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Sewer and Tank Flushing for Corrosion and Pollution Control

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ABSTRACT: This paper presents an overview of causes of sewer deterioration together with a discussion of control methods that can prevent or arrest this deterioration. In particular, the paper covers inline- and combined sewer overflow- (CSO) storage-tank-flushing systems for removal of sediments and minimizing hydrogen sulfide production resulting in the reduction of associated pollution and sewerline corrosion. During low-flow dry-weather periods, sanitary wastewater solids deposited in combined sewer systems can generate hydrogen sulfide and methane gases due to anaerobic conditions. Sulfates are reduced to hydrogen sulfide gas that can then be oxidized to sulfuric acid on pipes and structure walls by further biochemical transformation. Furthermore, these solids deposits or sediments are discharged to the urban streams during storm events which can cause degradation of receiving-water quality. Thus, dry-weather sewer sedimentation not only creates hazardous conditions and sewer degradation but contributes significant pollutant loads to the urban receiving waters during wet-weather high-flow periods.

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Performance of two technologies, i.e., the tipping flusher and the flushing gate (FG) was evaluated by a detailed examination of 18 facilities in Germany, Canada, and United States. As a result, both the tipping flusher and FG technology appear to be the most cost-effective means for flushing solids and debris from CSO-storage tanks, while the FG is considered to be the most efficient method for flushing large diameter, flat sewers. In addition, capsulated reviews of several cost-effectiveness analyses are reported demonstrating the comparative benefits of flushing technology.

INTRODUCTION

Past studies have identified urban CSO and stormwater runoff as major contributors to the degradation of urban lakes, streams, and rivers. Wastewater solids deposited in combined sewer (CS) systems during dry weather are major contributors to the CSO pollution load. In recent years, pollution caused by CSO has become a serious environmental concern. Although requirements may vary concerning allowable overflow amounts, the need for permit compliance has resulted in the design and construction of storage facilities as well as utilization of inline in-sewer storage or constructing deep tunnels. In the case of in-sewer storage, shallow slopes and low average velocities allow debris to settle along the invert of the sewer during storage periods. Accumulation of sediment results in a loss of storage capacity that may cause blockage, surcharge, or local flooding and septic conditions that create odor and corrosion problems. Estimates of dry-weather flow (DWF) deposition in CS systems range from 5 to 30 % of the daily suspended solids (SS) pollution loading. 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 after four days of antecedent dry weather causing a two-hour CSO will wash the equivalent of one-day's flow of raw-sanitary wastewater to the receiving waters. 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. An important parameter in the criteria for sewer self-cleansing is average shear stress. Average shear stress is the amount of force the fluid exerts on the wetted perimeter of the pipe. Another important parameter is bed-shear stress which is the amount of force the fluid exerts on the bed of sediment in the pipe. Bed-shear stress is related to bedload resuspension and movement.

In general, sewers will not maintain self-cleansing velocities at all times. The diurnal pattern of the 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 and the subsequent erosion and transport of these sediments, either as suspended load or bed-load, at times of higher flow. The deposited sediments will exhibit additional strength due to cohesion and provided that the peak DWF velocity or bed-shear stress is of sufficient magnitude to erode these sediments, the sewer will maintain self-cleansing operation at times of DWF. If this condition is not satisfied, then long-term "mature" sediment beds will form that may be scoured during occasional periods of extreme flow conditions. May et al. (1993), presented a definition to describe a self cleansing sewer as "an efficient self-cleansing sewer is one having a sediment-transporting capacity that is sufficient to maintain a balance between the amounts of deposition and erosion, with a time-averaged depth of sediment deposit that minimizes the combined costs of construction, operation and maintenance." To achieve such self-cleansing performance, this criteria applies:

1. Flows equaling or exceeding a limit appropriate to the sewer should have the capacity to transport a minimum concentration of fine-grain particles in suspension (applicable for all types of sewerage systems).
2. The capacity of flows to transport coarser granular material as bed-load should be sufficient to limit the depth of deposition to a specified proportion of the pipe diameter. This criteria generally relates to combined and stormwater systems. Limit of deposition considerations, i.e., “no deposition” generally applies to sanitary sewer designs. In this context, there must be sufficient shear forces in sanitary systems to avoid deposition of large particles.
3. Flows with a specified frequency of occurrence should have the ability to erode bed particles from a deposited granular bed that may have developed a certain degree of cohesive strength (applicable to all systems).

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

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

- Nalluri and Alvarez (1992), whose laboratory studies used synthetic cohesive sediments, concluded that there were two ranges of bed-shear stress at which erosion occurred: 2.5 N/m^2 for the weakest material, comprising a surface layer of fluid sediment: and 6 to 7 N/m^2 for the more granular and consolidated material below. It was found that, after erosion, the synthetic cohesive sediments behaved very much like non-cohesive material.
- Ristenpart and Uhl (1993) found in field tests that during dry weather an average bed-shear stress of 0.7 N/m^2 was required to initiate erosion, increasing to an average of about 2.3 N/m^2 during wet weather, or to 3.3 N/m^2 after a prolonged period of dry weather and presumably, consolidation of the deposited bed.
- Ashley (1992) has suggested that the bonds between particles at the surface of a deposited bed are weakened by the presence of the water, so that surface layers can be successively stripped away by the flow. Measurements in the Dundee, Scotland sewers indicated that it began to move at a fluid-shear stress of about 1.0 N/m^2, with significant erosion of a deposited bed occurring at bed-shear of 2.0 to 3.0 N/m^2. Taking account of a review of work by other researchers, Ashley concluded that most deposits should be eroded at a shear stress exceeding 6.0 to 7.0 N/m^2. In terms of flow velocity, it appears that velocities in excess of 1.0 m/s are needed to scour “mature” consolidated sediment beds. One rule-of-thumb used in Europe for designing flushing systems assumes that the peak velocity at the end of segment be flushed in at least 1.0 m/s.

In addition to CSO pollution, sewer sediments create odor problems. The production and release of hydrogen sulfide (H_2S) gas in municipal wastewater collection systems is responsible for odor complaints, the destruction of sewer pipes and other wastewater infrastructure facilities, and in rare instances has caused the death of sewer maintenance personnel. The process begins with the biological reduction of sulfate to sulfide by the anaerobic slime layer residing on pipe and sediment surfaces below the water in wastewater collection systems. The anoxic 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, aerobic bacteria (*Thiobacillus*) which reside on sewer walls and surfaces above the water line consume the H_2S gas and secrete H_2SO_4. In severe instances, the pH of the pipe can reach 0.5. This causes severe damage to unprotected collection system surfaces and may eventually result in the total failure of the sewer and the uncontrolled release of raw wastewater into the environment.

Control of dissolved H_2S in existing sewers can be achieved by in-sewer chemical addition or inline sewer flushing to reduce sediments and thereby reduce or eliminate dissolved H_2S. Numerous chemicals can be used to treat dissolved sulfide through oxidation, precipitation, or preventing sulfide formation. Iron salts that react with dissolved sulfide to form metal-sulfide precipitates have been applied in the collection system for effective sulfide control. Nitrates have also been used, as oxygen in the nitrate ion will be used before the sulfate ion oxygen resulting in less harmful nitrite and nitrogen.

The goal of flushing is to transport the resuspended sediment to strategic locations, i.e., to a point where the waste stream is flowing with sufficient velocity, to another point where flushing will be initiated, to a storage sump which will allow later removal of the stored contents, or to the wastewater treatment plant (WWTP). This reduces the amount of solids resuspended during storm events, lessens the need for CSO treatment and sludge removal at downstream storage facilities, and allows the conveyance of more flow to the WWTP.

Innovative methods for cleaning accumulated solids and debris in CSO and stormwater conveyance systems and storage tanks have emerged over the last 15 years. Some of the most effective methods use high-speed-flushing waves to resuspend sediments and transport them downstream. FG and tipping flushers for cleaning accumulated sludge and debris in CSO- and stormwater-storage tanks have emerged in Germany and Switzerland. Both methods create high-speed-flushing waves to resuspend sediment on the tank floor and sweep the resuspension to a disposal channel at the end of the tank.

This overview is based on a recent report published by U.S. Environmental Protection Agency (EPA) (Pisano et al. 1998). It presents the: (1) evaluation of H_2S concentrations in CS, (2) correlation between sediment characteristics and H_2S gas generation, and (3) effectiveness of flushing systems. In addition, by reviewing operational results of 18 sites in North America and Europe the effectiveness of system designs in terms of sediment removal and capital and operation and maintenance (O&M) costs were evaluated.

CHARACTERISTICS OF SEWER SEDIMENT

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

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

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

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

If the flow velocity or turbulence level decreases, there will be a net reduction in the amount of sediment held in suspension. The material accumulated at the bed may continue to be transported as a stream of particles without deposition. However, below a certain limit, the sediment will form a deposited bed, with transport occurring only in the surface layer (the limit of *deposition*). If the flow velocity is further reduced, sediment transport will cease completely.

The flow conditions necessary to prevent deposition depend on the pipe size and on properties of the sediment, such as particle size and specific gravity. Flocculation of fine particles can also be important. The flow velocities needed to entrain sediment tend to be higher than those at which deposition occurs.

SULFIDE GENERATION AND SEWERAGE STRUCTURE CORROSION

Hydrogen Sulfide in Sewer

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 wastewater collection system is usually free of sulfide. However, a dissolved form of sulfide 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 root cause of odor and corrosion in collection systems is sulfide, which is produced from sulfate by bacteria residing in a slime layer on the submerged portion of sewer pipes and structures. Once released from the wastewater as H_2S gas, odor and corrosion problems begin. Another type of bacteria utilizes H_2S gas to produce sulfuric acid (H_2SO_4) that causes the destruction of wastewater piping and facilities. 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 or force main. 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 zoogleal 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 the same way dissolved oxygen is used by aerobic bacteria. $SO_4^{=}$ concentrations are almost never limiting in normal domestic wastewaters. When $SO_4^{=}$ is utilized by these bacteria, sulfide ($S^{=}$) 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 ($H_2S_{(g)}$).

Sulfide Ion ($S^{=}$). The $S^{=}$ ion is a colorless ion in solution and cannot leave wastewater in this form. It does not contribute to odors in the ionic form.

Bisulfide Ion (HS^-). The HS^- (or hydrosulfide) ion is a colorless, odorless ion which can only exist in solution. It also does not contribute to odors.

H_2S (Aqueous) ($H_2S_{(aq)}$). H_2S can exist as a gas dissolved in water. The polar nature of the H_2S molecule makes it soluble in water. In the aqueous form, H_2S does not cause odor; however, this is the only sulfide specie that can leave the aqueous phase to exist as a free gas. The rate at which H_2S leaves the aqueous phase is governed by Henry’s Law, the amount of turbulence of the wastewater and the pH of the solution.

Hydrogen Sulfide (Gaseous) ($H_2S_{(g)}$). Once H_2S leaves the dissolved phase and enters the gas phase it can cause odor and corrosion. $H_2S_{(g)}$ is a colorless but extremely odorous gas that can be detected by the human sense of smell in very low concentrations. In high concentrations, it is also very hazardous to humans. In concentrations as low as 10 ppm (by volume [V]) it can cause nausea, headache, and conjunctivitis of the eyes. Above 100 ppm (V) it can cause serious breathing problems and loss of the sense of smell along with burning of the eyes and respiratory tract. Above 300 ppm (V) death can occur within a few minutes

Due to the continuous production of $S^{=}$ in wastewater, $H_2S_{(g)}$ rarely, if ever, re-enters the liquid phase. $S^{=}$ continuously produced by the slime layer replaces that which is lost to the atmosphere as $H_2S_{(g)}$ in the collection system. In addition, once the $H_2S_{(g)}$ is released it usually disperses throughout the sewer environment and never reaches a high enough concentration to be forced back into solution. The four sulfide chemical species are related according to the following equilibrium:

$$H_2S_{(g)} \leftrightarrow H_2S_{(aq)} \leftrightarrow HS^{-} \leftrightarrow S^{=}$$

pKa = 6.9 **pKa = 14**

where: pKa is defined as the ionization constant; the higher the pKa value the weaker the acid.

As indicated by the equilibrium equations, once H_2S is released into the gas phase, HS^{-} is immediately transformed into more $H_2S_{(aq)}$ to replace that which is lost. Concurrently, $S^{=}$ is transformed into HS^{-} to replace that lost to $H_2S_{(aq)}$. Through this type of continuously shifting equilibrium it would be possible to completely remove all $S^{=}$ from wastewater as $H_2S_{(g)}$ through stripping. This is generally not recommended or advantageous due to odor releases and the accelerated corrosion which can take place.

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

Factors Effecting 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 and large organics, to settle in the collection system piping. This increases the mass and surface area of material in the collection system upon which $SO_4^=$-reducing bacteria (slime layer) can grow, and can lead to an increased conversion of $SO_4^=$ to $S^=$.

Collection systems with sedimentation problems can experience $S^=$ concentration spikes during the historically high flow, cool temperature months. This phenomenon occurs when significant sand or grit accumulations exist and the particles are covered by an anaerobic slime layer that contains $SO_4^=$-reducing bacteria. Only the bacteria on the surface of the grit pile receive a continuous supply of $SO_4^=$ because they are exposed to the wastewater. The buried $SO_4^=$-reducing bacteria are not exposed to a continuous supply of $SO_4^=$. This forces them to exist in a semi-dormant, anaerobic state with very low cell activity (but they are not dead). When a high-flow event occurs, with sufficient velocity and shear force to resuspend the sediment, this enormous surface area of $SO_4^{=}$-reducing bacteria is suddenly exposed to ample $SO_4^{=}$ and they rapidly convert it to dissolved sulfide. This causes a relatively short duration, high $S^{=}$ event with resulting $H_2S_{(g)}$ release, odor and corrosion.

The grit particles and their attached $SO_4^{=}$-reducing bacteria that were semi-dormant are suspended and exposed to a tremendous quantity of $SO_4^{=}$ and quickly begin producing $S^{=}$. 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.

Temperature. In addition to the factors described above, summer conditions result in an increase of wastewater temperatures. Greater wastewater temperatures increase the metabolic activity of the $SO_4^{=}$-reducing organisms, causing faster conversion of $SO_4^{=}$ to $S^{=}$ and increased dissolved $S^{=}$ concentrations. It has been estimated that each incremental 7 ^{o}C (12.5 ^{o}F) increase in wastewater temperature doubles the production of $S^{=}$.

Flow Turbulence. Turbulence is a critical parameter to consider in preventing $H_2S_{(g)}$ 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. Henry's law states in effect:

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

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

The most common form of increased surface area is turbulence. In turbulent areas, small droplets are temporarily formed. When this happens, the forces governing Henry's law (partial pressure) quickly try to reach equilibrium between the liquid and atmospheric phases of the gas. The result is often a dramatic release of sulfide from the dissolved to the gaseous form. Structures causing turbulence should be identified and measures should be taken to protect and/or control the subsequent $H_2S_{(g)}$ 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 majority of wastewater collection systems for some portion of the year. A pH of 0.5 (which is approximately equivalent to a 7 % H_2SO_4) has been measured on surfaces exposed to severe $H_2S_{(g)}$ 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 been known to collapse due to loss of structural stability from corrosion. The process of concrete corrosion, however, is a step-wise process which can sometimes give misleading impressions. The following briefly describes the general process of concrete corrosion in the presence of a sewer atmosphere.

Freshly placed concrete has a pH of approximately 11 or 12, depending upon the 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 which 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 effect 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 pH of the surface. Eventually the surface pH is reduced to a level that can support the growth of bacteria (pH 9 to 9.5).

... The time it takes to reduce the pH is a function of the concentration of 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 some severe situations it can be accomplished in a few months. Once the pH of the concrete is reduced to around pH 9, biological colonization can occur. Over 60 different species of bacteria are known to regularly colonize wastewater pipelines and structures above the water line. Most species of bacteria in the genus *Thiobacillus* have the unique ability to convert $H_2S_{(g)}$ to H_2SO_4 in the presence of oxygen. Because each species of bacteria can only survive under a specific set of environmental conditions, the particular species inhabiting the colonies changes with time. Since the production of $H_2SO_4$from H_2S is an aerobic biological process, it can only occur on surfaces exposed to atmospheric oxygen.

Sulfuric Acid Production

As a simplified example, one species of *Thiobacillus* only grows well on surfaces with a pH between 9 and 6.5. However, when the H_2SO_4 waste product they excrete decreases the pH of the surface below 6.5, they die off and another species takes up residence which can withstand lower pH ranges. The succeeding species grows well on surfaces with a pH between 6.5 and 4. When the acid produced by these species drops the pH below 4, a new species takes over. The process of successive colonization continues until species, which can survive in extremely low pH conditions, take over. One such specie is *Thiobacillus* thiooxidans, which is sometimes known by its common name, *Thiobacillus* concretivorous, which is Latin for "eats concrete". This organism has been known to grow well in the laboratory while exposed to a 7 % solution of H_2SO_4. This is equivalent to a pH of approximately 0.5.

Sulfuric acid attacks the matrix of the concrete, which is commonly composed of calcium silicate (CaSi) hydrate gel, calcium carbonate ($CaCO_3$) from aggregates (when present), and un-reacted $Ca(OH)_2$. Although the reaction products are complex and result in the formation of many different compounds, the process can be generally illustrated by the following reactions:

$$H_2SO_4 + CaSi \leftrightarrow CaSO_4 + Si + 2H^+$$

$$H_2SO_4 + CaCO_3 \leftrightarrow CaSO_4 + H_2CO_3$$

$$H_2SO_4 + Ca(OH)_2 \leftrightarrow CaSO_4 + 2H_2O$$

The primary product of concrete decomposition by H_2SO_4 is calcium sulfate ($CaSO_4$), more commonly known by its mineral name, gypsum. From experience with this material in its more common form of drywall board, it is known that it does not provide much structural support, especially when wet. It is usually present in sewers and structures as a pasty white mass on concrete surfaces above the water-line. In areas where diurnal or other high flows intermittently scour the walls above the water-line, concrete loss can occur rapidly. The surface coating of gypsum paste can protect underlying sound concrete by providing a buffer zone through which freshly produced H_2SO_4 must penetrate. Because *Thiobacillus* bacteria are aerobic, they require free atmospheric oxygen to survive. Therefore, they can only live on the thin outer covering of any surface. This means that acid produced on the surface must migrate through any existing gypsum paste to reach sound concrete. When the gypsum is washed off fresh surfaces are exposed to acid attack and this accelerates the corrosion.

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

Another damaging effect of H_2SO_4 corrosion of concrete is the formation of a mineral called “ettringite”. The chemical name for ettringite is calcium sulfbaluminate hydrate. It is produced by a reaction between $CaSO_4$ and alumina, which is found in virtually all cements. 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 which occupies more space that it’s constituents. When ettringite forms, it lifts the corroded concrete away from the sound concrete and causes a faster corrosion by continually exposing new surfaces to acid attack. Although the rate of concrete loss is dependent upon a number of factors including ettringite formation, it is not uncommon to see concrete loss of one inch per year in heavy sulfide environments.

SEWER SEDIMENT CONTROL

Generally if sediments are left to accumulate in pipes, hydraulic restrictions can result in blockages at flow line discontinuities. Otherwise, the bed level reaches an equilibrium level. Conventional sewer cleaning techniques include rodding, balling, flushing, poly pigs, and bucket machines. These methods are used to clear blockages once they have formed but also serve as preventative maintenance tools to minimize future problems. With the exception of flushing these methods are generally used in a “reactive” mode to prevent or clear up hydraulic restrictions.

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

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. In recent years FG equipment for automated cleansing of sediments in both sewer pipes and CSO tanks has been developed in Germany.

Previous Research

In 1966, the EPA predecessor agency initiated a series of research efforts to demonstrate the feasibility of periodic flushing during dry weather. The first phase of work was performed by FMC Corporation at its Central Engineering Laboratories in Santa Clara, CA to determine the feasibility of a periodic flushing system for CS cleaning (FMC 1967). The study included a demonstration of the flushing concept, small-scale hydraulic modeling, and design and development of cost estimates for constructing test equipment (FMC 1967). The second phase produced a flushing evaluation facility consisting of 0.30 m (12 in.) and 0.45 m (18 in.) diameter test sewers about 488 m (1,600 ft) long, supported above ground (thus allowing for slope adjustment), including holding tanks at three points along the test sewer for the flushing experiments (FMC 1972). Limited periodic flushing of simulated CS laterals was accomplished. The report recommended a third phase be accomplished for flushing larger pipe sizes, flush wave sequencing, and determination of solids buildup over long periods of time.

In 1974, a CS management study focused on assessing alternative strategies for abating CSO discharges to portions of Boston Harbor (Process Research 1976). During this study a number of equations based on the critical-fluid-shear stress theory for estimation of dry-weather deposition and flushing criteria were developed. These equations were field checked roughly to ascertain solids accumulations. Although the model was crude, the agreement with visual-field observations was reasonable. The model was then used to analyze deposition problem segments within a service area of 1,200 ha (2,965 acres) entailing roughly 152,500 m (500,350 ft) of sewer. Roughly 3,000 manhole-to-manhole segments were analyzed for deposition and it was determined that roughly 17% of the segments contained about 75% of the estimated dry-weather wastewater deposition. It turned out that most of these segments were small-diameter CS laterals. Flushing criteria were empirically developed using data generated during the earlier

FMC research to estimate required flushing volumes.

In 1979, a three-year research and development program sponsored by EPA was conducted in Boston to determine the pollution-reduction potential of flushing combined sewer laterals using flush water from a water tanker. It was concluded that small-volume flushing would transport organics/nutrients and heavy metals sufficient distances [> 310 m (> 1,000 ft)] to make the option feasible and attractive (Pisano et al. 1979). Other relevant conclusions were:

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

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

- An empirical methodology was prepared for predicting planning level daily deposition solids, nutrient and organic daily collection system estimates within a collection system simply by knowing the total length of pipe within a service area, and average collection system pipe slope, and average per capita flow rates.

Sewer flushing of large-diameter CS was investigated for the City of Elizabeth, NJ (Clinton Bogert Associates 1985). It was concluded that daily flushing of troublesome deposition section within seven sub-areas using 12 automatic-flushing systems was estimated to reduce about 28 %

of the first-flush overflow pollutant loading from the service area. Control was monitored by centralized computer with local water level sensing for CS to be flushed ranging from 0.45 m (18 in.) to 1.4 m (60 in.). Construction of the12 flushing modules was completed in 1990. Estimated construction costs for complete modules (structural, mechanical, electrical, and site work excluding computer control) ranged from $175,000 for small-diameter up to $275,000 for large-diameter lines (costs based on ENR cost index of 5,000). No evaluation data has been reported regarding effectiveness.

Inline Flushing Gate

During the last several decades over 13,000 CSO-storage tanks have been constructed in Germany with over 500 comprising inline storage in sewers 1.8 m (72 in.) to 2.1 m (84 in.) diameter with lengths of 125 m (400 ft) to 180 m (600 ft). Discharge throttles control the outlet discharge to about twice average DWF plus infiltration. Many different methods for cleaning these pipes were tried over the years. The most popular has been the HYDROSELF® system developed in Germany about 11 years ago.

This system is a simple method that uses a washwater storage area and hydraulically-operated flap gates to create a cleaning wave to scour sewer inverts. 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 insystem water level reached a predetermined 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 actual arrangement for a given installation is site dependent. The flushing length, slope, and width determine the flush-water volume needed for an effective single flush of the system.

Figure 1 depicts a FG installation in Whitten, Germany for flushing an inline storage conduit 2m (78 in.) in diameter 770 m (2,530 ft) in length. This system is operated by the Ruhrverbund Authority. River water is pumped to the storage chamber for post operation after a CSO activation. The FG system has been used to clean settled debris and sediment in sewers, interceptors, tunnels, and 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 < 10,000 people, about 100 km (62 mi) northeast of Frankfurt). In that same year the first two pipe storage projects using the FG technology were implemented. As of 1995, in Europe there are 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 (10 in.) to 4.3 m (14 ft) in diameter and flushing lengths of up to 340 m (1,120 ft) for large-diameter pipes. The balance of FG installations is for cleaning sediments from CSO tanks. The largest tank project is in Paris, France for an underground 120,000 m^3 (32 Mgal) tank beneath a soccer field using 43 FG.

For larger sewers [diameter > 2 m (78 in.)], an inline flushing system may be used. The required storage volume for the flush water is created by erecting two walls in the sewer to form a flushwater 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 FG. Should the actual flushing length be longer than this value, then additional FG 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 flushwater storage area by creating a rectangular chamber inline or adjacent to the sewerline itself.

CSO STORAGE TANK CLEANING

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

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

Tipping Flushers

TF systems have been used in North America for five years (about 20 tanks with flushers in the United States, with most located in Michigan area), and have been operational in Germany and Switzerland for over 12 years. The TF system is extremely effective for subsequent cleansing of debris from the floors of all types of urban-storm-runoff (CSO and stormwater) tanks. These devices were initially developed in Switzerland.

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

The experience with U. S. TF systems indicates that dedicated secondary cleaning operations, using water cannons or high-pressure hoses, are not needed. If the first TF flush of the basin does not remove all of the sediment, the basin can be re-flushed or “mopped-up” by fire hoses. In Germany and Switzerland, tank sidewalls are generally hand trowelled to a very smooth finish to prevent buildup from occurring, and consequently do not require frequent washdown. “Mop-up” cleaning of the influent and washdown channels has been accomplished with small TF in large German tanks and in Saginaw, MI. Figure 2 shows the TF system for CSO tanks at the 14th Street CSO facility in Saginaw. The facility was one of the first in the U. S. to use the TF technology and in 1994 the project was awarded the 2nd place national ACEC design prize.

Flushing Gates

The FG was originally developed in Germany (1985) as a method for flushing sediments in pipe segments (inline storage or troublesome flat trunk and interceptor sewers), and then evolved for use in CSO tanks. In concept this scheme is depicted in Figures 3 and 4 from a facility in Sarnia, ON, Canada.

The system is comprised of two basic elements, a gate and a closed-circuit-hydraulic-actuation system utilizing a float-control mechanism. A low-level wall is constructed across the short axis of the influent end of the tank approximately 1.5 m (5 ft) to 2 m (6.5 ft) high. The wall is located on the influent end of the tank to guarantee filling the space behind the wall prior to filling the rest of the tank. The instantaneous opening of a stainless-steel gate that is mounted on the face of the wall activates the system. The release of the gate creates a “dam-break” scenario, which generates a high-velocity flushwave [generally maintaining a velocity in excess of 1.8 m/s (6 ft/s)]. Normally the width of the FG is approximately 70% of the effective flushing lane width. The volume retained behind the wall required for proper cleaning is a function of flushing length and floor slope. The “nominal” design volume can be adjusted by changing the height of a level standpipe on the backside of wall. The hydraulic system can also be connected to a central control system (on or off-site) with auto or manual override.

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

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

CASE STUDIES

18 Inline Sewer and Storage Tank Flushing Cases

The approach for examining the effectiveness of various types of flushing technologies in this paper is based on a current understanding of the characteristics of settling, resuspension, and transport of sewer and storage tank sediments. An evaluation methodology was developed to investigate 18 facilities in Germany and in North America (Pisano et al. 1998). The objectives of these evaluations included:

- Collect dimensional and operational data of CS inline and CSO storage-tank facilities that utilize FG or TF for cleaning;
- Evaluate the effectiveness of the system design in terms of sediment removal;
- Compare capital and O&M costs of FG and TF facilities with other cleaning methods.

Table 1 presents a guide outlining the major features of the 18 case studies. Contents of the table include location; flushing function, i.e., either flushing of storage pipe, conveyance pipe, or tank; tank geometry (rectangular or circular); flushing method, i.e., either FG or TF; flushing volumes for pipe configurations, either generated by offline or inline compartments; flushing volumes for tanks are noted as inline.

Inline versus offline refers to the relative location of the flushing volume. Due to space limitations, flush volumes are often generated inline with main convergence function accomplished by an underflow conduit or channel under the flush volume chamber. Vaults with large flushing volumes are commonly provided by offline configurations. Average slope refers to the slope of the conduit or section being flushed. Slope of flush volume refers to the floor slope of the flush vault. FG activation is accomplished either by passive float operation termed "hydraulic" or by an active electrical signal from an external location termed "electrical". Water source refers to the source of the water for flushing, i.e., “local waste” or “external supply”. Performance assessment is defined as follows: “Excellent” – all sediments in channel or bay cleaned with flush; “Good” – substantial removal of sediments in channel, i.e., 90% of flush lane or pipe is cleaned; “Fair” – partial removal of sediments, i.e., 50%.

One of the more interesting flow sheets of the case-study investigation was the Stadt-Essen storage facility. Details are provided in Figures 3 and 4. The facility features a unique inlet scheme where the underflow is concentrated in a vortex chamber that discharges back to the dry-weather sewer. Once the underflow capacity is exceeded, the influent channel to the FG fills which in turn fills the flush vaults and tank. The flushed sediments are collected in the mud sump for discharge back to the dry-weather sewer.

Information collected for four FG systems for CS are presented in Table 2. Estimated flush-wave peak velocity and flow depth at the end of flush segments were determined using survey hydraulic data as inputs into the EPA’s Stormwater Management Model (SWMM) (Huber and Dickinson 1988) with the Extended Transport Block (EXTRAN) (Roesner et al. 1988). The analysis assumes that if the terminal velocity at the end of the flush ≥ 1 m/s (≥ 3.28 ft/s) then the flush wave would have reasonably cleansed any deposits. At the far-right-hand side of Table 2 are the operator observations. Qualitative operator observations have good agreement with the quantitative modeled velocity. For example, the terminal velocity of Stadt Kirchhain is 0.60 m/s, which is the lowest velocity, and the operator observed only “Fair” flushing results. Summary results of SWMM EXTRAN simulations of FG performance for five rectangular tanks in Germany are presented in Table 3. Flushing volumes computed from the construction drawings are used as inputs into rectangular open channels (flushing lane).

Velocities shown are computed at the end section of the flushing lane, just prior to discharge into the end channel. There is reasonable agreement between estimated flush-wave velocities and the qualitative operator observations.

Cost Effectiveness of CSO Tank Cleaning Methods.

Four cleaning systems were compared for the Devine Street outfall CSO-storage tank in the City of Sarnia, ON, Canada, including manual cleaning, flushing spray, TF, and FG. The costs of these cleaning systems are shown in Table 4 (Parente 1995) . Because of water conservation and lower capital cost, the FG system using detained wastewater was selected as the most cost-effective alternative. This system requires less mechanical equipment, such as valves and supply lines, that are otherwise necessary for an external water source used for the TF. The O&M costs tend to be marginally lower since no additional costs are incurred for the supply of potable water for flushing purposes and the associated treatment of the flushing water.

Cost Effectiveness of Sewer Sediment Flushing.

A cost analysis comparing FG technology to conventional-large-pipe-cleaning operations using bucketing methods was conducted for an actual project under construction in Cambridge, MA. A system of FG to flush a 1,500 m (5,000 ft) length of large-diameter sanitary sewer [size range: 0.46 m (18 in.) to 1.2 m (48 in.)] and storm drains [size range: 0.6 m (24 in.) to 1.2 m x1.8 m (4 ft x (6 ft)] was examined. A present worth (9% interest, 30 years) savings of at least $500,000 is estimated (costs based on ENR cost index of 6,500) using the FG technology in lieu of periodic cleaning using conventional means.

Cost Effectiveness of Sewer Sediment and Hydrogen Sulfide Control Methods.

H_2S can be effectively controlled by using in-sewer chemical addition. A cost-effectiveness study was conducted by using FG technology in conjunction with iron salts addition in a long-flat-depositing sewer carrying warm-sanitary wastewater with high-organic loadings with estimated $H_2S_{(aq)}$ concentrations. The cost analysis was based on an inflation rate of 3.12% per year and discount rate of 7.1% for a 30-year term (ENR cost index of 6,500). Results indicated that the present worth costs for $FeCl_3$ treatment with and without FG for the treatment of corrosive and dangerous levels of $H_2S_{(aq)}$ were estimated to be $12.5 and 15.5 million, respectively. A saving of $3 million would be realized if chemical treatment with FG operation.

CONCLUSIONS

The control and reduction of H_2S in CS systems is of vital importance. From the evaluations of a combination of the 18 sewer and tank sediment flushing facilities and the case studies presented in the full report (Pisano et al. 1998) conclusions are summarized:

- Both the TF and FG technology appear to be the most cost- effective means for flushing solids and debris from tanks. The most efficient method for flushing large-diameter-flat sewers (containing sediment) is the FG technology.
- The performance of both types of flushing equipment for tanks and FG for sewers was rated as good to excellent. Based on calculations for most of the facilities using FG, the terminal velocities at the end of the flushing wave exceeded 1 m/s. This terminal velocity was adequate for cleansing.

- Cost-effectiveness analysis comparing FG gate technology versus conventional large-pipe cleaning operations using bucketing methods was conducted for an actual project undergoing construction. A system of FG to flush 1,500 m (5,000 ft) of large-diameter sanitary sewer and storm drains was examined. Present worth savings of at least $500,000 (costs based on ENR cost index of 6,500) is expected using the FG technology in lieu of periodic cleaning using conventional means.
- A desktop analysis was conducted to explore the use of FG technology for minimizing sediments in a long-flat depositing sewer carrying warm wastewater with high-organic loadings. $H_2S_{(aq)}$ levels attributable to both the slime layer and to accumulated sediments were estimated. The present worth costs for treating excessive and dangerous levels of $H_2S_{(aq)}$ with chemicals (iron salts) were estimated. FG technology was explored to reduce sediments and thereby reduce incremental H_2S loadings. As a result, a lower rate of chemical dosage would be needed.

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Table 1. Overview of Case Studies

Location	Flushing Function: Sewer – Storage	Flushing Function: Sewer – Convey	Flushing Function: Tank – Rect.	Flushing Function: Tank – Circ.	Flushing Method: Flushing Gate – Inline	Flushing Method: Flushing Gate – Off-line	Flushing Method: Tipping Flusher – Tank
Marht Wiesentheid, Germany	X				X		
Gemeinde Schauenburg, Germany	X				X		
Stadt Kirchhain, Germany	X					X	
Stadt Heidenheim, Germany		X			X		
Markt Grossostheim, Germany		X				X	
Osterbruch-Opperhausen, Germany		X				X	
Gemeinde Hettstadt, Germany	X					X	
Filterstadt-Bernhausen, Germany			X		X		
Stadt-Essen, Germany			X		X		
Markt-Wiesentheid, Germany			X		X		
Stuttgart-Wangen, Germany			X		X		
Heidenheim-Kleiner-Buhl, Germany			X		X		
Cheboygan, Michigan (MI), US				X	X		
Sarnia, Ontario, Canada			X		X		
Port Colborne, Ontario, Canada			X				X
Wheeler Avenue, Kentucky, US			X				X
14th Street Pumping Station, MI, US			X				X
Saginaw Township, MI, US			X				X

Table 2. Summary of German Combined Sewer Flushing Evaluation

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

Table 3. Summary of German Tank Flushing Case Studies

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

Table 4. Devine Street, Ontario, Canada , Tank Flushing; Capital and O&M Cost Comparison (costs based on ENR cost index of 6,500)

Type of Cleaning System	Capital Cost ($)	Unit Cost ($/$m^2$)	O&M Cost ($/event)	Unit O&M Cost ($/$m^2$/event)
Manual Cleaning	10,000	3.0	6,6000	1.92
Flushing Spray	680,000	198.0	1,550	0.45
Tipping Flusher	525,000	153.0	380	0.11
Flushing Gate	350,000	102.0	250	0.07