Sewer and Sediment Control

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U.S. Customary to SI (Metric)

U.S. Customary Unit			SI Unit	
Name	**Abbreviation**	**Multiplier**	**Symbol**	**Name**
acre	acre	0.405	ha	hectare
cubic foot	ft^3	28.32	L	liter
cubic feet per second	ft^3/s	28.32	L/s	liters per second
cubic feet per square foot per minute	$ft^3/ft^2/min$	0.305	$m^3/m^2/min$	cubic meters per square meter per minute
cubic inch	$in.^3$	0.0164	L	liter
cubic yard	yd^3	0.765	m^3	cubic meter
degrees Fahrenheit	^0F	0.555 (^0F-32)	^0C	degrees Celsius
feet per minute	ft/min	0.00508	m/s	meters per second
feet per second	ft/s	0.305	m/s	meters per second
feet	ft	0.305	m	meter(s)
gallon	gal	3.785	L	liter
gallons per acre per day	gal/acre/d	9.353	L/ha/d	liters per hectare per day
gallons per capita per day	gpcd	3.785	Lpcd	liters per capita per day
gallons per day	gal/d	$4.381x10^{-5}$	L/s	liters per second
gallons per minute	gal/min	0.0631	L/s	liters per second
inch	in.	2.54	cm	centimeter
mile	mi	1.609	km	kilometer
million gallons	Mgal	3785.0	m^3	cubic meters
million gallons per acre	Mgal/acre	8353	m^3/ha	cubic meters per hectare
million gallons per acre per day	Mgal/acre/d	0.039	$m^3/m^2/h$	cubic meters per square meter per hour
million gallons per day	Mgal/d	0.0438	m^3/s	cubic meters per second

Conversion Factors

U.S. Customary to SI (Metric)

U.S. Customary Unit			SI Unit	
Name	**Abbreviation**	**Multiplier**	**Symbol**	**Name**
parts per billion	ppb	1.0	μg/L	micrograms per liter
parts per million	ppm	1.0	mg/L	milligrams per liter
pound	lb	0.454	kg	kilogram
pounds per acre per day	lb/acre/d	1.121	kg/ha/d	kilograms per hectare per day
pounds per cubic foot	lb/ft^3	16.018	kg/m^3	kilograms per cubic meter
pounds per million gallons	lb/Mgal	0.120	mg/L	milligrams per liter
pounds per square foot	lb/ft^2	4.882	kg/m^2	kilograms per square meter
pounds per square inch	$lb/in.^2$	0.0703	kg/cm^2	kilograms per square centimeter
square foot	ft^2	0.0929	m^2	square meter
square inch	$in.^2$	6.452	cm^2	square centimeter
square mile	mi^2	2.590	km^2	square kilometer
square yard	yd^2	0.836	m^2	square meter
standard cubic feet per minute	std ft^3/min	1.699	m^3/h	cubic meters per hour
ton (short)	ton (short)	0.907	Mg (or t)	1,000 kilograms (0.907 metric ton)
tons per acre	ton/acre	2240	kg/ha	kilograms per hectare
tons per square mile	ton/mi^2	3.503	kg/ha	kilograms per hectare
yard	yd	0.914	m	meter

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Chapter 3 – Storm Runoff Solids Loading: From *Estimating Urban Wet-Weather Pollutant Loading,* paper presented at the Water Environmental Federation TMDL 2003 Conference, Chicago, Illinois, November 19, 2003 by Chi-Yuan Fan, Daniel Sullivan, and Richard Field of the Urban Watershed Management Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency.

Chapter 4 – Sewer Sediment Solids: From *Procedures for Estimating Dry Weather Pollutant Deposition in Sewerage System* (EPA-600/2-77-120, July 1977) and *Procedures for Estimating Dry Weather Sewage In-Line Pollutant Deposition – Phase II* (EPA-600/2-84-020, January 1984). Both reports were authored by Dr. William C. Pisano and Mr. Celso S. Queiroz of Energy & Environmental Analysis, Inc. Boston, Massachusetts. Dr. Pisano is now with Montgomery Watson Harza Inc. of Boston, Massachusetts.

Chapter 5 – Hydrogen Sulfide in Sewer: From *Sewer and Tank Sediment Flushing – Quality Assurance Project Plan (Category IV)*, draft interim document prepared by Montgomery Watson, Boston, Massachusetts and Odor & Corrosion Technology Consultants, Inc. Cypress, Texas. The Montgomery Watson project team included Dr. William C. Pisano and Mr. James R. Barsanti, and Odor & Corrosion Technology Consultants team included Dr. James Joyce and Mr. Harvey Sorensen, Jr.

Chapter 6 – Sewer Cleaning: From *Sewer and Tank Sediment Flushing: Case Studies* (EPA-600/R-98/157, December 1998) written by Dr. William C. Pisano and Mr. James R. Barsanti, of Montgomery Watson Harza and Dr. James Joyce and Mr. Harvey Sorensen, Jr. of Odor & Corrosion Technology Consultants.

Chapter 7 – Sewer Sediment Flushing – A Case Study: From *Sewer Sediment Flushing Evaluation and Design: A Case Study,* draft interim document prepared by Dr. William C. Pisano, Mr. James R Barsanti, and Mr. Frank J Ayotte of Montgomery Watson Harza, Boston, Massachusetts. Special acknowledgement is given to many individuals and firms that provided invaluable technical assistance and support during the development of the case study document. The cooperation of Mr. Owen O'Riordan of City of Cambridge Department of Public Works, Cambridge, Massachusetts, Mr. Bruno Cardiarelli of SEA Consultants, Inc., Cambridge, Massachusetts; Nicholas Grande and Gabriel Novac of Grande, Novac & Associates, Inc., Montreal, Quebec, Canada; and Jorgen Steinhardt and I. A. Michael Stegemann of Steinhardt GMBH, Germany is acknowledged and appreciated.

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Chapter 1
Introduction

Background

This report provides an integrated approach to manage the solids generated in urban wet weather flows (WWFs), both on the land surface and in drainage sewer systems. Threats to the quality of receiving waters by discharges from urban-storm-generated WWF, including combined sewer overflow (CSO) and polluted runoff from urban streets, are well known. During many storm events, large volumes of stormwater are drained via street inlets into the urban sewer system. The storm runoff washes off street dust-and-dirt and pollutants from catchment surfaces into the sewer system. Furthermore, the unsteady-state storm inflow resuspends sewer sediment that has settled in the sewer bottom, causing it to be transported downstream. Recently, researchers reported that sewer sediment deposited from prior storms contributed a significant amount of pollutants into receiving waters. This often creates a highly concentrated pollutant load. In most cases, CSO carries resuspended sewer sediment and generates a highly concentrated pollutant load sometimes associated with the “first-flush” phenomenon (Saget et al., 1996; Arthur and Ashley, 1998; Krebs et al., 1999). In most cases, CSO carries this resuspended sewer sediment into local waterways. Sewer sediment deposited during dry weather flow (DWF) contributes between 30% to 80% of pollutants into receiving waters (Ahyerre et. al., 2001).

The Problem

One of the underlying reasons so much sediment is deposited in combined sewers is hydraulic design. Combined sewers are sized to convey many times the anticipated peak DWF; they can carry up to 1,000 times the expected background DWF. Ratios of peak to average DWF usually range from 2 to 10 for interceptor sewers. The oversized and mildly sloping combined sewer segments possess a substantial potential for sedimentation during dry weather periods. DWF velocities are typically inadequate to maintain settleable solids in suspension and a substantial amount of sewer solids accumulated in the pipes. During rain storms, the accumulated solids may resuspend, because of the limited hydraulic capacity of the interceptor sewers, overflow to receiving waters. Suspended solids (SS) concentrations of several thousand parts per million are common for CSOs. This can produce shock loadings detrimental to receiving waters. Accumulation of sewer solids in sewers also result in a loss of flow-carrying capacity that may restrict/block flow and cause an upstream surcharge, local flooding, and enhanced solids deposition. Sewer-solid accumulation in urban drainage systems also creates septic conditions that pose odor, health hazards, and corrosion problems.

During low-flow periods, sanitary wastewater solids deposit in combined sewers because the flow velocity is usually less than the particle-settling velocity. Estimates of solids deposition range from 5% to 30% of the daily SS pollution loading (Pisano et al., 1998). The average dry period between storm events is about four days for many areas of the United States, especially along the eastern seaboard. If 25% of the daily pollution loading accumulates in the collection system, an intense rainstorm causing a two hour CSO, after four days of antecedent dry weather, will wash the equivalent of one-day's flow of raw-sanitary wastewater to the receiving waters. In Europe, average deposition rates have been measured to range from 30 to 500 g/m/d (Ashley and Crabtree, 1992). Even sewers supposedly designed to be 'self-cleansing' will have transient sediment deposits, and part of the load in transport will move near the bed (May et al., 1996). Furthermore, a one-day equivalent of raw-sanitary wastewater, discharged within a two-hour period, is twelve times the rate at which raw-sanitary wastewater enters the collection system.

Sewer sediments contain high concentrations of pollutants (80,000 mg/L of BOD_5; 200,000 mg/L of COD; and 200 mg/L of NH_3-N) (Arthur et al., 1996). As storm-flow intensities increase, resuspension of sewer sediment will occur. In combined sewers this occurs when they hydraulically overload and discharge as CSOs. The sewer-sediment layer contains organic materials and sulfides that can generate toxic, corrosive, and hazardous gases (e.g., hydrogen sulfide (H_2S) and methane, under anoxic conditions). Sulfates are reduced to H_2S and then oxidized to sulfuric acid by biochemical transformation; the acid attacks the sewer, thereby weakening its structural integrity. Extensive corrosion of concrete and their reinforcing bars results in cracks and infiltration and exfiltration of raw wastewater, causing overflow and WWTP overloading and groundwater contamination, respectively. Thus, control of sewer sediment not only protects urban receiving-water quality it also prevents hazardous conditions in sewerage systems and maintains the structural integrity of the sewer.

One of the challenges in protecting urban waterways lies in effectively managing contaminated sediments in both the sewer system and the receiving water. To enable urban communities to develop better plans to reduce the risks associated with WWF, research is needed to develop tools for a better understanding and assessment of the fate and transport of sediment solids and associated pollutants.

This report serves as a reference for the user community faced with the challenges to combat urban wet-weather-induced point and diffused sources of water pollution. It covers the gamut of engineering requirements, from pollution problem assessment tools for both desktop analysis and field investigation to determine extended problems of sewer sediment. It includes the following six chapters:

- Sources of sewer sediment and impacts (Chapter 2)
- Estimation of urban watershed solids loading (Chapter 3)
- Methodology for quantifying sediment-solids in sewer system (Chapter 4)
- Methods for field sampling and monitoring of hydrogen sulfide in sewer (Chapter 5)
- Sewer sediment control: sewer flushing (Chapter 6)
- A case study of sewer flushing system design and operation (Chapter 7)

The sewer sediment solids and associated pollutants found in combined sewers are mainly resulted from sanitary wastewater solids deposition during dry weather. These solids account for the majority of WWF pollution. All sources of WWF pollutants and their impacts are explained in Chapter 2. Methods for estimating solids that are washed-off from land surface during a storm event are presented in Chapter 3. A set of generalized procedures for estimating pollutant loadings associated with dry weather wastewater solids deposition in combined sewer systems is described in Chapter 4. Once the sewer segments most prone to sewer sedimentation are identified, sediment sampling is needed to determine actual sewer sediment and sedimentation characteristics. Chapter 5 describes sampling and monitoring procedures for measuring both the gas phase and dissolve phase of H_2S concentrations.

In order to reduce solids and associated pollutants entering in sewer systems, one must start with pollution prevention and source control by the best management practices (BMPs). Information on the urban stormwater BMPs implementation and evaluation are available in published literatures (ASCE, 2001; USEPA, 2002; Strecker et al., 2001; Strecker, 2002). Thus, Chapter 6 addresses only the management practices for in-sewer sediment solids control. The last chapter, Chapter 7 - Sewer Sediment Flushing, brings together information on the most recent case in planning and implementing in-sewer sediment control technologies in a large urban sewer-catchment. In this chapter, also includes estimated operation and maintenance costs as well as capital costs based on the Engineering News Record (ENR) Construction Cost Index of 6389 as of August 2001.

Chapter 2
Sewer Sediment

Sources of Sewer Sediment

The sediment-solids and associated pollutants found in combined sewer overflow result from resuspension of deposited DWF sanitary wastewater solids and wash-off from land surfaces during storm events. A review of the sources (Heaney et al., 1999) shows that directly-connected impervious areas contribute a high pollutant loading in separate storm sewers. For combined sewers, the largest solids and pollutant loads are likely to originate from sanitary wastewater input during dry weather. Ashley and Hvitved-Jacobsen (2002) categorized sources of sediment solids as shown in Table 1.

Table 1. Sources of sewer sediment

Source	Particle Characteristics	Description
Winter gritting/salting	Salt <1.5 mm, sand 1.3 mm.	Sand used up to 30% of total mass annually.
Road surfacing	All sizes possible.	Primarily inorganic.
Flow from ground	All sizes possible	Depending on sewer condition.
Industrial wastewater	Pretreatment standards	Pretreatment removal of toxic solids.
Construction sites	>1000 mm possible	All sizes organic, inorganic possible.
Flooding	>1000 mm possible	All sizes organic, inorganic possible.
Runoff from impervious areas	Typically solids < 250 μm enter sewer.	These solids may be up to 40% by mass of total. Roof surface up to 30% of total.
Sanitary wastewater	Up to 100 mm	Largest organic solids source – typically 97% of these solids. All enter sewer.
Soil erosion	Typically <1 mm	Organic and inorganic.
Wind-blown from sand/soil/litter	Large organics possible. Inorganics <5 mm	Entry via catchbasins/inlet. Size reduced when discharged into sewer.

Overland Surface Runoff Solids

The particulate and associated pollutants in urban stormwater come from atmospheric deposition, roof tops, parking lots, and streets/highways. Other sources include construction sites, commercial and industrial parking lots, automobile maintenance operations, leaking sewer infrastructure, accidental spills, and runoff from lawn irrigation.

Atmospheric Deposition

In the United States, each year millions of tons of pollutants are emitted into the troposphere zone of the atmosphere; this has the potential to redeposit in the urban and terrestrial watershed and be subsequently transported downstream to receiving waters. The factors affecting atmospheric deposition include wind speed and direction, dry dust fall, site temperature and precipitation (snow and rainfall), elevation and slope of the land, land use, and sources of air pollution (automobile, industrial, and residential emission). Pollutants in the atmosphere contribute significantly in urban WWF contamination through dustfall and by wash out. As reported by Cotham and Bidleman (1995) and Hilts (1996), enormous amounts of certain toxic pollutants contained in urban storm runoff are associated with atmospheric deposition.

Rooftops, Roadways, and Parking Lots

One of the major sources of pollutants in urban drainage catchments are runoff from: urban streets *(*Sansalon, 1996; Sansalone and Buchberger, 1996), highways (Shaheen, 1975; Montrejaud-Vignoles et al., 1996), building rooftops (Sakakibara, 1996; Förster, 1996; and Wada et al., 1996), and parking areas (Pitt et al., 1995; Nowakowska-Blaszezyk and Zakrzewski*,* 1996). In some cases, treated wood has been identified as a potential source of arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), and zinc (Zn) in stormwater (Weis and Weis, 1996). Table 2 depicts relationships between toxic pollutants in solids and urban land use.

Table 2. Toxic-pollutant concentrations from land use in France (Bertrand- Krajewski, 1993)

Land Use	Toxic Pollutant Concentration					
	Cd (Fg/g)	Cu (Fg/g)	Pb* (Fg/g)	Zn (Fg/g)	TPHs (mg/g)	PAHs (Fg/g)
Residential area	0.04–10.7	14–221	120–1,000	47–1,170	15.7–59.8	--
Commercial area	0.02–1.06	10.4	160–220	53–1,065	16.4–34.0	--
City downtown	2.6–7.0	143 - 390	1,880–2,550	470–534	8.8–51.8	--
Industrial area	0.7–3.4	228	488–1,410	655–1,445	61.9–507.0	--
Parking lot	1.0–14.6	206	2,000–15,000	1,600	--	--
Street	0.22–3.90	22–200	--	44–480	--	0.2–20
Highway	0.6–4.3	90–281	130–4,800	250–336	--	--

* Pb relates to the use of leaded gasoline.
Legend: Cd-cadmium, Cu-copper, Pb-lead, and Zn-zinc.
TPHs-total petroleum hydrocarbons, and PAHs-polycyclic aromatic hydrocarbons.

Distributions of heavy metals and hydrocarbons in urban stormwater are associated with their particulate fractions and the relative size of SS. Particles finer than 250 :m contain higher concentration of heavy metals and total petroleum hydrocarbons (TPHs) than particles larger than 250 :m and about 70% of the heavy metals are attached to particles finer than 100 :m (Ellis and Revitt, 1982). Vignoles and Herremans (1995) examined the heavy metal associations with different particles sizes in stormwater samples from Toulouse, France and discovered that the vast majority of the heavy metal loadings in stormwater were associated with particles less than 10 Fm in size. These results are shown in Table 3.

Table 3. Concentration of metals by size fraction

Particle Size Range (μm)	Metal Concentration															
	Cd		Co		Cr		Cu		Mn		Ni		Pb		Zn	
	μg/g	%*	μg/g	%*	μg/g	%*	μg/g	%*	μg/g	%*	μg/g	%*	μg/g	%*	μg/g	%*
> 100	13	18	18	9	21	5	42	7	86	8	31	7	104	5	272	7
50 – 100	11	11	16	5	25	4	62	8	59	4	27	5	129	7	419	11
40 – 50	11	6	25	4	26	2	57	3	70	3	31	7	181	10	469	12
32 – 40	6	5	20	6	50	6	46	4	53	3	31	7	163	9	398	10
20 – 32	5	5	18	6	23	3	42	4	54	4	27	5	158	8	331	9
10 – 20	6	9	22	10	39	9	81	11	85	7	39	10	247	14	801	20
< 10	14	46	53	60	134	71	171	63	320	71	99	59	822	46	1232	31

Legend: Cd-cadmium, Co-cobalt, Cr-chromium, Cu-copper, Mn-manganese, Ni-nickel, Pb-lead, and Zn-zinc.
* Distribution of metal pollutant weight among the different particle size range.

Snowmelt runoff is much greater in volume than typically considered in drainage designs, resulting in greater winter flooding than during the summer; however, there is still a notable lack of experience about urban runoff during the winter season (Thorolfsson and Brandt,1996). Saxton *et al.* (1996) conducted a study to characterize the pollution of snow versus snowmelt runoff at Eielson Air Force Base, Alaska and reported that snow was more contaminated than snowmelt runoff and that snowmelt runoff appeared to be representative of what reached surface water. Sansalone (1996) investigated the forms of stormwater and snowmelt heavy metals and reported that Zn, Cd, and Cu were mainly dissolved in stormwater, while only Cd was mainly dissolved in snowmelt.

Sanitary Wastewater Solids

According to Ashley and Hvitved-Jacobsen (2002), solids originating from sanitary wastewater sources can be categorized into the following types:

1. Fine fecal and other organic particles.
2. Large fecal and other organic matter.
3. Paper, rags, and miscellaneous sewage litter.

These categories also apply to commercial and other workplaces, where other substances may be added, subject to effluent controls. Industrial sources are also important, but due to the diversity of the inputs from industrial sources, they will not be considered further here. Garbage grinders, that are installed in many residential areas for disposal of kitchen wastes generate higher organic solids loading. Pollutant loads and concentrations from residential sources discharging to sewers are shown in Table 4.

Table 4. Pollutant loads and concentrations from residential sources (EPA 1992)

Parameter	Garbage Grinders		Toilets		Basins, Sinks, Appliances	
	gpcd	mg/L	gpcd	mg/L	gpcd	mg/L
BOD_5	11 - 31	2380	7 - 24	260	25 - 39	260
SS	16 - 44	3500	13 - 37	450	11 - 23	160
Nitrogen	0.2 - 0.9	79	4.1 - 16.8	140	1.1 - 2.0	17
Phosphorus	0.1	13	0.6 - 1.6	20	2.2 -3 4.	26

Results from the Jefferies and Ashley (1994) study of gross solids discharge in combined sewers can be interpreted to give a rate of 0.05 visible items /capita/day. The average disposal rate reported by Friedler et al. (1996) was 0.15 refuse items/capita/day, 72% of which was due to female toilet usage. The most common item of refuse (23% of those reported) was the tampon. According to Ashley et al. (2000) some 2.5 million tampons, 1.4 million sanitary towels, and 700,000 panty liners were found to be flushed into sewers in the United Kingdom every day. These items become floatable solids in CSO. Thus, the accumulation of trash on beaches and along shorelines of impacted waterways is the most obvious impact of floatable pollution. It is not only in the United Kingdom that the toilet is being used as a rubbish bin. A limited questionnaire survey was undertaken of the items disposed in 72 countries. Results indicated that some 33% of respondents claimed that sanitary items, other than feces and toilet paper, were regularly flushed, and in some countries 'disposable' napkins were also put into the toilet (Ashley et al, 1999). There will not likely be any significant reduction in these items found in sewers in the near future necessitating expensive screens and transport systems for their control and disposal (Ashley et al, 2000).

Impacts

In general, sewers will not maintain self-cleansing velocities at all times. The diurnal pattern of DWF and the temporal distribution and nature of sediments found in sewer flows may result in the deposition of some "juvenile" sediments at times of low flow. The subsequent erosion and transport of these sediments at times of higher flow during a storm-flow event, either as suspended load or bedload, contribute to the "first-flush" phenomena or polluted segment in CSO (Saget et al., 1996; Arthur et al., 1996; Arthur and Ashley, 1998; Krebs et al., 1999). During low flow dry weather periods, sanitary wastewater solids deposited in combined sewer systems can generate H_2S and methane gases due to anaerobic conditions. Sulfates are reduced to H_2S gas that can then be oxidized to sulfuric acid on pipes and structure walls by further biochemical transformation. Furthermore, these sediments are discharged to urban streams during storm-flow events and can cause degradation of receiving water quality. Thus, dry weather sewer sedimentation not only creates hazardous conditions and sewer degradation but also contributes significant pollutant loads to the urban receiving waters during wet-weather high-flow periods. Furthermore, broken sewer lines cause direct exfiltration of raw sanitary wastewater and sewer sediment leachate into subsurface groundwaters.

Structural Deterioration of Sewerage System

The primary cause of odor and corrosion in collection systems is the sulfide ion ($S^=$), which is produced from sulfate ($SO_4^=$) by bacteria residing in a slime layer on the submerged portion of sewer pipes and structures. Once $S^=$ is released from the wastewater as H_2S gas, odor and corrosion problems begin. Bacteria utilize H_2S gas to produce sulfuric acid (H_2SO_4) (Boon, 1995; Boon and Lister, 1975; Thistlethwayte 1972). For sanitary wastewater the main source of $S^=$ is $SO_4^=$. Sulfide generation is a bacterially mediated process occurring in the submerged portion of combined and sanitary sewers and force mains. Fresh sanitary wastewater entering a collection system is usually free of $S^=$. However, a dissolved form of $S^=$ soon appears as a result of low dissolved oxygen content, high-strength wastewater, low flow velocity, long detention time in the collection system, elevated wastewater temperature, and extensive pumping (EPA 1985).

The effect of H_2SO_4 on concrete surfaces in 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. In severe instances, pipe failure, disruption of service, street surface cave-ins, and uncontrolled releases of wastewater to surface streams can occur.

Receiving Water

From 40% to 80% of the total annual organic loading entering receiving waters from a city is caused by WWF. During a single storm event, WWF accounts for about 95% of the organic load as well as high loads of heavy metals and petroleum hydrocarbons (Field and Turkeltaub, 1981). CSO can have damaging impacts on receiving waters. The EPA evaluated the distribution and biological impacts of discharged particulates for selected CSO and storm drain points in the Seattle, Washington region (Tomlinson et al., 1980). The concentrations of SS, heavy metals, and chlorinated hydrocarbons were greater for the CSO than for the storm drains. Particulate distributions were influenced by various dispersion processes, including water density layering, near-bottom offshore streaming and advection along the shoreline Human enteric viruses were also detected in the CSO, but were not found in storm drainage or in any near outfall sediments. However, impacts of discharges on the freshwater benthos raised concern relative to the feeding success of sport fish due to polluted sediments.

Saul et al. (1999) investigated the production of undesirable solids in CSO as it related to social, economic, and ethnic factors. The goals of the research were first to determine the differences in sewer solids characteristics that were ultimately discharged to the receiving water and then to use the solids' characteristics to predict the efficiency of CSO treatment devices, especially CSO storage basins. St. Michelbach and Brombach (1999) showed that the nutrient content, especially of dissolved phosphorus, from CSO and existing WWTPs was endangering the health of Lake Constance. They proposed a simple methodology to estimate the nutrient loads from CSO to the lake the results of which can be used to determine the cost effectiveness of CSO improvement versus WWTP improvement.

Sanudo-Wilhelmy and Gill (1999) compared current pollutant concentrations in the Hudson River Estuary, New York with concentrations measured in the 1970's. The concentrations of Cu, Cd, Ni, and Zn have declined, while concentrations of dissolved nutrients (namely PO_4) have remained relatively constant during the same period. This suggests that WWTP improvements in the New York/New Jersey Metropolitan area have not been as effective at reducing nutrient levels within the estuary as heavy metals. Rather than inputs from point sources, the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary. Mason et al. (1999) showed that the Chesapeake Bay was an efficient trap for Hg. However, in the estuary, methylation of the mercury occurred, the Bay became a source of methylmercury, and on a watershed scale, only about 5% of the total atmospheric deposition of mercury was exported to the ocean.

Venkatesan et al. (1999) investigated the potential for using sediment cores to determine the history of chlorinated pesticide and PCB application in a watershed. They found that the sediment cores accurately reflected the length of use of these chemicals in the watershed, and that the surface sediment layer, after mixing and resuspension was accounted for, reflected the reduction in use that had occurred during the last few years. The long-term impacts of WWF- toxic pollutants to stream habitat are depended on bio-availability and accumulation of the substances by aquatic life. Herrmann et al. (1999) found that the concentration of ammonia plus urea in CSO was found to be a significant measure of the likelihood of a fish kill after an overflow event, more relevant than the concentration of ammonia alone.

Groundwater

In 1999, the EPA conducted a nationwide study to quantify leakage of sanitary and industrial wastewater sewer systems based on groundwater table elevations. The study indicated low levels of wastewater exfiltration (less than groundwater infiltration) in much of the midwestern and eastern parts of United States due to relatively high groundwater tables. However, problems of exfiltration in the western United States seem more widespread because of lower groundwater table (EPA, 2000). Thus, contamination of soils and groundwater in the vicinity of a leaking sewer does not appear to occur under conditions favorable to the infiltration of groundwater into sanitary sewers. Exfiltration events are likely to be more severe than infiltration events at locations where groundwater fluctuates. Possible groundwater contamination, resulting from sewers that have collapsed or catastrophically failed and from sewers which are believed to suffer from long-term deterioration, has been noted in groundwater contamination studies (EPA, 1989).

In those areas having shallow depth of wells and high permeability of soil, any surface contamination could easily migrate to the groundwater. Thus, a significant amount of groundwater contamination is as attributable to surface runoff as leaky sewer exfiltration. Squillace, et al. (1996) and Zogorski, et al. (1996) investigated urban stormwater as a source of groundwater MTBE contamination. Mull (1996) stated that traffic areas are the third most important source of groundwater contamination in Germany (after abandoned industrial sites and leaky sewers). The most important contaminants are chlorinated hydrocarbons, sulfate, organic compounds, and nitrates. Heavy metals are generally not an important groundwater contaminant because of their affinity for soils.

Trauth and Xanthopoulus (1996) examined the long-term trends in groundwater quality in Karlsruhe, Germany. Results indicated that the urban land use could cause a long-term adverse influence on the groundwater quality. The concentration of many pollutants have increased by about 30% to 40% over 20 yrs. In Dortmund, Germany, an infiltration trench for stormwater disposal caused Zn problems that were associated with the low pH value (about 4) in the infiltration water (Hütter and Remmler,1996).

Chapter 3
Storm Runoff Solids Loading

Introduction

This chapter presents methodologies for using relatively simple equations to estimate pollutant loading from urban drainage areas. The loading equations in this chapter account for floatable solids or street litter, highway sand due to winter deicing, street dust and dirt, and eroded soil-sediment from open space. The calculated results only indicate a magnitude of solids loading. For designing a stormwater pollution control system, field sampling and monitoring data are required to verify the estimated results.

Litter/Floatables

A large amount of the litter that enters urban drainage systems reaches receiving waters. Urban litter consists mainly of manufactured materials, e.g., such as plastic and paper wrapping, shopping bags, cigarettes and their packets, and items used in public parks, gardens, and fast food outlets. The total amount of material discharged can vary significantly depending on the degree to which the watershed is littered. Five studies (conducted in the NY/NJ Metropolitan Area; Jamaica Bay, NYC; Fresh Creek, NYC; Hartford, CT; and Newark, NJ) looked at the total amount of solid material discharged from CSOs on a dry weight basis and reported between 0.02 and 1.7 lb/acre/in. of rainfall (Newman and Leo, 2000).

A study in the City of Auckland, New Zealand (Cornelius et al., 1994) indicated that the annual litter loading rates from commercial, industrial, and residential areas are 1.35, 0.88, and 0.53 kg/ha-yr, dry weight bases (or 0.014, 0.009, and 0.006 m^3/ha-yr), respectively. The litter's bulk densities vary with land use (96.4 kg/m^3 for commercial, 97.8 kg/m^3 for industrial, and 88.3 kg/m^3 for residential areas). Although the commercial and industrial areas produced higher annual loadings per unit area, the residential areas contribute more total litter than all other areas combined because residential development occupied the largest area. Armitage and Rooseboom (2000) developed an empirical equation to determine annual volume of litter for South Africa:

$$T = \Sigma f_{sci} (V_i + B_i) A_i \qquad (1)$$

Where:
- T = total litter load in the waterways (m^3/yr)
- f_{sci} = street cleaning factor for each land use (varies from 1 for regular street cleaning to about 6 for no street cleaning services)
- V_i = vegetation load for each land use (varies from 0.0 m^3/ha-yr for poorly vegetated areas to about 0.5 m^3/ha-yr for densely vegetated areas)
- B_i = basic litter load for each land use (1.2 m^3/ha-yr for commercial; 0.8 m^3/ha- yr for industrial; and 0.01 m^3/ha-yr for residential)
- A_i = area of each land use (ha)

For each storm (>1 mm of rainfall) the litter volume can be estimated by using the following equation (Armitage and Rooseboom, 2000):

$$S = f_s\, T \,/\, \Sigma f_{si} \quad \text{......(2)}$$

Where: S = storm load in the waterways (m^3/storm)

f_s = storm factor (varies from 1.0 for storms occurring less that a week after a previous >1mm storm; to about 1.5 for a storm occurring after a dry period of about three weeks; to about 4.0 for a storm occurring after a dry period of more that about three months)

T = total litter load in the waterways (m^3/yr)

Σf_{si} = the sum of all the storm factors for all of the storms in the year (since this information is generally not available, a suggested alternative is to count the average number of significant storms in a year and multiply by 1.1)

Roadway Sanding for Snow/Ice Events

Roadway sand application is a common practice during the winter snow season for increasing track friction between highway surfaces and automobile wheels. Sanding is important to public safety because it provides safe conditions during treacherous winter weather. However, after snow-melt, sand becomes part of highway nonpoint source pollutants. Guo (1999) developed a method to determine the sand recovery during winter highway sanding. The sand recovery rate is defined by the ratio of the annual sand amount collected by the highway drainage system to the annual sand amount applied to the highway. The method is being adopted for estimating the amount of sand that escapes into the environment.

During winter, the total amount sand application can be estimated as:

$$W_s = w_s\, B_t\, L \quad \text{......(3)}$$

Where: W_s = sand amount in kg or lb
w_s = annual unit sand amount in kg/m^2 or lb/ft^2
B_t = width of traffic lanes in m or ft
L = distance of highway between two adjacent culverts in m or ft

A typical highway drainage hydraulic routing system for the snow removal process includes: (1) piling snow on both sides along the highway shoulders for snow storage; (2) roadway drainage gutter; (3) highway runoff collection system for releasing runoff that contains various types of pollutant with different concentrations to receiving streams. During a snow plowing operation, sand is applied only to traffic lanes. Snow mixed with sand are removed from the traffic lanes to a storage area which is located along the highway shoulders for compacting and piling. The captured snow volume can be estimated as

$$V_c = H_m\, B_s\, L \quad \text{......(4)}$$

Where: V_c = captured snow volume in m^3 or ft^3
H_m = maximum height of snow pile in m or ft
B_s = width of storage area in m or ft
L = distance of highway between two adjacent culverts in m or ft

Snow removed from the highway is placed in the storage area along highway with a maximum height of 7.5 ft. The compacted snow volume between two adjacent culverts can be estimated as

$$V_s = n\, m\, P_s\, B\, L \quad \text{......(5)}$$

Where: V_s = compacted snow volume in m^3 or ft^3
P_s = equivalent water depth to annual fresh snowfall depth
n = snow compact ratio, defined as 1 ft fresh snowfall equivalent to n ft compacted snow
m = snow-to-water depth ratio, defined as m ft fresh snowfall to produce 1 ft of water
B = total width of the paved highway area including traffic lanes, shoulder areas, and snow storage areas in m or ft
L = distance of highway between two adjacent culverts in m or ft

The snow volume capture rate (r) from the highway/paved surface by the storage area is defined by Guo (1999) as

$$r = V_c / V_s \qquad (6)$$

Since snow and sand will be well mixed during the plowing process, the amount of sand captured during this process and stored in the snow storage area is

$$W_c = r\, W_s \qquad (7)$$

Where:
W_c = sand amount in weight captured by the snow storage area
W_s = sand amount in weight applied
r = snow capture rate by storage area, which is the ratio of captured snow volume to the compacted snow volume in the storage area.

After snow melt, the recovery amount of the sand remaining in the storage area that needs to be recovered by street sweeping equipment is estimated as follows:

$$W_m = R_m\,(W_c - W_b) \qquad (8)$$

Where:
W_m = sand amount in weight collected by machine
W_b = sand amount in weight transport by runoff
R_m = efficiency of sand collection by machine, such as 0.80 to 0.90, depending on field operations

The sand amount transported (W_b) through the highway drainage ditch can be estimated by the event mean concentration method (Urbonas et al., 1996; Mosier, 1996):

$$W_b = \gamma_s\, E_w\, V_o \qquad (9)$$

Where: γ_s = specific weight of sand
E_w = empirical value of event mean concentration
V_o = total annual runoff volume

The sand recovery (W_t) between two adjacent culverts is:

$$W_t = W_m + e\, W_b \qquad (10)$$

In which: $e = 1$ for sand collection with a sand basin at the end of drainage system, or $e = 0$ for direct release through a culvert to the receiving stream. Therefore, one may estimate that the annual sand emitted to the environment would be $W_s - W_t$. In a case study, Guo (1999) reported that about 30% of solids were transported by storm runoff and collected by stormwater storage basins. Thus, without stormwater detention basins, this amount of solids would be discharged to receiving streams.

Street Dust and Dirt Accumulation

Sartor and Boyd (1972) reported that the build-up of dust and dirt between street cleanings was non-linear and of an inverse exponential form over a period of up to 10 days. Huber and Dickinson (1988) used three types of equations in the U.S. EPA's Stormwater Management Model (SWMM) for estimating the loading of dust and dirt accumulation:

Power-Linear Equation: $DD = DDFACT\,(T^{DDPOW})$ ……………………………..……………..…….(11)
$DD \leq DDLIM$

Exponential: $DD = DDLIM\,(1 - e^{-DDPOW \cdot T})$ ……………..…………………………….(12)

Michaelis-Menton: $DD = (DDLIM)(T) / (DDFACT + T)$ …………………………………...…(13)

Where:

DD = amount of dust and dirt accumulation, g
T = time, d

Units for *DDFACT* (a coefficient), *DDPOW* (an exponent), and *DDLIM* (the build up limit) are shown in Table 5.

Table 5. Dimensional units for dust and dirt accumulation equations coefficient

Equation	*DDFACT*	*DDPOW*	*DDLIM*
Power-Linear Equation	$g \bullet day^{(-DDPOW)}$	Dimensionless	g
Exponential	Not Used	day^{-1}	g
Michaelis-Menton	day	Not Used	g

Delleur (2001) indicates street dust and dirt loading are the result of deposition and removal rates plus permanent storage that is not removed by street cleaning equipment, as summarized in Table 6.

Table 6. Average values and range of street dust and dirt accumulation load

Type of Street	Initial Loading (g/curb-m)	Daily Deposition Rate (g/curb-m/d)	Maximum Observed Loading (g/curb-m)	Days To Observed Maximum Loading
Smooth/Intermediate Textures				
Average	150	9	>270	>25
Range	35 – 710	1 – 40	85 – 910	5 – 70
Rough/Very Rough Textures				
Average	370	15	>750	>30
Range	190 – 630	6 – 34	370 – (>1400)	10 – (>50)

Street Dust and Dirt Washoff

Based on field study by Sartor and Boyd (1972), the washoff can be expressed by the following first-order decay equation:

$N = N_0\,(1 - e^{-KR})$ ……………………………….…………….(14)

Where:

N = amount of street dust and dirt washoff, g/curb-m
N_0 = amount of initial street dust and dirt, g/curb-m
K = washoff coefficient (ranged 0.167 – 1.007 depending on rain intensity, street dirt loading category, and street texture category)
R = total rain depth, mm

Washoff is more efficient for the higher rain energy and smoother pavement (Delleur, 2001).

Soil Erosion

Soil erosion from an open land is considered by many to be a problem to receiving-water quality. The amount of soil loss can be computed by the Revised Universal Soil Loss Equation (RUSLE). The RUSLE computes sheet and rill erosion from rainfall and the associated runoff for a landscape profile. The equation is written as (Renard et al., 1996):

$$A = R \times K \times LS \times C \times P \qquad (15)$$

Where:
- A = annual soil loss from sheet and rill erosion, tons/acre
- R = rainfall and runoff factor; ranged 80–94
- K = soil erodibility factor; depended on soil type and organic matter, for 2–4% of organic matter, ranged 0.4–0.25
- LS = slope length and steepness or slope length-gradient factor
- C = cover and management factor; legume, C = 0.005; ryegrass, C = 0.1
- P = support practice factor; 0.3–1.0

The slope length-gradient factor (LS) can be determined by Equation 16 below:

$$LS = [0.065 + 0.0456\,(slope) + 0.006541\,(slope)^2]\,[(slope\ length)/72.5]^{NN} \qquad (16)$$

Where:
- $Slope$ = slope steepness, %
- $Slope\ length$ = length of slope, ft
- NN = slope steepness factor, ranged 0.2–0.5

Individual factor values can be entered directly into the formula or calculated from information provided by the user. The equations given are empirical and can be used for planning purposes. Actual measurement of pollutants is always the best way to understand and predict pollutant loads specific to any watershed, but it is often expensive and time consuming. These equations may be used to estimate the total maximum daily loads for watershed management plans, but for final design, field-monitoring data should be obtained.

Hypothetical-Case Example

A hypothetical urban watershed is presented to illustrate the application of pollutant loading estimation methods as described in this chapter. The total drainage area in this example is approximately 1,200 ha which consists of a mixture of land uses. The areal distribution of each land-use category is shown in Table 7.

Table 7. Land use areal distributions for hypothetical-case example

Land Use	Area (ha)
Low density residential areas	300
High density residential areas	100
School	20
Commercial areas	200
Light industrial areas	100
Parks	280
Streets, total length = 6 km	120
Minor arteries, total length = 2 km	50
Major arteries, total length = 1 km	30
Total	1,200

Area Characteristics

Land use parcel characteristics are addressed in terms of land area with roadway right-of-way (RW) characteristics in terms of width and length. The RWs are measured as assigned widths based upon the following criteria. Streets within a development have an average RW of 20 m, a minor artery has a 25m RW, and a major artery a 30m RW. The profiles for each RW in this case study are shown in Table 8.

Table 8. Roadway right-of-way characteristics for hypothetical-case example

Length (km)	RW (m)	Curb* (m)	Parking* (m)	Landscaped Strip* (m)	Sidewalk* (m)	Traffic Lanes (m)
6	20	2	4	3	3	8
2	25	2	4	3	3	13
1	30	2	4	6	3	15

* Parameters are summed from both sides of the street.

An aggregated analysis was used for the low density (single family houses) and high density residential areas, commercial, school, and light industrial land uses because they exhibited multi-parcel characteristics, such as parking. The lot and aggregated characteristics for residential parcels, commercial, schools, and light industries are presented in Tables 9 and 10, respectively.

Table 9. Lot characteristics for residential, commercial, schools, and industries in hypothetical-case example

Land use	No. of parcels	Each Parcel Area (m^2)	Roof Area (m^2)	Driveway/ Parking (m^2)	Landscaped Area (m^2)
Single family houses	1,200	2,500	500	300	1,700
Apartment buildings	50	20,000	6,000	9,000	5,000
Commercial buildings	20	100,000	45,000	35,000	20,000
Schools*	2	100,000	17,000	23,000	60,000
Light industries	5	200,000	100,000	80,000	20,000

* Areas include athletic fields

Table 10. Aggregate characteristics for each land use for hypothetical-case example

Land Use	Total Area (ha)	Roof Area (ha)	Parking/ Roadway (ha)	Landscaped Area (ha)
Low density residential areas	300.0	24.0	36.0	240.0
High density residential areas	100.0	30.0	45.0	25.0
School	20.0	3.4	4.6	12.0
Commercial areas	200.0	90.0	70.0	40.0
Light industrial areas	100.0	50.0	40.0	10.0
Parks	280.0	2.6	27.4	250.0
Streets, total length = 6 km	120.0	0	84.0	36.0
Minor arteries, total length = 2 km	50.0	0	38.0	12.0
Major arteries, total length = 1 km	30.0	0	21.0	9.0
Total	1,200.0	200.0	366.0	634.0

Litter/Floatable Solids

The empirical equation (Eq. 1) developed by Armitage and Rooseboom (2000) was used to determine annual litter volume (T) in m^3/yr. The estimated litter/floatable solids volume and loading are summarized in Tables 11 and 12, respectively.

Table 11. Calculations of litter/floatable solids volume for hypothetical-case example

Land Use	A_i (ha)	B_i (m^3/ha-yr)	V_i (m^3/ha-yr)	f_{sci}	Litter Volume Eq. (1) (m^3/yr)
Low density residential	300.0	0.01	0.02	1	9
High density residential	100.0	0.02	0.02	1	4
School	20.0	0.02	0.03	1	1
Commercial areas	200.0	1.20	0.03	1	246
Light industrial areas	100.0	0.80	0.03	1	83
Parks	280.0	0.50	0.01	1	143
Total					**486**

Table 12. Summary of litter/floatable solids loading for hypothetical-case example

Land Use	Litter Volume (m^3/yr)	Bulk Density (kg/m^3)	Litter Loading (kg/yr)
Low density residential	9	88.3	795
High density residential	4	88.3	353
School	1	88.3	88
Commercial areas	246	96.4	23,714
Light industrial areas	83	97.8	8,117
Parks	143	88.3	12,627
Total	**486**		**45,694**

The estimated total annual litter and floatable solids loading is about 45,700 kg.

Road Sand

Sand loading estimates, due to winter sand application, were calculated using the method developed by Guo (1999), and the results are summarized in Table 13.

Table 13. Amount of sand discharged to receiving water for hypothetical-case example

Type of roadway	Length (km)	Lane Width (m)	Road Surface Area (m^2)	Sand (1) Application Rate (kg/m^2/yr)	Sand Applied Eq. (3) (kg/yr)	Sand (2) Recovered Eq. (8) (kg/yr)	Sand (3) Transported Eq. (9) (kg/yr)
Street	6	8	48,000	2	96,000	67,200	28,800
Minor artery	2	13	26,000	5	130,000	91,000	39,000
Major artery	1	15	15,000	10	150,000	105,000	45,000
Total							**112,800**

Notes: (1) Local Dept. of Public Works road services inventory records, assumed average values.
(2) Amount of sand recovered by street cleaning operation.
(3) Amount of sand removed by storm runoff and discharged to receiving water.

The amount of road sand discharged into receiving water is estimated to be 112,800 kg/yr.

Street Dust and Dirt

Street Dust and Dirt Accumulation

The Michaelis-Menton equation (Eq.13) was used for estimating the street dust and dirt accumulation between storm events. Results are presented in Table 14.

Table 14. Street dust and dirt accumulation rates and loading for hypothetical case study

Type of roadway	Length (km)	Total Curb Length (curb-m)	Maximum Build Up Limit(1) (g/curb-m)	Estimated Dust and Dirt Accumulation(2) (kg)
Street	6	12,000	250	2,760
Minor arterial	2	4,000	180	660
Major arterial	1	2,000	150	280
Total	9	18,000		3,700

Notes: (1) Selected from published *DDLIM* values, Delleur (2001)
(2) Between storm events loading calculated from Eq. (13): $DDFAC$ = 0.9d and T = 10 d

Street Dust and Dirt Washoff

Street dust and dirt washoff loadings were estimated based on the first-order decay equation (Eq.14) and results are presented in Table 15.

Table 15. Street dust and dirt washoff loadings for hypothetical case study

Type of roadway	Total Curb Length (curb-m)	Estimated Dust and Dirt Accumulation (N_0) Between Storm Events (kg)	Washoff Coefficient (K)	Solids Washoff Loadings to Sewer(1) (kg)
Street	12,000	2,760	0.5	2,530
Minor arterial	4,000	660	0.75	645
Major arterial	2,000	280	1.0	278
Total	18,000			**3,453**

Notes: (1) Loadings per storm calculated from Eq. (14): average rain depth = 5 mm

Each storm carries 3,453 kg solids to the drainage sewer systems. Total solid washoff loadings generated by 20 rainfall (>5 mm) events over a year will be 69,000 kg.

Soil Erosion

The majority of soil erosions are from park open space and landscaped areas. There are no construction activities in the example, otherwise much higher soil erosion would be generated. The calculations of amount of soil loss were based on Equation 15 and results are summarized in Table 16.

Table 16. Soil erosion load for hypothetical-case example

Land use	Landscaped Area		Soil Erosion	
	(ha)	(acre)	ton/yr	kg/yr
Residential, school, commercial, and industrial areas	384	950	25	22,600
Parks	250	620	23	22,300
Total				**44,900**

The total soil erosion from this urban watershed is estimated about 44,900 kg/yr.

Summary of Solids Loading

A summary of total annual solids loadings of each category is indicated in Table 17.

Table 17. Summary of total annual solids loadings for hypothetical-case example

Solid Category	Annual Loadings (kg)
Litter/floatable solids	45,700
Highway/street sands	112,800
Street dust and dirt	69,000
Soil erosion	44,900
Total	**272,400**

A total annual solids loading discharged from the watershed land surface is estimated about 272,400 kg or 272.4 tonnes. However, a highly significant portion of pollution, that in the dissolved solids form is not presented in the estimated values. Solids falling directly onto the surface of a waterway, such as a large lake, during rainfall is not accounted for. Sewer sediment contains very high concentrations of organic (oxygen demanding) pollutants and a significant amount of suspended solids compared to the other categories that are addressed in the Chapter 4.

Chapter 4
Sewer Sediment Solids

Introduction

Deposition of sewage solids during dry weather in combined sewer systems has long been recognized as a major contributor to "first-flush' phenomena occurring during wet-weather runoff periods. Estimation of these loadings for a given sewer system is an extremely difficult task. Measurement for extended periods is possible but extremely expensive. Techniques presently available to estimate dry weather deposition in sewerage systems involve the use of computer models that are both complex and expensive and requiring more effort than appropriate for preliminary "first-cut" assessments (Sonnen, 1977; Ashley et al., 1999; Bachoc, 1992).

The U.S. Environmental Protection Agency developed a set of generalized procedures for estimating pollutant loadings associated with dry weather sewage solids deposition in combined sewer systems. It utilizes data and information from three sewerage systems in eastern Massachusetts (Pisano and Queiroz, 1977) and one in the City of Cleveland, Ohio (Pisano and Queiroz, 1984). A complete exposition of the analysis procedure, assumptions and methodologies has been previously given in two aforementioned referenced documents, and will not be presented here.

The predictive equations developed in the previous study relate the total daily rates of pollutant deposition within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter and other parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models were presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include suspended solids (SS), volatile suspended solids (VSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), organic nitrogen by the Kjeldahl method (TKN) and total phosphate (TP). Sewer system age and degree of maintenance were also considered. Factors were presented for estimating the increase in collection system deposition resulting from improper maintenance. The empirical least squares approach was used to formulate the final equations that are presented along with summarized results from the previous study.

Overview of Approach

An empirical model relating pollutant deposition loading to collection system characteristics is described in this Chapter. The approach is to use least squares to fit parameters of a postulated model. The model form is a single-term power function relating total daily sewage solids deposition over a collection system to simple sewer catchment characteristics, including service area, length of pipe and average pipe slope. The major steps in the analysis are depicted in Figure 1. Sewer system data including manhole-to-manhole length, slope, size, shape and age are assembled for entire collection systems in Step A. This information is used in Step B to compare total daily sewage solids deposited in these collection systems for a wide variety of different operating conditions. These quantities are estimated using an existing exogenous model that uses extremely detailed information to compute deposition loadings throughout an entire collection system network.

The simulated deposition loadings for different input conditions constitute the dependent variable data in the regression analysis. The independent variable data is prepared in Step C as a result of the analysis of assembled data from Step A and detailed outputs from Step B. The dependent variable data was generated from an exogenous predictive analysis, while the independent variable data was obtained from primary collection system data and from a secondary analysis of the exogenous simulation outputs with selected collection system data.

The regression analysis is performed in Step D to prepare the simplified predictive relationships. The entire process is designed to eliminate using the complicated network model requiring thousands of individual bits of technical information.

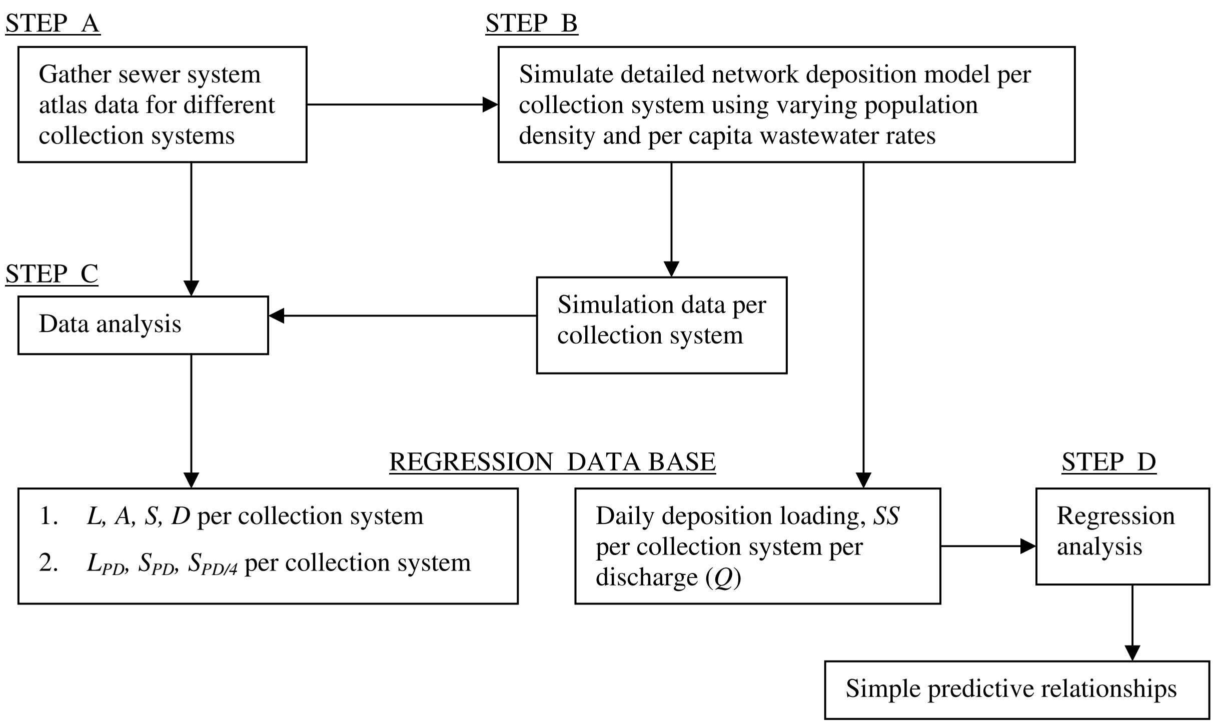

Figure 1. Overview of Method of Approach

Independent and Dependent Variables
The list of variables considered in the regression analysis is the following:

1. Total collection system pipe length (L) -- ft or m
2. Service area of collection system (A) -- acre or ha
3. Average collection system pipe slope (S) -- ft/ft or m/m
4. Average collection system pipe diameter (D) -- in. or mm
5. Length of pipe corresponding to 80% of the solids deposited in the system (L_{PD}) – ft or m
6. Slope corresponding to L_{PD} (S_{PD}) -- ft/ft or m/m

7. Slope corresponding to 1/4 of the percentage of pipe length (L_{PD}) below which 80% of the solids deposit ($S_{PD/4}$) -- ft/ft or m/m
8. Flow rate per capita, including allowance for infiltration (Q) -- gpcd or Lpcd
9. Daily total sewage solids deposition loading in collection system (TS) -- lb/d or kg/d (dependent variable predicted from deposition model)

It was determined in the prior study that the mean pipe slope alone would not be adequate to explain the effects of the pipe slopes on the variations of the deposition loads. A better characterization of the sewer slopes could be obtained by defining various parameters at the flatter sewer slope range. Two other pipe slope parameters besides the mean pipe slope were selected for inclusion into the regression model.

The collection system slope parameters S_{PD} and $S_{PD/4}$ were arbitrarily defined with the sole aim of better defining the range of the pipe slope distribution function. These collection system slope parameters were defined after reviewing several plots of the cumulative distribution of pipe slopes for several collection systems. Other choices could have also been made.

Estimates of collection system pipe length, service area, average pipe slope and average diameter were prepared from direct inventory and analysis of sewer system atlas information. Estimates of L_{PD}, S_{PD} and $S_{PD/4}$ were prepared from a detailed analysis of simulated data generated from a complex sewer system network deposition model. The total daily deposition load, *TS*, is also computed using this model. Finally, it is clear that the deposition process is also strongly affected by the wastewater flows in the system. Variations in population density and the degree of infiltration affects the dry weather flow rates. These effects were incorporated into the per capita wastewater rates (Q) used in the deposition model simulations and in the regression analysis.

Models

Both linear additive and multiplicative models were investigated. Untransformed observed values of the dependent and independent variables are initially used, leading to a strictly linear regression equation. In another case the observed values of both the dependent and independent variables were transformed by taking their natural logarithms, leading to a linear equation in the logarithmic domain which can be put into a non-linear multiplicative form.

Regression Method

The linear regression program used to empirically establish the relationships of the total daily suspended solids (*TS*) deposition within a sewerage collection system with the independent variables is one that operates in a step-forward manner. At each step in the analysis, the particular variable entered into the regression equation accounts for the greatest amount of variance between it and the dependent variable, i.e., the variable with the highest partial correlation with the dependent variable. The program is flexible to allow any independent variable to be: (1) left free to enter the regression equation by a criterion of the sum of squares reduction; (2) forced into the regression equation; or (3) kept definitely out of the regression equation in one given selection. The procedure permits examination of several alternative considerations of the independent variables. It is done by optional selections of variables to be forced in and out of the regression equation, or to be simply left free to enter the equation using variance reduction criteria.

Observation of the relative change in the standard error of estimate was used as the stopping rule in the regression analysis. An increase of the standard error at a given step indicates that the additional information realized by introducing the variable is off-set by the loss in degrees of freedom. This implies that the particular variable can be eliminated in the regression equation.

The Students T statistics computed for each of the regression coefficients of the final relationships all exceeded 4.0, and averaged about 9.5 using the aforementioned stopping rule. A value of 1.96 is considered statistically significant at 95 percent confidence limits for large sample size (greater than 100 observations).

Sewer Sediment Solids Loading Models

Introduction

Regression results reported in earlier work (Pisano and Queiroz, 1977 and 1984) are summarized in this section. Various predictive models are described, relating total suspended solids deposition within a collection system with independent variables under the assumption of clean pipe conditions. These relationships are therefore applicable for situations in which the sewer piping system is properly maintained. These equations were developed from data assembled from three major sewerage systems in Eastern Massachusetts and one in Cleveland, Ohio.

General Description

The physical characteristics of the three major collection systems used in this analysis derived from three prior studies. The first area, covering portions of West Roxbury In Boston, Dedham, Newton arid Brookline is strictly separated. The second area covering major portions of Dorchester and South Boston, two neighborhoods of the Boston metropolitan area, is a mixed, combined and separate area, while the third basin covering a portion of the City of Fitchburg is served by a combined sewer system. The total pipe footage for all three areas entails 196 mi of separate and combined sewer systems encompassing a total area of 8.9 mi^2.

The Easterly District in the City of Cleveland is bordered on the west by the Westerly District extending along the Cuyahoga River; on the south by the Southerly District, generally extending along Woodland, Holton, Parkhill and Abell Avenues; on the east by the communities of Euclid, Cleveland Heights, South Euclid, East Cleveland, and Shaker Heights; and on the north by Lake Erie. The Easterly District of the City totals approximately 16,000 acres and includes the downtown area, with an additional 25,000 acres tributary from the surrounding areas. The existing sewerage system within the Easterly District is almost entirely combined. Tributary areas outside of the city use sewers and drains for conveyance of drainage to downstream water courses. The available topographic data showed that most of the Easterly District is relatively flat with a ground slope under 2.0% averaging at about 0.5%.

Alternative Model Selections

In this section several regression models are recommended for user application. Alternative forms reflecting the availability of data and/or user resources will be presented. The simple forms require little data and have the least predictive reliability, whereas the more complicated models, requiring greater user resources and data availability, provide estimates with higher reliability.

Equations calibrated with field data collected from Boston and Fitchburg, MA and Cleveland, OH (Pisano and Queiroz, 1984) are:

Boston and Fitchburg, MA:

Simplest Model:

$[R^2 = 0.85]$: $$TS = 0.0011\,(L^{1.1})(S^{-0.44})(Q^{-0.51}) \qquad (17)$$

Intermediate Model:

$[R^2 = 0.85]$: $$TS = 0.0013\,(L^{1.2})(D^{0.61})(A^{-0.18})(S^{-0.42})(Q^{-0.51}) \qquad (18)$$

Elaborate Model:

$[R^2 = 0.95]$: $$TS = 0.00073\,(L^{0.81})(S_{PD}^{-0.82})(S_{PD/4}^{-0.11})(Q^{-0.51}) \qquad (19)$$

Cleveland, OH:

Simplest Model:

$[R^2 = 0.88]$: $TS = 0.0012\ (L^{1.1})(S^{-0.43})(Q^{-0.54})$ ……………………………..……..….(20)

Elaborate Model:

$[R^2 = 0.94]$: $TS = 0.00017\ (L^{0.95})(S^{-0.32})(S_{PD}{}^{-0.52})(S_{PD/4}{}^{-0.15})(Q^{-0.52})$ ………………….…..(21)

Where:

- A = service area of collection sewer system, acre
- D = average sewer diameter, in.
- L = total sewer length, ft
- L_{PD} = sewer length corresponding to 80% of the solids deposited in the sewer system, ft
- Q = flowrate per capita, including allowance for infiltration, gpcd
- S = average sewer slope, m/m
- S_{PD} = sewer slope corresponding to L_{PD}, ft/ft
- $S_{PD/4}$ = sewer slope corresponding to ¼ of the percentage of sewer length (L_{PD}) below which 80% of the solids deposit, ft/ft
- TS = daily total wastewater solids deposition loading in collection system, lb/d

As shown above, all R^2 values of these regression models are ≥ 0.85. The differences of R^2 values between Boston and Fitchburg, MA and Cleveland, OH are < 5% for the Simplest Model and < 1% for the Elaborate Model. However, with all of the uncertainties involved in such calculations, R^2 = 0.94 may be as good as R^2 = 0.85. With this in mind, using the Simplest Model for a load calculation could be very useful.

Effects of Age and Maintenance

The above regression equations were derived from deposition data computed under the assumption of clean pipes with no bottom sediments from prior storms. In this section the impact of poorly maintained systems was examined by arbitrarily assuming various levels of prior sediment accumulation in the pipes (Pisano and Queiron, 1977). These sediment levels would change the bottom cross-sectional shape of the pipe channel, the depth of flow, the hydraulic radius, and the shear stress characteristics accordingly.

Two cases simulating different degrees of maintenance other than perfect clean pipe conditions were considered. In the first case, or the intermediate maintenance category, sediment beds ranging from 1 to 3 in. in depth were assumed for all pipes with slopes < 0.0075. A sediment bed of 3 in. was assumed for all pipes with slopes < 0.0005. The bed depths then ranged linearly starting at 3 in. for a pipe slope of 0.0005 up to one in. for a pipe slope of 0.0075. This range was established using judgment and also based on visual inspection of numerous combined sewer laterals in eastern Massachusetts sewerage systems. In the second category of maintenance, the zero maintenance case, sediment beds ranging from 3 to 6 in. for the same range of slopes was considered.

Considering the two age and maintenance criteria mentioned here, the deposition model was used to estimate total deposition loadings for each of the 75 sewer systems for each of the four per capita waste generation rates of 40, 110, 190 and 260 gpcd. Before similar regression computations were performed on the deposition results obtained for pipes with bottom deposits, a comparison was made of the total deposited loads computed under the assumptions of clean and sedimented pipes.

For each basin the ratios of *TS* computed for sedimented pipes with sediment beds of 1 to 3 in. and 3 to 6 in. and the *TS* values for clean pipes were calculated for all four per capita waste rates considered, i.e., 40, 110, 190 and 260 gpcd. The resulting ratios were very stable for a given per capita waste rate for both cases of sediment deposits. The mean and coefficient of variation of these ratios are presented in Table 18 for both conditions of bottom deposits.

Table 18. Average values of the ratios of computed loads in deposited pipes over clean pipes

Ratios	Average Values of Ratios for per Capita Wastewater Rates (gpcd)			
	40	110	190	260
$TS_{1\text{-}3\text{ in. prior sediment}}/TS_{\text{clean pipe}}$	1.263 (0.18)	1.186 (0.14)	1.128 (0.07)	1.094 (0.12)
$TS_{3\text{-}6\text{ in. prior sediment}}/TS_{\text{clean pipe}}$	1.312 (0.14)	1.211 (0.11)	1.151 (0.09)	1.121 (0.09)

Note: The numbers in parenthesis indicate the coefficient of variation of the ratios.

The results shown on Table 18 suggest that the prediction of TS in sedimented pipes could be accomplished by a simple functional multiplicative correction of the results given by any of the regression equations for clean pipes. An equation was fitted using the data of Table18 for each of the bed deposit conditions. These equations are:

For a system with deposits ranging from 1 to 3 in.:

$$TS_{1\text{-}3\text{ in.}} = 1.68\, Q^{-0.076}\, TS_{\text{clean}} \qquad (R^2 = 0.988) \ldots\ldots (22)$$

For a system with deposits ranging from 3 to 6 in.:

$$TS_{3\text{-}6\text{ in.}} = 1.79\, Q^{-0.084}\, TS_{\text{clean}} \qquad (R^2 = 0.999) \ldots\ldots (23)$$

Where: Q = flow per capita, and TS_{clean} = load of total solids computed from any of the above regression equations (Eq. 17 to 21).

The R^2 values indicated above refer to the regression of the ratios of TS on the values of flow per capita. The small difference found between the two conditions of bottom deposits may well be the result of an inappropriate accounting of these factors by the deposition model. On the other hand it may simply have resulted from the particular combination of pipe diameters and sediment depths used as data, which may have led to actually small differences in flow depths above the sediment levels, and therefore small differences in shear stress between the cases.

Organic Pollutant Loading

A regression was performed between TS and each one of the other 6 indicators, including BOD_5, COD, TKN, NH_3, P, and VSS (Pisano and Queiron, 1977). The resulting regression equations are presented in Table 19, with their associated correlation coefficients. Estimates of the total daily BOD_5, COD, TKN, NH_3, P and VSS depositing loads within a given collection system can be made using the regression equations in Table 19 with the predicted TS loading calculated from any of the regression equations (Eq. 17 to 22) for clean pipe conditions and the bias correction factors for pipes with sediment beds given in Eq. 23.

Table 19. Regression of different pollutants on *TS*

Regression Equation (lb/d)	Correlation Coefficient
$BOD_5 = 0.344\, TS^{1.308}$	0.80
$COD = 0.875\, TS^{1.04}$	0.77
$TKN = 0.039\, TS^{1.135}$	0.67
$NH_3 = 0.017\, TS - 0.0336$	0.44
$P = 0.0076\, TS - 0.006$	0.67
$VSS = 0.689\, TS^{1.308}$	0.97

Estimate of Sewer Length and Slope

The total sewer length of the combined sewer system, *L*, is generally assumed to be known. In cases where it is not known, crude estimates may suffice and the estimated sewer length, *L'*, can be determined from the service area of the collection sewer system, *A*, using the following expressions (Pisano and Queiron, 1977):

For low population density (10 – 20 people/acre)

$$L' = 169\,(A)^{0.93}; \quad (R^2 = 0.82) \quad \ldots\ldots (24)$$

For moderate-high population density (30 – 60 people/acre)

$$L' = 239\,(A)^{0.93}; \quad (R^2 = 0.82) \quad \ldots\ldots (25)$$

If data on pipe slope is not available, the average sewer slope, *S'*, can be estimated from the average ground slope S_g using the following equation (Pisano and Queiron, 1977):

$$S' = 0.35(S_g)^{0.82}; \quad (R^2 = 0.96) \quad \ldots\ldots (26)$$

Procedure for Estimating *TS* Deposited

As indicated in Eqs. 17 through 21, the R^2 values between Simplest Models and Elaborate Models are 0.85 and 0.95 for Boston and Fitchburg, MA and 0.88 and 0.94 for Cleveland, OH, respectively. They are < 5% for the Simplest Model and < 1% for the Elaborate Model. With all of the uncertainties involved in such calculations, R^2 = 0.94 may be as good as R^2 = 0.85. With this in mind, using the Simplest Model for a load calculation is illustrated in the following generalized procedure for estimating *TS* deposited as shown in Figure 2.

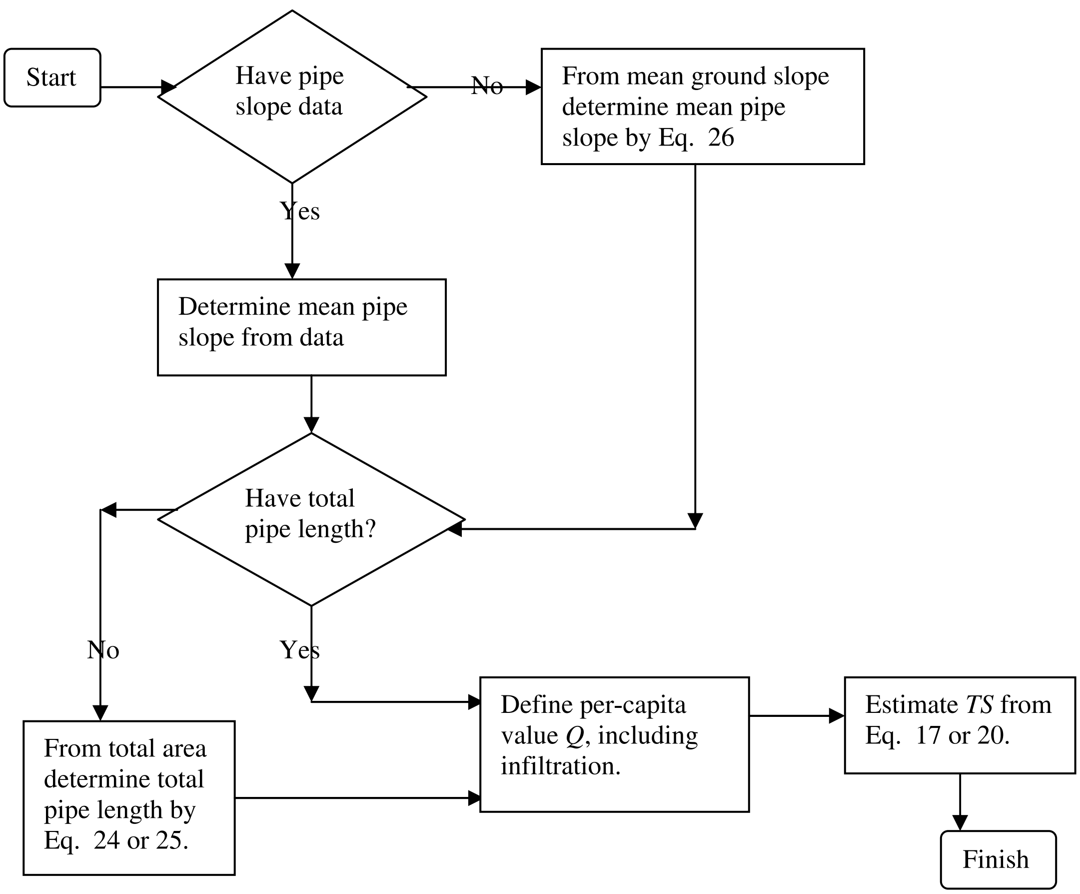

Figure 2. Steps to Determine Deposited Solids (*TS*).

Hypothetical-Case Example

A hypothetical urban watershed is presented to illustrate the application of pollutant loading estimation methods as described in this chapter. The total drainage area in this example is approximately 1,200 ha which consists of a mixture of land uses as described in Table 7 (Chapter 3). The sewer length of each land use category is estimated and summarized in Table 20.

Table 20. Sewered area in each category of land-use

Land Use	Area (ha)
Low density residential areas	300
High density residential areas	100
School	20
Commercial areas	200
Light industrial areas	100

The Simplest Model (Eq. 17) was used for calculating sewer sediment solid loading. Results are summarized in Table 21.

Table 21. Estimated sewer sediment solids loading

Land-use	Population Density (p/ha)	Sewer Length(1) (m)	Sewer Slope(2) (m/m)	Solids Loading(3) (kg/d)
Low density residential	30	24,000	0.01	36.3
High density residential	150	12,000	0.01	17.0
Commercial areas	150	23,000	0.01	34.7
Light industrial areas	150	12,000	0.01	17.0
Total				105.0

(1) Estimates were based on population density and Equations 24 and 25
(2) Estimates were based on ground slope and Equation 26
(3) Estimates were based on Equation 17; flowrate per capita, Q = 200 L/d

The estimated total annual sewer-sediment solids loading is 38,300 kg.

By using the equations listed in Table 19, the organic pollutants associated with *TS* can be estimated. Results are summarized in Table 22.

Table 22. Estimated organic pollutant loading

Regression Equation (lb/d)	Organic Pollutant Loading		
	lb/d	kg/d	kg/yr
$BOD_5 = 0.344\ TS^{1.308}$	152.0	70.0	25,550
$COD = 0.875\ TS^{1.04}$	111.0	50.0	18,250
$TKN = 0.039\ TS^{1.135}$	7.7	3.5	1,280
$NH_3 = 0.017\ TS - 0.0336$	1.8	0.8	300
$P = 0.0076\ TS - 0.006$	0.8	0.4	150
$VSS = 0.689\ TS^{1.308}$	303.0	137.0	50,000

Table 22 results show that the sediment solids contain high level of decomposed human wastes that are the main source of sulfide ($S^{=}$) (Nielsen 1991). The root cause of odor and corrosion in collection systems is $S^{=}$, which is produced from sulfate by bacteria residing in a slime layer on the submerged portion of sewer pipes and structures. Identification of potential problem areas before structure damage requires field investigation of $S^{=}$ concentrations in the sewerage system being addressed in Chapter 5.

Chapter 5
Hydrogen Sulfide in Sewer

Introduction

Sanitary wastewater solids deposited in combined sewers (CS) systems during dry weather is a major contributor to the CSO-pollution load. Furthermore, 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 H_2S by bacteria. The hydrogen sulfide is then converted to sulfuric acid, which disintegrates sewer pipes. Thus, dry weather sewer sediments create odor and sewer decomposition problems in addition to the CSO pollution (Fan et al., 2001).

The production and release of H_2S gas in municipal wastewater collection systems is responsible for numerous odor complaints and the destruction of sewer pipes and other wastewater facilities. 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 H_2S gas after picking up two hydrogen ions from wastewater. Once released to the sewer atmosphere, an aerobic bacteria (Thiobacillus) which resides on sewer walls and surfaces above the water line consume the H_2S gas and secrete sulfuric acid. In severe instances, the pH of the pipe can reach as low as 0.5. This causes severe damage to unprotected collection system surfaces and can eventually result in the total failure of the sewer piping and the uncontrolled release of raw wastewater to the environment.

This chapter describes detailed procedures and methods for conducting field sampling and monitoring procedures to determine transient levels of H_2S generation of agitated beds within the presence of oxygen during simulated storm conditions.

Background

For domestic wastewater the main source of sulfide ($S^=$) is sulfate ($SO_4^=$). Sulfide generation is a bacterially mediated process occurring in the submerged portion of combined and sanitary sewers and force mains. Fresh domestic wastewater entering a collection system is usually free of $S^=$. However, a dissolved form of $S^=$ soon appears as a result of low dissolved oxygen content; high-strength wastewater; low flow velocity and long detention time in the collection system; elevated wastewater temperature; and extensive pumping. The chemistry of sulfur cycle, microbial process in sewer networks, and mechanisms of corrosion are covered elsewhere (Thistlethwayte 1972; U.S. EPA, 1985; Hvitved-Jacobsen 2002). This section briefly discusses the relationship of $SO_4^=$ reduction, biochemical oxidation, and the factors affecting those biotransformations in sewer.

Once released from the wastewater as H_2S gas, odor and corrosion problems begin. Another type of bacteria utilizes H_2S gas to produce H_2SO_4 that causes the destruction of wastewater piping and facilities. Operation and maintenance (O&M) expenditures are required to correct the resulting damage caused by this H_2SO_4. In severe instances, pipe failure, disruption of service and uncontrolled releases of wastewater can occur.

The first step in this bacterially mediated process is the establishment of a slime layer below the water level in a sewer. This slime layer is composed of bacteria and inert solids held together by a biologically secreted protein "glue" or film 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 or Zooglea film 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 a way equivalent to dissolved oxygen is used by aerobic bacteria. Sulfate concentrations are almost never limiting in normal domestic wastewaters. When $SO_4^{=}$ is utilized by these bacteria, $S^{=}$ is the by-product. The rate at which $S^{=}$ is produced by the slime layer depends on a variety of environmental conditions including the concentration of organic food source or biochemical oxygen demand (BOD), dissolved oxygen concentration, temperature, wastewater velocity, and the area of the normally wetted surface of the pipe.

As $SO_4^{=}$ is consumed, the $S^{=}$ 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^-), dissolved H_2S ($H_2S_{(aq)}$), and H_2S gas ($H_2S_{(g)}$). The rate at which H_2S leaves the aqueous phase is governed by Henry's Law and other factors (Hvitved-Jacobsen, 2002).

Factors Affecting Sulfide Concentration

Settleable Solids.
Periods of low flow in the collection system correlate to lower average wastewater velocities. Low-flow velocities allow material, usually grit, to settle in the collection system piping. This increases the mass and surface area of material in the collection system upon which $SO_4^{=}$ reducing bacteria (slime layer) can grow, and can lead to an increased conversion of $SO_4^{=}$ to $S^{=}$. The interaction between a large quantity of bacteria and an almost unlimited food source will create dissolved $S^{=}$ 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 (US EPA 1985).

Temperature.
Higher wastewater temperatures increase the metabolic activity of the SO_4=-reducing organisms, causing faster conversion of $SO_4^{=}$ to $S^{=}$ and increased dissolved $S^{=}$ concentrations. It has been estimated that each incremental 7° C (12.5° F) increase in wastewater temperature doubles the production of $S^{=}$ (Fan et al., 2001).

Flow Turbulence.
Turbulence is a critical parameter in controlling $H_2S_{(g)}$ release from wastewater. The effects of $H_2S_{(g)}$ 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. Any action that serves to increase the surface area of the liquid also increases the driving force from the liquid to the gas phase. Thus, structures causing turbulence should be identified and retrofitted to eliminate hydraulic jump, improve streamlining transmission, and reduce the subsequent $H_2S_{(g)}$ releases. This same release mechanism is exhibited whenever wastewater containing dissolved sulfide is aerated.

Structural Corrosion

Thiobacillus aerobic bacteria, which commonly colonize pipe crowns, walls and other surfaces above the waterline in wastewater pipes and structures, have the ability to consume $H_2S_{(g)}$ and oxidize it to H_2SO_4. This process can only take place where there is an adequate supply of $H_2S_{(g)}$ (> 2.0 ppm_v), high relative humidity, and atmospheric oxygen. These conditions exist in the most of wastewater collection systems for part of the year. A pH of 0.5 (approximately equivalent to a 70 mL/L of H_2SO_4 concentration) has been measured on surfaces exposed to severe $H_2S_{(aq)}$ environments (> 50 ppm_v in air).

The effect of H_2SO_4 on concrete surfaces exposed to the sewer environment can be devastating. Sections of collection interceptors and entire pump stations have collapsed due to loss of structural stability from corrosion. The process of concrete corrosion, however, is a step by step process that can sometimes give misleading impressions. The following briefly describes the general process of concrete corrosion in the presence of a sewer atmosphere:

Freshly poured concrete has a pH of approximately 11 to 12, depending upon the composition of mixed aggregates. This high pH is the result of the formation of calcium hydroxide [$Ca(OH)_2$] as a by-product of the hydration of cement. $Ca(OH)_2$ is a very caustic crystalline compound that can occupy as much as 25% 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 affect of carbon dioxide (CO_2) and $H_2S_{(g)}$. 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 wastewater flow and react with the $Ca(OH)_2$ to reduce the surface pH. 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 CO_2 and $H_2S_{(g)}$ in the sewer atmosphere. It can sometimes take years to lower the pH of concrete from 12 to 9, however, in severe situations it can be accomplished in a few months. Once the pH of the concrete is reduced to about pH 9, biological colonization can occur. More than 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 $H_2S_{(g)}$ to H_2SO_4 in the presence of oxygen. Since the production of H_2SO_4 from H_2S is an aerobic biological process, it can only occur on surfaces exposed to atmospheric oxygen.

The color of corroded concrete surfaces can be various shades of yellow caused by the direct oxidation of H_2S 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 H_2S concentrations are often yellow because of the higher oxygen content. This same phenomena can be observed around the outlets of odor scrubbers using hypochlorite solutions to treat high $H_2S_{(g)}$ concentrations.

Another damaging effect of H_2SO_4 corrosion concrete is the formation of a mineral called "ettringite" calcium sulfbaluminate hydrate ($3CaO \bullet Al_2O \bullet 3CaSO_4 \bullet 32H_2O$) or gypsum ($CaSO_4 \bullet 2H_2O$) produced by the incomplete reaction H_2SO_4 and cement. It forms at the boundary line between the soft $CaSO_4$ layer and the sound, uncorroded concrete surface. Ettringite is damaging because it is an expansive compound that occupies more space than its 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 depends on a series of factors including ettringite formation, it is not uncommon to see concrete loss of 1 in. per yr in high sulfide environments.

Sampling and Monitoring

The control of H_2S in wastewater systems is of vital importance to the wastewater industry. The biological and chemical processes resulting in sulfide production in wastewater are well understood, but there are significant contributing factors about which we know nothing. Settled solids and other debris in sanitary sewers and wastewater collection systems provide a greatly increased surface area upon which anaerobic sulfate reducing bacterial slime can grow, thereby increasing the incremental (per ft) sulfide production potential of sewers.

Objective of Field Investigation

The objective of field investigation is to determine the change in concentration of dissolved H_2S. Subsequent reduction in $H_2S_{(g)}$ can also be measured as a secondary objective. The field monitoring measures the sulfide production in a sewer containing moderate to heavy settled solids and debris, sample and characterize the solids in the sewer. An additional facet of the field investigation will measure in-situ dissolved sulfide concentrations inside the interstitial spaces of a typical debris pile in the sewer. From knowledge of the practical pore space volume and the surface area, the specific sulfide production rate can be determined. The mass of sulfide can be calculated, and H_2S could be prevented by cleaning the upstream sewers.

From an analytical standpoint, the primary objectives of field investigation are to determine the following:

- The mass of sulfide generated in-situ by a known type and quantity of debris
- The reduction of sulfide that can be achieved by removing sewer debris
- The sewer headspace H_2S concentrations of a clean and dirty sewer
- The odor and corrosion reduction achieved by removing sewer debris
- The ventilation dynamics of a sewer being flushed
- The approximate odor potential of flushing a debris laden sewer
- The effect of flushing on the downstream long-term corrosion potential

Hydrogen sulfide and Dissolved Sulfide Sampling and Testing Procedures

Hydrogen sulfide in the gas and dissolved phases are the focus of the field inspections. Hydrogen sulfide gas testing includes measuring H_2S gas concentration at the manholes upstream and downstream from the test area. Measurements can be taken at the manhole access points before, during and after flushing. Dissolved sulfide testing includes measuring dissolved sulfide ion concentration in the wastewater upstream and downstream from the test area and at specific points in between. Samples shall be collected before and after flushing. Additional dissolved sulfide ion measurements can be taken from the debris piles within the sewer, prior to flushing. These measurements are taken in-situ by a project engineer experienced in sulfide sampling and confined space entry (CSE). The following procedures shall be used to measure H_2S gas and dissolved sulfide ion concentration.

Air samples are analyzed for H_2S by three instruments equipped with an extension hose, H_2S gas detection tubes, and a H_2S gas detection and recording station. Liquid samples are analyzed using Gastec tubes for dissolved H_2S. Continuous dissolved H_2S sampling can be accomplished by an American Sigma Streamline model 800 SL (or equivalent) automatic portable liquid samplers.

The Industrial Scientific STX70 or TMX412 gas detector and recording station are used to continuously monitor the H_2S gas concentration in the sewer. The Industrial Scientific STX70 and TMX412 are small portable units enclosed in impact resistant case.

These instruments contain a passive H_2S electrochemical diffusion type sensor. The sensor signal is monitored on a single channel in the range of 0 to 999 ppm at 1 ppm increments. The data is displayed on the LCD digital display and recorded into memory by the data logger according to preconfigured parameters set by the sampling personnel. The unit has sufficient memory to store 3600 data points and can record H_2S gas concentrations at intervals of 1 s to 5 min. Recording data at 5-min interval allows for 12.5 days of continuous data collection.

The STX70 and TMX412 are programmed using a personal computer to record H_2S gas samples at specified time intervals. Typically, data loggers are programmed for 2 minutes, which allows for a total of 5 d. The hydrogen sulfide gas monitoring station is secured tightly with rope so that it hangs inside the manholes without coming into contact with wastewater. The gas detectors should be calibrated according to the manufacturers recommended schedule using manufacturer supplied equipment and NBS traceable calibration gas.

Wastewater Sampling

Sensidyne Model 211L and 211LL Gastec (or equal) tubes can be used to determine dissolved sulfide concentrations in wastewater. Gastec tubes draw wastewater by capillary forces through an indicator compound that reacts with the dissolved sulfide ions and changes from white to light brown color. The range of sulfide measurements on the 211L and 211LL Gastec tubes is 0 to 100 ppm and 0.5 to 20 ppm, respectively. This type of detection tube can be performed within one minute on freshly collected samples. Immediate field-testing is required because the sulfide ion is very unstable; it is easily stripped from solution and is easily oxidized by bacteria and available electron acceptors. The alternative wet chemical methods require that each sample be preserved and transported to a lab for testing. Both of these actions artificially lower the dissolved sulfide concentration. Also, the tubes can be carried into the sewer by the project engineer. Liquid grab samples are collected in 2 in. diameter by 3 in. tall sampling containers lowered to the water surface. The sample is retrieved and immediately tested for dissolved sulfide concentration. For quality assurance (QA), duplicate measurements are needed every 10 samples with at least one duplicate sample per day. The QA objective for 211L is +/- 15% (or 0.5 mg/L). The QA objective for 211LL is +/- 15% (or < 0.25 mg/L). If duplicate samples are not within the QA objective run duplicate samples for the next 3 samples. If duplicate samples continue not to be within the QA objective, suspend sampling and contact the manufacturer.

Pore Space Sampling

Liquid samples from within the matrix of the debris layers in the sewer will be collected using a new sampling apparatus. The apparatus consists of a stainless steel sampling cylinder with an O-ring seat for a Gastec tube and a sample collection nozzle that consists of a cylinder with perforated walls and a stainless steel screen filter inside. The entire apparatus is inserted into the debris layer. The cylinder has perforated walls and a stainless steel screen filter inside. Small debris and water from the void spaces in the debris layer passes through the holes in the cylinder to the interior screen, which removes the debris and allows water to accumulate for analysis. The driving force is the pressure differential between the water surface and the sample nozzle in the debris. The device can also be equipped with a 5 mL syringe to provide additional suction if needed.

Continuous Dissolved Sulfide Sampling

American Sigma Streamline model 800SL automatic portable liquid samplers (or equal) should be used to collect wastewater samples over a 24-hour period at each desired sampling location. The sampler contains 24 - 575 mL plastic bottles that can be programmed to collect one 100 mL sample per hour. The ends of the Gastec 211LL (or 211L) tube can be broken off and then inserted into each bottle when the sampler is set up (blue end up). As each bottle is filled, the sulfide reaction and color change occurs. When the sampler is opened the following day, the dissolved sulfide measurements are read directly off of the scale on the side of the tube. The bottles are cleaned and re-loaded with fresh Gastec tubes and another day of sampling continues. The sampler can be moved to another location or left in the same location for additional data collection.

Collecting three samples and testing for dissolved sulfide will confirm the consistency of the continuous sampling data. The tubes will be read at time zero and read again after 24 hours. Quality assurance and quality control (QA/QC) from previous continuous sampling projects indicate a change of less than 5% over 24 hours. It is understood that wastewater streams are different. If the test concentration varies by more than 0.5 mg/L, then the continuous sampling period will be reduced to a length of time that is within the stated limits.

Chapter 6
Sewer Cleaning

Introduction

As stated, 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 sewers, is the mobilization of loose solids on the urban ground surface and transported into the sewerage system by surface storm runoff. These particulates may settle out in the system and be scoured and resuspended during wet weather 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 underlying reason 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 resuspend 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.

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 reduce 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 driven 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 m (12 in.) in diameter.

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 m (24 in.) in diameter.

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 m^3 (1,000 gal), a high pressure water pump, an auxiliary engine, a powered drum reel holding at least 152 m (500 ft) of 1 in. 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 m (1000 ft) of 1.3 cm (1/2 in.) steel cable and various sized buckets and tools. The cable drum and engine are mounted on a framework that includes a 1 m (36 in.) vertical A-frame high enough to permit lifting the cleaning bucket above ground level. Typically two machines of the 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 cylindrical buckets. 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 et al., 1996). Information on design procedures and methodology for silt traps is scarce.

Sewer Flushing Systems

Flushing of sewers either by manual or by automated means is generally meant to reduce hydraulic restriction problems and infrequently as a pollution prevention approach. Flushing of sewers has been a concern dating back to the Romans. Ogden (1892) describes 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 waveform by either rapidly adding external water or creating a "dam break" effect by quick opening of a restraining gate. 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 goal 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 that will allow later removal of the stored contents, or to the wastewater treatment plant). 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. 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—sulfide odor and corrosion reduction.

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 3, is comprised of a balanced hinged gate with the same shape of the cross section of 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 that 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 et al. (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 m (328 ft) stretch required about 700 flushes to clean an initial deposit of about 100 mm (4 in.). Flushing frequency can be reduced if the upstream head can be increased. For example, the number of flushes with a 0.5 m (1.6 ft) head is 24 times more than that required for a 1.5 m (4.9 ft) head.

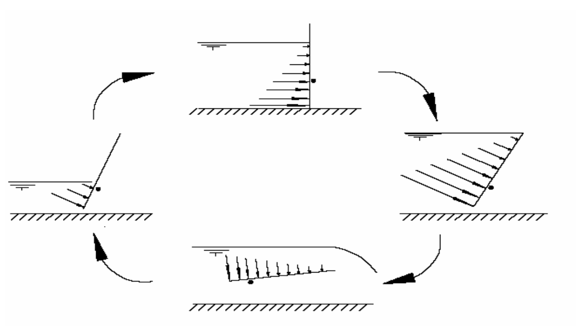

Figure 3. The Sequence of Hydrass® Sewer Flushing Gate Operates

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 m (6 to 7 ft) diameter with lengths 125 to 180 m (400 to 600 ft). Discharge throttles control the outlet discharge to about twice the average dry weather flow plus infiltration. Many different methods for cleaning these pipes were tried over the years. One of the most popular flushing systems has been the Hydroself® system was developed by Steinhardt Wassertechnik, Taunusstein about 11 years ago (Pisano et al., 1997).

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 "dam break" 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. The actual arrangement for a given installation is site dependent. The sewer size, length, and slope determine the flush water volume needed for an effective single flush of the system.

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 km 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% of the projects are designed to flush sewers, interceptors and tunnels ranging from 0.25 m to 4.3 m (0.8 to 14 ft) in diameter and flushing lengths of up to 340 m (1100 ft) for large diameter pipes and up to 1000 m (3300 ft) 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 m^3 (31.6 Mgal) tank beneath a soccer field using 43 flushing gates (Pisano et al., 1997).

For large diameter sewers greater than 2 m (78 in.) 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%) 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

Biogest® 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 pump 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 (Pisano et al., 1997).

U.S. EPA Automatic Vacuum Flushing System

A new design of sediment flushing system was developed by the U.S. EPA (2003). The system includes a flushing-water reservoir that can be installed in either a CSO storage tank or in a combined sewer. The reservoir has an ingress-egress port through which WWF is received from and discharged and an air release valve that closes when the reservoir is substantially full to create a water-retaining vacuum. As the system surge passes and the water level falls, the vacuum seal is broken as air enters the reservoir through an air intake conduit, releasing the water from the reservoir to flush accumulated sediment solids from the storage tank or combined sewer. The reservoir defines a box-like receptacle having a top portion and downwardly-extending sidewalls. The floor of the reservoir is the floor of the storage tank or sewer line flush chamber in which the reservoir is installed. The ingress-egress port is positioned in one of the sidewalls along the bottom edge thereof. The reservoir opens to the sewer line flush chamber or storage tank through the ingress-egress port. The opening height of the port is about 2 to 4 in. higher than the historical height of the sediment-solid layer. The air intake conduit extends from an upper opening in the reservoir to a lower opening along a sidewall, other than the sidewall with the ingress-egress port. The air intake conduit may be in the form of a rectangular duct defined by a partition wall or in the form of an air intake tube connected to the reservoir at the upper opening by a tee joint. The lower opening is sized to be about 30% of the size of the ingress-egress port. The lower opening is about 5 to 8 cm (2 to 3 in.) higher than the top of the ingress-egress port.

In use during a storm, when the CSO storage tank or sewer line flush chamber downstream of the reservoir is filling up with W WF during a storm, the flow enters the reservoir through the ingress-egress port in the reservoir. As the liquid level rises in the reservoir, positive pressure automatically opens the air release valve allowing air to purge from the reservoir. When the reservoir is full, the air release valve automatically closes. During draining of the sewer or storage tank (e.g., after a storm), a vacuum is created in the air space of the reservoir that holds the liquid up in the reservoir. When liquid in the sewer or storage tank is drained to a predetermined level (below the elevation of the air intake conduit opening), air is drawn into the reservoir via the air intake conduit, breaking the vacuum inside the reservoir. Thus, water in the reservoir is quickly released through the ingress-egress port to the downstream storage tank or sewer, resuspending the settled sewer solids and transporting them to a sediment pit for final disposal.

The reservoir may be installed in an upstream end of the storage tank and/or sewer line with the ingress-egress port facing the downstream end of the storage tank or sewer line flush chamber. The ends of the reservoir may be mounted to the floor of the storage tank or sewer line flush chamber. When installed in the WWF storage tank, the volume of the reservoir will be based on the volume of the storage tank. For sewer line applications, the reservoir volume will depend on the size and the total length of the sewer line to be flushed.

Hydraulic Laboratory Testing of U.S. EPA Automatic Vacuum Flushing Device

A laboratory hydraulic flume was used to simulate a reach of sewer or storage tank. The flushing device was fabricated and installed at the head-end of the flume. The removed sediment was collected at the end of the flume and weighed. Water is held up by vacuum and is released upon dissipation of the vacuum in the vacuum-flushing device rather than through closing and opening of a mechanical gate in the gate-flushing device. The test results indicate that sediment removal efficiency of the vacuum-flushing device is close to the gate-flushing device (Guo et al., 2004).

Flushing Small Diameter Sewers

A field research program sponsored by EPA was conducted in the Dorchester area of Boston to determine the pollution reduction potential of flushing combined sewer laterals. It was concluded that small volume flushing of a 300 mm (12 in.) diameter pipe at a slope of 0.0049 would transport organics/nutrients and heavy metals sufficient distances (up to 305 m, 1000 ft) to make the option feasible and attractive (Pisano et al., 1979). The test segments were flushed three times each on five different days and the effectiveness (i.e., incremental removals at each downstream manhole by special sampling) of the flushes was empirically estimated based on the observed results in each field test. Table 23 presents the results of a single 1.4 m^3 (375 gal) manual flush to scour, entrain and transport materials within 30 cm to 46 cm (12 in. to 18 in.) pipes.

Table 23. Percent of pollutant removal by manual flush in small diameter sewers

Pollutant	Flushing Length 76 m (250 ft)	Flushing Length 213 m (700 ft)	Flushing Length 305 m (1000 ft)
Organic/Nutrient Deposits (BOD, TP, TN)	75–90%	65–75%	35–45%
Total Suspended Solids Deposits	75%	55–65%	18–25%

Flushing Small Diameter Sewers using a Dosing Siphon

A self-flushing tank, or "dosing siphon", designed to clean small diameter sewers has recently been developed in Germany as shown in Figure 4 (Pisano et al., 2001). The mechanism is placed in a manhole with an inlet from a water source such as a catch basin, sump pump, or from infiltrating groundwater. When the manhole is filled to a certain elevation, the mechanism creates a siphon and releases 0.76-1.13 m^3 (200-300 gal) of water in the manhole to the sewer. Since it is designed for smaller pipes, it works with low inlet flows, is less expensive to construct, and requires less space. It is designed for sewer diameters of 300 mm (12 in.) or less and can clean up to 183 m (600 ft) of sewer. The dosing siphon type mechanism is a patented device produced by Steinhardt (Pisano et al., 2001).

Figure 4. Dosing Siphon Top View and External Drum

The siphon mechanism resides in a solid stainless steel external drum open at the bottom to allow fluid within the manhole storage area to enter the device. Inside the external drum are guides bolted to the drum and attached to the discharge pipe connected to the sewer being flushed. Within this section is a stainless steel flexible hose having a solid connection to the sewer at the bottom and oversized section (larger diameter cup) at the top. On rising water level the flexible hose rises within the drum due to buoyancy force on the cup at the top of the hose. At a certain level the hose cannot extend any further and is now at maximum elevation. As the water level continues to rise and then spills over the fixed weir causing an unbalanced force on the top-side of the ring. At that point the hose collapses inducing the siphon effect, thus rapidly draining the contents of the manhole out the discharge pipe connected to the sewer. The effective volume of the flush equals the product of the height of the flexible hose and the effective cross section of the manhole.

Tests and Observations of Dosing Siphon

Tests were conducted with the dosing siphon at Cambridge, Massachusetts by the Montgomery Watson Harza project team on June 8, 15, and 21, 2001 (Pisano et al., 2001). Pertinent dimensions of the 25 cm (10 in.) vitrified clay pipe (VCP) segment 82 m (270 ft) test segment, upstream and downstream manholes. The flushing volume for each test was generated by filling the upstream manhole from a nearby fire hydrant. Seven repetitive flushing experiments were conducted on each day. Dye was introduced into the flushing waters to note time of arrival of the flushing wave. Peak velocity was then computed. Sediment characteristics were noted at the end of each flush. Base flow in the 25-cm (10 in.) segment averaged about 5 cm (2 in.). Volume of flush equaled 0.78 m^3 (207 gal) and peak velocities averaged about 1.1 m/s (3.6 ft/s).

Pre-flush and post-flush experiment sediment scrapings within the downstream manhole were performed on June 15 and June 21. All material within a portion of the downstream manhole was removed before the seven experiments were conducted. After all tests were performed the same area of the manhole was again scrapped. The following describes an assessment of the results:

Dosing Siphon Testing and Sediment Scraping Results at Museum Street, June 15, 2001

The second round of dosing siphon flush tests was conducted on June 15. The test program consisted of repeatedly filling with hydrant water end-of-the-line manhole having the dosing siphon directly connected into the test segment. A fill volume of approximately 0.76 m^3 (200 gal) generated a flush wave with a peak velocity noted 82 m (270 ft) at the downstream manhole of 1.1 m/s (3.6 ft/s). The experiment was repeated seven times. Sediment depths and the nature of sediments in the downstream manhole were visually noted after each flush.

Before starting the flush sequence, a sediment scraping was performed in the downstream manhole from a predetermined portion of the manhole base and placed in a container. The area was scrapped to the invert. After the seven experiments were performed, residual sediments in the downstream manhole were again scraped in exactly the same manner and placed in second container. These samples were retained for visual inspection and assessment. The following results are noted below.

- Approximately 300 g were collected in the pre-flush sample and about 900 g collected in the post-flush sample.
- There were 5 stones retained on the # 4 sieve, ranging from 0.64 cm to 1.25 cm (¼ in. to ½ in.) in the pre-flush sample.
- There were 31 stones well retained on the # 4 sieve, ranging from 0.64 cm to 1.9 cm (¼ in. to ¾ in.) in the post-flush sample.

The stones were removed and the remaining portions of each sample were visually inspected to approximate fractions of the residual mass per sieve size with the results presented in Table 24.

Table 24. Approximate fractions of residual mass per sieve size (after rocks removed)

Sieve Size Range	Pre-Flush Sample	Post-Flush Sample
> #10 and < #4	10%	30%
> #50 and < #10	10%	20%
> #200 and < #50	5%	20%
Organic Materials	75%	30%

Large grain sand and small gravel are typically retained by the #10 sieve. Material in excess of 0.64 cm (¼ in.) is retained on the #4 sieve. Medium grain sand is typically noted as #50 sieve, and very fine sand (i.e., "sugar sand" found on most Florida beaches) is typically captured by the #200 sieve.

Subsequent to the above observations, the collected rock was then carefully washed. All stones pre-flush and post-flush were crushed granite and evidently had been inadvertently discharged into the upstream recently upgraded manhole.

Dosing Siphon Testing and Sediment Scraping Results at Museum Street, June 21, 2001

The third round of dosing siphon flush tests was conducted on June 21. Procedural details were the same as the round two experiments. A fill volume of approximately 0.76 m^3 (200 gal) triggered the device sending flush water having a peak velocity noted 82 m (270 ft) downstream of 1.1 m/s (3.6 ft/s). The experiment was repeated seven times. Sediment depths and the nature of sediments in the downstream manhole were visually noted after each flush.

Before starting the flush sequence a sediment scrapping was performed in the downstream manhole from a predetermined portion of the manhole base and placed in a container. The area was scrapped to pipe invert. After the seven experiments were performed residual sediments in the downstream manhole were again scrapped in exactly the same manner and placed in second container. These samples were then visually inspected.

In the morning of June 22, the two samples were placed in two long plastic garden trays and hand spread for visual inspection and assessment. The following results are noted below:

- Approximately 500 g were collected in the pre-flush sample and about 1000 g were collected in the post-flush sample.

- There were 20 stones in excess of #4 sieve, ranging from 0.64 cm to 1.25 cm (¼ in. to ½ in.) in the pre-flush sample.

- There were 38 stones well in excess of #4 sieve, ranging from 0.64 cm to 1.9 cm (¼ in. to 3 in.) in the post-flush sample.

The stones were removed and the remaining portions of each sample were visually inspected to approximate fractions of the residual mass per sieve size with the results presented in Table 25.

Table 25. Approximate fractions of residual mass per sieve size (after rocks removed)

Sieve Size Range	Pre-flush Sample	Post-flush Sample
> #10 and < #4	10%	25%
> #50 and < #10	15%	25%
> #70 and < #50	30%	30%
> #200 and < #50	20%	10%
Organic Materials	25%	10%

The #70 sieve gradation for the large amount of small grain sand was added to the observations. The post-flush sample was far grittier than the pre-flush sample over the entire range. The large oblong rock was a piece of concrete that had been attached in the sediment bed for a long period as it was discolored and corroded.

Conclusions from Testing

Pisano et al. (2001) concluded that the dosing flushing scheme was capable of transporting large inorganic dense aggregate by combination of probably bed load movement and perhaps saltation (rising and falling, i.e., bouncing within the pipe segment). The earlier field research experiments conducted in the 1970s (Pisano et al. 1979) would not have anticipated such a favorable result. It is probable that such favorable transport conditions have resulted from repeated flushing in short period of time precluding “stickiness” conditions. Since the dosing siphon device is meant to be filled either by infiltration or inflow mechanisms, repeated operation in a short time period is a probable design condition.

The other point worth noting is that the residual materials after flushing were more inorganic in nature which is important from “first-flush” and odor and corrosion prevention perspective. The results although preliminary and the measures of performance admittedly crude are encouraging.

Chapter 7
Sewer Sediment Flushing - A Case Study

Introduction

This chapter describes a case study 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 H_2S levels. This case study uses information developed from Fresh Pond Parkway Sewer Separation and Surface Enhancement Project in Cambridge, Massachusetts (Pisano et al., 2001). Grit deposition within both domestic 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 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.

Over the last twenty years, the City of Cambridge has enhanced drainage service for improving the water quality in the Alewife Brook and the Charles River. This area is north and west of Harvard Square and within dense heavily traveled urban regions.

Background Characteristics

Fresh Pond Parkway Sewer Separation Project

Over the last twenty years, the City of Cambridge has separated old combined systems to sanitary and storm 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 a 100 ha (250 acre) catchment North and West of Harvard Square within a highly urbanized and heavily traveled area.

Grit deposition within both existing 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 then streams under as siphons, and the hydraulic level of the receiving water body that frequently backwaters into the storm systems. The existing and recently constructed storm drains on Fresh Pond Parkway and Concord Avenue have invert slopes of approximately 0.0003 to 0.0005. Deposition of any residual stormwater solids not captured by the surface best management practices (BMPs) that discharge into these conduits would be severe. Since no chemical salting during winter conditions can be tolerated in the low, flat Fresh Pond Reservation watershed, heavy winter sanding only exacerbates potential deposition problems. Figure 5 depicts the Wheeler Street storm drain, which is the wet-weather flow outlet from the catchment area. Sediment deposition was observed up to the spring line of the conduit.

Figure 5. Wheeler Street 2.8 m Storm Drain Sewer Half Filled with Sediments

To overcome this problem, automated flushing systems, using quick opening (hydraulically operated) flushing gates to discharge collected stormwater, will flush grit and debris to downstream collector grit pits (either sumps in the flush vault structure or manholes). Grit pits will not be provided on the sanitary systems being flushed. The storm and sanitary sewer systems to be flushed are within the Fresh Pond Parkway near the Cambridge Water Treatment Plant (CWTP), continue East to Concord Circle and then northeast to the Fresh Pond Circle. Both systems then proceed down Wheeler Street. Figure 6 shows the locations of the sanitary sewer and storm drain flushing vaults. The piping systems consist of approximately 1000 m (3280 ft) of sanitary trunk sewers, ranging from 460 mm to 600 mm (18 in. to 24 in.), and approximately 1620 m (5314 ft) of existing storm drains with pipe sizes ranging from 900 mm to 1.2 m by 1.8 m (36 in. to 4 ft by 6 ft.)

Description of Piping Systems to be Flushed

The storm and sanitary sewer systems to be flushed are located within the 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 Massachusetts Bay Transportation Authority - Conrail railroad tracks and terminate near the Alewife Parking Garage. The piping systems consist of approximately 555 m (1820 ft) of sanitary trunk sewers, ranging from 460 mm to 600 mm (18 to 24 in.), and approximately 1620 m (5314 ft) of existing storm drains with pipe sizes ranging from 975 mm (24 in.) to 1.52 m by 1.83 m (5 ft by 6 ft). Figure 6 shows the general locations of the flushing vaults.

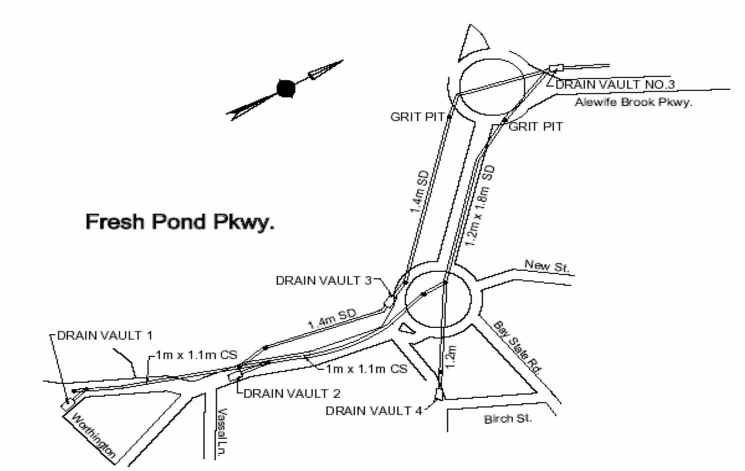

Figure 6. Fresh Pond Parkway – Locations of Flushing Vaults

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 pits downstream was designed for the Fresh Pond Project. The design utilized quick opening flushing gates (hydraulically driven) that release stored water to create a “dam break” flush wave to cleanse and move sediments downstream to a grit pit.

Figure 7 shows a typical storm sewer-flushing chamber with quick opening gate designed for the City of Cambridge. The Fresh Pond Parkway flushing gate chamber is shown in Figure 8. During a rainfall event, stormwater from the incoming storm drain fills the sump adjacent to the flush chamber. Then stormwater is pumped 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 75 to 100 mm (3 to 4 in.) and a velocity range between 0.5 to 0.75 m/s (1.6 to 2.5 ft/s) at the end of the pipe segment being flushed.

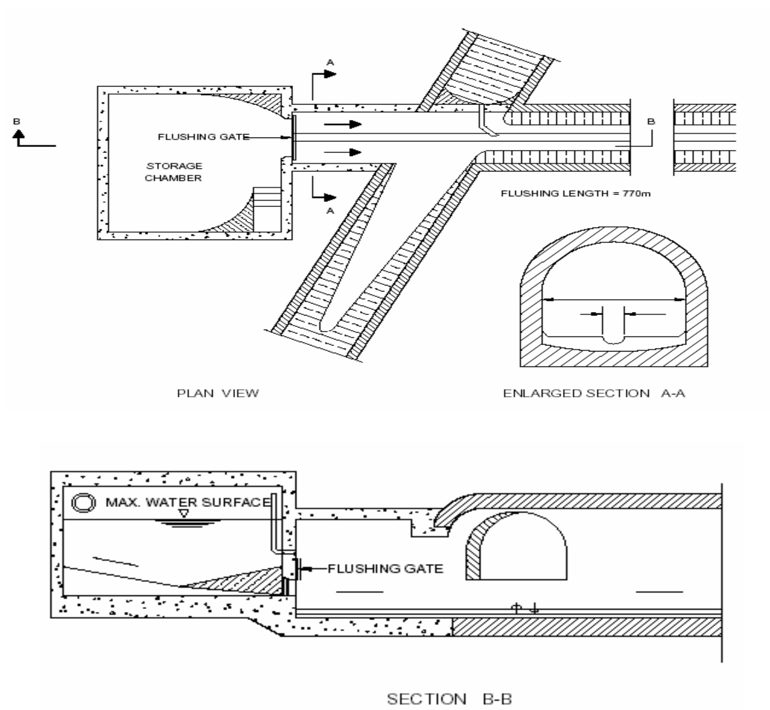

Figure 7. Flushing Storage Configuration with Flushing Gate Installation

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 and used for periodic flushing of the sanitary sewers. 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.

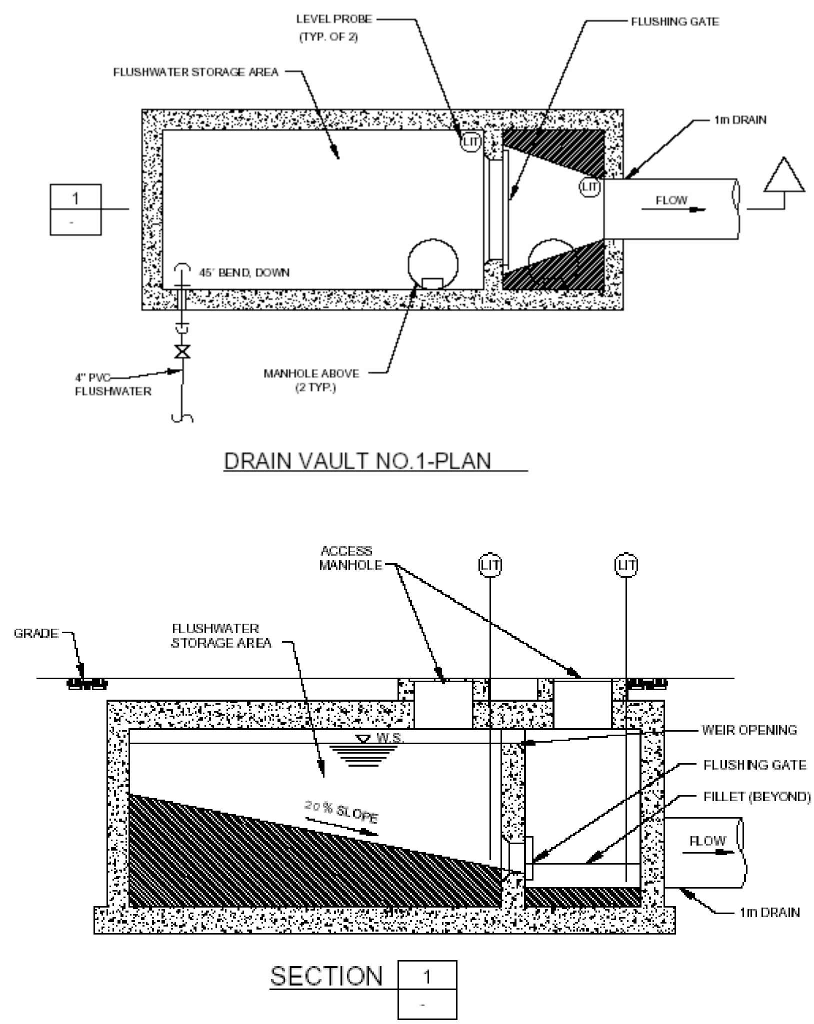

Figure 8. Fresh Pond Parkway – Flushing Gate Chamber

Physical Site Constraints
The design problems in separating the existing combined sewer system, increasing the level of drainage service from 1 yr to 10 yrs, and providing a means to routinely flush the sanitary and storm drainage system were included in the following:

The Fresh Pond Parkway in this area consists of four lanes conveying 30,000 to 50,000 vehicles per day with several rotaries having multiple directional ingress pathways. The Parkway has been historically a utility corridor for 17 other major electric, telephone, communication, gas, and water supply conduits. The inverts of both the sanitary and combined sewers are nearly the same as the sanitary system. Effective sewer separation mandated re-laying new sanitary trunk systems to permit cross connections. Traffic management was horrific as major commercial enterprises had direct access to the Parkway and had to be maintained.

Design Process

At the onset of the design in mid 1997, the flushing volumes for the storm drain vaults noted in Table 26 were developed. The design information regarding pipe size, roughness, shape, slope, and the distance between the proposed flushing vault and the downstream receiving pit (i.e., the flushing length that requires sediment transport), were provided. These volumes were then adjusted upwards where feasible to account for uncertainty, expected high amount of sand used during winter operations on Fresh Pond Parkway, and the extreme space limitations, imposed by other utilities within the Fresh Pond Parkway. It is noteworthy that 17 other utilities share the same four-lane corridor. Flushing volumes for the sanitary sewers were also upsized. Over the course of the final design and during construction, pipe sizes, slopes and alignments were field modified due to the complexity of existing utilities in the streets. At the onset of design, as-built horizontal and vertical alignments of utilities were only partially known. However, the initial flush volumes remained unchanged. The final piping configuration and flushing volumes were reanalyzed by the flushing gate vendor in mid 2001 and were deemed adequate and sufficient.

Table 26. **Flush vault design information summary**

Location	Downstream Flushed Pipe Size (m)	Flushing Pipe Length (m)	Flush Water Volume (m^3)
Drain Vault #1	0.98, 1.37	393	12.1
Drain Vault #2	0.98 ,1.07	216	12.5
Drain Vault #3	1.37	220	12.2
Drain Vault #4	1.22, 1.22 by 1.83	343	13.8
Drain Vault #5	1.85 by 1.52, 1.83	472	44.6
Sanitary Vault #1	0.46	201	9.6
Sanitary Vault #2	0.60	350	7.3

Proprietary flushing volume sizing rules have been developed in Germany based on a combination of physical modeling, mathematical modeling and empirical visual observations of prototype pipe flushing installations using rapid opening flush gate and other conventional more slowly opening valve schemes. The salient feature of the flushing gate technology is the ability of the gate to be instantly unlatched, to fully open, and to create flush wave with initial velocities. Typical gate opening times are 0.1 s with releasing the retained water within 10 s. The initial gate opening is best characterized as a hydraulic “dam break.”

Justifications for providing flushing systems for the new 600 mm sanitary trunk sewer system are provided in Table 27. Average peak dry weather and peak infiltration flow velocities throughout most of the year excluding inflow periods will not approach 1 m/s (3.28 ft/s) as a limit. Peak daily velocity and shear stress conditions for the upstream 450 mm (18 in.) sanitary trunk sewer are less than the estimates provided for the downstream 600 mm (24 in.) sanitary sewer noted in Table 27.

In addition to the low discharge velocities, the domestic waste tributary to the Fresh Pond Parkway and Concord Avenue sanitary system is unusual for two reasons. First, the waste contains high quantities of fats, oils and grease (FOG) discharged into the sewers from the numerous restaurants in the catchment. While a rigorous FOG program is in place, complete control is not possible. Grease buildups have been a significant problem and are expected to continue. Second, the new CWTP disposes (by permit) filtration backwash process waste on a daily basis into the sanitary sewer system. High levels of silt, soils and larger sized inorganic material within a congealed matrix of coagulants and other flocculation aids will be disposed into the sewer system on a daily basis. Since the new sewers are flat in the area, significant deposition problems exacerbated by the combination of FOG and CWTP process wastes are expected.

Table 27. Design flow and velocity evaluation for 600 mm sanitary trunk sewer

Measured Flows (11 months)	Flow (L/s)	Velocity (m/s)	Shear Stress (N/m^2)
Peak Daily Dry Weather Flow	79	0.73	1.8
Average Yearly Dry Weather Flow	37	0.58	1.3
Average Summer Dry Weather Flow	28	0.56	1.1

The design basis for the self-cleansing of the storm drain system assumed that the peak flow velocities for the 3-month storm should exceed 1 m/s (3.28 ft/s). The USEPA Stormwater Management Model (SWMM) was used to simulate system flows for the trunk sewers for the regional 3-month storm having a peak hourly intensity equal to 10 mm/hr (0.4 in./hr) with a total rainfall depth of 50 mm (2 in.). The results indicated that peak velocities for the new storm drain system consisting of existing drains, rehabilitated combined sewers or new drains (box culvert) designed to handle up to a10-year storm having peak intensity of 58 mm/hr (2.28 in./hr) did not exceed 0.5 m/s (1.64 ft/s). Flow velocities for lesser, more frequent storms will be even smaller and more problematic with respect to solids deposition. Automated flushing systems with downstream grit collection were therefore provided.

Hydraulic Modeling Simulation of Flushing Technology

The Stormwater Management Model (SWMM) with Extended Transport Block (EXTRAN) was used to investigate the efficiency of the flushing technology. Simulation output takes the form of water surface elevations and discharge at selected system locations. Computed results are only approximate since EXTRAN does not model the "dam break" phenomenon inherent to the flush gate technology. EXTRAN was developed by the USEPA and is described in total in the User's Manual (Huber and Dickinson, 1988). The SWMM model was used to evaluate pipe-flushing facilities in Germany and for the Fresh Pond Parkway Sewer Separation Project in Cambridge, Massachusetts. The evaluation results for the German facilities have been reported elsewhere (Pisano, et al., 1998) and have been reported here for completeness.

Evaluation of Systems in Cambridge

The basic conveyance element input data required in EXTRAN are specifications for shape, size, length, roughness, connecting junctions and ground (rim) and invert elevations. Pipe lengths were discretized into approximately equal sections. These discretized sections varied from 9 to 60 meters (30 to 200 ft). Pipe sections were assumed to be circular (equivalent diameters calculated) or rectangular. The following parameters were kept constant in pipe simulations:

- Computation time increment = 1 s.
- Manning roughness coefficient = 0.013 for new concrete, 0.015 to 0.016 for worn concrete and 0.011 for plastic
- Gate opening time in 6 to 10 s.
- Flow hydrographs at the flushing gate are assumed to increase linearly from zero to a constant flow in two seconds and also to decrease linearly from the constant rate to zero in two seconds.
- Upstream of the conduit/tank was assumed to be the input and downstream was assumed to be a free overflow.

Table 28 summarizes the hydraulic data and results from the respective flushing gates determined from the hydraulic modeling evaluations of the Cambridge facilities. The listed results are at the downstream end of the pipe or channel flushed.

Table 28. Summary of pipe flushing hydraulic modeling simulations in Cambridge, MA

Location	Flush Volume (m^3)	Flush Length (m)	Pipe Slope	Pipe Size (m)	Flow Velocity (m/s)	Flow Depth (m)
Drain Vault #1	12.1	393	0.0007	0.98, 1.37	0.39	0.06
Drain Vault #2	12.5	216	0.0009	0.98, 1.07	0.60	0.09
Drain Vault #3	12.2	220	0.0008	1.37	0.42	0.06
Drain Vault #4	13.8	343	0.001	1.22, 1.22 by 1.83	0.34	0.05
Drain Vault #5	44.6	472	0.0001	1.85 by 1.52, 1.83	0.29	0.04
Sanitary Vault #1	9.6	201	0.0003	0.46	0.50	0.08
Sanitary Vault #2	7.3	350	0.001	0.60	0.42	0.09

Interpolated EXTRAN results

Interpolated EXTRAN results for intermediate locations are noted in Table 29 through Table 35 for each flush vault. Inspection of the modeling results noted in Table 29 through Table 35 indicates that flushing velocities in excess of 0.7 m/s at the end of the flushing length are not realized. The flushing gate vendor has reviewed these results and has noted that EXTRAN does not explicitly model the "dam break" gate opening and release of flush water within vaults with floor slopes typically at 10% to 20%.

Table 29. Drain vault No.1 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	2.86	470
61	0.78	195
122	0.67	152
183	0.53	110
244	0.44	95
305	0.39	88
366	0.37	85
386	0.42	58

Note: Flush Volume = 12.1 m^3
Reach 1: Diameter = 150 mm; Length = 175 m
Reach 2: Diameter = 213 mm; Length = 210 m

Table 30. Drain vault No.2 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	3.04	628
61	1.04	210
122	0.81	165
183	0.70	122
208	0.60	95

Note: Flush Volume = 12.5 m^3
Reach 1: Diameter = 1067 mm; Length = 17 m
Reach 2: Diameter = 965 mm; Length = 191 m

Table 31. Drain vault No. 3 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	3.00	482
61	0.78	195
122	0.61	137
183	0.48	116
220	0.42	64

Note: Flush Volume = 12.2 m^3
Pipe Diameter = 213 mm; Flush Length = 220 m

Table 32. Drain vault No. 4 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	2.88	488
61	1.52	210
122	1.04	168
183	0.84	67
244	0.37	61
305	0.30	58
343	0.42	21

Note: Flush Volume = 13.8 m^3
Reach 1: Diameter = 1219 mm; Length = 175 m
Reach 2: Diameter = 1219 x 1829 mm rectangular; Length = 168 m

Table 33. Drain vault No. 5 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	3.17	851
61	0.98	366
122	0.55	198
183	0.55	168
244	0.49	140
305	0.37	122
366	0.29	116
427	0.24	107
473	0.34	43

Note: Flush Volume = 44.6 m^3
Reach 1: Diameter = 1524 x 1829 mm rectangular; Length = 76 m
Reach 2: Diameter = 1829 mm ; Length = 396 m

Table 34. Sanitary vault No. 1 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	2.78	805
61	0.73	213
122	0.62	155
183	0.56	107
201	0.51	76

Note: Flush Volume = 9.5 m^3
Pipe Diameter = 457 mm; Flush Length = 201 m

Table 35. Sanitary vault No. 2 EXTRAN results

Distance downstream (m)	Velocity (m/s)	Depth (mm)
0	2.22	457
61	1.18	152
122	0.92	128
183	0.81	113
244	0.76	95
305	0.40	104
352	0.46	58

Note: Flush Volume = 7.2 m^3
Pipe Diameter = 610 mm; Flush Length = 352 m

Alternative Sources of Flush Water

Several possible sources of flush waters and collection systems were considered in the initial design of the flushing systems.

In the initial phase of planning for the new separation system design, several hundred meters of abandoned large diameter (1–2 m or 3.3–6.6 ft) water distribution conduits were investigated for use as flushing volume collectors using inputs from nearby catch basins. These conduits would then discharge to downstream flushing gate structures. These systems were considered feasible, attractive and cost effective given the premium of space and the high cost of constructing vaults in the parkway system. These systems were not pursued as the design of major large diameter storm drains was altered, moving the need for the flushing chambers further downstream and away from the abandoned conduits.

Second, the notion of filling stormwater-flushing chambers from roof drains of the newly constructed Cambridge Water Department treatment facility was investigated in the initial phase. This concept was also abandoned, because the need for flushing chambers in this area was obviated as the major new conduits were moved further downstream.

In the final design, the notion of utilizing pumped stormwater from major drains directly into the storm flushing chambers was selected. The sanitary systems are planned to be flushed daily using pumped spent filtrate waters from the new water treatment plant.

Integration of New Conveyance System/Flushing Vaults and Grit Pit Functionalities

As shown in Figure 6, the new sewerage and drainage system piping at the intersection of Fresh Pond Parkway and Lakeview Avenue. Sanitary Vault #2 and Drain Vault #1 are also depicted in Figure 6. Pumped process (backwash) filtrate flow from the new Cambridge WTP is daily pumped into Sanitary Vault #1. This vault is filled and overflow continues 215 m down to Sanitary Vault #2. This scheme is used in lieu of an external water source to flush the sanitary trunk sewers as the City of Cambridge pays the Massachusetts Water Resources Authority for disposal of filtrate volumes. Both vaults will be flushed at least once daily. Controls at both vaults are programmed to flush in sequence once full.

During a rainfall event, stormwater from the incoming storm drain to Drain Vault #1 fills the sump adjacent to the flush chamber. Then stormwater is pumped from the sump into the flush chamber. A level sensor within the flushing volume chamber relays water level data to the PLC in the control panel which terminates pump operation when the chamber reaches a predetermined fill elevation. A level sensor in the downstream storm drain notes when the water level in down stream drain in sufficiently low to initiate the flushing operation. Activation of the hydraulic power pack then causes the flush gate to unlatch creating the flush wave. Once the system has been activated it is possible to repeat the process during a multi-peaked storm event. A generic 24-hr time clock function adds an additional level of operational flexibility. For example, it is possible to interrogate the system 24 hours after the "fist-flush" to unlatch any partially filled flush volumes. This procedure is the same for all other drain vaults.

An adjustable bottom-acting gate on the side of the entrance to the pump wet well controls the depth of storm flow entry. This feature can be used to ensure that the vault is not filled with base flows and allow bed load sediment to flow into the sump during storm events. The seven receiving grit pits (either as a manhole or integrated within the flush vault chamber) have been sized to provide maximum capture volume given the extraordinary spatial site constraints along the parkway. Average capture volume per pit is about 3 m^3. Inspection of the grit pits is programmed on a quarterly basis with clean out every two years. The flushing systems will be field tested in the summer of 2001 and will be put into operation when all upstream sewer separation work has been completed.

Equipment for each pipe flushing system includes an embedded anchoring system, frame, gate, locking and sealing mechanism, hydraulic cylinder, hydraulic tubing, hydraulic pump, reservoir, valves, mechanical connections, the electronic control panel, expansion modules, solenoids, motor, relays, timers and level sensing equipment.

Each flushing gate is fabricated of stainless steel equipped with bronze bushings for the hinges and locking mechanism. The gate is fixed to the flushing chamber wall stainless steel anchors. The flushing gate hinge mechanism is designed to allow for full travel and permit manual lifting of gate flap to a minimum of 135^0 from the vertical plane (when the gate is fully closed). The hinges are adjustable in two directions. Material for hinges and the locking mechanism is stainless steel and bronze.

A hydraulic power pack is located in the control panel for each flushing gate. Hydraulic pressure is not used to lock the gates or to keep the gates closed. The hydraulic cylinder requires no more than 200 psi to release or open the locking mechanism. There is only one hydraulic cylinder and one hydraulic line for each gate. The hydraulic cylinder is constructed of stainless steel. There is no sealing material inside or in the operating shaft. The hydraulic cylinder has no mechanical or friction seals, no piston rings or sealed shaft. The cylinder is sealed and is leak proof.

There is one manually operated control panel, equipped with a selector switch for LOCAL/OFF/REMOTE operation. In LOCAL (manual) mode any of the flushing gates linked can be flushed from the hydraulic power pack/control panel. In REMOTE mode, a contact closure is the signal to open the flush gate. Water level indicators are explosion-proof, continuous, flexible, level transmitter type. These devices control the operation of the flushing system. Water level indicators are located in the flushing volume chamber and in the downstream pipe to note chamber fill level and the downstream pipe water level. Each level probe is equipped with a stilling well to protect it from physical damage.

Each control panel controls the local (manual) flushing of the system from a series of cabinet face mounted pushbuttons and selector switches. Each is equipped with a PLC and a three-position selector switch, which will allow for LOCAL/OFF/REMOTE operation. Each control panel enclosure houses controls for the hydraulic equipment and for all of the electronic components. A second enclosure within the first separates the electronic components from the hydraulic ones. All operational status alarms are manually reset and both alarms and status lights have dry contacts for future SCADA system connection. Each control panel allows for manual operation (pushbutton) of the flushing system, so that any of the flush ways may be flushed at random. Once a flush is started the control panel cannot accept another signal, other than abort, until the flush is completed. It is equipped with a status light indicating which flushing gate is operating. The panel is also equipped with indicator lights to show if high water level conditions exist in the storage areas. The PLC is used to control the duration of the flush by using various internal timers and relays and by taking the water level in the sump into consideration.

Drain Vaults and Sanitary Vaults
Table 36 presents the design aspects and functions of each of the flush vaults.

Table 36. Flushing vault functions

Flush Vault	Flushing Function	Grit Collection Location	In-line Grit Collector	Flush Water Source	Flush Water Pre-treated	Flushing Vault Used as Junction Structure
Drain Vault #1	Yes	DV # 3	No	Stormwater(1)	No	No
Drain Vault #2	Yes	D/S Grit Manhole	Yes	Stormwater(2)	No	Yes
Drain Vault #3	Yes	DV # 5	No	Stormwater(2)	No	Yes
Drain Vault #4	Yes	D/S Grit Manhole	No	Stormwater(2)	No	Yes
Drain Vault #5	Yes	D/S Grit Manhole	No	Stormwater(2)	No	Yes
Sanitary Vault #1	Yes	N/A	No	WTP	Yes(4)	Yes
Sanitary Vault #2	Yes	N/A	No	WTP	Yes	Yes

Notes:
1. Pumped from local storm drain system manhole.
2. Pumped at vault.
3. Pumped Water Treatment Plant (WTP) filtrate.
4. Vortex separator used to pretreat pumped flow from the WTP by removing heavy grit from being conveyed by gravity from SV #1 to SV #2.

Operation and Maintenance
In order to maintain effective system operation, routine scheduled maintenance must be performed. Maintenance procedures for the flush vaults and grit pits are presented below.

Flushing Vaults
A typical flushing gate vault maintenance procedure is outlined below.

Task 1: Check flushing gates including electrical: Each flushing gate vault should be visually inspected on a monthly basis. The consistent operation of these devices will ensure that the full capacity of the storm drain is available during the course of a wet weather event. The inspection should include verification of proper operation of flushing equipment as well as sensing instrumentation and other electrical equipment.

This task requires two personnel over the course of two hours, as these structures are typically located in traffic sensitive areas. All equipment operation can be visually verified from the surface and confined space entry procedures are not required to perform this task.

Task 2: Check instrumentation/controls: Instrumentation and controls will be inspected on a quarterly basis. The inspection will provide a more detailed analysis of the operation of the flushing vaults. The flushing vault will be manually activated, as controls and electrical equipment are monitored. This will provide a direct indication of the status and operation of the equipment.

This task requires two personnel over the course of two hours as these structures are located in traffic sensitive areas. All equipment operation can be visually verified from the surface and confined space entry procedures are not required to perform this task.

Task 3: Clean pump wet well: Each pump wet well should be cleaned on an annual basis. During the operation of the wet well pumping units debris and detritus will remain as they are entrained within the source. The debris is left behind as part of the function of the wet well pumping system. The debris will gradually accumulate and impede the operation of the equipment. The debris and detritus should be removed from the pump wet well on an annual basis to allow minimize odors from entrained organic materials and as part of preventative maintenance. This task requires three personnel over the course of four hours as these structures are considered confined spaces and require set-up and breakdown time to perform adequate cleaning of these facilities. Cleaning will also require the services of external water supplies and pipe cleaning devices. Table 37 summarizes the annual labor requirements for operation and maintenance of the flushing gates.

Table 37. Flushing gate vault annual labor requirements

Task	Crew Size	Time (h)	Labor/event (man-h)	Frequency (times/yr)	Annual Labor (man-h)
1	2	2	4	12	48
2	2	2	4	4	16
3	3	4	12	1	12

Grit Pits

Grit pits operate passively by removing heavy entrained matter from the stormwater by reducing the velocity and allowing settling to occur. Failure to remove the collected materials will reduce the efficiency of the devices and cause the grit to settle in the drain pipes reducing the capacity of the drains. Cleaning will ensure continued operation and reduced maintenance costs over the equipment life-span. Cleaning will require the use of vactor-type truck and an outside water source as well as the disposal of collected residuals.

This task requires three personnel and confined space entry procedures depending on the size and configuration of the grit pit. Table 38 summarizes the annual labor requirements for operation and maintenance of the grit pits (either a manhole or a sump integrated in a flush vault chamber).

Table 38. Grit pit annual labor requirements

Task	Crew Size	Time (h)	Labor/event (man-h)	Frequency (times/yr)	Annual Labor (man-h)
1	3	3.5	10.5	2	21

Sediment Accumulation and Estimating Methodology

The first step in estimating maintenance requirements for a collection system is to characterize the sediments in the system. The process will determine the characteristics and quantity of material that is anticipated to settle within the collection system that will need to be flushed.

Stormwater Runoff Solids Characteristics

The Construction Industry Research and Information Association (CIRIA) in the United Kingdom (UK) characterizes medium strength stormwater as containing 300 mg/L SS load (particles < 200 μm (transported in suspension) and 50 mg/L grit (particles > 250 μm moving as bed load). These are average values from UK urbanized areas, serviced by catchbasins with little sump volume, with nominal street cleaning. The National Urban Runoff Program (NURP) reports a median SS value of 180 mg/L (range of median values from 141 mg/L to 224 mg/L) developed from long term measurements in 21 urbanized catchments (9 across the US). It is important to note that none of the NURP measurement programs in the early 1980s sampled bed-load as this is extremely difficult to accomplish in practice. European sewer solids research initiatives in the 1990s noted the importance of the particle size distribution. Pisano and Brombach (1996) reported the results of several hundred solids settling curves for a wide variety of waste types (dry weather flow, CSO, storm water, street solids, sediment scraping, pipe slime) collected across North America and Germany over the last two decades.

Using this collective body of information, an assumed mass solids distribution of stormwater solids including both grit and lighter particles is considered. The distribution is presented in Table 39. Settling velocities noted reflect worn angular particles at 10 degrees Celsius. Inspection of Table 39 indicates that the greatest preponderance of materials is associated with solids particles in the 16–62 μm range associated with settling velocities between 0.02 to 0.25 cm/s (0.008 to 0.1 in./s). As a matter of note, mass settling velocities determined from most settling column tests of stormwater, which have excluded bed-load materials, are generally within the lower end of the range noted above. An overall SS concentration, including grit and suspended load, equal to 300 mg/L is assumed for the heavily urbanized catchment tributary to the Fresh Pond Parkway system.

Table 39. Assumed stormwater runoff solids characteristics

Category	Size (μm)	Settling Velocity (cm/s)	% mass per category
Very fine gravel	> 2000	30.0	1
Very coarse sand	> 1000	15.0	2
Coarse sand	> 500	7.0	4
Medium sand	> 250	2.8	5
Fine sand	> 125	1.0	14
Very fine sand	> 62	.25	20
Coarse silt	> 31	.06	26
Medium silt	> 16	.02	18
Fine silt	> 8	.01	6
Very fine silt	> 4	.005	2
			Sum = 100

Next, solids removal associated with a comprehensive, closely spaced system of catch basins and fairly rigorous street sweeping program within the area are included to reduce the above assumed distribution of stormwater solids). In most areas of Cambridge the rule is generally about one catch basin per 1.5 acres. Typically, street sweeping (mechanical) occurs within the Fresh Pond Parkway catchment about 12–15 times per yr.

Measured NURP results indicate on the average, 15% to 20% SS reductions for urbanized areas occur when street sweeping is routinely practiced. Ashley (1992) reported European results noting solids removal per solids sizes for mechanical type street sweeping. His results have been generalized to fit within the 10 particle sizes noted in Table 40 and are given below.

Table 40. Solids removal per solids size for mechanical street sweeping

Particle Size (μm)	Effectiveness (%)
>2000	80
>1000	70
>500	60
>250	55
>125	45
>62	30
>31	15
Otherwise zero	

Pitt (1984) measured the solids removal effectiveness of 100 catch basins and concluded that solids removal is principally a function of the rate of incoming gutter flow. Removal rates approach 45% when the inflow is discharging less than 0.05 cfs and is negligible for flow rates in excess of 1.5 cfs. Using judgment and research and development experience with catch basin performance conducted in Dorchester by Process Research (1976), Pitt's results are generalized in Table 41 to fit into the overall conceptual solids distribution scheme used so far.

Table 41. Solids removal per solids size for typical Cambridge urban catchment area

Particle Size (μm)	Effectiveness (%)
>2000	100
>1000	90
>500	80
>250	60
>125	40
>62	20
>31	10
Otherwise zero	

Using the above formulations, the initial assumed solids distribution of stormwater into the catchment is reduced to reflect the collective impacts of the surface-related Best Management Practices (BMP's). The final average SS concentration after this reduction is 145 mg/L that falls within the range of NURP reported values but higher than CIRA assumptions for clean stormwater that is 60 mg/L. Removal associated with catch basin programs is 23% while street sweeping accounts for an overall reduction of 18%. Table 42 shows the characteristics of stowmwater runoff solids in Cambridge, Massachusetts. The median settling velocity noted in the "final" mass solids distribution in Table 42 is 0.06 cm/s which is consistent with measured stormwater values.

Table 42. Stormwater runoff solids characteristics in Cambridge, MA urban catchment

Category	Size (μm)	Settling Velocity (cm/s)	Initial / (Final) (% mass per category)
Very fine gravel	> 2000	30.0	1 / (0.0)
Very coarse sand	> 1000	15.0	2 / (0.1)
Coarse sand	> 500	7.0	4 / (0 .3)
Medium sand	> 250	2.8	5 / (0.9)
Fine sand	> 125	1.0	14 / (4.6)
Very fine sand	> 62	.25	20 / (11.2)
Coarse silt	> 31	.06	26 / (19.9)
Medium silt	> 16	.02	18 / (18.)
Fine silt	> 8	.01	6 / (6)
Very fine silt	> 4	.005	2 / (2)
			Sum = 100 / (63.0)
Initial SS = 300ml/L; Final SS = 145 mg/L			

Runoff Volumes

Average annual runoff volumes for the catchment are computed assuming a total of 1000 mm (3.28 ft) of rainfall per yr and 75% conversion to runoff. The annual volume of runoff for the Fresh Pond Parkway catchment (100-ha or 250 acre) is approximately 822,000 kL (217 Mgal).

Potential Wet Weather Solids Deposition

The mass of annual solids deposition within the Fresh Pond Parkway catchment is estimated as follows. Assuming quiescent settling with an average forward flow velocity of 0.3 m/s (1 ft/s), all particles having settling velocity greater than 0.06 cm/s (0.02 in./s) are expected to deposit. Table 42 indicates that the mass concentration of particles having settling velocities less than 0.06 cm/s (0.02 in./s) equals 78 mg/L. The difference between the final average SS concentration (145 mg/L) and the mass concentration of particles with settling velocities less than 0.06 cm/s (0.02 in./s) will settle in the storm pipes. This equals 67 mg/L. Annual solids' depositions in the Fresh Pond Parkway storm drain system resulting from stormwater inputs are shown in Table 43 below. Estimates for the annual deposited masses equal the total runoff volume times the concentration of deposited materials above.

Table 43. Annual solids deposition in the fresh pond parkway system

Runoff Volume (kL)	Mass Concentration (mg/L) (Particles less than 0.06 cm/s)	Annual Solids Deposition (kg)
822,000	67	55,000

Bulk specific weights of such fine-grained sediments have been noted by the Construction Industry Research and Information Association (CIRA) to be 1602 kg/m^3 (100 lb/ft^3). This specific weight does not reflect any waterlogged materials that may be entrapped within the sediments. Floatables and trash generated within the entire catchment will be inordinately high due to the large preponderance of eating establishments, hotels and malls. While the catch basins in the area will capture much of this material, some material will invariably escape from the catch basins into the storm drain system. Much of this material will become water logged and sink due to the very low forward outflow conditions. To account for this, the bulk specific weight is reduced to 1,250 kg/m^3 (85 lb/ft^3). On an annual basis, the seven grit pits will be cleaned twice.

Cost Analysis

Operation and Maintenance Costs

This section includes the basis for estimates of annual utility costs, preventive maintenance, parts replacement and structural repairs as needed.

Annual operation and maintenance (O&M) cost estimates are summarized in Table 44. The costs are developed from the stormwater management system operation and maintenance recommendations. The actual costs for O&M are dependent on the amount of operational equipment in service at any given time. The cost estimates are based on the labor estimates presented in Tables 37 and 38 annual labor requirements for flushing gate vault and grit pit, respectively.

The unit costs are based upon the number of man hours estimated to perform the given task plus the cost of specialized equipment for cleaning as well as the facility operation and maintenance cost including electrical, structural and mechanical upkeep and repair. The rates include overhead and equipment necessary to perform the required tasks (i.e., maintenance staff at $75/man-h and vactor/flusher truck at $120/h).

Table 44. Annual operation and maintenance cost estimates

Task	**Annual Unit Cost**
Flushing Vaults - Inspection	$3,600
Flushing Vaults - Check Controls	$1,200
Flushing Vaults - Clean	$1,380
Flushing Vaults - Electrical, Mechanical & Structural	$1,000
Grit Pits - Clean	$2,400

Cost Effectiveness Analysis of Automated Flushing versus Periodic Manual Sediment Removal

This 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. Assumptions for the cost analysis of both alternatives are listed below:

1. Pipe cleaning costs assume inflation rate of 3.12% per yr.
2. Stormwater pipes are cleaned every 5 yrs, and sanitary pipes are cleaned every 3 yrs.
3. Flushing costs are based on inflation rate of 3.12% per yr and discount rate of 7.1% per yr.
4. Discount Period = 30 yrs.
5. Maintenance labor cost = $75/man-hr.
6. Sanitary systems will be flushed daily using spent process water from the water treatment plant.
7. Storm systems will be flushed approximately every two weeks depending on rainfall.

Capital costs for the flushing facilities reflect final construction costs with all change orders, and include excavation and backfill, hauling, pavement, gravel, dewatering, hazardous soil disposal, piping, traffic maintenance, equipment, structures and mobilization. Since the flushing facilities have been built at piping system intersection points, total facility construction costs have been adjusted to only include flushing and grit capture functions.

Grit pits have been included for the storm systems only. Pit volumes average about 3 m^3 (793 gal). Small diameter 75 mm-100 mm (3-4 in.) force mains from the Cambridge Water Treatment plant to the sanitary flushing systems are included in the capital cost estimates. Operation and maintenance costs for flushing sites include hydraulic oil, routine inspection and servicing, power, and removal of collected sediments from the storm system vaults on a semi-annual basis. Trucking and disposal costs are not included.

Capital Costs for the Automated Flushing Systems

The capital costs of the flushing systems include the flushing vaults, the grit sumps/manholes (storm only), small above ground vaults to house the hydraulic power pack units to trigger the flushing systems and electrical pumping controls, and chambers as appropriate to pump storm water into the flushing chambers.

No additional sewage treatment costs associated with added " flush water" is included for the two sanitary sewer chambers at Fresh Pond Circle as this volume. It is already paid for as spent filtrate from the City of Cambridge new water treatment plant. No such costs are included for the storm system, as collected stormwater will be used to flush the storm drain pipes. 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. Pertinent cost summary details of the flushing systems are given in Table 45 and Table 46.

Table 45. Flushing system capital costs (ENR Construction Cost Index = 6389, August 2001)

Location	Gross Construction Cost ($)	Apportioned Flushing System Cost ($)
Drain Vault #1	210,000	170,000
Drain Vault #2	290,000	240,000
Drain Vault #3	325,000	265,000
Drain Vault #4	335,000	275,000
Drain Vault #5	771,000	661,000
Downstream DV#5 Grit Pit	N/A	80,000
Sanitary Vault #1	187,000	147,000
Sanitary Vault #2	158,000	132,000
Force Mains for Sanitary Vaults	N/A	82,000
Totals	2,276,000	2,052,000

Table 46. Flushing system operation and maintenance costs

Flushing System	Average Annual Cost ($)	Present Value Cost ($)
Storm Drain	17,600	1,475,000
Sanitary	7,040	236,000
Total	24,640	1,711,000

The overall present worth cost including capital and operation and maintenance costs over a 30 year period for the automatic storm and sanitary sewer flushing systems is estimated to equal $3,766,000. Average capital cost of flushing volume is approximately $18,000/m^3.

Costs for Manual Cleaning

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. Unit cleaning costs were obtained from actual contractor bids for the cleaning construction package of existing storm and sanitary sewers within the project area and then used to estimate cleaning of all newly constructed and rehabilitated pipes as follows:

1. 1067 mm (42 in.) Storm Drain -$102.00/m ($34.00/ft)
2. 1219 mm (48in.) Storm Drain -$129.00/m ($43.00/ft)
3. 1372 mm (54 in.) Storm Drain -$163.50/m ($54.50/ft)
4. 1829 mm (72 in.) Storm Drain- $267.00/m ($89.00/ft)
5. 1.22 m x 1.83 m (4 ft by 6 ft) Storm Drain -$232.50/m ($77.50/ft)
6. 1.85m by1.52 m (5 ft by 6 ft) Storm Drain - $312/m ($96.00/ft)
7. 457 mm (18 in.) - 610mm (24 in.) Sanitary -$49.50/m ($15.00/ft)
8. Storm Sewer Cleaning Mobilization $55,000
9. Sanitary Sewer Cleaning Mobilization $5,000

Present worth costs for cleaning the storm drain system at 5-yr intervals for a 30-yr period equals $4,692,000. Similarly, the present worth cost for manually cleaning the sanitary sewer system at 3-year intervals equals $920,000. Total present worth costs for the 30-yr period equals $5,612,000. No trucking and sediment disposal costs for either alternative are assumed. On a life cycle basis, the automated flushing scheme is more cost effective than periodic manual cleaning with savings of $1,850,000. 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.

References

Ahyerre, M., G. Chebbo, and M. Saad (2001). Sources And Erosion Of Organic Solids In A Combined Sewer. *Urban Water* (G.B.), **2**(2).

American Society of Civil Engineers (2001). *Guide for Best Management Practice (BMP) Selection in Urban Developed Areas.* Urban Water Infrastructure Management Committee's Task Committee for Evaluating Best Management Practices, American Society of Civil Engineers, Reston, VA.

American Society of Civil Engineers and Water Environment Federation (1998). *Urban Runoff Quality Management*, ASCE, Manuals and Report of Engineering Practice No. 87, Reston, VA. WEF, Manual of Practice No. 23, Alexandria. VA.

Armitage, N. and A. Rooseboom (2000). The Removal of Urban Litter from Stormwater Conduits and Streams: The Quantities Involved and Catchment Litter Management Options. *Water South Africa,* **26** (2), 181. http://www.wrc.org.za

Arthur S. and R.M. Ashley (1998). The Influence Of Near Bed Solids Transport On First Foul Flush In Combined Sewers. *Wat.Sci.Tech.* (G.B.) **37** (1).

Arthur S., R.M. Ashley, and C. Nalluri (1996). Near Bed Solids Transport In Sewers. *Wat.Sci.Tech.* (G.B.) **33** (9)

Ashley R M., T. Hvitved-Jacobsen, and J-L. Bertrand-Krajewski (1999). Quo Vadis Sewer Process Modelling? *Wat.Sci.Tech.* (G.B.) **39 (** 9).

Ashley, R. M. and R.W. Crabtree (1992). Sediment Origins, Deposition And Build-Up In Combined Sewer Systems. *Wat. Sci. Tech.* (G.B.) **25** (8).

Ashley, R. M. and T. Hvitved-Jacobsen (2002). Management of Sewer Sediments. In *Wet-Weather Flow In The Urban Watershed Technology and Management*, Field, R. and D. Sullivan (Eds.) CRC Press/ Lewis Publishers, Boca Raton, FL.

Ashley, R. M., N. Souter, D. Butler, J. Davies, J. Dunkerley, and S. Hendry (1999). Assessment of the Sustainability of Alternatives for the Disposal of Domestic Sanitary Waste. *Wat.Sci.Tech.* **39,** 5.

Ashley, R. M., N. Souter, D.J. Blackwood, S. Hendry, J. Moir, and J. Dunkerley (2000). The Relative Sustainability Of Flushing or Binning Sanitary Waste. Submitted to *J Envi. Eng* American Society of Civil Engineers, Reston, VA.

Ashley, R.M. and R.W. Crabtree (1992). Sediment Origins, Deposition and Build-up in Combined Sewer Systems. *Wat. Sci. Techn.* 25 (8), 1−12.

Bachoc, A. (1992). Location And General Characteristics Of Sediment Deposits Into Man-Entry Combined Sewers. *Wat.Sci.Tech.* (G.B.) **25**,(8).

Bertrand-Krajewski J-L., H. Madiec, O. Moine (1996). Two Experimental Sediment Traps: Operation and Solids Characteristics. *Wat.Sci.Tech.* **33**, 9.

Bertrand-Krajewski, J.L. (1993). Solid Transport Modeling in Combined-Sewer Systems: The HYPOCRAS Model (France). *HOUILLE BLANCHE,* No. 4, ISSN 0018-6368.

Boon, A..G. (1995). Septicity in Sewers: Causes, Consequences and Containment. *Wat. Sci. Techn.* **31** (7), 237–253.
Boon, A..G. and A.R. Lister (1975). Formation of Sulphide in a Rising-Main Sewer and its Prevention by Injection of Oxygen. *Prog. Wat. Technol.* **7**(2), 289–300.
Chebbo, G., D. Laplace, A. Bachoc, Y. Sanchez, and B. Le Guennec (1995). *Technical Solutions Envisaged in Managing Solids in Combined Sewer Networks*, International Conference on Sewer Solids-Characteristics, Movement, Effects and Control, Dundee, Scotland.
Cornelius, M.; T. Clayton, G. Lewis, G. Arnold, and J. Craig (1994). *Litter Associated with Stormwater Discharge in Auckland City, New Zealand.* Island Care New Zealand Trust, Auckland.
Cotham, W. and T. Bidleman (1995). Polycyclic Aromatic Hydrocarbons and Polychlorinated Biphenyls in Air at an Urban and a Rural Site near Lake Michigan, *Environ. Sci. & Technol.* **29**: 2782-2789.
Delleur, J.W. (2001). Sediment Movement in Drainage Systems. Chapter 14. *Stormwater Collection Systems Design Handbook.* Mays, L.W. (Ed.) McGraw-Hill, New York, NY
Ellis, J.B.and D.M. Revitt. (1982). Incidence of Heavy Metals in Street Surface Sediments: Solubility and Grain Size Studies. *Water, Air, and Soil Pollution,* **17** (1).
Fan, C-Y., R. Field, W.C. Pisano, J. Barsanti, J.J. Joyce, and H. Sorensen (2001). Sewer and Tank Flushing for Sediment, Corrosion, and Pollution Control. *Water Resour. Plan. & Managt.* **127** (3).
Field, R., and R. Turkeltaub (1981). Urban Runoff Receiving Water Impacts-Program Overview. *J. Environ. Eng. Div.* **107,** 1, 83.
Förster, J. (1996). Heavy Metal and Ion Pollution Patterns in Roof Runoff. *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 241.
Guo, J. C-Y. (1999). Sand Recovery for Highway Drainage Designs, *J. Irrig. & Drainag. Eng.* **125** (6).
Guo, Q., C-Y. Fan, R. Raghaven, and R. Field (2004). Gate and Vacuum Flushing of Sewer Sediment: Laboratory Testing. *J. Hydulic Eng.* ASCE (In Press)
Heaney J P., L. Wright, D. Sample, R. Field, and C-Y. Fan (1999). Innovative Wet-Weather Flow Collection, Control, and Treatment Systems for Newly Urbanizing Areas in the 21st Century. In: *Sustaining urban water resources in the 21st century* (Ed. Rowney C., Stahre P., Roesner L A.) ASCE. ISBN 0-78440-0424-0.
Herrmann, T., C. Bruns, B. Gatje, and G. Ilgen (1999). Urea - The Reason for Fish Kill after Overflow Events from Combined Sewers? *Proc. The Eighth International Conference on Urban Storm Drainage.* August 30 - September 3, 1999, Sydney, Australia. Edited by I.B. Joliffe and J.E. Ball. The Institution of Engineers Australia, The International Association for Hydraulic Research and The International Association on Water Quality. 1296.
Hilts, P. (1996). Fine Particles in Air Cause Many Deaths, Study Suggests. *The New York Times*, May 9, 1996.
Huber, W.C. and R.E. Dickinson (1988). *Storm Water Management Model User's Manual, Version 4*, EPA/600/3-88/001a; NTIS PB88-236641/AS, U.S. Environmental Protection Agency, Athens, GA.
Hütter, U. and F. Remmler (1996). Stormwater Infiltration at a Site with Critical Subsoil Conditions: Investigations of Soil, Seepage Water, and Groundwater. *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 713.
Jefferies, C. and R.M. Ashley (1994). The Behaviour Of Gross Solids In Sewer Systems. *EWPC*, **4** (5).
Hvitved-Jacobsen, T. (2002). *Sewer Process: Microbial and Chemical Process Engineering of Sewer Networks.* CRC Press, Boca Raton, Florida.
Krebs, P., P. Holzer, J.L. Huisman, and W. Rauch (1999). First-Flush of Dissolved Compounds. *Wat. Sci. Tech.* **39**, 9, 55.
Mason, R.P., N.M. Lawson, A.L. Lawrence, J.J. Leaner, J.G. Lee, and G.R. Shew (1999). Mercury in the Chesapeake Bay. *Marine Chemistry*. **65**, 1-2, 77.
May, R.W.P., J.C. Ackers, D. Butler, and S. John (1996). Development Of Design Methodology For Self-Cleansing Sewers. *Wat. Sci. Tech.*, (G.B.) **33** (9).
Montrejaud-Vignoles, M., S. Roger, and L. Herremans. (1996). Runoff Water Pollution Of Motorway Pavement In Mediterranean Area. *Proc. 7th Int. Conf. on Urban Storm Drainage,* IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany.
Mull, R. (1996). Water Exchange Between Leaky Sewers and Aquifers. *Proc. 7th Int. Conf. On Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 695.

Newman, T. L. and W.M. Leo (2002). Characterization of Urban-Source Floatables. In *Proceedings of WEF Specialty Conference 2000: Collection Systems Wet Weather Pollution Control.*
Nielsen, P.H. (1991). Sulfur Sources for Hydrogen Sulfide Production in Biofilm from Sewer Systems. Water Sci. Tech. **23**(1).
Nowakowska-Blaszczyk, A. and J. Zakrzewski (1996). The Sources and Phases of Increase of Pollution in Runoff Waters in Route to Receiving Waters. In: *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany.
Pisano, W.C. and C.S. Queiroz (1977). *Procedures for Estimating Dry Weather Pollutant Deposition in Sewerage Systems*, Report No. EPA-600/2-77/120, NTIS PB 270 695, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.
Pisano, W.C. and C.S. Queiroz (1984). *Procedures for Estimating DryWeather Sewage InLine Pollutant Deposition-Phase II*, Report No. EPA-600/2-84/020, NTIS PB 84141 480, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.
Pisano, W.C., D. Connick, C. Queiroz, and J. Aronson (1979). *Dry Weather Deposition and Flushing for CSO Pollution Control*, EPA/600/2-79-133; NTIS PB 80 118 524, U.S. Environmental Protection Agency, Cincinnati, OH.
Pisano, W.C. and H. Brombach (1996). Solids Settling Curves. *Water Environment & Technology*, **8**(4). Water Environment Federation, Alexandria, VA.
Pisano, W.C., G. Novac, and N. Grande (1997). Automated Sewer Flushing Large Diameter Sewers. *Collection Systems Rehabilitation and O&M: Solving Today's Problems and Meeting Tomorrow's Needs*, Section 12. Wade, M. (Ed.) Water Environment Federation, Alexandria, VA, 12-9-12-20.
Pisano, W.C.; Barsanti, J.; Joyce, J.; Sorensen, H. (1998). *Sewer and Tank Sediment Flushing: Case Studies.* EPA-600/R-98/157. NTIS PB 99-127839INZ, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH.
Pisano, W.C., J.R. Barsanti, and F.J. Ayotte (2001) *Sewer Sediment Flushing Evaluation and Design: A Case Study.* Draft interim report under EPA Contract No. 68-C98-157, Urban Watershed Management Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Edison, NJ.
Pitt, R., R. Field, M. Lalor, and M. Brown (1995). Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability. *Wat. Environ. Research* **67**(3): 260.
Process Research, Inc., (1976). *A Study of Pollution Control Alternatives for Dorcester Bay*, Metropolitan District Commission, Boston, MA.
Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (1996). *USDA-ARS Agriculture Handbook No. 703: Predicting Soil Erosion by Water – a Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. Soil and Water Conservation Society, Ankeny, IA.
Saget, A., G. Chebbo, and J-L. Bertrand-Krajewski (1996). The First-Flush Sewer Systems, *Wat. Sci. Tech.* Vol. **33**, 9, 101-108.
Sakakibara, T. (1996). Roof Runoff Storm Water Quality. *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 157.
Sansalone, J. (1996). Immobilization of Metals and Solids Transported in Urban Pavement Runoff. *North American Environ. Congress '96. Anaheim, CA.* America Society of Civil Engineers, Reston, VA.
Sansalone, J.J. and S.G. Buchberger (1996). Characterization of Solid and Metal Element Distributions in Urban Highway Stormwater. In: *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 253.
Sanudo-Wilhelmy, S.A. and G.A. Gill (1999). Impact of the Clean Water Act on the Levels of Toxic Metals in Urban Estuaries: The Hudson River Estuary Revisited. *Evniron. Sci. Technol.* **33**, 20, 3477.
Sartor, J.D. and G.B. Boyd (1972). *Water Pollution Aspects of Street Surface Contaminants.* EPA-R-2-72-081; NTIS PB , U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.
Saxton, G., K. Siftar, and P. Fowler (1996). Quantifying the Pollutant Characteristics of Snow Versus Snowmelt Runoff in a Reliable and Economical Manner at Eielson Air Force Base, AK. In: *Proc. WEFTEC'96, 69th Annu. Conf. & Expo., Dallas, TX.* Water Environment Federation, Alexandria, VA.

Saul, A.J., J.K. Houldsworth, J. Meadowcroft, D.J. Balmforth, C. Digman, D. Butler, and J.W. Davies (1999). Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflows. *Proc. The Eighth International Conference on Urban Storm Drainage.* August 30 - September 3, 1999, Sydney, Australia. Edited by I.B. Joliffe and J.E. Ball. The Institution of Engineers Australia, The International Association for Hydraulic Research and The International Association on Water Quality. 482.

Shaheen, D.G. (1975). *Contributions of Urban Roadway Usage to Water Pollution*. EPA-600/2-75/ 004; NTIS PB 245 854, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.

Sonnen, M. (1977). *Abatement of Deposition and Scour in Sewers*, Report No. EPA-600/2-77/212, NTIS PB 276 585, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.

Squillace, P.J., J.S. Zogorski, W.G. Wilber, and C.V. Price (1996). Preliminary Assessment of the Occurrence and Possible Sources of MTBE in Groundwater in the United States, 1993 - 94. *Environ. Sci. & Technol.,* **30**, 5, 1721.

St. Michelbach, G.W. and H. Brombach, (1999). Nutrient Impact from CSOs on Lake Constance. *Proc. The Eighth International Conference on Urban Storm Drainage.* August 30 - September 3, 1999, Sydney, Australia. Edited by I.B. Joliffe and J.E. Ball. The Institution of Engineers Australia, The International Association for Hydraulic Research and The International Association on Water Quality. 474.

Strecker, E.W., M.M. Quigley, B.R. Urbonas, J.E. Jones, and J.K. Clary (2001). Determining Urban Storm Water BMP Effectiveness, ASCE Journal of Water Resources Planning and Management, Vol. 127, No. 3, p. 114.

Strecker, E. (2002). Low-Impact Development (LID): Is it Really Low or Just Lower. In *Proceedings of an Engineering Foundation Conference Linking Stormwater BMP Designs and Performance to Receiving Water Impacts Mitigation*; Snowmass, CO, American Society of Civil Engineers, Reston, VA..

Thistlethwayte, D.K.B. (1972). *Control of Sulphides in Sewerage Systems.* Ann Arbor Science, Ann Arbor, MI.

Thorolfsson, S.T. and J. Brandt (1996). The Influence of Snowmelt on Urban Runoff in Norway. *Proc. 7th Int. Conf. On Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 133.

Tomlinson, R.D., B.N. Bebee, A.A. Heyward, S.G. Munger, and R.G. Swartz (1980). *Fate and Effects of Particulates Discharged by Combined Sewers and Storm Drains*, EPA-600/2-80-111, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH.

Trauth, R. and C. Xanthopoulos (1996). Non-point Pollution of Groundwater in Urban Areas. *Proc. 7th Int. Conf. on Urban Storm Drainage,* IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 701.

U.S. Environmental Protection Agency (1985). *Design Manual Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants*, EPA/625/1-85/018, U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (1985). *Design Manual: Odor And Corrosion Control In Sanitary Sewerage Systems And Treatment Plants*. EPA/625/185/018, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA

U.S. Environmental Protection Agency (1989). *Results of the Evaluation Groundwater Impacts of Sewer Exfiltration*, NTIS No. PB95-158358, Municipal Facilities Division, Office of Water, U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (1992). *Manual For Wastewater Treatment/Disposal For Small Communities*. EPA/625/R-92/005, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

U.S. Environmental Protection Agency (2000). *Exfiltration in Sewer Systems*. Report No. EPA/600/R-01/034. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH

U.S. Environmental Protection Agency (2002). *Considerations in the Design of Treatment Best Management Practices (BMPs) to Improve Water Quality*. EPA publication number pending. Urban Watershed Management Branch. Water Supply and Water Resources Division, National Risk Management Research Laboratory, Edison, NJ. (http://www.epa.gov/ednnrmrl/).

U.S. Environmental Protection Agency (2003). *System and Method for Vacuum Flushing Sewer Solids.* United States Patent No. 6,655,402. U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C.

Venkatesan, M.I., R.P. de Leon, A. van Geen, and S.N. Luoma (1999). Chlorinated Hydrocabon Pesticides and Polychlorinated Biphenyls in Sediment Cores from San Francisco Bay. *Marine Chemistry*. **64**, 1-2, 85.
Vignoles, M. and L. Herremans (1995). Metal Pollution of Sediments Contained in Runoff Water in the Toulouse City. *NOVATECH 95, Second International Conference on Innovative Technologies in Urban Storm Drainage,* May 30-June 1, 1995. Lyon, France, Organized by Eurydice 92 and GRAIE. p.611.
Wada Y., H. Miura, and K. Hasegawa (1987). Model Building And Analysis Of Runoff Water Quality Of Flush From The Street Gully Pots. *Proceedings of the 4th International Conference on Urban Storm Drainage*, Lausanne, Switzerland, 60-65.
Wada, Y., H. Miura, and O. Muraoka (1996). Influence of Discharge Pollutants from the Highway at Rainfall on Water Quality of the Public Water Body. *Proc. 7th Int. Conf. on Urban Storm Drainage*, IAHR/IAWQ Joint Committee on Urban Storm Drainage, Hannover, Germany, 461.
Weis, P. and J.S. Weis (1996). Leaching from Chromated-Copper-Arsenic (CCA) Treated Wood and Effects in Chesapeake Bay. Abstract Book: *SETAC 17th Annu. Meeting*, Washington, DC., 88.
Zogorski, J.S., A.B. Morduchowitz, A.L. Baehr, B.J. Bauman, D.L. Conrad, R.T. Drew, N.E. Korte, W.W. Lapham, J.F. Pankow, and E.R. Washington (1996). Fuel Oxygenates and Water Quality: Current Understanding of Sources, Occurrence in Natural Waters. *Environmental Behavior, Fate, and Significance*. Executive Office of the President, Office of Science and Technology Policy, Washington, DC.