both sanitary sewage flow and pollutant concentrations from the drainage area.

Transport of wet- and dry-weather flow by the Transport Block is based on representation of flow as a kinematic wave. Disturbances are propagated only in the downstream direction and backwater effects are limited to only a single conduit. Surcharging is modeled by storing excess flow at the upstream non-conduit until capacity is freed to accept the stored flow. Equations for gradually varied, unsteady flow are used by Transport to calculate the velocity and depth of flow along the sewer system. This procedure is not appropriate for analysis of system segments that consistently experience significant surcharge conditions. In such cases, the Extran (Extended Transport) Block must be used.

Practical Application and Calibration

Calibration of the model is the only practical way to assure that the substantial array of input parameter values assigned accurately represents the system being modeled. Model calibration consists of adjusting selected input parameters so that the computed output matches observed monitoring results at key points in the system. On completion, a calibrated model should provide a good match between predicted and observed results, when applied to data sets that were not used in the calibration step. When this criterion is met, the model is considered validated or verified.

Model calibration requires synoptic rainfall and flow measurements for a number of storm events. Rainfall data should be obtained from one or more gages located in or close to the drainage area. Flow monitoring should be conducted at representative locations in the system. Monitoring overflows at the largest CSO points in systems with a number of different CSO locations is advisable. Even the best model predictions are only approximations of reality, and emphasis on the largest CSOs will help to secure the best accuracy for the most significant discharges, and thus the best overall estimate of CSO volumes and pollutant loads for the system as a whole. In addition to the overflows, flow monitoring stations should be located at one or more points in the collection system upstream of the regulators. This is necessary to calibrate the model parameters defining the drainage area features that control the conversion of rainfall to flows in the collection system.

An adequate number of storm events (usually 5 to 10) should be monitored and used in the calibration. This is important because of possible malfunctions in different flow sensors at different times, and also to compensate for variations in rainfall distribution over the drainage area. The point rainfall measurement at the rain gage provides only an approximation of the distribution over the entire drainage area, so variations in individual events should be expected.

The availability of a sufficient number of different storm events also will facilitate and improve the model calibration. Many users prefer to base the calibration on the model's ability to reproduce the overall results from a number of different events, rather than attempt to match instantaneous flow measurements.

Flow measurements almost always will be made using automatic sensing units, but it is important to provide operator inspection and supervision. Sensors tend to clog and generate erroneous readings, which can seriously impede model calibration efforts if left undetected.

In addition to timely maintenance of the flow meters, operator supervision also can assure that the location being monitored is not surcharged at the time of flow measurement. The existence of a surcharged condition is essential information for reliable application of the simulation model.

For lines that surcharge, the Extran Block must be used, rather than the normal Transport Block. This adds complexity to the model analysis, not so much in the computations, but in the model's sensitivity to the accuracy of the input parameters assigned. Where Extran is employed, a better definition of ground truth (pipe diameters, slopes, lengths, etc.) is required.

Applying the model is more cumbersome for systems with many regulators and overflow points. Modeling large, complex systems also imposes significant demands on available computer memory for input and output files. This is a serious consideration for model analyses performed on PC platforms. The practical effect is to impose a limit on the length of rainfall record that can be analyzed.

For large or complex systems, practical maximum record lengths are a year or less, and in some cases could be less than a 6-month simulation. When the period analyzed is short, it is important that the most appropriate period of the rain record be selected for analysis, so that the model provides representative projections of system or control performance. Independent analysis of rain data can assist in selecting an appropriate portion of the overall rainfall record.

Many applications of the SWMM model do not independently compute the surface runoff quality as above, and then combine it with the sanitary sewage quality characteristics to define the quality of the CSOs. A common approach is to directly assign values for quality characteristics of the combined sewage and CSOs, based on local CSO monitoring data or the quality of wet-weather inflows to the POTW. When an average concentration value is assigned for all storms (or a concentration correlated with storm size when the data so indicates), the model will not reproduce individual event quality, but provides acceptable estimates of pollutant loads averaged over the analysis period. Many analysts believe that such projections have equal or better reliability, because of the uncertainties associated with the use of the build-up/wash-off model routines and the difficulty commonly encountered in calibrating this model component.

Rainfall Analysis

Precipitation is the driving force that mobilizes and transports pollutants via CSOs to receiving waters. Evaluating the precipitation characteristics of an area can assist in analyzing issues such as the estimation of CSO pollutant loads, the water quality impacts they produce, and the assessment of control strategies. When the basic analysis is performed using a simulation model such as SWMM, separate analysis of the rainfall record can assist in selecting the most appropriate rainfall periods or events to use in the model analysis.

Rainfall is highly variable, and excursions of individual events above typical or average values of parameters such as intensity, duration, and volume, can be considerable. The greater the magnitude of rainfall volume or intensity, the more rarely it occurs. Statistical analysis of rainfall records can define the frequency distribution (or probability of occurrence) of magnitudes of the various rainfall parameters. Such probabilities often are expressed in terms of return period or recurrence interval.

Hourly rainfall records for rain gages in the United States are available from the National Weather Service's (NWS's) National Climatic Data Center (NCDC) in Asheville, North Carolina. Each record is identified by a unique 6-digit number, consisting of a 2-digit state code followed by a 4-digit gage number. The information in a gage record includes the location, latitude and longitude, elevation of the measurement site, and the depth of hourly rainfall recorded (in 0.01 inches). The date and hour are recorded for each depth in the record.

The NWS generates regional summary reports from time to time, but for all NWS gages, the basic data are readily available in electronic format from both the NCDC and commercial sources. The electronic data include records from both previously and currently operating stations in the 50 states. These records include daily rainfall data for over 25,000 stations, hourly data for over 5,500 stations, and 15-minute data from over 2,700 stations. Approximately 8,000 rain gages currently operate across the country. The increased use of personal computers over the past decade has allowed interested parties to conveniently obtain and analyze the actual data for a particular location, avoiding the need to rely on published summaries.

A long-term sequence of rainfall data can be analyzed in a number of different ways to develop relatively concise characterizations, which may then be used for engineering purposes. Common methods for characterizing rainfall include total volumes, event statistics, return period/volume curves, and intensity-duration frequency curves. Each method is described below.

Total Volumes

A common basis for describing rainfall is the total volume of rainfall occurring each year. The NWS publishes annual totals as well as deviations from the average for each rain gage in its network. Definitions of wet- and dry-year rainfall can be made by comparing a particular year's rainfall to the long-term average. Monthly totals and averages also can be computed in the same way to examine seasonal differences. Evaluating annual or seasonal rainfall totals is a common basis for selecting a specific time period to use in detailed simulation modeling.

Event Statistics

Information may be developed on the characteristics of individual storm "events" for a site. If the sequence of hourly volumes is grouped into separate events, then each event may be characterized by its duration, volume, average intensity, and the time interval between successive events. The event data can be analyzed using standard statistical procedures to determine the mean and standard deviation, as well as probability distributions and recurrence intervals. A computer program, "SYNOP," performs a statistical analysis of the rainfall data in a NWS record (U.S. EPA, 1989). It segregates the hourly rainfall values into independent storm events, and determines the parameters of each event (volume, duration, average intensity, and interval since the preceding storm). The array of individual event values is analyzed to determine the mean and standard deviation or coefficient of variation for selected stratifications of the data set, producing results sorted by month and by year, as well as for the entire period of record. Outputs include information on the frequency distribution and recurrence period for the event parameter values. This report also presents summaries of rainfall statistics developed for rain gages in different areas of the country.

Return Period/Volume Curves

The frequency of occurrence for a given magnitude of a storm event parameter such as volume may be shown as a plot of its probability distribution, as illustrated in Figure 3-6. The plot indicates that approximately 10 percent (90th percentile) of the storm events in the 42-year record used for the analysis, deposited about 1.5 inches or more of rain. If the statistical analysis indicates an average of 60 storm events per year, this would mean that six storms per year had a rainfall volume equal or greater than 1.5 inches. Furthermore, six events per year averages one event per 2 months, so the 1.5-inch rain event could be characterized as the storm-event volume with a 2-month return period, or the "2-month storm."

Note that this 2-month storm definition is not related to duration; the 252 storms equal or greater than 1.5 inches during the 42-year period (10 percent x 42 year x 60 per year) would have a range of durations. The return period-volume relationship is different than corresponding relationships that are based on rainfall intensity-duration (e.g., 1-year, 6-hour storm) curves provided by other design storm determinations. The relationships from a storm "event" analysis are more appropriate for the assessment of storage requirements because events, by definition, provide storm volumes that are typically followed by dry periods that average several days, during which a CSO storage unit is emptied.

The specific values for storm parameters vary regionally, but the event summary and distribution plot (Figure 3-6) illustrates the nature of the storm event statistics produced by any rain gage. Table 3-3, which lists summary event statistics for rain gages in different regions of the country, illustrates both the general similarity as well as the regional differences in rainfall characteristics.

Intensity-Duration Frequency Curves

Curves of this nature are another way of characterizing the variable rainfall at a site. A typical set of intensity-duration frequency curves is illustrated by Figure 3-7. For this record, a 60-minute duration (1-hour) rainfall intensity of about 1 inch/hour occurs once every year. One-hour intensities that are higher than this occur more rarely (e.g., 2 inches/hour every 10 years). Note also that rainfall with an average intensity of 1 inch/hour also may occur over longer durations, at less frequent recurrence intervals.

A major use of these families of rainfall characterization curves is to design hydraulic structures (e.g., storm drains, culverts), where short-duration peak flows must

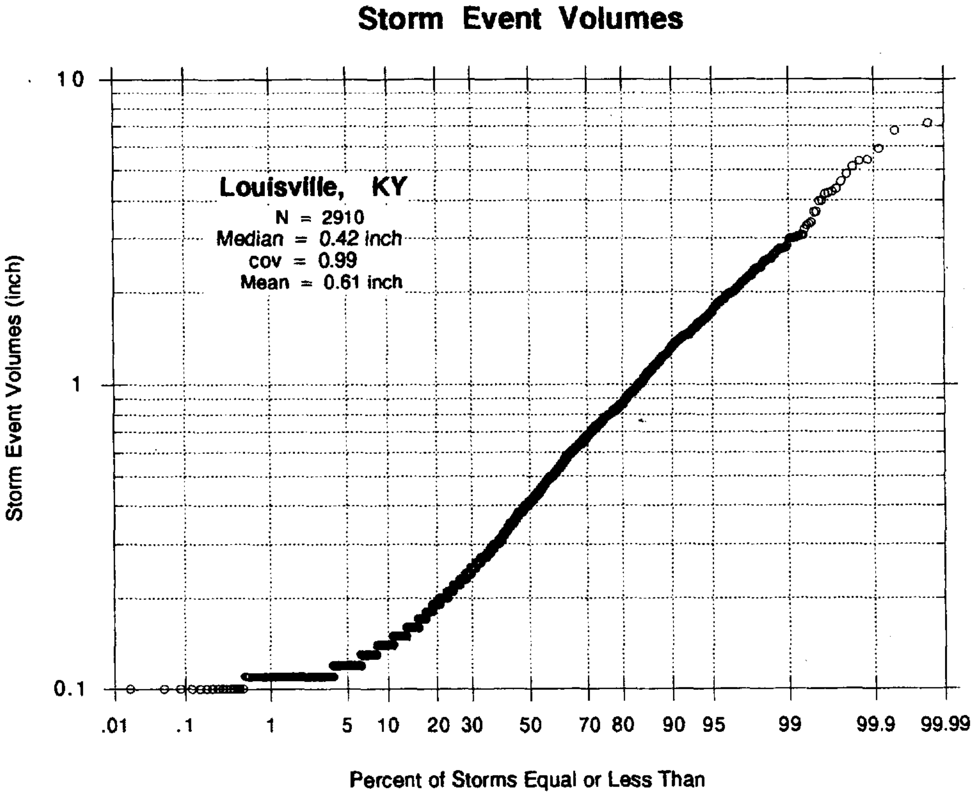


Figure 3-6. Probability distribution of storm event volumes.

Table 3-3. Rainfall Characteristics for Six U.S. Locations[a]

	Annual Averages		Event Rainfall Statistics Mean Storm Event				Storm Event Volumes for Three Recurrence Intervals[d] (in)		
							Return Period		
City	Number of Storms[b]	Rain Volume (in)	Volume (in)	Intensity (in/hr)	Duration (hr)	Delta[c] (days)	3 mo	6 mo	1 yr
Atlanta, GA	66	47.4	0.71	0.112	9.4	5.55	2.0	2.6	3.2
Louisville, KY	69	42.0	0.61	0.092	9.5	5.34	1.6	2.1	2.6
Portland, ME	64	41.9	0.66	0.065	12.5	5.79	1.8	2.3	2.8
Newark, NJ	64	41.8	0.65	0.076	11.1	5.76	1.7	2.2	2.8
Chicago, IL	58	33.4	0.57	0.095	9.1	6.29	1.5	2.1	2.6
Portland, OR	72	34.2	0.47	0.034	15.7	5.08	1.4	1.8	2.3

[a] Based on 42 years of records, from 1949 through 1990.
[b] Storm events greater than 0.1 inches with a minimum of 6 dry hours to separate storm events.
[c] Delta is the average interval between the midpoint of storm events.
[d] The tabulation of recurrence interval volumes indicates rainfall volumes for events that recur on average 3-, 6-, and 12-month intervals.

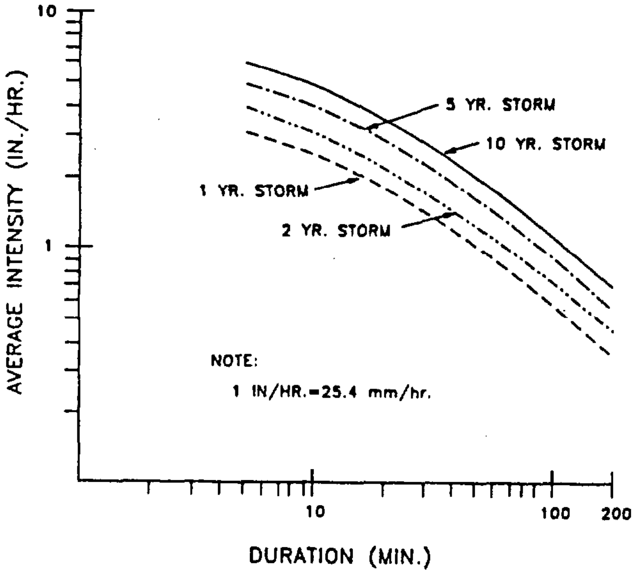


Figure 3-7. Illustration of intensity-duration curve (Moffa, 1990).

be considered to avoid local flooding. They also may be applied to the design of CSO treatment units where peak flow is a relevant design parameter.

These curves are developed by analyzing an hourly rainfall record in such a way as to compute a running sum of volumes for consecutive hours equal to the duration of interest. The set of volumes for that duration are then rank ordered, and based on the length in years of the record, the recurrence interval for any rank/value is determined. This rainfall analysis procedure is used to calculate the local value for a design storm such as a 1-year, 6-hour design condition.

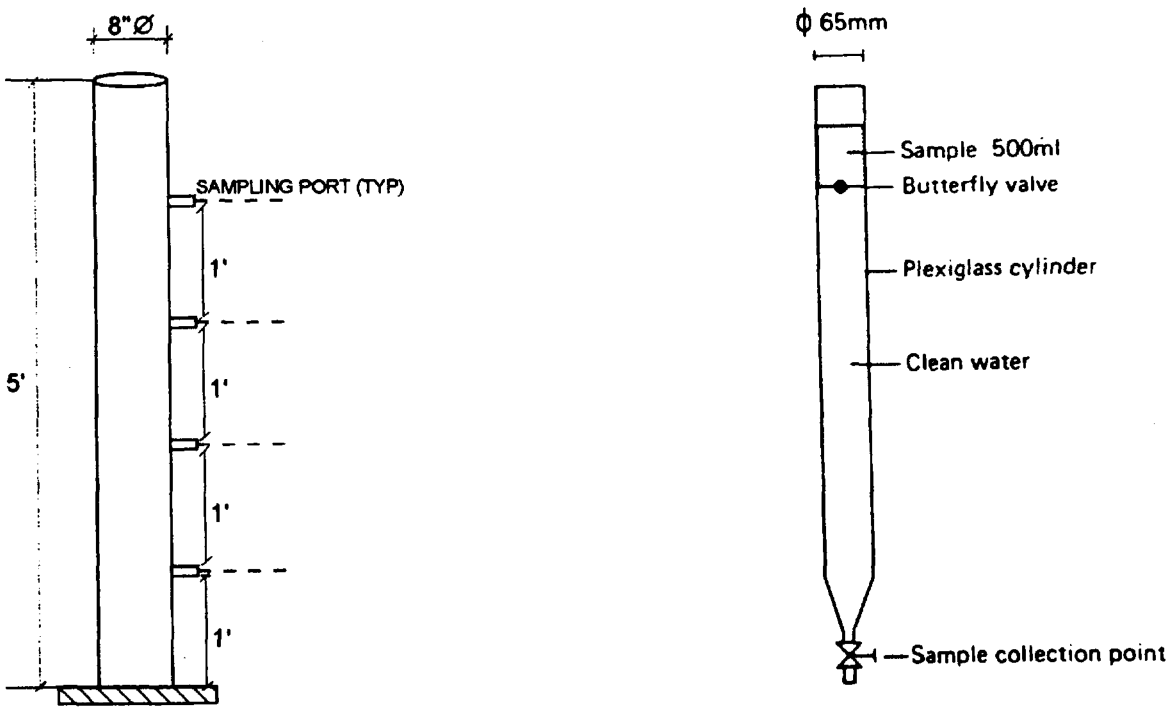
Treatability Tests

CSO treatment technologies such as sedimentation basins and swirl/vortex units remove particulate pollutants by employing design parameters and unit configurations that enhance the separation of solids by settling. Therefore, the settling velocity of the pollutants in the CSOs to be treated has an important influence on performance and should be considered in developing design details.

Bench-scale tests can be employed to determine the typical range of CSO settling velocities. A number of variations of the procedure and equipment are used for these tests. Figure 3-8 is a schematic illustration of several settling test column designs. Test procedures vary with the design of the test apparatus and are described briefly below for the units illustrated. Results obtained from either procedure can be analyzed to determine the probability distribution of particle settling velocities in the CSO sample tested, and displayed as illustrated on the plot shown in the lower portion of Figure 3-8.

For the 8-in-diameter by 5-ft-tall test column with multiple sample ports, the column is filled to the top with a sample of the water to be tested, and then stirred to distribute the settleable solids uniformly throughout the column. A sample at time zero is analyzed to establish initial conditions. Samples are then withdrawn from each port at selected time intervals. They are analyzed to determine the concentration of TSS that remains at the sample location after the elapsed time interval.

For the other test unit, clean water is used to fill the column up to the level of the butterfly valve at the upper end. A 500-ml sample is then added at the top of the cylinder. After the sample has been properly stirred, the butterfly valve is opened and particles in the sample settle through the body of clean water. Water samples containing settled suspended solids are collected from the bottom cone at various elapsed times ranging from 1 to 60 minutes, and analyzed for TSS. For a 60-cm settling distance, the test results will provide the



TYPICAL SETTLING COLUMNS

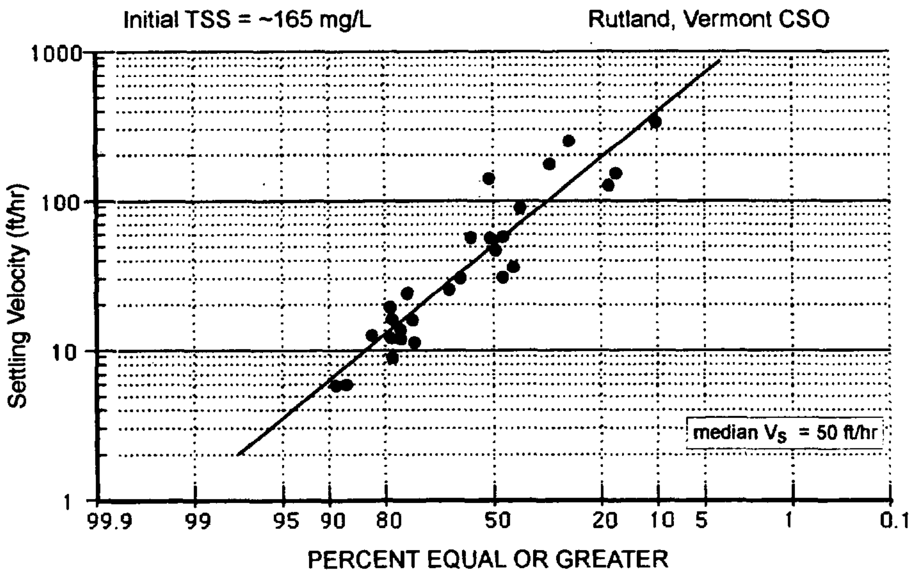


Figure 3-8. CSO settling velocity—typical test equipment and sample results.

distribution of particle settling velocities in the range of 1 to 60 cm/min (2 to 120 ft/hr).

TSS normally is selected as the pollutant analyzed, but other pollutants of concern also could be selected to provide information on the settleability of BOD, for example.

A number of different approaches have been used to analyze, summarize, and interpret settling column test results. A procedure that provides useful results recognizes that particulates are present in combined sewer overflows in a range of particle sizes and settling velocities, and that it is appropriate to characterize settling properties in terms of a settling velocity distribution. Such distributions define the cumulative percentages of solids having settling velocities greater than a specified value. Test data can be analyzed to develop this information by following these steps:

1. For each measured concentration (each sample port and sample time), the difference between the concentration and the amount present initially is used to compute a percent removal.
2. Since each combination of depth to a sample point, and elapsed time between the start of the test and the time the sample is taken, reflects a specific distance settled in a specific interval of time, each sample corresponds to a settling velocity (ft/hr). Each such value corresponds to a percent removed value computed from the measured concentration. The results can be interpreted as the percentage of TSS in the sample that has settling velocities equal to or greater than the value represented by the settling distance and sample time.
3. The results then are plotted on graph paper with a probability scale to indicate the frequency distribution of pollutant settling velocities in the sample. CSO settling velocity characteristics developed in this manner are shown in Figure 3-8.

Test results can be displayed on probability plots to illustrate the range in settling velocities of the suspended solids (or other pollutants) in the CSOs. Results from different samples at a particular site or from different CSOs also can be summarized and compared by listing the median (50 percent) and/or the 90th percentile settling velocity.

For example, settling tests conducted on CSO samples at Washington, DC, indicated that for 11 samples during eight events, the median settling velocity ranged between about 1 and 30 ft/hr. For these same samples, 10 percent of the particles had settling velocities in the range 10 to 300 ft/hr (Washington, DC, 1992).

Median CSO settling velocities at other locations were measured in the range of 5 to 50 ft/hr in one city and estimated from particle settling velocity data to be in the range 50 to 100 ft/hr in another (Dufresne-Henry, Inc., 1992). Both of these results can be considered to fall in the same general range as the Washington data, given the inherent variability. Several tests on New York City CSOs, in contrast, provided median settling velocities in the range of 1 to 3 ft/hr (NYC DEP, 1993). However, the CSO quality at this location is suspected to be significantly influenced by ground-water infiltration.

The variability in available data from different locations emphasizes the importance of local testing to determine design parameters for CSO controls that are based on sedimentation. The significant variability exhibited by different samples at the same site indicates the importance of (a) testing a sufficient number of samples (at least 6 to 12 in most cases) to define a representative range of conditions for the site, and (b) testing samples from representative parts of a storm.

The latter is particularly important if the overflow has a significant first flush effect, because particle sizes and settling velocity are significantly different in different parts of the overflow event. Part of the wide variation in median settling velocities in the Washington, DC, data set is attributed to this factor.

Care is required in collecting samples used in settling column tests to ensure that results provide representative settling characteristics of the flows to be treated. Samples should be collected from an appropriate point in the collection/overflow system. In addition, sampling equipment and procedures should be checked to assure that the sample itself properly collects the solids that are present. Sample intake locations and intake velocities must be established to capture the heavier solids present in most CSO flows.

Settling velocity test results can guide design decisions by determining the removal efficiency that a CSO control unit will provide for particles with selected settling velocities, when the unit processes CSO flows at the design flow rate (or other applied rates of interest).

For sedimentation basins, a relationship between steady state removal efficiency and the hydraulic loading rate and particle settling velocity is provided by the following equation (Fair and Geyer, 1954).

$$R = 1 - [1 + \frac{1}{n} - \frac{V_s}{Q/A}]^{-n}$$

where:

R = fraction of initial solids removed (R x 100 = percent removal)

n = a parameter that provides a measure of the degree of turbulence or short-circuiting, which tends to reduce removal efficiency

V_s = settling velocity of particles

Q/A = rate of applied flow divided by surface area of basin (an "overflow velocity," often designated the overflow rate)

The upper plot in Figure 3-9 illustrates the relationship between the design size of a sedimentation basin (expressed as an overflow rate, gpm/ft^2 or ft/hr) and removal efficiencies for a range of particle settling velocities, as provided by the above equation (U.S. EPA, 1986).

For swirl/vortex units, the design capacity and performance do not relate directly to an overflow rate based on surface area, as is the case for sedimentation basins. An indication of the relationships of interest as they apply to a swirl unit based on the EPA design is provided by the lower plot in Figure 3-9. This plot is adapted from information developed from a series of experiments in Sweden on a 1.17-m diameter swirl concentrator, supplemented with data from two full actual operating concentrators (Lygren and Damhaug, 1986).

Figure 3-9 summarizes the interrelationship between removal efficiency, applied flow rate, and particle settling velocity. Comparing these relationships with local test data that defines the distribution of settling velocities in the CSO flows to be treated, will permit estimates of expected performance relative to a particular size fraction at any design flow selected for evaluation. In addition, overall performance estimates for a selected unit design size (over the range of projected CSO flows) may be developed by incorporating the relationships in a simulation model (e.g., the Storage-Treatment Block of SWMM). In this case, the continuous distribution of settling velocities can be incorporated by dividing the distribution into three to five size fractions and assigning an average settling velocity to each. The performance analysis would be applied independently to each of the fractions. Design decisions could then be based either on projected results for a selected size fraction, or on the combined results for all fractions.

Technology Selection

Factors That Influence Technology Selection

Selecting a specific control technology, or as is often the case, the combinations of technologies to be incorporated in a comprehensive CSO control program, requires an engineering evaluation that considers a variety of elements. The following elements usually have a major influence on technology selection:

- The layout and hydraulic characteristics of the combined sewer system and overflow points.
- The number and size of overflow locations, the distance they are separated, and the feasibility of consolidating multiple overflows at a point at which a control technology can be applied.
- The magnitude (volumes, peak flow rates) that will occur at individual overflow control locations, which influences the size requirements for specific technologies.
- Available space and other siting constraints in the vicinity of CSO locations.
- The performance goal that is applicable for the system as a whole and/or for specific overflow locations.
- The ability of a particular technology to provide effective control of specific pollutants that are contributing to designated use impairment.

Such a comprehensive evaluation, addressing the system as a whole and identifying control needs at specific CSO locations, and site features that influence the applicability of individual technologies, is essential to develop an effective CSO control program. Surveys are necessary to establish characteristics of the study area that are pertinent to technology selection. In addition, the hydraulic characteristics of the combined sewer/CSO system must be characterized by a monitoring/modeling effort. Performance/applicability factors that relate to individual control technologies also must be evaluated.

The principal performance factors that relate to the applicability of the individual CSO control technologies addressed in Chapter 4 are discussed below.

In-System Controls/In-Line Storage

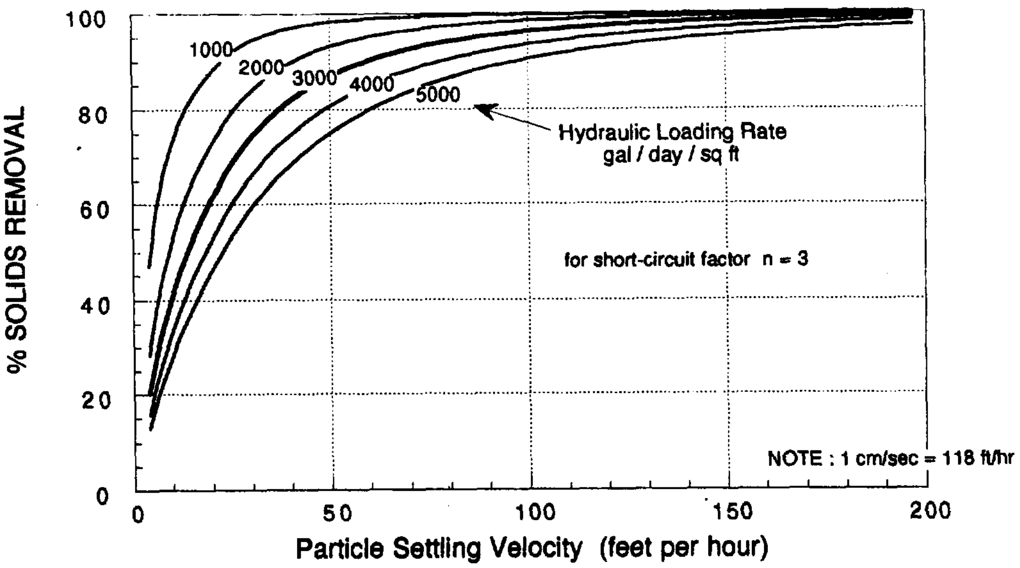
All CSO control programs should incorporate in-system controls appropriate for the features of the local combined sewer system. Both the measures that are applicable and the degree of control they will provide are variable and site-specific. However, the increase in in-line storage and reduction in overflows produced by in-system controls generally will be cost effective, since they represent modifications of existing facilities. Many of the applicable measures will require relatively minor engineering and cost commitments.

To the extent that the existing collection system can be adapted to increase the retention of wet weather flows, it will reduce the required design capacity and cost of other control technologies that must be applied. This technology, therefore, is essential and should be a component of all control plans.

Increases in the utilization of the available hydraulic capacity of the existing combined sewer system for containing wet weather flows will increase the risk of street and basement flooding. This situation must be carefully considered in establishing the maximum in-line storage that can be safely achieved, and in many cases will require a model analysis to define acceptable conditions. Even with model projections as a guide,

SEDIMENTATION BASIN

adapted from Fig 7 [EPA 1986]



SWIRL CONCENTRATOR

adapted from Fig 2 [Lygren 1986]

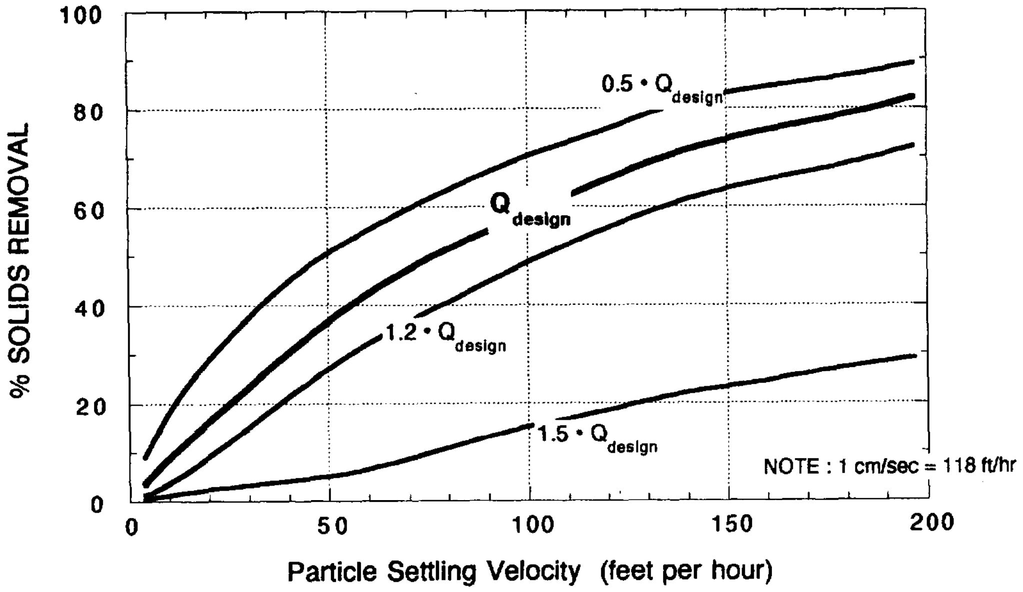


Figure 3-9. Effect of particle settling velocity and hydraulic loading rate on TSS removal efficiency.

weirs should be raised in incremental stages with suitable follow-up monitoring. Increased collection system storage also will increase the potential for accumulating sediment deposits. Operation and maintenance efforts can increase for the effective application of in-system controls, because effective performance relies on continuing reliable operation of regulators, tide gates, and pump stations, and on preventing sediment deposits from accumulating to problem levels.

Storage—General

Storage technology is probably the most favorable control technology to consider as a general rule. For the volumes captured at a CSO location, storage removes all pollutants (pathogens, floatable and dissolved pollutants, solids) from discharge at that location. When captured flows are delivered to the POTW, treatment is provided at that point and discharge occurs at the plant outfall. For discharges at the overflow point produced by storms in excess of the storage capacity, sedimentation in the storage unit provides a degree of treatment, and where disinfection may be required, all or part of the storage volume may be utilized to provide contact time.

However, despite the theoretical attractiveness of storage technology, a number of factors limit its applicability. For relatively high levels of control, storage volumes are large, with corresponding costs. Cost effectiveness may be very poor if storage technology is applied separately to multiple CSO locations, or to CSOs with relatively small discharges. Consolidation of a number of existing CSOs for treatment by a single storage unit may involve substantial modifications to the collection system and significant disruption of the service area during installation. Storage units are often difficult to site because of the need for adequate space and other constraints imposed by land use in the area.

When all CSO flows captured by storage are returned to the interceptor for conveyance to and treatment by an existing POTW, the treatment plant loadings increase, as do the solids residual and sludge handling requirements. The ability of the POTW to respond to changes in operation required to accommodate the implementation of CSO storage technology must be adequately addressed by the control program studies.

These factors apply to both surface and tunnel storage technologies. Selection factors specific to each of these technologies are discussed below.

Off-Line Near-Surface Storage/Sedimentation

This technology balances control provided by storage to capture CSOs and return them to the POTW for treatment and direct discharge. It may limit the furnished storage to a capacity that is feasible based on local site constraints and cost considerations. However, for CSO volumes that are not captured, it provides effective sedimentation treatment by utilizing efficient settling basin design features. This control technology provides effective reductions in suspended solids and associated pollutants, is very effective for control of floatables, and provides contact time for disinfection when control of bacterial levels is required. CSO flows captured by storage will result in an increase in flows and solids that must be processed by the POTW.

While less costly than tunnel storage up to certain storage requirements, surface storage often is difficult to site. Combination surface storage/sedimentation designs may permit more efficient utilization of available space and optimize the level of control that can be applied at a particular location. The overall performance level that can be achieved depends on the proportion of the CSOs that are captured and returned to the POTW versus treated by sedimentation and discharged at the overflow location.

The sedimentation unit should produce reductions in pollutants such as suspended solids and BOD equivalent to primary treatment. This control should completely remove floatables and effectively disinfect for bacteria.

Deep Tunnel Storage

Deep tunnels are the most costly storage capacity, but they are less constrained by considerations of surface space availability and construction impacts to the community. Large storage volumes are more readily effected than in the case of surface storage, and tunnel designs also can provide conveyance of captured volumes to the eventual treatment/discharge location.

Geotechnical conditions influence the feasibility of applying this technology at any site, and consolidation and other collection system modifications may require significant effort to deliver CSOs to the tunnel. This will be site specific and depend on the tunnel alignment and its location with respect to the existing overflows. As with any storage technology, the ability of the POTW to process the captured flows must be considered in the technology selection process. This may have particular importance in the case of tunnel storage, because of the ability to capture very large percentages of the wet weather flows.

In low-lying areas with little topographical relief, using tunnels to control CSO may serve the additional purpose of reducing flooding problems.

Coarse Screening

The control provided by this technology is limited to removal of large objects, and its principal use is to protect downstream control units. It is addressed in Chapter 4 because it is commonly included with a variety of control technologies as part of the overall control system.

Other than the removal of debris and floatable materials, coarse screens accomplish little in the way of removal of other pollutants. As such, they would not normally be considered as a stand-alone CSO control. There may be exceptions, as in a case of relatively small CSOs discharging to segments of water bodies where aesthetic appearance and floatables are the only significant water quality impact.

Proper maintenance and frequent cleaning of these screens is important both to ensure effective operation and to avoid restrictions to flow, which might induce upstream flooding.

Swirl/Vortex Technologies

These controls are attractive primarily because of their relatively low cost and space requirements in relation to the degree of treatment they can provide. They are applied at individual overflow points to provide some level of treatment before direct discharge.

They provide effective removal of grit and heavy solids, and are quite effective for control of floatables. For settleable solids and BOD, the removal capabilities appear to range from nominal to moderately low, and performance is influenced to a major degree by the site-specific particulate settling characteristics of the CSOs to be treated. Pollutant removal is provided by a combination of solids separation from the flows that discharge and of the underflow that is returned to the combined sewer system. The latter often accounts for a significant fraction of the overall pollutant removals. As a result, appropriate bench testing to define settling velocities usually is necessary to determine the basic applicability of this technology at the site and the appropriate design parameters.

The very short residence time resulting from the typical high rate design limits the ability to provide disinfection contact time, and for locations where bacterial control is required, additional storage/contact chambers are usually incorporated in the system design.

Disinfection

In all cases where CSO control must include reductions in bacterial levels to protect a designated use, disinfection technology must be applied. It essentially will never be considered independent of any other control technology, because bacterial contamination is not the exclusive water quality issue for CSO control and because pretreatment to reduce solids that otherwise shield the bacteria normally is necessary for effective disinfection.

Adequate contact time must be provided, usually in tanks associated with the control technology applied at the overflow location. However, in cases where the outfall lines are sufficiently long to provide necessary contact, they may be used. For control technologies involving storage or sedimentation treatment, the storage volumes usually are sufficient to provide the required disinfection contact time. For CSO control technologies such as screens or swirl/vortex units, which have very short residence times, separate provisions must be made to provide contact for disinfection.

Optimizing Storage-Treatment CSO Controls

For CSO control systems that utilize a combination of storage and treatment methods, a cost-optimization analysis should be performed to determine the most cost-effective combination of design sizes. For a given performance level, the design capacity, and hence cost of a treatment unit such as a sedimentation device, can be reduced by using a storage unit that absorbs the higher flows during parts of the storm, and delivers flow to the treatment unit at both a lower, averaged rate and at a more uniform influent rate.

The upper plot in Figure 3-10 illustrates the concept by indicating the array of combinations of storage capacity and design capacity for a treatment unit. Large amounts of equalization storage permit the installation of small treatment units. Conversely, when little or no storage is provided to capture the short duration peaks of the variable CSO flows, a very large treatment capacity must be provided to avoid either degraded performance due to excessive applied rates, or the need to bypass the treatment unit. When this relationship is developed for a particular set of site conditions (using a SWMM model analysis or other suitable procedure), and the relationship between increasing size and increasing cost is applied for both storage and treatment units, a summary relationship such as that illustrated by the lower plot in Figure 3-9 can be developed. This indicates the relationship between the reduction in the costs for a treatment unit as smaller design capacities become applicable and the corresponding use of larger and more costly storage capacities. Total cost of the combination system, which is the sum of the individual unit costs, passes through a minimum, which represents the most cost-effective design combination.

The concept applies directly to the design of a control system to be installed at a particular CSO overflow point, and relates most closely to the off-line near-surface storage/sedimentation technology discussed in Chapter 4. It can be applied to the design of disinfection facilities by associating chemical dosage and/or type with the "treatment" element, and the

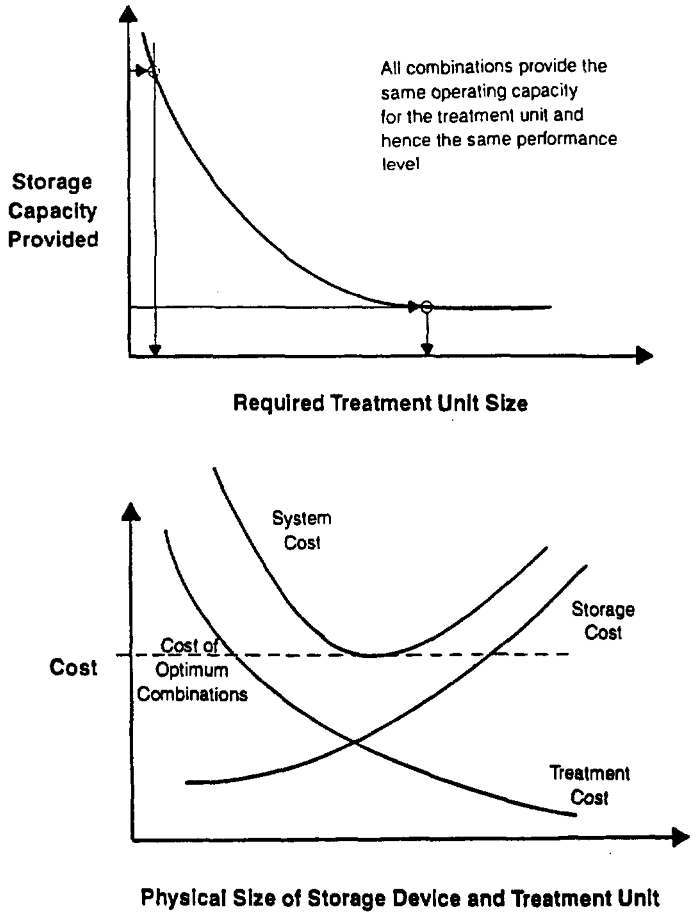


Figure 3-10. Cost optimization of storage-treatment.

contact time required with the "storage" element of the optimization analysis.

The optimization concept generally is not applicable in the case of swirl/vortex technologies, because providing storage upstream of the inlet to these devices usually is considered inappropriate.

Theoretically, the analysis also could be extended to the case where the control approach is based on storage at overflow points, but where treatment at the POTW follows pump-back or bleed-back of captured overflows. Direct application of a cost optimization analysis in this case is complicated by several factors. For example, in most cases the capacity of the treatment units is already established by the existing facility design and both the existing dry weather flows in the system and the possibility that captured overflows from a number of overflow points may be involved. In addition, federal or state regulations may impose requirements for performance of a storage unit (such as number of overflows permitted or minimum percent capture) that may conflict with the strict cost optimization of an overall system that relies on maximizing the available treatment capacity of the POTW.

However, in cases where the collection system has the hydraulic capacity to deliver wet weather flows at rates greater than a POTW can process, and the design of additional parallel primary treatment facilities for these flows is being considered, using an optimization analysis would increase the cost effectiveness of the design.

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When an NTIS number is cited in a reference, that document is available from:

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Chapter 4
CSO Control Technologies

In-System Controls/In-Line Storage

Introduction

One of the more readily implementable and cost-effective approaches to achieving immediate reductions in CSO volumes is to utilize the available storage and conveyance capacity of existing collection systems and the available treatment capacity at the POTW. Optimizing the use of in-line storage and maximizing flows to the POTW reduces overflow volumes by allowing a larger fraction of the total flow from a storm event to be conveyed to the POTW for treatment. This control approach is only feasible if sufficient capacity is available in the collection system and at the treatment plant.

A number of "in-system" technologies or strategies can contribute to maximizing in-line storage, maximizing flows to the POTW, and reducing overflow volumes, including:

- Collection system inspection and maintenance.
- Tidegate maintenance and repair.
- Reduction of surface inflow.
- Adjustment of regulator settings.
- Enlargement of undersized pipes to eliminate flow restrictions.
- Removal of obstructions to flow, such as sediments.
- Polymer injection to reduce pipe friction.
- In-system flow diversions through existing system interconnections.
- Adjustment and/or upgrade of pumping station operations.
- Partial separation of storm drain connections from combined sewers.
- Infiltration removal.

Prior to implementing these practices, communities should undertake a program of detailed data collection, flow monitoring, and modeling to fully characterize the features and behavior of their combined sewer systems. The results of these system characterizations can be used to evaluate the performance of each regulator, and to identify the potential for utilizing storage in conduits upstream of the regulator, eliminating flow bottlenecks, and improving pump station operations. The goal of all these measures is to optimize the storage and conveyance capacity of the combined system.

Many types of in-system controls can be implemented with relatively minimal engineering and cost, although detailed hydraulic analyses are required. Evaluating and optimizing system components may serve to reduce the overall scope of a community's CSO problem, thereby reducing the size and/or number of more capital-intensive CSO control facilities required to meet overall CSO control goals. In-system controls generally will be most effective where upstream drainage systems consist of large-diameter pipe laid on shallow gradients.

Disadvantages to increasing in-line storage through implementation of in-system controls may include an increased risk of basement or street flooding, increased opportunity for sediment deposition, and higher costs associated with increases in maintenance efforts to ensure that regulators, tidegates, and other features are functioning properly and are in good repair.

When evaluating potential in-system controls, criteria can be set for allowable changes in predicted flow velocities and peak hydraulic grade line elevation. Using output from a detailed system model such as SWMM, time-varying flow velocities in conduits subject to backwater could be reviewed both for existing conditions and for conditions once the proposed in-system controls are implemented. The criteria could be to ensure that minimum carrying velocities are restored once the storm ends and the backwater subsides. Similarly, changes to the peak hydraulic grade line in conduits upstream of the proposed controls could be limited to a set maximum above existing conditions, or to a minimum depth below grade. Setting criteria for predicted increases to the hydraulic grade line requires judgment, and the criteria could vary within a given drainage system, based on knowledge of conduit depth, previous reports of flooding, tidal impacts, and other factors.

This manual focuses primarily on regulator modifications and control, and the use of real-time control systems, as a means to optimize in-line storage and conveyance of flows to the POTW. Sewer separation and infiltration removal are two more capital-intensive collection system control strategies. These strategies are discussed only briefly in Chapter 2, but have been well described by others (U.S. EPA, 1974a, 1975a; Metcalf & Eddy, Inc., 1981). Similarly, actions to increase in-system storage which are related to maintenance, such as tidegate inspections and sewer flushing, and actions associated with best management practices, are not addressed in this manual. Key references provided at the end of this chapter address these items (WPCF, 1989; Metcalf & Eddy, Inc., 1991a; Field, 1990).

Regulators

Regulators control the amount of flow that enters an interceptor from an upstream combined system, and provide an overflow relief point (the CSO) for flows in excess of the interceptor capacity. Regulators fall into two broad categories: static and mechanical. Static regulators feature no moving parts and, once set, are usually not readily adjustable. Examples of static regulators include side weirs, transverse weirs, restricted outlets, swirl concentrators (flow regulators/solids concentrators), and vortex valves. Mechanical regulators are more readily adjustable and may respond to variations in local flow conditions, or be controlled through a remote telemetry system. Examples of mechanical regulators include inflatable dams, tilting plate regulators, reverse-tainter gates, float-controlled gates, and motor-operated or hydraulic gates.

Many of the older float-operated mechanical regulators are erratic in operation and require constant maintenance. In Saginaw, Michigan, many existing float-operated regulators were replaced by vortex valves, due to the unreliability and excessive maintenance associated with the mechanical regulators (U.S. EPA, 1985b). In Boston, Massachusetts, many float-operated regulators have been replaced over the years with static regulators.

Following are descriptions of types of regulators and gates which have been installed in more recent CSO control projects, or have been used to replace older, less reliable types. The reader is referred to other sources (WPCF, 1989; Metcalf & Eddy, Inc., 1991a; and Urbonas and Stahre, 1993) for more detailed descriptions of other regulator types.

Vortex Valves

Vortex valves are static regulators that allow dry weather flow to pass without restriction, but control higher flows by a vortex throttling action (Figure 4-1). Vortex valves have been used to divert flows to CSO treatment facilities, control flow out of storage facilities, and replace failed mechanical regulators. The advantages of vortex valves over standard orifices include (Urbonas and Stahre, 1993):

- The discharge opening on the vortex valve is larger than the opening on a standard orifice sized for the same discharge rate, thereby reducing the risk of blockage.
- The discharge from the vortex valve is less sensitive to variations in upstream head than a standard orifice.

Vortex valves are sized based on design flow and head. Typically, a vortex valve manufacturer will provide a table listing the ranges of flow and head appropriate for the various models and sizes of vortex valves available. The design flow corresponds to the dry weather flow capacity of the downstream conveyance capacity. The

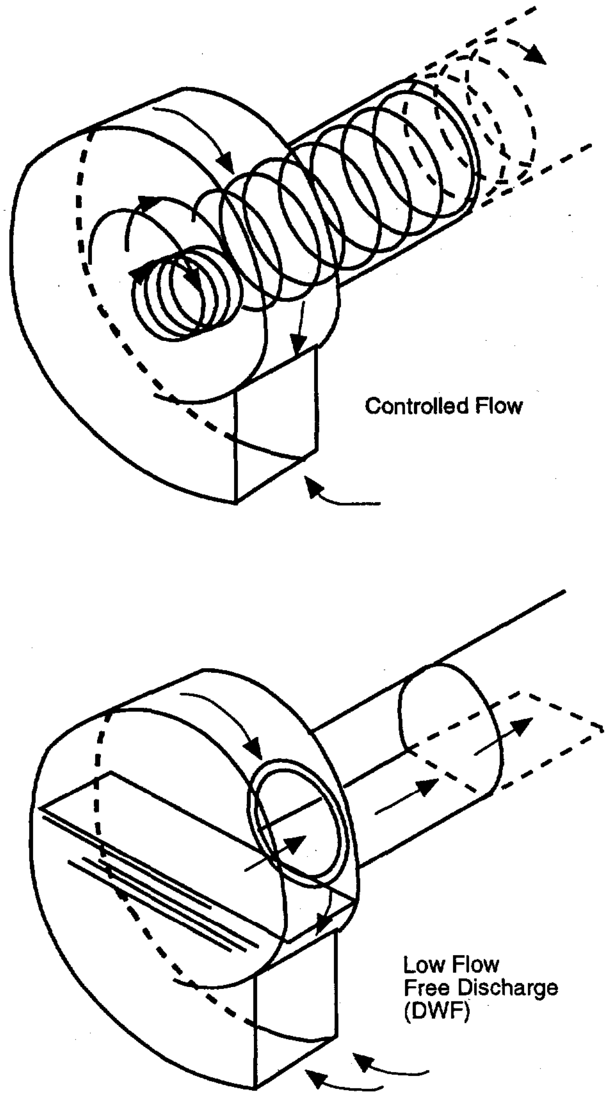


Figure 4-1. Example of a vortex valve (Metcalf & Eddy, Inc., 1991a).

peak head is usually dictated by the maximum upstream hydraulic grade line allowable without undue risk of flooding. A high outlet relief should be provided to ensure that upstream flooding does not occur.

Vortex valves used as CSO regulators are commonly mounted in reinforced concrete structures. Such structures should be channelized with benching to eliminate "dead" flow areas. The valves are typically constructed of stainless steel and have been reported to require little maintenance (H.I.L. Technology, Inc., 1988, 1991).

The European wirbeldrossel and wirbelvalve (Figure 4-2) are similar to the vortex valve, with a tangential inlet and vertical bottom outlet. The flow chamber for the wirbeldrossel is horizontal and cylindrical, while the flow chamber for the wirbelvalve is slanted with a conical bottom. These devices feature an air supply pipe to prevent cavitation which might otherwise develop in the rotational flow. As with the vortex valve, the wirbeldrossel and wirbelvalve provide greater restriction of flow and less sensitivity to upstream head than similarly sized standard orifices. In Europe, these devices have been used primarily to control the release of flow from storage facilities (Urbonas and Stahre, 1993).

Inflatable Dams

An inflatable dam is a reinforced rubberized fabric device which, when fully inflated, forms a broad-crested transverse weir. When deflated, the dam collapses to take the form of the conduit in which it is installed. A dam can be inflated with air, water, or a combination of both. Water provides the best control of the weir crest, but air control is usually associated with lower costs for equipment, particularly if rapid inflation-deflation cycles are required. Air inflation is also required where the dam may be exposed to freezing temperatures (APWA, 1970).

Inflatable dams are typically positioned to restrict flow in an outfall conduit or combined sewer trunk. The dams, which normally remain fully inflated, can act as regulators by directing flow into an interceptor, and preventing the diversion of flow to an outfall until the depth of flow exceeds the crest of the dam (Figure 4-3). Inflatable dams are controlled by local or remote flow or level sensing devices, which regulate the height of the dam to optimize in-line storage and prevent upstream flooding. The dam height is controlled by controlling the air or water pressure in the dam.

Since inflatable dams are typically constructed of rubber or strong fabric, they are subject to puncture by sharp objects. These devices generally require relatively little maintenance, although the associated air supply should receive periodic inspection to ensure reliable operation (WPCF, 1989).

Motor- or Hydraulically Operated Sluice Gates

Similar to inflatable dams, motor- or hydraulically operated gates typically operate in response to local or remote flow or level sensing devices. Normally closed gates can be located on overflow pipes to prevent overflows except under conditions when upstream flooding is imminent. Normally open gates can be positioned to throttle flows to the interceptor to prevent interceptor surcharging. Controls can be configured to fully open or close gates, or to modulate gate position. The level of control and general reliability of motor-operated gates make them well suited for use in conjunction with real-time control systems (Figure 4-4).

Elastomeric Tide Gates

While not actually regulators, tide gates are intended to prevent the receiving water from flowing back through the outfall and regulator and into the conveyance system. Inflow from leaking tide gates takes up hydraulic capacity in the downstream interceptors and increases the hydraulic load on downstream treatment facilities. Elastomeric tide gates provide an alternative to the more traditional flap-gate style tide gates, which are prevalent in many CSO communities. Tide gates have historically required constant inspection and maintenance to ensure that the flaps are seated correctly, and that no objects or debris prevent the gate from closing. Warpage, corrosion, and a tendency to become stuck in one position also characterize flap-gate style tide gates. Elastomeric tide gates are designed to avoid the maintenance problems associated with the flap gates (Figure 4-5). In particular, the elastomeric gates are designed to close tightly around objects that might otherwise prevent a flap gate from closing (Field, 1982).

Regulator Controls

Static Regulators

Static regulators have no moving parts and thus offer no opportunity for additional control once the weir elevations or orifice dimensions are set. Adjustable weirs may allow some degree of manipulation between storm events. Modifications to static regulators, however, generally can be achieved at relatively low cost. For example, if a collection system hydraulic model indicates that upstream storage could be optimized by raising an existing masonry weir in the overflow pipe at a regulator, the immediate benefits of such actions may justify the cost of the relatively minor construction work required to adjust the weir. Modification of restricted outlets requires more extensive demolition and excavation work, and would have to achieve a greater reduction in overflow volume to match the cost effectiveness of raising weirs.

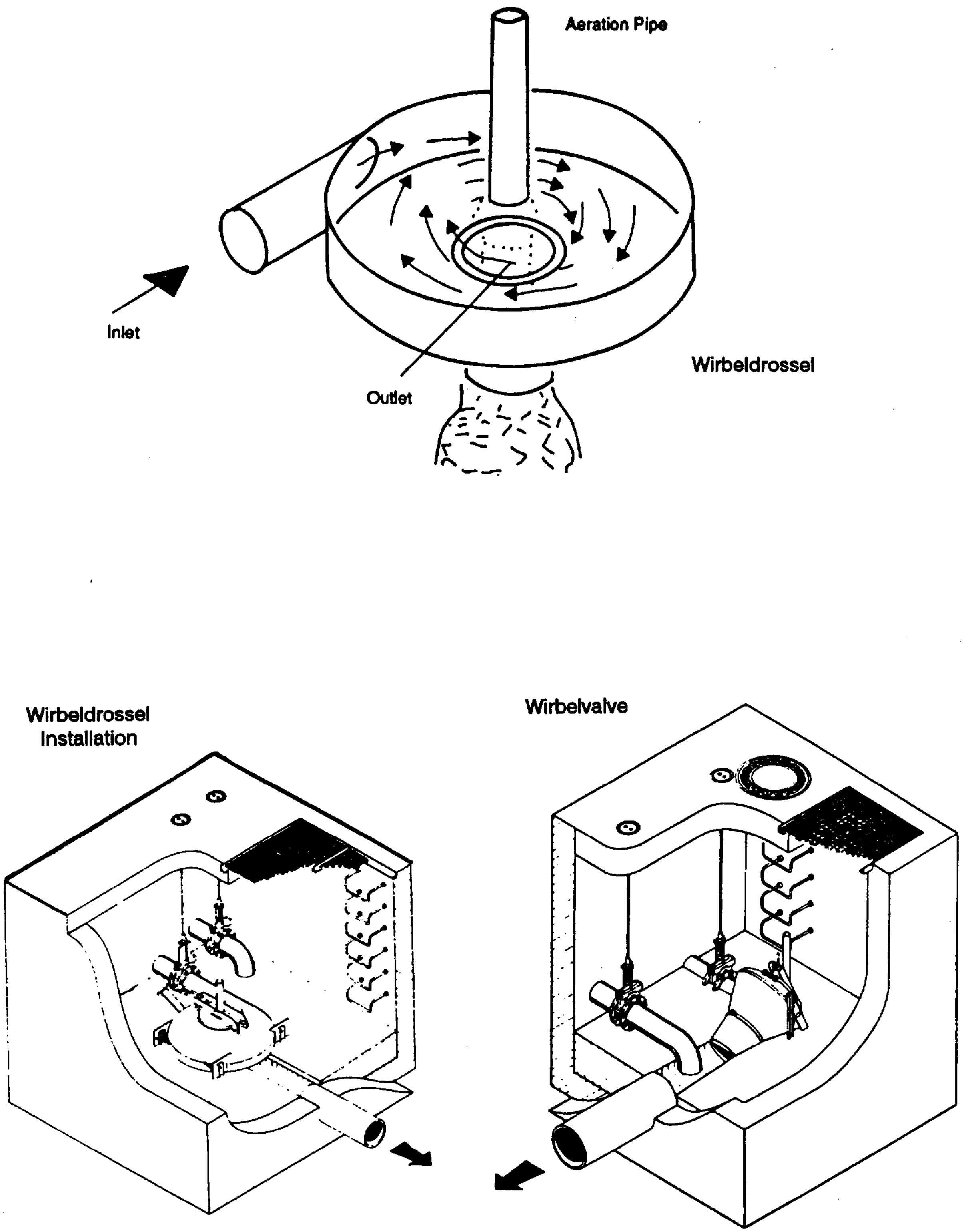


Figure 4-2. Example of a wirbeldrossel and wirbelvalve (Urbonas and Stahre, 1993).

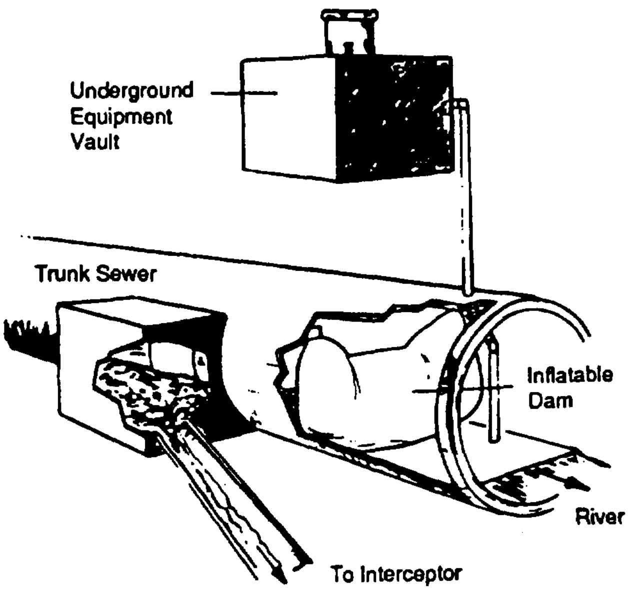


Figure 4-3. Example of an inflatable dam (WPCF, 1989).

Local Control

Local regulator control is most appropriate where a single regulator is associated with an outfall, or where the behavior of a regulator would not influence or be influenced by the behavior of another regulator in the system. Many of the older style mechanical regulators, such as reverse tainter gates, respond to local water level in the sewer through a float mechanism. These types of regulators are unreliable in many installations, require constant maintenance, and are slow to react to rapidly changing flow conditions (U.S. EPA, 1985b). More advanced local control systems feature electronic flow or water level monitoring devices, which control motor-operated gates or inflatable dams. These systems appear to be more reliable than the old float-controlled mechanical gates.

System-Wide Real-Time Control

Real-time control (RTC) systems can provide integrated control of regulators, outfall gates, and pump station

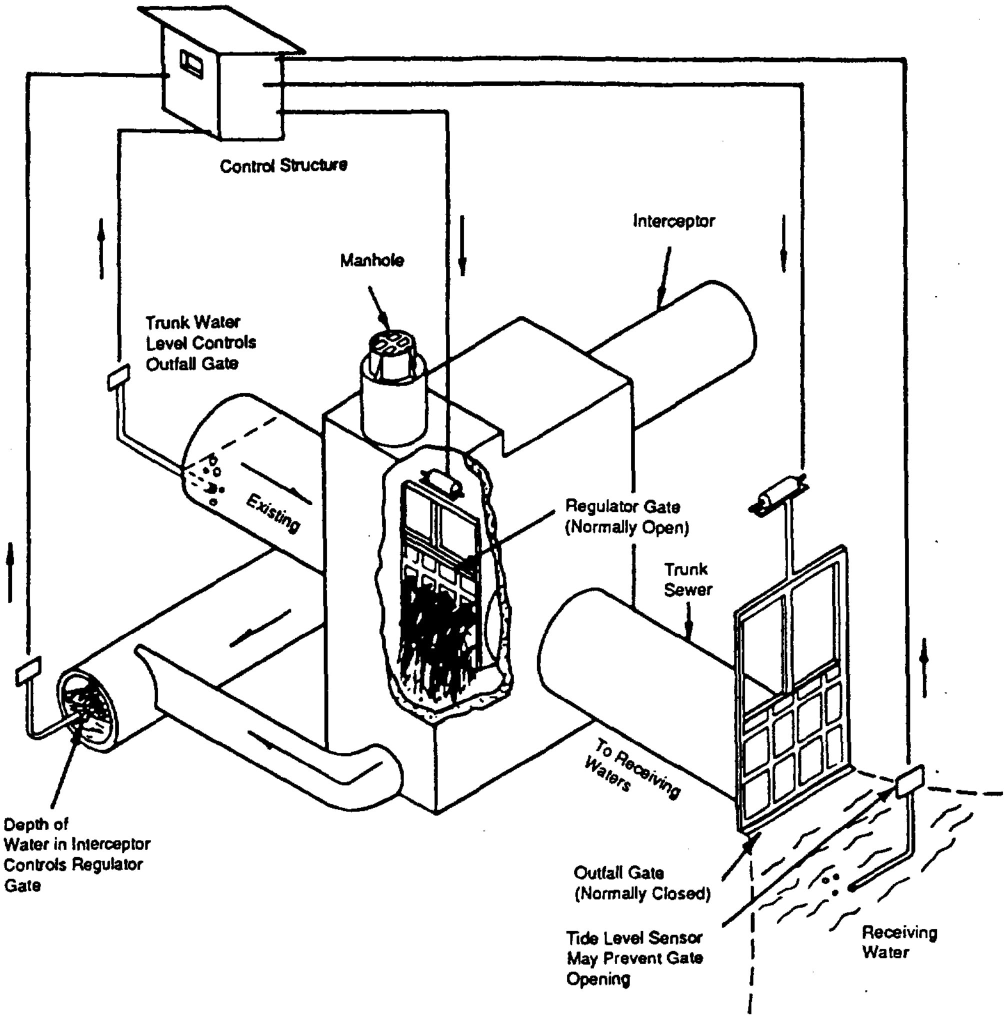


Figure 4-4. Example of a motor-operated gate regulator (WPCF, 1989).

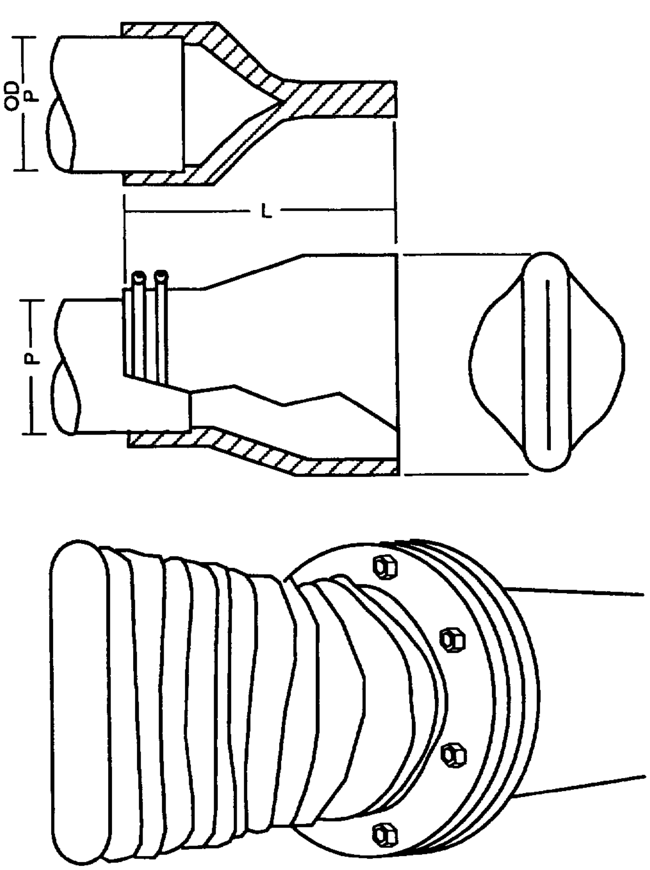


Figure 4-5. Example of an elastomeric tide gate (WPCF, 1989).

operations based on anticipated flows from individual rainfall events. Feedback control adjustments are based on actual flow conditions within the system. Computer models associated with the RTC system allow evaluation of expected system response to control commands before the commands are executed. As with any plan for improving in-line storage, to take the greatest advantage of RTC, a collection system must have relatively flat upstream slopes and sufficient upstream storage and downstream interceptor capacity.

An RTC system typically includes the following control features (James and Stirrup, 1986):

- Sensors to detect flow, water level, rainfall, and/or pollutant concentration.
- Circuitry and software to transform the signals from the sensors into numerical quantities.
- Circuitry and software to drive the control mechanisms (usually gates).
- Rainfall and/or runoff forecasting software running in real time.
- A computer acting as both data logger and controller.
- For an integrated RTC system, telemetry equipment for the communication of data among the various regulators.

A control strategy based on RTC must identify the control system constraints and evaluate alternatives for developing the optimum control strategy within those constraints. Examples of constraints which could define the limits of an RTC system include (Trotta et al., 1977):

- Capacities of interceptor and trunk sewers, storage facilities, and POTW.
- Rainfall runoff forecast models.
- Data acquisition system.
- Computer hardware and software.
- Control timestep.
- Human error and equipment malfunction.

Evaluation of the costs and impacts of addressing these constraints may dictate to what extent an RTC system will be appropriate for a given community. For example, if little excess capacity is available in the collection system, the benefits of RTC may not justify the costs. Similarly, a community must have sufficient staff resources to inspect and maintain the remote sensing equipment to minimize the risk of equipment malfunction.

The configuration of an RTC system depends on a community's overall CSO control goal. For example, control of average annual CSO volume may require a different control strategy than control of mean annual CSO frequency. For this reason, evaluation of the feasibility of an RTC system should be conducted as part of a long-term CSO control plan.

One of the older RTC systems in the United States has been operated by the Municipality of Metropolitan Seattle since 1973. Regulators in the Seattle system feature vertical in-line sluice gates to throttle flow into the interceptors and store flow in the upstream combined sewers. Overflow weirs upstream of the gates prevent upstream flooding during extreme events. The original computer-augmented treatment and disposal (CATAD) control system monitored flows and water surface levels in the combined system, and provided integrated, remote control of pump station and regulator gate operation.

A 1990 study evaluated the most cost-effective means for upgrading the Seattle RTC system and providing additional storage of CSO flows. The study found that improvements to the RTC system would be more cost effective for providing additional in-line storage than construction of off-line storage facilities. Improvements to the RTC system included development of a hydrologic model of the CSO system, instrumentation upgrades, database development, integration of the hydrologic model and database into a simulation program, and control strategy design.

The hydrologic model can estimate flows into the system for up to 6 hours into the future, based on predicted rainfall and current conditions within the system. Information on current conditions is continually input through a supervisory control and data acquisition (SCADA) system. Initial simulation runs assume a relatively simple, local control strategy. Following the initial simulation, an optimal control strategy is computed using an optimizing algorithm. A flow-routing model then checks the optimized strategy for feasibility. Infeasible strategies are rejected, while optimal strategies which are modeled to be feasible are sent to the SCADA system for execution (Vitasovic et al., 1990).

With the continuing improvements to computer and instrumentation technologies, and the cost-effectiveness of in-system control vs. new facilities, RTC systems are gaining in popularity for both CSO and stormwater control.

Off-Line Near-Surface Storage/Sedimentation

Off-line, near-surface storage/sedimentation facilities consist of tanks that store and/or treat combined sewer flows diverted from combined trunk sewers and interceptors. These facilities provide storage up to the volume of the tanks, as well as sedimentation treatment for flows that pass through the facilities in excess of the tank volume. Coarse screening, floatables control, and disinfection are commonly provided. The phrase "near-surface" means that these facilities are constructed at depths that allow the use of traditional open-cut excavation techniques, as opposed to the deep tunnel facilities described in the section of this document on deep tunnel storage.

Process Theory

The sizing of sedimentation structures at POTWs historically has been based on discrete particle settling theory. Type 1 discrete particle settling theory relates the terminal settling velocity of a particle to an overflow rate and ratio of depth to detention time, which can then be used as a basis for sizing a sedimentation basin. Detailed discussions of discrete particle settling theory are provided in other texts (Metcalf & Eddy, Inc.,1991a; WEF, 1992). For CSO storage/sedimentation facilities, the basic discrete particle settling model must be expanded to account for the non-steady-state conditions that occur as a CSO storage/sedimentation tank fills, overflows, and is dewatered.

A number of mathematical models have been developed to predict sedimentation behavior in settling tanks. One such model, developed for preliminary evaluation of storage/sedimentation facilities, identifies four distinct operating phases that may occur in a CSO storage/sedimentation tank (Lessard and Beck, 1991):

- Fill, when flow is entering the tank but the tank is not overflowing.
- Quiescent settling, when the tank is partly or completely filled, with no flow entering or leaving the tank.
- Dynamic settling, when the tank is full and overflowing.
- Draw, when the tank is being dewatered to the sanitary system.

This model can be used to estimate the change in selected pollutant concentrations and sludge mass over time, given an array of input parameters such as tank size, particle settling velocity, and percent settleable fraction. The model provides an approach for estimating both the performance of a storage/sedimentation tank, and the subsequent hydraulic and pollutant load on the POTW resulting from dewatering of the storage/sedimentation tank. The following aspects of CSO storage/sedimentation tank behavior, which were considered in developing the model, summarize storage/sedimentation tank dynamics (Lessard and Beck, 1991).

Fill

During the initial stages of tank filling, turbulence created by the influent flow prevents the contents of the tank from settling. As the tank fills, there may be some fraction of the total tank volume above which the influent turbulence no longer inhibits sedimentation. For larger tanks, the fraction of total volume required before sedimentation occurs is relatively small; for small tanks, turbulence may influence a greater percent of the total tank volume.

Quiescent Settling

The percentage of solids that settle during the quiescent settling phase depends upon the settling velocity profile and the duration of the settling period. The extent of quiescent settling that occurs during the lag period between the end of the storm flows to the facility and the start of the tank dewatering process may impact the solids loading rates on the POTW as the tanks are dewatered.

Dynamic Settling

Under dynamic settling conditions, the behavior of the tank is essentially the same as a typical primary settling tank at a POTW. Key parameters for estimating removals during this phase include an average particle settling velocity, overflow rate, detention time, and the fraction of a particular pollutant that could be considered settleable.

Draw

Two issues are considered when evaluating the draw phase and the effect of dewatering a CSO storage/sedimentation facility on the POTW:

- Pollutant concentration
- Timing of dewatering

The pollutant concentration in the dewatering flow depends on the sludge handling process at the CSO facility. Some tanks are aerated or provided with mechanical means for resuspending solids prior to pumpback. Other facilities may provide high-rate dewatering of the clarified volume, with separate pumping of the sludge. Some facilities are dewatered by gravity, with or without separate disposal of settled solids. In general, it is assumed that the sludge is resuspended to a given depth, which corresponds to a given fraction of the total tank volume. The load on the POTW can then be estimated from the two volumes, the concentrations within the two volumes, and the dewatering rate(s).

Ideally, the dewatering phase should be initiated as soon as capacity is available at the POTW and in the conveyance system between the CSO facility and the POTW. This ensures that the greatest tank capacity is available for the next storm. Theoretically, a dewatering system could be activated automatically on a telemetered signal from the POTW, once flow at the POTW drops below a specified value. In practice, however, many CSO facilities are designed with manually activated dewatering systems. One of the benefits of manual activation is that POTW operators can evaluate the impacts of sustained peak storm flows on POTW performance, before potentially prolonging the peak flows by dewatering the CSO facility. The solids loads from a storage/sedimentation facility may be particularly difficult to handle for a system which already has been stressed. In addition, some POTWs that serve combined systems may implement special operating procedures during wet weather to mitigate the impact of peak storm flows, particularly on biological treatment systems. Delaying the dewatering of a CSO facility may impact the level of control achieved with a storm that follows immediately. However, if immediate dewatering of a CSO facility results in the upset or washout of a secondary treatment system, the overall impact on receiving waters may be greater.

Process Design

Sizing criteria for a storage/sedimentation tank vary, depending upon the intended goal of the CSO control facility. As discussed in Chapter 3, typical CSO control goals may include:

- Providing a specified minimum treatment level, such as the equivalent of primary treatment for flows up to a specified design condition.
- Providing a level of treatment required to meet receiving water quality standards for storm flows up to a given recurrence interval.
- Providing full capture of the first flush (highest mass loadings during the storm event), then a reduced level of treatment for subsequent flows.
- Reducing the number of annual overflow events and/or total annual overflow volume to a specified level.

Selection of the control strategy may depend on local, state, or federal regulations; a community's long-term CSO control plan; or requirements of a permitting authority. All strategies require an estimate of the flows expected under the given design condition. Computer models, such as SWMM which is described in Chapter 3, can be used to simulate the behavior of a combined sewer system. System behavior can be simulated for a specific storm of previously defined characteristics, and on a continuous basis, reflecting the precipitation history of a selected time period (commonly one year). The continuous simulation models the impact of succeeding storms on system performance, which may impact facility sizing and dewatering rates. Sizing based on modeled flows is, therefore, an iterative process.

General concepts related to each of the above CSO control goals are discussed in Chapter 3. Additional process design considerations that apply to storage/sedimentation facilities are described below.

Sizing To Provide a Specified Minimum Treatment Level

The minimum treatment level most commonly identified for CSO control facilities is primary treatment, although facilities also have been sized to provide a specified minimum detention time for disinfection. Primary settling tanks at POTWs are sized based on overflow rates and detention times, which are in turn derived from particle settling velocities. Tables 4-1 and 4-2 present examples of design overflow rates and detention times for primary settling tanks (WEF, 1992). Since combined flows generally have a higher fraction of heavier solids than separate sanitary flows, the values presented in Tables 4-1 and 4-2 may be conservative for CSO applications. In addition, a study of the relationship between solids removal performance and overflow rates suggests that the performance expected from a given design overflow rate may be affected by other factors

Table 4-1. Typical Overflow Rates for Primary Settling Tanks (WEF, 1992)

		Overflow Rate	
Source	Condition	$m^3/m^2/d$	gpd/ft^2
Metcalf & Eddy, Inc., 1991a; U.S. EPA, 1975b	Primary treatment followed by secondary:		
	Average flow	32-48	800-1,200
	Peak flow	80-120	2,000-3,000
WEF, 1992	All units in service:		
	Maximum day flow	49	1,200
	Peak flow	81	2,000
WEF, 1992	One unit out of service:		
	Peak flow	163	4,000
Great Lakes-Upper Mississippi River Board, 1978	Larger area of:		
	Average flow	41	1,000
	Peak hour flow	61	1,500

Table 4-2. Typical Detention Times for Primary Settling Tanks (WEF, 1992)

Source	Condition	Detention Time
Metcalf & Eddy, Inc., 1991a	Primary treatment followed by secondary	1.5 to 2.5 hours, 2 hours typical
WEF, 1992		1 to 2 hours based on peak flows
Fair et al., 1968		Minimum 2 hours in 3m (10 ft) side water depth
U.S. Army, 1978	Primary treatment followed by activated sludge	1.5 hours
	All other conditions	2.5 hours

such as design details, loading variations, recycle flows, temperature, and proportions of inert-to-volatile and soluble-to-insoluble material in the flow (WEF, 1992). Sizing criteria should consider both overflow rates and detention times. Determining the actual settling velocity distribution of the solids in the CSO to be treated, as described in Chapter 3, will provide a more accurate assessment of the appropriate design overflow rate.

Since influent hydrographs for CSO control facilities tend to exhibit more sharply defined peaks, which are not typical of POTW influent hydrographs, and periods of no flow, the concept of the "average" flow to a CSO facility does not have as much physical significance as at POTWs. Thus, if overflow rates or detention times are used as a basis for design of a CSO control facility, considering peak flow conditions may be more appropriate than attempting to define an "average" flow. If the shape of the influent hydrograph is known, then the total volume of flow that has entered the facility at the timestep when the peak occurs can be determined and compared against the total tank volume. If the peak flow occurs before the tank is full, then the actual maximum overflow rate would occur on the falling leg of the influent hydrograph.

The actual maximum overflow rate, therefore, would be less than the calculated overflow rate associated with the actual peak influent flow. This condition would provide a degree of conservatism in the sizing of facilities based on peak overflow rates.

Sizing To Meet Water Quality Standards

Water quality impacts influence the level of treatment that permitting agencies require CSO control facilities to achieve. Wasteload allocation studies (which include water quality monitoring and modeling) can be used to determine the effluent characteristics and level of treatment needed to achieve a given water quality goal. Once the required level of treatment is established, the design can then evaluate tank sizes and configurations to meet the required level of control.

Sizing To Capture First Flush

A number of CSO facilities have been designed to capture the more concentrated combined flows that may occur during the initial stages of a storm event. The key to designing such a facility is to define the limits of the first flush, which will in turn define the volume of capture required. Chapter 3 defines and discusses the use of the first flush as a design criterion.

Sizing To Reduce the Number of Overflow Events

Use of this criterion requires continuous simulation to estimate the flow associated with storms of various recurrence intervals. As discussed in Chapter 3, the definition of an "overflow event" also must be clearly established. An overflow event may be defined as a treated overflow, an untreated overflow, or an event in which flow receives less than a defined level of treatment. The established definition may determine whether a storage-only or flow-through storage/sedimentation facility is appropriate for the application. A related consideration is whether flows in excess of the design storm are to bypass the facility or flow through the facility and potentially receive a lower level of treatment than provided under design conditions.

Process Flow

The arrangement of unit processes at a storage/sedimentation facility varies depending on the goal of the CSO control strategy (i.e., primary treatment vs. first flush capture) and hydraulic considerations. A typical arrangement includes a regulator, bar screens, settling tank(s), and an outfall. Disinfection may be required and can be provided upstream and/or downstream of the settling tanks. Figure 4-6 presents a schematic for a typical layout of a storage/sedimentation facility.

Regulators

Typical regulator/influent arrangements include:

- *Overflow from remote regulator conveyed to CSO facility by influent conduit.* Depending on the type of regulator used, the bedload could tend to remain in the interceptor. The regulator should be designed to maximize the in-system storage capacity of the upstream pipe network.
- *Overflow from sanitary wetwell.* A common arrangement is to combine a CSO facility with a standard sanitary sewage pumping station. As flow exceeds the capacity of the sewage pumps, flow in the pump station influent channel overtops a weir, and passes to the CSO facility influent channel. This arrangement typically occurs downstream of coarse screening apparatus.

The regulator or influent piping arrangement should provide some means for a relief overflow to protect the facility from flooding. In Newport, Rhode Island (Figure 4-6), a high flow relief weir is located in a manhole adjacent to the side weir regulator controlling flow into the facility influent conduit. The facility includes provisions for disinfecting the high level overflow. In addition, a positive means for isolating the facility should be provided. The Newport facility and the MWRA Prison Point facility both feature a modulating influent gate to throttle flow into the facility when the water surface in the facility reaches a high level.

Bar Screens

Most storage/sedimentation facilities provide some means for coarse screening of the influent, such as catenary-type mechanically cleaned screens. Isolation gates for the barscreens should be provided, along with a bypass or a redundant channel. Coarse screening is described in more detail later in this chapter.

Influent vs. Effluent Pumping

Hydraulic conditions often require influent or effluent pumping to or from a CSO facility. Operationally, effluent pumping is preferable, since the pumps run only during a storm large enough to overflow the tanks. The disadvantage of effluent pumping is that the elevation of the entire facility must be set by the hydraulic grade line of the influent conduit. If the influent conduits are well below grade, then relying on gravity flow into the facility could require significant excavation and construction. Influent pumping allows the elevation of the facility to be set independently from the influent conduit elevations. Ideally, the facility elevation is set such that the facility effluent, and possibly the facility dewatering piping, flow by gravity. If influent pumping is selected, wetwell and pump sizing must consider the range of flows expected.

Disinfection

If required, disinfection is typically provided by liquid sodium hypochlorite, dosed by metering pumps, and paced by influent flow. Some facilities include additional discharge control based on chlorine residual. Dosing typically is applied at the tank influent channel to maximize contact time. Some facilities (Newport, Washington Street; MWRA Prison Point) include a second dosing location after sedimentation to augment the original dose. One drawback to dosing upstream of the settling tanks is that the flow at that location contains a higher concentration of solids than downstream of the tanks. Thus, while contact time is gained by dosing upstream of the tanks, actual "contact" between the bacteria and the disinfectant may not be as effective. Auxiliary uses of disinfection may include periodic disinfection of sludge piping and the spray wash system. Dechlorination also may be required due to concerns over the potential toxic impacts of chlorine residuals on the receiving waters. Disinfection and dechlorination are discussed in more detail later in this chapter.

Solids Handling–Screenings

A number of methods have been used to handle screenings from mechanically cleaned bar screens. Some methods require separate disposal of the screenings, while others return the screenings to the interceptor. Screenings handling options are discussed in more detail later in this chapter.

Solids Handling–Sludge and Grit

Due to the intermittent operation of CSO facilities, mechanical sludge collection equipment typically is not provided. Rather, tank floors are sloped to a center or side trough and flushing systems help direct solids to the trough. The trough is sloped back to a dewatering system drawoff for either pumping or gravity flow back to the interceptor. Exceptions to this arrangement are the circular open tanks in the Springfield, Illinois,

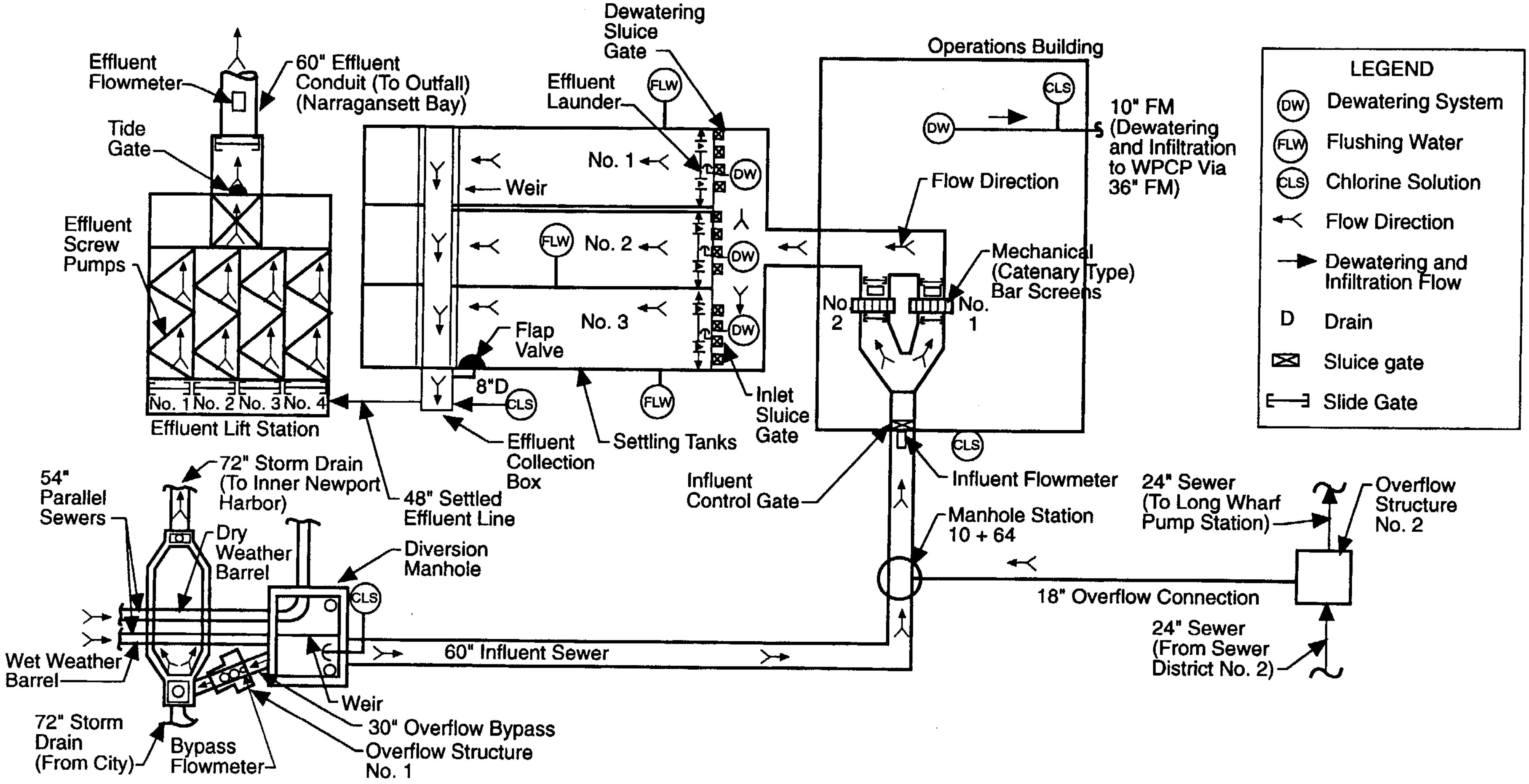


Figure 4-6. Flow schematic for typical storage/sedimentation facility, Newport, Rhode Island (Metcalf & Eddy, Inc., 1991b).

Sanitary District, Lincoln and Taylorville facilities, which feature mechanical sludge scrapers that are activated automatically on tank level. The potential solids loads on the POTW during pumpback operations should be considered in evaluating sludge and grit handling alternatives.

Design Details

Many of the design details for CSO storage/sedimentation facilities are influenced by variations in treatment goals, local hydraulic conditions, and other site-specific considerations. As a result, a variety of methods or strategies have been developed to address such issues as facility activation, flow distribution, tank flushing, and other aspects of facility design. The following examples of design details have been incorporated into currently operating CSO storage or storage/sedimentation facilities.

Facility Influent Gates

Influent gates can prevent dry weather flow from entering the facility, control the rate of wet weather flow to the facility, and protect the facility from flooding or activating during equipment failure or regular maintenance. Examples of influent gate operations are:

- *MWRA Cottage Farm:* Flow passes over a weir to an inlet structure. Three 72-inch sluice gates in the inlet structure open automatically when the liquid in the inlet structure reaches a high level. One gate is left open several inches to prevent splashover from triggering facility startup (U.S. EPA, 1977a).
- *Saginaw, Michigan, Hancock Street:* The original design provided a sonic level sensor in the CSO facility influent conduit, set to open sluice gates to the facility on high level, then close the gates on low level. Once on line, gate operation was erratic and the controls were changed to require manual closing of the gates on low level. Non-rising stem sluice gates were used, but a 1990 study recommended using rising stem gates to avoid submergence of the stem threads (U.S. EPA, 1980).
- *MWRA Prison Point:* A hydraulic sluice gate is controlled by water level in an inlet structure and in the stormwater wetwell. The facility gate will modulate to throttle flow into the facility on a high flow condition in the inlet chamber. The gate also is provided with a manual remote control (Maguire, 1981).
- *Newport, Rhode Island, Washington Street:* The normally open hydraulic sluice gate throttles flow into the facility on high level in the effluent screw pump wetwell by closing and reopening in 2-inch increments on rising or falling high level. High level float switches in the influent channel and the effluent wetwell automatically close the gate completely as a backup in case the gate-modulating system fails (Metcalf & Eddy, Inc., 1991b).

Flow Distribution

CSO storage/sedimentation facilities commonly are designed with multiple rectangular tanks. Flow is distributed such that the tanks fill sequentially to minimize maintenance and cleanup following small storms. At some point in the process of filling, flows are equalized so that all tanks are completely full before overflow occurs. Examples of flow distribution include the following:

- *MWRA Prison Point:* The inlet structure has one dry weather flow (DWF) channel and three wet weather channels. On high level in the DWF wetwell, the DWF gate throttles causing flow to backup in the inlet structure. On high level in the inlet structure the first storm gate opens. A bubble tube in the first tank signals the next gate to open before the first tank water surface reaches the effluent weir. The third gate operates in a similar manner. Once all gates are open and all tanks are at the same level, the water surface uniformly rises to the effluent weir elevation. This operating strategy allows the tanks to fill sequentially, while preventing overflow until all tanks are full. Available storage capacity in the inlet structure provides a delay between throttling of the DWF gate and opening of the first storm gate, preventing short-cycling of the storm system (Maguire, 1981).
- *Newport, Rhode Island, Washington Street:* The elevation of the influent sluice gates for one tank is lower than the elevation of the gates for the other two tanks. Flow in the influent channel will pass into tank 1 first, then the second two. All gates are located below the effluent weir elevation, so all tanks will be completely full before the facility overflows. There are three manual sluice gates for each tank. All gates are normally kept open, although operators can allow tanks 2 and 3 to fill sequentially by monitoring tank levels and manually operating the gates (Metcalf & Eddy, Inc., 1991b).
- *Saginaw, Michigan, Hancock Street:* Influent pumps initially discharge to one bay. When this bay is 60 percent full, the sluice gate to the second bay is opened. Two additional bays follow the second bay. Once all bays are at the 60 percent fill level, they all will fill evenly, and thus all overflow at once (U.S. EPA, 1980).

Tank Configuration and Details–Rectangular Tanks

Rectangular tanks are the most common configuration for CSO storage/sedimentation facilities. A major advantage of rectangular tanks is that common-wall construction or installation of interior walls allows the total volume to be compartmentalized. As noted above, sequential filling of compartments can reduce cleanup efforts during smaller storms. Figure 4-7 presents a plan and profile for a typical rectangular storage/sedimentation tank. A number of design considerations are related to tank configuration and appurtenant details:

Surface Geometry

For rectangular primary settling tanks at POTWs, length-to-width ratios are typically in the range of 3:1 to 5:1. In theory, tank geometry is intended to minimize flow patterns that might resuspend settled solids or otherwise disrupt the settling process. The critical scour velocity is calculated as follows (WEF, 1992):

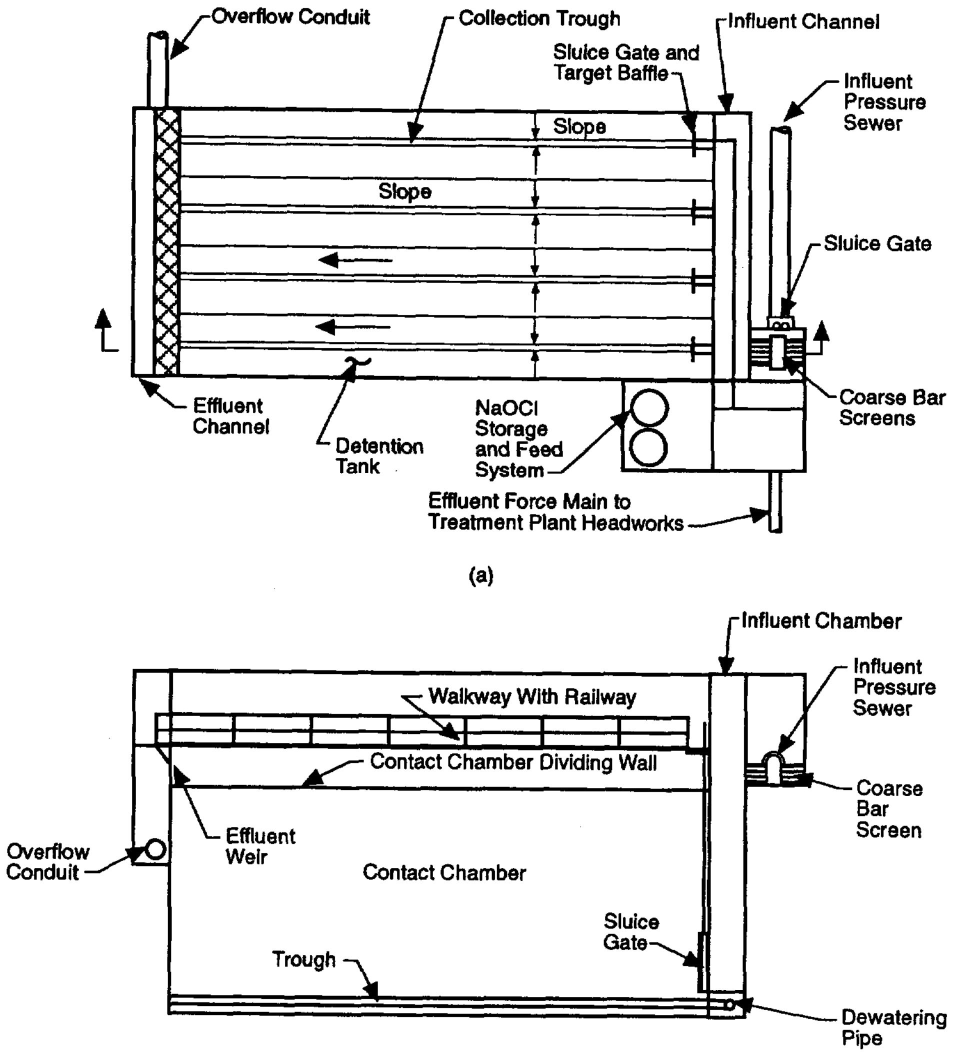
$$V_H = \{[8k(s-1)gd]/f\}^{0.5}$$

where:

V_H = critical scour velocity
k = constant for type of scoured particles
s = specific gravity of scoured particles
g = acceleration due to gravity
d = diameter of scoured particles
f = Darcy-Weisbach friction factor

Typical values for k range from 0.04 for unigranular sand to 0.06 for sticky, interlocking material. The units in the equation may be either U.S. customary or SI (Metcalf & Eddy, Inc., 1991a).

In practice, the width of primary settling tanks commonly is constrained by the available width of mechanical sludge collection equipment. Since such equipment is typically not provided at CSO storage/sedimentation facilities, the constraints on tank width are not as rigid. In addition, the general reliability of length-to-width ratio as a design tool has been questioned (WEF, 1992). For tanks intended for storage only, geometry is of even less concern. Table 4-3 presents typical dimensions for



(a)

(b)

Figure 4-7. Plan and profile for a typical rectangular storage/sedimentation facility (Metcalf & Eddy, Inc., 1991a).

Table 4-3. Typical Rectangular Tank Dimensions for Storage/Sedimentation Facilities

Source/Location	Dimension (ft) Length	Width	Side-Water Depth
Metcalf & Eddy, Inc., 1991a[1]	80-130	16-32	10-15, 12 typically
WEF, 1992[1]			10
Great Lakes-Upper Mississippi River Board, 1978[1]			7 minimum
U.S. EPA, 1975b[1]			10-13
Milwaukee Humboldt Ave. (Medina et al, 1981)	420	75	16
Saginaw Hancock St. (U.S. EPA, 1980)	206	52	10
Southgate/Wyandotte, Michigan[2] (Hubbell, 1990)	222	362	25
MWRA Prison Point (Maguire, 1981)	94	23.5	12
Newport, Washington St. (Metcalf & Eddy, Inc., 1991b)	130	25	12

[1] Values for primary settling tanks
[2] Large tank is compartmentalized

settling tanks from published texts and examples of actual dimensions at CSO storage/treatment facilities.

Floors

As noted above, to facilitate solids handling, floors are typically sloped to a center or side trough, which is in turn sloped back to the dewatering system drawoff. Flushing systems generally are required to ensure complete solids removal. A number of installations have been developed in Europe with multiple grooves or channels in the tank floor, in an attempt to maintain self-cleaning velocities across the entire floor area. This type of design is more expensive to build, and operating experience shows that some flushing is still required to prevent the build-up of solids (Stahre and Urbonas, 1993). Table 4-4 presents examples of floor slopes at installations in the United States.

Baffles

Most facilities include influent baffles to dissipate energy in the influent flow and to minimize short circuiting through the tank. Commonly of timber construction, the design of the influent baffles for CSO storage/treatment tanks is similar to influent baffles for rectangular primary settling tanks. Details of influent baffle designs can be found in the literature (WEF, 1992; Stahre and Urbonas, 1993). Effluent scum baffles control the discharge of floatables, a desired goal of CSO abatement strategies. The effluent baffles for CSO storage/treatment tanks typically consist of steel plates or concrete beams that extend below the water surface. Mechanical scum collection troughs are less common.

Flushing Systems

Flushing systems are provided at storage/sedimentation facilities to assist in solids handling and general cleanup following facility activation. Due to the intermittent operation of CSO control facilities, it is important to keep tanks clean between storms to minimize odor buildup and maintain tank capacity. As tanks are dewatered, heavier solids that have settled out will not necessarily be resuspended unless some mechanical means such as aeration or mixing is provided. Without fully resuspending settled solids, pressurized flushing systems can be used to direct the settled solids towards the sludge drawoff hoppers. The two types of flushing systems commonly found in CSO facilities in the United States are header-mounted spray nozzles, located around the perimeter of the tank, and high-pressure, manually controlled monitor nozzles, mounted on turrets.

Spray headers are used to wash down walls, but may not be effective in moving solids along the bottoms of the tanks. The advantage of spray headers is that little operator attention is required. Monitor nozzles are intended primarily for moving solids along tank floors towards central gutters and sludge drawoffs. They also are effective for cleaning walls, but are more labor intensive than the spray headers.

Some facilities feature only one type of system (Oakport, California), while others (Newport, Washington St.; Saginaw, Hancock St.) feature both. In some facilities where monitor nozzles are provided, hose gates and flexible hose are provided to reach corners or other

Table 4-4. Examples of Floor Slopes for Storage/Sedimentation Facilities

	Slope (ft/ft)	Location
Floor slope to center trough	0.0833	MWRA Prison Point (Maguire, 1981)
	0.0833	Saginaw, Michigan, Hancock St. (U.S. EPA, 1980)
	0.0870	Newport, Rhode Island, Washington Street (Metcalf & Eddy, Inc., 1991b)
Center trough slope to drawoff	0.0167	Saginaw, Michigan, Hancock Street (U.S. EPA, 1980)
	0.0115	Newport, Rhode Island, Washington Street (Metcalf & Eddy, Inc., 1991b)

spots out of the range of the monitor nozzles (MWRA Cottage Farm).

Some European installations feature "tipping flushers," which consist of cylindrical containers mounted above the width of the tank by an off-center swivel mechanism. Each container has an asymmetrical discharge opening running the length of the container. At the end of a storm event, after the storage/sedimentation tank has been dewatered, a flushing water pump fills the tipping flusher. When the tipping flusher is nearly full, the center of gravity shifts, causing the container to rotate and discharge its contents. The force of the sudden rush of water moves remaining solids along the floor of the tank. Tipping flushers may not be effective in tanks longer than approximately 160 feet (Brombach, 1989).

A number of facilities located near rivers utilize river water as the source of flushing water. The Bannockburn, Scotland, facility, which features a circular tank, experienced silting of the river intake and clogging of spray nozzles; the spray system was abandoned. The Saginaw, Hancock Street facility and the Bay City, Michigan, facility both use river water for flushing, while the Chapaton, Michigan, Retention Basin uses lake water. The Chapaton facility can use its flushing system to resuspend solids for dewatering, but this option generally is not used.

The MWRA Prison Point facility uses river water from the Charles River for plant water. The river water is supplied by gravity through an auto-backflushing strainer. A stormwater stripping pump provides a backup source of flushing water. The MWRA Cottage Farm facility uses an on-site well as a flushing water source.

The Newport Washington Street facility uses city water as a source for flushing water. The city water is fed through an air gap into a break tank. On low level in the break tank, a valve on the city water supply opens. On high level, the city water valve closes and a "Flushing Water Ready" indicator light is activated at the main control panel.

Tank Configuration and Details–Circular Tanks

Circular tanks typically feature one of two types of inlet configurations: center column feed with influent baffles, similar to circular primary settling tanks; and tangential feed, more common in Europe, which creates a swirling motion within the tank. Tangential feed tanks are in-line devices intended primarily for storage of the initial storm flows, with an overflow located upstream of the tank. A vortex valve throttles the underflow from a center bottom drawoff to the downstream interceptor (Brombach, 1989). Flushing systems for center-feed circular tanks typically feature header-mounted nozzles and/or manual flushing with hoses fed from yard hydrants. Tangential feed tanks are intended to be essentially self-cleaning. Typical dimensions for circular tanks are presented in Table 4-5.

Table 4-5. Typical Dimensions of Circular Storage and Storage/Sedimentation Tanks

	Dimension (ft)		
Type	**Diameter**	**Side-Water Depth**	**Bottom Slope**
Primary			
(Metcalf & Eddy, Inc., 1991a)	40-150	10-15 12 typical	1:12
CSO			
Bannockburn, Scotland (Henderson et al., 1981)	66	9.5	1:8.25
Decatur, Illinois, McKinley Ave. (BGMA and CMT, 1977)	85	24.8	
Lincoln, Illinois (CMT, undated)	130		
Springfield, Illinois, Spring Creek (CMT, undated)	180		
Springfield, Illinois, Sugar Creek (CMT, undated)	210		1:3*

* 1:3 slope is on sides of tank near bottom

Tank Access

The need for a cover over a tank depends on a number of factors, including the elevation of the tanks with respect to grade, proposed development on or adjacent to the site, public safety and security, the potential for odors, and general aesthetics. A common practice is to provide a walkway inside the tank, above the maximum water surface, to provide access for maintenance and cleaning. Explosion-proof lighting and electrical fixtures are required, since the tanks could be exposed to potentially explosive sewage gases or chemical spills that could be conveyed through the collection system. Walkways must be provided with railings and toeplates, as required by the appropriate building and safety codes. Covered tanks must be provided with emergency exits, in accordance with applicable codes. In some facilities, portions of the roof slab are removable, allowing a compact front-end loader to be lowered into the tank to assist in grit handling.

Tank Dewatering Systems

Standard practice is to return the contents of tanks to the sanitary collection system by gravity, if hydraulically feasible, or by pumping. Trade-offs between influent pumping with gravity effluent flow, and gravity influent flow with effluent pumping should be evaluated during design. Multiple tanks should have the capability of sequential dewatering. One common method for providing sequential dewatering is to pipe the dewatering drawoff lines to a common header. Motor-operated or hydraulic valves on the drawoffs are set to open and close sequentially. The dewatering header could also be piped to rapid dewatering pumps and solids stripping pumps. Centrifugal pumps are appropriate for the rapid dewatering of storage/sedimentation tanks, while plunger pumps should be considered for solids handling. Examples of dewatering systems at currently operating CSO facilities include:

- *MWRA Cottage Farm:* Tanks are dewatered by gravity to the interceptor. Approximately 1 hour is required to drain the full 1.2-million gallon capacity of the facility (U.S. EPA, 1977a).
- *Bannockburn, Scotland:* Tank is dewatered by screw pump to the interceptor (Henderson et al., 1981).
- *Oakport, California:* Tanks drain by gravity to interceptor, one tank at a time. Sequential dewatering minimizes the amount of time that sludge is exposed to the air, thereby minimizing odors (McCormick et al., 1990).
- *Southgate/Wyandotte, Michigan:* Gravity dewatering to interceptor is controlled by a flow meter and control valve (Hubbell, 1990).
- *MWRA Prison Point:* Manually controlled hydraulic gates drain the tanks to a stormwater wetwell, which is dewatered by a 500-gpm centrifugal stripping pump. The stormwater wetwell is sized to hold the entire contents of one tank (Maguire, 1981).
- *Newport, Rhode Island, Washington Street:* Two 800-gpm vertical dry-pit non-clog centrifugal pumps are provided for rapid dewatering, while two 85-gpm duplex plunger pumps are provided for solids stripping. One of each type of pump is intended as a standby, although a "rapid dewatering" mode allows both centrifugal pumps to run, then both duplex plunger pumps (Metcalf & Eddy, Inc., 1991b).

Ventilation and Odor Control

Tanks, screenings areas, wetwells, and other areas within storage/sedimentation facilities that are exposed to sewage gases must be ventilated to prevent the accumulation of potentially explosive and/or corrosive gases and to control the buildup of moisture and condensation. Evacuation of sewage gases is required for personnel safety and equipment longevity, while control of moisture is important since damp surfaces can provide an environment for bacteria that oxidize hydrogen sulfide to sulfuric acid, resulting in accelerated corrosion. Ventilation systems for process areas are sized based on the volume of the space to be ventilated and a specified ventilation rate (typically in terms of air changes per hour). For areas exposed to sewage gases, ventilation rates of 6-12 air changes per hour are typical (U.S. EPA, 1985a; Great Lakes-Upper-Mississippi River Board, 1978). Two-speed fans allow a lower rate of ventilation when spaces are not occupied and a higher rate when personnel are present. This arrangement lowers operating costs for facilities that are not continuously staffed. Intake louvers are sized based on a maximum face velocity and commonly are interlocked with supply and/or exhaust fan operation. The designer should consult applicable codes, ordinances, standards, and manufacturer's literature to establish design criteria for a particular application.

Where storage/sedimentation facilities are located in the vicinity of residential, commercial, or recreational areas, or where the exhaust from the facility ventilation system may otherwise impact a sensitive receptor, a means for controlling odors in the exhaust gas should be considered. Two of the more common processes for removing odors from exhaust gas are wet scrubbing and activated carbon adsorbtion. Activated carbon systems generally are applicable for air flows up to 2,000 cfm, while wet scrubbers are more appropriate for air flows greater than 2,000 cfm (U.S. EPA, 1985a). Activated carbon may also be applied as a polishing step, following wet scrubbing.

Discharge permits may be required for ventilation exhaust from CSO facilities. The designer should consult current federal, state, and local codes regarding exhaust air discharge permit requirements.

Wet Scrubbers

Wet scrubbers function by providing contact between the exhaust air and a scrubbing solution, which removes the odorous compounds through one or more of the following processes (U.S. EPA, 1985a):

- Condensation of odorous vapors
- Removal of odorous particulates
- Odor adsorbtion into the scrubbing solution
- Odor reaction with an oxidizing scrubbing solution
- Emulsification of odorous gases in a chemical reagent

Wet scrubbers can be arranged in a vertical, counter-current flow configuration, or in a horizontal, cross-flow configuration. A typical wet scrubber system includes the following features:

- Scrubbing tower, housing the following:
  - scrubbing solution spray system
  - inert packing material, to promote liquid/solid contact
  - mist eliminator, to minimize loss of scrubbing fluid in the exhaust air

  - scrubbing solution wet well
  - drain
- Exhaust fan with ductwork, including bypass of scrubbing tower
- Scrubbing solution recycle pumping system
- Chemical storage and feed equipment, including:
  - metering pumps
  - storage tanks
  - piping, valves, and appurtenances
  - instrumentation and controls (pH, oxidation-reduction potential [ORP] probes)

Potassium permanganate and sodium hypochlorite are two of the more common oxidizing agents used in wet scrubbers. Scrubbing solutions also may include an acid or base to keep the pH of the solution in an optimum range for odor compound removal or neutralization. Selection of the appropriate scrubbing solution should be based on the types and concentrations of the odor-causing constituents to be removed. Pilot testing should be undertaken to establish design and performance criteria for a full-scale system.

Some scrubber units are provided with a constant flow of make-up water and a continuously overflowing scrubbing solution wetwell. The constant renewal of scrubbing solution minimizes the build-up of solids in the scrubbing solution resulting from the reaction between hydrogen sulfide and sodium hypochlorite. The overflow from these units is commonly piped to a sanitary drain.

Activated Carbon Adsorption Unit

Activated carbon adsorbtion units remove odors through the adsorbtion of odor-causing compounds onto the surface of the activated carbon media. A typical activated carbon system consists of a vessel supporting a bed of granular activated carbon, an exhaust fan, and ductwork.

Sodium hydroxide-impregnated carbon commonly is used in odor control applications, as it has a higher capacity to remove hydrogen sulfide than non-impregnated or potassium hydroxide-impregnated carbon. A further advantage of the impregnated carbon is that it can be regenerated in-place, using 50-percent sodium hydroxide solution. Non-impregnated spent carbon must be removed from the vessel and thermally regenerated in a multiple hearth furnace. If impregnated carbon is to be specified, the design must include appropriate chemical piping, valves, and drains to permit in-situ sodium hydroxide regeneration.

Design of an activated carbon odor control system should include the following steps (U.S. EPA, 1985a):

- Characterization of the exhaust air to be treated.
- Identification of effluent criteria.
- Selection of the adsorbent.
- Completion of pilot studies to establish expected performance, estimated useful life of carbon, and design criteria.
- Application of pilot data to full-scale design.

The designer is referred to manufacturer's literature and published design guides (U.S. EPA, 1985a) for additional information pertaining to odor control system design.

System Controls and Operation

Due to the uncertainty in predicting the nature of precipitation and storm flows, CSO facilities typically are designed for automatic activation. Facility activation is triggered by sensing of flow or water surface elevation, as a regulator activates and flow is diverted to the facility. Regulator activation can be passive (i.e., sideweir, orifice) or mechanical (i.e., inflatable dam). Mechanical regulator activation can be triggered by a flow signal or water surface elevation, or through a real time control system, as described in the first section of this chapter.

In general, the simpler the activation system, the more reliable the operation. For example, at the Newport, Rhode Island, Washington Street facility (Figure 4-6), flow enters the facility influent conduit from a static sideweir regulator. Once flow reaches the facility, catenary bar screens and a hypochlorite dosing system activate from a mercury float switch in the influent channel. Flow enters the tanks through normally open manual sluice gates, with the elevations of the gates set so that one tank fills first. No sophisticated controls are required until the effluent weir overflows, causing activation of the effluent screw pumps. Examples of activation strategies for other facilities are described above (see "Design Details").

More sophisticated controls are required for influent/effluent pumping, facility dewatering, and hypochlorite dosing for disinfection.

Pumping Systems (Influent/Effluent)

Influent and/or effluent pumping commonly is controlled by wetwell elevation, as in a standard sanitary pumping station. Wetwell design, pump design, and control strategy must consider the peaked hydrograph typical of storm flows and must either attenuate or be able to respond to relatively rapid changes in flow rate. Some type of variable speed control is used for pumps.

Screw pumps are well suited for CSO applications since the pump discharge varies directly with influent flow. The drawback to screw pumps is the space requirement, especially for higher lifts. Influent pumps must be capable of passing solids that fit through coarse screens.

Overflow relief must be provided to protect the facility from flooding if the influent or effluent pump capacity is exceeded. Relief could be in the form of an overflow weir, which activates when a wetwell backs up, or it could be a remote regulator, which works in conjunction with a modulating gate. On high level, the gate would throttle, causing an upstream regulator to activate. It is advisable to have simple backup, such as a mercury float switch, which would close the facility gate completely on high-high level in the facility, in case the gate modulating controls fail.

Facility Dewatering

As discussed under Process Theory, initiation of a facility dewatering sequence typically is a manual operation. The operators must ensure that the conveyance system and POTW capacity have been restored following the storm. Programmable logic controllers allow for automatic control and switch-over from rapid dewatering pumps to solids handling pumps once the dewatering sequence is initiated. Where gravity dewatering is possible, some facilities feature a flow control valve for more precise regulation of flow to the interceptor.

Grit can be troublesome for pumpback operations. Some facilities have a separate means to handle grit and heavier solids, such as providing access for removal via a vacuum truck. Other facilities provide a separate set of pumps for solids removal. Some facilities aerate and mix the tank contents to facilitate solids removal.

Disinfection

A detailed discussion of disinfection control strategies is provided later in this chapter.

Process Variations

The design of CSO storage/sedimentation facilities is not standardized. Some early facilities were intended to be experimental prototypes for evaluating emerging technologies. Process variations that have been implemented are described below.

Fine Mesh Screening with Sedimentation

This process variation is intended to augment solids and floatables removals through storage/sedimentation tanks. A potential drawback to this variation is that static fine screens tend to easily clog.

- *MWRA Cottage Farm:* Horizontal fixed screens with 0.2-inch openings are located between the scum baffle and effluent weir. The screens are hinged to allow them to swing open by hydraulic pressure if clogged. Flow passes under the baffle, up through screens, then over the weir. The screens are manually flushed during tank cleanup following a storm (U.S. EPA, 1977a).
- *Atlanta, Georgia, Intrenchment Creek:* 50-mesh (300-µm) static screens are installed upstream of the sedimentation tanks. The screens were subject to blinding during the first flush and when there were heavy grease loads (West et al., 1990).

Aeration/Mixing of Tank

At some facilities where the tank is not intended to function as a flow-through treatment facility, aeration and/or mechanical mixing prevents sludge from turning septic and generating odors, and facilitates solids handling. If aeration or mixing is considered, the potential benefits should be evaluated against the additional operation and maintenance costs associated with the aeration or mixing equipment.

- *Decatur, Illinois, Seventh Ward and Lincoln Park:* Blowers provide aeration until the first flush tank can be dewatered. Aerating the tank keeps contents mixed, minimizes odor problems, and makes the tank easier to clean after a storm (BGMA and CMT, 1977).
- *Milwaukee, Wisconsin, Humboldt Avenue:* Seven mechanical mixers resuspend solids once the storm is over to facilitate dewatering. Mixing reduces the cleanup effort after a storm (Medina et al., 1981).

Flow Balance Method

The in-receiving water flow balance method involves using floating pontoons and flexible curtains to create an in-receiving water storage facility. CSO flows fill the facility by displacing the receiving water that normally occupies the storage facility. The CSO flows are then pumped to the collection system following a storm. The technology has been used for CSO control in Brooklyn, New York, where floating pontoons were permanently installed in the receiving water near the CSO outlets. The feasibility of this technology depends in part on whether the storage facility would significantly impact the aesthetic value of the surrounding area, and whether the structure would hinder navigation. Other site-specific concerns include the availability of volume due to tidal variations in coastal water, and the need to protect from damage due to high winds or wave action. Standard marina technology was used in the Fresh Creek, Brooklyn demonstration project to prevent damage.

Deep Tunnel Storage

Introduction

Deep tunnel storage often is considered as an alternative to near-surface storage/treatment facilities where space constraints, potential construction impacts, and other issues challenge the feasibility of near-surface facilities. The major advantage of deep tunnel storage is that relatively large volumes can be stored and conveyed with little disturbance to existing surface features. In congested urban areas, near-surface CSO control facilities can be difficult to site, and the only available open spaces for such facilities often include recreational areas such as river-front parks or ball fields. Deep tunnel construction may avoid some of the issues arising from the use of open spaces and minimize the disruptions associated with the extensive open-cut excavation associated with near-surface facilities.

Deep tunnel construction does not completely avoid the issues related to siting of open excavations, however, as excavations at work shafts, access shafts, vent shafts, and drop shafts are required, along with excavations for near surface consolidation conduits. Handling and disposal of excavate can also present challenges in coordinating truck traffic and identifying disposal locations. In Rochester, New York, tunnel excavate was successfully used to fill low areas around an airport and the POTW, as well as other areas identified by the owner. Allowable truck routes were specified to minimize impacts on local neighborhoods. The feasibility of deep tunneling must be established through geotechnical investigations, as well as evaluation of other concerns such as the potential for encountering hazardous wastes, the impacts on adjacent structures, and construction logistics.

A typical deep tunnel system includes the following features:

- Regulators, to divert and control storm flows to the tunnel system.
- Consolidation conduits, to convey flows from regulators to the tunnel system.
- Coarse screening, to remove large debris and protect downstream pumps.
- Vertical dropshafts, to deliver flow to the tunnel and dissipate energy.
- Air separation chambers, to allow release of air entrained in the dropshafts.
- Tunnel, sized to store and convey flows from a given design condition.
- Access shafts, for maintenance personnel and equipment.
- Vent shafts, for balancing air pressure.
- Dewatering system, to pump volume stored in the tunnel to the POTW once conveyance system and treatment capacity is restored.
- Odor control systems at certain venting locations.

Design considerations for each of these components are described below.

Regulators

Regulators control flow into the interceptor from a combined trunk sewer and serve as the diversion point for routing excess flows to the tunnel system. Regulator types are reviewed earlier in this chapter.

In the Metropolitan Water Reclamation District of Greater Chicago's Tunnel and Reservoir Project (TARP), sluice gates in the regulator structures regulate flow into the tunnel system and can be opened in advance of an expected storm (Dalton and Goyal, 1989).

Consolidation Conduits

Routing a deep tunnel to provide direct interception of every CSO outfall in a community's combined sewer system is not feasible. Rather, construction of near-surface consolidation conduits from selected outfalls or regulators to a more centrally located deep tunnel is a cost-effective alternative. The feasibility and cost of constructing consolidation conduits may be one of the factors that influences the configuration, depth, and route of a deep tunnel system. Conversely, the route of the tunnel system may dictate the requirements for consolidation conduits. Aspects to consider in evaluating the use of near-surface consolidation conduits include:

- Potential disruptions to traffic, utilities, access to businesses, and other impacts on the community and the environment during construction of consolidation conduits.
- Cost of consolidation conduits compared to cost of multiple drop shafts; minimizing the number of drop shafts typically will be cost effective.
- Impacts of near-surface soil conditions on consolidation conduit construction methods (wetlands, unsuitable soils, bedrock elevation, etc.).
- Impacts of subsurface geology on tunnel construction methods and tunnel routing.

Consolidation conduits are sized based on the peak flows from the design condition for which CSO control is to be provided. For example, suppose a community's long-term CSO control strategy is to route all flows from a particular design storm to the deep tunnel system. A computer model of the community's combined sewer system, such as SWMM, generates values of the peak flow from the design storm at each node where the proposed consolidation conduits intercept flow. These peak flows are used for preliminary sizing of the consolidation conduits. The model then is expanded to include the proposed conduits, and subsequent model runs are used to refine the peak flows, particularly where one conduit intercepts the flow from more than one node. Through this iterative process, the optimum size of the consolidation conduits can be developed.

Consolidation conduits sized to convey peak storm flows may be of substantial size, and may present opportunities for in-line storage. Gates on the downstream end of consolidation conduits can be operated in conjunction with a real-time control system to optimize the use of storage and conveyance capacity in the tunnel system. Construction methods for near-surface consolidation conduits can include open-cut excavation and soft ground tunneling.

Relief points must be provided for flows to the consolidation conduits in excess of the design storm peak flow. A convenient location for relief is where the flow enters the consolidation conduit, as these structures are commonly located at existing regulators or on existing outfalls. In some cases, one relief overflow can serve a number of hydraulically connected CSOs, thus reducing future monitoring and maintenance costs by reducing the number of overflow locations.

Coarse Screening and Grit Removal

At the downstream end of consolidation conduits, coarse screening equipment can remove large, bulky solids such as branches and logs before the flow enters the dropshaft. For a system with a large number of dropshafts, providing coarse screening at each dropshaft may not be feasible, both in terms of cost and operation and maintenance requirements. For this reason, screening facilities may be located in the tunnel itself. Coarse screening and grit removal can be accomplished by screens and sumps located just before the dewatering pump station, usually a low point in the tunnel system. Screenings can be removed by a rake mounted on a bridge crane located at the ground surface. The rake is lowered to the underground trash rack to retrieve and raise screenings to the surface for disposal. A clamshell bucket can remove grit material from a sump located ahead of the dewatering pumps. The Chicago TARP system incorporates trash and grit removal facilities at the intake tunnels of the dewatering pump station (Variakojis and Quintanilla, 1989). In the Rochester, New York, deep tunnel system, screening facilities were provided at the downstream ends of each of the two main branches of the tunnel system. Coarse screening equipment is discussed in more detail later in this chapter.

Vertical Dropshaft

The function of the vertical dropshaft is to deliver flow from the near-surface conveyance system to the deep tunnel system, dissipating the energy in the flow to the extent possible and providing a means to remove air entrained in the flow as it passes down the shaft. Dropshaft design considerations and dropshaft types include (Westfall, 1990):

Dropshaft Design Considerations

Dropshafts have three basic components:

- Inlet structure, to provide the transition between horizontal and vertical flow.
- Vertical shaft barrel, to convey flow to the lower elevation and dissipate energy in the flow.
- Bottom chamber, to dissipate energy in the vertical flow and provide a means to separate and release air entrained in the dropshaft.

Dropshaft design is influenced by one or more of the following factors (Westfall, 1990; St. Anthony Falls Hydraulic Laboratory, 1971).

Variable Discharge

CSO outfall hydrographs tend to show distinct peaks. A consolidation conduit connecting a number of outfalls or regulators to a dropshaft may provide some attenuation of peak flows, but the dropshaft still will be exposed to a range of flows and must be capable of functioning within the expected range.

Impact on Dropshaft Floor

The impact of the flow on the dropshaft floor depends on the depth of the drop. For even relatively shallow drops, provisions should be made to reduce the magnitude of the impact. Alternatives for dissipating the energy in the flow include inducing a hydraulic jump in the shaft, creating a vortex action in the shaft, increasing wall friction in the shaft, and providing a plunge pool in the shaft floor. The plunge pool can be created by forming a sump in the floor or by providing a weir downstream of the shaft to back up flow. The depth of a plunge pool is determined from the Dyas formula (WPCF/ASCE, 1974):

$$\text{Depth} = \frac{(h^{1/2})\,(d_c^{\ 1/3})}{2}$$

where:

h = depth of drop (ft)

d_c = critical flow depth in shaft inlet (ft)

Entrained Air

The air that becomes entrained in the flow as the flow passes down the dropshaft can be both beneficial and detrimental to the dropshaft operation. The benefits of entrained air include:

- Minimizing the potential for subatmospheric conditions in the shaft, which would cause cavitation.
- Providing a cushion to absorb the impact of the falling water.

Disadvantages to entrained air include:

- Increasing the volume of the flow, which may increase the required dropshaft size.
- Requiring a separate means for removing the entrained air, to avoid a build up of pressure.

Headloss in the Dropshaft

If the hydraulic gradeline in the tunnel is close to the hydraulic gradeline in the near-surface conveyance system, excessive headloss in the dropshaft can cause flows to back up in the near-surface system.

Surge Relief

Six out of a total of 40 vertical dropshafts in the Rochester, New York, tunnel system were oversized to provide surge relief from transient hydraulic pressures that could develop in the tunnels (Holzbach, 1990).

Types of Dropshafts

Different types of dropshafts have been developed based on hydraulic studies. Selection of dropshaft type depends on the relative importance of the design considerations noted above. Four of the more common dropshaft types are discussed below (Westfall, 1990).

Drop Manholes

Drop manholes are used in near-surface conveyance systems to drop flow from a higher sewer into a lower sewer. The manholes minimize turbulence that would otherwise promote the release of sewage gas and erosion of the manhole. A separate access manhole commonly is provided to the lower sewer, so that maintenance personnel can avoid climbing down the wet shaft. Drop manholes are suitable for drops up to 70 feet. For drops of greater than 70 feet, one of the following dropshaft types should be considered.

Vortex Dropshafts

Flow is introduced into vortex dropshafts tangentially, causing flow to spiral down the shaft in a vortex flow pattern. Centrifugal forces keep the flow in contact with the wall, dissipating energy through friction and creating an open inner core, through which entrained air may escape. The vortex flow pattern forces air bubbles toward the center core, further reducing the amount of entrained air. The central air core also tends to maintain atmospheric pressure in the shaft, thereby minimizing the potential for cavitation. A relatively smooth transition from horizontal to the vortex vertical flow minimizes turbulence at the inlet, which also minimizes air entrainment. Kinetic energy remaining in the flow is dissipated either through creating a hydraulic jump in the shaft, or by a plunge pool at the bottom of the shaft.

Five types of tangential inlet configurations have been developed (Figure 4-8), including (Westfall, 1990):

- *Circular:* The dropshaft is concentric with the vortex inlet, which has a horizontal floor.
- *Scroll:* The sides of the vortex inlet, with a horizontal floor, curl towards the dropshaft.
- *Spiral:* The approach channel issues a vortex flow into the dropshaft by winding downwards.
- *Tangential:* The approach channel contracts at its junction with the dropshaft so as to project the flow tangentially around the walls.
- *Siphonic:* Generally used for outlets from a reservoir, a series of siphons are located around the entrance so as to produce a vortex flow down the dropshaft.

Hydraulic studies have suggested that the spiral and tangential inlets perform best, while the tangential inlet is easier to construct (Westfall, 1990). The vortex shaft results in minimal air entrainment and significant energy dissipation, but headloss is significant. A vortex type might not be appropriate where the difference in hydraulic gradient between the tunnel and the near-surface conveyance system is minimal.

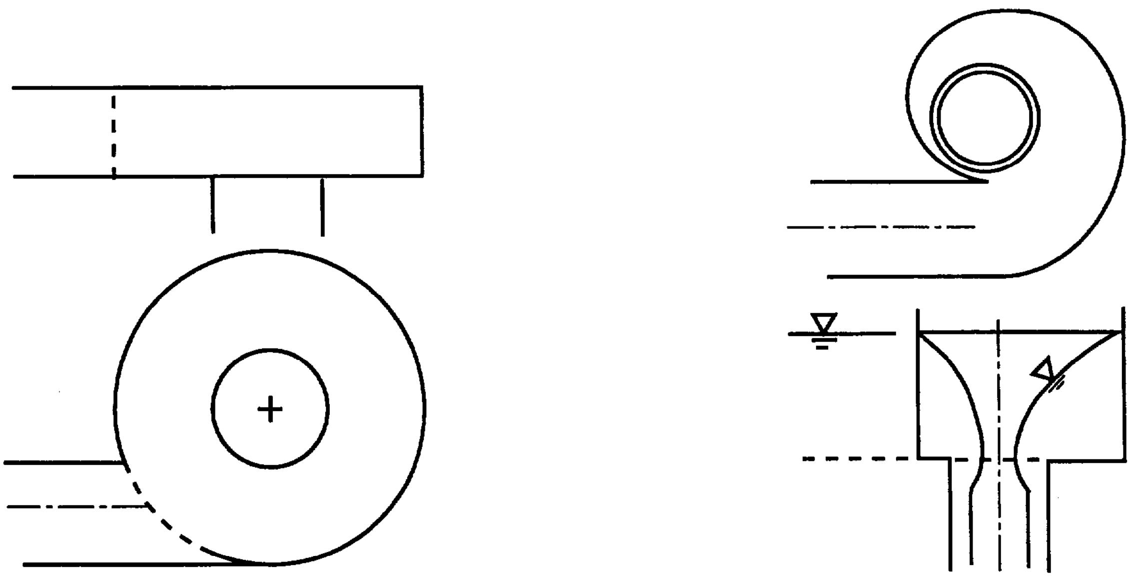
Morning Glory

These drop structures feature a circular crested weir for inlet control and commonly are used for reservoir outlets. Flow characteristics are determined from weir control, orifice control, and differential head control.

Direct Drop Air Entraining Type

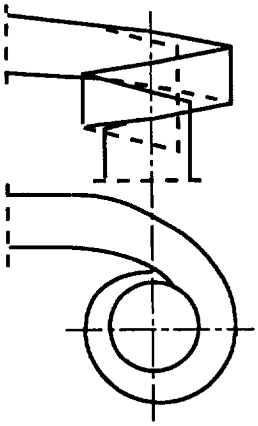
The inlet structure for this dropshaft allows flow to enter the dropshaft radially, entraining air to the extent that the shaft flows full. The full-flowing shaft promotes energy dissipation through wall friction, and the entrained air provides a cushion for absorbing energy at the bottom of the shaft. A large air separation chamber is required at the bottom of the shaft, along with a separate venting system to evacuate the air before it enters the tunnel system.

Two variations of the direct drop style were developed for Chicago's TARP system. Both types are capable of

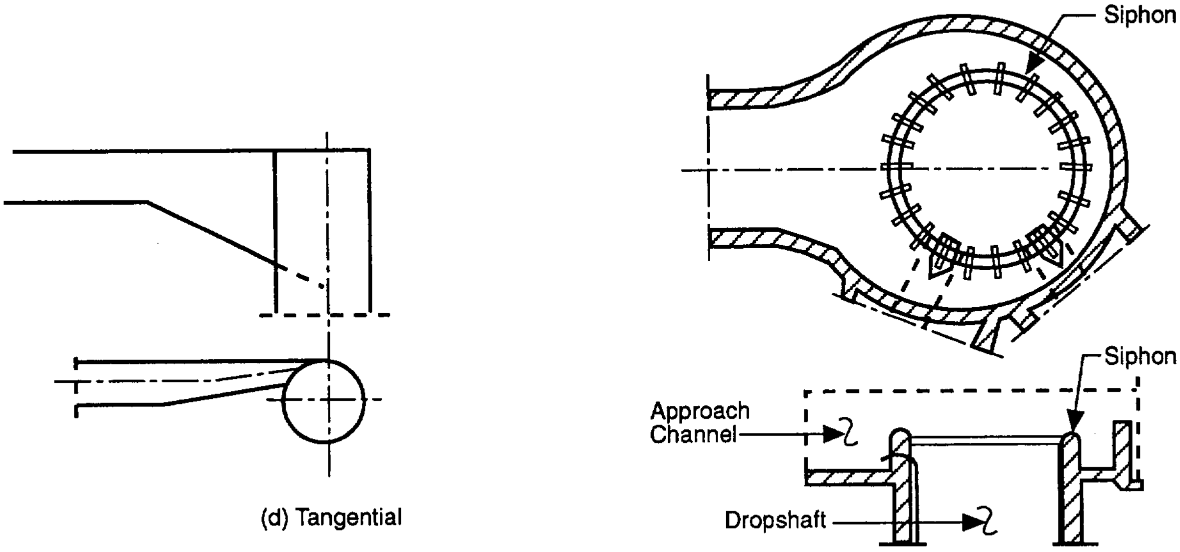


(a) Circular

(b) Scroll



(c) Spiral



(d) Tangential

(e) Siphon

Figure 4-8. Examples of tangential inlet configuration (Westfall, 1990).

passing a wide range of flows at approximately 20 percent of the headloss of similarly sized vortex-type dropshafts. The E-15 (Figure 4-9) features an air vent located inside the drop shaft. Slots in the vertical wall separating the dropshaft from the air vent allow air to be re-entrained in the falling water. Recirculating the air provides a more consistent mix of air and water, resulting in a more uniform flow in the dropshaft. The air separation chamber at the bottom of the shaft features a sloped roof to direct the released air back towards the vent. The E-15 shaft was used for shaft diameters up to 9 feet, with a maximum flow of 600 cfs.

The D-4 dropshaft was developed for dropshaft diameters greater than 9 feet (Figure 4-10). The air vent for the D-4 shaft is a separate shaft, located downstream of the dropshaft. The air vent feeds into the dropshaft above the crown of the incoming sewer, so air is recycled to the top. The air separation chamber for the D-4 has a flat roof. The D-4 is suitable for dropshafts up to 20 feet in diameter, and flows up to 4,500 cfs.

The air separation chambers and shaft structures for both types of direct-drop dropshafts are large structures, and must be suitably anchored to withstand the forces and vibrations generated by the falling flow. The floors of the air chambers in the TARP system are lined with a metal coating to minimize erosion from grit carried in the flow. Drop shafts initially may be oversized to provide access to the tunnel during construction. The finished diameter of the dropshaft is sized based on the following equation (Westfall, 1990):

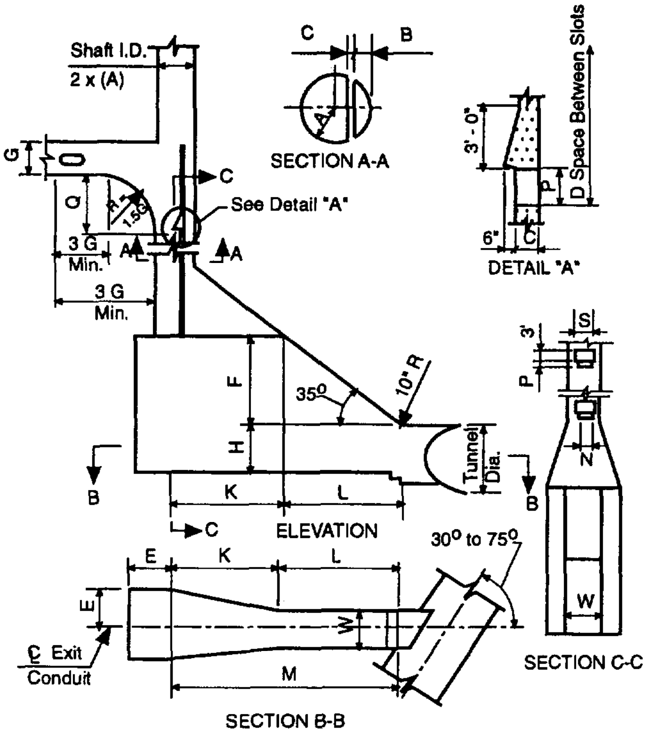
$$\frac{Q}{(g^{1/2})(D^{5/2})} = 0.2$$

where:
Q = design flow (cfs)
g = acceleration of gravity (ft/sec^2)
D = finished shaft diameter (ft)

Over 200 of the direct-drop style dropshafts, some of which have been operating for 20 years, have been installed in Chicago's TARP system.

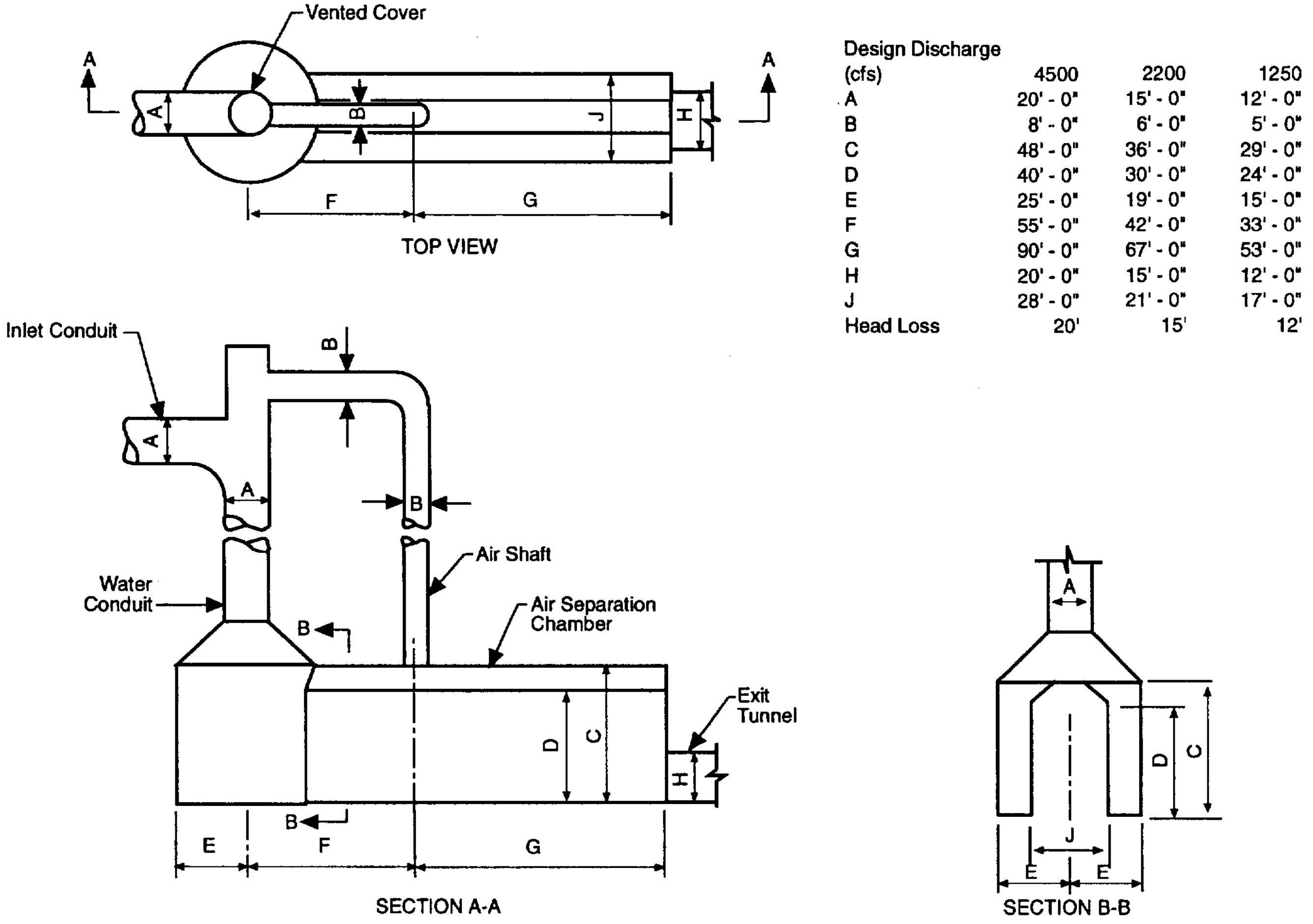
Tunnels

Sizing and routing of deep storage tunnels, as with any major CSO control system, is a complex process, requiring the review of a series of alternatives before arriving at the optimal configuration. The storage volume required to meet a given CSO control goal is developed through the use of a system model such as SWMM, or a more simplified routing technique. Alternatives encompassing variations in tunnel diameter, length, route, depth, and construction methods that meet the required storage and conveyance needs are then developed and evaluated. Topics to consider in



Design Discharge (cfs)	600	280	140
Shaft I.D.	9' - 0"	7' - 2"	5' - 8"
A	4' - 6"	3' - 7"	2' - 10"
B	2' - 9"	2' - 6"	2' - 6"
C	1' - 0"	1' - 0"	0' - 9"
D (Max)	10' - 0"	7' - 6"	5' - 6"
E	9' - 0"	6' - 8"	5' - 0"
F	20' - 3 1/2"	15' - 0 1/2"	11' - 2 1/2"
G	Variable, Equal to Pipe Dia. (But Not To Exceed I.D. of Shaft)		
H (Max)	12' - 0"	9' - 8"	8' - 0"
(Min)	9' - 0"	6' - 8"	5' - 0"
W (Min)	6' - 9"	4' - 9"	4' - 0"
H x W (Min)(ft^2)	81	45	25
K	27' - 0"	20' - 3"	14' - 10"
L	29' - 0"	21' - 6"	16' - 0"
M	56' - 0"	41' - 9"	30' - 10"
N (Min)	4' - 0"	3' - 6"	3' - 0"
P (Max)	1' - 6"	1' - 3"	1' - 0"
N x P (Min)(ft^2)	6	4.4	3
Q			
S (Min)	32' - 6"	24' - 0"	18' - 1"
Head Loss	5' - 0"	4' - 6"	4' - 0"
	9.0'	5.5'	4.7"

Figure 4-9. The E-15 dropshaft (Westfall, 1990).



Design Discharge (cfs)	4500	2200	1250
A	20' - 0"	15' - 0"	12' - 0"
B	8' - 0"	6' - 0"	5' - 0"
C	48' - 0"	36' - 0"	29' - 0"
D	40' - 0"	30' - 0"	24' - 0"
E	25' - 0"	19' - 0"	15' - 0"
F	55' - 0"	42' - 0"	33' - 0"
G	90' - 0"	67' - 0"	53' - 0"
H	20' - 0"	15' - 0"	12' - 0"
J	28' - 0"	21' - 0"	17' - 0"
Head Loss	20'	15'	12'

Figure 4-10. The D-4 dropshaft (Westfall, 1990).

developing tunnel sizing and route alternatives are discussed below.

Subsurface Conditions

A substantial subsurface exploration program is necessary to evaluate the feasibility of deep tunneling and to identify the most appropriate tunneling techniques. Depth to bedrock, rock strength, discontinuities and weaknesses in the rock structure, and ground-water conditions can impact the selection of tunnel route and construction method. Softer rocks allow a faster penetration rate, but also may require additional temporary and permanent support structures. Harder rocks, while requiring less support, generally require a slower rate of excavation. Excessive ground-water may cause tunnel flooding or local collapse, and may require special ground treatment techniques such as dewatering, grouting, or ground freezing. Discontinuities, fault zones, and other areas of local weakness or variation may preclude the use of certain tunneling techniques. The elevation of the top of the bedrock is an important consideration in setting the vertical alignment. In some cases, it may also be cost effective to route the tunnel at a deeper elevation if doing so would avoid difficult areas or "mixed face" conditions (Thompson and Dobbels, 1991). In Rochester, New York, the surface topography would have allowed the downstream leg of the tunnel system serving the west side of the city to be set at a constant grade to the POTW. While allowing gravity flow to the POTW, the downstream end of this vertical alignment would have risen above the top of bedrock. The designer preferred to keep the entire segment in rock to ensure maximum support against transient pressure waves when the tunnel was filling or flowing full. The final vertical alignment, therefore, consisted of an inverted siphon, which allowed a tunnel boring machine (TBM) to excavate at a constant but steeper grade entirely in rock to a downstream control structure, at which point the rising leg of the siphon was excavated up to the POTW (Holzbach, 1990).

Encountering hazardous materials can have a severe effect on project schedule and cost. Delays may occur to identify the nature and extent of the wastes, develop and implement disposal and/or treatment options, and obtain permits. An environmental assessment along the route of a proposed tunnel and at proposed shaft locations allows the designer to identify routes that avoid areas of known or potential contamination. A limited review for preliminary siting might include review of available agency files and data on known locations of oil or hazardous materials spills, and review of past and present land use along proposed routes (Thompson and Dobbels, 1991). During design, a more detailed study, including soil borings, monitoring wells, and sampling, may be required. The potential requirement for subsurface easements from property owners also should be investigated.

Excavation Method

Three methods for deep rock tunnel excavation are TBMs, road header machines, and drill-and-blast methods. These methods are described below; the advantages and disadvantages of each technique are summarized in Table 4-6.

TBMs

TBMs feature a rotating, cutting head of a size equal to the full cross-sectional area of the tunnel to be excavated. Horizontal hydraulic thrust cylinders force the rotating cutting head forward into the rock. The body of the TBM is supported by hydraulic legs, which push against the walls of the tunnel, anchoring the TBM against the thrust applied to the cutting head. When the hydraulic thrust cylinders are fully extended, the main support legs are retracted and the TBM is advanced forward to start the next cutting cycle. Figure 4-11 shows the cutting cycle for a typical TBM system. The cutting heads feature a means to remove the excavated material from the cutting area, commonly by discharging the excavate to a conveyor system. The type and configuration of cutters on the cutting head vary, depending on the anticipated geologic conditions. In rock, roller or disc cutters are more reliable than drag cutters, which are more appropriate for soft ground conditions (Whittaker and Frith, 1990).

Rock Header Machines

These machines feature a relatively small-diameter boom-mounted rotary cutting head, supported by a tracked base. The cutting head is worked back and forth across the rock face by manipulating the boom. The rock debris is picked up at the base of the rock face by a conveyor system running through the base of the machine. The most common boom machines are the milling-type and ripping-type. The milling-type generally is best suited for hard rock conditions and features a conical cutting head that rotates in the same axis as the boom. The ripping-type cutting head rotates on a horizontal axis perpendicular to the boom and is best suited for softer rock conditions (Whittaker and Frith, 1990).

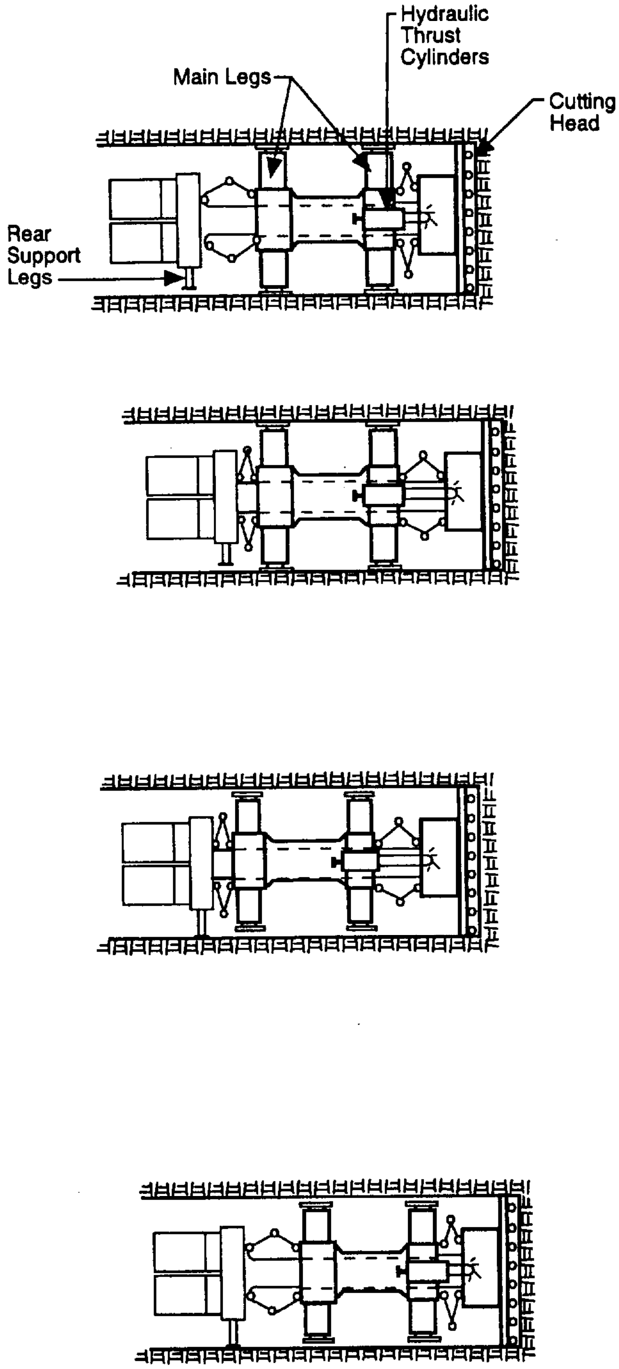
Drill-and-Blast Methods

The steps involved in drill-and-blast methods include (Whittaker and Frith, 1990):

- *Drilling:* The number of blast holes required in the rock face depends on the diameter of the tunnel and the strength of the rock. In addition to the blast holes, a number of burncut holes, without explosive charges, are drilled into the rock face to relieve the explosive stress. Drilling rigs may be mounted on the haulage tracks or on separate tracks of wider gauge than the haulage tracks, or they may be rubber tire- or tread-mounted.

Table 4-6. Advantages and Disadvantages of Deep Tunnel Excavation Methods

Method	Advantages	Disadvantages
TBM	• Rapid excavation to final tunnel diameter and grade • Disturbance of surrounding rock minimized • Well suited for long reaches of constant cross section	• Cutting face can become jammed where high rock stresses create "squeezing" condition • Usually long lead times required to fabricate new machines (use of reconditioned machines can reduce lead time) • Usually not economical if multiple tunnel diameters are required
Rockheader machines	• One machine can excavate different tunnel diameters • Typically lower lead times for delivery than TBMs • If tunneling conditions change, machine can be easily withdrawn to allow use of drill and blast methods	• Rate of advancement is lower than for TBMs • Rate of advance depends more on operator skill and rock fracture patterns • Cannot typically apply as much force to rock as TBMs
Drill and blast methods	• Can be used in most rock conditions	• Relatively slow rate of advance • Higher potential for damage to surrounding rock during blasting



Step 1.
Start of boring cycle. Machine clamped, rear support legs retracted.

Step 2.
End of boring cycle. Machine clamped, head extended, rear support legs retracted.

Step 3.
Start of reset cycle. Machine unclamped, rear support legs extended.

Step 4.
End of reset cycle. Machine unclamped, head retracted. Machine now ready for clamping and beginning boring cycle.

Figure 4-11. Cutting cycle for a typical tunnel boring machine (Whittaker and Frith, 1990).

- *Blasting:* The strength of the explosive charge also depends on the diameter of the tunnel, the local geology, and the proximity of adjacent structures. The weight of explosive can be limited by a specified maximum allowable blasting vibration. Following detonation, smoke fumes must be exhausted before personnel return to the blasting areas. Reversible fans in conjunction with ventilation tubes minimize the exposure of workers to the blasting fumes.
- *Debris Clearance:* Once personnel can safely return to the blasting areas, the roof, face, and sides of the tunnel are visually inspected and the loose rock is removed. A variety of methods and machines are available to handle excavation, including rocker shovels and scraper action loaders, which discharge into rail-mounted cars, conveyors, or slurry pipelines.
- *Ground Support:* Temporary supports protect personnel, control overbreak, and support loosened rock around the perimeter of the tunnel. Even tunnels in hard, competent rock may require temporary supports for localized weak zones. Common types of temporary support include arched steel ribs, rock bolting, and shotcrete. Permanent linings in drill-and-blast tunnels typically are installed once the excavation is complete, although in larger tunnels, excavate removal and concrete placement can be more readily coordinated.

In general, if geologic conditions are suitable for using a TBM, then tunnel routing and sizing should be directed toward longer reaches of constant diameter tunnel. Straighter tunnels are usually preferable, since TBMs have a limited turning radius. If subsurface conditions preclude use of TBMs, then excavation volume can be optimized by using tunnel segments with different cross-sectional areas. In any case, work generally proceeds upgradient to minimize the opportunity for ground-water infiltration to pond at the work face. The direction of excavation can influence the location of work shafts and tunnel layout.

Consolidation Conduit Layout

As noted above, tunnel routing must be developed in conjunction with near surface consolidation conduit design. The capacity for storage in consolidation conduits and upstream collection systems may reduce the size and/or location of tunnels required.

Potential Operating Strategies

Strategies to control flow into and through a tunnel should be considered when developing the optimal size and configuration of the tunnels. For example, certain diversion structures in the Rochester, New York, tunnel system are capable of diverting flow to two different sections of the tunnel system. If one system of the tunnel fills more rapidly than the other, remotely controlled gates redivert flow to the tunnel section with greater remaining capacity (Kent, 1992). Designing control structures with automatic gates allows such operating strategies, especially if provided in conjunction with a real-time control system.

Access, Vent, and Work Shafts

Work shafts and access shafts are required to move personnel, equipment, and materials in and out of the tunnel during construction and once the tunnels are operational. The size of construction work shafts may be dictated by the size of the excavation machinery used. The land around a work shaft commonly is used as a staging area for equipment and supplies, and is subject to heavy vehicular traffic associated with excavate removal. One study estimated that 2 to 3 acres are required at each construction access shaft location (Wheatley, 1991).

Permanent access shafts for tunnel maintenance and inspection may be developed from construction work shafts or incorporated into other structures, such as screening houses or control structures.

Vent shafts provide for the passive movement of air in and out of the tunnel during filling and dewatering, responding to differences in pressure between the tunnel and the above-grade atmosphere. Vent shafts may be provided with odor control. In Rochester, New York, intermediate vent shafts are not provided with odor control, whereas carbon adsorbtion odor control is provided at a screening facility on the upstream end of the inverted siphon to the POTW, and also at the downstream end of the inverted siphon. In addition to odor-causing compounds, emissions can include volatile organic compounds (VOCs).

Vent and access shafts typically feature a concrete pad at grade, with either gratings or an appropriate cover to secure the opening. The total area required for permanent access or vent shafts is 1/4 acre or less.

Dewatering Pump Station

Deep tunnel storage and conveyance systems typically feature a dewatering pumping station at the downstream end of the tunnel system, although gravity drainage systems do exist. The pumping station may be dedicated to the tunnel system or integral to a POTW sanitary influent pumping station. If coarse screening is not provided at upstream locations, then screening facilities should be provided at the pump station. Figure 4-12 shows a tunnel system dewatering pump station.

Tunnels are sloped to ensure a sufficient carrying velocity and to facilitate dewatering. A tunnel slope of 0.1 percent has resulted in minimal problems with grit

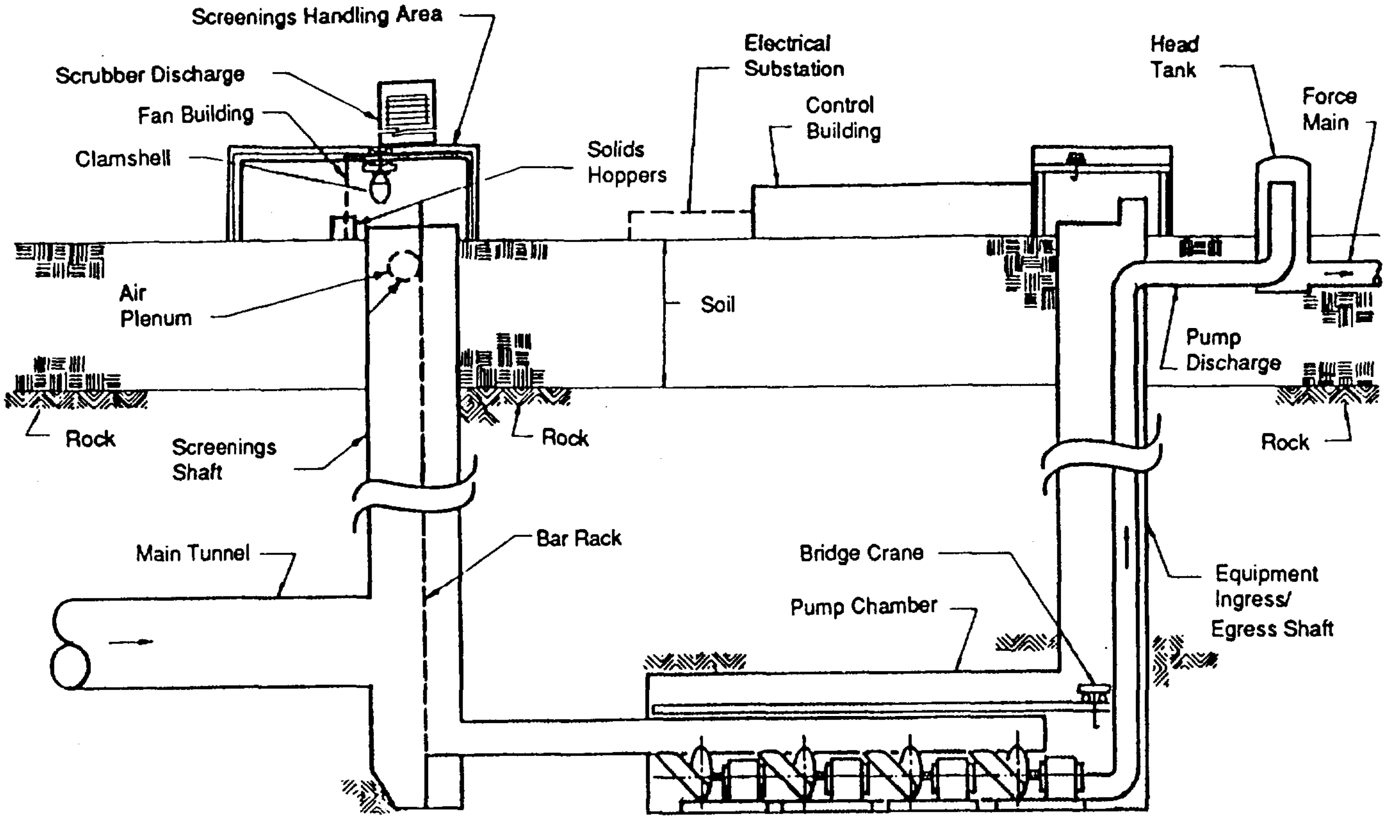


Figure 4-12. Tunnel system dewatering pump station (MWRA, 1990).

deposition in Rochester, New York. Though much of the pumping station equipment may be located below grade, an above-ground superstructure is required to house screenings handling equipment, odor control equipment, and/or electrical and operations control equipment. Dewatering rates are determined by POTW primary and secondary treatment capacities.

Active tunnel air venting may be provided at pumping stations for use during dry periods, when anaerobic conditions in tunnel sediment can produce odors. The method of venting can be by drawing air into the tunnel through drop shafts and access shafts, and venting at the pumping station, or by pushing air through the tunnel and out the shafts. The selected direction of air movement may depend on the desired location for odor control facilities and the location of sensitive receptors.

In Rochester, New York, combined sewage from the east side of the city feeds a tunnel system that drains to a 275-mgd pumping station. This pumping station, which also handles sanitary flows, features nine pumps, with the largest having a capacity of 38,200 gpm. The station provides a total lift of approximately 145 feet, and was designed to allow expansion to a capacity of 400 mgd.

Flows from the west side of Rochester feed a second tunnel system, which drains by gravity to the POTW. This tunnel system was originally planned to pass under the Genessee River, with a gradient which would have required downstream pumping to the POTW. The local topography, however, would allow a conduit to be suspended over the Genesee River, which in turn would raise the tunnel gradient high enough to allow gravity flow to the POTW. A second benefit of this design was that the crossing of the Genesee River gorge was designed with an integral pedestrian walkway, providing access between two parks on opposite sides of the river. At the downstream end of the inverted siphon on the west side tunnel, gates allowed the siphon to drain to the main pumping station. This operating strategy makes the volume of the siphon available for storage at the start of the storm event (Kent, 1992; Holzbach, 1990).

The pumping station on the Chicago TARP Mainstream System features pumps housed in two independent underground chambers, in order to provide backup capacity. Each housing can accommodate four pumps. The pumps provide service at two rated heads, 150 feet and 330 feet; therefore, the required pumping head range from 60 feet to 330 feet is obtained by throttling cone valves. Vertical, single-suction volute pumps with vertical, constant-speed motors are used, with pump casings encased in concrete to support the motors and control vibration. Energy for the 85,000 hp of pumping (57,000 hp of high head and 28,000 hp of low head) is supplied through two independent substations that tie into independent transmission lines with switchover capability (Variakojis and Quintanilla, 1989). Table 4-7 summarizes the capacities of the pumps (Dalton and Goyal, 1989). Once a storage reservoir is completed, this pumping station will have the capability of operating in three modes:

Table 4-7. Chicago TARP Mainstream Pumping Station Capacities

No. of Pumps	Rating at Maximum Head	Head Range
North Pumphouse		
1	330 cfs (213 mgd) at 330 ft	240-330 ft
1	220 cfs (142 mgd) at 330 ft	240-330 ft
2	330 cfs (213 mgd) at 150 ft	60-150 ft (1 future)
South Pumphouse		
1	330 cfs (213 mgd) at 330 ft	240-330 ft
1	220 cfs (142 mgd) at 330 ft	240-330 ft
1	330 cfs (213 mgd) at 150 ft	60-150 ft (future)
1	160 cfs (103 mgd) at 150 ft	60-150 ft

- Pumping from the tunnels to the POTW
- Pumping from the tunnels to the storage reservoir
- Pumping from the storage reservoir to the POTW

The pumping rate of storm flows to the POTW is controlled to maintain a maximum flow to the POTW of 1.5 times DWF. Average DWF to the POTW is 903 mgd, which leaves 455 mgd of capacity available for treatment of storm flows (Dalton and Goyal, 1989).

A supervisory control and monitoring system (SCMS) provides the following remote control functions at the Mainstream Pumping Station (Dalton and Goyal, 1989):

- Pump control and monitoring
- Power circuit breaker control and monitoring
- Dewatering tunnel gate control and monitoring
- Tunnel discharge valve control and monitoring
- Closed circuit television control

Tunnel System Operation

Deep tunnel storage systems can have various operating strategies. The simplest operating strategy allows the system to fill with no restrictions at the dropshafts until the tunnels, dropshafts, and consolidation conduits are filled and an overflow occurs. An alternative operating strategy is to prioritize areas served by the system. Under this strategy, flows to a dropshaft of low priority are throttled in order to allow inflow from a higher priority dropshaft. A higher priority is assigned to a dropshaft that serves an area with a more sensitive receiving water. A real time control system can be used to operate the throttling gates. If the volume of captured CSO does not exceed the storage capacity, the stored flow is pumped to the treatment facility during the dry weather period. The Chicago TARP system pumps excess volume to large pit-type storage reservoirs when the tunnel system is filled to capacity.

Storage of combined flows allows solids deposition in the tunnel system. In unlined tunnels, a concrete invert increases velocities and reduces solids deposition. Solids can be resuspended by flushing the tunnels during dry weather. Sources of flushing water include existing interceptor sewers or surface waters. Flushing water can be removed using high head pumps capable of handling the high solids concentration expected during flushing. The required volume of flushing water is determined by the diameter, length, and grades of the tunnel sections.

Coarse Screening

Process Description

Coarse screening equipment, consisting of vertical or inclined steel bars spaced evenly across a channel, with or without mechanical raking apparatus, traditionally is located at the headworks of POTWs to remove from the influent flow large objects that might otherwise damage downstream equipment or clog downstream pipes. Depending on the clear spacing between the bars, coarse screens also can entrain rags and floatables. Coarse screening equipment is installed at CSO control facilities, both for the protection of downstream equipment and to provide floatables removal.

The types of bar screens used at CSO control facilities include trash racks, manually cleaned screens, and mechanically cleaned screens. The major features of each type are (Metcalf & Eddy, 1991a; WEF, 1992):

- Trash racks
  - Typically 1.5- to 3-inch clear spacing between bars
  - Intended to remove large objects such as timber planks and stumps
  - Often followed by bar screens with smaller clear spacing
- Manually cleaned bar screens
  - 1- to 2-inch clear spacing between bars
  - Bars set 30 to 45 degrees from the vertical

  - Screenings are manually raked onto a perforated plate for drainage prior to disposal
  - Commonly used in bypass channels for mechanically cleaned bar screens
- Mechanically cleaned bar screens
  - 0.25- to 1-inch clear spacing between bars
  - Bars set 0 to 30 degrees from the vertical
  - Electrically driven rake mechanism either continuously or periodically removes material entrained on the bar screen
  - Common types of mechanically cleaned screens include chain-driven, with front or back cleaning; reciprocating rake; catenary; and continuous

Automatically activated, mechanically cleaned screens are recommended for CSO facilities. Of the mechanically cleaned bar screens, the catenary type most commonly is selected for CSO control facilities (Figure 4-13). Catenary screens are rugged and reliable. All sprockets, bearings, and shafts are located above the screenings channel, reducing the potential for damage and corrosion and facilitating routine maintenance. The cleaning rake is held against the bars by the weight of its chains, allowing the rake to be pulled over large objects that are stuck in the bars and that might otherwise jam the rake mechanism. The chain-driven, front or back cleaning types are better suited for separate sanitary flows, and may be susceptible to jamming and increased maintenance if exposed to the range of debris present in combined flows. Reciprocating rake screens have limited capacity to handle peak screenings loads. Continuous self-cleaning screens tend to have a higher capacity for solids handling than the more traditional design, and have potential for application at CSO control facilities. More detailed descriptions of screening devices are in the literature (Metcalf & Eddy, Inc., 1991a; WEF, 1992; U.S. EPA, 1977b).

Process Design

The following discussion of design considerations for coarse screening equipment includes hydraulic considerations, equipment details, solids handling, and process flow. Supplemental information is available from equipment manufacturers and the literature (Metcalf & Eddy, Inc., 1991a; WEF, 1992).

Hydraulic Considerations

A straight upstream channel provides the most uniform flow velocity distribution across a screen, which, in turn, will result in a more even distribution of solids entrained on the screen. The headloss across a clean bar screen can be estimated from the following equation (Metcalf & Eddy, Inc., 1991a):

$$h_L = \frac{1}{0.7}\left(\frac{V^2 - v^2}{2g}\right)$$

where:

h_L = headloss, ft (m)

0.7 = an empirical discharge coefficient to account for turbulence and eddy losses

V = velocity of flow through the openings of the bar rack, ft/s (m/s)

v = approach velocity in upstream channel, ft/s (m/s)

g = acceleration due to gravity, ft/s^2 (m/s^2)

For coarse screens, the approach velocity should be at least 1.25 ft/s to minimize deposition, while the velocity through the bars should be less than 3 ft/s to prevent entrained solids from being forced through the bars (Metcalf & Eddy, Inc., 1991a). Instrumentation provided with mechanically cleaned bar screens is configured to trigger cleaning cycles so that headloss across the bar screen is limited to 6 inches.

At POTWs, solids deposited in the screenings channel during periods of low flow sometimes can be resuspended during peak flow periods. At CSO control facilities, however, peak flows generally occur during the early part of the storm, after which the flow gradually tails off. There is typically no equivalent to the diurnal peak flows which could repeatedly scour the bar screen channel. In addition, towards the end of a storm, as flows subside, backwater from a storage/sedimentation tank effluent weir can create quiescent conditions in the bar screen channel. A means to flush or otherwise handle solids deposited in the screenings channel, therefore, should be provided.

A redundant or standby bar screen should be provided so that peak flow to the facility can be maintained with one unit out of service. Screenings channels with sets of stop log grooves or slide gates will allow each bar screen to be isolated from the influent flow for maintenance.

Equipment Details

Data have been published that relate estimated screenings quantities to bar screen spacing for separate sanitary sewer systems, but these data do not apply to combined systems, which may produce higher screenings loading rates during storm events (WEF, 1992). The 0.5- to 1.0-inch range for bar spacing is common for mechanically cleaned screens at CSO control facilities.

Suitable guards, railings, and gratings should be provided around the screening equipment to ensure operator safety. Electrical fittings and devices associated with the screening equipment must conform to the exposure rating for the space in which the equipment is located (Great Lakes-Upper Mississippi River Board, 1978). If screens discharge to screenings

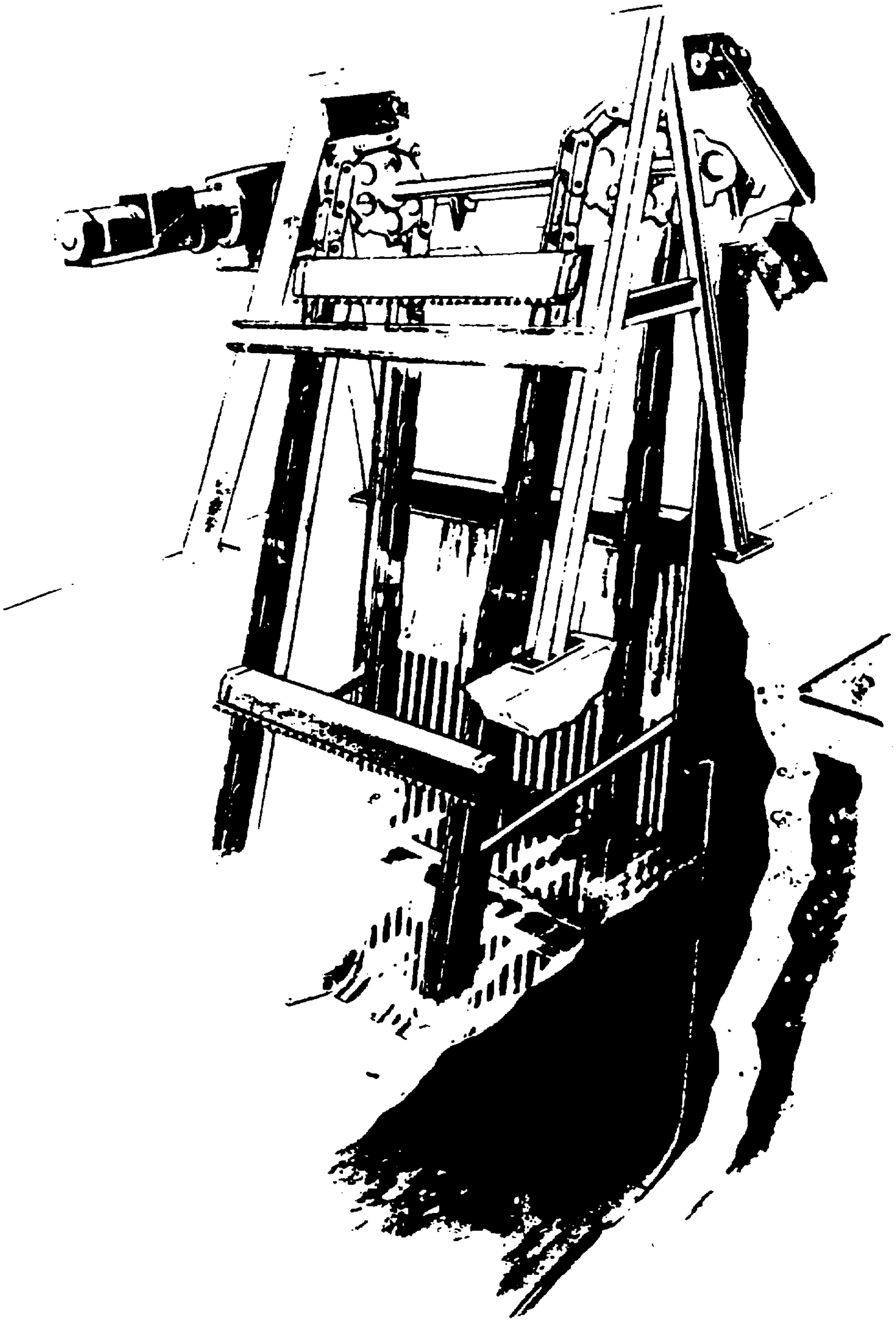


Figure 4-13. Catenary-type mechanically cleaned bar screen (WEF, 1992).

carts or containers, hoisting and transport equipment is needed to transfer the screenings from the containers to a truck for disposal. A monorail-mounted hoist can provide such capability.

Solids Handling

The quantities of screenings removed at CSO facilities can be highly variable, depending on the configuration of the drainage system, the time of year, the interval between storms, and other factors. Average CSO screenings loads range from approximately 0.5 to 11 cf/MG, with peaking factors based on hourly flow ranging from 2:1 to greater than 20:1. The bulk density of screenings from combined flows range from 40 to 70 lb/cf (WEF, 1992).

Methods for handling screenings from mechanically cleaned bar screens vary among existing CSO control facilities. Examples of handling methods include:

- *Newport, Rhode Island, Washington Street:* Screenings from this storage/sedimentation facility are discharged into 1-cubic yard capacity bins, which are manually wheeled to a monorail hoist. A lifting/dumping frame is attached to the bin to keep the bin in an upright position while being carried on the hoist. The frame features a release arm for dumping the contents of the bin into a truck for disposal (Metcalf & Eddy, Inc., 1991b).
- *Atlanta, Georgia, Intrenchment Creek:* Screenings from the headworks of this physical/chemical CSO treatment facility are discharged into conveyors, which carry the screenings to collection bins. During operation material has spilled repeatedly on the floor and the conveyor belts have jammed. A study of this facility's operations recommended that future facilities use an alternative screenings handling system (West et al., 1990).
- *MWRA Cottage Farm:* This detention facility features trash racks upstream of bar racks, both mechanically cleaned, catenary type. The trash rack screenings are deposited into dumpsters, while the bar rack screenings are discharged to a sluiceway and flushed back to the interceptor (U.S. EPA, 1977a).
- *MWRA Prison Point:* Screenings from this detention facility are discharged to a conveyor belt and carried to a sorting table. From the sorting table, screenings are fed manually into a hammermill grinder, then discharged back to the interceptor. Material unsuitable for grinding, such as bricks or heavy-gauge scrap metal, is removed at the sorting table and disposed of separately (Maguire, 1981).

Process Flow

As at POTWs, bar screens at CSO control facilities are located at the head of the facility, upstream of the tanks and process equipment, but typically downstream of the regulator that diverts flow to off-line facilities. Some facilities, such as the MWRA Cottage Farm and Atlanta Intrenchment Creek facilities, are equipped with larger-opening trash racks upstream of smaller-opening, mechanically cleaned bar screens. As noted above, at Cottage Farm both the trash racks and bar screens are catenary-type mechanically cleaned. A performance study at this facility noted that very little material was collected on the trash racks, and suggested that manually cleaned trash racks would have been suitable (U.S. EPA, 1977a).

At the Decatur, Illinois, McKinley Avenue facility, a manually cleaned bar screen with 2-inch openings was provided as a bypass for times when the mechanically cleaned catenary screen was out of service. During an operational study, concerns were raised that the manual screen might become subject to clogging if forced into operation since personnel may not be available at the facility (which normally is not staffed) to manually clean it. The study recommended that if manual bypass screens were provided, they should be sized to capture only objects that are large enough to damage downstream equipment (BGMA and CMT, 1977).

System Controls and Operation

Controls for mechanically cleaned bar screens include some combination of the following:

- Manual start/stop
- Automatic start/stop on timer
- Automatic start/stop on differential head

At CSO facilities, activation of mechanically cleaned bar screens is triggered by remote sensing of flow into the facility, or water level in the screening channel. Timed cycles, if used, should include a high differential head override. Near-continuous operation may be required during the initial phase of the storm when a greater portion of leaves, litter, and other solids may be carried in the initial peak flows to the CSO facility. Automatic start-up of the bar screens should include a time delay to prevent premature initiation of operation due to transient surges in flow.

Table 4-8 presents examples of bar screen installations at CSO control facilities. The table indicates bar screen type, bar spacing, screenings handling method, and control sequence.

Table 4-8. Examples of Bar Screen Installations at CSO Control Facilities

Location	Facility Type	Bar Screen Type	Bar Spacing (in)	Screening Disposal Method	Operation/Control
Newport, Rhode Island Washington St. (Metcalf & Eddy, Inc., 1991b)	Storage/treatment	Catenary	0.75	Discharge to 27-cf carts	Auto start on high level float switch; continuous operation
Atlanta, Georgia Intrenchment Creek (West et al., 1990)	Storage/treatment	Trash rack	3.0	Discharge to conveyor	
			0.75	Discharge to conveyor	
MWRA Cottage Farm (U.S. EPA, 1977a)	Storage/treatment	Catenary (trash rack)	3.5	Discharge to dumpster	Auto start on high level
		Catenary	0.5	Discharge to sluiceway	Auto start on high level
MWRA Prison Point (Maguire, 1981)	Storage/treatment	Catenary	0.5	Discharge to conveyor, to sorting table, then to hammermill grinder	Control by timer, differential head, or manual
MWRA Constitution Beach (Hayden-Wegman, 1989)	Coarse screening/ disinfection	Catenary	1.0	Discharge to carts	Automatic start/stop controlled by water level
MWRA Somerville Marginal Pretreatment Facility (Tighe & Bond, Inc., 1990)	Coarse screening/ disinfection	Catenary	0.5	Discharge to conveyor to storage container	Auto start on water level; stop after time delay following gate closure.
MWRA Fox Point (Hayden-Wegman, 1991)	Coarse screening/ disinfection	Catenary	0.75	Discharge to container	Auto start/stop on water level
Decatur, Illinois McKinley Ave. (BGMA and CMT, 1977)	Storage/swirl concentrator	Catenary	1.0	Discharge to cart	Auto start/stop on differential head
Washington, DC NEB Swirl Facility (O'Brien & Gere, 1992)	Swirl concentrator	Catenary	1.0	Discharge to 80-cf fixed bins; bins emptied by vacuum truck	Control by timer or differential head

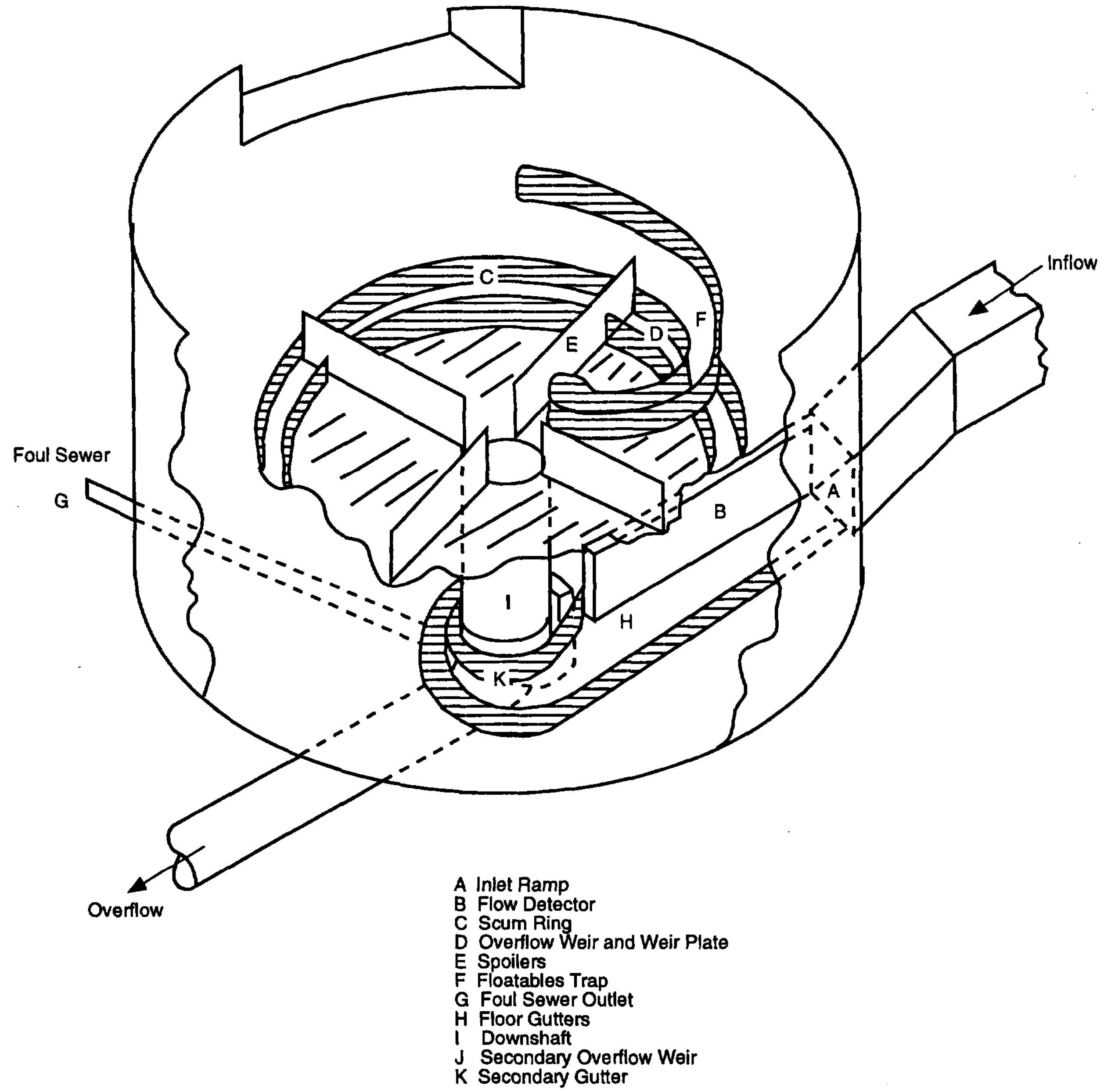
Swirl/Vortex Technologies

Swirl concentrators and vortex separators are compact flow throttling and solids separation devices that provide flow regulation and a rough level of solids and floatable removal in combined flows. The technology originally was applied in England in the 1960s, and since has evolved into a number of configurations. Three of the more common technologies are the EPA swirl concentrator, the Fluidsep vortex separator, and the Storm King hydrodynamic separator. The differences among the three separator types came about through experimental work aimed at creating flow conditions within the unit that would optimize the liquid/solid separation.

Theory

Although each of the three types of separators is configured differently, the operation of each unit and the mechanism for solids separation are similar. Flow entering the unit is directed around the perimeter of a cylindrical shell, creating a swirling, vortex flow pattern. The swirling action throttles the influent flow, and causes solids to be concentrated at the bottom of the unit. The throttled underflow containing the concentrated solids passes out through a foul sewer outlet in the bottom of the unit, while the clarified supernatant passes out through the top of the unit. The underflow is typically discharged to the downstream interceptor for treatment at the POTW. Various baffle arrangements capture floatables in the supernatant. The floatables are carried out in the underflow when the unit drains, once storm flows subside.

The mechanism for solids separation is created by the flow patterns within the unit. Flow initially follows a path around the perimeter of the unit. After one revolution, the flow is deflected into an inner swirl pattern, which has a lower velocity than the outer swirl. Gravity separation occurs as particles follow a "long path" through the outer and inner swirl. The quiescent inner swirl, as well as tangential breakaway of particles from the cyclonic flow field and drag forces along the walls, bottom, and in the shear zone between the inner and outer swirl, all contribute to solids separation. Secondary currents direct particles across the floor of the unit towards the foul sewer outlet. Examples of each of the three common types of swirl/vortex units are presented in Figures 4-14 through 4-16.



A Inlet Ramp
B Flow Detector
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

Figure 4-14. Example EPA swirl concentrator (U.S. EPA, 1982).

Performance of swirl/vortex devices depends primarily upon hydraulic throughput and the settling characteristics of the solids in the combined flow. The settling characteristics are particularly important. The EPA swirl concentrator is most effective at removing solids with characteristics similar to grit (0.2 mm diameter, 2.65 specific gravity), while the particle settling velocity profile of the flow to be treated is required to predict the removal efficiency of the Fluidsep and Storm King devices. Determining the particle settling velocity distribution in samples of the actual flow to be treated is strongly recommended in order to better predict actual solids removal efficiencies.

Opinions differ as to the effect of turbulence and free vortex formation on performance. The EPA swirl is designed with vertical baffles to "reduce the rotational energy of the liquid above the weir plate, and between the scum ring and the weir" (U.S. EPA, 1982). These baffles, along with a flow deflector at the inlet, disrupt the free vortex flow, with the intent of creating a more "gentle" swirl. Laboratory studies showed that the baffles improve solids separation performance (U.S. EPA, 1972). The Fluidsep, by comparison, features no vertical baffles or flow deflectors, with the specific intent of encouraging free vortex flow. The researchers who developed the Fluidsep unit contend that the free vortex creates less turbulence than the disrupted flow patterns in the EPA swirl. The differences among the three common types of swirl devices are outlined in the section called Design Details.

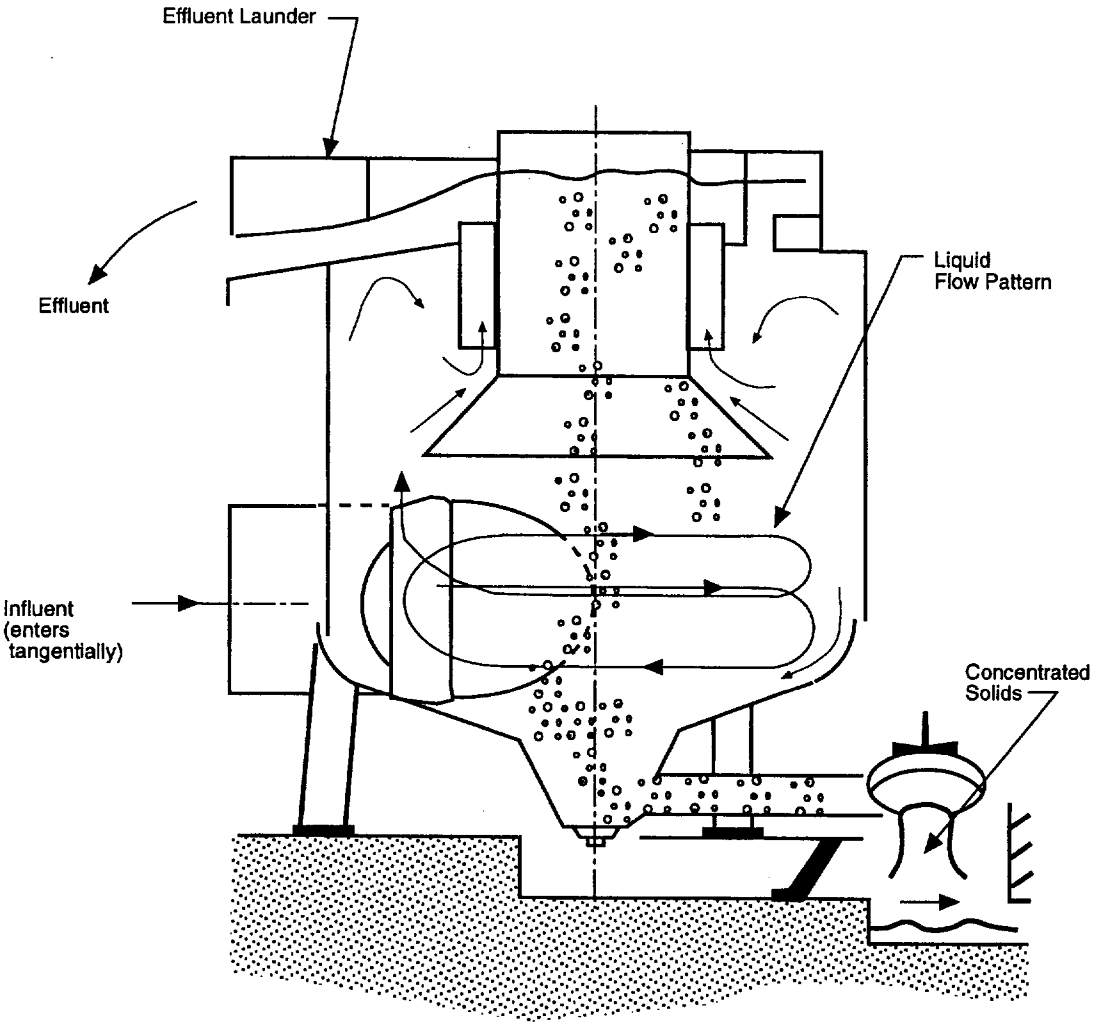


Figure 4-15. Example Fluidsep vortex separator (Metcalf & Eddy, Inc., 1991a).

Process Design

The design of swirl concentrators and vortex separators is based on the scale-up of empirical data from experiments on model systems. Researchers used models to develop optimum configurations and dimensions for a given set of conditions (flow, solids settling velocity distribution). Model dimensions were then scaled-up to match the conditions of the intended application, using Froude's Law of Similarity.

The methodology for sizing swirl concentrators varies among the three types of devices. A detailed procedure for the design of the EPA swirl concentrator has previously been published (U.S. EPA, 1982), while the sizing computations for the Fluidsep vortex separator and the Storm King hydrodynamic separator are mostly proprietary. A general description of the methodology for sizing these units is provided below. The reader is referred to the EPA swirl concentrator design procedures (U.S. EPA, 1982) and the respective manufacturers of Fluidsep and Storm King for more specific sizing information.

EPA Swirl Concentrator

During the 1970s, EPA conducted a series of performance studies on secondary-flow-motion wastewater control/ treatment devices, which were the prototypes for the standard EPA swirl concentrator. The purpose of these studies was to develop the optimum configuration of swirl chamber elements and dimensions to achieve flow regulation and maximum solids separation from a typical CSO flow.

The solids settling velocity distribution in the typical flow used in the studies was determined by sampling a number of grit chambers. The actual settling velocity distribution used in the EPA design is presented in Figures 4-17 and 4-18. Average settling velocity profiles from other sampling studies of combined and sanitary wastewater are presented in Figure 4-19. For the prototype performance studies, synthetic solids were created to match the "standard" settling velocity distribution developed from the grit chamber studies (U.S. EPA, 1972, 1975c).

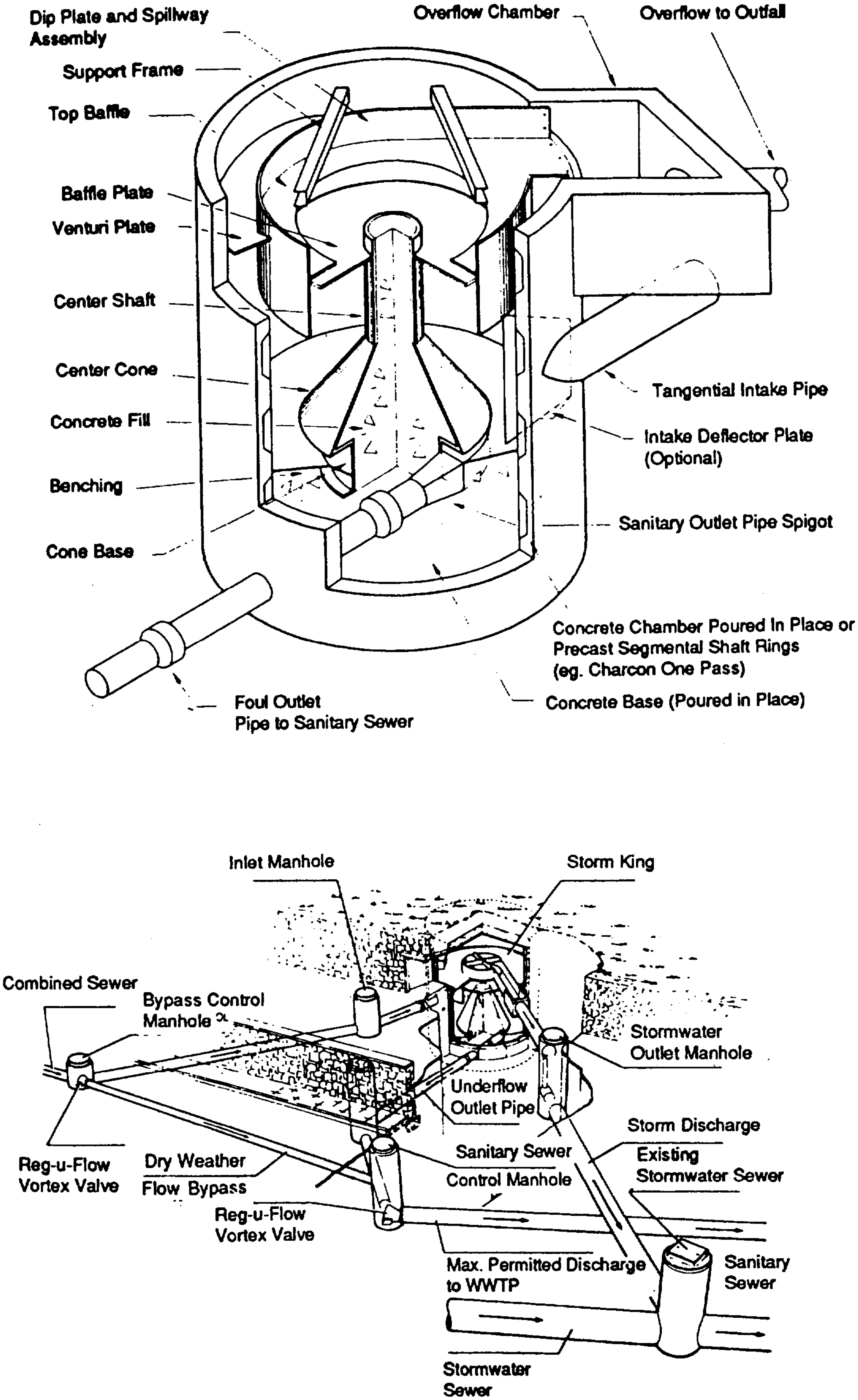


Figure 4-16. Example Storm King hydrodynamic separator (H.I.L. Technology, Inc. undated).

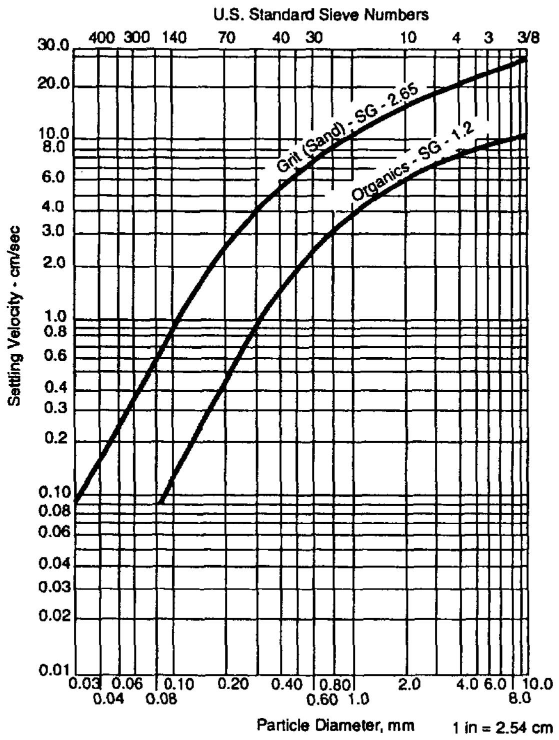
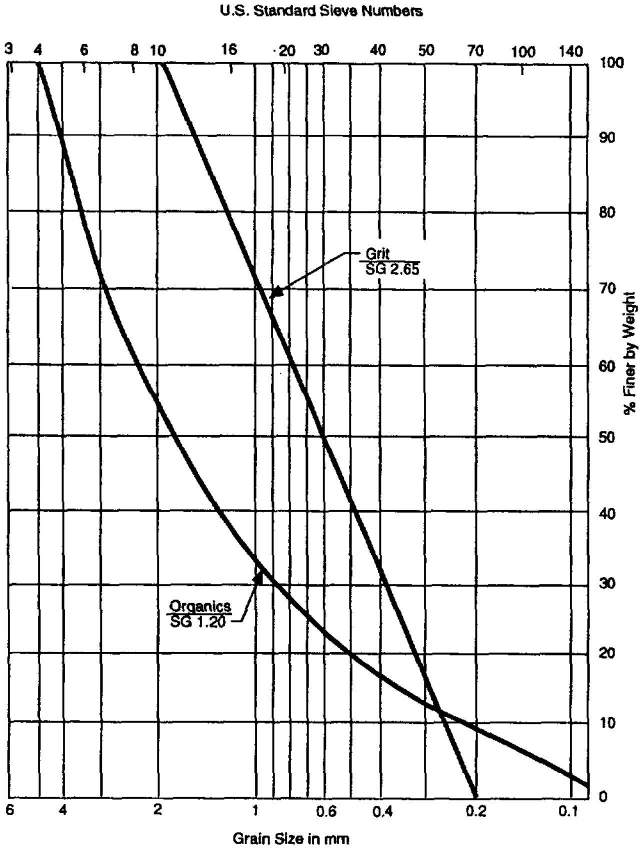


Figure 4-17. Particle settling velocities for grit and organic material in still water (U.S. EPA, 1982).

As a result of the studies with the synthetic waste, solids removal performance was correlated with flow and the ratio of swirl chamber diameter to inlet diameter (D_2/D_1). A series of curves were produced that related discharge to the parameter D_2/D_1, for a range of values for inlet diameter and percent settleable solids removal. Given the flow and the desired settleable solids removal, the curve will yield the value of D_2/D_1 corresponding to the selected inlet diameter, assuming a ratio of unit diameter to weir height (D_2/H) of 0.25. Additional curves were developed for revising the D_2/D_1 ratio based on a D_2/H ratio of other than 0.25, since in some cases the available head may make H a controlling parameter. All of these design curves are presented in U.S. EPA, 1982. The remainder of the unit is dimensioned in proportion to the values of D_2, D_1, and H determined in the initial steps.



U.S. Sieve Size	Size mm	Size in.	% Finer by Weight Grit	% Finer by Weight Organics
4	5.0	(0.020)	100	100
10	2.0	(0.08)	100	53
20	0.84	(0.034)	63	31
40	0.42	(0.017)	31	17
50	0.30	(0.012)	18	14
70	0.20	(0.008)	0	10

Figure 4-18. Typical gradation for grit and organic material (U.S. EPA, 1982).

In practice, the EPA swirl concentrator is intended to be primarily an in-line flow regulator, and is not intended to remove the lighter solids that may be found in combined flows. A suggested method for estimating the actual solids removal performance of a swirl concentrator involves comparison of the actual solids settling velocity profile of the flow to be treated with the theoretical settling velocity profile for grit developed by EPA. From Figure 4-17, grit particles of 0.2 mm have a settling velocity of approximately 2.5 cm/sec. A swirl concentrator designed in accordance with EPA recommendations (U.S. EPA, 1982) is intended to remove 90 percent of grit-sized particles. Given an actual settling velocity distribution curve, the swirl might be expected to remove 90 percent of the particles with settling velocities equal to or greater than 2.5 cm/sec. On this basis, an overall estimated solids removal rate can be computed.

Two factors may contribute to the appearance of lower-than-expected removal efficiencies for the EPA swirl. Since the expected performance is based on the removal of particles in the size and weight range of grit, much of the material the swirl is specifically intended to remove would be in the bed load carried along the bottom of the interceptor. If the swirl unit is installed in an off-line arrangement, where flow is diverted to the swirl through a side weir or high-outlet regulator, then the bed load would most likely be carried down the

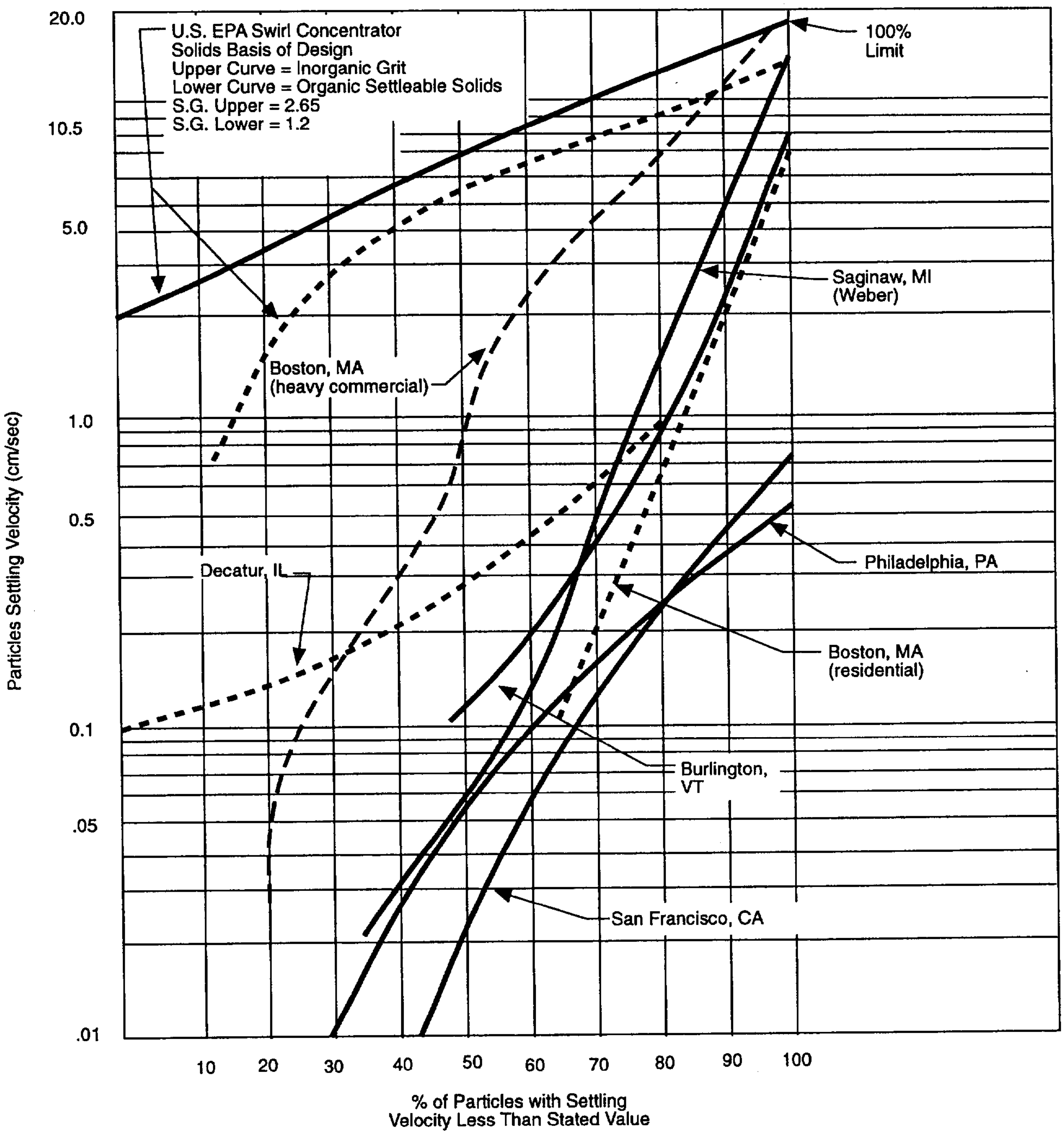


Figure 4-19. Settling velocity profiles of combined and sanitary wastewaters (Pisano, 1990).

interceptor and would not be part of the influent to the swirl. Similarly, a swirl unit located downstream of a storage tank may not receive the heavier fraction of solids that it is capable of removing.

In addition, the sampling apparatus used to assess swirl performance may not take a representative sample of the influent flow. A single sample draw-off located at mid-depth in the influent pipe might not pick up heavy solids passing to the unit in the bed load. The sampler intake velocity also must be sufficient to carry the heavier grit particles into the sampler. Since the bed load solids may constitute a significant fraction of the total solids mass loading, failure to pick up the bed load solids in the swirl influent, effluent, and underflow could skew the overall performance results.

Fluidsep Vortex Separator

As with the EPA swirl, the standard configuration of the Fluidsep vortex separator evolved through a series of studies aimed at optimizing the solids removal efficiency of the unit. However, rather than basing the design on a "typical" CSO solids settling characteristic, as EPA did, a generalized design procedure was developed. This procedure can be used for any given solids settling distribution, stated performance level for the final swirl design, and design discharge. Therefore, the user is required to perform studies of the existing CSO solids settling characteristics before the Fluidsep vortex separator can be designed.

The first step in the design procedure for site-specific applications is to determine the actual solids settling velocity profile in the CSO to be treated. Froude's Law of Similarity then is applied to the "real-world" solids distribution to obtain a model solids distribution curve. Model tracer removal curves then are applied to the model solids distribution curve to develop a curve of predicted removal efficiency versus flow for given vessel geometries (Pisano, 1990). A nominal D/H ratio of 2.5 initially is used for the design, although the final ratio chosen depends on considerations such as the available head, site area, and construction costs. Designs are available with D/H ratios varying from 0.5 to 3.0. This information then is used by Fluidsep to design the final swirl through a proprietary process.

Since the design is based on actual solids settling characteristics determined through sampling CSO discharges, removal efficiency predictions for the Fluidsep vortex separator should be more precise than for the EPA swirl. However, inflow solids stratification still can pose problems in accurately characterizing the influent, thereby making removal efficiency calculations difficult.

Storm King Hydrodynamic Separator

The design of the Storm King hydrodynamic separator is based on the solids settling velocity profile of the CSO to be treated, and the hydraulic loading or overflow rate. Through studies with its unit, the manufacturer of the Storm King has developed a series of optimal overflow rates for particular ranges of solids to be removed. Thus, if the influent flow rate and the distribution of solids are known, the manufacturer can provide a unit of diameter determined from the optimum overflow rate for the given size of material to be removed. As with the Fluidsep vortex separator, the specific dimensional details for the vessel, as well as the inlet, outlet, and other features of the Storm King, are proprietary. The Storm King separator differs from the Fluidsep primarily in the location of the solids outlet and the introduction of internal components designed to stabilize secondary flows.

General Hydraulic Considerations

In addition to the specific sizing procedures discussed above, the configuration of a swirl unit, or even the feasibility of installing a swirl unit, may depend upon system hydraulics. One of the main considerations is to determine to what level the influent sewer can be surcharged without causing upstream flooding. This elevation, in conjunction with the elevation head on the effluent weir, will set the elevation of the unit with respect to the influent sewer. For example, Figure 4-20 indicates an empirically derived curve of head versus discharge per linear foot of weir length for a circular weir (U.S. EPA, 1972). For a maximum flow of 300 cfs and a circular weir length of 60 feet, the discharge would be 5 cfs/ft, corresponding to a head of approximately 3 feet. If entrance losses were neglected, the weir crest then would be set 3 feet below the maximum hydraulic grade line allowed in the influent sewer.

Since overloading the swirl units decreases performance, the units are provided with some manner of overflow weir to relieve peak flows. The EPA swirl design recommends that flows to the unit be limited to twice the design flow (U.S. EPA, 1982), and both the Fluidsep and Storm King swirls are designed for the peak flow. The crest elevation of the side overflow relief weir can then be determined from the head on the weir at the maximum flow using Figure 4-20.

If the available head is minimal, the geometry of the unit may be modified, in certain instances, to reduce the required head. Pumping the foul sewer discharge also has been employed at installations where the system hydraulics prevent gravity flow of the foul sewer discharge to the interceptor.

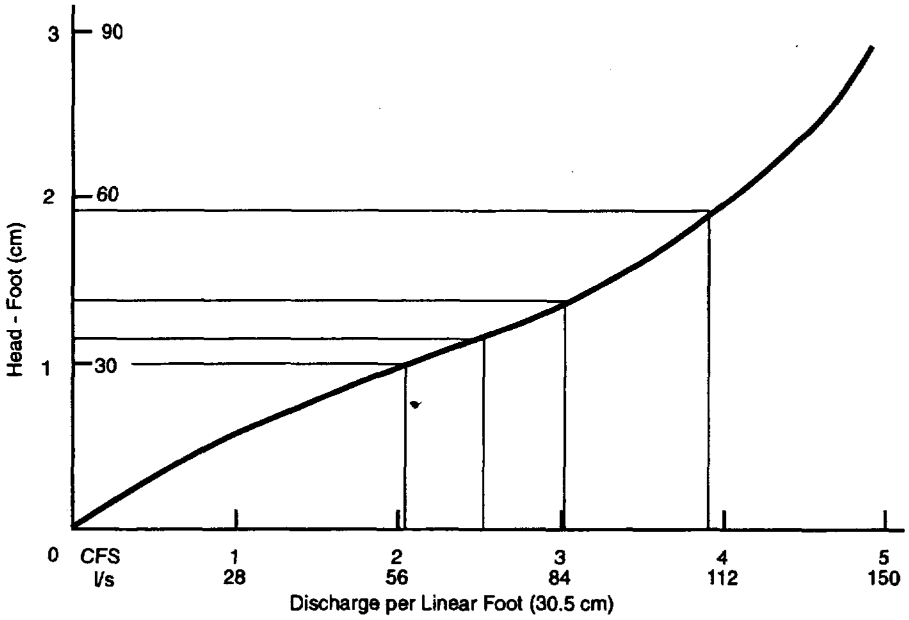


Figure 4-20. Head vs. discharge per linear foot of weir length for a circular weir (U.S. EPA, 1982).

Process Flow

Four of the common layouts for swirl concentrator and vortex separator installations are illustrated in Figure 4-21. Selection of the best arrangement for a particular application may depend on the overall system-wide CSO control strategy, treatment goals, cost, and/or site availability.

Off-Line, Stand Alone

With this arrangement (Figure 4-21a), a regulator diverts flows in excess of the interceptor capacity to the swirl/vortex unit. Diversion weirs and vortex valves are examples of regulators that have been used for this purpose. The supernatant or effluent is discharged from the separator to the receiving water while the concentrated foul sewer underflow is returned to the interceptor. An upstream relief overflow, or high level weir in the swirl unit typically is provided to protect the unit during extreme storm flows.

Off-Line, With Storage Tank

This arrangement (Figure 4-21b) is similar to the off-line stand alone arrangement except that the effluent from the swirl/vortex unit discharges to a storage tank rather than directly to the receiving water. The foul sewer underflow similarly is returned to the interceptor. The potential benefit of locating a swirl/vortex unit in series upstream of a storage tank is that the unit can capture much of the grit and heavy solids that otherwise would settle out in the storage tank. In addition to making cleanup easier, removal of a fraction of the solids load may reduce the required hypochlorite dosage if disinfection is provided.

In-Line, Stand Alone or With Storage Tank

With this arrangement (Figures 4-21c,d), the swirl/vortex unit acts as a regulator, throttling flow to allow only the underflow to continue down the interceptor. The overflow from an in-line unit passes either to the receiving water or to a storage tank. The unit is sized such that peak dry weather flows pass to the interceptor without being throttled. This arrangement may be the most appropriate for the EPA swirl concentrator, which is intended to be primarily a flow-regulating device. Locating the swirl device in an in-line arrangement also will provide the best opportunity for the unit to remove the heavier fraction of solids in the flow. One drawback to an in-line arrangement is the wear and tear associated with constant exposure to flow. Should maintenance or repairs be required, provisions must be made to handle the dry weather flow until the repairs are completed.

Other Unit Processes

Many swirl/vortex facilities are designed with upstream mechanically cleaned bar racks. The bar racks protect the swirl unit from being clogged or otherwise damaged by large objects carried in the flow, and may improve floatables removal. For installations where the underflow is pumped, the bar racks also help protect the downstream pumping equipment. Swirl units have been installed in England without upstream bar racks. At the Alma Road swirl unit in Bristol, England, no blockages of the foul sewer outlet were reported during the first 3 years of operation (Smisson, 1968). In-line swirl concentrator installations that do not require pumping of the concentrated underflow may not require upstream

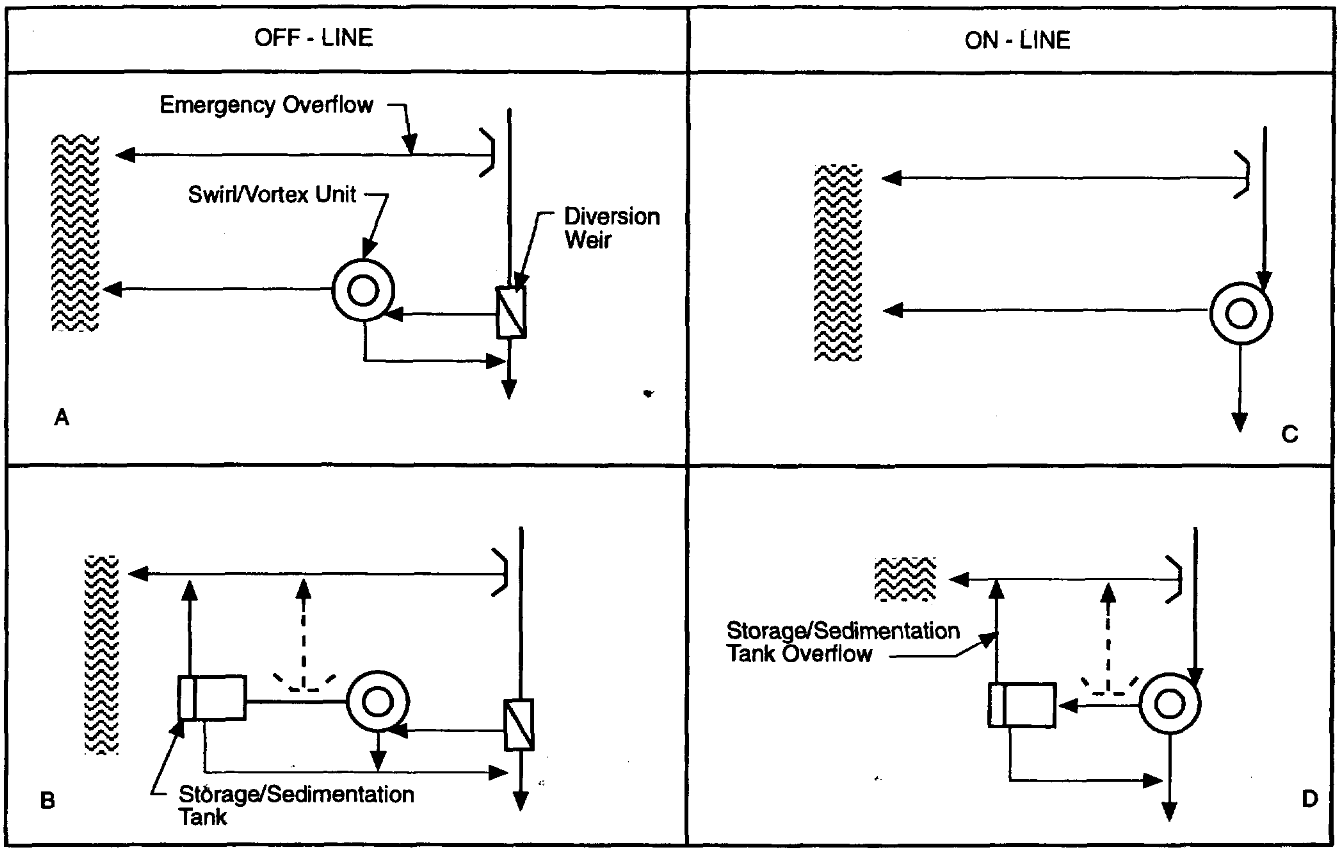


Figure 4-21. Common layouts for swirl/vortex installations (Pisano, 1990).

bar racks, as flow regulators are not provided with upstream coarse screening.

Performance Considerations

As noted above, the performance of swirl units is influenced primarily by solids settling characteristics and flow rate, and the apparent performance also may be affected by sampling techniques. Performance data for swirl units is relatively scarce, due in part to the relatively small number of installations in the United States, and also to the difficulty in obtaining data from existing units. Performance evaluations and monitoring of CSO control facilities present a number of logistical problems due to the intermittent nature of facility operation. Sampling and analysis crews must be able to mobilize on short notice, at odd hours, and for uncertain durations in order to obtain the types of data necessary to evaluate performance. Even with automatic sampling devices, supervision is required to ensure that the sampling runs smoothly. In addition, as noted above, sampling systems must be designed and installed so as to obtain a true representative sample of the solids distribution in the influent flow. Samples that do not include an appropriate fraction of the bedload may result in underestimation of the influent solids load, which may in turn result in underestimation of the solids removal performance.

The definition of performance for swirl units is not uniform. Researchers have distinguished between the removals attributable to solids separation, and the removals attributable to the function of the unit as a regulator. In a performance evaluation of the Washington, D.C., Northeast Boundary (NEB) swirl facility (O'Brien & Gere, Inc., 1992), the overall removal efficiency was determined from the ratio of influent to effluent mass loadings. The removal efficiency due to flow diversion was estimated by assuming that the foul sewer solids concentration equalled the influent solids concentration. The theoretical effluent load due to flow diversion then was obtained by subtracting the assumed foul sewer load from the influent load. The theoretical removal rate due to flow diversion was then calculated:

$$\text{removal} = \frac{(\text{influent load}) - (\text{theoretical effluent load})}{\text{influent load}}$$

The removal efficiency due to solids separation then was estimated by the difference between the actual overall removal efficiency and the theoretical removal rate due to flow diversion.

Evaluation of the performance of a Storm King hydrodynamic separator in Walsall, England (Hedges, 1992), identified a treatment factor ε, such that

$$\varepsilon = \frac{\text{(foul sewer load/influent load)}}{\text{(foul sewer flow/influent flow)}}$$

If a device provided no treatment, but simply divided the flow, then $\varepsilon = 1$. If some degree of separation and concentration occurred, then ε would be greater than 1.

Design Details

The interior features of swirl units vary among the three general types: EPA swirl concentrators, Fluidsep vortex separators, and Storm King hydrodynamic separators. In addition, since the technology has been evolving, variation exists in the design details among currently operating swirl devices of the same general type. For the EPA swirl concentrator, the dimensions and orientation of troughs, baffles, and other details are developed from the basic sizing dimensions "D1" and "D2" (inlet diameter and vessel diameter) in accordance with design procedures (U.S. EPA, 1982). For the Fluidsep and Storm King devices, sizing criteria for weirs, baffles, and other details are not available in the literature. Table 4-9 compares the key features of the three common types of separator units (refer also to Figures 4-14 through 4-16).

Chamber Construction

Concrete is the most common material of construction for the swirl chambers, although stainless steel and epoxy-coated carbon steel also have been used. Trowelled finishes and/or epoxy wall coatings have been suggested to minimize clinging of material to the chamber wall (U.S. EPA, 1984). The performance study of the Washington, D.C., NEB swirl facility recommended providing smoother coatings for the floors and walls, and rounding off the edges of the floor gutters to reduce turbulence. This study also recommended increasing the floor slope to minimize the deposit of solids on the floor (O'Brien & Gere, Inc., 1992). Examples of chamber construction are presented in Table 4-10.

Interior Baffle/Cone Construction

Interior baffles, flow deflectors, and similar components typically are constructed of carbon or stainless steel. Corrosion in the Lancaster, Pennsylvania, EPA swirl, prompted a recommendation to use stainless steel (U.S. EPA, 1984). A performance study of the Washington, D.C., NEB swirl facility presented the following recommendations regarding interior hardware for EPA swirls (O'Brien & Gere, Inc., 1992):

- Extend the floatables weir so that the weir skirt is directly over the entrance flow deflector baffle (as indicated in U.S. EPA, 1982). This adjustment creates a more continuous "inner wall" of water, and therefore, a more quiescent inner settling zone.
- Locate weir plate hangers on the inside face of the weir to reduce turbulence.
- Provide a continuous, smooth overflow weir plate and skirt to reduce turbulence.
- For multiple swirl units, set weirs to provide an even flow split at the most typical flow rates, rather than the peak design flow.

When a Storm King hydrodynamic separator was installed for the Walsall Metropolitan Borough in England, the interior base cone was constructed of light gauge stainless steel and served as a permanent form for concrete. The vessel top, including dip plate, top baffle plate, outlet chamber and channel, and floatables trap, was fabricated in sections, then bolted together at the site. A concrete platform ring cast into the vessel body supported the top assembly (H.I.L. Technology, Inc., undated).

Piping/Flow Control

The inlet pipe to a swirl unit should be laid at as shallow a slope as possible to minimize turbulence, yet maintain self-cleaning velocities. EPA recommends sizing the foul outlet for three-times DWF, and notes that it is difficult to size the underflow pipe to act as a throttle. The use of a sluice gate, motor-operated gate, or vortex valve on the foul sewer discharge is recommended to control the underflow (U.S. EPA, 1982). An underflow pipe sized to throttle flow is of smaller diameter and more prone to clogging. The level of control required for the underflow is governed by local hydraulic conditions and downstream interceptor capacity.

At the Lancaster, Pennsylvania, and West Roxbury, Massachusetts, EPA swirls, the foul outlets are controlled by vortex valves, located away from the swirl chamber. Sediments observed in the lower-velocity flow upstream of the vortex valves prompted a suggestion that the vortex valves be cast into the base of the swirl unit (U.S. EPA, 1984).

At the Decatur, Illinois, McKinley Avenue Swirl Facility (BGMA and CMT, 1977), a vortex valve on the interceptor acts as a regulator, allowing dry weather flows to pass uninhibited, but throttling flows greater than the interceptor design capacity. The throttled flows back up and pass over a weir to the McKinley Avenue facility. During startup, adjustments to the overflow weir were required to develop the design head on the vortex valve. Once the proper head was developed, the discharge from the vortex valve followed its design curve fairly well. During an 11-month performance study, the vortex valve did not become plugged.

Table 4-9. Comparison of Design Details for Swirl/Vortex Devices

	EPA Swirl Concentrator	Fluidsep Vortex Separator	Storm King Hydrodynamic Separator
Floor	Flat, or less than 2% slope; curved gutters to direct solids and DWF to foul sewer outlet	Floor sloped 4-6%; smooth; no gutters	Floor sloped; no radial gutters
Foul sewer outlet	Asymmetric; orifice offset from center of rotation of swirl	Conical outlet in exact alignment with center of rotation	Annular trough along base of interior cone, halfway between wall and center of unit
Influent entrance	Located at floor of unit; features flow deflector, to cause first revolution flow to be deflected inwards, minimizing turbulence and creating interior rotating water mass	Located at floor; no flow deflector provided	Located at mid-depth of unit; no flow deflector
Treated effluent exit	Past vertical, cylindrical scum baffle, then over vertical, cylindrical weir onto horizontal clear water plate, leading to central drop shaft; shaft passes down through center of unit, discharging below bottom of vessel	Flow passes up through annular opening between vertical, cylindrical scum baffle, and cone shaped baffle; flow passes over roof of vessel to outlet	Flow passes up through annulus between horizontal, circular baffle plate, and cylindrical, vertical dip plate; flow passes over top of circular baffle to outlet
Baffles and flow directing features	Series of vertical baffles at surface, perpendicular to rotational flow, dampens free vortex formation - influent flow deflector, effluent weir scum baffle	No baffles to dampen vortex; inner, cone-shaped baffle deflects downward lighter particles carried up by secondary currents; cylindrical scum baffle.	Horizontal, circular top baffle; cylindrical dip plate located at shear zone; interior cone along centroidal rotational axis
Floatables removal	Vertical flow deflector extends across top of unit, directing floating material to a channel; channel crosses weir plate to vertical vortex cylinder at wall of overflow downshaft; vortex draws material beneath weir plate, where it is dispersed and contained under weir plate and inside weir skirt; when storm flow subsides, floatables are drawn down and exit through the foul outlet	Vertical, cylindrical floatables skirt creates annulus with cone baffle; floatables retained behind skirt, and removed out foul sewer as flows subside	Floatables captured behind dip plate; manually removed, or passed to WWTP when water level subsides
Underflow control	Difficult to size underflow pipe to act as throttle; suggest use of gate or vortex valve to control underflow	Vortex action at underflow draw off throttles underflow, or vortex valve can be used	Use vortex valve to control underflow

Table 4-10. Examples of Swirl/Vortex Chamber Construction

Location	Swirl Type	Diameter (ft)	Chamber Construction	Reference
Lancaster, PA	EPA Swirl	24	Concrete	U.S. EPA, 1984
West Roxbury, MA	EPA Swirl	12	Carbon steel with epoxy coating	U.S. EPA, 1984
Decatur, IL (McKinley Ave.)	EPA Swirl	25	Concrete	BGMA and CMT, 1977
Washington, DC	EPA Swirl	57	Concrete	O'Brien & Gere, Inc., 1992
Presque Isle, ME	EPA Swirl	18.5	Stainless steel plate inside concrete shell	WPCF, 1989
Burlington, VT	Fluidsep Vortex	40	Concrete (proposed)	Ganley and McCarthur, 1991
Decatur, IL (7th Ward)	Fluidsep Vortex	44	Concrete	Wilcoxon and Hunsinger, 1991
Walsall Metropolitan Borough	Storm King	17.3	Concrete w/stainless steel base cone	H.I.L. Technology, Inc., undated
Clevedon, Avon	Storm King	19.7	Concrete	H.I.L. Technology, Inc., 1992

From the regulator, flow to the facility passes to a screen house. A 54-in inlet pipe from the mechanically cleaned bar screens to the swirl unit was installed at a "minimal" slope. During operation, solids were deposited in the bar rack channels and the inlet pipe. During cleanup following a storm, these solids had to be manually flushed down through the swirl unit. Increasing the slope of the inlet pipe would minimize solids deposition in the pipe, and facilitate cleanup of the screening chamber.

At the Washington, DC, NEB swirl facility (O'Brien & Gere, Inc., 1992), inflatable dams serve as regulators, diverting dry and wet weather flows to the facility. In wet weather, pressure in the dams is increased to divert more flow to the facility and to optimize in-system storage. The dams also can be deflated to relieve upstream flooding and/or excessive flow to the facility. From the dams, flow passes through mechanically cleaned bar racks, then to the three 57-foot diameter EPA swirl concentrators.

During operation of the NEB swirls, air periodically bubbled up through the effluent downshaft. The release of this entrained air could possibly reduce the capacity in the downshaft and cause premature surcharging of the overflow weir. Vents consisting of four vertical pipes were installed in the downshaft of one of the units, and were effective in eliminating this problem. The foul sewer underflow was pumped to the interceptor using torque-flow pumps.

For the Storm King hydrodynamic separator installed for the Walsall Metropolitan Borough, England, the foul sewer underflow is controlled by a vortex valve (H.I.L. Technology, Inc., undated).

The Fluidsep vortex separator system in Saginaw, Michigan, captures "first flush" flows by utilizing in-system storage and then filling two retention tanks having vortex throttles to permit continuous drainage. When the "first flush" storage capacity is filled, pumped discharge to vortex solids separators commences. Pumped underflow from the separators is detained by a third tank, while treated overflow enters a fourth tank. The continuous drainage from the two retention tanks permits optimal use of the separators and treatment tanks, particularly for long intermittent storms (Pisano, 1989).

Spray Wash Systems

Automatic spray wash systems reduce the manual cleanup effort following activation of a swirl unit. The potential benefit of an automatic wash system is greater for multiple-unit installations. EPA suggests installing two spray headers in each swirl unit: one under the horizontal circular weir plate, and one along the wall of the chamber, above the maximum water level. The hydraulic pressure on the underside of the circular weir plate may cause material to stick (U.S. EPA, 1982).

Operating experience has yielded mixed results with respect to spray wash systems. The Lancaster, Pennsylvania, EPA swirl was designed with two spray headers, in accordance with EPA recommendations (U.S. EPA, 1982). During a performance study, material hung up on the spray header, and a manual wash down system using hoses was suggested (U.S. EPA, 1984). The West Roxbury EPA swirl had no spray wash system or problems regarding clinging material (U.S. EPA, 1984). The Decatur McKinley Avenue EPA swirl does not have a spray header system. Washdown is accomplished manually using hoses from adjacent yard hydrants. A performance study noted that post-operation cleanup was time consuming, and suggested installing an automatic spray system in the swirl unit (BGMA and CMT, 1977). The EPA swirl units at the Washington, DC, NEB facility were provided with spray headers around the walls of the chambers. The spray systems worked well flushing material from the walls, but were ineffective at moving material across the floor of the units and into the gutters (O'Brien & Gere, Inc., 1992). The Fluidsep vortex separators installed at the Decatur Lincoln Park and 7th Ward Facilities do not feature automatic spray wash systems. As with the McKinley Avenue facility, washdown of these units is accomplished using hoses from adjacent yard hydrants (Drake and Hunsinger, 1990).

Structural Covering

A roof over a swirl unit is not required for functional purposes, but can be beneficial for safety and aesthetics purposes. If a roof is provided, a manhole should be provided over the floatables vortex cylinder to allow rodding of the floatables trap and foul sewer outlet (U.S. EPA, 1982). Walk-in access is most convenient and safe for removal of large floatables. An inspection walkway should be provided around the perimeter of the vessel to allow access to the weir and scum plate.

A domed cover, grating, and open tank were each considered in the design of the McKinley Avenue EPA swirl. The advantage of a dome or grate is that personnel, especially intruders, are protected from falling in. The disadvantage of a dome (or other type of solid roof) is that it creates a confined space, requiring ventilation, lighting, and appropriate safety procedures before entering the unit for maintenance. An open-grate covering eliminates these concerns, but also makes maintenance more cumbersome by restricting access. In the end, the McKinley Avenue swirl was constructed without a roof or grating. These types of considerations, including safety, maintenance access, and cost of appurtenances such as lighting and ventilation, should be evaluated on a site-specific basis.

System Controls and Operation

One of the advantages of swirl/vortex units is that they have no moving parts, and thus operation of the unit itself is governed solely by hydraulics. However, upstream regulators, mechanically cleaned bar screens, upstream or downstream pumping systems, and disinfection systems that may be associated with the swirl/vortex units typically are provided with some degree of automatic control to allow unattended startup and operation. Float switches or bubble tubes detect storm flows through rising water levels. These devices typically activate the mechanically cleaned bar screens and the disinfection system, if provided.

Some dewatering and washdown operations are designed for automatic control, while others are designed for manual operation. As an example, automatic spray wash systems could be activated on dropping water levels in the swirl unit. Refer to the sections on In-System Controls/In-System Storage, Coarse Screening, and Disinfection for additional details on the control strategies for these operations.

Process Variations

EPA recommends procedures for modifying the basic swirl design to serve as degritter, primary separator (for sewage), and for treatment of erosion runoff (U.S. EPA, 1982). In Rochester, New York, a pilot program evaluated the use of a degritter and primary separator for treating combined sewage. Flow passed through the degritter first, then the primary separator. Tests were run without chemical addition, with polymer, with polymer and alum, and with polymer, alum, and phosphorus spikes. Chemical addition did not enhance performance. The authors believe that the mode of chemical addition was responsible for the lack of improvement. Inadequate velocity gradients and/or contact time due to in-line mixing of chemicals may not have provided efficient floc development (U.S. EPA, 1979a).

Other studies demonstrate the ability of swirl degritters designed in accordance with EPA procedures to meet the projected removal rates for grit-sized particles (U.S. EPA 1974b, 1977c, 1981). These devices may be effective as off-line devices at treating swirl concentrator underflows or CSOs with particularly high fractions of grit-sized particles. The major difference between a swirl concentrator and a swirl degritter is that the degritter features a conical bottom hopper for collecting the settled grit and delivering it to a separate grit washing system. The swirl degritter has no capability to regulate flow, as the bottom outlet is solely intended for the removal of the grit.

Disinfection

Disinfection of overflows is a common goal of CSO control strategies. Since liquid sodium hypochlorite is the most commonly selected means for disinfecting CSOs, this section focuses on the design of liquid sodium hypochlorite systems. Alternative technologies such as ultraviolet radiation, ozone, gaseous chlorine, and chlorine dioxide are identified in Chapter 2 and addressed in the literature (White, 1992; WPCF, 1986; U.S. EPA, 1986; Chlorine Institute), but are not presented in detail in this manual. Dechlorination is discussed at the end of this section.

Process Theory

Disinfection effectiveness is measured in terms of reduction in bacterial concentration. The overall chlorine dose required to achieve a given bacterial kill is the sum of the chlorine demand and the chlorine residual. Since a number of substances found in CSOs can exert a chlorine demand in addition to the demand created by bacteria, the actual chlorine demand of the combined wastewater to be treated is best assessed using actual laboratory studies or pilot tests.

The expected change in bacterial concentration as a function of chlorine residual and contact time can be estimated using the Collins model, which was originally developed from pilot studies on primary effluent (White, 1992).

$$y_t = y_o\,(1 + 0.23\ Ct)^{-3}$$

where:

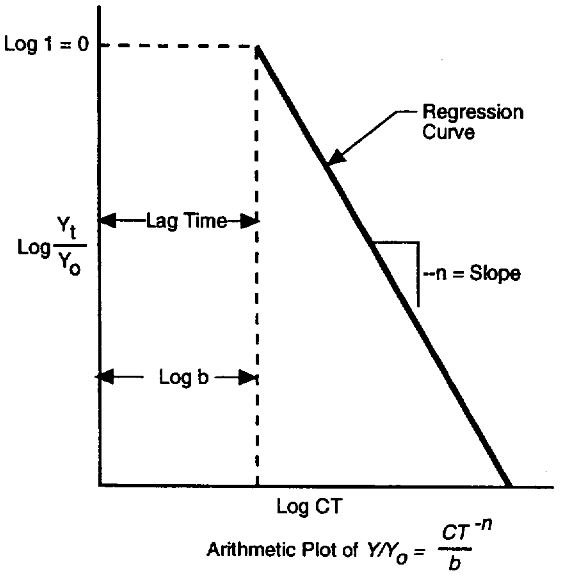
y_t = bacterial concentration after time t (MPN/100 ml)
y_o = original bacterial concentration (MPN/100 ml)
C = chlorine residual concentration after time t (mg/l)
t = contact time (min)

This equation, however, does not accurately reflect bacterial kills at low values of Ct. A modified model proposed the following relationships, which are illustrated graphically in Figure 4-22 (White, 1992):

$y_t/y_0 = 1.0$ for $Ct < b$
$y_t/y_0 = (Ct/b)^{-n}$ for $Ct > b$
b = X intercept when $y_t/y_0 = 1$
n = slope of regression line

This model requires laboratory or pilot data to define the relationship between y_t/y_0 and Ct. The values of b and n in the equation are obtained from a regression line through the data points.

The relationships described by the Collins model require thorough mixing and ideal plug flow during the contact time. Since the disinfection capability of chlorine species depends on physical contact between the chlorine-containing molecules and the bacteria, the



Arithmetic Plot of $Y/Y_o = \frac{CT^{-n}}{b}$

Figure 4-22. Graphical representations of log Y_t/Y_o versus log CT (White, 1992).

effectiveness of the dispersion of the chlorine solution into the flow can have a significant impact on the overall disinfection efficiency.

Adequate mixing is important to ensure dispersion of the chlorine solution in the flow. The intensity of mixing can be defined by the velocity gradient, G, as follows (White, 1992):

$$G = (P/\mu V)^{1/2}$$

where:
G = mean velocity gradient (sec^{-1})
P = power requirement (ft x lb/sec)
μ = absolute fluid viscosity (lb x sec/ft^2)
V = mixing chamber volume (ft^3)

For mixing by diffuser, the power requirement, P, can be expressed as:

$$P = (Q \times h)/(3{,}960 \times \text{eff})$$

where:
Q = flow through diffuser (gpm)
h = headloss in diffuser (ft)
eff = efficiency (assume = 1.0)

An alternative method for computing the velocity gradient in open channels (U.S. EPA, 1973a) is:

$$G = 1{,}730\ (v \times s)^{1/2}\ (\mu)^{-1/2}$$

where:
G = velocity gradient (sec^{-1})
v = velocity (ft/sec)
s = slope of channel (ft/ft)
μ = absolute viscosity (cp)

The parameter "GT", equal to the product of the velocity gradient and the contact time while under the influence of mixing, has been identified in pilot studies as a key to disinfection efficiency at low contact times. It has been suggested that providing turbulence during the contact time improves the level of bacterial kill (U.S. EPA, 1973a, 1979b).

One of the challenges to disinfecting CSOs is the limited contact time typically available at CSO control facilities. The limited detention time can be particularly problematic due to the higher solids concentrations in CSOs compared with secondary POTW effluent. The solids can shield the bacteria from exposure to the disinfecting agent, reducing the efficiency of the disinfection process. Separate plug-flow contact chambers generally are not provided at CSO facilities due to space and/or cost constraints. Contact time for disinfection commonly is limited to the detention time in the tanks (for a storage/sedimentation facility) and/or in the outfall pipe. A number of studies published in the 1970s investigated means for achieving high bacterial kills at lower contact times, using increased mixing intensity, increased disinfectant dosage, chemicals having a higher oxidation rate than chlorine, or a combination thereof (Crane Co., 1970; Geisser and Garver, 1977; Tift et al., 1977; U.S. EPA, 1973a,b, 1974c, 1975d, 1976, 1979a,b). These methods are generally referred to as "high-rate disinfection."

There is no clear definition as to what constitutes a "high-rate" disinfectant dosage or a "high-rate" value for GT, other than those values for which acceptable reduction in bacteria concentrations are achieved at detention times less than the conventional values of 15 to 30 minutes. For example, one study on high-rate disinfection produced the relationships between fecal coliform reduction, GT, and chlorine dosage presented in Figure 4-23 (U.S. EPA, 1979b). A GT of 10,000 with a detention time of 1 minute would be considered a high-rate application. Under these conditions, as indicated in Figure 4-23, 99.99 percent (4-log) fecal coliform reductions are achieved with a chlorine dosage of approximately 5 mg/l. If the velocity gradient G were reduced, a corresponding increase in chlorine dosage is required to achieve the same level of bacterial kill at the same 1-minute detention time. Another study reported approximately 99.99 percent total coliform reduction with a 10 mg/l chlorine dosage and a GT of approximately 5,000 (2-minute detention), with G = 40 sec^{-1} (U.S. EPA, 1973a).

When using bench-scale or pilot studies to assess the chlorine demand of the flow to be treated, consideration should be given to the principles of high rate disinfection, particularly with regard to the anticipated available contact time, and the effects of mixing and turbulence of projected required dosages.

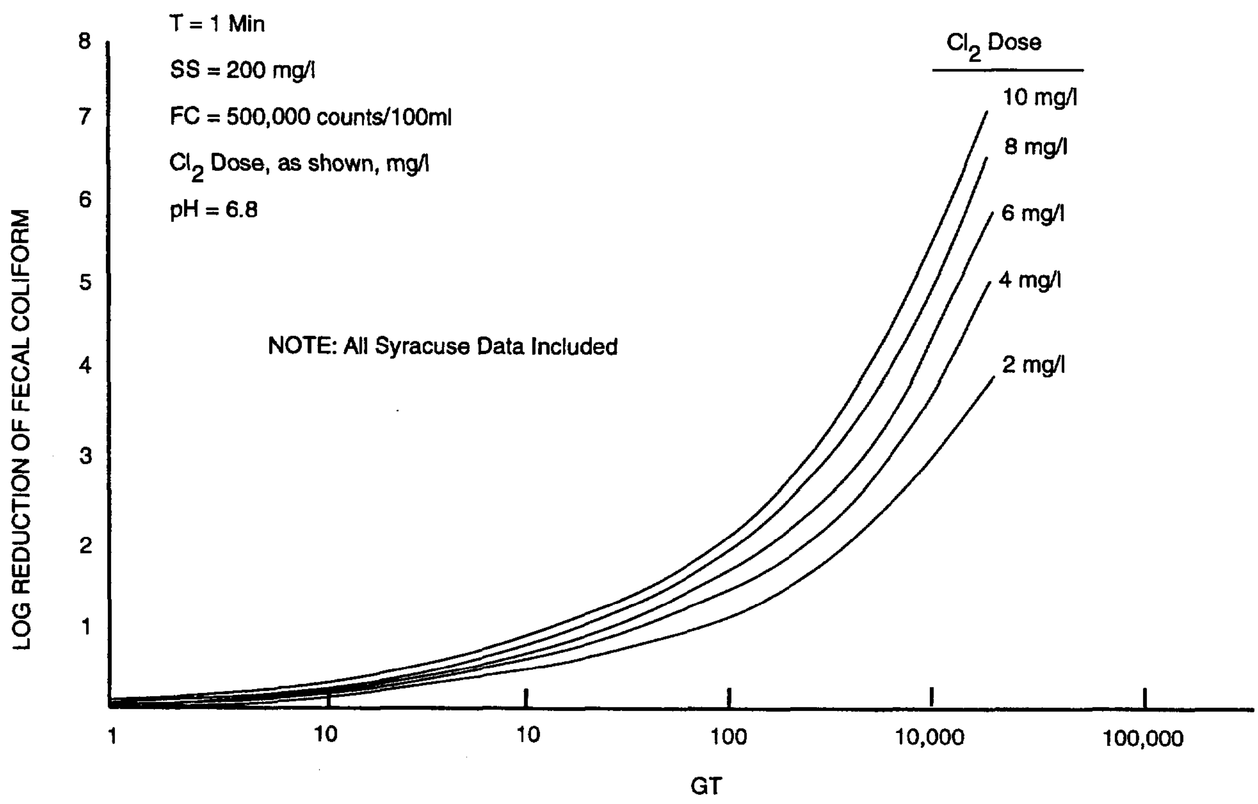


Figure 4-23. Relationship between GT and bacterial kill (U.S. EPA, 1979b).

Process Design

Sizing of disinfection equipment is based on the required dose rate and expected flow. In some states, the permitting agency may specify a maximum required dosing capacity, such as 25 mg/l at peak flow. In other states, the permitting agency may specify the maximum allowable bacteria concentration, such as 1,000 MPN/100 ml fecal coliform. Where a maximum coliform bacteria discharge limit is provided, some knowledge of influent flow bacteria concentration and chlorine demand is required to estimate the required dosage. Given an average influent bacteria concentration, y_0, a value for the required effluent bacteria concentration, y_t, and a specified minimum contact time (15 min at peak flow is typical [Metcalf & Eddy 1991a]), the required residual can be estimated from the Collins model. For example, typical primary effluent might have an initial bacteria concentration $y_0 = 38 \times 10^6$ MPN/100 ml (White, 1992). If the discharge requirement is 1,000 MPN/100 ml, then:

$$1{,}000 = 38 \times 10^6 \times (1 + 0.23\ Ct)^{-3}$$

where:

$Ct = 142$

For $t = 15$ min, $C = 9.47$ mg/l

Allowing for an immediate (3-5 minutes) demand of 8 mg/l, and a die away demand during contact time (25+ minutes) of 1 mg/l, then the estimated dosage for the above example would be about 19 mg/l.

As noted above, final sizing of the disinfectant dosing system should be based on pilot studies the actual combined flow to be treated. If a storage/sedimentation tank is to provide contact time, actual required dosages may be higher than predicted by models, due to the concentration of solids in the influent combined flow. Pilot studies also should allow evaluation of other high-rate disinfection techniques, such as increasing mixing intensity and using chemicals with a higher oxidation rate than hypochlorite. Equations such as the Collins model estimate the relationship between dosage and contact time for a given reduction in bacterial concentration, and therefore provide a basis for designing pilot tests for assessing actual dosages required.

Once the required maximum dosage is established, the metering pump capacity can be computed based on the estimated strength of the hypochlorite solution. The strength of hypochlorite solution is presented as a "trade percent," which is essentially a percent by volume, computed as:

$$\text{trade percent} = \frac{\text{g/l available } Cl_2}{10}$$

The weight percent of available chlorine is the trade percent divided by the specific gravity of the solution:

$$\text{weight percent available chlorine} = \frac{\text{trade percent}}{\text{specific gravity}}$$

The specific gravity of a hypochlorite solution of a given strength is not constant; rather, it depends on the amount of excess sodium hydroxide the manufacturer uses to promote stability. For example, to compute the required metering pump capacity for a CSO facility with a peak flow of 40 mgd, using 10 percent (trade) sodium hypochlorite (specific gravity = 1.14) and a 15 mg/l dose rate, let:

Q_p = metering pump capacity (gph)
C_p = concentration of stock sodium hypochlorite (mg/l)
Q_f = peak effluent flow (mgd)
C_f = required sodium hypochlorite dose rate (mg/l)

then:

$$Q_p \times C_p = Q_f \times C_f \times 41{,}667 \text{ gph/mgd}$$

$$C_p = \%\text{ available } Cl_2 \text{ by weight} = \frac{10\%}{1.14} = 8.8\%$$

$$C_p = 8.8\% \times (10{,}000 \text{ mg/l})/1\% = 88{,}000 \text{ mg/l}$$

$$88{,}000 \text{ mg/l} \times Q_p = 15 \text{ mg/l} \times 40 \text{ mgd} \times 41{,}667 \text{ gph/mgd}$$

$$Q_p = 284 \text{ gph}$$

Process Flow

At CSO storage/treatment facilities, liquid sodium hypochlorite usually is introduced at the upstream end of the facility to maximize the contact time in the tanks. Some facilities also provide a second dosing location downstream of the storage tanks to ensure that a desired residual is achieved. CSO control facilities may feature upstream relief overflows to protect the facility from flooding during extreme events. These remote overflows also may be suitable locations for hypochlorite addition. They can be served by piping from chemical storage and feed equipment located at the main CSO facility, and controlled by remote telemetry. Table 4-11 presents examples of hypochlorite systems currently in use at CSO control facilities. A schematic of a typical hypochlorite system is presented in Figure 4-24.

In addition to effluent disinfection, other uses of hypochlorite at CSO facilities may include:

- Odor control scrubbers
- Sludge pipe disinfection
- Spraywash system

These applications are discussed earlier in this chapter.

Design Details

Components of typical hypochlorite systems include:

- Storage tank
- Metering pumps
- Dilution water supply
- Piping and valves
- Diffuser
- Chlorine residual analyzer

These components are discussed below. Additional information is available in the literature (White, 1992; WPCF, 1986; U.S. EPA, 1986).

Storage Tank

Sodium hypochlorite is delivered to a CSO facility in liquid form by truck, while smaller quantities can be delivered in 55-gallon drums. Sizing considerations for bulk storage tanks include projected usage of chemical, including auxiliary uses such as odor control, delivered strength, and rate of decomposition of hypochlorite. Hypochlorite is delivered with solution strengths ranging from 10 to 15 percent. Higher strength solutions require less storage volume, but deteriorate more rapidly. A 10 percent solution is most economical (White, 1992). Chemical storage tanks, whether above or below ground, must meet the applicable federal, state, and local regulations and fire codes.

Metering Pumps

Because of the relatively low metering pump capacities required for hypochlorite dosing, positive-displacement diaphragm pumps commonly are used for this purpose. Pumps can be controlled by variable speed drives, by stroke length positioners, or both. Pacing of the metering pumps in proportion to flow is a common control strategy. Dosing locations at the influent end of the facility should be paced by the influent flow, while dosing locations at the effluent end of the facility should be paced by the effluent flow (White, 1992). The need for additional control of dosage based on effluent residual may depend on permit requirements and potential water quality impacts of a high residual.

Dilution Water

Since sodium hypochlorite solution dose rates are low enough to be expressed in terms of gallons per hour, dilution water is provided as a carrier fluid to ensure a reasonable flow velocity. Hypochlorite dilution water typically is controlled by a solenoid valve and rotameter. The valve opens when the hypochlorite pumps are activated. The rotameter is set to provide sufficient flow to maintain a minimum 2 ft/sec velocity in the piping to

Table 4-11. Examples of Sodium Hypochlorite Disinfection Systems at CSO Control Facilities

Facility Location	Facility Type	Dosing Location(s)	Startup Control	Dose Rate Control	Other Details
Newport, RI Washington Street	Storage/treatment	Influent channel; tank effluent collection box	Influent channel mercury float switch	Pump speed paced by either influent or effluent flow; manual stroke adjustment	Manual dose control for remote upstream overflow
Newport, RI Wellington Avenue	Microstrainer	Effluent forcemain	Lead stormwater pump activation	Pump stroke controlled by effluent flow	
Saginaw, MI Hancock Street	Storage/treatment	Upstream of tanks	Influent pump activation	Pump speed paced on facility flow	Progressive cavity pumps provided for dosing caused operational problems
Oakport, CA	Storage/treatment	Influent lift station wetwell, near pump suction			
MWRA Prison Point	Storage/treatment	Influent channel upstream of tanks	Opening of tank inlet gate	Pump speed controlled by flow; pump stroke controlled manually	
		Each of four storm pump suctions, downstream of tanks	Storm pump activation	Pump speed controlled by flow; pump stroke controlled by CRA	
MWRA Cottage Farm	Storage/treatment	Influent channel	Influent pump activation	CRA located halfway down influent channel controls dose to maintain 1 ppm residual	Rotodip feeder provided for hypochlorite dosing
MWRA Somerville Marginal Pretreatment Facility	Coarse screening/ disinfection	Upstream of influent sluice gates in inlet channel	Capacitance probe in drainage channel upstream of facility opens inlet gates and starts equipment on high level	Initial high first flush dose provided for first 10 minutes, then control switched to pacing on effluent flow	
MWRA Constitution Beach	Coarse screening/ disinfection	Flow channel through facility	Start/stop on high/ low water level in facility	Pump speed controlled by CRA output; manual stroke adjustment	
MWRA Fox Point	Coarse screening/ disinfection	Flow channel through facility; dewatering pump discharge	Start/stop controlled by ultrasonic depth/ velocity flowmeter in flow channel	Speed controlled by facility flow; stroke controlled by CRA	

the diffuser. A manual bypass should be provided around the solenoid and rotameter.

Piping

A typical sodium hypochlorite piping system includes:

- Calibration standpipe, for checking pump capacity.
- Pulsation dampeners, to absorb the impulses from the diaphragm metering pumps and provide smoother flow.
- Back pressure valves, to ensure that the check valves on the metering pump discharges seat properly.

Where chemical storage and feed equipment is located at a higher elevation than the dosing locations, siphon conditions may develop that could prematurely drain the contents of a storage tank. Backpressure valves can prevent the siphon from developing, depending on the valve setting and the relative elevations of the fluid surface in the storage tanks and the valve. Some installations also feature motor-operated valves on the drawoff from the tank to prevent the contents of the tank from siphoning or leaking between storms.

PVC or CPVC piping with solvent-welded joints commonly is used for hypochlorite systems. Solvent-welded joints are less susceptible to leakage as compared with screw-type joints (White, 1992).

Diffuser

The diffuser disperses the sodium hypochlorite solution into the flow. Proper mixing is critical to disinfection efficiency, since chlorine species must come in contact with bacteria to exert the bactericidal effects. A variety

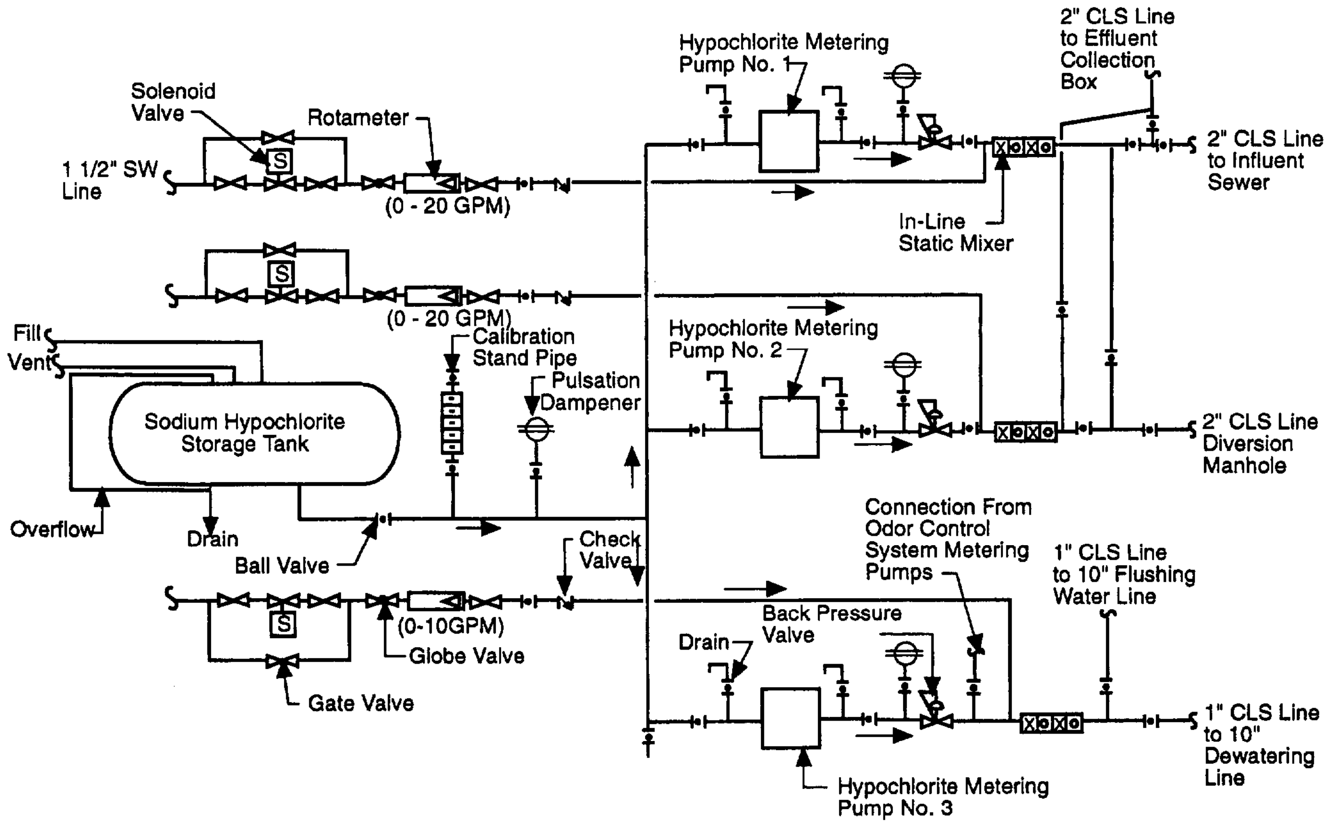


Figure 4-24. Schematic of typical liquid sodium hypochlorite system (Metcalf & Eddy, Inc., 1991b).

of diffuser types and configurations are commonly used, including in-channel and in-pipe arrangements. One common arrangement is to suspend a section of perforated PVC pipe across a channel or pipe. The exit velocity of the chlorine solution from across-channel perforated pipes should be approximately 25-30 ft/sec (White, 1992). Examples of diffuser types are presented in Figure 4-25. The reader is referred to the literature (White, 1992) for additional information on diffusers.

Chlorine Residual Analyzer (CRA)

The CRA is useful as part of a control loop for hypochlorite feed and for residual monitoring purposes. Some discharge permits specify a minimum effluent residual, where residual has been correlated with a given level of disinfection. Some discharge permits specify a maximum residual, where the concern is the toxic effects of chlorine on the receiving waters. For chlorine dose control based on chlorine residual, the residual sample point should be located immediately downstream of the chlorine application point, so that the sample is taken within 15-30 seconds of application. The total loop time between application of chlorine and response of the metering pump controls to the chlorine residual signal should range from 2 to 5 minutes (White, 1992). If the CRA is located near the sample point, the sample piping may be coiled or looped to create the minimum detention time. CRAs should not be located, however, in areas exposed to explosion hazards. Although the CRA could be provided with the appropriately rated enclosure, this enclosure would have to be opened periodically to replace the stock chemicals and provide routine service. For chlorine residual monitoring and reporting purposes, the sample point should be located as far downstream of the dosage point as practical.

The design of a CRA installation for a CSO facility must consider both the higher effluent solids present in CSO effluent as compared with secondary POTW effluent, and the intermittent operation of the facility. The higher solids concentration suggests that the sample may need to be filtered to minimize the potential for clogging or other interference with the CRA operation. In addition, bare electrode cell CRAs may be more appropriate for CSOs than permeable membrane cells. Although the bare electrode cells use more chemical than the permeable membrane cells, the bare electrode cells may be less sensitive to higher solids concentrations.

During periods between storms, when the CSO facility is inactive, clean water should be continually flushed through the CRA to prevent the buildup of slime or algae and to keep the analyzer cell fresh. A flow of 0.2 to 0.5 gpm should be sufficient for this purpose. The

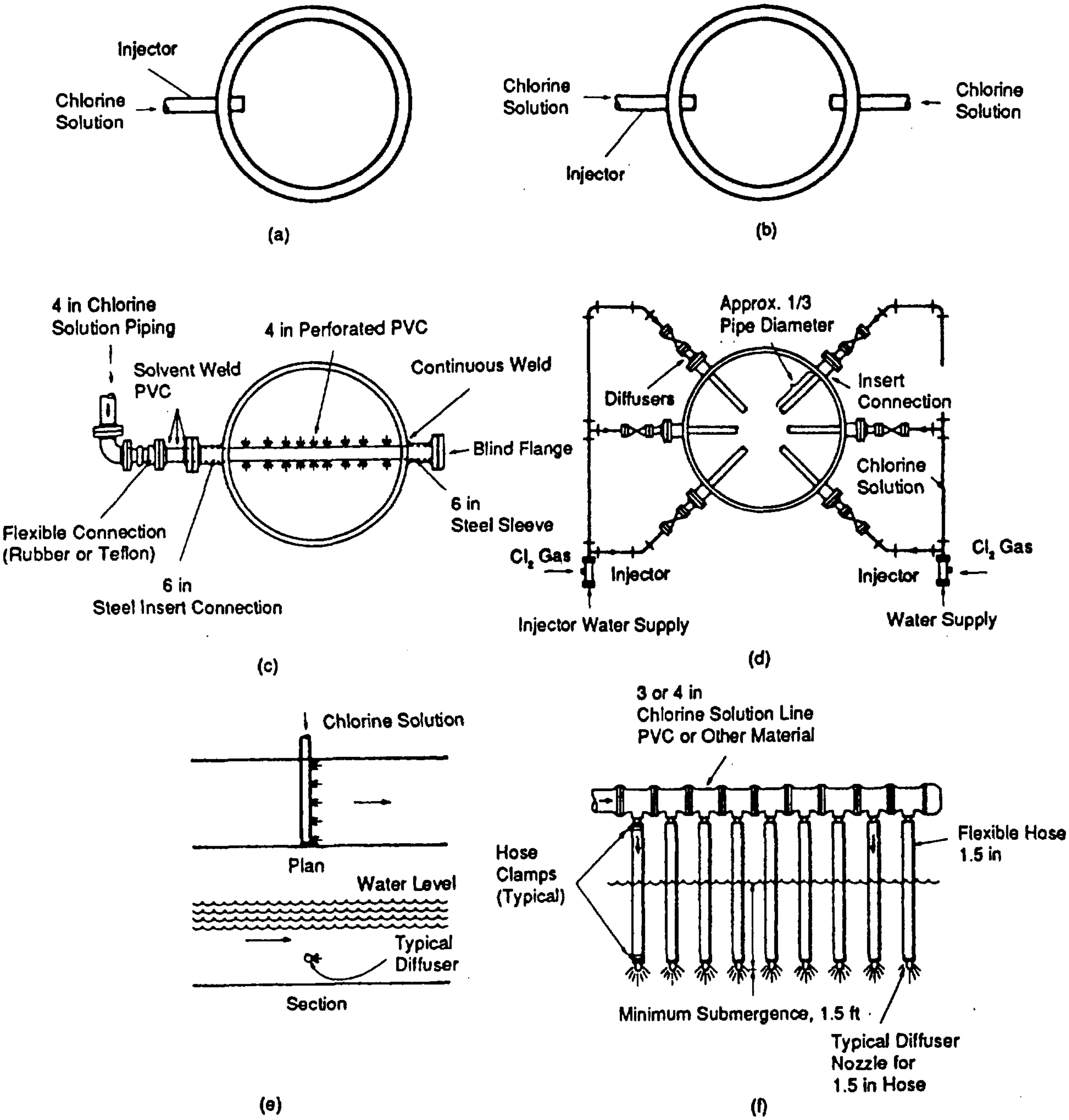


Figure 4-25. Typical diffusers used to inject chlorine solution: (a) single injector for small pipe, (b) dual injector for small pipe, (c) across-the-pipe diffuser for pipes larger than 3 ft in diameter, (d) diffuser system for large conduits, (e) single across-the-channel diffuser, and (f) typical hanging-nozzle-type chlorine diffuser for open channels (Metcalf & Eddy, Inc., 1991a).

0.5 gpm should be sufficient for this purpose. The chemical feed in the analyzer can be deactivated between storms, but the electronics should remain powered. When the facility activates during a storm event, the control system should ignore the signal from the CRA until the chemical feed system in the CRA is reactivated, and the CRA starts reading an actual residual.

System Controls and Operation

A common method for controlling the hypochlorite dose rate is through pacing the metering pump speed or stroke in proportion to facility flow. Some facilities provide compound loops, where pump speed is paced by flow and stroke is controlled by chlorine residual. Aspects of dosage control based on plant flow and chlorine residual were described earlier. Since CSO control facilities typically are not staffed on a full-time basis, some means of automatic activation usually is required. Simpler control systems are considered more reliable for facilities without a staff. Examples of typical startup controls include mercury float switches in the influent channel, and startup on activation of influent pumps.

One of the disadvantages of hypochlorite disinfection systems is that sodium hypochlorite solutions are unstable, and the strength of a hypochlorite solution decreases over time as the hypochlorite ions break down. The actual rate of hypochlorite decay depends on a number of factors. Decay is accelerated by exposure to heat, light, and certain heavy metal cations, particularly iron. Sodium hydroxide is added to hypochlorite solutions by manufacturers to improve stability. The decomposition rate increases with increasing solution strength.

Routine testing of the hypochlorite strength should be part of standard facility maintenance procedures. The benefits of monitoring hypochlorite strength are:

- Due to the intermittent nature of CSO facility operations, quantities of hypochlorite may remain in the storage tank for extended periods. Since the dose rate depends on the solution strength, overestimation of the solution strength may result in underdosing the flow.
- Over a period of time, records on the decay rate and quantities used of various strengths of hypochlorite will allow the operator to determine an optimum strength and delivery schedule.

The strength of a hypochlorite solution in terms of weight percent can be determined by making two consecutive 1:100 dilutions of a sample of hypochlorite, and then analyzing for chlorine concentration. The concentration in mg/l of the diluted sample is equal to the concentration in weight percent of the original solution.

Process Variations

Dechlorination

A major disadvantage of chlorine-based disinfection systems is that the residual chlorine concentration may have a toxic effect on the receiving waters, due either to the free chlorine residual itself or the reaction of the chlorine with organic compounds in the effluent. One report on chlorine toxicity concluded that continuous effluent concentrations of greater than 0.01 mg/l may exert toxic effects on resistant organisms, while concentrations greater than 0.002 mg/l may harm many aquatic organisms. A variety of stable chloroorganic compounds may be formed as byproducts of the chlorination of wastewater, and certain chloroorganics can exert toxic effects on aquatic species (White, 1992; Brungs, 1973; Jolley, 1975). With the relatively short contact times available at many CSO control facilities, high residuals can be of particular concern and may require consideration of dechlorination alternatives. Two common means for dechlorinating treated effluent are through application of gaseous sulfur dioxide and liquid sodium bisulfite solution. A sulfur dioxide dosing system requires apparatus similar to a gaseous chlorine disinfection system, while sodium bisulfite requires apparatus similar to a liquid sodium hypochlorite dosing system. Since the hypochlorite disinfection systems have been more reliable than gaseous chlorine systems for intermittent operation in CSO control applications, a liquid sodium bisulfate system also may be preferable to a gaseous sulfur dioxide system for dechlorination of treated CSOs.

Sizing of a sodium bisulfite dechlorination system is based on the following relationships (White, 1992):

- Sodium bisulfate is usually provided as a 38 percent solution.
- One gallon of 38 percent sodium bisulfite is equivalent to 2.17 pounds of sulfur dioxide.
- Stoichiometrically, 0.9 parts of sulfur dioxide are required to remove 1.0 part of chlorine; actual ratios can be as high as 1.05 parts sulfur dioxide to 1.0 part chlorine.

Chemical storage and feed equipment for sodium bisulfite is identical to the equipment required for hypochlorite systems. Sodium bisulfite storage tanks should be located away from and be clearly distinguished from hypochlorite tanks, since the mixing of these two chemicals results in a violent temperature reaction (White, 1992).

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When an NTIS number is cited in a reference, that document is available from:

National Technical Information Service
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Springfield, VA 22161
703-487-4650

EPA documents with a number that begins with 600 or 625 can be ordered from EPA's Office of Research and Development:

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513-569-7566 (fax)

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Chapter 5
Costs for CSO Control Technologies

This chapter summarizes information on costs associated with construction and operation of treatment technologies presented in this report. This information can be used to develop preliminary budgetary estimates and provides a basis for comparing technologies. The cost information also can be useful in characterizing economic sensitivity in relation to various design alternatives for a proposed facility. Readers should consult the source documents cited for additional detail.

The cost relationships reflect a consolidation of cost data, some of them estimates, compiled from a number of comprehensive cost assessments that extract data from facility plans and from a number of individual site studies not included in the broad-based data sets. As noted, actual costs for CSO facilities varied considerably for facilities of similar type and design capacity. This is attributable to a variety of site-specific factors that influence project costs.

The primary parameter influencing the estimated cost for a CSO treatment facility is either design flow rate or storage volume. For treatment-based control measures that are designed on the basis of flow rate, costs are related to flow rate in million gallons per day (MGD). For storage facilities, the primary design parameter is storage volume, or the storm size selected as a design basis, and the cost relationship is based on storage volume in million gallons (MG).

Sources of Cost Data

Cost estimating procedures for CSO storage and treatment facilities have been available since the late 1970s. Updates have been developed at regular intervals. Recent cost data for CSO storage and treatment facilities have been developed (U.S. EPA, 1992) and other sources of cost information exist (Field, 1990; U.S. EPA, 1976, 1977a,b).

The cost curves developed from the literature are based on a compilation of information extracted from actual construction costs, estimates developed for CSO facility plans, consultant-supplied data for specific projects, and other published sources. The costs provided for CSO control do not include land acquisition; engineering, legal, fiscal, or administrative services; contingencies; or construction loan interest. The exception to this is screening facilities, where these cost components could not be isolated and extracted.

Other cost estimating references, such as those extrapolated from POTW costs (U.S. EPA, 1978, 1980), may be used to refine estimates developed from CSO costing references, but should be used cautiously. Many POTW costing procedures are based on average daily flow, while CSO facilities usually are based on peak flow or storm volume. Possible differences in the relationship between peak and average flow and its translation to the design surface area should be considered.

Construction Costs for CSO Controls

Figure 5-1 summarizes the relationship between construction cost and design capacity for a range of CSO control technologies. These cost curves are based on recent studies that assembled information on CSO control costs (U.S. EPA, 1992), and reflect the cost of the basic structure and ancillary equipment (e.g., grates, valves, conduits). Associated pumping facilities are included for some, but not all of the facilities. Land acquisition and professional service costs are excluded. The source report provides details on cost elements included for individual sites. Local cost estimates for these elements should be developed and added for a more complete estimate, whenever appropriate.

Most of the cost curves display a line of best fit through the plotted data, in addition to the plotted points showing cost versus design size for individual sites. The linear regression line is described by an equation of the following form:

$$\text{COST} = a\,Q^b \quad \text{or} \quad \text{COST} = a\,V^b$$

where Q is the design flow in MGD for treatment units, and V is the storage volume in MG, and the values a and b are unique for each line fit.

The construction cost relationships shown by Figure 5-1 are summarized by the equations in Table 5-1.

Inspection of the relative scatter of individual site values about the regression lines in Figure 5-1 provides a

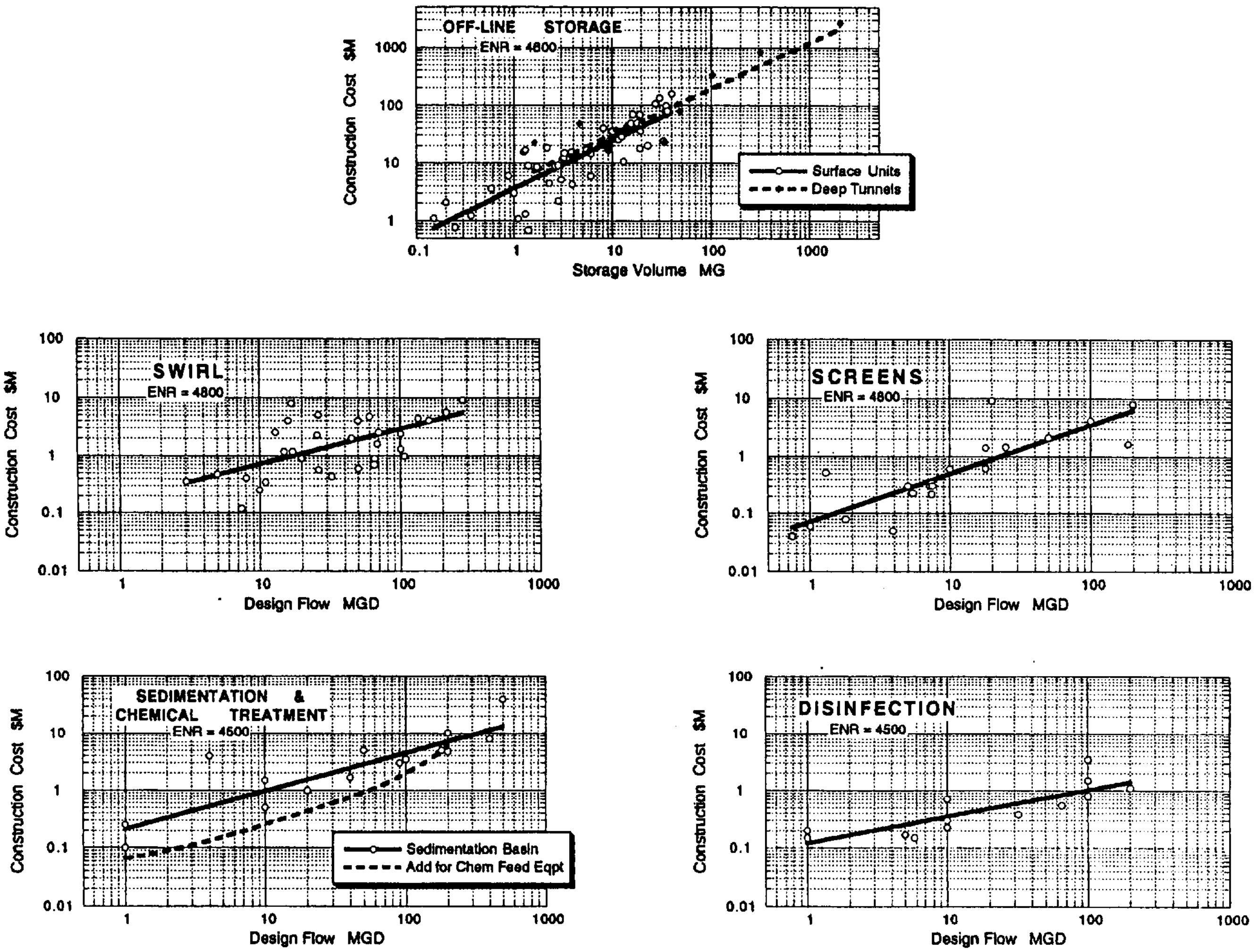

Figure 5-1. Construction costs for CSO controls.

Table 5-1. Cost Equations for CSO Control Technology

CSO Control Technology	Cost Equation*	Applicable Design Range	ENR Index
Storage basins	$3.637\ V^{0.826}$	0.15 to 30 MG	4,800
Deep tunnels	$4.982\ V^{0.795}$	1.8 to 2,000 MG	4,800
Swirl concentrators	$0.176\ Q^{0.611}$	3 to 300 MG	4,800
Screens	$0.072\ Q^{0.843}$	0.8 to 200 MG	4,800
Sedimentation	$0.211\ Q^{0.668}$	1 to 500 MG	4,500
Disinfection	$0.121\ Q^{0.464}$	1 to 200 MG	4,500

* V = volume (MG); Q = flow rate (MGD).

sense of the degree of uncertainty in the above cost relationships. Reliable cost estimates for a particular CSO control facility require a conventional material take-off and application of normal costing procedures, when facility design is sufficiently advanced to support such an analysis.

O&M Costs for CSO Controls

Operation and maintenance costs are difficult to predict because of the intermittent use of CSO treatment facilities. Actual O&M costs are indicated in the data in Figure 5-2 to be a function of the number of overflows experienced by the facility, as well as the design capacity.

The frequency at which a specific CSO facility receives an overflow event to process depends strongly on the capacity of the collection system it serves and varies from one year to another, depending on the amount and pattern of rainfall experienced.

The significant effect of the frequency of activation is illustrated by the O&M cost curves for screening facilities, shown in Figure 5-2. All the major components of O&M costs, such as energy consumption, labor requirements, residuals disposal, and equipment maintenance are a function of the facility use. This, in turn, is a function of the rainfall quantity and the number of wet weather events; therefore, O&M costs are highly site specific. The O&M curves that appear in published reports and literature should be used cautiously.

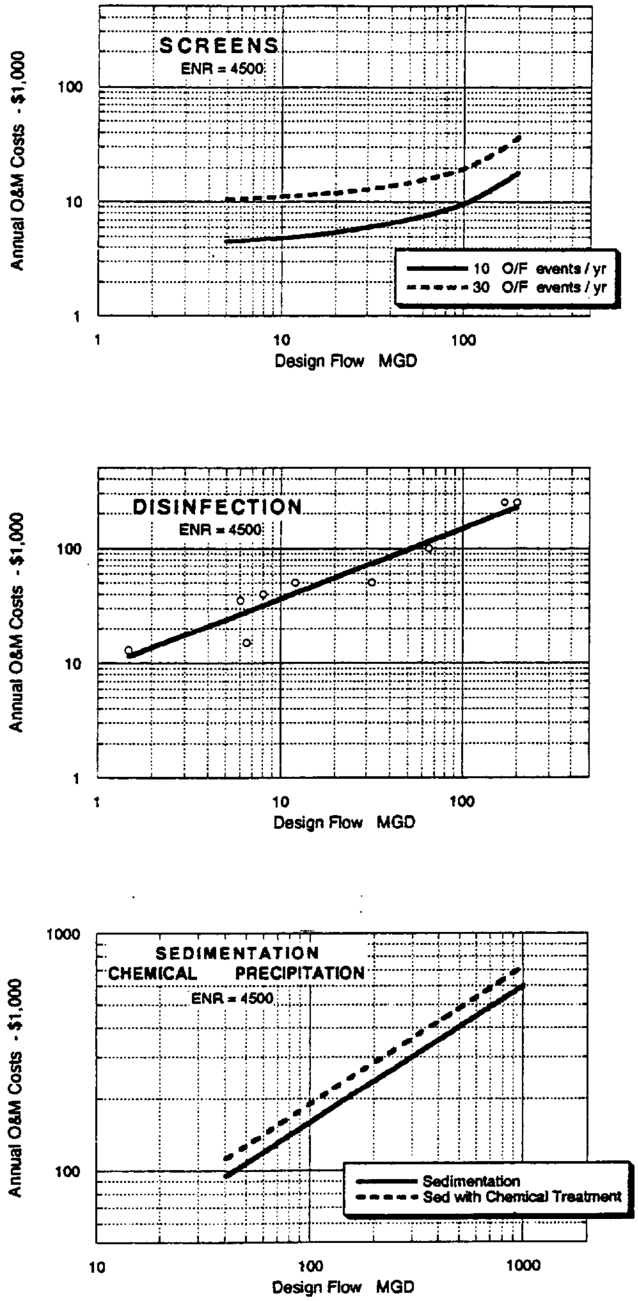

Figure 5-2. O&M costs for CSO controls.

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