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Sewer and Tank Sediment Flushing: Case Studies

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by

William C. Pisano and James Barsanti
Montgomery Watson
40 Broad Street, Suite 800
Boston, MA 02109

and

James Joyce and Harvey Sorensen, Jr.
Odor & Corrosion Technology Consultants, Inc.
11250 West Road Building L
Houston, TX 77065

Contract No. 8C-R059-NTSX

Project Officer

Chi-Yuan Fan
Water Supply and Water Resources Division
National Risk Management Research Laboratory
Edison, NJ 08837

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
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CINCINNATI, OH 45268

Notice

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

Past studies have identified urban combined sewer overflow (CSO) and stormwater runoff as major contributors to the degradation of many urban lakes, streams, and rivers. Sewage solids deposited in combined sewer (CS) systems during dry weather are major contributors to the CSO-pollution load. Innovative methods for cleaning accumulated sludge and debris in CSO and stormwater conveyance systems and storage tanks have emerged over the last 15 years by creating high speed flushing waves to resuspend deposited sediments. Cleansing efficiency of periodic flush waves depends on flush volume, flush discharge rate, sewer slope, sewer length, sewer flow rate, sewer diameter and population density. Maximum flushing volumes at upstream points are limited by available space, hydraulic limitations and costs. Maximum flushing rates at the downstream point are limited by the regulator/interceptor capacities prior to overflow. The relationship between cleaning efficiency and pipe length is important. The aim of flushing is to wash the resuspended sediment to strategic locations, i.e., to a point where the waste stream is flowing with sufficient velocity, to another point where flushing will be initiated, to a storage sump which will allow later removal of the stored contents, or to the wastewater treatment plant (WWTP). This reduces the amount of solids resuspended during storm events, lessens the need for CSO treatment and sludge removal at downstream storage facilities, and allows the conveyance of more flow to the WWTP or to the drainage outlet. This report will demonstrate that sewer system and storage tank flushing that reduces sediment deposition and accumulation is of prime importance to optimizing performance, maintaining structural integrity, and minimizing pollution of receiving waters.

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Acronyms and Abbreviations

ac	Acre
aq	Aqueous
BOD	Biochemical oxygen demand
ºC	Degrees Celsius
cfs	Cubic feet per second
cm	Centimeter
CS	Combined sewer
CSHG	Calcium Silicate Hydrate Gel
CSO	Combined sewer overflow
DO	Dissolved oxygen
EDP	Environmental Design & Planning, Inc.
EPA	United States Environmental Protection Agency
EXTRAN	Extended Transport Block
fps	Feet per second
ft	Feet
gpd	Gallons per day
gpm	Gallons per minute
HP(hp)	Horsepower
hr	hour
in	Inch
kPa	kiloPascals
l	Liter
lps	Liters per second
m	Meter
mg	milligram
MG	Million gallons
MGD	Million gallons per day
mm	Millimeter
N	Newton
NRMRL	National Risk Management Research Laboratory
pkwy	Parkway
POTW	Publicly Owned Treatment Works
ppm	Parts per million
psi	Pounds per square inch
QAPP	Quality Assurance Protection Plan
R&D	Research & Development
sec	second
SS	Suspended solids
SWMM	Stormwater Management Model
TF	Tipping flusher
US	United States
WWTP	Wastewater treatment plant
$	Dollars
%	Percent
"	inch

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Chapter 1
Introduction

Past studies have identified urban combined sewer overflow (CSO) and stormwater runoff as major contributors to the degradation of many urban lakes, streams, and rivers. Sewage solids deposited in combined sewer (CS) systems during dry weather are major contributors to the CSO-pollution load. In recent years, pollution caused by CSO has become a serious environmental concern. Although requirements vary from state to state concerning allowable overflow frequencies, compliance has resulted in the design and construction of storage facilities as well as utilization of in-line storage or constructing deep tunnels. In the case of in-line storage, shallow slopes and low mean velocities allow debris to settle along the invert of the pipe during storage periods. Accumulation of sediments results in a loss of storage capacity that may cause surcharge or local flooding and the establishment of septic conditions that create odor and corrosion problems.

Some simple calculations illustrate the potential impacts of overflows on receiving waters. Estimates of dry weather flow deposition in combined sewer systems have ranged from 5 to 30 percent of the daily pollution loading. If 25 percent of the daily pollution loading accumulates in the collection system, an intense rainstorm lasting two hours after four days of antecedent dry weather may wash the equivalent of a one-day's flow of raw wastewater overboard to the receiving waters. The average antecedent dry period between storm events is about four days for many areas of the U.S., especially along the eastern seaboard. Furthermore, a one-day equivalent of raw wastewater discharged within a two-hour period, is twelve times the rate at which raw wastewater enters the collection system.

This report will demonstrate that sewer system and storage tank flushing that reduces sediment deposition and accumulation is of prime importance to optimizing performance, maintaining structural integrity, and minimizing pollution of receiving waters.

Project Scope

The U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory's (NRMRL's) Office of Research and Development's Urban Watershed Management Branch, Water Supply and Water Resources Division have supported the development of this project report for the investigation of sewer and tank sediment flushing. The report is designed to provide information and guidance to meet the following objectives:

1. Investigate the cost-effectiveness of combined sewer in-line and CSO storage tank flushing systems for removing combined sewer sediments and CSO storage tank bottom deposits at actual installation sites in urban watersheds.

2. Develop a long-term combined sewer hydrogen sulfide monitoring program.

To meet these objectives, the following tasks were developed:

1. Identification of 18 sites in North America and Europe for evaluation of in-line (10) and CSO storage tank (8) flushing systems.

2. Desk Top analyses of published and unpublished information on the range of hydrogen sulfide concentration combined sewers, the correlation between sediment characteristics and hydrogen sulfide generation, and the effectiveness of combined sewer flushing systems to:

    - Decrease the rate of hydrogen sulfide generation during dry weather conditions by removing an important and often significant contributory source of available microbial food;

- Eliminate potential for creating highly unsafe transitory hydrogen sulfide levels associated with rapid biological activity of resuspended sediments during high flow conditions;

- Lessen the potential for sewer decomposition associated with elevated hydrogen sulfide generation; and

- Maximize sewer flow carrying capacity by removing sediment/blockages.

3. Collect and analyze operational information on the 18 identified sites regarding:

   - The effectiveness of systems design in terms of sediment removal;

   - Capital and operation and maintenance costs;

   - Operational problems and lessons learned from these sites.

4. Perform cost-effective-benefit analyses of the 18 identified/selected in-line and storage tank flushing systems.

5. Develop a generic Quality Assurance Protection Plan (QAPP) for conducting a field program for monitoring and analyzing long term sediment characteristics and hydrogen sulfide generation rates within a problem combined sewer system.

Background

Innovative methods for cleaning accumulated sludge and debris in CSO and stormwater conveyance systems and storage tanks have emerged over the last 15 years by creating high speed flushing waves to resuspend deposited sediments. In the last ten years, at least three new passive hydraulic systems have been developed and installed in Europe to routinely flush sewer deposits and wet weather storage tanks. In Europe, 77 installations have been in operation since 1985 to flush sewers, interceptors and tunnels ranging from 0.25 to 4.3 meters (10 inches to 14 feet) in diameter and flushing lengths of up to 335 meters (1100 feet) for large diameter pipes and 1000 meters (3300 feet) for smaller diameter.

Cleansing efficiency of periodic flush waves depends on flush volume, flush discharge rate, sewer slope, sewer length, sewer flow rate, sewer diameter and population density. Maximum flushing volumes at upstream points are limited by available space, hydraulic limitations and costs. Maximum flushing rates at the downstream point are limited by the regulator/interceptor capacities prior to overflow. The relationship between cleaning efficiency and pipe length is important. The aim of flushing is to wash the resuspended sediment to strategic locations, i.e., to a point where the waste stream is flowing with sufficient velocity, to another point where flushing will be initiated, to a storage sump which will allow later removal of the stored contents, or to the wastewater treatment plant (WWTP). This reduces the amount of solids resuspended during storm events, lessens the need for CSO treatment and sludge removal at downstream storage facilities, and allows the conveyance of more flow to the WWTP or to the drainage outlet.

Flushing gates and tipping flushers for cleaning accumulated sludge and debris in CSO and stormwater storage tanks have emerged in Germany and Switzerland. Both methods create high speed flushing waves to resuspend sediments on the tank floor and sweep these materials to a disposal channel at the end of the tank. The flushing gate system has been used extensively in Europe with 209 installations and 436 units in operation since 1985. Approximately 60 percent of the installations are for cleaning sediments from CSO tanks. The tipping flushers were initially developed in Switzerland, and were optimized to present design in Germany. Presently there are several thousand CSO tanks throughout Europe using the tipping gate technology.

Odor and Corrosion Perspective

Sewer sediments create odor and sewer decomposition problems in addition to CSO pollution. The production and release of hydrogen sulfide gas in municipal wastewater collection systems is responsible for numerous odor complaints and the destruction of sewer pipes and other wastewater facilities. Sulfates are released from organic substances contained in the sewer sediments by bacteria under anaerobic conditions. In the absence of dissolved oxygen and nitrates, sulfates serve as electron acceptors and are chemically reduced to sulfides and to hydrogen sulfide by bacteria. The hydrogen sulfide is then converted to sulfuric acid, which disintegrates the sewer pipes.

The process begins with the biological reduction of sulfate to sulfide by the anaerobic slime layer residing below the water surface in wastewater collection systems. The anaerobic bacteria utilize the oxygen in the sulfate ion as an electron acceptor in their metabolic processes. The resulting sulfide ion is transformed into hydrogen sulfide gas after picking up two hydrogen ions from wastewater.

Once released to the sewer atmosphere, aerobic bacteria (Thiobacillus) which reside on sewer walls and surfaces above the water line consume the hydrogen sulfide gas and secrete sulfuric acid. In severe instances, the pH of the pipe can reach 0.5. This causes severe damage to unprotected collection system surfaces and may eventually result in the total failure of the sewer piping and the uncontrolled release of raw wastewater to the environment.

For obvious reason, the control and reduction of hydrogen sulfide in wastewater systems is of vital importance. While, the biological and chemical processes resulting in sulfide production in wastewater are well understood, there are significant contributing factors are not understood. Even the well known Pomeroy-Parkhurst equations contains an empirical “M Factor” to account for the unknown biological and chemical transformations which occur with sulfide in wastewater (USEPA, 1985).

Settled solids and other debris in sanitary sewers and wastewater collection systems can provide a greatly increased surface area upon which anaerobic sulfate reducing bacterial slime can grow, thereby increasing the incremental (per foot) sulfide production potential of sewers. Methods need to be developed to measure the sulfide production in a sewer with moderate to heavy settled solids and debris and sample and to characterize the solids in the sewer.

It is important to develop a method to measure in-situ dissolved sulfide concentrations inside the interstitial spaces of a typical debris pile in the sewer. By measuring the pore space dissolved sulfide concentration in a typical debris pile and by removing the debris pile and characterizing the debris by sieve size and mineralogy, the additional surface area provided by the pile can be calculated. From knowledge of the practical pore space volume and the surface area, the specific sulfide production rate can be determined. This would allow calculation of the mass of sulfide that could be prevented by cleaning the upstream sewers.

The method analyzed to clean the pipes in this study is passive flushing. This technology holds great potential as an economical way to maintain sewers in a clean and free flowing condition. Clean sewers provide maximum wastewater carrying capacity thereby preventing sewer overflows and protecting the environment. There is another benefit to be gained by maintaining sewers in a clean and free flowing condition, namely, sulfide odor and corrosion reduction. However, the flushing event that disturbs the settled debris and solids and carries them downstream will generate a significant turbulent wave. This hydraulic wave will release the sulfide in the debris pore spaces and subject it to turbulence. The turbulence associated with the hydraulic wave will strip dissolved sulfide from the wastewater and release it as hydrogen sulfide gas. Although the event is short-lived, the concentrations produced may cause a short burst of odor release from the sewer that could result in odor complaints. Identification of the potential for odor release and complaints as a result of sewer flushing may require measurement of the instantaneous spike in sewer headspace hydrogen sulfide concentrations caused by the hydraulic wave. Sewers that have not been cleaned in many years may have accumulated significant debris piles that may cause a large spike in hydrogen sulfide release when first flushed. However, following one or two flush events, the debris piles should be smaller or totally removed, thus reducing the hydrogen sulfide spikes for the second, third and subsequent flushing events.

Previous Research

In 1966, EPA through its federal water program initiated research to demonstrate the feasibility of periodic flushing during dry weather. The first phase of work performed by FMC Corporation included a study of the overall flushing concept, small-scale hydraulic modeling, and design and development of cost estimates for constructing test equipment (FMC, 1966). The second phase produced a flushing evaluation facility consisting of 0.30 meter and 0.45 meter (12 and 18 inch) diameter test sewers about 488 meters (1600) feet long, supported above ground (thus allowing for slope adjustment), including holding tanks at three points along the test sewer for the flushing experiments (FMC, 1972). Limited periodic flushing of simulated combined sewer laterals was accomplished. The report documenting this research recommended a third phase be made for flushing larger sizes of pipe, flush wave sequencing, and determination of solids buildup over long periods of time.

In 1974, a combined sewer management study performed by Process Research, Inc., Cambridge, Massachusetts, focused on assessing alternative strategies for abating CSO discharges to portions of Boston Harbor was completed (Process Research, 1974). As part of the research work conducted during this study a number of theoretical formulas for prediction of dry weather deposition and flushing criteria were developed. The development of the deposition analysis techniques stemmed from critical fluid shear stress considerations. The theoretical formulas were roughly field checked to ascertain solids accumulations. Although the model was crude, the agreement with visual field observations was reasonable. The model was then used to analyze deposition problem segments within a service area of 1200 hectares (3000 acres) entailing roughly 152,500 meters (0.5 million feet) of sewer. Roughly 3000 manhole-to-manhole segments were analyzed for deposition and it was determined that roughly 17 percent of the segments contained about 75 percent of the estimated dry weather wastewater depositions. It turned out that most of these segments were small-diameter combined sewer laterals. Flushing criteria were empirically developed using data generated during the earlier FMC research to estimate required flushing volumes.

In 1979, a three year research and development (R&D) program sponsored by EPA was conducted by Environmental Design & Planning, Inc. (EDP) in the Dorchester area of Boston to determine the pollution reduction potential of flushing combined sewer laterals. It was concluded that small volume flushing would transport organics/nutrients and heavy metals sufficient distances to make the option feasible and attractive (EPA, 1979). Relevant conclusions were as follows:

- Approximately 20 to 40 percent of heavy metal (cadmium, chromium, copper, lead, nickel, and zinc) associated with particles entrained by flush waves will not settle within a two hour settling period.

- An automated sewer flushing module using a simple hydraulic gate powered by an air cylinder, and time clock triggered, operated without intervention for a 5.5-month period to back up wastewater and retract and induce flush waves. Flushed pollutant loads were comparable to removals noted by manual flush tanker means.

- An empirical methodology was prepared for providing first-cut deposition solids, nutrient and organic daily collection system estimates simply by knowing the total length of pipe, service area, average pipe slope or ground slope, and per capita wastewater flow rate. Methods were also developed to determine which segments in collection systems should be flushed to remove specified portions of deposits.

Based on the prototype success of the flushing R&D project, a full-scale demonstration project was recommended to obtain full-scale experience in Boston. Clinton Bogert & Associates completed a detailed cost-effectiveness study in 1980 with support from EDP focusing on the Dorchester neighborhood in Boston. It was concluded from the cost-effectiveness analysis that sewer flushing can be an adjunct to, but cannot substitute for, structural alternatives and that the use of storage treatment available in large combined sewers in conjunction with sewer flushing could reduce the cost of large stand-alone satellite storage facilities.

Sewer flushing of large-diameter combined sewers was investigated in the CSO Facility Plan for the City of Elizabeth, NJ by Clinton Bogert & Associates. It was concluded that daily flushing of troublesome deposition section within seven sub-areas using 12 automatic flushing systems was estimated to reduce about 28 percent of the first flush overflow pollutant loading from the service area. Control is by level sensing to centralized computer control. Combined sewers to be flushed ranged from 0.45 to 1.4 meters (18 to 54 inches). Construction of 12 flushing modules was completed in 1990. Estimated construction costs for complete modules (structural, mechanical, electrical, and site work excluding computer control) ranged from $175,000 for small diameter lines up to $275,000 (costs based on ENR cost index of 5000). No evaluation data has been reported regarding effectiveness.

Chapter 2
Conclusions

The following conclusions were derived from the evaluations of the 18 sewer and tank sediment flushing facilities and the case studies developed in Section 5.

1. The tipping flusher and flushing gate technology appear to be the most cost-effective means for flushing solids and debris from tanks. The most efficient method for flushing large diameter flat depositing sewers is the flush gate technology.

2. In general, the performance of both types of flushing equipment for tanks and flush gates for sewers was rated as good to excellent. Based on calculations for most of the facilities using flushing gates, the terminal velocities at the end of the flushing wave exceeded 1 m/second. This terminal velocity was adequate for cleansing.

3. Cost effectiveness analysis comparing flushing gate technology versus conventional large pipe cleaning operations using bucketing methods was conducted for an actual project undergoing construction. A system of flushing gates to flush 1500 m of large diameter sanitary sewer and storm drains was examined. Present worth savings of at least $500,000 is expected using the flush gate technology in lieu of periodic cleaning using conventional means.

4. A desktop analysis was conducted comparing the use of the flushing gate technology to minimize potentially overflowing pollutant loads as an alternative to downstream high rate satellite treatment. The desktop analysis showed that periodic flushing of long flat depositing reach of a conduit prior to an overflow was extremely cost effective and superior to a satellite treatment facility.

5. A desktop analysis was conducted to explore the use of flushing gate technology for minimizing sediments in a long flat depositing sewer carrying warm sewage with high organic loadings. Dissolved hydrogen sulfide levels attributable to both the slime layer and to accumulated sediments were estimated. The present worth costs for treating excessive and dangerous levels of hydrogen sulfide with chemicals (iron salts) were estimated. Flushing gate technology was explored to reduce sediments and thereby reduce incremental hydrogen sulfide loadings. The cost effectiveness of chemical treatment versus flushing with reduced chemical treatment indicated that flushing as an adjunct to chemical treatment is cost effective.

Recommendations

1. A demonstration project using flushing gate system to minimize sewer deposits within CSO impacting a receiving water should be conducted. The project should involve long term pre and post construction overflow flow and pollutant characterization. The pre project relationship between dissolved sulfide and sediment deposits should also be understood. Instantaneous hydrogen sulfide levels during post construction flushing conditions should be monitored to note nuisance level potential of instantaneous hydrogen sulfide spikes. A cost effective analysis demonstrating the benefits of this technology using actual field experience. Operation and Maintenance requirements should be prepared to document this work.
2. Experimental laboratory work to document the kinetics of sediment generation of hydrogen sulfide is recommended followed by full-scale demonstration work.

Chapter 3
Sewer Sediments and Sewage Gases Estimation Techniques

Introduction

As noted in the Chapter 1, solids deposition in flat sewerage systems can be significant, in some situations on the order of 15 to 20 percent of the total daily solids input. In combined sewer systems, these accumulations can be scoured during wet events and can contribute to first flush conditions. During overflow events, high concentrations of these accumulated pipe deposits can be discharged into the environment. Satellite CSO treatment facilities have been used worldwide to handle such problems. In Chapter 6 the cost effectiveness of using automated sewer flushing technology is conducted.

To perform these calculations, a desktop procedure is utilized to estimate the amount of depositing solids in a long pipe segment during low flow average condition, and then to estimate during high flow conditions the amount of solids scoured from the sediment beds, re-suspended, and carried toward the overflow location. Important concepts underlying this crude desktop procedure have been developed using results from recent European research, which focused on sewer self, cleansing criteria.

Nature of Sewer Solids and Sediment Movement in Sewers

The generic term *sewer sediment* is used to describe any type of settleable particulate material that is found in storm water or sewage and is able to form bed deposits in sewers and associated hydraulic structures. Some particles of very small size or low density may remain in suspension under all normal flow conditions and would be transported through a sewerage system as *washload.* Such particles have a negligible effect on the hydraulic capacity of sewerage systems, but can have an important influence on pollutant loading in the flow and at points of discharge such as treatment works and sewer overflows.

By contrast, larger (inorganic and organic) and denser particles (inorganic with a specific gravity in the range of 1.5 to 2.5) having settling velocities in the range 0.2 centimeters/second to 30 centimeters/second that are constantly inputted into sanitary systems, but at low rates (5 - 15 mg/l typical), may only be transported by peak flows that occur relatively infrequently. In some cases, they may form permanent stationary deposits at the point of entry to the sewer system.

If liquid flows over a sediment bed in a sewer running full or partially full, hydrodynamic lift and drag forces are exerted on the deposited particles. If two combined forces do not exceed the restoring force, then *entertainment* occurs, resulting in the movement of the particles at the flow/sediment boundary. Not all the particles of a given size at the flow/sediment boundary dislodge and move at the same time because the flow is turbulent and contains short term fluctuations in velocity. The limiting condition, below which sediment movement is negligible, known as the *threshold of movement,* is usually defined in terms of either the critical bed shear stress or the critical erosion velocity.

Once sediment is entrained, it may travel down the sewer in one of two general ways. Finer, lighter material tends to travel in *suspension,* while heavier material travels in a rolling, sliding mode as *bedload*. In the transport of suspended sediment, there is a continuous exchange between particles settling out and those being entrained upwards into the flow. Under certain conditions, fine grained and organic particles can form a highly concentrated mobile layer of '*fluid mud'* near the invert (Ashley, 1992).

If the flow velocity or turbulence level decreases, there will be a net reduction in the amount of sediment held in suspension. The material accumulated at the bed may continue to be transported as a stream of particles without deposition. However, below a certain limit, the sediment will form a deposited bed, with transport occurring only in the surface layer (the limit of *deposition*). If the flow velocity is further reduced, sediment transport will cease completely. The flow conditions necessary to prevent deposition depend on the pipe size and on properties of the sediment, such as particle size and specific gravity. Flocculation of fine particles can also be important. The flow velocities needed to entrain sediment tend to be higher than those at which deposition occurs.

Sewer Self Cleansing Criteria

An important parameter in the criteria for sewer self-cleansing is average shear stress. Average shear stress is the amount of force the fluid exerts on the wetted perimeter of the pipe. Another important parameter is bed shear stress which is the amount of force the fluid exerts on the bed of sediment in the pipe. Bed shear stress is related to bed load scour and movement.

Historically, in respect to the sediments found in sewerage systems, the design of systems has been based on a set of conditions that prevent the deposition of sediments in pipes. These conditions are based on a minimum velocity of flow or a minimum shear stress that the flow should exert on the walls of the pipe to maintain self-cleansing conditions. The minimum velocity of flow or minimum shear stress corresponds to a particular depth of flow or with a particular frequency of occurrence. Available design criteria were reported by the Construction Industry Research and Information Association (CIRIA, 1987), and a summary of these, outlined by Nalluri and Ab Ghani (1996), are recorded in Table 3-1 and Table 3-2.

Table 3-1. Minimum Velocity Criteria

Source	Country	Sewer Type	Minimum Velocity (m/s)	Pipe Conditions
American Society of Civil Engineers (1970)	USA	Sanitary	0.6	Full/Half-full
		Storm	0.9	Full/Half-full
British Standard (1987)	UK	Sanitary	1.0	Full
		Combined	1.0	Full
Bielecki (1982)	Germany	Not noted	1.5	Full

Table 3-2. Minimum Shear Stress Criteria

Source	Country	Sewer Type	Minimum Shear Stress (N/m^2)	Pipe Conditions
Lysne(1969)	USA	Not noted	2-4	Not noted
ASCE(1970)	USA	Not noted	1.3-12.6	Not noted
Yao (1974)	USA	Storm	3.0 - 4.0	Not noted
		Sanitary	1.0 - 2.0	Not noted
Maguire	UK	Not noted	6.2	Full/Half-full
Bischof (1976)	Germany	Not noted	2.5	Not noted

These criteria take no account of the characteristics of the sediment, of the suspended sediment concentration, the bed load or of any cohesion between the sediment particles. Nonetheless, inspection of Table 3-1 and Table 3-2 indicates that as stand alone criteria taken individually and/or jointly, minimum velocity and minimum shear stress levels of 1 meter/second and 2 N/m^2 be realized on a regular basis. Recent work by many researchers has shown that a single value of minimum velocity or shear stress cannot adequately describe the self cleansing conditions in all pipes of different size, roughness and gradient for a range of sediment characteristics and flow conditions.

In practice, sewer pipes will not be maintained self-cleansing at all times. The diurnal pattern of the dry weather flow and the temporal distribution and nature of sediments found in sewer flows may result in the deposition of some sediments at times of low flow and the subsequent erosion and transport of these sediments, either as suspended load or bed-load, at times of higher flow. The deposited sediments will exhibit additional strength due to cohesion and provided that the peak dry weather flow velocity or bed shear stress is of sufficient magnitude to erode these sediments, the sewer will maintain self cleansing operation at times of dry weather. May, et. al. (1996), presented a definition to describe a self cleansing sewer as "an efficient self-cleansing sewer is one having a sediment-transporting capacity that is sufficient to maintain a balance between the amounts of deposition and erosion, with a time-averaged depth of sediment deposit that minimizes the combined costs of construction, operation and maintenance." To achieve such self-cleansing performance, the following criteria apply:

1. Flows equaling or exceeding a limit appropriate to the sewer should have the capacity to transport a minimum concentration of fine-grain particles in suspension (applicable for all types of sewerage systems).

2. The capacity of flows to transport coarser granular material as bed-load should be sufficient to limit the depth of deposition to a specified proportion of the pipe diameter. This criteria generally relates to combined and storm water systems. Limit of deposition considerations, i.e., “no deposition” generally applies to sanitary sewer designs. In this context, there must be sufficient shear in sanitary systems to avoid deposition of large particles.

3. Flows with a specified frequency of occurrence should have the ability to erode bed particles from a deposited granular bed that may have developed a certain degree of cohesive strength (applicable to all systems).

To meet these criteria, new guidelines have recently been developed (CIRIA, 1996), and are currently being adopted throughout Europe for the design of sewers to control sediment problems. Design criteria for the transport of fine grained material in suspension, the transport of coarser sediments as bed load and the erosion of cohesive sediment deposits and guidelines on the minimum flow velocity and pipe gradient for different types and sizes of sewer are outlined. To account for the effects of cohesion (Criterion 3, above), the design flow condition should produce a minimum value of bed shear stress of 2.0 N/m^2 on a flat bed with a Colebrook White roughness of 1.2 millimeters (CIRIA, 1996).

The third criterion is of specific interest to the problem of cleansing accumulated mature sediment beds. Various researchers have studied the flow conditions required to release particles from a deposited bed, which has developed a degree of cohesion. Summaries of investigations forming much of the basis for Criterion 3 are as follows:

- *Nalluri and Alvarez* (1992), whose laboratory studies used synthetic cohesive sediments, concluded that there were two ranges of bed shear stress at which erosion occurred: 2.5 N/m^2 applying for the weakest material, comprising a surface layer of fluid sediment: and 6 to 7 N/m^2 for the more granular and consolidated material below. It was found that, after erosion, the synthetic cohesive sediments behaved very much like non-cohesive material.

- *Ristenpart and Uhl* (1993) found in field tests that during dry weather an average bed shear stress of 0.7 N/m^2 was required to initiate erosion, increasing to an average of about 2.3 N/m2 during wet weather, or to 3.3 N/m^2 after a prolonged period of dry weather and presumably, consolidation of the deposited bed.

- *Ashley* (1993) has suggested that the bonds between particles at the surface of a deposited bed are weakened by the presence of the water, so that surface layers can be successively stripped away by the flow. Measurements in the Dundee, Scotland sewers indicated that it began to move at a fluid shear stress of about 1 N/m^2, with significant erosion of a deposited bed occurring at bed shear of 2 to 3 N/m^2. Taking account of a review of work by other researchers, Ashley concluded that most deposits should be eroded at a shear stress exceeding 6 to 7 N/m^2.

Desktop Procedure

A desktop procedure, developed for a recent sediment deposition investigation of the sediment accumulation problems in the South Ottawa Tunnel, Ottawa, Canada (Montgomery Watson, 1998) was used. The entire conduit is considered as a single "tank" with no differentiation of heavy particles settling at the front end of the tunnel in contrast to finer particles settling in mid-sections. The desktop procedure is a single cell mass balance model for large diameter sewer lines. Inputs are: daily flow rates; average daily minimum hourly, and maximum hourly discharge. A calendar year of flow data is used.

The desktop procedure analyzes deposition on a daily basis noting accumulations of inorganic and organic deposits as well as scour and erosion of prior deposits over the course of the input time series. Inorganic and organic solids are input on a daily basis as an invariant concentration basis, i.e., and independent of flow quantity.

The procedure investigates the settling and scouring behavior of material loosely categorized as inorganic "grit" and or large organic particles having fall settling velocities ranging between 0.1 and 30 cm/sec.

Table 3-3. Assumed Inorganic Material Composition

Sieve Size #	**Mesh Opening**	**Relative Mass Fraction**	**Assumed Composition By Specific Gravity**				**Sum**
	(mm)	(%)	1.7	1.9	2.1	2.5	
4	4.76	1	40	40	10	10	100
6	3.36	2	35	35	15	15	100
10	2.00	11	35	35	15	15	100
16	1.25	10	30	30	20	20	100
20	0.84	15	30	30	20	20	100
30	0.60	10	30	30	20	20	100
40	0.42	12	20	20	30	30	100
50	0.30	12	20	20	25	35	100
70	0.20	16	15	15	30	40	100
100	0.15	8	10	10	30	50	100
200	0.025	3	5	5	40	50	100
Sum		100					

As presented in Table 3-3, material is noted by sieve size varying from # 4 sieve size (3/8" gravel) to #200 sieve (0.075 mm- fine sand). Relative fractions per sieve size are noted along with density breakdown per sieve ranging from 1.7 (soil) to 2.5 (sand). The inorganic material distribution shown in Table 3-3 represents average value conditions.

Table 3-4 notes fall velocities for each of the sieve sizes and specific gravity subcategories. Fall velocities are computed using the worn angular assumption and sewage temperature of 10°C, which is very common. Table 3-5 depicts a similar assumed distribution of organic particles and estimated fall velocities. This data was developed by US EPA in the early 1980's to establish the basis of design for the hydraulic model studies leading to the design of the Swirl Concentrator (EPA, 1982).

Table 3-4. Distribution of Inorganic Material Settling Velocities

Sieve Size #	Mesh Opening (mm)	Fall Velocity* (cm/s)			
		density=1.7	Density=1.9	density=2.1	density=2.5
4	4.76	15.5	20.0	24.0	33.0
6	3.36	9.4	12.0	14.6	20.0
10	2.00	7.0	9.0	11.0	15.0
16	1.25	5.6	7.2	8.8	12.0
20	0.84	4.7	6.0	7.3	10.0
30	0.60	3.3	4.9	5.9	8.1
40	0.42	2.5	3.2	4.0	5.4
50	0.30	1.8	2.3	2.8	3.8
70	0.20	1.0	1.3	1.5	2.1
100	0.15	0.61	0.78	0.95	1.3
200	0.075	0.24	0.30	0.37	0.5

*Worn Angular Particles, Temperature = 10°C

Table 3-5. Assumed Organic Material Size, Composition and Settling Velocities

Sieve #	Mesh Opening (mm)	Mass Fraction (%)	Fall Velocity* (cm/s)
4	4.76	0.5	9.0
6	3.36	25	7.5
10	2.00	23	6.0
20	0.84	21	3.3
30	0.60	14	1.5
40	0.42	3	0.9
50	0.30	4	0.5
70	0.20	9.5	0.1

* Temperature = 10°C
Specific Gravity = 1.1

The daily mass input into the desktop procedure is assumed to be in the range of 3 to 15 mg/l inorganic and 5 to 15 mg/l organic. The desktop procedure uses flow inputs to develop daily flow velocities (average, maximum, and minimum) and shear stress (average, maximum, and minimum). The shears are used to determine deposition and erosion potential. If the average shear stress is smaller than the critical shear stress for that sieve size and density, as determined by Macke (1982) and Brombach (1993), deposition will occur.

Erosion of the bed load is based on maximum hourly shear stress. Maximum shear stress is compared to 2 N/m^2 as determined by CIRIA standards. When the shear stress is above 2 N/m^2, erosion of the bed load occurs.

The degree of erosion, as a function of average fluid shear stress, used in the Desktop procedure generally follows the empirical work of Nalluri and Avarez (1992), Ristenpart and Uhl (1993), and Ashley (1993) noted above. Table 3-6 demonstrates the full range of deposition and erosion potential as a function of discharge, velocity, and shear stress for a 3.05 meter tunnel. These results were prepared using the full annual range of expected flows into the new 7km InterIsland Tunnel connecting the Nut Island Headworks Facility with the new Deer Island Wastewater Treatment Plant in Boston.

Table 3-6. Assessment of 3.05 Meter Tunnel

Discharge (m^3/sec)	**Velocity (m/s)**	**Fluid Shear (N/m^2)**	**Deposition or Erosion Potential**
2.6	0.36	0.27	Severe deposition
3.5	0.47	0.48	Moderate to severe deposition
4.4	0.60	0.74	Mild to moderate deposition
5.3	0.72	1.04	Slight to mild deposition
6.1	0.84	1.43	Skims juvenile sediments
7.0	1.06	1.86	None to slight erosion top layer
8.8	1.20	2.85	Slight to mild erosion of consolidated beds (2-5%)
10.5	1.44	4.15	Mild erosion of consolidated beds (5-15%)
13.2	1.80	6.47	Moderate erosion of consolidated beds (15-25%)
15.8	2.17	9.3	Substantial erosion (25-35%)
17.5	2.41	11.5	Substantial erosion (35-50%)

Note: K_b=1.2 millimeters = rough concrete

Chapter 4
Hydrogen Sulfide and Sulfuric Acid Estimation Techniques

SULFIDE GENERATION IN SEWERS

Sulfide generation is a bacterially mediated process occurring in the submerged portion of sanitary sewers and force mains. Fresh domestic sewage entering a wastewater collection system is usually free of sulfide. However , a dissolved form of sulfide soon appears as a result of the following conditions:

- Low dissolved oxygen content
- Long detention time in the collection system
- Elevated wastewater temperature

The root cause of odor and corrosion in collection systems is sulfide, which is produced from sulfate by bacteria residing in a slime layer on the submerged portion of sewer pipes and structures. Once released from the wastewater as hydrogen sulfide gas, odor and corrosion problems begin. Another type of bacteria utilizes hydrogen sulfide gas to produce sulfuric acid that causes the destruction of wastewater piping and facilities. Operation and maintenance expenditures are required to correct the resulting damage caused by this sulfuric acid. In severe instances, pipe failure, disruption of service and uncontrolled releases of sewage can occur.

Fresh domestic sewage entering a wastewater collection system is usually free of sulfide. When certain conditions exist within the collection system, dissolved sulfide soon begins to appear. These sulfide producing conditions are low dissolved oxygen content, high-strength wastewater, long detention times, extensive pumping and high wastewater temperatures. The first step in this bacterially mediated process is the establishment of a slime layer below the water level in a sewer pipe or force main. This slime layer is composed of bacteria and inert solids held together by a biologically secreted protein "glue" called zooglea. When this biofilm becomes thick enough to prevent dissolved oxygen from penetrating it, an anoxic zone develops within it. Approximately two weeks is required to establish a fully productive slime layer in pipes. Within this slime layer, sulfate reducing bacteria use the sulfate ion ($SO_4^{=}$), a common component of wastewater, as an oxygen source for the assimilation of organic matter in the same way dissolved oxygen is used by aerobic bacteria. Sulfate concentrations are almost never limiting in normal domestic wastewaters. When sulfate is utilized by these bacteria, sulfide ($S^{=}$) is the by-product. The rate at which sulfide is produced by the slime layer depends on a variety of environmental conditions including the concentration of organic food source (BOD), dissolved oxygen concentration, temperature, wastewater velocity, and the area of the normally wetted surface of the pipe.

As sulfate is consumed, the sulfide by-product is released back into the wastewater stream where it immediately establishes a dynamic chemical equilibrium between four forms of sulfide; the sulfide ion ($S^{=}$), the bisulfide or hydrosulfide ion (HS^{-}), aqueous hydrogen sulfide ($H_2S_{(aq)}$), and hydrogen sulfide gas ($H_2S_{(g)}$).

Sulfide Ion ($S^{=}$)

The sulfide ion carries a double negative charge indicating that it reacts primarily by giving up two electrons in the outer shell. It is a colorless ion in solution and cannot leave wastewater in this form. It does not contribute to odors in the ionic form.

Bisulfide Ion (HS^-)

The bisulfide (or hydrosulfide) ion carries a single negative charge. This is because one of the negative charges of the sulfide ion is taken up by a positively charged hydrogen ion. It is a colorless, odorless ion which can only exist in solution. It also does not contribute to odors.

Hydrogen Sulfide (Aqueous)

Hydrogen sulfide can exist as a gas dissolved in water. The polar nature of the hydrogen sulfide molecule makes it soluble in water. In the aqueous form, hydrogen sulfide does not cause odor; however, this is the only sulfide specie that can leave the aqueous phase to exist as a free gas. The rate at which hydrogen sulfide leaves the aqueous phase is governed by Henry's Law, the amount of turbulence of the wastewater and the pH of the solution.

Hydrogen Sulfide (Gaseous)

Once hydrogen sulfide leaves the dissolved phase and enters the gas phase it can cause odor and corrosion. Hydrogen sulfide gas is a colorless but extremely odorous gas that can be detected by the human sense of smell in very low concentrations. In high concentrations, it is also very hazardous to humans. In concentrations as low as 10 ppm it can cause nausea, headache and conjunctivitis of the eyes. Above 100 ppm it can cause serious breathing problems and loss of the sense of smell along with burning of the eyes and respiratory tract. Above 300 ppm death can occur within a few minutes. For these reasons, the Occupational Safety and Health Administration (OSHA) has established an 8-hour, time-weighted, personal exposure limit of 10 ppm (U.S. EPA, 1985).

Due to the continuous production of sulfide in wastewater, hydrogen sulfide gas rarely, if ever, re-enters the liquid phase. Sulfide continuously produced by the slime layer replaces that which is lost to the atmosphere as hydrogen sulfide gas in the collection system. In addition, once the hydrogen sulfide gas is released it usually disperses throughout the sewer environment and never reaches a high enough concentration to be forced back into solution.

The four sulfide chemical species are related according to the following equilibrium:

$$H_2S_{(g)} \rightleftharpoons H_2S_{(aq)} \overset{pKa = 6.9}{\rightleftharpoons} HS^- \overset{pKa = 14}{\rightleftharpoons} S^=$$

$H_2S_{(g)}$	$H_2S_{(aq)}$	HS^-	$S^=$
hydrogen sulfide gas	hydrogen sulfide (dissolved)	bisulfide ion	sulfide ion

As indicated by the equilibrium equations, once hydrogen sulfide is released into the gas phase, bisulfide ion is immediately transformed into more aqueous hydrogen sulfide to replace that which is lost. Concurrently, sulfide ion is transformed into bisulfide to replace that lost to aqueous hydrogen sulfide. Through this type of continuously shifting equilibrium it would be possible to completely remove all sulfide from wastewater as hydrogen sulfide gas through stripping. This is generally not recommended or advantageous due to odor releases and the accelerated corrosion which can take place.

The quantitative relationship between the four sulfide species is controlled by the pH of the wastewater. The sulfide ion ($S^=$) does not exist below a pH of about 12 and as indicated by the pKa, is in a 50/50 proportional relationship with the bisulfide ion (HS^-) at a pH of 14. Since the normal pH of wastewater is far lower, the sulfide ion is rarely experienced. The pKa of much greater importance is the one controlling the proportional relationship between the bisulfide ion and $H_2S_{(aq)}$. Most domestic wastewater has a pH near 6.9. This means that at the pH of normal wastewater, half of all sulfide present exists as the bisulfide ion and the other half exists as aqueous hydrogen sulfide (a dissolved gas). Since the concentration of dissolved gases in solution are primarily controlled by the specific Henry's Law coefficient for that gas, they can be released from solution to exist as the free gas form. Once subjected to turbulence or aeration, wastewater can release the dissolved gas as free hydrogen sulfide gas, and more bisulfide ion is transformed into the dissolved gas form to replace that lost to the atmosphere.

Settleable Solids

Periods of low flow in the collection system correlate to lower average wastewater velocities. Low flow velocities allow material, usually grit and large organics, to settle in the collection system piping. This increases the mass and surface area of material in the collection system upon which sulfate reducing bacteria (slime layer) can grow, and can lead to an increased conversion of sulfate to sulfide.

Collection systems with sedimentation problems can experience sulfide concentration spikes during the historically high flow, cool temperature months. This phenomenon occurs when significant sand or grit accumulations exist and the particles are covered by an anaerobic slime layer that contains sulfate-reducing bacteria. Only the bacteria on the surface of the grit pile receive a continuous supply of sulfate because they are exposed to the wastewater. The buried sulfate-reducing bacteria are not exposed to a continuous supply of sulfate. This forces them to exist in a semi-dormant, anaerobic state with very low cell activity (but they are not dead). When a high flow event occurs, with sufficient velocity and shear force to re-suspend the sediment, this enormous surface area of sulfate reducing bacteria is suddenly exposed to ample sulfate and they rapidly convert it to dissolved sulfide. This causes a relatively short duration, high sulfide event with resulting hydrogen sulfide gas release, odor and corrosion.

The grit particles and their attached sulfate-reducing bacteria that were semi-dormant are suspended and exposed to a tremendous quantity of sulfate and quickly begin producing sulfide. The interaction between a large quantity of bacteria and an almost unlimited food source will create dissolved sulfide spikes that are subsequently released in areas of high turbulence. This trend is common and well documented in many cities with similar grit deposition problems such as Boston, Los Angeles, St. Louis, and Houston.

Temperature

In addition to the factors described above, summer conditions result in an increase of wastewater temperatures. Greater wastewater temperatures increase the metabolic activity of the sulfate reducing organisms, causing faster conversion of sulfate to sulfide and increased dissolved sulfide concentrations. It has been estimated that each incremental 7 degree C (12.5 degree F) increase in wastewater temperature doubles the production of sulfide.

Sulfuric Acid Production

Thiobacillus aerobic bacteria, which commonly colonize pipe crowns, walls and other surfaces above the water-line in wastewater pipes and structures, has the ability to consume hydrogen sulfide gas and oxidize it to sulfuric acid. This process can only take place where there is an adequate supply of hydrogen sulfide gas (>2.0 ppm), high relative humidity and atmospheric oxygen. These conditions exist in the majority of wastewater collection systems for some portion of the year. A pH of 0.5 (which is approximately equivalent to a 7 percent sulfuric acid solution) has been measured on surfaces exposed to severe hydrogen sulfide environments (>50 ppm in air).

The simplified and balanced equation for the biological metabolic process which converts hydrogen sulfide to sulfuric acid is presented below:

Thiobacillus Bacteria

$H_2S_{(g)}$	+	$2\ O_2$	$\rightarrow$	H_2SO_4
hydrogen sulfide gas		atmospheric oxygen		Sulfuric acid

Turbulence Reduction
Turbulence is a critical parameter to consider in preventing hydrogen sulfide gas release from wastewater. The effects of sulfide odor and corrosion are increased by orders of magnitude at points of turbulence. Henry's law governs the concentration of gas over a liquid containing the dissolved form of the gas. Henry's law states in effect:

> The concentration of a gas over a liquid containing the dissolved form of the gas is controlled by the partial pressure of that gas and the mole fraction of the dissolved gas in solution.

Since this law governs the relationship between the dissolved form and gaseous form of sulfide over a given surface area, any action which serves to increase the surface area of the liquid also increases the driving force from the liquid to the gas phase.

The most common form of increased surface area is turbulence. In turbulent areas, small droplets are temporarily formed. When this happens, the forces governing Henry's law (partial pressure) quickly try to reach equilibrium between the liquid and atmospheric phases of the gas. The result is often a dramatic release of sulfide from the dissolved to the gaseous form. Structures causing turbulence should be identified and measures should be taken to protect and/or control the subsequent hydrogen sulfide gas releases. This same release mechanism is exhibited whenever wastewater containing dissolved sulfide is aerated.

Concrete Corrosion
The effect of sulfuric acid on concrete surfaces exposed to the sewer environment can be devastating. Sections of collection interceptors and entire pump stations have been known to collapse due to loss of structural stability from corrosion. The process of concrete corrosion, however, is a step-wise process which can sometimes give misleading impressions. The following briefly describes the general process of concrete corrosion in the presence of a sewer atmosphere.

Freshly placed concrete has a pH of approximately 11 or 12, depending upon the mix design. This high pH is the result of the formation of calcium hydroxide [$Ca(OH)_2$] as a by-product of the hydration of cement. Calcium hydroxide is a very caustic crystalline compound which can occupy as much as 25 percent of the volume of concrete. A surface pH of 11 or 12 will not allow the growth of any bacteria; however, the pH of the concrete is slowly lowered over time by the effect of carbon dioxide (CO_2) and hydrogen sulfide gas (H_2S). These gases are both known as "acid" gases because they form relatively weak acid solutions when dissolved in water. CO_2 produces carbonic acid and H_2S produces thiosulfuric and polythionic acid. These gases dissolve into the water on the moist surfaces above the sewage flow and react with the calcium hydroxide to reduce the pH of the surface. Eventually the surface pH is reduced to a level that can support the growth of bacteria (pH 9 to 9.5).

The time it takes to reduce the pH is a function of the concentration of carbon dioxide and hydrogen sulfide in the sewer atmosphere. It can sometimes take years to lower the pH of concrete from 12 to 9, however, in some severe situations it can be accomplished in a few months.

Once the pH of the concrete is reduced to around pH 9, biological colonization can occur. Over 60 different species of bacteria are known to regularly colonize wastewater pipelines and structures above the water line. Most species of bacteria in the genus Thiobacillus have the unique ability to convert hydrogen sulfide gas to sulfuric acid in the presence of oxygen. Because each species of bacteria can only survive under a specific set of environmental conditions, the particular species inhabiting the colonies changes with time. Since the production of sulfuric acid from hydrogen sulfide is an aerobic biological process, it can only occur on surfaces exposed to atmospheric oxygen.

As a simplified example, one species of Thiobacillus only grows well on surfaces with a pH between 9 and 6.5. However, when the sulfuric acid waste product they excrete decreases the pH of the surface below 6.5, they die off and another species takes up residence which can withstand lower pH ranges. The succeeding species grows well on surfaces with a pH between 6.5 and 4. When the acid produced by these species drops the pH below 4, a new species takes over. The process of successive colonization continues until species, which can survive in extremely low pH conditions, take over. One such specie is Thiobacillus thiooxidans, which is sometimes known by its common name, Thiobacillus concretivorous, which is Latin for "eats concrete". This organism has been known to grow well in the laboratory while exposed to a 7 percent solution of sulfuric acid. This is equivalent to a pH of approximately 0.5.

Sulfuric acid attacks the matrix of the concrete, which is commonly composed of calcium silicate hydrate gel (CSHG), calcium carbonate from aggregates (when present), and un-reacted calcium hydroxide. Although the reaction products are complex and result in the formation of many different compounds, the process can be generally illustrated by the following reactions:

$$H_2SO_4 + CaSi \rightleftharpoons CaS0_4 + Si + 2\ H+$$

$$H_2SO_4 + CaCO_3 \rightleftharpoons CaS0_4 + H_2CO_3$$

$$H_2SO_4 + Ca(OH)_2 \rightleftharpoons CaS0_4 + 2\ H_2O$$

The primary product of concrete decomposition by sulfuric acid is calcium sulfate ($CaS0_4$), more commonly known by it's mineral name, gypsum. From experience with this material in its more common form of drywall board, we know that it does not provide much structural support, especially when wet. It is usually present in sewers and structures as a pasty white mass on concrete surfaces above the water line. In areas where diurnal or other high flows intermittently scour the walls above the water line, concrete loss can occur rapidly. The surface coating of gypsum paste can protect underlying sound concrete by providing a buffer zone through which freshly produced sulfuric acid must penetrate. Because Thiobacillus bacteria are aerobic, they require free atmospheric oxygen to survive. Therefore, they can only live on the thin outer covering of any surface. This means that acid produced on the surface must migrate through any existing gypsum paste to reach sound concrete. When the gypsum is washed off fresh surfaces are exposed to acid attack and this accelerates the corrosion.

The color of corroded concrete surfaces can be various shades of yellow caused by the direct oxidation of hydrogen sulfide to elemental sulfur. This only occurs where a continuous high concentration supply of atmospheric oxygen or other oxidants are available. The upper portions of manholes and junction boxes exposed to high hydrogen sulfide concentrations are often yellow because of the higher oxygen content there. This same phenomena can be observed around the outlets of odor scrubbers using hypochlorite solutions to treat high concentrations of hydrogen sulfide gas.

Another damaging effect of sulfuric acid corrosion of concrete is the formation of a mineral called "ettringite". The chemical name for ettringite is calcium sulfbaluminate hydrate. It is produced by a reaction between calcium sulfate and alumina, which is found in virtually all cements. It forms at the boundary line between the soft calcium sulfate layer and the sound, uncorroded concrete surface. Ettringite is damaging because it is an expansive compound which occupies more space that it's constituents. When ettringite forms, it lifts the corroded concrete away from the sound concrete and causes a faster corrosion by continually exposing new surfaces to acid attack. Although the rate of concrete loss is dependent upon a number of factors including ettringite formation, it is not uncommon to see concrete loss of I inch per year in heavy sulfide environments.

Metal Corrosion

Concrete is not the only material that can be affected by the corrosive action of hydrogen sulfide gas. Most metals, including stainless steel, can also be attacked and destroyed by exposure to the strong mineral acid, sulfuric acid. Metals can be corroded by two means, acid decomposition by exposure to sulfuric acid produced by Thiobacillus bacteria, and direct molecular attack. Most free metals are bi-valent cations, meaning that they carry two positive charges and react primarily by gaining two electrons in their outer shell (M++). The sulfide component of hydrogen sulfide gas supplies these two electrons resulting in a metal sulfide and two free hydrogen ions.

$$M^{++} + H_2S \rightleftharpoons MS + 2H^+$$

The metal has a much stronger affinity for the sulfide than hydrogen causing the release of two free hydrogen ions. In this manner, the metal is converted from a strong metal-metal bonding arrangement into a much weaker metal sulfide product. At the same time metals are exposed to the acidic effect of the free hydrogen ions. This condition results in missing rungs of former manhole steps, the corroded and weakened manhole covers and rings, and brass and copper fittings turned dark bluish-black, the color of nickel and copper sulfide.

Trends in Sulfide Production

Hydrogen sulfide has always existed in wastewater. Recent trends of water conservation, industrial pretreatment, and design deficiencies can significantly increase sulfide generation. This increase in sulfide generation leads to additional odor and corrosion problems.

Water Conservation Practices

Utilities and water purveyors have recognized the benefit of promoting water conservation practices. Prompted by water shortages around the country, water conservation practices were shown to not only preserve a precious resource but also save utilities money by delaying planned expenditures for plant upgrades, system capacity increases, and storage facilities. Although cost-efficient and practical for the water industry, water conservation has caused an increase in dissolved sulfide concentrations in wastewater systems.

Reduced wastewater flows from water conservation practices can cause reduced velocities and longer residence time in the collection and transmission systems. These conditions allow more time for the reduction of sulfate, creating higher dissolved sulfide concentrations and they also increase the general septicity of the wastewater. Since less water is entering the wastewater collection system while the organic load remains the same, the strength of the wastewater in terms of BOD_5 also increases. This increases the biological activity of the slime layer and causes the faster consumption of dissolved oxygen and the creation of anaerobic conditions. Anaerobic conditions also cause the production of organic acids, which drop the pH of the wastewater. Since a small shift downward in the pH of the wastewater can cause a dramatic increase in hydrogen sulfide gas release, the anaerobic drop in pH can also increase the release of odor-causing hydrogen sulfide gas.

Although water conservation has increased the dissolved sulfide concentration of wastewater, little evidence suggests a general increase in total sulfide mass. However, the Henry's Law coefficient governing the release of hydrogen sulfide gas from wastewater is dependent only upon sulfide concentration in the liquid phase, not mass. Therefore, any increase in the dissolved sulfide concentration of wastewater will increase the release of hydrogen sulfide gas.

Industrial Pretreatment

Perhaps the greatest contributor to increased dissolved sulfide concentrations in municipal wastewater is industrial pretreatment (Public Law 92-500). The Clean Water Act, mandated that the nation's water supplies be protected through a variety of mechanisms. One such mechanism is to require cleaner wastewater discharges from our Publicly Owned Treatment Works (POTW). One concern with treated wastewater discharges was the bio-accumulation of heavy metals in the environment. High concentrations of certain metals, such as lead, copper, mercury, chromium, and zinc were shown to have toxic effects on animals and plants. Some of these metals can pass through a wastewater treatment plants and enter the receiving stream or water body where they could be bio-accumulated to dangerous concentrations. As a result, the U.S. Environmental Protection Agency (EPA) required municipalities to implement industrial pretreatment programs, under which heavy metals and other contaminants from industrial sources were identified and treated. Removing heavy metals removed a potential sulfide removal mechanism. Dissolved forms of sulfide (bisulfide ion and sulfide ion) have a strong affinity for metals. One of the most common methods used to remove sulfide from wastewater is to add metal salts, usually ferrous iron compounds. Metal salts combine with sulfide and precipitate an insoluble metal sulfide. Before 1980, a common source of heavy metals in wastewater was industrial discharges from steel mills, electro-plating operations, photo-finishing, and electronics manufacturing. As of 1995, all such operations pre-treat their wastewater to remove metals prior to discharge to a POTW.

The targeted heavy metals also exhibit a toxic effect on bacteria in the slime layer that produce sulfide. Toxicity or inhibition of the sulfate-reducing bacteria in the slime layer by the targeted heavy metals naturally reduced their health and activity, which reduced sulfide production. Removing the source of the toxicity allowed the slime layer bacteria to flourish and produce even more sulfide. In 1989, the United States Congress ordered a study to assess the impact of the industrial pretreatment program on sulfide generation. The study indicated that both of the above mechanisms were responsible for a general increase in sulfide in domestic wastewater.

Over a period of several years, influent wastewater at the Hyperion Wastewater Treatment Plant in Los Angeles, California, was analyzed for several constituents including sulfide and total metals concentrations. As the data in Table 4-1 dramatically indicate, influent sulfide to the plant increased at the same time that total metals concentrations decreased. This trend has continued since 1980 and is considered a direct effect of industrial pre-treatment. Therefore, industrial pretreatment has resulted in an increase in sulfide in wastewater.

Design Deficiencies

Wastewater and collection system facility designers often under state the increasing trend in sulfide odor and corrosion related problems and neglect to incorporate controls into their designs. Often the relatively complex relationships between wastewater characteristics, slime layer formation, sulfide production bio-kinetics, sulfide chemistry, corrosion biology, gas release, and ventilation dynamics are not fully understood are not fully understood.

Tabe 4-1. Dissolved Sulfide and Total Metals Concentration Trends at Hyperion WWTP,Los Angeles, CA (Joyce, 1998)

Year	**Total Metals Concentration** (mg/l)	**Dissolved Sulfide Concentration** (mg/l)
1981	19.0	1.0
1982	17.0	2.0
1983	16.0	3.0
1984	14.0	4.0
1985	13.0	4.5
1986	12.5	5.0
1987	11.0	7.0
1988	10.0	8.0
1989	8.0	10.0
1990	7.0	12.0
1991	6.0	12.5
1992	5.0	13.0
1993	3.5	13.5
1994	3.0	15.0

The following examples should be noted as potential odor and corrosion catastrophes and should be avoided:

- force mains routed on a downhill gradient can experience premature crown failure
- drop manholes with 4.5 to 6 meter (15 to 20 foot) hydraulic freefalls causing extreme turbulence and hydrogen sulfide release
- unlined, unprotected pipe conveying wastewater for distances up to 48 kilometers (30 miles)
- manifolded force main systems for distances up to 24 kilometers (15 miles), detention times of two or three days, and 360-degree slime layers producing dissolved sulfide with no chance of reaeration

Flushing Relationship to Hydrogen Sulfide Generation

Description of the Process

Wastewater, stormwater or riverwater can be collected and stored in chambers or upstream sewers for release as a flush wave. As the flush wave travels down the sewer, the shear forces applied to the upper layer of the sediments exceeds the bonding strength of the solids, and eroded particles are moved downstream with the flow. In the process of traveling down the sewer, the upper layer of solids are removed and moved downstream with the flush water.

Odor Producing Conditions

The following scenarios illustrate how flushing may produce odor conditions.

- Remaining water in the pipe can contain high concentrations of dissolved sulfide. The turbulence associated with the flush wave may release peak concentrations of hydrogen sulfide gas at the downstream flushing terminus.

- Decomposing and hydrolyzing organic solids in the sewer materials can produce locally high soluble BOD concentrations in the matrix of the solids. Due to the presence of sulfate and sulfate reducing organisms in the matrix of the solids, it can be expected that high dissolved sulfide concentrations can exist in the upper layer of solids (approximately 2 to 6 centimeters). When this layer of solids is removed by a flush event, the dissolved sulfide present inside the matrix of the solids will be released into the flush water. Turbulence associated with the flush water will then cause release of the dissolved sulfide as hydrogen sulfide gas. This may cause odor and corrosion producing conditions.

- When flushing deep deposits, once a fresh layer of solids is scoured away the new surface of the solids will presumably be the solids previously buried deeper within the solids mass. The biological population in this freshly exposed layer of solids will likely be strict anaerobes. This class of bacteria also contains species that can reduce sulfate. Prior to being exposed to the flush event, these solids received very little flux of sulfate, since most sulfate was reduced to sulfide by the previous layer. Since the now exposed solids have been buried for some time, the anaerobic decomposition of organic matter can produce a rich mixture of organic acids and other short-chain carbon compounds. These organic acids and other anaerobic products make the soluble BOD of the mixture very high. Now that the freshly exposed layer is subjected to ample sulfate in the flush water flow, the metabolism of the sulfate reducing organisms is greatly accelerated and significant quantities of dissolved sulfide will again be formed. This newly formed sulfide is therefore available for release as hydrogen sulfide during the next flushing event.

- As the flush wave moves down the sewer at significant velocities, friction between the air and water creates a very large bowlus of air traveling down the pipe with very high concentrations of hydrogen sulfide present. When this air arrives at the downstream flushing terminus, a peak spike of hydrogen sulfide odor may need controlling.

Invert Erosion

It is important to consider the effect of flushing on the condition of the partially corroded pipe. Will the high velocity water cause erosion of the partially corroded and pasty pipe walls? This may be a concern when flushing older pipe systems or new systems recently impacted by corrosion. The basis of this concern is a series of observations noted in 1997 in Phoenix, Arizona. The following is an excerpt from a recent investigation in Phoenix, Arizona noting the erosion of stones and aggregates on a downstream new interceptor system from upstream piping areas (OCTC, 1997).

Example of Invert Erosion: Phoenix, Arizona

During an investigation of the twin 1.8 meter (72 inch) diameter sewers entering the 91st Avenue Wastewater Treatment Plant (WWTP) on June 18, 1997, the flow in the pipe was approximately 0.9 meters (3 feet) deep at the invert and moving at an estimated 1.5 m/s (5 fps). This was a reduced flow condition from previous inspections in this sewer, and it allowed the inspector to physically make contact with the invert of the sewer. As the inspector stood on the bottom of the pipe, a groove, approximately 8 to 10 centimeters (3 to 4 inches) wide and 10 centimeters (3 inches) deep, was detected in the sewer invert. As the inspector probed the length and depth of the groove with his boot to determine the dimensions, a rock approximately 4 centimeters (1.5 inches) in diameter struck the toe of his boot with considerable force. The rock was retrieved, examined, and found to be a semi-round, river-gravel type silica rock with one fracture plane. The rock was relatively clean and did not have a slime layer attached. The rock resembled what could be used as concrete aggregate in upstream piping. The precise source of the rock could not be determined. During the 15 minutes that the inspector was in the pipe more than two dozen rocks were noted to travel down the pipe inside the groove in single-file fashion.

The groove was probed further and found to extend as far as the inspector could reach both in an upstream and downstream direction from the manhole. It is believed that the groove extends the entire length of the sewer in this reach. It was concluded that the groove is caused by the impacts caused by stones, rocks, and other hard debris traveling down the pipe with the flow. Because of the high wastewater velocity and hydraulic shear forces developed in the fast-flowing Salt River Outfall (SRO), it is suspected that all hard debris and rocks which enter the SRO (and pipes of similar hydraulic characteristics) produce invert erosion until they reach the 91st Avenue WWTP.

It could not be determined with certainty that the reinforcing steel has been severed by the groove; however, estimating from the depth of the groove and the normal reinforcing mesh coverage in reinforced concrete pipe (RCP), the steel reinforcing in the bottom of the pipe has most likely been compromised.

The source of the debris that is causing the invert corrosion cannot be definitely determined, although the type and size of the rocks are very similar to what would normally be used as concrete pipe aggregate. The pure silica, acid-proof, river-gravel stone aggregate historically used as concrete aggregate in the Phoenix area comes from the Salt River basin. The stones are crushed and screened to produce the proper gradation for concrete mix designs. The crushing operation produces very hard, sharp, angular pieces ideal for concrete aggregate. It is this type of aggregate that has been noticed during these inspections to be protruding from the surface of corroded pipes. The aggregate protrudes from the concrete matrix because silicate stones are inert to strong reducing acids such as the sulfuric acid produced by Thiobacillus bacteria from hydrogen sulfide gas. The concrete matrix (predominantly calcium silicate, calcium carbonate, and calcium hydroxide), however, is easily dissolved by sulfuric acid leaving the inert silicate stones protruding from the corroded concrete surface.

The older, shallow surface sewers of all SRO member communities are most likely the source of the rocks. The rocks move slowly or intermittently in these shallow sewers due to the lack of sustained flushing velocities. When moving slowly or intermittently the rocks do not tumble with great force and their impact locations are scattered across a large area of the bottom of the pipe. When these rocks enter the fast-flowing SRO or other large diameter sewers with sustained high velocities, the rocks are overwhelmed by the hydraulic forces and align themselves in single-file fashion as they move quickly down the pipe. This causes the impacts from all these stones to be concentrated in a very narrow band directly in the invert of the pipe. The combination of the mass (weight) of the stones, their velocity, tumbling action caused by asymmetrical shapes and the concentration of all impact sites directly at the invert of the pipe is causing the groove. If not addressed or corrected the erosion of the invert will continue to the point of pipe breach. Once this happens, the pipe bedding and surrounding soils will likely be liquefied and either moved or transported downstream. This will leave portions of the bottom of the pipe unsupported and promote pipe settlement, fracture, and eventual destruction of the pipe requiring replacement.

From a brief study of the physics of this erosion phenomenon, it can be determined that the greatest damage is caused by those stones and rocks having sufficient mass to impart a significant impact under the acceleration of gravity. As the stones tumble within the pipe they are continuously striking the bottom of the pipe, rebounding, being launched briefly a few inches above the invert, and then strike the invert again a short distance downstream. It can be determined that the larger stones and rocks cause the greatest damage; however, it can certainly be argued that the smaller stones also contribute to the phenomenon (less than #4 sieve) but to a much less degree.

Dissolved Sulfide Prediction Procedure

The dissolved sulfide estimation procedure used in the desktop analyses was developed by Montgomery Watson to estimate the amount of dissolved sulfide which can be produced by wastewater under a variety of gravity and force main situations and the corrosion which results from the release of dissolved sulfide to hydrogen sulfide gas. This procedure is used in conjunction with the solids deposition and erosion procedure noted earlier in this chapter. This procedure uses the classical Pomeroy/Parkhurst dissolved sulfide generation equations, with the exception that additional logic have been added to account for variables not anticipated in the original equations. The procedure consists of two parts: one for dissolved sulfide generation based on the Pomeroy equations, and a second part to estimate corrosion rates in wastewater collection systems. This second part estimates the corrosion rate of concrete, steel, brick, mortar and other materials subjected to hydrogen sulfide environments. This procedure is for use in gravity sewers, wet wells, junction boxes, siphons and force main discharge manholes downstream of sulfide producing sewers and force mains.

Sulfide Model Development

The dissolved sulfide generation rate is most affected by BOD and temperature. An increase in temperature increases the metabolic rate of the bacteria and the rate of sulfide production. The term "effective BOD" has been used as a convenient way to combine the temperature and BOD effects. The equation for this relationship is as follows:

$$(EBOD) = (BOD) \times (1.07)^{(T-20)}$$

Where:

EBOD = effective BOD, mg/l
BOD = standard BOD_5, mg/l
T = temperature, deg C
1.07 = empirical factor

The Pomeroy and Parkhurst equation noted below is used to predict dissolved sulfide buildup. This equation accounts for the various factors affecting sulfide buildup in typical municipal wastewater applications (Pomeroy, 1985). A common form of the equation is presented below (where D/4 represents the hydraulic radius):

$$S_2 = S_1 + (M)\ (t)\ [EBOD\ (D/4 + 1.57)]$$

Where:

S_2 = predicted sulfide concentration at time t_2; mg/l
S_1 = sulfide concentration at time t_1; mg/l
$t = t_2 - t_1$ = flow time in a given sewer reach with constant slope, diameter, and flow; hr
M = specific sulfide flux coefficient; m/hr
D = pipe diameter; ft

An M factor of 1×10^{-3} m/hr is generally reasonable for force mains in which conditions are favorable for sulfide buildup (ie: infrequent flow, low velocities, high temperatures, long retention times, very low dissolved oxygen, and moderate to high BOD). The default value for M in the sulfide generation procedure is 3×10^{-4} m/hr and has been found to be a good approximate value when all force mains and gravity sewers are considered. This value can be adjusted up or down to account for the specifics of each system to be modeled.

Dissolved Oxygen Effects

The Pomeroy/Parkhurst equations for prediction of sulfide buildup assume that little or no dissolved oxygen is present. One of the requirements for use of the equations is that less than 0.5 mg/l dissolved oxygen be present for the equations to be accurate. This is due to the sulfide oxidation effects of the aerobic zone on top of the slime layer. Typically, wastewater contains more than 0.5 mg/l dissolved oxygen. If the effect of this oxygen is ignored, the model will over-estimate sulfide production. Facultative bacteria are a type of common sewer bacteria that utilize dissolved oxygen, when available, but can also respire in its absence. These bacteria will utilize the available dissolved oxygen (D.O.) until it is depleted. Then, in the absence of dissolved oxygen, the bacteria will begin utilizing first nitrate and then sulfate as their oxygen source. Unprocessed municipal wastewater typically has a limited nitrate concentration. Once oxygen and any nitrate is depleted, the bacteria will begin to utilize sulfate as an oxygen source and produce sulfide. The time required for depletion of the DO should be accounted for in the determination of sulfide buildup so that the most accurate results are obtained.

To account for dissolved oxygen concentrations higher than 0.5 mg/l, the Pomeroy/Parkhurst equations have been modified to include logic which estimates the time for oxygen depletion. The time required for depletion of the dissolved oxygen is calculated with the following equation:

$$t_{DO} = \frac{DO}{SOUR\ (1/10^3)\ (VSS)}$$

Where:

t_{DO} = time required for bacterial dissolved oxygen depletion, hr
DO = initial dissolved oxygen concentration, mg/l
SOUR = specific oxygen uptake rate, mg O_2/g VSS-hr
VSS = volatile suspended solids concentration, mg/l (represents bacterial concentration)

Subtracting the time required for oxygen depletion from the detention time yields the time remaining for sulfide production. This assumes that sulfide accumulation does not occur during periods when dissolved oxygen concentrations are greater than 0.5 mg/l. Substituting the time remaining for bacterial sulfide production into the equation for prediction of sulfide buildup results in an equation which accounts for the presence of DO. The equation is expressed as follows for a force main or full flowing pipe:

$$S_2 = S_1 + (M)\ t_S\ [EBOD\ (D/4 + 1.57)]$$

Where:

S_2 = predicted sulfide concentration at time t_2; mg/l
S_1 = sulfide concentration at time t_1; mg/l
M = specific sulfide flux coefficient; m/hr
$t_S = t - t_{DO}$ = time remaining for sulfide accumulation; hr
D = pipe diameter; ft

If enough dissolved oxygen is present, many bacteria will not utilize sulfate as an oxygen source and therefore not produce sulfide, and other bacteria in the aerobic zone on the slime layer will oxidize sulfide produced in the anoxic zone and suppress sulfide release back into the wastewater.

Chapter 5
Overview of Sewer Cleaning
Flushing Systems and CSO Tank Cleaning Technology

The deposition of sewage solids during dry weather in combined sewers has long been recognized as a major contributor to "first-flush" phenomena. Another manifestation of first-flush, in addition to the scouring of materials already deposited in the lines, is the first flush of loose solid particles on the urban ground surface that are transported into the sewerage system and not trapped by catch basins or inlets. These particulates may settle out in the system and be scoured and resuspended during wet periods. Such materials also create first flush loading from storm drainage systems. Deposition of heavy solids is also a problem in separate sanitary systems.

One of the underlying reasons for considerable sewage solids deposition in combined sewers is the hydraulic design. Combined sewers are sized to convey many times the anticipated peak dry weather sewage flow. Combined sewer laterals can carry up to 1000 times the expected background sewage flow. Ratios of peak to average dry weather flow usually range from 2 to 10 for interceptor sewers. The oversized combined sewer pipes possess substantial sedimentation potential during dry weather periods. Dry weather flow velocities are typically inadequate to maintain settleable solids in suspension which tend to accumulate in the pipes. During rainstorms, the accumulated solids can re-suspend and overflow to receiving waters.

Generally if sediments are left to accumulate in pipes, hydraulic restrictions can result in blockages in flowline discontinuities. Otherwise, the bed level reaches an equilibrium level. A number of conventional cleaning techniques are described below, followed by a discussion of various manual and automated flushing methods.

Over the past 50 years nearly 15,000 CSO tanks have been constructed world-wide. In the US there are approximately 300 facilities mostly off line at the end of collection systems. The balance are mostly in Europe with nearly 14,000 constructed in Germany. Tank cleaning methods are reviewed.

Conventional Sewer Cleaning Techniques

Conventional sewer cleaning techniques include rodding, balling, flushing, poly pigs and bucket machines. These methods are used to clear blockages once they have formed, but also serve as preventative maintenance tools to minimize future problems. With the exception of flushing these methods are generally used in a "reactive" mode to prevent or clear up hydraulic restrictions. As a control concept, flushing of sewers is viewed as a means to reduce hydraulic restriction problems as well as a pollution prevention approach.

Power Rodding

Power rodding includes an engine and drive unit, steel rods and a variety of cleaning and driving units. The power equipment applies torque to the rod as it is pushed through the line, rotating the cleaning device attached to the lead end. Power rodders can be used for routine preventative maintenance, cutting roots and breaking up grease deposits. Power rodders are efficient in lines up to 0.30 meters (12 inches).

Balling

Balling is a hydraulic cleaning method in which the pressure of a water head creates high velocity water flow around an inflated rubber cleaning ball. The ball has an outside spiral thread and swivel connection that causes it to spin, resulting in a scrubbing action of the water along the pipe. Balls remove settled grit and grease buildup inside the line. This technique is useful for sewers up to 0.60 meters (24 inches).

Jetting
Jetting is a hydraulic cleaning method that removes grease buildup and debris by directing high velocities of water against the pipe walls at various angles. The basic jetting machine equipment is usually mounted on a truck or trailer. It consists of water supply tank of at least 3.8 cubic meters (1,000 gallons), a high pressure water pump, an auxiliary engine, a powered drum reel holding at least 152 meters (500 feet) of one inch hose on a reel having speed and direction controls and a variety of nozzles. Jetting is efficient for routine cleaning of small diameter, low flow sewers.

Pigging
Poly pigs, kites, and bags are used in a similar manner as balls. The rigid rims of bags and kites cause the scouring action. Water pressure moves these devices against the tension of restraining lines. The shape of the devices creates a forward jet of water. The poly pig is used for large sanitary sewers and is not restrained by a line, but moves through the pipe segment with water pressure buildup behind it.

Power Bucket
The power bucket machine is a mechanical cleaning device effective in partially removing large deposits of silt, sand, gravel, and grit. These machines are used mainly to remove debris from a break or an accumulation that cannot be cleared by hydraulic methods. In cases where the line is so completely plugged that a cable cannot be threaded between manholes, the bucket machine cannot be used. The bucket machine is usually trailer or truck mounted and consists mainly a cable storage drum coupled with an engine with controllable drive train, up to 300 meters (1000 feet) of 1.3 centimeter (1/2-inch) steel cable and various sized buckets and tools ranging up to in diameter. The cable drum and engine are mounted on a framework that includes a 0.9 meter (36 inch) vertical A-frame high enough to permit lifting the cleaning bucket above ground level. Typically two machines of same design are required. One machine at the upstream manhole is used to thread the cable from manhole to manhole. The other machine is used at the downstream manhole has a small swing boom or arm attached to the top of the A-frame for emptying buckets. The bucket is cylindrical. The bottom of the bucket has two opposing hinged jaws. When the bucket is plugged through the material obstructing the line, these jaws are open and dig into and scrape off the material and fill the bucket. When the bucket is pulled in the reverse direction, the jaws are forced closed by a slide action. Any material in the bucket is retained as the bucket is pulled out through the manhole.

Silt Traps
Silt traps (or grit sumps) have successfully been used to collect sewer sediments at convenient locations within the system with the traps being periodically emptied as part of a planned maintenance program. The design and operational performance of two experimental rectangular (plan) shaped silt traps in French sewer systems was reported (Bertrand-Krajewsk, Madiec, and Moine, 1996). Information on design procedures and methodology for silt traps is scarce.

Sewer Flushing
Flushing of sewers has been a concern dating back to the Romans. Ogden (1892) described early historical efforts for cleaning sewers in Syracuse, New York at the turn of the century. The concept of sewer flushing is to induce an unsteady wave by either rapidly adding external water or creating a "dambreak" effect by quick opening a restraining gate. This aim is to re-suspend, scour and transport deposited pollutants to the sewage treatment facility during dry weather and/or to displace solids deposited in the upper reaches of large collection systems closer to the system outlet. The control idea is either to reduce depositing pollutants that may be resuspended and overflow during wet events and/or to decrease the time of concentration of the solids transport within the collection system. During wet weather events these accumulated loads may then be more quickly displaced to the treatment headworks before overflows occur or be more efficiently captured by wet weather first flush capture storage facilities.

Recently, Gatke and Borcherding (1996) investigated the effectiveness of long distance flushing of a 4.5 meter (14.8 feet) diameter CSO tunnel 360 meters (1180 feet) in length using a physical (1:24 scale) hydraulic model coupled with numerical simulation techniques. The work showed that a reservoir 15.5 meters (50.8 feet) high with about a release volume of 360 cubic meters (95,100 gallons) would be adequate for cleansing sediments.

Manual flushing methods usually involve discharge from a fire hydrant or quick opening valve from tank truck to introduce a heavy flow of water into the line at a manhole. Flushing removes floatables and some sand and grit, but is not very effective for removing heavy solids. In recent years, automated flushing equipment has emerged in France and Germany.

Hydrass ®

The Hydrass flushing system developed in France, and shown in Figure 5-1, is comprised of a balanced hinged gate with the same shape as the cross section as the sewer. At low flows the self-weight of the gate holds the gate in the vertical position and the sewer flow builds up behind the gate. The depth of flow continues to build up behind the gate until the force created by the retained water becomes sufficient to tilt the gate. As the gate pivots about the hinge to a near horizontal position, the sewer flow is released and this creates a flush wave which travels downstream and subsequently cleans any deposited sediment from the invert of the sewer. The gate then returns to the vertical position and the cyclic process is repeated, thus maintaining the sewer free of sediment. Gates are positioned in series at intervals dictated by the nature, magnitude and location of the sedimentation problem. Chebbo, Laplace, Bachoc, Sanchez and LeGuennec (1995) reported the effective operation of the Hydrass system. This system has been installed on a segment of the Marseilles Number 13 trunk. A 100 meter (328 feet) stretch required about 700 flushes to clean an initial deposit of about 100 millimeters (4 inches). Flushing frequency can be reduced if the upstream head can be increased, i.e., the number of flushes with a 0.5 meter (1.6 feet) head is 24 times that required for a 1.5 meter (4.9 feet) head.

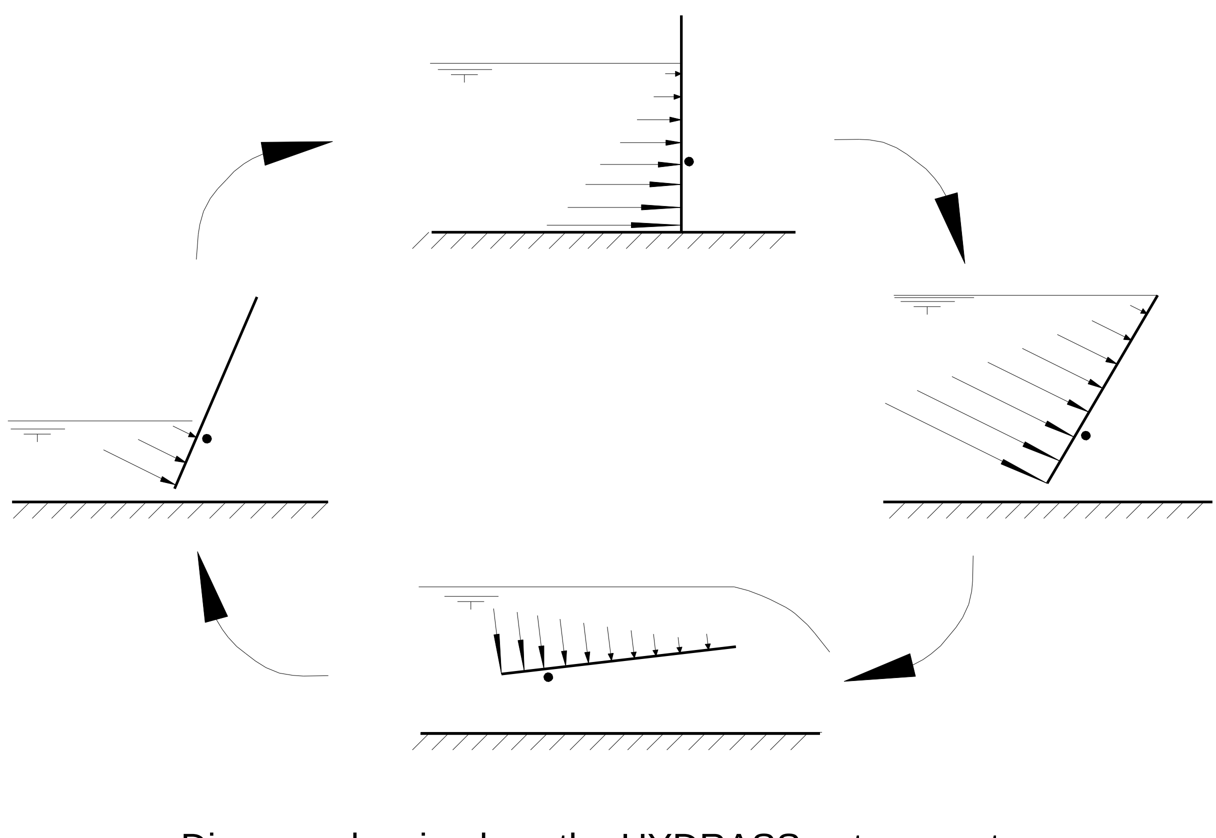


Diagram showing how the HYDRASS gate operates

Figure 5-1. Hydrass®

Hydroself®

In recent years pollution caused by CSO has become a serious environmental concern. Over 13,000 CSO tanks have been constructed with over 500 being in-line pipe storage tanks 1.8 to 2.1 meter (6 to 7 feet) diameter with lengths 125 to 180 meters (400 to 600 feet). Discharge throttles control the outlet discharge to about twice average dry weather flow plus infiltration. Many different methods for cleaning these pipes were tried over the years. The most popular has been the HYDROSELF® system developed by Steinhardt Wassertechnik, Taunusstein about 11 years ago.

The HYDROSELF® system is a simple method that uses a wash water storage area and hydraulically operated flap gates to create a cleaning wave to scour inverts of sewers. This system consists of a hydraulically operated flap gate, a flush water storage area created by the erection of a concrete wall section, a float or pump to supply hydraulic pressure and valves controlled by either a float system or an electronic control panel. The water level in the sewer is used to activate the release and/or closure of the gate using a permanently sealed float controlled hydraulic system. The flushing system is designed to operate automatically whenever the in-system water level reached a pre-determined level, thereby releasing the gate and causing a "dambreak" flushing wave to occur. Activation by remote control is also possible. This technology does not require an outside water supply, can be easily retrofitted in existing installations with a minimal loss of storage space, and may operate without any external energy source. The system consists of a hydraulically operated flap gate, a flush water storage area created by the erection of a concrete wall section, a float or pump to supply hydraulic pressure and valves controlled by either a float system or an electronic control panel. See Figure 5-2. The actual arrangement for a given installation is site dependent. The flushing length, slope and width determine the flush water volume needed for an effective single flush of the system.

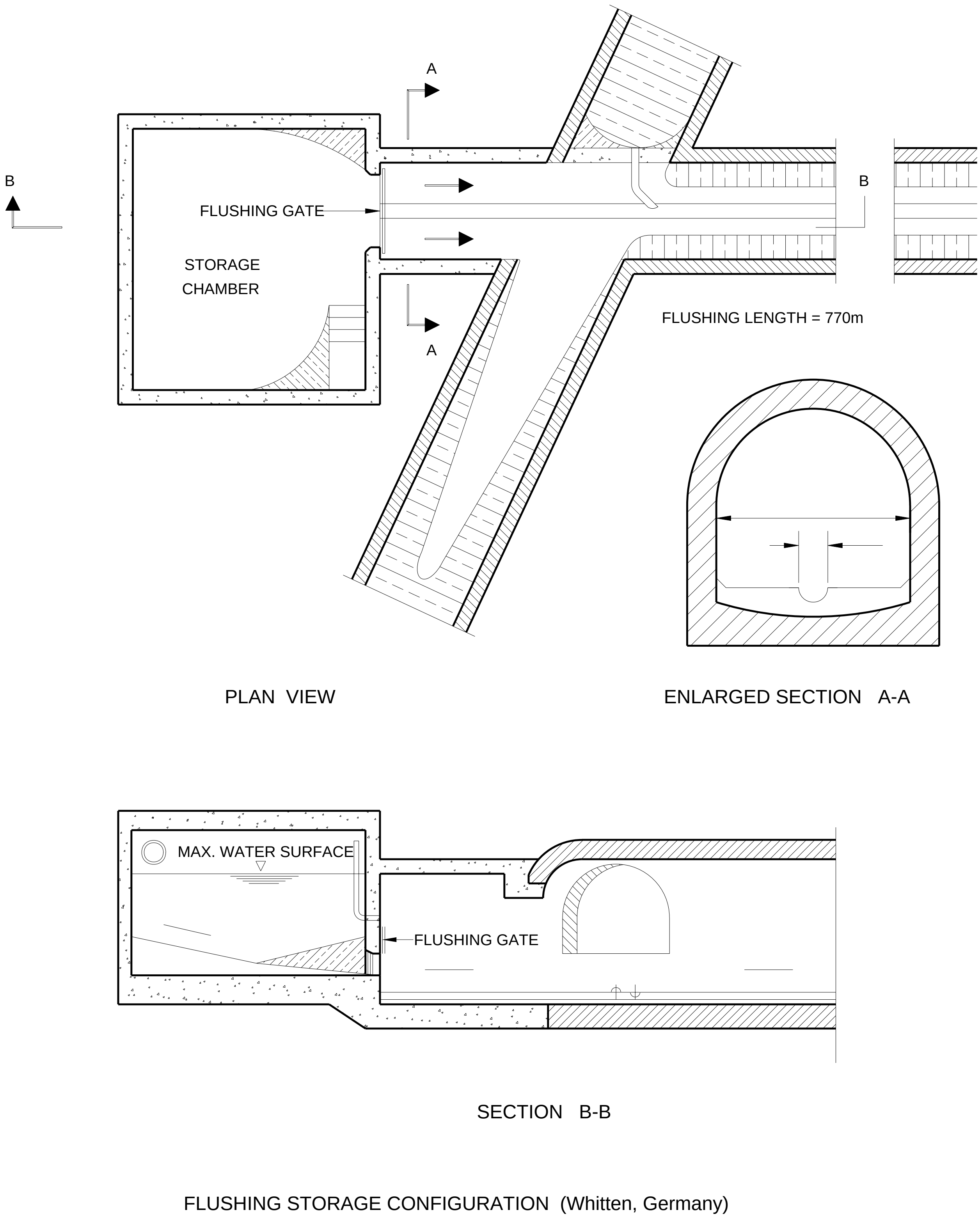


Figure 5-2. Flushing Gate

The HYDROSELF® system has been used to clean settled debris in sewers, interceptors, tunnels, retention and detention tanks in Germany and Switzerland. This technology was first used in 1986 for cleaning a tank in Bad Marienberg (a small town with a population less than 10,000 people, about 100 kilometers northeast of Frankfurt). In that same year the first two pipe storage projects using the flushing gate technology were implemented. This system has been used extensively in Europe with 284 installations with over 600 units in operation. Approximately 37 percent of the projects are designed to flush sewers, interceptors and tunnels ranging from 0.25 meters to 4.3 meters (0.8 to 14 feet) in diameter and flushing lengths of up to 340 meters (1100 feet) for large diameter pipes and up to 1000 meters (3300 feet) for small diameter pipes. The balance of flushing gate installations is for cleaning sediments from CSO tanks. The largest project in Paris, France cleans an underground 120,000 cubic meter (31.6 million gallons) tank beneath a soccer field using 43 flushing gates.

For large diameter sewers greater than 2 meters (78 inches) the flushing system may be installed in the sewer pipe itself. The required storage volume for the flush water is created by erecting two walls in the sewer pipe to form a flush water storage area in between the two walls. For the area to remain free of debris, a reasonable floor slope (5 to 20 percent) must be provided in the storage area. The requirements for the storage area slope will determine, in most instances, the maximum flushing length possible for a single flush gate. Should the actual flushing length be longer than this value, then additional flushing gates must be installed to operate in series with the first one. In order to increase the maximum flushing length it is also possible to build additional flush water storage area by creating a rectangular chamber in-line or adjacent to the sewer line itself.

BIOGEST® Vacuum Flushing System

A variation of the HYDROSELF® is the BIOGEST®, which is a system comprised of a concrete storage vault and a vacuum pump system to create a cleaning wave to scour the inverts of sewers. The system consists of a flush water storage area, diaphragm valve, vacuum pump, level switches, and a control panel for automatic operation of the system. The water level in the sewer is used to activate the vacuum pump. The vacuum pump evacuates the air volume from the flush chamber and as the air is evacuated the water is drawn in from the sewer and rises in the chamber. The vacuum pumps shuts off when a predetermined level in the flushing vault is reached. A second level sensor detects the water level in the sewer and activates the flush wave. The flush wave is initiated by opening the diaphragm valve above the flush chamber and subsequently releasing the vacuum and vault contents.

Storage Tank Cleaning Alternatives

Introduction

There are many ways to clean debris and sediment in storage tanks. The most simple and primitive cleaning methods include hand labor with shovels, brooms and high-pressure hoses for small tanks, or small bulldozers and clamshells for larger tanks. The most modern and sophisticated technologies include tipping flushers and flushing gates and are often self-actuating.

Originally tanks were cleaned utilizing automated cleaning options such as traveling bridges, fixed spray headers and nozzles and submerged mixers. These types of automated cleaning options are primary cleaning operations. Ineffective primary cleaning options often required manual cleaning such as water cannons or high pressure hoses to be an integral part of the overall tank cleaning procedure. Manual cleaning procedures such as water cannons or high pressure hoses are secondary cleaning options. However, as technology and personnel confidence has evolved many tanks now incorporate only a primary source of cleaning because it operates efficiently (i.e., tipping flushers and flush gates). From a functional perspective a primary method of cleaning is considered highly effective if little "mop-up" cleaning is required. Often the "mop-up" incorporates visual tank inspection and periodic washdown of debris in tank corners and other locations that were bypassed by the primary flushing operation. Some flushing methods are nearly self sufficient and require little or no personnel interaction other than starting the system (tipping flushers and flush gates), while others need operators to guide the cleaning operation (water cannons and traveling bridge). In Germany, over 13,000 CSO tanks (mostly rectangular) have been constructed, and two premier technologies have evolved: tipping flushers and flush gates.

It is important to note that the method of flushing also impacts the configuration of the tank's bottom. Bottom sloping enhances the removal of settled solids during tank draining and cleaning operations. If header nozzle systems are used for washdown the tank is typically configured with a center trough, traversing the length of the tank, and sloping towards the effluent end and the tank bottom slopes from the side walls to the trough at 3-10 percent. Where tipping flushers or "flush" gates are used the channel bottom slopes at 2-3 percent from the flusher end toward a large, wide collecting trough at the opposite end of the tank.

The floor design should consider the maximum admissible slopes to ensure high scouring velocities during drainage and cleaning operations, while optimizing the depth, area and overall storage tank volume. Tank bottom design should incorporate input from the flushing equipment supplier to assure proper operation and sizing. The design of the end trough for tipping flusher and flush gate installation is as critical as the tank design and must be sufficiently wide in its cross section to prevent "splash back" from occurring. Peculiarities in terms of special side sloping are discussed with each method.

There are five practical methods that are feasible from an operational standpoint for cleaning the accumulated sludge and debris in storage tanks. Two of the methods are similar and include wash down nozzles attached to a moveable bridge and fixed headers and jetting nozzles. The three remaining cleaning methods are mixers, tipping flushers and flushing gates.

Primary Flushing Systems

Traveling Bridge

There are three general types of traveling bridges that have been used to clean CSO storage tanks. Discussions specific to each of the three are provided below.

Traveling Bridge - Scraper

The Ruhrverbund Sewage Authority in Essen, Germany maintains 93 WWTP's, several hundred CSO tanks and a number of multi-purpose water resource reservoirs, water treatment plants and groundwater recharge systems. In the last 50 years the Ruhrverbund has tried and discarded many types of cleaning equipment and dozens of different types of channels on the tank floor to increase tractive shear on draindown. One fairly common method developed 10-15 years ago (but not having any other installations since) was a traveling bridge with a hard rubber blade or "squeegee" that moved sludge on the tank bottom to a side channel. From the side channel sludge was pumped vertically to a channel trough at top of the tank wall, then drained to a local sewer. Montgomery Watson personnel visited Germany in April 1994 to inspect various tank cleaning systems. Visual inspection of the traveling bridge scraper operation at several facilities showed poor scraper performance (it was impossible to get the floor cleaned and odors were a problem). However, the side channel sludge pickup system worked satisfactorily.

Traveling Bridge - Suction Pickup

The Ruhrverbund maintains about 6 tanks with traveling bridges having pumped suction manifolds that "suck" up sludge to a discharge channel at the top of the tanks and ultimately drain to WWTP's. Such arrangements are commonly used in secondary clarifiers in Europe and the Ruhrverbund tried this idea on CSO tank sludge. Visual inspection of the latest constructed facility indicated that small "wind rows" of sludge remained, and additional, extensive secondary washdown was necessary to supplement the bridge performance.

Traveling Bridge with Washdown Nozzles

There are only two known traveling bridges with washdown nozzles installed in the United States, Worcester, Massachusetts and Spring Creek, New York. The Worcester tank will be discussed for the purpose of this report.

Figure 5-3(a) depicts the traveling bridge arrangement installed at this facility. The storage tank has a volume of 5700 cubic meters (1.5 million gallons) with two cells 57 meters by 15.3 meters by 5.8 meters (187 feet by 50 feet and 19 feet) deep. The slope from the sidewalls to the center of the cell is 4 percent and a sloped sump is located at the center of each cell. Each cell is equipped with a moveable bridge which is operated by a two-speed chain drive at 1.5 and 2.5 meters (5 and 8 feet) per minute. The bridge is equipped with a traveling pump (95 liters/second, 1500 gpm), a ductile iron pipe system with 52 spray nozzles spaced 0.3 meters (1 foot) on center for the horizontal bottom and 3 nozzles on each of the vertical pipe assemblies, and a water cannon. On the outside of each basin is a 1.35 meter (4.5 feet) wide water trough that runs the entire length of the tank, and supplies water for the washdown system. Two passes are generally sufficient to clean the tank. Visual inspection indicates that the side vertical nozzles are not required to clean the tank walls because nothing adheres to them.

This system has been in operation for five years and has performed very efficiently although it requires significant operation and maintenance and is costly. One advantage of this system is that the primary and secondary modes of cleaning are located in a central location, the bridge. The disadvantages of this system include:

- Significant water consumption during the cleaning operation;
- The traveling bridge mechanism requires frequent maintenance;
- The initial installation requires extensive alignment of the bridge mechanism;
- Many mechanical components;
- The system requires a secondary mode of cleaning (i.e., water cannons);
- High structural costs associated with the water supply reservoir for each basin; and
- Since the traveling bridge is located above the high water elevation in the storage tank, it must be used with an open tank concept.

Mechanical Mixers and Submerged Jets

The basic principle involved with this technique is different from washdown systems that aim to clean sediments from empty tanks. Mechanical mixers and water jets operate on the premise of resuspending settled debris before drawdown begins and maintaining all materials in suspension until the tank is completely drained. Re-suspension of solids requires an introduction of energy to create necessary turbulence. This method is very popular for small tanks in central Germany. The actual placement of the mixers requires considerable adjustment to optimize mixing and establish proper mixing currents and flow directions

Estimates of required mixing energy could be assumed using criteria established for aerobic digesters depending on inorganic solids concentration. As the water depth in a tank decreases during the drawdown procedure, the mixing power must increase proportionally to properly maintain solids suspension.

Although capital cost data is not available for installations of this type, it is clear that this system requires a considerable amount of energy in addition to equipment and operational costs similar to those for header and nozzle systems. A serious disadvantage of this system is the requirement to manually clean the residual inorganic solids on the tank floor following draindown, consequently requiring extensive secondary cleaning operations. Since a secondary cleaning operation must be utilized in conjunction with this technology, an open tank layout must be employed. Advantages of this system are that the captured solids are more uniformly returned to WWTP via the pumpback operation and that little additional water is used.

This technology is most appropriate for circular tanks because circulation can easily be accomplished with few dead spots. Designers are constantly experimenting with fillets and baffles in rectangular tanks because flow currents are extremely complicated to predict when using mixers. A submerged jet is depicted in Figure 5-3(b).

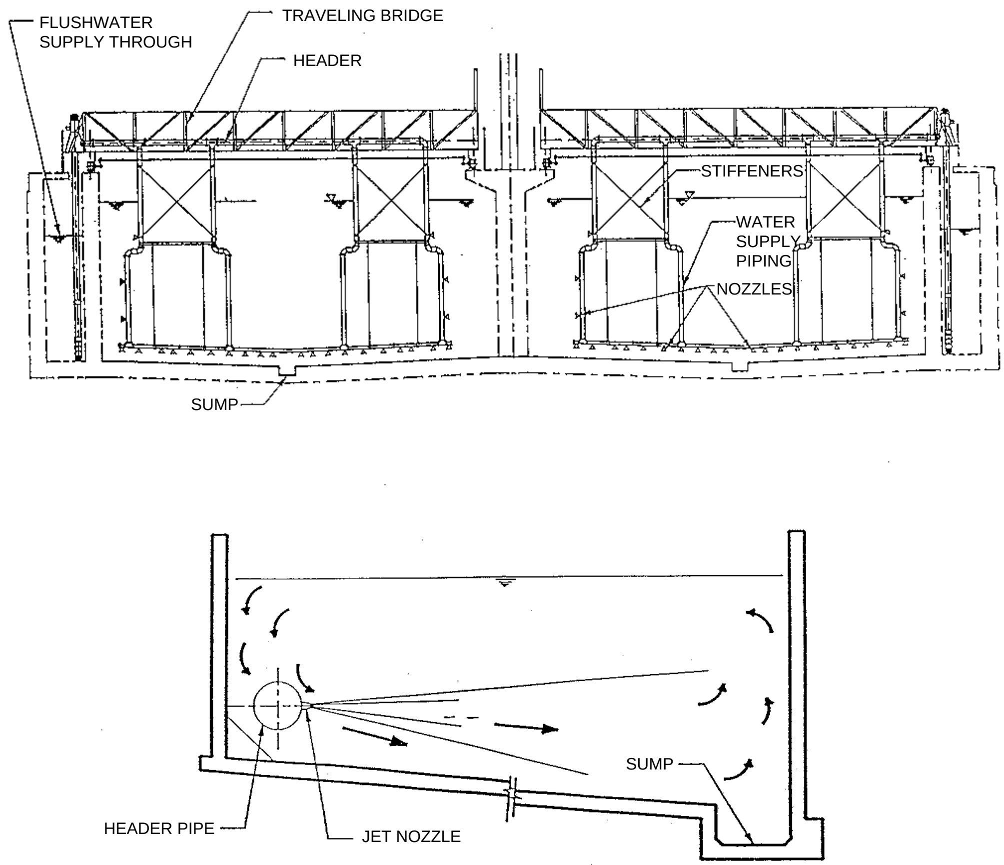


Figure 5-3 (a) Traveling Bridge (Adapted City of Worcester, 1998)
(b) Submerged Jet

Fixed Spray Nozzles and Headers

Fixed spray nozzle and header systems are generally comprised of an extensive piping network with multiple valves, booster pumps and controls and a washdown wet well. The spray headers and nozzles are generally suspended inside the tanks. This alternative requires secondary cleaning operations, typically with water cannons, because of the inefficiency of the spray nozzles to clean the entire tank. A dedicated secondary cleaning system must be used in conjunction with this technology, and thereby necessitates an open tank concept be incorporated. The tank bottom required for this system slopes steeply (approximately 10 percent) from the sidewalls to a center trough, and the center trough slopes at 2 - 3 percent toward an effluent trough. Disadvantages associated with this alternative include:

- Significant water consumption during the cleaning operation;
- The system requires a secondary mode of cleaning (i.e., water cannons);
- Floatables get caught on the header system; and
- Excessive sediment and debris can accumulate in areas where the nozzles do not reach.

Experience has shown that fixed spray headers and nozzles have been somewhat effective at some installations but do have some limitations. The Toronto Easterly Beaches Phase 1 tank (3800 cubic meters, 1 million gallons) could not be washed all at once because the washdown system demand, both pressure and flowrate, depleted the city supply system. Ultimately the tank was washed in quadrants to relieve the strain on the city system. The Saginaw, Michigan Weiss Street Facility 36,100 cubic meters (9.5 million gallons) tank had 1830 meters (6000 feet) of 0.41 meter (16 inch) diameter pipe with nozzles spaced 1.2 meters (4 feet) on-center and 24 water cannons to perform the cleaning operations. Since this system was installed four other tanks have been built by the city and all have incorporated tipping flushers as the primary cleaning technology. The cost and disadvantages associated with this alternative do not make it a feasible option for this installation. A typical spray header and nozzle arrangement is depicted in Figure 5-4.

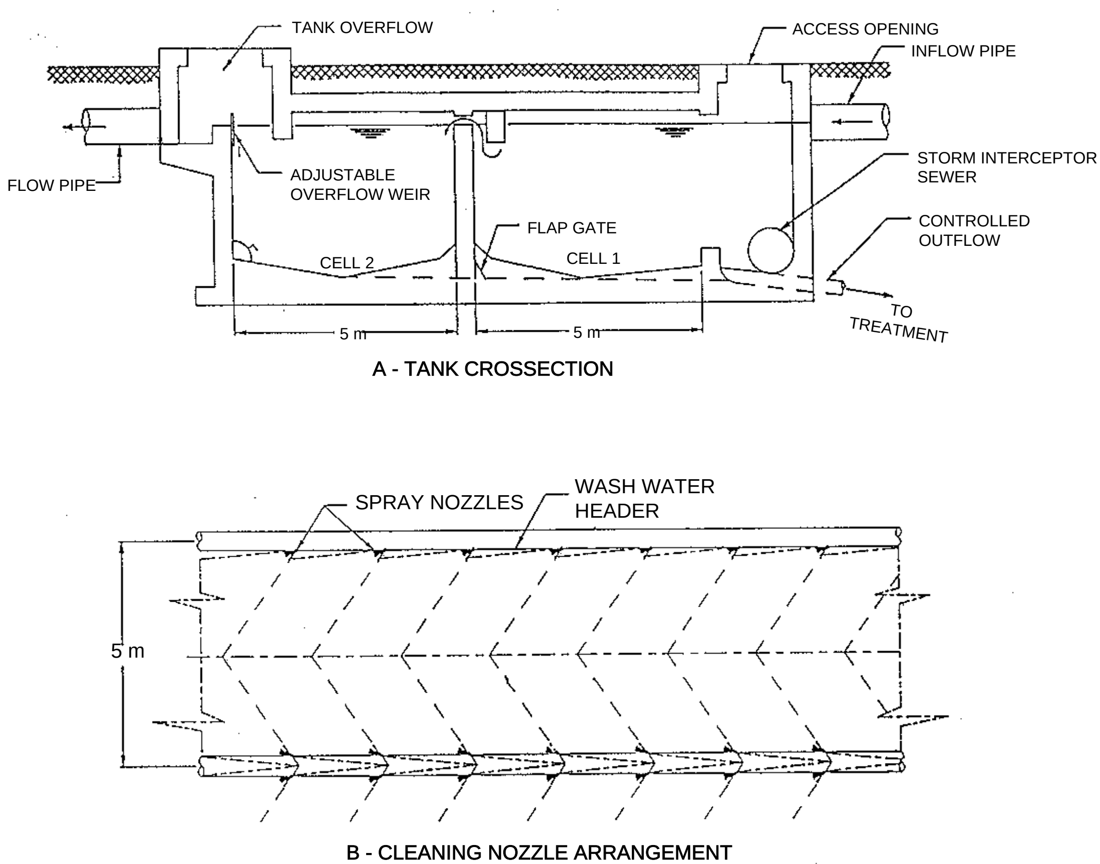


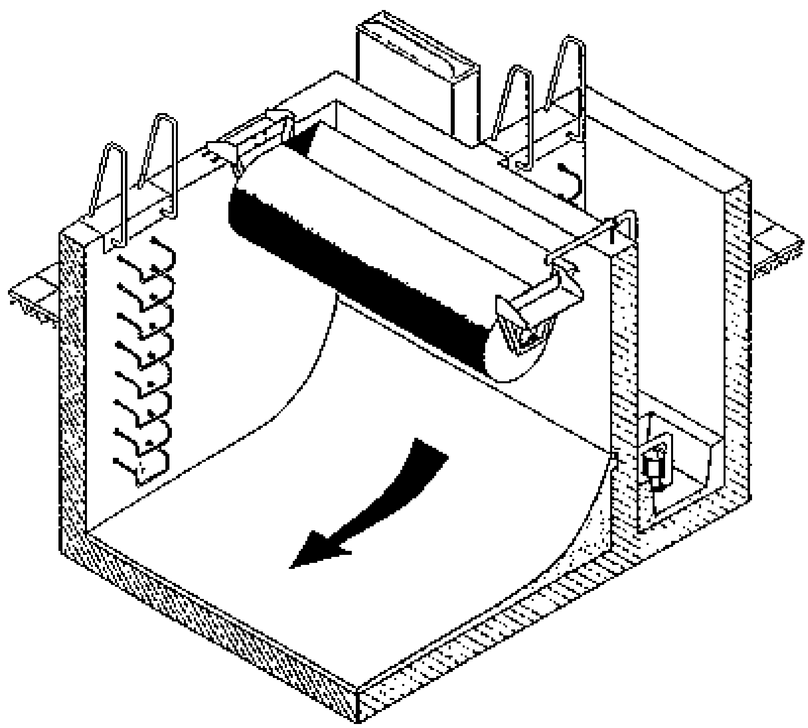
Figure 5-4. Fixed Spray Header and Nozzle Arrangement

Tipping Flushers

Tipping flushers (TF) systems have been used in North America for three years (about 15 tanks with flushers in the US, with most located in Michigan area), and have been operational in Germany and Switzerland for over 9 years. Tipping flushers are extremely effective for subsequent cleansing of debris from the floors of all types of urban runoff tanks. These devices were initially developed in Switzerland.

The system generally include filling pipes and valves, a pumping system and wet well (where restricted by the site conditions), and the tipping flusher vessels. The TF is a cylindrical stainless steel vessel that is ideally suspended above the maximum water level on the back wall of the storage tank. The units can be filled with river water; ground water or potable water, but require a filling system consisting of 5 to 7.6 centimeters (2 to 3 inches) headers with appropriate controls. Just prior to overtopping the vessel with water, the center of gravity shifts and causes the unit to rotate and discharge its contents down the back wall of the tank. A curved fillet at the intersection of the wall and tank floor redirects the flushwater (with minimum energy loss) horizontally across the floor of the tank. The fillet size depends on the size of the flusher. The flushing force removes the sedimented debris from the tank floor and transports it to a collection sump located at the opposite end of the tank.

The experience with US TF systems to date indicates that dedicated secondary cleaning operations, using concurrently operated water cannons or high pressure hoses, are not needed. If the first flush of the basin does not remove all of the sediment, the basin can be re-flushed or "mopped-up" by fire hoses. In Germany and in Switzerland, tank sidewalls are generally hand trowelled to a very smooth finish to prevent buildup from occurring, and consequently don't require frequent washdown. "Mop-up" cleaning of the influent and washdown channels has been done utilizing small tipping flushers in large German tanks and in Saginaw, Michigan. See Figure 5-5 for an example of a tipping flusher installation.



TYPICAL TIPPING
FLUSHER INSTALLATION

Figure 5-5. Tipping Flusher (adapted from UFT, 1998)

Flushing Gates

The flushing gate was originally developed in Germany (1985) as a method for flushing sediments in pipe segments (in-line storage or troublesome flat trunk and interceptor sewers), and has evolved for use in CSO tanks. As described earlier in this chapter, flushing gates have been used as the means to flush and cleanse deposits and debris from CSO tanks in about 350 German installations. In concept this scheme is depicted in Figure 5-6 and 5-7 from a recent design in Cincinnati, Ohio.

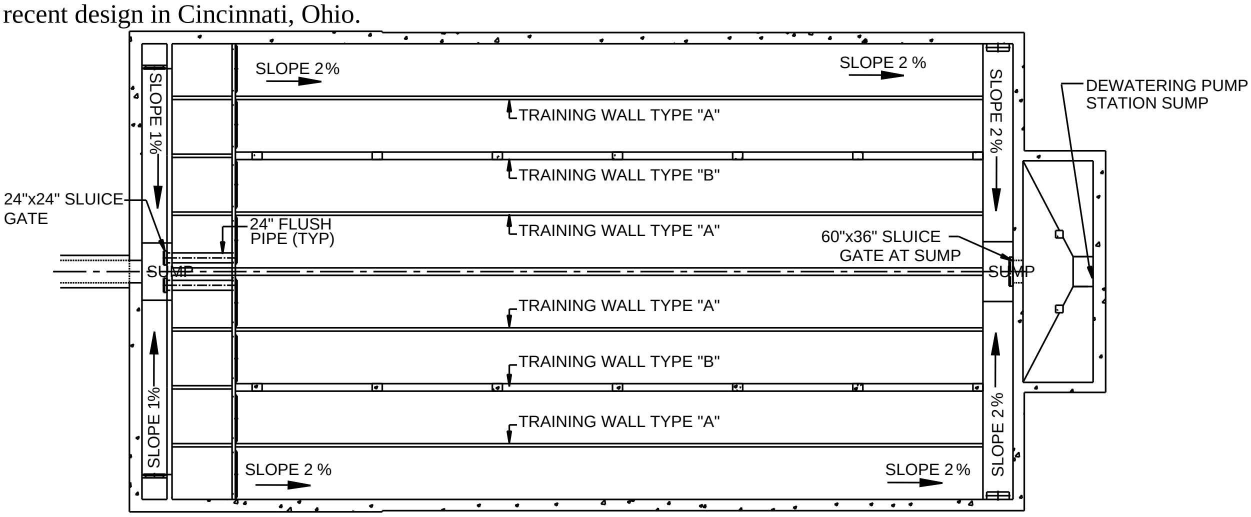


Figure 5-6. Plan View, Clough Creek CSO Treatment Facility, Cincinnati, Ohio

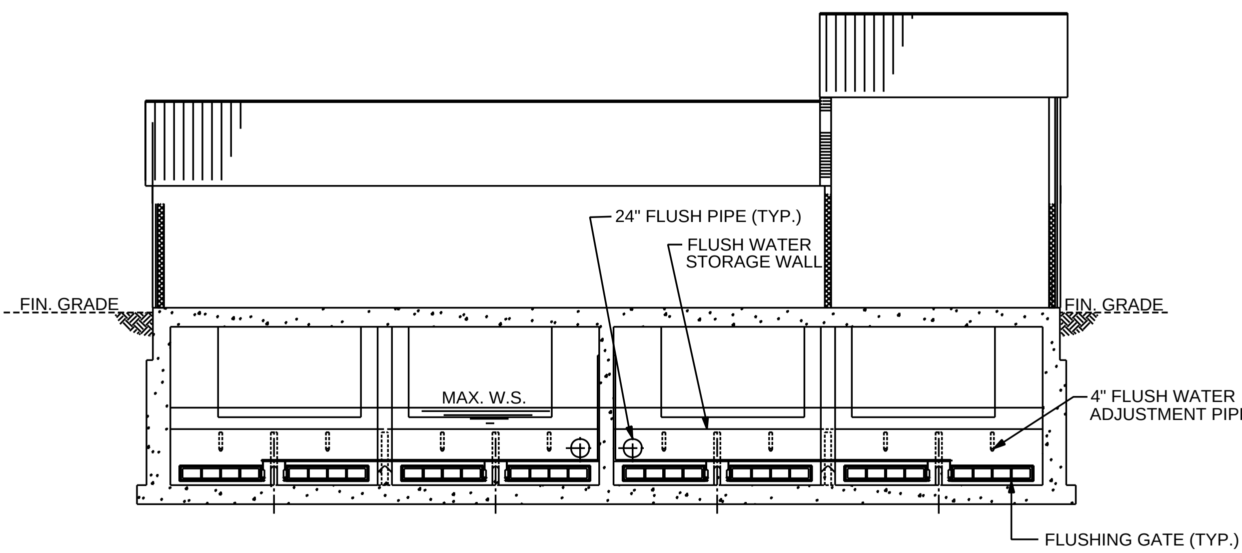


Figure 5-7. Section View, Clough Creek CSO Treatment Facility, Cincinnati, Ohio

The system is comprised of two basic elements, a gate and a closed circuit hydraulic actuation system utilizing a float control mechanism. A low-level wall is constructed across the short axis of the influent end of the tank approximately 1.5 to 2 meters (5 to 6.5 feet) high. The wall is located on the influent end of the tank to guarantee filling the space behind the wall prior to filling the rest of the tank. The instantaneous opening of a stainless steel gate that is mounted on the face of the wall activates the system. The release of the gate creates a "dam break" scenario, which generates a high velocity flush wave (generally trying to maintain a velocity in excess of 1.8 meters/second (6 feet/second). Normally the width of the flushing gate is approximately 0.7 the effective flushing lane width. The volume retained behind the wall required for proper cleaning is a function of flushing length and floor slope. The "nominal" design volume can be adjusted by changing the height of a level standpipe on the backside of wall. The hydraulic system can also be connected to central control system (on or off-site) with auto or manual override.

These systems have tank floors that slope from the flush gate location to the collection trough at 1 – 3 percent. The flush gates require training walls on the tank bottom that are about 0.4 to 0.5 meters (15 inches to 18 inches) high, and run the full length of the tank to control the flow direction of the wave. All walls parallel to the path of flushing flow should be perpendicular to the tank bottom, with no fillets, to ensure the lower wall edges are cleaned.

In function, this technology is similar in concept to tipping flushers. One main difference between the two technologies is that the tipping flushers are suspended above the tank floor and flush down sidewall, thereby taking advantage of the energy conversion from potential to kinetic. In practice, this means that the flushing gate needs about 20 percent more flushing volume than tipping flushers for comparable tank floor slope and tank lengths. However, since the flush volume consists of stored CSO, there is no additional cost associated with this volume. The experience with flush gate systems to date indicates that dedicated concurrent secondary cleaning operations, using water cannons or high pressure hoses, are not needed. If the flush of the basin using tank contents does not remove all of the sediment, the basin can either be re-flushed (requiring and external water source for filling), or "mopped-up" using fire hoses. To date flushing basins with tank contents has not required mop-up in German tanks. The largest length flushed with flushing gates is 90 meters (295 feet) while flushing lengths of 70 meters (230 feet) are fairly common.

Secondary Flushing Systems

Water Cannons

Water cannons are typically used to washdown corners, areas around piping, and other hard to reach places. They are typically used in conjunction with spray header systems (both fixed and traveling bridge) and mechanical mixers and submerged jets. These systems require extensive piping and valve networks, booster pumps, a supply wet well and are strictly operated manually. The use of water cannons requires an open storage tank configuration.

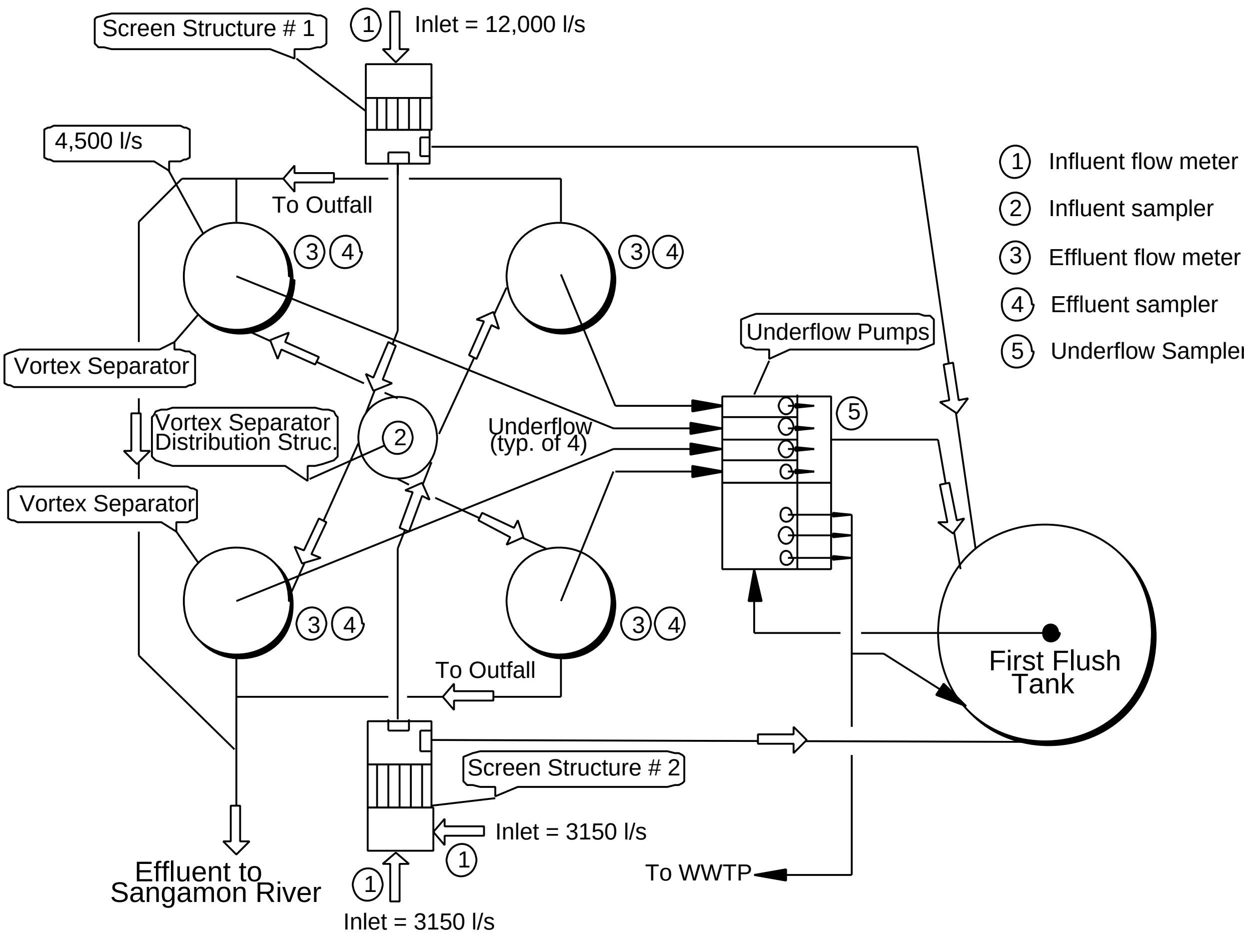
Water cannons typically have a maximum discharge rate of 25 liters/second (400 gpm) each at a working pressure of 2.8 to 5 cm/m^2 (40 to 70 psi) and have a useful working spray radius of 20 to 30 meters (70 to 100 feet). Cannons can rotate 360 degrees horizontally and have about 100 to 120 degrees range of motion in the vertical direction. Water cannons should be provided with shut-off/isolation valves and 2.5 centimeter (1 inch) nozzles. Spray down and cleanup times required per cannon vary depending on the facility, type of solids loading, and time of solids exposure (open tanks). However, cleanup times of 5 to 15 minutes per water cannon are common.

High Pressure Hoses

Most CSO facilities have washdown high pressure hose systems on-site for miscellaneous cleanup operations. This system can often be utilized for secondary cleaning operations by providing hose gates where required. This system requires a piping and valve network, booster pumps and a supply wet well. Hose gate connections are provided throughout the facility to accommodate cleaning operations. If this technology is used as a true secondary flushing system it will require an open tank layout. Hose connections are typically 3 centimeters (1-1/4 inch) and utilize similar water usage and pressure requirements to a water cannon system. Hoses allow the flexibility to move the discharge point around because the hose is not fixed like water cannons.

Novel Approach For Cleaning Circular Tanks

The Lincoln Park facility in Decatur, Illinois consists of two mechanical screening facilities, a 7500 cubic meter (2 million gallons) open circular "first flush" storage tank, a 11 meter (36 feet) diameter vortex flow dividing chamber (two asymmetric flow inputs of 11,000 l/s and 7200 l/s (176,000 gpm and 114,000 gpm) are divided into four 4550 l/s (72,000 gpm)) waste streams, four 13.6 meter (45 feet) diameter vortex solids separators, and a treated effluent to the Sagamon River. Figure 5-8 presents on overall schematic for the facility.



Lincoln Park Facility Monitoring Locations

Figure 5-8. Lincoln Park Schematic

Diverted wet-weather flows (WWF) (two inputs) are first passed through mechanically cleaned, automatically controlled, catenary screens. A manually cleaned bar screen is provided for emergency bypass. Downstream of each screen chamber are two liquid-level actuated, motorized sluice gates directing flow into the "first flush" retention tank. The tank diameter is 36 meters (118 feet) with a side water depth of 8.5 meters (28 feet). The tank is equipped with mixers and aerators and the tank floor slopes to a circular gutter draining to a pumping station. When the tank level rises to a pre-set level, control gates direct any additional inflows to the vortex flow divider with outputs into the four vortex solids separators. Foul underflows from the bottom of the four separators are pumped into the "first flush" tank. The pumping station also dewaters the tank and the separators after an event.

Cleanout of the circular "first flush" tank includes several novel design and operational concepts. First, the two main gravity feeds to the tank are tangentially fed during an event. Secondary flow currents are established moving most of the solids to the center zone of the tank, a common design attribute on hundreds of circular tanks in Germany. After an event the cleaning operation involves two steps. The contents of the tank are kept in motion while being slowly pumped to the interceptor. This circulation feature is accomplished by a feed from the center of the tank with a separate recirculation loop and a tangential return. When the tank is fully drained, no sediment is typically observed from the perimeter tank walls inward for about 4.5 to 6 meters (15 to 20 feet). From there the sediments grade from about 1 cm in depth to about 15 centimeters (6 inches) in the center region of the tank. Two high-pressure water monitors on opposite sides of the tank are then used to cleanse the remaining sediments to the center well in about six minutes.

Chapter 6
Case Evaluations

This chapter presents facility evaluation data of combined sewer in-line and CSO storage tank flushing systems. The objectives of these evaluations included the following:

- Collect dimensional and operational data of combined sewer in-line and CSO storage tank facilities that utilize flushing gates or tipping flushers for cleaning;

- Evaluate the effectiveness of the system design in terms of sediment removal;

- Compare capital and operation and maintenance costs of flushing gate and tipping flusher facilities with other cleaning methods.

Table 6-1 presents a guide outlining the major features of the 18 case studies. Contents of the table include location; flushing function, i.e. flushing of storage pipe, conveyance pipe or tank; tank geometry (rectangular or circular); flushing method, i.e. flushing gate, tipping flusher or other; flushing volumes for pipe configurations, either by generated off-line or in-line compartments; flushing volumes for tanks are noted as in line. Information for other miscellaneous tank reviews are provided following the 18 case studies.

Table 6-1. Overview of Case Studies

Case Number	Location	Flushing Function				Flushing Method		
		Pipe Storage	Pipe Convey.	Tank		Flush Gate		Tipping Flusher
				Rect.	Circular	In-line	Off-line	
1	Marht Wiesentheid, Germany	X				X		
2	Gemeinde Schauenburg, GER	X				X		
3	Stadt Kirchhain, GER	X					X	
4	Stadt Heidenheim, GER		X			X		
5	Markt Grossostheim, GER		X				X	
6	Osterbruch-Opperhausen, GER		X				X	
7	Gemeinde Hettstadt, GER	X					X	
8	Filterstadt-Bernhausen, GER			X		X		
9	Stadt-Essen, GER			X		X		
10	Markt-Wiesentheid, GER			X		X		
11	Stuttgart-Wangen, GER			X		X		
12	Heidenheim-Kleiner-Buhl, GER			X		X		
13	Cheboygan, Michigan				X	X		
14	Sarnia, Ontario, Canada			X		X		
15	Port Colborne, Ontario, Canada			X				X
16	Wheeler Avenue, Kentucky			X				X
17	14^{th} Street Pumping Station, MI			X				X
18	Saginaw Township, MI			X				X

A standard evaluation form was prepared and distributed to operators at several facilities in Germany and in North America. In-line versus off-line refers to the relative location of the flushing volume. Due to space limitations, flush volumes are often generated in-line with main convergence function accomplished by an underflow conduit or channel under the flush volume chamber. Vaults with large flushing volumes are commonly provided by off-line configurations. Average slope refers to the slope of the conduit or section being flushed. Slope of flush volume refers to the floor slope of the flush vault. Flush gate activation is accomplished either by passive float operation termed "hydraulic" or by an active electrical signal from an external location termed "electrical". Water source refers to the source of the water for flushing, i.e. "local waste" or "external supply". Performance assessment is defined as follows: "Excellent" – all sediments in channel or bay cleaned with flush; "Good" – substantial removal of sediments in channel, i.e. 90% of flush lane or pipe is cleaned; "Fair" – partial removal of sediments, i.e. 50-70% of flush lane or channel cleaned with flush. The following case studies, consisting of tables and narratives summarize the findings for each site.

Case Studies: Combined Sewer Flushing Facilities using Flushing Gates

The following are summaries of the pipe flushing facilities that were evaluated in Germany.

Case No. 1- Marht Wiesentheid

Details of the Marht Wiesentheid flushing facility are noted in Table 6-2. The in-line CSO storage conduit is a 1.8 m (6 ft diameter) circular pipe, 46.8 m (153 ft) in length. The storage pipe is throttled at its outlet using a flow regulator to maintain outflow equal to twice average dry weather flow (plus infiltration). An inline flushing vault holding 14 cubic meters (3700 gal.) is used to cleanse the storage pipe. The flushing gate is activated by hydraulic float control. Operators note excellent performance in cleansing deposits during flushing.

Table 6-2. Marht Wiesentheid, Germany

Question	Response
In-Line or Off-Line	In-Line
Year Constructed	1992
Flow type	Combined
Pipe size and shape	1800 mm circular
Length	46.8 m
Average Slope	1%
Pipe Material	Concrete
Flush Gate Dimensions (l w)/Material	2.8 m x 1.31 m / Stainless steel
Flush Vault Volume	14 cubic meters
Flush Vault Dimensions (l w h)	2.5 m x 4.84 m x 1.15 m
Slope of flush vault	20%
Water Source	Local waste
Method of Gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/1 person
Performance Assessment	Excellent

Case No. 2 – Gemeinde Schauenburg

The Gemeinde Schauenburg storage facility (Germany) is very similar to the facility at Marht Wiesentheid (Case 1). Details are noted in Table 6-3. This facility is a CSO storage pipe 2 m (78 inch) circular in diameter 64 m (210 ft) in length. Flushing volume of 5.5 m^3 (1450 gal.) is used and the flushing gate operates by hydraulic float activation. The gate activates when the downstream flow controller permits the storage to drain. The operators note “fair” performance for this facility.

Table 6-3. Gemeinde Schauenburg, Germany

Question	Response
In-Line or Off-Line	In-Line
Year Constructed	1988
Flow type	Combined
Pipe size and shape	2000 mm circular
Length	64 m
Average Slope	1 %
Pipe material	Asbestos Cement
Flush Gate Dimensions (l w) / Material	1.2 m x 0.4 m Stainless steel
Flusher Volume	5.5 cubic meters
Flusher Dimensions (l w h)	2 m x 3 m x 0.91 m
Slope of flush vault	20%
Water Source	Local waste
Method of gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/2 person
Performance Assessment	Fair

Case No. 3 – Stadt Kirchhain

The Stadt Kirchhain facility, listed in Table 6-4, has an off-line flushing gate that is used to flush the deposited sediments in the 1600 mm pipe to a downstream regulator which empties into a downstream 300 mm sewer. Figure 6-1 depicts the plan view of one of the two off-line flushing vaults used in the Stadt Kirchhain facility (Germany). Figure 6-2 depicts the plan view of the downstream flow control chamber throttling the twin storage pipes.

Table 6-4. Stadt Kirchhain, Germany

Question	Response
In-Line or Off-Line	Off-Line
Year Constructed	1991
Flow type	Combined
Pipe size and shape	1600 mm circular
Length	115 m
Average Slope	0.4%
Pipe material	Concrete
Flush Gate Dimensions (l w)/Material	1.2 m x 0.4 m Stainless steel
Flush Vault Volume	4 cubic meters
Flush Vault Dimensions (l w h)	2 m x 2.5 m x 1 m
Slope of flush vault	20%
Water Source	Local Waste
Method of gate Activation	Electrical
Frequency of Inspection/Crew Size	Not Available
Performance Assessment	Fair

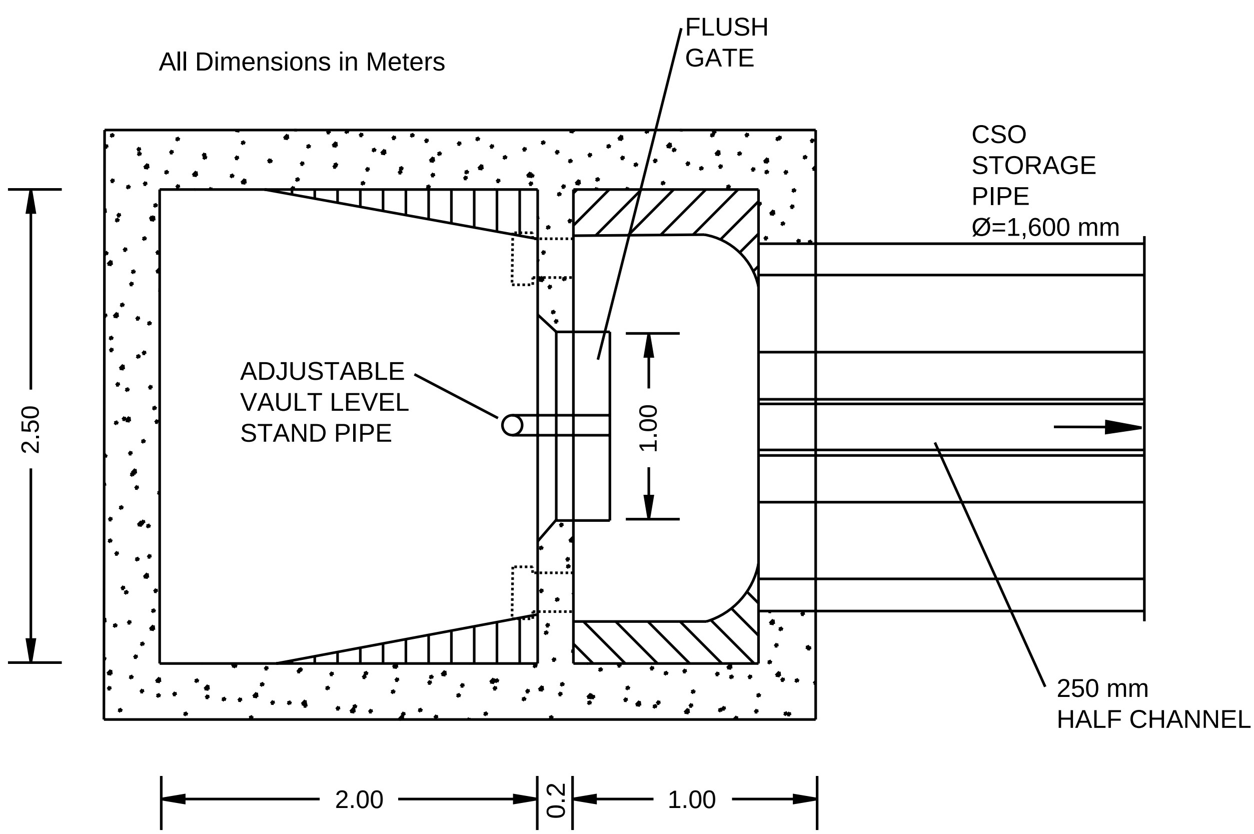


Figure 6-1. Stadt Kirchhain - Off-Line Flushing Vault Plan View

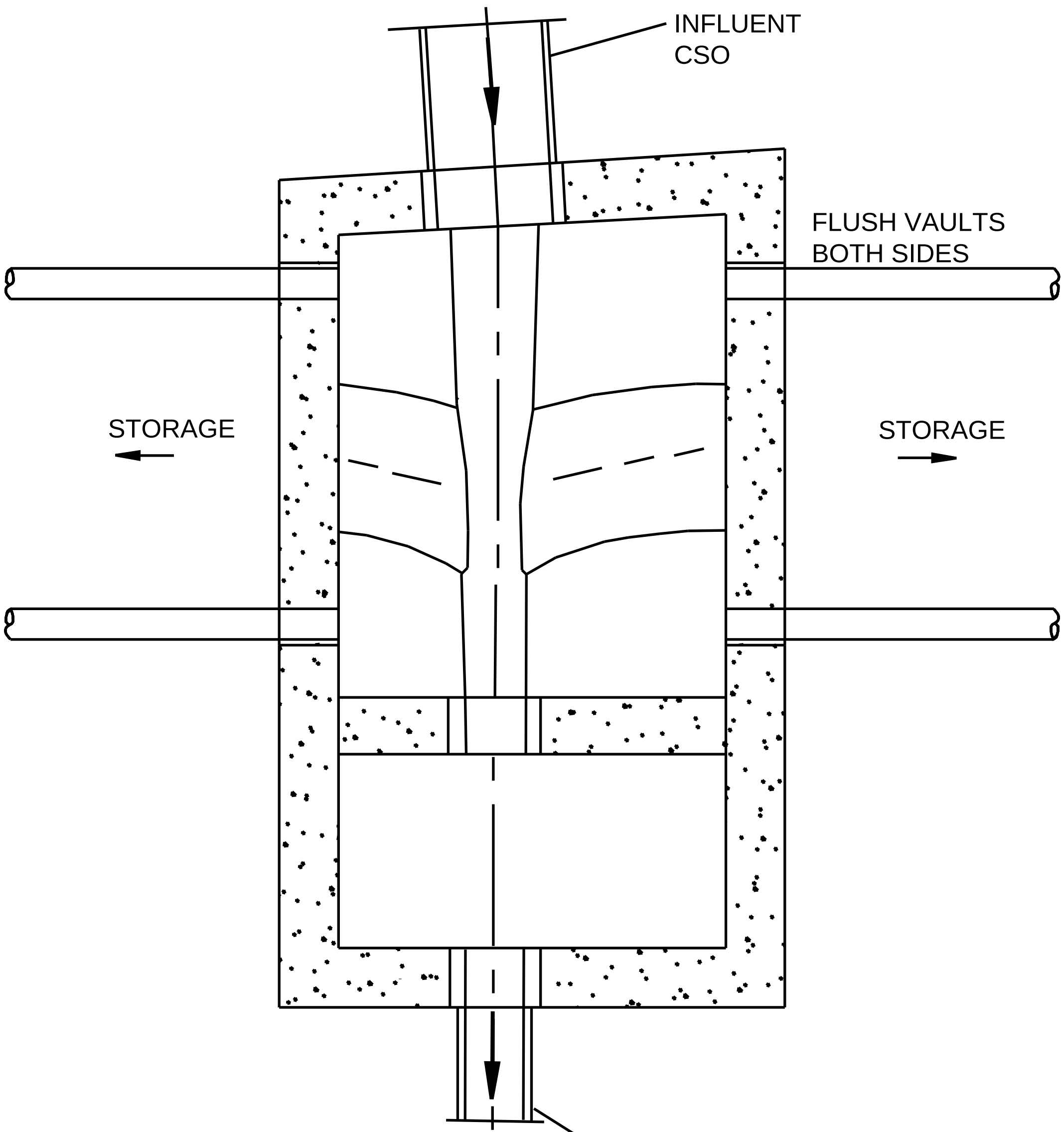


Figure 6-2. Stadt Kirchhain - Plan View Downstream Control Chamber

Case No. 4- Stadt Heidenheim

Details of the Stadt Heidenheim facility are noted in Table 6-5. The Stadt Heidenheim facility has an in-line flushing chamber that is located within the regulator structure on the dry weather conduit. Extreme wet weather flows overtop the weir in the center of the structure into a 1200 mm bypass conduit. Plan and section views of the overall regulator, flushing vault and bypass chamber are depicted in Figures 6-3 and Figure 6-4.

Table 6-5. Stadt Heidenheim, Germany

Question	Response
In-Line or Off-Line	In-Line
Year Constructed	1993
Flow type	Combined
Pipe size and shape	2200 mm circular
Length	240 m
Average Slope	Not Available
Pipe Material	Concrete
Flush Gate Dimensions (l w)/Material	1.2 m x 0.4 m Stainless steel
Flush Vault Volume	10 cubic meters
Flush Vault Dimensions (l w h)	3 m x 5 m x 0.7 m
Slope of flush vault	10%
Water Source	Local Waste
Method of Gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/2 person
Performance Assessment	Good

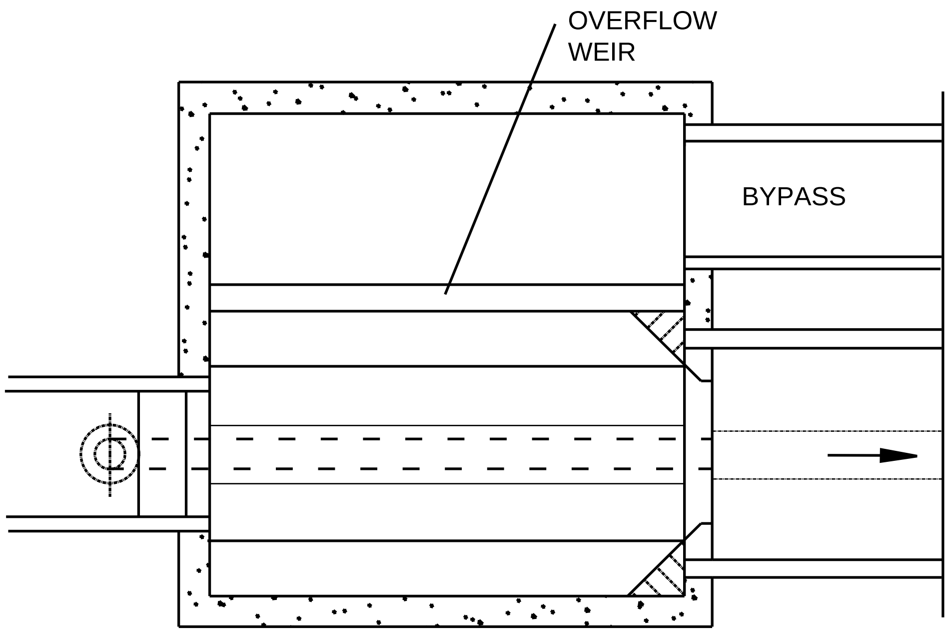


Figure 6-3. Stadt Heidenheim - Plan View

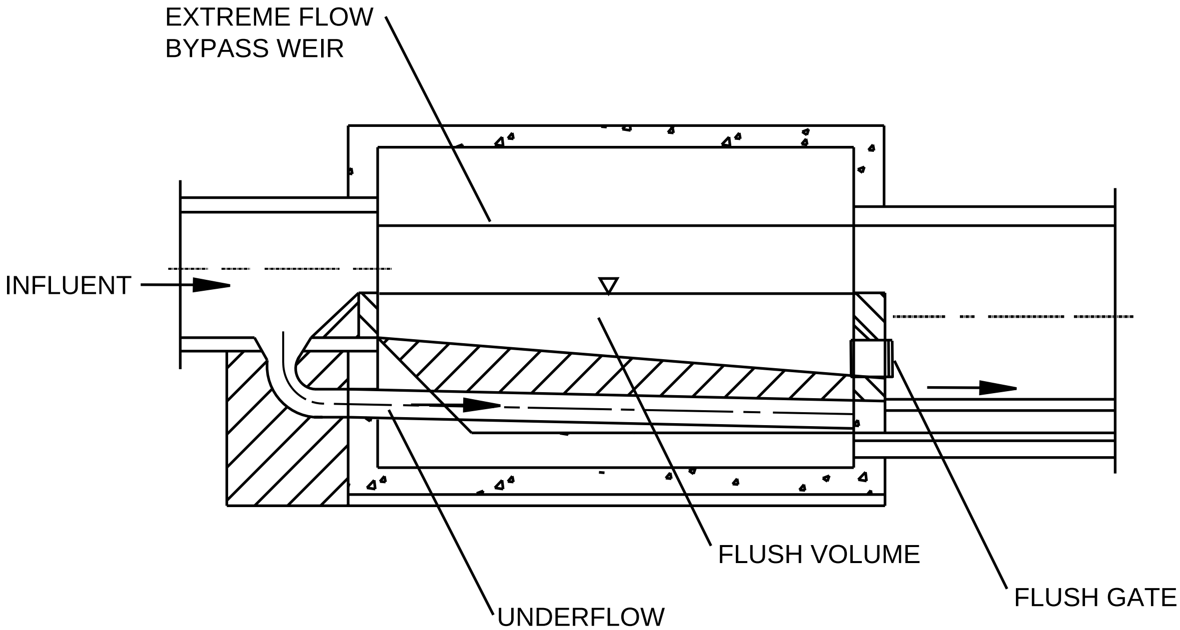


Figure 6-4. Stadt Heidenheim - Section View

Case No. 5 – Markt Grossostheim

Details of the Marktt Grossostheim facility are presented in Table 6-6. The flushing vault and storage facility involves an off-line storage compartment created by a spill weir from the dry weather channel. Extreme overflows can then bypass the side spill storage compartment. These bypasses are controlled by a mechanical operated bending weir. The downstream flow throttle is a mechanical knife valve controlled by direct measurements of a magnetic meter.

Table 6-6. Markt Grossostheim, Germany

Question	Response
In-Line or Off-Line	Off-Line
Year Constructed	1993
Flow type	Combined
Pipe size and shape	2200 mm circular
Length	190 m
Average Slope	9.4%
Pipe material	Not Available
Flush Gate Dimensions(l w) Material	1.5 m x 0.4 m Stainless steel
Flush Vault Volume	15 m^3
Flush Vault Dimensions (l w h)	6.5 m x 2.2 m x 1.03 m
Slope of flush vault	15%
Water Source	Local Waste
Method of Gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/2person
Performance Assessment	Excellent/Good

Case No. 6 – Osterbruch-Opperhausen

Details of the Osterbruch-Opperhausen facility are noted in Table 6-7. Sectional views of this facility are presented in Figure 6-5. The flushwater chamber is filled by an upstream 100 mm pumped pipe. The flushing gate is utilized to clean the downstream 250 mm combined sewer conduit. The flush vault is placed on the head of the combined sewer and 1000 m (3250 ft) of downstream conduit to a regulator location where flushed solids are discharged into receiving sewer.

Table 6-7. Osterbruch-Opperhausen, Germany

Question	Response
In-Line or Off-Line	Off-Line
Year Constructed	1989
Flow type	Sanitary
Pipe size and shape	250 mm circular
Length	1000 m
Average Slope	0.1%
Pipe material	Vetrified Clay Pipe
Flush Gate Dimensions (l w)/Material	0.5 m x 0.4 m Stainless steel
Flusher Volume	2 m^3
Flusher Dimensions (l w h)	2.4 m x 1.6 m x 0.75 m
Slope of flush vault	20%
Water Source	River Water
Method of Gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/2person
Performance Assessment	Excellent/Good

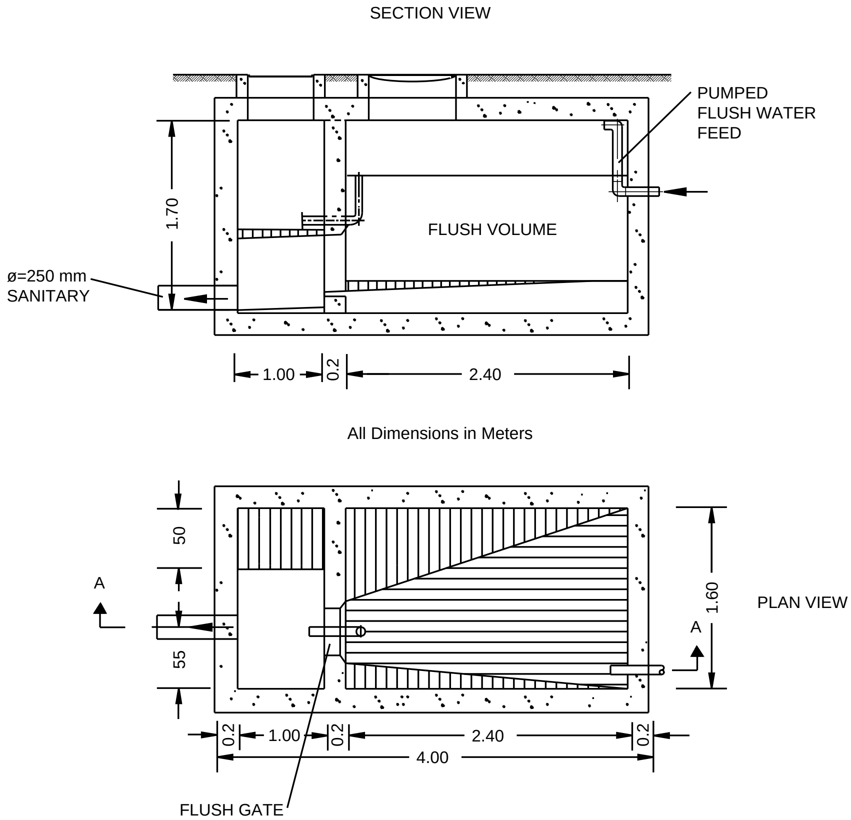


Figure 6-5. Osterbruch-Opperhausen - Sectional Views

Case No. 7 – Geimeide Hettstadt

Details of the Geimeide Hettstadt facility are noted in Table 6-8. The storage element is an off-line CSO pipe conduit 1600 mm (66 inch) in diameter, 224 m (735 ft) in length. The off-line flushing chamber holds 10 m^3 (2700 gal.) and is filled during overflow events. Operators have noted good to fair performance.

Table 6-8. Gemeinde Hettstadt, Germany

Question	Response
In-Line or Off-Line	Off-Line
Year Constructed	1992
Flow type	Combined
Pipe size and shape	1600 mm circular
Length	224 m
Average Slope	0.5%
Pipe material	Concrete
Flush Gate Dimensions (l w)/Material	1.5 m x 0.4 m Stainless steel
Flusher Volume	10 cubic meters
Flusher Dimensions (l w h)	5 m x 2.7 m x 0.75 m
Slope of flush vault	15%
Water Source	Local Waste
Method of Gate Activation	Hydraulic
Frequency of Inspection/Crew Size	After each activation/2person
Performance Assessment	Good/Fair

Hydraulic Analysis Flushing Gate Performance for Sewers

The Stormwater Management Model (SWMM) with Extended Transport Block (EXTRAN) was used to investigate the efficiency of the German sewer pipes that use flushing technology. Simulation output takes the form of water surface elevations and discharge at selected system locations. EXTRAN was developed by the U.S. EPA and is described in total in the User's Manual, EPA/600/3-88/001b.

The basic conveyance element input data required in EXTRAN are specifications for shape, size, length, roughness, connecting junctions and ground (rim) and invert elevations. These data for pipe and tank flushing were obtained from the evaluations of the German facilities. Pipe and tank lengths were discretized into two or three equal sections. These discretizied sections varied from 15 to 30 meters (50 to 100 feet). Pipe sections were assumed to be circular (equivalent diameters calculated) and tank sections (flushing bays) were assumed to be rectangular. An additional 30 meter (100 feet) section was added to the downstream tank conduit to simulate a grit pit. The following parameters were kept constant in both pipe and tank simulations:

- Computation time increment = 1 second
- Manning roughness coefficient = 0.015
- Gate opening time in 10 seconds
- Flow hydrographs at the flushing gate are assumed to increase linearly from zero to a constant flow rate in 5 seconds and also to decrease linearly from the constant rate to zero in 5 seconds.
- Upstream of the conduit/tank was assumed to be the input and downstream was assumed to be a free overflow.

Table 6-9 summarize the hydraulic data (length, slope, size and flush volume) and results (velocity, depth, and flush volume/length of flush) from the respective flushing gates determined from the evaluations of the German facilities. The listed results are at the downstream end of the pipe or channel flushed. At the far right hand side of Table 6-9 is listed the operator observation. Qualitative operator observations have excellent agreement with the quantitative modeled velocity. For example the terminal velocity of Stadt Kirchhain is 0.60 m/s, which is the lowest velocity, and the operator observe only "Fair" flushing results.

Table 6-9. Summary of Pipe Flushing Results

Location	Length (m)	Slope	Size (m)	Velocity (m/s)	Depth (m)	Flush Vol. (m^3)	Operator Observation
Marht Wiesentheid	47	1.0%	1.8	3.1	0.40	14	Excellent
Stadt Heidenheim	241	1.0%	2.2	1.0	0.09	10	Good
Stadt Kirchhain	115	0.4%	1.6	0.60	0.07	4	Fair
Markt Grossostheim	191	0.94%	2.2	1.2	0.11	15	Excellent / Good

Case Studies: CSO Storage Tank Flushing Facilities using Flush Gates

The following are summaries of the CSO tank flushing facilities that were evaluated in Germany and North America.

Case No. 8 – Filterstadt-Bernhausen

Details of the Filterstadt-Bernhausen CSO tank facility using flush gates to cleanse the tank after activations are noted in Table 6-10. The tank volume is 1000 m^3 and consists of two unequal sized bays (5.65 m and 4.65 m). Flushing is accomplished by two vaults with two flusher systems per bay. No flushing training walls are provided. The end channel transports the flushed deposits to a central throttled outlet. The flush gates are activated by hydraulic float control when the tank drains after an event through a 300 mm (12 inch) throttle.

Table 6-10. Filterstadt-Bernhausen, Germany

Question	Response
Year Constructed	1990
Type of Flow	Combined
Covered or Open Tank	Covered
Number Of Bays	2
Number of Flushers/Bay	2
Training Walls per Flusher	No
Flush Channel Dimensions (l w h)	36 m x 5 m x 3.5 m
End Trough Dimensions l w d	8 m x 12 m x 1.2 m
Flush Channel Slope	2.5%
Flush Gate Dimensions(l w) Material	1.5/1.75 m x 0.4 m Stainless steel
Flush Vault Volume	2@ 10 m^3 / 2@ 8.5 m^3
Flush Vault Dimensions (l w h)	2.5 m x 5.65 m x 1.0 2.5 m x 4.65 m x 1.0 m
Slope of flush vault	20%
Water Source	Combined
Method of Gate Activation	Hydraulic
Method of Removing Flushed Sediments	Underflow Throttle (400 mm) to WWTP
Frequency of Inspection/Crew Size	After each activation/Not Available
HVAC System/Type	Yes/Grating
Odor Control System/Type	No
Electrical System Explosion Proof	No
Performance Assessment	Good

Case No. 9 – Stadt-Essen

Details of the Stadt-Essen storage facility are noted in Table 6-11, has each flush vault equipped with two gates, and training walls are not installed within individual bays. The Stadt Essen layout is depicted in Figures 6-6 and 6-7. It features a unique inlet scheme where the underflow is concentrated in a vortex chamber that discharges back to the dry weather sewer. Once the underflow capacity is exceeded, the influent channel to the flushing gates fills which in turn fills the flush vaults and tank. The flushed sediments are collected in the mud sump for discharge back to the dry weather sewer.

Table 6-11. Stadt-Essen, Germany

Question	Response
Year Constructed	1993
Type of Flow	Combined
Covered or Open Tank	Covered
Number Of Bays	3
Number of Flushers/Bay	2
Training Walls per Flusher	Yes
Flush Channel Dimensions (l w h)	55 m x 3 m x 3.4 m
End Trough Dimensions l w d	5 m x 20 m x 0.5 m
Flush Channel Slope	0.5%
Flush Gate Dimensions (l w)/Material	1.5/1.75 m x 0.4 m Stainless steel
Flusher Volume	12 m^3
Flusher Dimensions (l w h)	4 m x 1.4 m x 2.85 m (2) 3.20 m (4)
Slope of flush vault	20%
Water Source	Combined
Method of Gate Activation	Electric
Method of Removing Flushed Sediments	Underflow Sluice Gate (200 mm) to WWTP
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	Yes/ Ventilation Pipes - 300 mm Intake and 450 mm Exhaust
Odor Control System/Type	No
Electrical System Expolosion Proof	No
Performance Assessment	Good

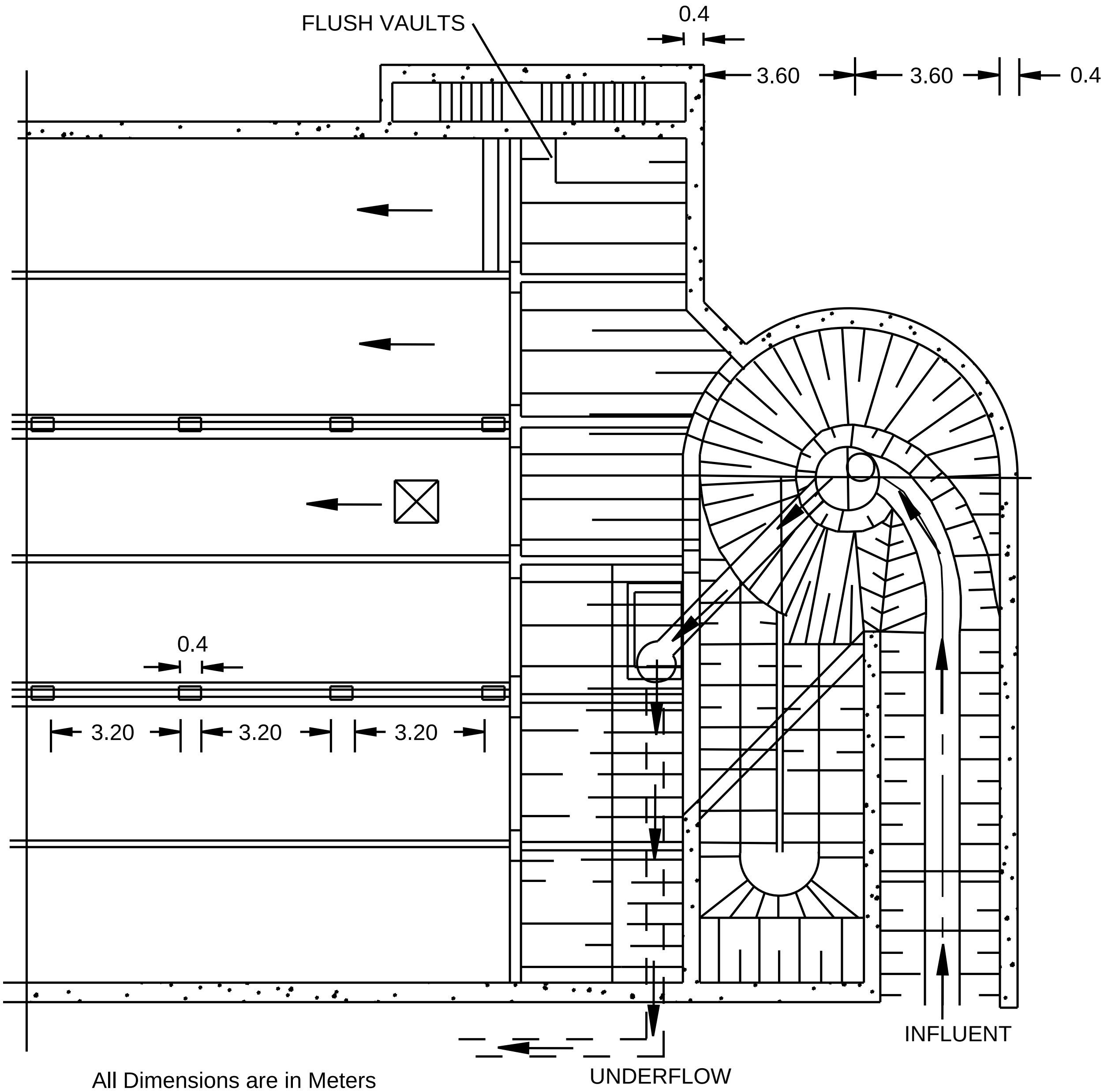


Figure 6-6. Stadt-Essen - Plan View, Tank Influent

All Dimensions are in Meters

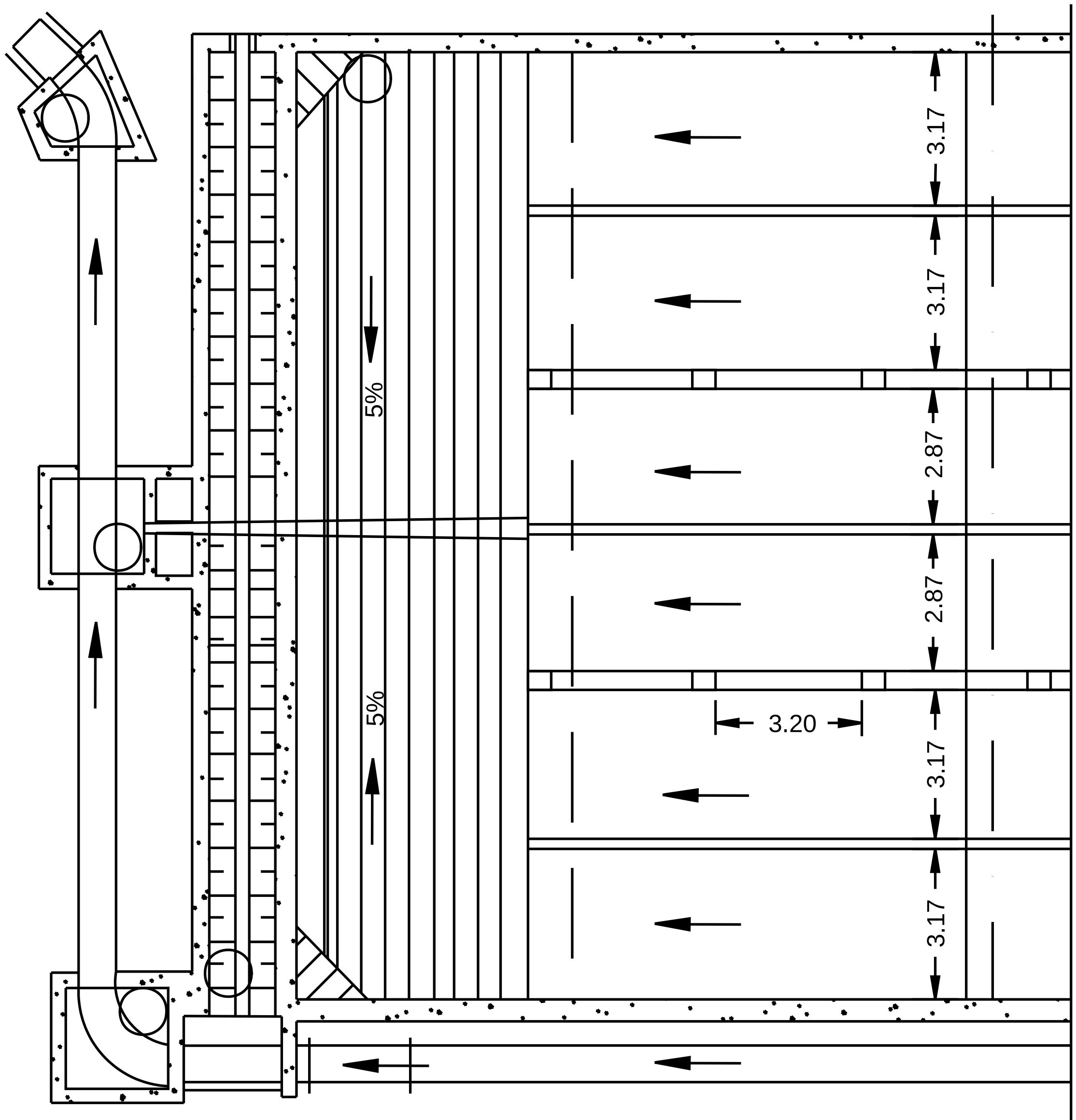


Figure 6-7. Stadt-Essen - Plan View, Tank Effluent

Case No. 10 – Markt-Wiesentheid

A section view of this facility is depicted in Figure 6-8. This facility has a unique flush vault filling arrangement. Flow enters the facility at the effluent end of the tank via a dry weather conduit integral to the tank that is regulated downstream. As flow in the dry weather conduit increases during wet weather, flow surcharges a 300 millimeter conduit that is connected at the springline of the dry weather conduit on an adverse slope which fills the flush vaults.

Table 6-12. Markt-Wiesentheid, Germany

Question	Response
Year Constructed	1992
Type of Flow	Combined
Covered or Open Tank	Open
Number Of Bays	5
Number of Flushers/Bay	1
Training Walls/Flusher	Yes
Flush Channel Dimensions (l w h)	41 m x 4.84 m x 3 m
End Trough Dimensions l w d	2 m x 25 m x 0.5 m
Flush Channel Slope	1.5%
Flush Gate Dimensions (l w)/Material	2.8 m x 0.4 m Stainless steel
Flusher Volume	12.7 m^3
Flusher Dimensions (l w h)	2.5 m x 4.8 m x 1.3 m
Slope of flush vault	20%
Water Source	Combined
Method of Gate Activation	Electric
Method of Removing Flushed Sediments	Underflow Flap Gate
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	No
Odor Control System/Type	No
Electrical System Expolosion Proof	No
Performance Assessment	Excellent/Good

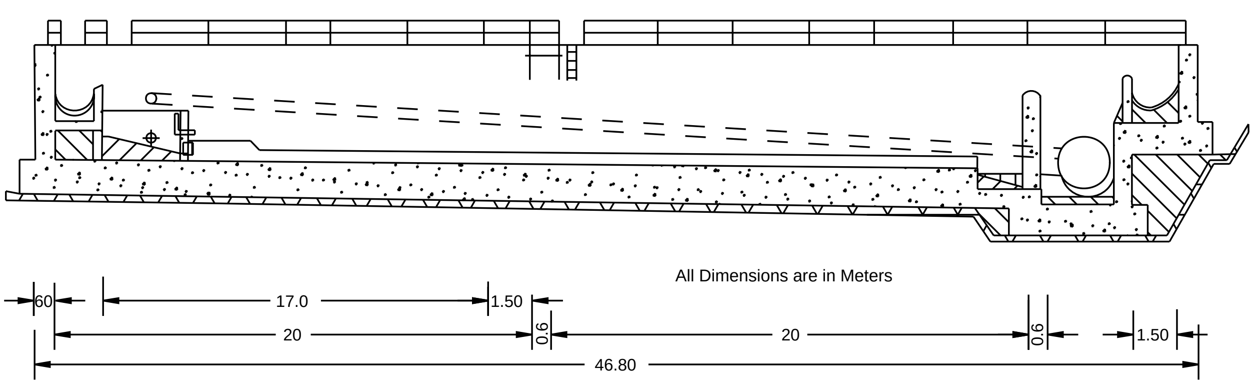


Figure 6-8. Markt-Wiesentheid - CSO Storage Tank, Section View

Case No. 11- Stuttgart-Wangen

Details of the Stuttgart-Wangen CSO storage facility are provided in Table 6-13. The tank consists of a single rectangular bay 67m (220 ft) in length with rectangular cross section 3.6 m x 1.8 m (12 ft x 6 ft). The flush gate is activated by external electric signal after the tank section has been noted by level sensor to drain.

Table 6-13. Stuttgart-Wangen, Germany

Question	Response
Year Constructed	1993
Type of Flow	Combined
Covered or Open Tank	Covered
Number Of Bays	1
Flush Channel Dimensions (l w h)	67 m x 3.6 m x 1.8 m
End Trough Dimensions l w d	6.5 m x 3.6 m x 0.9 m
Flush Channel Slope	0.5%
Flush Gate Dimensions (l w)/Material	2.8 m x 0.4 m Stainless steel
Flusher Volume	18 m^3
Flusher Dimensions (l w h)	5 m x 3.6 m x 1.15 m
Slope of flush vault	14.5%
Water Source	Combined
Method of Gate Activation	Electric
Method of Removing Flushed Sediments	Pumps
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	Yes/Ventilated Manhole Lids
Odor Control System/Type	No
Electrical System Expolosion Proof	No
Performance Assessment	Excellent/Good

Case No. 12 – Heidenheim-Kleiner-Buhl

Details of the Heidenheim-Kleiner-Buhl CSO storage facility are provided in Table 6-14. The flush gates are activated in sequence by external electric signal after the tank contents have been noted to drain. Level in the receiving sewer is also noted prior to activating the flush gates

Table 6-14. Heidenheim-Kleiner-Buhl, Germany

Question	Response
Year Constructed	1992
Type of Flow	Combined
Covered or Open Tank	Covered
Number Of Bays	6
Number Flushers/Bay	1
Training Walls/Flusher	Yes
Flush Channel Dimensions (l w h)	30 m x 4.85 m x 3.6 m
End Trough Dimensions l w d	5 m x 17.5 m x 1.5 m
Flush Channel Slope	1.0%
Flush Gate Dimensions (l w)/Material	1.85 m x 0.4 m Stainless steel
Flusher Volume	28.5 m^3
Flusher Dimensions (l w h)	5 m x 2.5 m x 1.45 m
Slope of flush vault	15%
Water Source	Combined
Method of Gate Activation	Electric
Method of Removing Flushed Sediments	Underflow Sluice Gate to WWTP
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	Yes/Ventilation Shafts
Odor Control System/Type	No
Electrical System Explosion Proof	Yes
Performance Assessment	Excellent/Good

Case No. 13 - Cheboyan

Details of the circular CSO storage facility utilizing the flush gate technology in Cheboyan, Michigan are noted in Table 6-15. This facility features a circular tank construction with a diameter of 30.5 m (100 ft) Seven flushing bays direct flush waves across the length of the tank to a sump channel on one side of the tank. This flushing configuration is the first ever for circular tanks. In Germany, there are 3 circular tanks using flush gate technology but the flushing arrangement features flushing vaults located at the center of the tank with flushing lanes extending in a radial direction to the end trough at the tank perimeter. Figure 6-9 depicts plan and section views of the CSO circular storage tank in Cheboyan, Michigan. Photos of this facility are presented in Figure 6-10.

Table 6-15. Cheboygan, Michigan

Question	Response
Year Constructed	1997
Type of Flow	Combined
Covered or Open Tank	Open
Number Of Bays	7
Number Flushers/Bay	1
Training Walls/Flusher	Yes
Flush Channel Dimensions (l w h)	See Figure 6-9
End Trough Dimensions l w d	See Figure 6-9
Flush Gate Dimensions (l w)/Material	2.8 m x 0.4 m Stainless steel
Flush Channel Slope	2.0%
Flusher Volume	13 - 16 m^3
Flusher Dimensions (l w h)	See Figure 6-9
Slope of flush vault	20%
Water Source	WWTP Effluent
Method of Gate Activation	Hydraulic
Method of Removing Flushed Sediments	Underflow Pipe to WWTP
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	No
Odor Control System/Type	No
Electrical System Explosion Proof	No
Performance Assessment	Excellent/Good

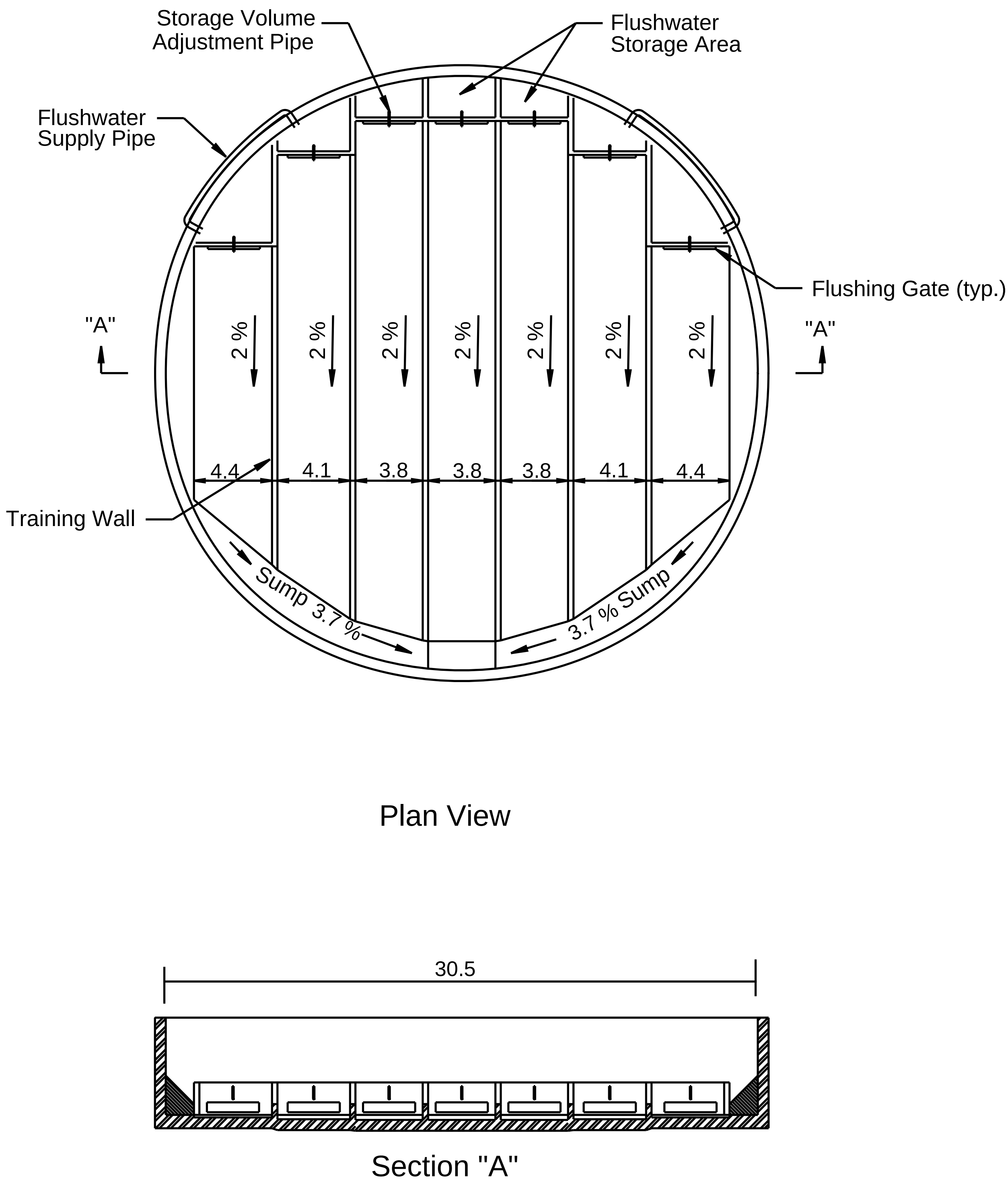


Figure 6-9. Cheboygan - Circular CSO Storage Tank, Plan and Section Views

Figure 6-10. Cheboygan - Photograrhs of Circular CSO Storage Tank

Case No. 14 - Sarnia

Details of the first North American CSO storage facility located in Sarnia, Ontario, Canada utilizing the flush gate technology are given in Table 6-16. This facility is an underground covered tank with a storage volume of 8400 m^3 (2.2 million gallons). Twenty flushers cleanse the tank after each event. Plan and sectional views of this facility are provided in Figure 6-11 and Figure 6-12. Photos of the hydraulic gate opening mechanism are shown in Figure 6-13. The operation of this facility has been noted as excellent.

Table 6-16. Sarnia, Ontario Canada

Question	Response
Year Constructed	1996
Type of Flow	Combined
Covered or Open Tank	Closed
Number Of Bays	10
Number of Flushers/Bay	2
Training Walls/Flusher	Yes
Flush Channel Dimensions (l w h)	38.5 m x 3.9 m x 0.5 m
End Trough Dimensions l w d	2 m x 79.7 m x 0.7 m
Flush Gate Dimensions (l w)/Material	2.8 m x 0.4 m Stainless steel
Flush Channel Slope	2.0%
Flusher Volume	10 m^3
Flusher Dimensions (l w h)	2.5 m x 3.5 m x 1.6 m
Slope of flush vault	20%
Water Source	Combined
Method of Gate Activation	Hydraulic
Method of Removing Flushed Sediments	Sluice Gate to WWTP
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	Not Available
Odor Control System/Type	Not Available
Electrical System Explosion Proof	Not Available
Performance Assessment	Excellent

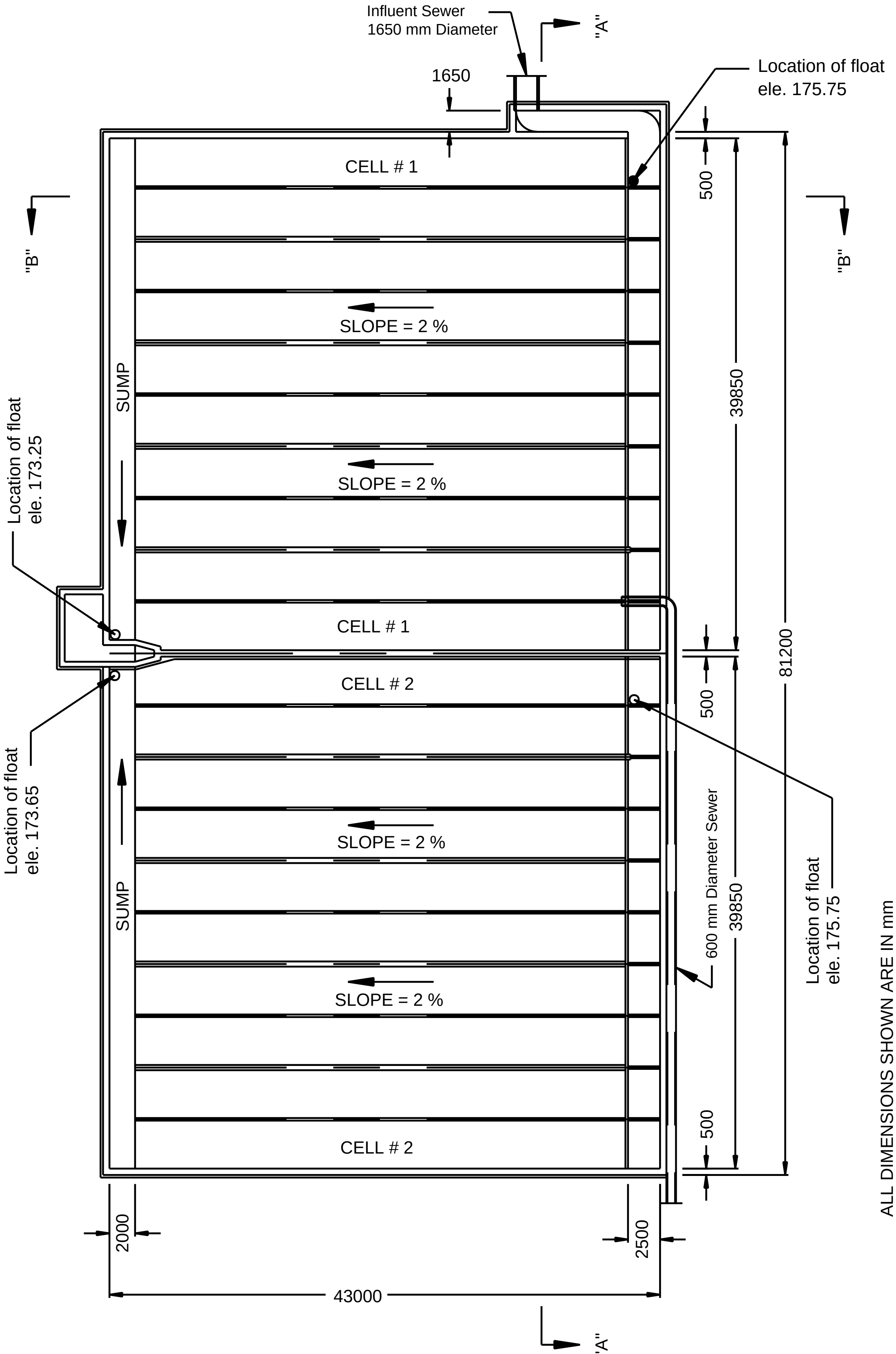
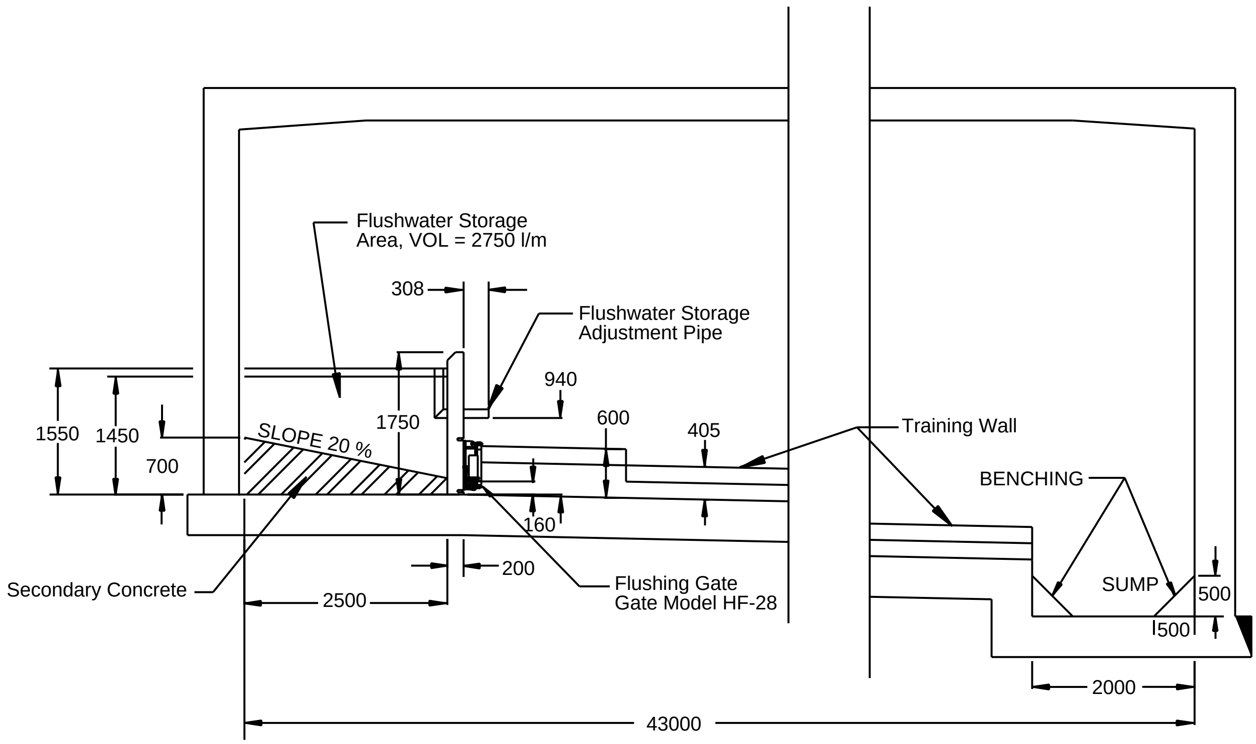


Figure 6-11. Sarnia - CSO Storage Tank, Plan View



ALL DIMENSIONS SHOWN ARE IN mm

Figure 6-12. Sarnia - CSO Storage Tank, Section View

Figure 6-13. Sarnia - Photographs of Hydraulic Opening Mechanism

Hydraulic Analysis of Flushing Gates for Rectangular Tanks

Summary results of SWMM EXTRAN simulations of flush gate performance for five rectangular tank for five rectangular tanks are presented in Table 6-17. Flushing volumes computed from the construction drawings are used as inputs into rectangualer open channels (flushing lane). Velocities shown are computed at the end section of the flush lane, just prior to discharge into the end channel. There is good agreement between velocity and operator observations.

Table 6-17. Summary of Tank Flushing Results

	Length (m)	Slope	Width (m)	Height (m)	Velocity (m/s)	Depth (m)	Flush Vol. (m^3)	Observation
Filderstadt-Berhausen	36	2.5%	5	3.5	1.33	0.05	8.5	Good
Stadt Essen	55	0.5%	3	3.4	0.92	0.07	12	Good
Markt Wiesentheid	41	1.5%	4.84	3.0	1.30	0.06	12.7	Excellent / Good
Stuttgart Wangen	67	0.5%	3.6	1.8	0.83	0.06	18	Excellent / Good
Heidenheim Kleiner Buhl	30	1.0%	4.85	3.6	1.61	0.06	28.5	Excellent / Good

Evaluation of Flushing Gates for Tanks

Flushing gates use a flushing water storage compartment separated from the actual CSO tank to produce a flushing transient wave for cleaning the tank floor and to wash the settled matter into a mud sump of adequate volume and suitable benching at the opposite tank side.

The following design considerations are important for maximizing the effectiveness of flushing rectangular tanks using flush gate technology:

- The tank inlet should be designed such that flushing water reservoirs are filled before the storm tank compartments. This ensures that the necessary supply of flushing water to clean tanks from short storms of small volume. Filling the tank at the effluent side of the tank requires additional conduits to fill the flushing water reservoirs located at the influent tank side. Careful hydraulic considerations are necessary to assure adequate filling of all desired storage units.

- Depending on the tank filling concept, the inlet overflows should route the inflow sequentially into the different tank compartments. Overflow weirs of different heights can control inflow to individual compartments.

- The tank floor should be horizontal across the direction of flushing, and sloped from 0.5 to 2%.

- The flusher opening must be a minimum of 150 mm above the tank floor.

- Larger tanks should be compartmentalized into bays with a width of 3 to 5 m. Training walls should be sized to prevent the flush wave from spilling into adjacent bays.

- The tank side walls should be perpendicular to tank floor with no fillets to ensure cleaning of side walls.

- The tank side walls should be hand troweled to a smooth finish. No sidewall spray systems are necessary provided a smooth finish is achieved.

- The "mud sump" volume depends on the flushing volume, and hence of the width of the individual flushing bay as well as the possibility to flush the entire tank with multiple cells in sequential mode. The mud sump generally has a central emptying pit with a sluice gate or pump outlet. The bottom of the sump slopes gently towards this outlet sump, with a step between the tank bottom and the beginning of the slope. This step is important in order to contain the reflected wave in the mud sump.

- An adjustable standpipe in the flushing water reservoir allows for "fine-tuning" of the flushing volume in case the reflected wave throws water and debris back onto the tank floor.

- A 5% lateral slope of the mud sump is frequently used. In case of large tanks and one outlet this will result in fairly deep outlets.

- The flush volume depends on the length, width and slope of the flushing bay, and is roughly 1m^3/m width and per 10 m length at a slope of 0.5%. A slope of 1 % reduces this requirement by 15%, and a 2% slope reduces the requirement by 25%. A maximum flushing length of 105m for normal tanks is suggested.

- The flushing gate mechanism is released hydraulically, either by means of an autonomous float mechanism, or by means of a more sophisticated control system that utilizes other criteria such as interceptor and WWTP capacity, for flushing and emptying (Parente et al., 1995).

Case Studies: CSO Storage Tanks Utilizing Tipping Flusher Technology

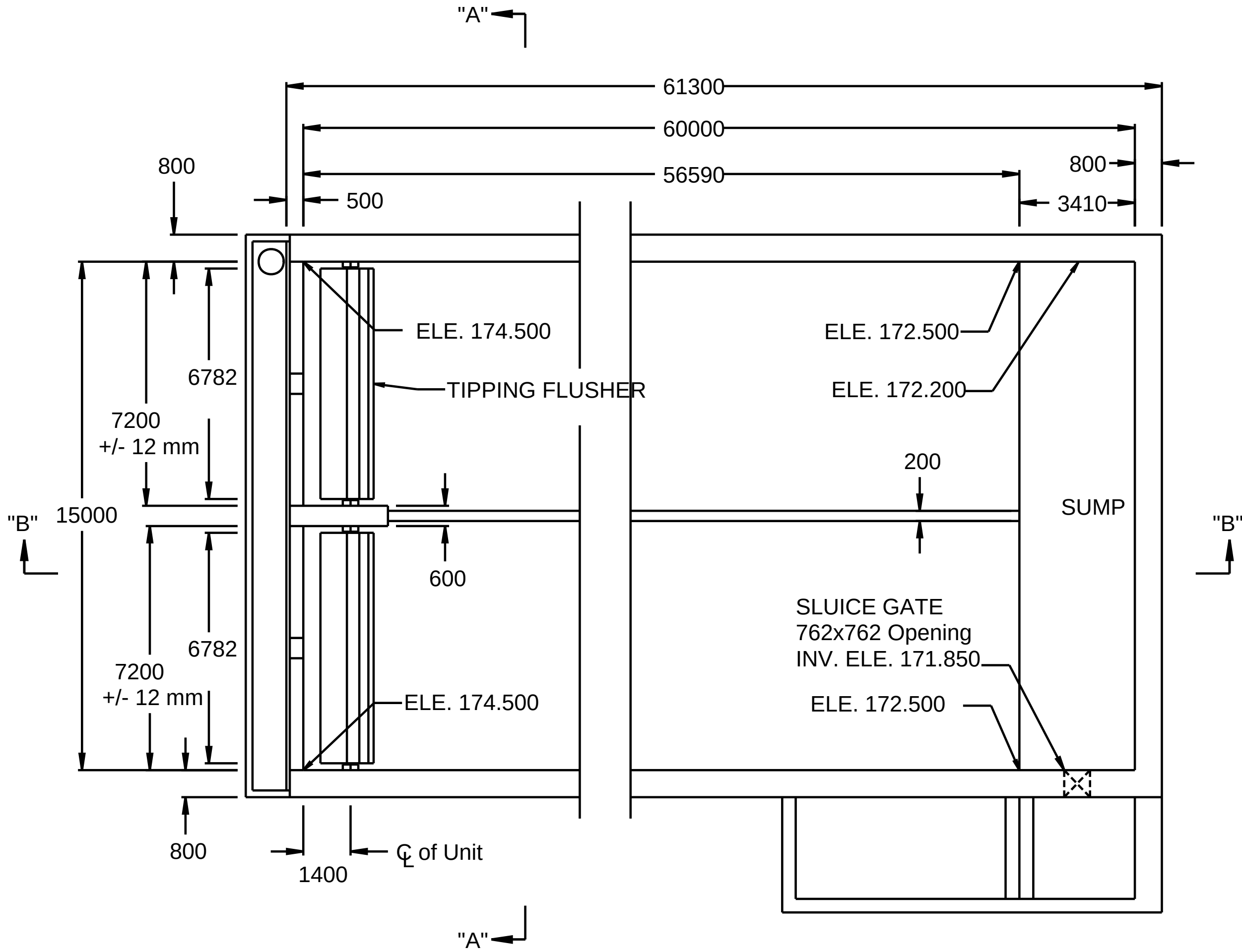
The following tables summarize the evaluations of the tipping flusher rectangular tank facilities.

Case No. 15 – Port Colborne

Details of the Port Colborne, Ontario CSO storage facility utilizing tipping flushers are given in Table 6-18. Plan and profile views of this facility are presented in Figure 6-11. Photos of this facility are shown in Figure 6-12.

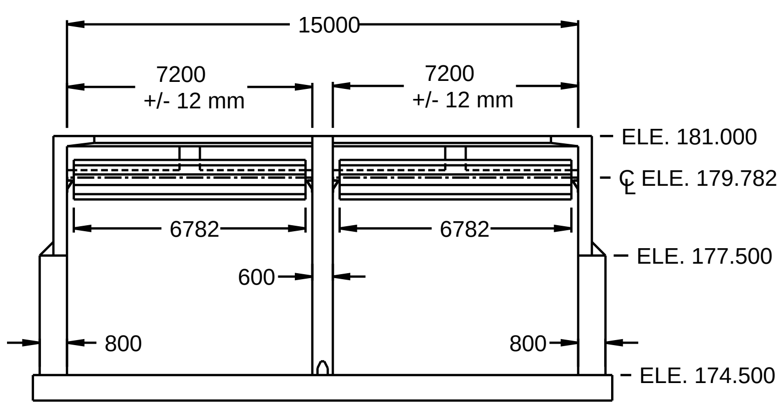
Table 6-18. Port Colborne, Ontario, Canada

Question	Response
Year Constructed	1996
Type of Flow	Combined
Covered or Open Tank	Open
Number Of Bays	2
Flushers/Bay	2
Training Wall/Flusher	Yes
Flush Channel Dimensions (l w h)	57 m x 7.2 m x 0.6 m
Height Off Floor	5.3 m
Front or Rear Tip	Rear
Fillet Radius	1.4 m
End Trough Dimensions l w d	3.4 m x 13.8 m x 0.65 m
Flush Channel Slope	1.5%
Flush Volume	8.2 m^3
Water Source	Fresh
Method of Removing Flushed Sediments	Underflow Sluice Gate
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	No
Odor Control System/Type	No
Electrical System Explosion Proof	No
Performance Assessment	Excellent



PLAN VIEW

ALL DIMENSIONS SHOWN ARE IN mm



SECTION "A"-"A"

Figure 6-14 (a/b). Port Colborne - CSO Storage Tank, Plan and Section Views

Figure 6-15. Port Colborne - CSO Storage Tank, Plan View

Case No. 16 – Wheeler Avenue

Details of the Wheeler Avenue, Louisville, Kentucky CSO storage facility are provided in Table 6-19. Plan view of the Wheeler Avenue facility is presented in Figure 6-16. Photos of the facility are provided in Figure 6-17.

Table 6-19. Wheeler Avenue, Louisville, Kentucky

Question	Response
Year Constructed	1997
Type of Flow	Combined
Covered or Open Tank	Open
Number Of Bays	1
Number Flusher/Bay	4
Training Wall/Flusher	Yes
Flush Channel Dimensions (l w h)	38 m x 4 m x 0.41 m
Height Off Floor	2.9 m
Front or Rear Tip	Rear
Fillet Radius	1.2 m
End Trough Dimensions l w d	2.4 m x 19 m x 0.6 m
Flush Channel Slope	1.6%
Flush Volume	6 m^3
Water Source	Fresh
Method of Removing Flushed Sediments	Underflow Sluice Gate
Frequency of Inspection/Crew Size	Not Available
HVAC System/Type	No
Odor Control System/Type	No
Electrical System Explosion Proof	No
Performance Assessment	Excellent

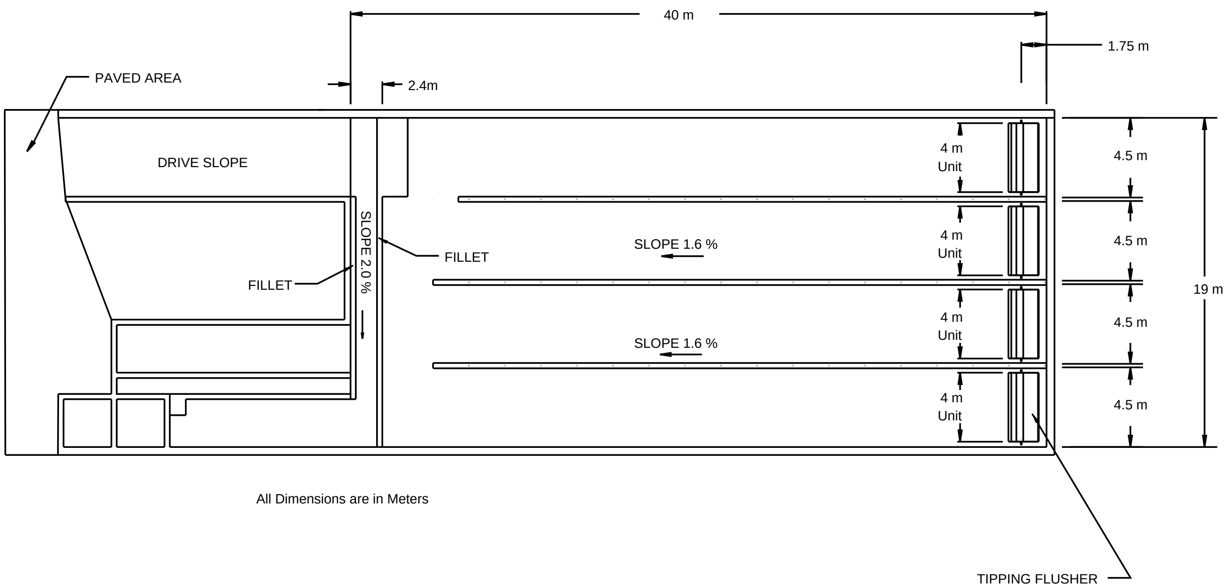


Figure 6-16. Wheeler Avenue - CSO Storage Tank, Plan View

Figure 6-17a. Wheeler Avenue - Photographs of Overall CSO Storage Tank

Figure 6-17b. Wheeler Avenue - Photographs of Filling Tipping Flushers and Overall CSO Storage Tank

Case No. 17 – 14th Street Pumping Station

The 14th Street Pumping Station in Saginaw Michigan functions as a regulation facility to pass dry weather flow to the East Side Tunnel leading to the WWTP, and as a pump station with 3 pumps, each with 2800 lps (100 cfs) capacity, to dewater drainage from four low-level trunk sewers discharging from the 14th Street district 80 hectares (200 acres). Land is mostly heavy industrial car manufacturing together with scattered residences. Pumped overflows occur about 12 times per year. The fifth main sewer to the station drains the 16th Street district with an 340 hectares (850 acre) catchment. The 16th Street district is long and narrow in shape, flat, and discharges into a 14-foot arch pipe with little slope. Solids deposition is considerable. Excess wet weather flows discharge over backwater gates into box culverts (collecting the pumped discharge from the station), and then proceeds through a 762 m (2500 ft) open ditch to the Saginaw River. Overflows occur 30-40 times per year. A wet weather connection from the 16th Street sewer into the station's wet well is used only in emergency. The total hydraulic flow capacity tributary to the 14th Street Pumping Station from both districts is about 13,000 lps (460 cfs).

The layout of the 14th Street Pumping Station treatment complex during wet weather operation is shown in Figures 6-18. It includes the following features:

- 22,000 m^3 (6.0 million gallons) of various storage elements consisting of in-line, first flush off-line, detention sedimentation treatment storage, underflow storage from vortex separators, and ditch storage overflow with pump back.

- Outflows from all storage facilities are equipped with vortex throttles to permit continuous gravity drainage to WWTP.

- All concrete tanks use tipping bucket flushers for ease in cleanup.

- Vortex solids separators precede conventional sedimentation tanks to ease solids cleanup.

Initially, first flush related flow from both the 16th Street and 14th Street districts are captured by in-system storage (2850 m^3, 0.75 million gallons) and then by tanks B1 and B2 (8550 m^3, 1.5 million gallons), Both tanks have vortex throttles to permit continuous drainage to the WWTP. This is the first in the United States of this type of CSO storage.

When Tanks B1 and B2 are filled, pumped discharge occurs with initial processing by three 11 m (36 ft) diameter reinforced concrete vortex solids separators each with a maximum capacity of 2830 l/s (100 cfs). Pumped underflow from the separators passes to Tank B3 (throttled outflow to WWTP). Treated overflow from the vortex separators discharges in a channel over the top of existing box culverts and into a new 7600 m^3 (2 million gallons) detention and storage facility (Tank B4) with chlorination. Outflow from the separators can also bypass Tank B4 and discharge directly into box culverts draining to the Saginaw River.

Tank B4 will provide 45 minutes of detention with "one pump on" (common event) and will provide further treatment of "clear water" overflow from the vortex solids separator. The overflow from Tank B4 discharges into the box culverts draining to the ditch. New backwater gate structures were installed near the River and the ditch rehabbed (stone lined and reverse graded) to create 9500 cubic meters (2.5 million gallons) of inexpensive storage. Retained ditch storage is drained after an event to a new drop shaft discharging to the East Side Tunnel.

Long term simulations indicate that the "continuous drain" operation for Tanks B1 and B2 permit capture with bleedback to WWTP without disinfection of half the annual runoff volume. Although the 1 year 1-hour storm is the most severe design condition, the more likely events of concern are spring multiple day intermittent rainfall events. The vortex tank throttles permits optimized overall utilization of Tank B1 and B2 and the complex of vortex separators with Tank B4 treatment.

The sum of all tank discharges (vortex throttles) plus the two dry weather underflow vortex throttles had to equal existing wet weather discharge from this catchment. This new requirement was imposed by regulating agencies since the City was planning to accept dry weather flows from nearby communities deactivating small WWTPs.

Additional estimated cost savings associated with the sedimentation tank tipping bucket flushers in contrast to conventional high pressure spray systems are significant (approximately 33 percent) while the requirement for flushing water was decreased by 25 percent (Pisano, 1985).

A total of 23 tipping flushers are used to clean tanks B1 (4 tipping flushers), B2 (2 tipping flushers), B3 (6 tipping flushers), and B4 (10 tipping flushers). The performance of this cleansing system has been noted by the maintenance staff to be very satisfactory. Only one flush per lane is required. Figure 6-20 depicts a photo of tanks B1 through B3. Figure 6-22 depicts a photo of tank B4 after overflow activation. Since the facility is very close to the WWTP, draindown of all tanks is typically accomplished in 6-12 hours. Photos depicting a cleaning sequence for Tank B4 are depicted in Figures 6-23 (a to d).

Figure 6-18. 14th Street Pumping Station - Tanks B1, B2 and B3

Figure 6-19. 14th Street Pumping Station - Tank B4

Figure 6-20a. 14th Street Pumping Station - Flushing and Sequence for Tank B4

Figure 6-20b. 14th Street Pumping Station - Flushing and Sequence for Tank B4

Figure 6-20c. 14th Street Pumping Station - Flushing and Sequence for Tank B4

Case No. 18- Saginaw Township Center Road Storage Tank

The first operational tipping flusher sedimentation tank installation within the United States, the Center Road Storage Tank, is located in Saginaw Township, Michigan. The tank was constructed in 1989 and handles overflows from a catchment of 514 hectares (1270 acres) with a design peak flow of 5943 lps (210 cfs).

The tank has no odor control provisions, and contains multiple bays with a total volume of 19000 m^3 (5 million gallons). In the first third of the tank which is utilized as first-flush storage, three tipping flushers are used to clean heavy sediments and sand. Water cannons and fire hoses are used to clean the remainder of the tank.

The tipping flushers cleanse a length of approximately 55 m (180 ft). Generally the performance of the tipping flushers has been satisfactory. However, two flushes are necessary after major storms as sediments contain some inorganic material. Flush waves have been observed to break up into rivulets near the end of the flushing lane.

Evaluation of Tipping Flushers

The following design considerations are important for maximizing the effectiveness of flushing rectangular tanks using tipper flusher technology:

- The size of a tipping flusher (TF) required to clean a given tank depends on the flushing distance, the height the unit is suspended above the tank invert, and the slope of tank floor in the flushing direction. The TF's vary in size from 0.02 - 2 m^3/ m (12 to 160 gal/foot) of flusher length, with a maximum length/span of approximately 11 m (35 feet).
- The maximum effective flushing length is between 160- 175 ft because the wave cannot be sustained and tends to break up into rivulets beyond this distance. Experience with flushing in the 55 to 60

meters (180 to 200 ft) range is mixed, and it has been observed that often 2 flushes are necessary to achieve adequate cleaning.

- Tank floors should slope from the flusher location to the collection trough at 1 - 3 % (2 % is desirable because quality control is difficult for flatter slopes).
- Tipping flushers require flushing lanes that are about equal to the width of the flusher to control the flow direction of the flush wave. This is accomplished by training walls that are about 0.4 to 0.6 m (15 to 18 inches) high, and run the full length of the tank terminating at the collection trough.
- All walls parallel to the path of flushing flow should be perpendicular to the tank bottom, with no fillets, to ensure the lower wall edges are cleaned.
- There is an upper effective height limit for placement of the tipping flusher where additional height does not enhance the flusher's performance further, (approximately 5.5 m, or 18 ft).
- The wall beneath the flushers must be continuous (i.e., contain no openings, penetrations or obstructions), to assure wave continuity.
- Side walls should be hand troweled to ensure smooth surface. No sidewall spray systems are necessary.
- Tanks with shallow sidewater depth of sidewater depth of long length are a concern using tipping flusher technology as the gate will tip near floor level.

Other Flushing Case Studies

Other researchers (Parente et. al., 1995) have collected survey data for several European CSO rectangular tank facilities using flush gates. The following are brief summaries of the findings.

City of Essen, Germany

The City of Essen has two CSO tanks utilizing flushing gates. One facility, in operation since 1991, has a volume of 1500 m^3 (395,000 gallons). The tank is divided into 3 bays with each bay approximately 5 m (16 ft) wide and 34 m (112 ft) long. The cleaning effectiveness was reported as very good without a need for any manual cleaning.

The second facility, in operation since 1993, has a volume of 2700 m^3 (710,000 gallons). The tank is divided into 6 bays with each bay approximately 2.5 m (8 ft) wide and 46 meters (151 ft) long. The cleaning effectiveness was reported as very good with a need to clean walls once a year due to the heavily polluted corrosive wastewater handled by the tank.

City of Konstanz, Germany

The City of Konstanz has a CSO tank utilizing flushing gates. The facility, in operation since 1992, hs a volume of 2000 m^3. The tank is divided into 3 bays with each bay approximately 7 m (23 ft) wide and 18 m (59 ft) long. The cleaning effectiveness was reported as generally good. Konstanz is located on a lakeshore with minimal slopes and heavy accumulation of sediment inside the sewer system during dry weather. During rain events, excess water is pumped to storm overflow tanks, with heavy first-flush concentration. The filling of the tank is from flushing water reservoir side, with heavy matter spilling into the flushing vaults. These materials clutters the flusher gate and mechanism, which occasionally fails to close properly because of debris and clogging. His preference was to use pre-clarified water for the flushing reservoirs to reduce potential for clogging the gate. The tank is drained by gravity through a regulator back to the pump station. The tank control system is programmable, allowing for adjustments in accordance with operation experience.

City of Augsburg, Germany

The City of Augsburg has a covered CSO tank utilizing flushing gates. The facility, in operation since 1994, has a volume of 4900 m^3 (1.3 million gallons). The tank is divided into 9 bays with each bay approximately 5 m (16 ft) wide and 50 m (164 ft) long. The cleaning effectiveness was reported as very good without a need for any manual cleaning. The flushing reservoirs are filled first and no problems with solids accumulating/clogging the gate have been reported. Some sediments deposit on wall crowns and weir sills and require occasional hosing down were reported. The tank floor was clean, with no deposition in the corners. In order to prevent clogging of the sludge pumps when emptying the mud sump, the owner installed mixing equipment to keep heavy sludge concentrations and debris in suspension during operation. The City has found stainless steel conduits to be more dependable then copper for the hydraulic flushing gate actuators.

City of Elizabeth, New Jersey - Mechanical Flap Gate Flusher

Flushing of large diameter combined sewers was investigated during the City of Elizabeth Combined Sewer Pollution Abatement Program completed in 1986. The program concluded that daily flushing of sewers particulary prone to solids deposition in seven subsections of the City by constructing 12 flushing modules would reduce the first flush overflow pollution by approximately 28%.

A total of 12 flushing modules were installed in sewers ranging in size from 0.45 to 1.4 m (18 to 54 inches) with slopes as low as 0.02% and were designed to produce sewer flushing in pipe runs up to 305 m (1000ft) long. Figure 6-22 presents plan and section views for a typical Elizabeth flushing system.

The flushing modules are underground structures with above ground control cabinets. Each module has a dry and a wet chamber. The wet chamber is constructed around the existing sewer and houses a hydraulically operated flap gate mounted on a shaft across the sewer supported on two bearings. The flap gate is sized to match the dimension of the sewer in which it is installed. The flap gate is normally open but closes at a controlled time (usually at night, during periods of low flow). The gate is designed to automatically open when the stored sewage volume rises to a preset level needed to create a flushing wave adequate to resuspend and transport the deposited sewage solids to the interceptor at a flow rate which will not cause overflow at the downstream regulators. The wet chamber also contains level switches and ultrasonic level sensors to provide signals for opening and closing of the gate. The dry chamber is adjacent to the wet chamber and houses the mechanical and electrical equipment such as the flap gate actuator, the hydraulic power unit as well as auxiliary equipment. A number of facilities are still in operation. No performance evaluations of these facilities have been conducted. This facility is unique in the United States and another such facility has yet to be installed.

Case Studies: Cost Effectiveness Studies of CSO Tank Cleaning Methods

The following two case studies present cost effectiveness evaluations that were prepared for CSO storage tanks in North America. The Eastern Beaches study compares cost effectiveness of tipping flushers with other methods. The Sarnia study compares cost effectiveness of flushing gates and tipping flushers with other methods.

Case Study: Eastern Beaches, Toronto, Ontario, Canada

Environment Canada in conjunction with the International Joint Commission has designated the City of Toronto Waterfront as one of the 42 Remedial Action Plan (RAP) areas within the Great Lakes drainage basin. The City of Toronto has been carrying out an extensive program of pollution abatement over the past 30 years to meet the RAP objectives. The City has prepared a pollution abatement program for CSO and stormwater runoff and has developed a Sewer System Master Plan for the combined and storm sewers. As a component of the Master Plan, the Eastern Beaches, located within the City of Toronto, were determined to have first priority in pollution abatement to ensure that the beaches remain open for body contact water recreational purposes. Environmental Assessment studies analyzed various pollution abatement strategies and determined that detention tanks would be the most feasible alternative for controlling pollution originating from CSO and stormwater runoff entering the nearshore waters along the Eastern Beaches (Parente et. al., 1994).

The first of two tanks, located at Kennilworth Avenue, was put into service in July 1990 to intercept 1 CSO and 5 storm sewer outfalls. High volume spray nozzle cleaning system was used to cleanse sediments from the tank after activations. This tank has been in operation for the past 4 years and has been monitored with respect to pollution abatement efficiency, beach closure impacts and operation/maintenance impacts. Monitored data from this tank indicated that the seasonal pollutant removal from the beach area has averaged approximately 2,800 kilograms (6160 pounds) of sediments and 130 kilograms (286 pounds) of BOD. The resultant beach closures has been reduced from 35% prior to tank installation down to 4% of the swimming season.

Based on the encouraging monitoring results from the first installation, the City has proceeded with the installation of a second tank at MacLean Avenue to remove all other CSO within the immediate area. This second tank, approximately 3.5 times larger than the first tank, has a storage volume of 8,000 m^3 (2.1 million gallons) and is located approximately 1 kilometer (0.62 miles) east of the first tank.

Design criteria for the MacLean Avenue detention tank included the following:

- Provide 8,000 m^3 (2.1 million gallons) of storage (4,000 m^3 for CSO and 4000 m^3 for stormwater runoff) to eliminate untreated CSO and stormwater discharge to beach area;

- Operation and maintenance concerns to address the most efficient cleaning system, water conservation considerations, minimal entry requirements, and control of possible odors.

- Due to the site constraints, the detention tank dimensions were finalized having a length of 100 m (330 ft), a width of 15 m (49 ft) and average depth of 6 m (20 ft).

Operation and Maintenance
During the design phase of the MacLean Avenue tank, discussions were held with the operating staff regarding their experience in operating the first tank for the past 4 years and also their experience in operating a combined sewage balancing tank further up the system which was constructed in 1914. In addition to this transfer of operating experience, contact was made with several other municipalities designing or operating combined sewage tanks to obtain their experience. The main comments/requirements from the various sources identified the following operating features related to tank flushing and odor control:

- Efficient method of cleaning is essential to minimize manned entry requirements and to ensure deposition of sediments does not occur;

- An odor control system is essential to prevent public complaints during tank operation.

During the process of detaining the flows, settlement of suspended solids will occur. To minimize and facilitate removal of the settled solids, the detention tank will be cleaned after every usage. Three methods for removal of the sediments were investigated: tipping flushers, flushing spray, and manual cleaning. Flushing spray and manual cleaning systems are described below.

Flushing Spray
A spray flushing system utilizes spray nozzles oriented in such a manner that the spray from the nozzles covers the entire floor area and the floor has sufficient grade to ensure effective sediment transport. These nozzles generally require water at a relatively high pressure and large volumes to provide the scouring of the sediments. The tank floor requires a longitudinal slope of 2% and lateral slope of 10%. The floor is graded to divert the wash water to a sump where it is pumped to the sanitary sewer.

The spray nozzles are selected to provide sufficient wash water volume and pressure that the settled sludge is re-suspended. From experience at the Kennilworth detention tank, selected nozzles with a capacity of 3.85 lps (50.8 gpm) at a pressure of 415 kPa (60 psi) are required, Because of the high flow and pressure demands, cleaning of the first tank is carried out in sections.

Manual Cleaning
This method requires manned entry to the tank during the cleaning process and the use of hoses to flush the tank floor. Manual cleaning ensures a high level of effectiveness because the operators can be flexible with the usage of time and water based on the level of sediments to be removed. This method is the most labor intensive and most hazardous due to the requirement of working in a confined space. The equipment cost of this alternative is minimal, but the operational cost is higher due to the longer time the maintenance crews have to remain on site. This does not include cost of mobile equipment such as hoses, safety equipment, etc. The volume of flushing water required will vary due to personnel work

practices, but is anticipated to be equal to or greater than that required by the flushing spray method. This method is being applied for cleaning the High Park tank constructed in 1914.

The cost comparison of the three cleaning systems is shown in Table 6-20.

Table 6-20. Capital and Operation and Maintenance Cost Comparison

Type of Cleaning System	Storage Volume (m^3)	Floor Area (m^2)	Unit Construction Cost ($/$m^2$)	Unit O & M Cost ($/$m^2$)
Tipping Flusher (MacLean Avenue)	8000	1360	141	0.075
Flushing Spray (Kennilworth Avenue)	2250	660	290	0.30
Manual Cleaning (High Park)	2400	790	2	1.77

*Excludes water and electrical costs.

In evaluating these tank flushing alternatives and evaluating experiences with all three practices, it was determined that the tipping flusher alternative was the most effective and economical. The flushing system for each compartment consists of a TF at each end of the tank compartment with the tank floor sloped at a grade of 2% to a central channel designed to intercept the flush wave and its re-suspended sediments. To incorporate water conservation practices in this design and since the flush water supply is not required to be at a high operating pressure, a small pump has been installed to pump lake water through the outfall force main and into the TF. A valve system has been installed such that the force main may be operated both as a discharge main and also as an intake main.

Odor Control

The odor control for the venting system of the second tank is similar to the first tank. The venting system is designed to convey the displaced air during the tank filling process by means of an underground pipe system to the surface control structure where the air is passed through an air filter system consisting of activated carbon. The treated air is then expelled to the atmosphere approximately 6 m (20 ft) above ground surface. A similar system has been in operation at the first tank with the filter media requiring replacement after 3 years of operation.

The housing for the filter system is located approximately 130 m (426 ft) west of the tank. The structure also houses the main control center for all the mechanical equipment and monitoring system.

Case Study: Sarnia Ontario

The pollutant loadings from combined sewer overflows (CSO's) and storm water outfall discharges to the Sarnia waterfront and the St. Clair River have resulted in beach postings, reduced waterfront recreational activities and degradation of aquatic habitat. The City of Sarnia carried out a Pollution Control Planning (PCP) Study to develop a master plan in reducing the pollution loadings to the Sarnia waterfront. One of the recommendations of the PCP study is to construct four CSO tanks that would intercept and retain CSO during storm events. The first of the recommended CSO tanks is located at the Devine Street outfall, which has a contributory area equivalent to 40 percent of the combined sewer area within the City of Sarnia. The required size of the tank was determined to be 10,700 m^3 (2.8 million gallons) such that the tank would reduce CSO discharge events to the St. Clair River to between 3 to 5 events per year (Parente et.al., 1995).

The purpose of this detention tank (see Case No. 14, Table 6-16 for evaluation data of this facility) is to detain the overflow volume until the conveyance capacity and/or treatment capacity is available. During the operation of the facility, settlement of suspended solids will occur along the bottom of the tank. It is therefore necessary to remove the settled solids after each event to eliminate caking, the accumulation of these solids, and to avoid the formation of gases and odors as a result of decaying organics.

The design of the tank was to incorporate the most efficient and reliable cleaning method such that operation and maintenance would not impose high demands during tank operations. The detention tank is situated within an existing residential park with an available effective hydraulic depth (outlet elevation to overflow elevation) of 4.3 m (14 ft). Based on the existing site restrictions and storage volume requirements, this tank requires a cleaning system to effectively clean a floor with a surface area of 3,440 m^2 (37,000 ft^2).

Cleaning Alternatives
The following four cleaning methods were identified for the Devine Street CSO tank:

- Manual Cleaning
- Flushing Spray
- Tipping Flusher, and
- Flushing Gate.

The estimated capital, operation and maintenance costs for the four flushing alternatives for the tank are provided in Table 6-21.

Table 6-21. Alternatives Capital and Operation and Maintenance Cost Assessment

Alternative	Capital Cost	Capital Cost/m^2	O & M Cost/Event	O & M Cost/m^2
Manual	$10,000	$2.91	$6600	$1.92
Flushing Spray	$680,000	$197.67	$1548	$0.45
Tipping Flusher	$525,000	$152.62	$378	$0.11
Flushing Gate	350,000	$101.74	$250	$0.07

Operation and maintenance costs include labor, cost of potable water for cleaning at $0.40/$m^3$, and cost of sewage treatment for external flushwater at $0.45/$m^3$.

Due to water conservation and the lower capital cost, the flushing gate system using detained sewage was selected to be the most cost effective alternative. This system requires less mechanical equipment such as valves and supply lines that are necessary for an external water source. The operation and maintenance costs tend to be marginally lower since no additional costs are incurred for the supply of potable water for flushing purposes and the associated treatment costs for the flush water.

Chapter 7
Desktop Analysis

This chapter describes three case studies aimed at assessing the cost-effectiveness of sewer flushing technology from different performance perspectives These performance perspectives are minimization of maintenance costs, reduction of sediments CSO first flush, and reduction of sediments to lower hydrogen sulfide levels. The first case study utilizes information developed for Fresh Pond Parkway Sewer Separation and Surface Enhancement Project in Cambridge, MA. A cost analysis was performed in this case study to compare flushing technologies versus conventional sewer cleaning methods. The second case study uses the desktop procedure described in Chapter 3 to investigate the pollution control effectiveness for a typical Northeast combined sewer catchment. The number of combined sewer overflows was determined using long term flow measurements. A cost analysis was performed to investigate present worth costs of satellite treatment versus flushing technology. The last case study investigated the cost effectiveness of sewer flushing versus chemical addition for hydrogen sulfide control.

Case Study One: Fresh Pond Parkway Sewer Separation and Surface Enhancement Project Storm and Sanitary Sewer Flushing

In Chapter 5, different methods of manual cleaning are presented which are costly and maintenance intensive. In this case study, the cost effectiveness of sewer flushing, utilizing flushing gates, versus periodic manual cleaning and sediment removal is investigated.

Over the last twenty years, the City of Cambridge has aggressively separated old combined and over and under sewerage systems throughout the City to enhance drainage service and to improve the water quality in the Alewife Brook and the Charles River. Presently, the City is in the construction phase of separating the CAM 004 area (25 hectares, 250 acres,) catchment. This area is north and west of Harvard Square and within dense heavily traveled urban regions.

Grit deposition within both sewerage and storm drainage systems is a major problem because of general flatness of the area, presence of several shallow streams that the sewerage (storm and sanitary) systems must cross under as siphons, and the hydraulic level of the receiving water body that frequently backwaters the storm systems. To overcome this problem in the CAM 004 area, automated flushing systems using quick opening (hydraulic operated) flushing gates to discharge collected stormwater will flush grit and debris to downstream collector grit pits.

Description of Piping Systems to be Flushed

The storm and sanitary sewer systems to be flushed are located within the CAM 004 catchment area. These systems start on the Fresh Pond Parkway near the Cambridge water treatment plant, continue east to the Concord Circle and then northeast to the Fresh Pond Circle. Both systems then proceed down Wheeler Street under the MBTA/Conrail railroad tracks and terminate near the Alewife Parking Garage. The piping systems consist of approximately 1400 m (4,666 ft) of sanitary trunk sewers, ranging from 460 mm to 1.2 m (18 inch to 48 inches), and approximately 1620 m (5,400 ft) of existing storm drains with pipe sizes ranging from 600 mm (24 inches) to 1.2m by 1.8 m (4 ft by 6 ft). There is a major overflow into the Alewife Brook from the sanitary sewer system just beyond the Alewife Parking Garage.

Two construction contracts have been prepared for the overall sewer separation and surface enhancement project along the Fresh Pond Parkway between Huron Avenue and Fresh Pond Circle. Flushing systems are included in one of the two construction contracts. Construction startup is expected in September 1998. Figure 7-1 depicts the general locations of the flushing vaults.

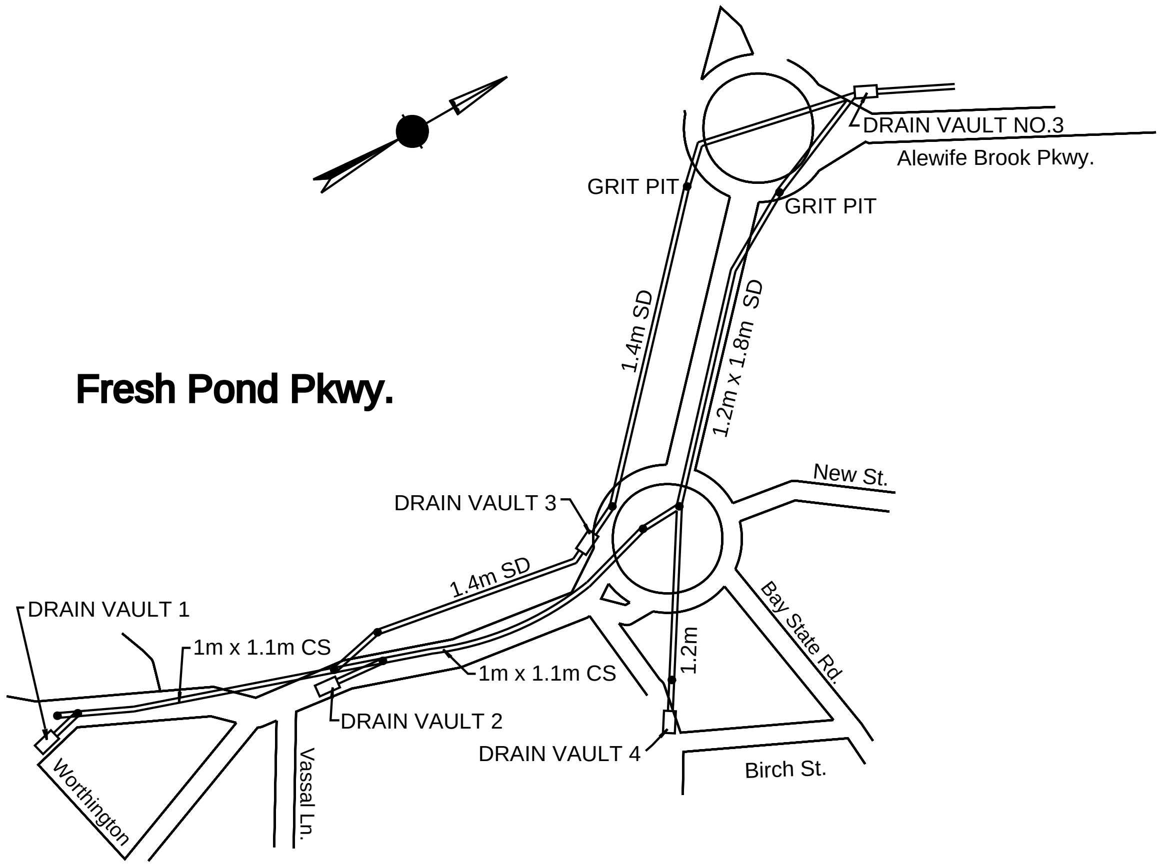


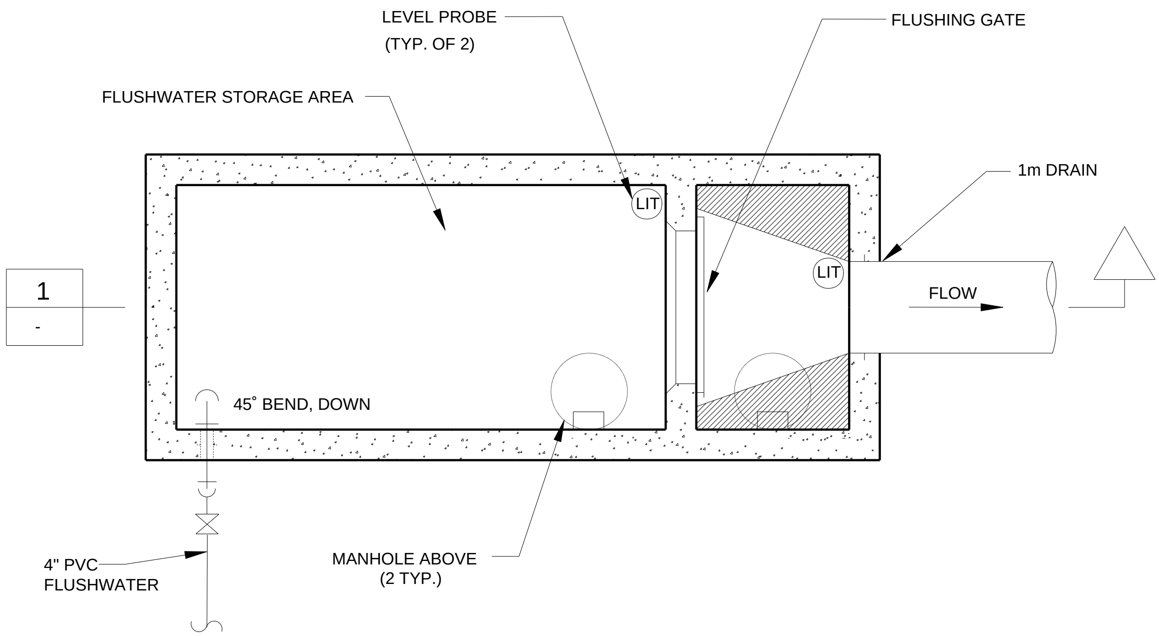
Figure 7-1. Fresh Pond Parkway - Locations of Flushing Vaults

Description of Flushing Vaults

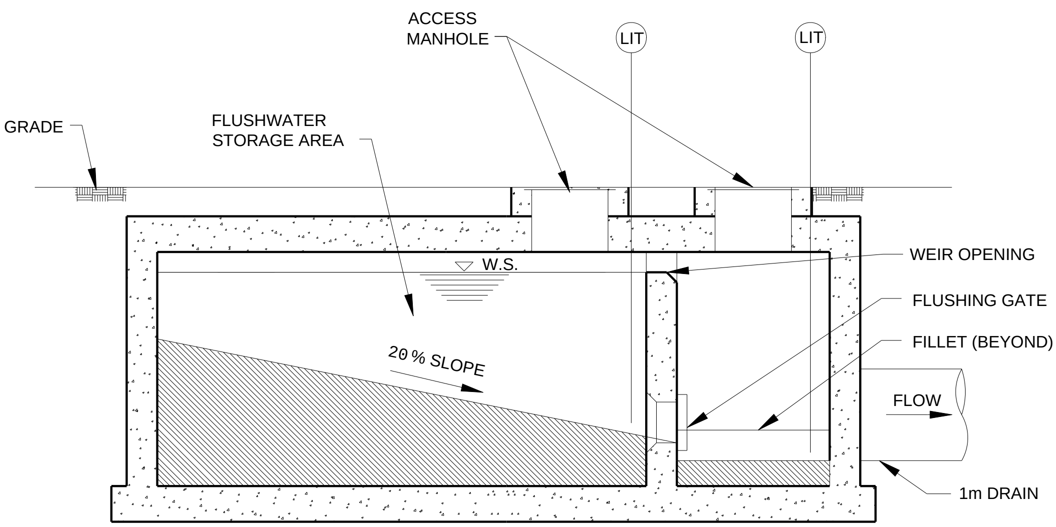
Another alternative is to retain pipes with flat slopes, but provide periodic cleaning of these pipes by automatic passive means to maintain hydraulic capacities. The use of flushing chambers at specific locations, with grit collection chambers downstream were designed for the Fresh Pond Project. The design utilized quick opening flushing gates (hydraulically driven) that release stored water to create a "dambreak" flush wave to cleanse and move sediments downstream to a grit pit. Several hundred such installations have been implemented in Western Europe since 1985.

Figure 7-2 shows a typical storm sewer flushing chamber with quick opening gate designed for the City of Cambridge. During a rainfall event, stormwater from the incoming storm drain fills the sump adjacent to the flush chamber. Submersible pumps then pump stormwater from the sump into the flush chamber. Each flush chamber volume was sized based on the roughness, slope, size and length of the pipe being flushed. The "flush wave" is designed to have a depth of approximately 100 to 150 millimeters (4 to 6 inches) and a velocity range between 0.9 to 1.2 meters/second (3 to 4-feet/second) at the end of the pipe segment being flushed. Once filled, the pumps shut off and a timer is initiated that automatically initiates the flushing sequence 24 hours after the rain event.

Process water (back wash) from the new Cambridge water treatment plant will be pumped to the new sanitary system and collected in sanitary sewer flushing vaults for periodic flushing of the sanitary sewers.



DRAIN VAULT NO.1-PLAN



SECTION 1 -

Figure 7-2. Fresh Pond Parkway - Flushing Gate Chamber

This approach is intended to minimize the daily operation of the system and provide the flexibility of cleaning the pipes on demand. It would be cost-effective due to reduced initial capital costs and minimal long term operational and maintenance costs versus a typical pumping station that requires daily maintenance and power.

Life Cycle Cost Comparison: Automated Flushing versus Periodic Manual Removal

This preliminary analysis presents life cycle costs for two alternative systems to clean the major storm and sanitary systems described above over a thirty-year period. Catch basin cleaning and cleaning of all incidental lateral lines tributary to both systems were not included. The cost of each alternative system does not include estimates of materials to be removed and disposed. Notwithstanding this limitation, all costs necessary to remove deposits to street level using either scheme are included.

Details of the Automated Flushing Systems

The automated flushing scheme consists of the following three separate flushing and grit capture systems:

- Near the new water treatment plant on Fresh Pond Parkway to the Concord Circle (sanitary and storm) including costs of collector manholes for the storm lines. Daily flushing of the sanitary system and periodic flushing of the storm system (assumed every two weeks; flush vaults are filled using captured stormwater);

- Concord (Sozio) Circle to the Fresh Pond Circle (sanitary and storm) including the cost of collector manholes for the storm system. Daily flushing of sanitary system and periodic flushing of storm system (assumed every two weeks; flush vaults are filled with pumped captured stormwater);

- Fresh Pond Circle to the south side of the B&M railroad crossing at the site of a new grit and sand collector area. The storm drain and both sanitary trunk sewers will be flushed. Twice weekly flushing of sanitary systems and periodic flushing of storm system (assumed every two weeks); flush vaults are filled with pumped captured stormwater);

The capital costs of the flushing systems include the flushing vaults, the grit capture chambers (storm only), small above ground vaults to house the hydraulic power pack units to trigger the flushing systems, and chambers as appropriate to pump storm water into the flushing chambers. External flush water (stormwater runoff) will be used to flush the sanitary systems from the Fresh Pond Circle to the Alewife rotary garage. The additional cost of sewage treatment of added flushwaters was included for the two sanitary sewer chambers at Fresh Pond Circle. Approximately 757,060 liters (200,000 gallons) are needed for flushing on an annual basis. No such costs are included for the storm system, as collected storm water will be used to flush the storm lines. Incidental costs of pumping storm water to flushing vaults are included. It is assumed that on a quarterly basis all vaults will be cleaned of collected materials. Trucking and disposal costs are not included. Police detail costs are also not included. Pertinent summary details of the flushing systems are given in Table 7-1.

Table 7-1. Flushing System Summary

Location	Pipe Service	Pipe Diameter (meters)	Flushing Segment Length (meters)	Flushing Volume (liters)
Drain Vault #1	Drain	0.91, 1.06, 1.37	390	12,083
Drain Vault #2	Drain	1.06	235	9,725
Drain Vault #3	Drain	1.37	240	10,917
Drain Vault #4	Drain	1.22, 1.22 by 1.83	350	12,655
Drain Vault #5	Drain	1.83	443	39,640
Sanitary Vault #1	Sanitary	0.4	215	5,845

Sanitary Vault #2	Sanitary	0.6	350	6,363
Sanitary Vault #3	Sanitary	0.4	426	9,202
Sanitary Vault #4	Sanitary	1.22	426	24,059

Table 7-2 summarizes the life cycle costs for sanitary and storm sewer flushing vaults for the locations noted above. Present worth costs per gallon flushing volume averaged about $44 per liter ($165 per gallon).

Details of the Manual Cleaning System
It is assumed that the sanitary systems will be cleaned on a three year cycle and the storm lines cleaned on a five-year cycle. Existing sediment levels (about one-third of pipe depths) can reoccur in a five year period (estimated).

Unit cleaning costs were obtained from contractor bids for the cleaning construction package of the storm and sanitary sewers within the project area as follows:

- 914 mm (36 inch) Storm Drain -$75.00/meter ($25.00/foot)
- 1067 mm (42 inch) Storm Drain -$102.00/meter ($34.00/foot)
- 1219 mm (48inch) Storm Drain -$129.00/meter ($43.00/foot)
- 1372 mm (54 inch) Storm Drain -$163.50/meter ($54.50/foot)
- 1829 mm (72inch) Storm Drain- $267.00/meter ($89.00/foot)
- 1.22 m x 1.83 m (4'x 6') Storm Drain -$232.50/meter ($77.50/foot)
- 457 mm (18inch) Sanitary -$19.50/meter ($6.50/foot)
- 610 mm (24") Sanitary -$21.00/meter ($7.00/foot)
- 1219 mm (48") Sanitary -$60.00/meter ($20.00/foot)

No trucking and disposal costs are assumed. On a life cycle basis, the automated flushing scheme is about $400,000 cheaper. The reader must also be aware that the avoidance of potential real and societal costs of flooding caused by surcharged and clogged drains and sewers is not reflected in this cost estimate. In addition, the nuisance level costs associated with traffic disruption on Fresh Pond Parkway (4 lanes with 50,000 vehicles per day) are also not reflected. An independent estimate of traffic disruption places a present value of $3 million. Last, the analysis does not take into account the fact that even after separation is completed, overflows can occur at the end of the sanitary system which is 2 kilometer (1.2 miles) downstream. Periodic flushing of the sanitary sewer trunk lines will minimize the amount of scoured and suspended solids discharged from this overflow into Alewife Brook during major wet periods.

Table No. 7- 2. Cost Effectiveness Analysis Flushing versus Manual Cleaning

Manual Pipe Cleaning	**Present Worth Cost ($M)**	**Flushing Chamber Sites**	**Present Worth Cost ($M)**
Sanitary Sewer Cleaning	0.9	Fresh Pond Circle Site	1.1
Storm Drain Cleaning	3.4	Concord Circle Site	1.5
---		Water Treatment Plant Site	1.3
Total	4.3	Total	3.9

Notes:

1. Pipe cleaning costs assume inflation rate of 3.12% per year.

2. Stormwater pipes are cleaned every 5 years, and sanitary pipes are cleaned every 3 years.

3. Flushing costs are based on inflation rate of 3.12% per year and discount rate of 7.1% per year.

4. Term = 30 years

5. Flushing costs for the sanitary systems include payment to the MWRA for all external applied flushing water. The annual flush waters for the sanitary systems = 757,060 liters (200,000 gallons). Current cost factor of $5.68/3,785 liters (1000 gallons) used.

6. Maintenance labor cost = $60/hour.

7. Sanitary systems to Fresh Pond Circle assumed to be flushed.

8. Storm systems will be flushed approximately every two weeks depending on rainfall.

9. Capital costs for flushing sites include excavation and backfill, hauling, pavement, gravel, dewatering, hazardous soil disposal, piping, traffic maintenance, equipment, structures and mobilization.

10. Operation and maintenance costs for flushing sites include hydraulic oil, routine inspection and servicing, power, and removal of collected sediments. Trucking and disposal costs are not included.

Case Study Two: Cost Effectiveness of Sewer Flushing versus Conventional Treatment

Over the last two decades, numerous investigators have noted that routine flushing of flat sewers on a continual (i.e., one to three day interval) basis could decrease the amount of solids available for scour, resuspension and transport to overflows. Until recently, flushing equipment has not been available to accomplish this idea in practice.

This case study investigates the cost effectiveness of utilizing the flush gate technology to flush on a routine basis sewer deposits within a large flat sewer to minimize “first flush” at a downstream overflow. The alternative conventional approach would be to use a satellite treatment facility such as a retention or detention treatment tank or vortex separator technology. The basic idea is to ascertain whether flushing on a routine basis can be a cost-effective adjunct to other treatment schemes or even viewed as a stand-alone control.

The case study is developed from actual data in a Northeast community. The first step in the investigation is to compute solids loadings in the overflow over the course of a year. Life cycle costs to handle these loadings using satellite CSO treatment are next computed. Next, flush gate technology is used to flush on a routine basis the same flat stretch of sewer, thereby reducing the amount of available solids that would be scoured and carried out the downstream overflow during high flow events. Life cycle costs are computed for this alternative “preventative” scheme and compared with the costs involved with satellite treatment.

Description of Area

The sewer catchment covers an area of 1600 hectares (4000 acres). The land use is mixed with a portion of heavy industrial and food processing establishments. The sewers are old, separated and carry heavy inorganic and organic settleables solids loadings. Inorganic loadings generally inflow from cracks in sewer and manholes. Organic loadings derive from food processing wastes, average about 15 mg/l, and are generally large rapidly settling particles.

Flow monitoring data collected at the end of the catchment prior to entry into a 1.8 m (72 inch) line were used as input to the desktop procedure. A summary of the input flow data is presented below Statistics of the average daily velocity, average, maximum hourly velocity, average daily and average peak hourly shear stress levels within the 1.8 meter (72 inch) sewer are presented in Table 7-3.

Overflow at the downstream regulator occurs when hourly flow levels exceed 2632 lps (60 MGD). The desktop procedure notes events occurred when the average daily flow rate exceeded 2632 lps (60 MGD) or when the peak hourly flow rate was less then 2632 lps (60 MGD). A summary of the events including number of activation's, peak overflow rate and total volume of overflow are listed below in Table 7-4. There are 21 events with a total annual overflow volume of 676,400 cubic meters (178 million gallons). Overflow peaks range up to 877 lps (20 MGD). The organic settleable solids input to the outfall line from the catchment is 879 metric tons (970 tons). During the 21 overflow events, about 230 metric tons (256 tons) of organic solids discharge to the receiving water (average concentration equals 290 mg/L.)

Table 7-3. Average Daily and Average Maximum Hourly Velocity and Shear Stress

Average Daily Velocity:	0.70 m/s (2.3 fps)
Average Maximum Hourly Velocity:	0.85 m/s (2.8 fps)
Average Daily Shear Stress:	0.84 N/m^2
Average Maximum Hourly Shear Stress:	1.2 N/m^2

Table 7-4. Pertinent Overflow Characteristics

Number of Overflows:	21
Total Volume Overflow:	676,400 m^3 (178 MG)
Range Overflow Discharges:	43 to 868 lps (1-20 MGD)
Total Hours Activation:	228 hour
Total Organic Settleable Solids:	232,000 kg (512, 200 lb) Loadings in Overflows
Total Organic Settleable Solids:	881,000 kg (1,938,000 lb) Input to System
Average Concentration:	290 mg/l Organic Settleable Solids overflow
Average Daily Input:	15 mg/l Organic Settleable Solids

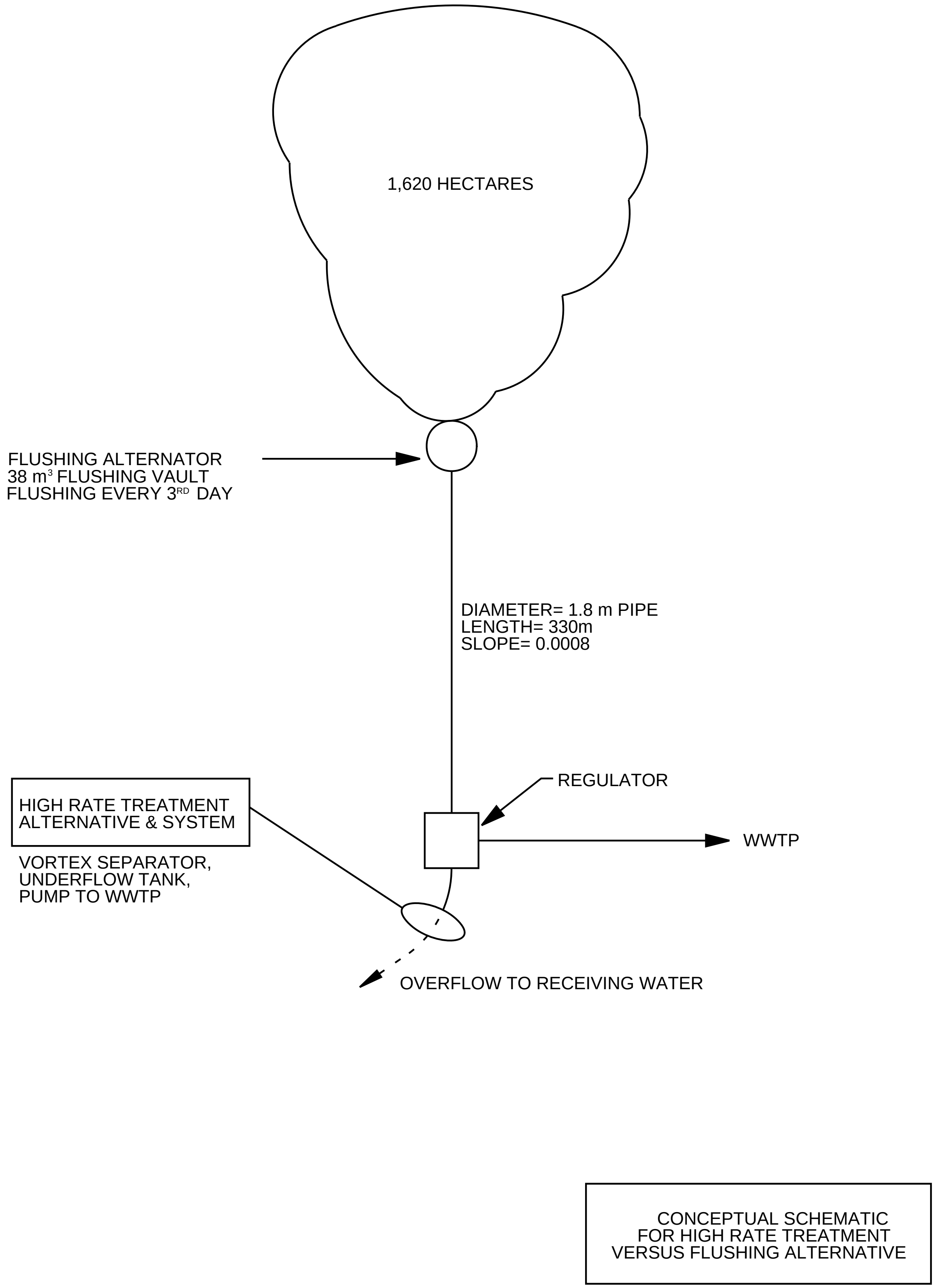


Figure 7-3. Conceptual Schematic for High Rate Treatment.

A conventional satellite treatment at the overflow facility consists of a vortex separator and underflow storage facility. A conceptual schematic of alternative controls are depicted in Figure 7-3. A satellite treatment system to handle the 21 overflows is assumed. The facility consists of a 9 meter (30 foot) diameter vortex separator, a 760 cubic meters (0.2 million gallon) underflow tank (sized to retain 5% maximum overflow), headworks including course screening, dewatering pumps (both vortex separator and underflow tank need pumping to WWTP after events), electrical and instrumentation controls, and general site civil and yard piping. Capital and operational costs were estimated for the facility using a procedure previously developed and used for CSO facility planning in Cincinnati and Toronto.

Present value costs for this configuration are shown below:

Capital	\$ 2,620,000
O & M	\$49, 000 /yr
Present Worth Cost	\$3,150,000 (i = 9%, 30 years)

Estimated effectiveness of this satellite facility is depicted in below. It is assumed that the vortex separator will remove 75% of the incoming organic settleable solids. The maximum influent applied hydraulic loading is 8.5 lps/m^2 (12 gpm/ft^2) during the 21 overflow periods. Average applied loading on the separator is 6.6 lps/m^2 (9.3 gpm/ft^2). Vortex separators are typically designed to remove heavy settleable solids with hydraulic loadings typically in the 14 to 21 lps/m^2 (20 to 30 gpm/ft^2) range. High performance is expected in this case study.

In an alternative scheme, an off-line flushing module just upstream of the 330 m (1000 ft) reach of 1.8 m (72 inch) pipe having with a flush volume of 38 cubic meters (10,000 gallons) is programmed to flush during night hours every three days except when flows are above average in the trunk sewer (wet overflow periods). It is assumed that the flush wave on each day of flushing will move 80 percent of the existing sediment build up (noted in the desktop procedure) to the regulator and pass to the downstream WWTP.

This flushing scheme is primitive but efficient. The summary results using the desktop procedure including the flushing scheme are shown below in Table 7-5. This simple scheme reduces the annual organic settleable solids in the overflow by 92.8%. These solids would have to otherwise be handled during wet periods by the satellite treatment scheme. As stated above, the fixed interval-flushing scheme could be modified to include more intelligent options such as more frequent flushing during extended dry periods when severe deposition is occurring. Such schemes could easily be programmed.

Table 7-5. Comparison Satellite Treatment Versus Automatic Flushing

Satellite Treatment Alternative

Number Overflows:	21
Organic Settleable Solids Overflow:	232,700 kg/yr (512,200 lb./yr)
Organic Settleable Solids Removable by Satellite Treatment :	174,600 kg/yr (384,150 lb/yr) (Assume 75 % Capture)
Residual Organic Settleable Solids:	58,200 kg/yr (128, 050 lb/yr) out to receiving water

Automatic Flushing Alternative

Residual Organic Settleable Solids overflow:	16,490 kg/yr (36,280 lb/yr)
Organic Settleable Solids to WWTP:	216,300 kg/yr (475,920 lb/yr) instead of overflow (i.e., attributable to flushing)
Percent Reduction of Organic Settleable Solids loadings Attributable to flushing:	92.8%

As noted in the Case 1 Study examining flushing vaults in the Fresh Pond Parkway project in Cambridge, the average present worth per gallon of flushing vaults equals $44 per liter ($165 per gallon) The largest flush scheme proposed in the Fresh Pond Project was an 42 m^3 (11,000 gallons) vault flushing 427 m (1400 ft) of 1.8 m (72 inch) storm drain.

Using this estimate the present worth cost for the 42 m^3 (11,000 gallon) flushing scheme assumed in this case study is $1,760,000. The summary cost effectiveness comparison of the two technologies are noted below in Table 7-6.

Table 7-6 - Present Worth Cost Comparison – Flushing Gate vs. Satellite Treatment

	Effectiveness (% Capture)	Present Worth
Satellite Treatment	75%	$3,150,00
Flush Gate Technology	92.8%	$1,760,000

It is evident that the flushing scheme utilizing the flush technology appears to be more cost effective than conventional high rate satellite treatment.

Case Study Three: Cost Effectiveness of Sewer Flushing versus Chemical Addition for Hydrogen Sulfide Control

General

Hydrogen sulfide will be produced as previously discussed in Chapter 3 in sewers with an anaerobic environment and an active slime layer. Sediment accumulations can further increase the generation of dissolved hydrogen sulfide. Hydrogen sulfide can be treated in a dissolved state or as a gas once it is stripped from wastewater. The analysis in this section will focus on treating dissolved sulfide because dissolved sulfide treatment will ultimately reduce the quantity of hydrogen sulfide that is stripped from solution. This section presents a cost analysis of chemically treating dissolved sulfide within a long, flat depositing sewer for a city in the southern United States with high BOD, high volatile solids, and elevated wastewater temperature. Flush gate technology will be used to minimize sediments, thereby reducing hydrogen sulfide contributions generated from the deposited solids.

The sewer solids deposition and erosion procedure described in Chapter 4 is used to compute daily solids deposition levels. Once the annual history of deposition and erosion of solids has been computed using this procedure, dissolved hydrogen sulfide levels are next computed. First, dissolved hydrogen sulfide levels are computed for the slime layer covering the perimeter of the pipe. Pomeroy's method is used and is described in Chapter 5. Next, dissolved hydrogen levels are computed attributable to accumulated sediments. In the initial deposition and erosion calculations, surface area for each sediment size remaining on a given day is tallied. Total sediment surface area is computed on a daily basis. In the dissolved sulfide calculations, a portion of the surface area of sediments is used within the Pomeroy formulation to calculate the incremental gain of dissolved hydrogen sulfide attributable to the sediment layer. The total dissolved hydrogen sulfide levels at the end of the pipe segment is the sum of the initial levels entering the pipe segment, the increment attributable to the slime layer, and if present, the additional increment associated with the sediments.

Chemical Treatment of Dissolved Sulfide

Numerous chemicals can be used to treat dissolved sulfide through oxidation, precipitation, or preventing sulfide formation. These chemicals include pure oxygen injection, hydrogen peroxide, chlorine, potassium permanganate, nitrate solutions, and iron salts. Chemicals must provide sulfide treatment from the point of application to the WWTP for this case study comparison. Following are descriptions of each of the potential chemicals and their potential application for this case study.

Pure Oxygen

Pure oxygen or air can be added to sewers to oxidize dissolved sulfide. However, more than one injection point is required for prolonged treatment of dissolved sulfide because of the tremendous oxygen uptake demand of the wastewater and slime layer. This option is not considered for the case study comparison because more than one injection point is required to treat dissolved sulfide along the length of sewer.

Hydrogen Peroxide

Hydrogen peroxide can oxidize hydrogen sulfide very quickly but it is a non-specific oxidant and will oxidize other compounds beside sulfide. However, peroxide is only effective up to 45 minutes after application before it decomposes to water and oxygen. Hydrogen peroxide is dangerous to handle in high concentrations and hazardous to humans. It would require specific chemical storage and handling equipment procedures, as do most of the oxidizing odor control chemicals. Hydrogen peroxide is not recommended for this case study because of its quick decomposition after application.

Chlorine

Chlorine could also oxidize the same compounds as peroxide but the longer half-life and toxic nature of chlorine would prohibit dosing large slugs of the chemical required to be effective. Chlorine would also react with organics to produce a variety of chlorinated organic compounds (chloroform, formaldehyde and other mono and polysubstituted chlorinated organic compounds of indeterminable chemical composition). These compounds could then, depending upon the physical and chemical properties, be released at downstream processes. Chlorine is also hazardous to handle and requires strict adherence to health and safety procedures and is not considered the most desirable alternative for this case study.

Potassium Permanganate

Potassium permanganate could be used but the production of manganese dioxide from its use and the batch nature of the chemical mixing process would make it a difficult system to operate. Potassium permanganate is also a hazardous chemical to handle and has explosion precautions for contact with dry powder. Permanganate application would require particulate control during mixing and personnel respirators must be worn during mixing. This is also the most expensive chemical (on a per pound of sulfide removal basis) to use for sulfide removal and is not considered appropriate for this

Nitrate Solution
Nitrate, if provided in sufficiently high concentrations directly onto the solids in the siphon, would have the effect of suppressing or stopping sulfide production in the upper layers of the sediments. Bacteria will use free oxygen first, then reduce nitrate before reducing sulfate. Therefore, if nitrate is present the bacteria will not reduce sulfate to sulfide. This would reduce, although not eliminate, the evolution and release of hydrogen sulfide at the treatment plant. Nitrate can not act quickly enough to be of much use over the entire length of the siphon and an overdose could violate discharge requirements or cause bulking in the secondary clarifiers at the WWTP However, the massive logistical effort and cost of applying that much nitrate uniformly to the siphon is impractical.

Iron Salts
Iron salts will react with dissolved sulfide to form metal-sulfide precipitates. The metal-sulfide floc typically does not settle in the collection system because of its characteristics and is often removed in the secondary treatment stage of a WWTP. A metal salt residual can be maintained in the collection system and effective sulfide control can be accomplished up to 40 kilometers from an application point with the proper environment. Because of these reasons the case study cost analysis was performed using iron salts to treat the anticipated dissolved sulfide loading.

Flushing Gates for Sulfide Reduction
As discussed in Chapter 4, flushing gates are used to periodically clean pipes that can accumulate sediment. However, sediment in collection systems can also contribute and actually increase hydrogen sulfide production. Therefore, if a flushing gate is installed on a segment of a collection system to keep the pipes relatively free of debris then the corresponding sulfide generation should decrease.

Case Study Description
The case study in this section represents a city located in the southern part of the United States. Cities in this part of the country typically have wastewater characteristics with high BOD concentrations and elevated temperatures that can lead to substantial hydrogen sulfide concentrations (when compared with locations in cooler climates). The specific mean and maximum wastewater characteristics for this case are contained in Table 7-7.

Table 7-7. Wastewater Characteristics

Parameter	Average Daily	Average Daily Maximum	Average Daily Minimum
Discharge (lps)	3468	6571	2707
BOD5 (mg/l)	570	928	197
VSS (mg/l)	376	760	39
TSS (mg/l)	464	913	272
Temperature (deg. C)	29	32	16

The desktop procedure described in Case Study 2 was used to analyze a 1.8 m diameter sewer. This procedure calculated sediment and erosion behavior, calculated dissolved sulfide concentrations using the Pomeroy method described in the Chapter 4, and calculated dissolved sulfide attributed to the accumulated sediments. The sewer is 915 meters long and has a slope of 0.0007. The dissolved sulfide concentration entering the pipe was assumed to be 0.25 mg/l. It is assumed that the allowable dissolved sulfide concentration entering the WWTP is 0.75 mg/l. Three 50 m^3 gallon flush gates must be installed to clean the 915 m long conduit (flush gates are spaced equally along the pipe length to clean 305 meters each). The flush gates are programmed to flush every third day during low flow conditions.

Based on the above information the desk-top procedure revealed that 383,750 kilograms of sulfide was produced in this segment of the sewer per year. Approximately 208,200 kilograms of sulfide was produced in the sediment layer of the siphon and the remainder was attributed to the slime layer on the pipe walls.

Cost Analysis

Two conditions were analyzed for this case study; 1) treating the yearly hydrogen sulfide mass with chemicals and 2) using a combination of flushing gates and chemicals to treat the total sulfide mass. Present worth calculations will be estimated for both scenarios.

Iron salts are assumed to treat the dissolved sulfide concentration for this sewer segment. Specifically, ferrous chloride will be used for the analysis. Ferrous chloride solution has approximately 0.12 kilograms of iron per liter of solution and a capital cost of $0.16/liter. Field experience indicates that approximately 0.82 kilograms of iron is required to treat 0.45 kilograms of sulfide. Therefore, the general cost of treatment per kilogram of sulfide is approximately $2.42. The capital cost for the chemical addition equipment is approximately $50,000 (installed) and the yearly operation and maintenance cost is $10,000. The flushing gate systems are based on a flushing vault volume of 50 m^3 and a present value cost of \$35,200/m^3. Costs assume an inflation rate of 3.12% per year, discount rate of 7.1%, and a 30-year term.

Condition 1 - Sulfide Treatment with Ferrous Chloride

The estimated present worth cost for treatment of 383,750 kilograms of dissolved sulfide per year (assuming that sediment contributes to the total sulfide mass) is $15.5 million.

Condition 2 - Sulfide Treatment with Ferrous Chloride and Flushing Gates

This condition assumes that the total sulfide mass contribution from the sediment (208,200 kg) bed is eliminated by using the flushing gates to minimize sediment accumulation in the pipe. The estimated present worth cost for treatment of 175,900 kilograms of dissolved sulfide per year using ferrous chloride to treat the dissolved sulfide and plus the present worth cost of the flushing gate system to minimize the sulfide formation is $12.5 million.

Summary of chemical treatment costs and flushing gate costs for both conditions are shown in Table 5-10.

Table 5-10. Chemical Treatment Costs

	Chemical Cost ($)	Flushing Cost ($)	Total Cost ($)
Condition 1	15,500,00	N/A	15,500,00
Condition 2	7,200,000	5,200,000	12,500,000

It appears that the overall system of employing flushing in combination with chemical treatment of residual unacceptable dissolved hydrogen sulfide levels is cheaper than only chemical treatment.

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