SEWER-SEDIMENT CONTROL:
OVERVIEW OF AN EPA WET-WEATHER FLOW RESEARCH PROGRAM

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ABSTRACT: This paper presents a historical overview of the sewer sediment control projects conducted by the Wet-Weather Flow Research Program of the U. S. Environmental Protection Agency. Research presented includes studies of the causes of sewer solids deposition and development/evaluation of control methods that can prevent sewer-sediment accumulation. Discussions focus on the relationship of wastewater characteristics to flow-carrying velocity, abatement of solids deposition and solids resuspension in sewers, and sewerline flushing systems for removal of sewer sediment. Methods for abating sewer sedimentation include steeper sewer slopeage, pipe bottom shapes that maintain high velocity during low-flow conditions, and periodic sewer flushing. The future research program plan for sewer-sediment control is also presented.

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INTRODUCTION

Combined-sewer wastewater solids deposition during dry-weather flow (DWF) periods and their subsequent resuspension during wet-weather flow (WWF) periods has long been recognized as a major contributor to the highly-polluted segment or first-flush phenomenon of the combined-sewer overflow (CSO) event. Another potential cause of the polluted segment, in addition to the resuspension of material deposited in lines during DWF periods, is the resuspension and conveyance of solid particles on the urban-ground surface into the urban-drainage system. These particles can either go through the system or settle out in the system and be available for washout during periods of higher storm-generated flows. One of the underlying reasons for wastewater-solids deposition is the combined-sewer-hydraulic design. Combined sewers are sized to convey many times the anticipated peak dry-weather wastewater flowrate. During dry-weather conditions the flowrates and associated velocities and shear forces are too low to carry a significant portion of the suspended solids (SS), allowing them to settle. During many wet-weather conditions, flowrates (shear forces) are high enough to both resuspend these solids and carry them to the CSO point. The annual magnitude of the CSO SS loadings generated during storm periods has been estimated to be as much as 30 percent of the annual dry-weather wastewater loadings (Field and Struzeski 1972). As a result, a large residual sanitary-pollution load, over and above that normally carried, is discharged over a relatively short interval of time, often resulting in a relatively high polluted segment of the CSO event. Thus, during the initial period of a storm event, SS concentrations of several thousand milligrams per liter (mg/L) are not uncommon for CSOs. These high SS and associated pollutant loadings cause ecological risk

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in receiving waters.

In recognizing the problems of WWF-induced water pollution, the Federal Water Pollution Control Administration, the predecessor of the U. S. Environmental Protection Agency (EPA) launched the Storm and Combined Sewer Overflow Research Program in 1965 (now called the Wet-Weather Flow [WWF] Research Program). This paper presents an overview of the WWF Research Program's Sewer Sediment Control Subprogram that commenced with sewer flushing studies in 1967 (FMC 1967b and 1972) which subsequently gave rise to sediment characterization and control projects (Field 1989, 1995; Field et al. 1996).

CAUSES AND IMPACTS OF SEWER SEDIMENT

One of the underlying reasons for considerable solids deposition in combined sewers is their hydraulic design. Combined sewers are sized to convey many times the anticipated peak dry-weather wastewater flow. Combined sewers can carry up to 1,000 times the expected sanitary- or dry-weather wastewater flow because they are designed for very infrequent (e.g., 1 in 5 yr and 1 in 10 yr) storm-flow events. In large portions of the total length of conventional combined-sewer systems (CSS), it is impossible to attain DWF velocities that have high enough shear forces to carry SS or resuspend sediment. This condition allows for continuous DWF solids deposition. Furthermore, it is usually even more difficult to obtain adequate solids-carrying velocities in the upstream segments of a combined-sewer system due to flat grades and low flows (FMC 1967a, b).

Tomlinson et al. (1980) and Klemetson et al. (1980) conducted a number of studies on the transport of sewer sediment in receiving waters. Further mathematical modeling evaluation of the CSO sediment transport in receiving waters was documented by Keefer and Clyde (1985). Their work contains a linear, implicit, finite-difference flow model and an explicit, finite-difference sediment-transport model. Experiments with the sediment model indicate that it can be used for qualitative assessments of the fate of various sediment-size fractions in receiving streams if properly calibrated.

Solids that enter the CSS that originate from roof tops, streets and highways, construction sites, commercial and industrial parking lots, automobile maintenance yards, and lawn irrigation and runoff contribute substantial amounts of toxic-laden particles. Accumulations of these particles during DWF conditions results in a layer of sewer-bed sediment which undergoes a series of anaerobic biotrasformations that result in the release of noxious and hazardous hydrogen sulfide (H_2S). The H_2S is then converted to sulfuric acid (H_2SO_4) on the interior surface of sewerlines. H_2SO_4 is highly corrosive to the sewerage system causing structural disintegration. The primary product of concrete decomposition by H_2SO_4 is calcium sulfate ($CaSO_4$) or gypsum. Further reaction between $CaSO_4$ and alumina produces calcium sulfuraluminate hydrate or "ettringite." 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 a concrete loss of 1 in./yr in heavy sulfide environments. Thus, dry-weather-sewer sediment creates odor and sewer-decomposition problems, in addition to the CSO

pollution (Pisano et al. 1998).

TRANSPORT OF SEWER SOLIDS

Sewer flow-carrying velocities for solid-phase matter were first evaluated at a sewer pilot system

in 1967 (FMC 1967a). Results indicated that the flow velocity for resuspension of the settled

solids was much greater than the flow velocity in which solids would settle (*i.e.*, solids

resuspension ≥ 0.44 m/s [1.44 ft/s] vs. solids settling < 0.27 m/s [0.88 ft/s]). Microscopic

examination of the sewer-sediment samples collected from the test pilot sewerline found sand-

like particles with a size range of $40 - 900$ μm having a specific gravity range of $2.4 - 2.6$.

These particles required the highest flow velocity to be resuspended from the bottom of the test

sewerline. Another investigation was conducted to determine the settling characteristics

(including size and specific gravity distributions) of solids in sanitary wastewater, CSO, and

stormwater runoff (Dalrymple et al. 1975). The settling velocity distributions, for road dust (10

$- 20$ μm) and wastewater solids ($74 - 149$ μm), appeared to relate to Stokes' law for spherical

particles at these size ranges. According to Stokes, for Reynolds numbers (R_e) < 1, particle

settling velocity (v_s) can be expressed as:

$$R_e = \frac{v_s d}{\mu} \quad …..……………………..………………….. (1)$$

$$v_s = \frac{d^2(\gamma_s - \gamma_w)}{18\mu} \quad ………..………………………………… (2)$$

where:

v_s = particle settling velocity d = effective particle diameter

γ_s = particle specific gravity γ_w = fluid specific gravity

μ = fluid viscosity

Sonnen (1977) developed a subroutine, named SETVL, to determine particle settling velocity for

a wide range of R_e values. The general equation used in the subroutine is:

$$ v_s = \left[\frac{4gd(\gamma_s - \gamma_w)}{3C_d\gamma_w} \right]^{1/2} $$ .... (3)

where:

v_s = particle settling velocity d = particle diameter

γ_s = particle specific gravity γ_w = fluid specific gravity

C_d = drag coefficient g = acceleration due to gravity

For R_e > 3,000, a C_d value of 0.4 is assumed to start the computation. If the calculated R_e is <

3000, turbulent conditions do not exist and the value of C_d is computed by this equation:

$$ C_d = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34 $$ ....(4)

This leads to a new value of v_s. By using Newton's Method of iteration with the values of R and

C_d, convergence to a final solution will occur. In addition to the SETVL subroutine for

computing particle settling velocity, Sonnen (1977) also developed three other subroutines that

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were added to the 1973 version of the EPA Stormwater Management Model's (SWMM) Extended Transport Block (EXTRAN). These subroutines included SCRDEP for computing scour, deposition, and transport of solids in various sewer shapes, SCROUT for reporting intermediate simulation information about the state of solids in a sewer system, and TREAT for tabulating solids removal (by fractions) and costs in a treatment plant. The earlier version of EXTRAN has two components: a hydraulic model and a quality model. While the hydraulic model has been continuously maintained and updated, the quality model encountered problems early on and has been essentially abandoned. It has never been distributed to the public as was EXTRAN and the rest of the SWMM blocks. However, the theory adopted by Sonnen in 1977 for simulation of solids transport in a sewer system can be useful for predicting the fate and transport of sewer solids and their control.

In a sewer, as in a natural channel, sediment can be transported in suspension, as bedload rolling or sliding along the bed, or interchangeably by suspension and bedload. To facilitate analysis and understanding, sediment loads are usually classified three ways: bedload, suspended load, and washload. Sonnen (1977) defined *bedload* as solid materials that move near the pipe bottom, *suspended load* as materials that have at one time been deposited and have subsequently been swept from the *bedload* into the overlying flow, and *washload* as particles that have entered the pipe at its upstream junction and have been determined to remain in suspension under the given flow condition but can change over time. Most of the model formulations described below were taken from the book by Graf (1971) on sediment transport and the book by an ASCE Task Committee (1975) on sedimentation engineering.

Bedload Transport

For bedload transport, Sonnen (1977) used Kalinske (1947) data to derive the following relationships for computing mass of solids in motion per unit width of pipe:

$$\frac{q_s}{u_* d} = 2x10^{-(\tau_0)_{cr}/\tau_0}; \qquad 0.3 < \frac{(\tau_0)_{cr}}{\tau_0} \leq 2.0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

$$\frac{q_s}{u_* d} = 434.1x10^{-2.17(\tau_0)_{cr}/\tau_0}; \qquad \frac{(\tau_0)_{cr}}{\tau_0} > 2.0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

$$\frac{q_s}{u_* d} = 27x10^{-4.77(\tau_0)_{cr}/\tau_0}; \qquad \frac{(\tau_0)_{cr}}{\tau_0} \leq 0.3 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

Where

q_s = volume rate of solids movement per unit width, m^3/s-m

u_* = shear velocity, $(\tau_0/\rho)^{0.5}$, m/s

d = median particle diameter, mm

τ_0 = shear stress = $\Upsilon r_h s$, N/m^2

$(\tau_0)_{cr}$ = critical shear stress, obtained at moment of particle incipient motion

(resuspension), N/m^2

ρ = density of water, kg/m^3

Υ = specific weight of water, N/m^3

r_h = hydraulic radius of flow, m

s = the energy slope, m/m

The values of $(\tau_0)_{cr}$ are related to d:

$$(\tau_0)_{cr} = 0.7105\,d^{1.0648}, \quad d \geq 6 \text{ mm}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

and

$$(\tau_0)_{cr} = 0.3208\,d^{0.2238}, \quad d < 6 \text{ mm}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

Suspended-Load Transport

Sonnen (1977) adopted Equation (10), attributed to Rouse (1937), for relating suspended sediment concentration with flow depth:

$$C_y = C_a \left(\frac{D-y}{y}\frac{a}{D-a}\right)^Z \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

Where:

C_y = the concentration of suspended particles at depth, y, kg/m^3

D = total depth of flow, m

C_a = reference concentration near the bed, kg/m^3

a = the reference depth where C_a occurs, taken as $2d_{60}$, m

d_{60} = diameter of particle of which 60% are finer, mm

z = v_s/ku_*

v_s = settling velocity of particles in quiescent water, m/s

k = von Karman "constant" equal to 0.385

u_* = shear velocity, $(g\ r_h\ s)^{0.5}$, m/s, for $g,\ r_h,\ s$ see equation 3, 5, 6, and 7 definitions

The value of C_a is estimated for each particle size from the relationship:

$$C_a = \frac{1}{11.6} \frac{g_s}{u_*' a'} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(11)$$

in which

u_*' = shear velocity computed with a hydraulic radius with respect to the grains of

solids, $(g\ r_h'\ s)^{1/2}$, m/s

a' = reference depth, m, essentially equal to a in equation 10

g_s = the amount of bedload transport per unit width, kg/s-m, for each particle size

determined in equations 5 – 7

r_h' = the portion of total hydraulic radius attributable to the grains of solids, m

To determine r_h', Sonnen (1977) derived the following expression:

$$\frac{V}{u_*'} = 5.75 \log(12.27 \frac{r_h'}{d_{60}}) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(12)$$

in which V is the average velocity in the pipe and its value is provided from EXTRAN hydraulic

model. Equation (12) can then be solved iteratively for r_h'. All variables on the right-hand side

of Equation (10) are defined and C_y can then be computed.

To get a better estimate of the flux of suspended load in a pipe, Sonnen (1977) divided the entire

flow depth into five equal intervals. Values of C_y were computed at midpoints of each interval.

Values of corresponding velocity, u_y were computed from the following velocity distribution

equations given by ASCE (1975):

$$u_y = u_*[5.5 + 5.75 \log \frac{u_* y}{v}]; \quad R_{e(10)} = \frac{u_* d_{60}}{v} \leq 10 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

or

$$u_y = u_*[8.5 + 5.75 \log \frac{y}{d_{60}}]; \quad R_{e(10)} = \frac{u_* d_{60}}{v} < 10 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

in which v is the kinematic viscosity of water (1.00×10^{-6} m^2/s at 20° C)

The mass of suspended load movement per unit width and time, g_{ss} (kg/m-s), is obtained by

summing over the five depth intervals as:

$$g_{ss} = \Sigma (C_y u_y \frac{D}{5}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

The total mass moved through the pipe in a given time interval is obtained by multiplying g_{ss} by

width and by the time elapsed.

Washload Transport

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The sediment routing model adopted the following relationship, attributable to Durand (1953) from his work on solid-liquid mixtures in pipes, for separating the deposit-free regime from the deposit regime:

$$\frac{V_c}{\sqrt{2\,gD\,(S_s - 1)}} = F_L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

Where:

V_c = the critical velocity, m/s

D = water depth, m

S_s = the specific gravity of the solids, dimensionless

F_L = a dimensionless parameter ranging from 0.8 to 1.1

but the model adopted the value of 0.9

When flow is at the computed "critical" velocity V_c or greater, all particles entering the pipe with a specific gravity of S_s or less will not deposit. Their effective settling velocity in the flow can be taken as zero. At flow velocities less than V_c, a portion of the particles may be able to deposit. Under this condition, the model uses the following equation to estimate the proportion of particles that are removed:

$$PART = \frac{w}{Q / A_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

where w is the effective settling velocity (m/s), Q is the flow through the pipe (m³/s), and A_s is the surface area of the flowing pipe (m², width of the flowing water times the length of the pipe). The effective settling velocity is computed by a linear interpolation between 0 and v_s:

$$w = \frac{V_c - V}{V_c} v_s \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(18)$$

where v_s is the settling velocity in an ideal, quiescent tank. The washload is computed as:

$$WL_i = TRANS_i(1 - PART) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(19)$$

where WL_i is the washload, kg, in particle size group i moved through the pipe in the time

period, and $TRANS_i$ represents the total solids, kg, in particle size i that enter the pipe from the

upstream junction in the current time period. The remainder of $TRANS_i$ will deposit in the bed.

This deposited materials cannot became part of the washload in the same time period.

The above equations (3 through 19) formed the basis of Sonnen's version of the "EXTRAN"

water-quality model for routing particles by size as bedload, suspended load , or washload, and

kept track of the net deposition to, or the resuspension from, the bottom deposit in each sewer

segment. To facilitate simulation of sewer-sediment control, conduits with cunette sections were

added to both the hydraulic and water quality models. Three cunette shapes were incorporated:

circular pipe with semicircular cunette, circular pipe with rectangular cunette, and rectangular

pipe with rectangular cunette. The tabulated values of hydraulic radius, surface width, and

cross-sectional area for the corresponding cunette conduits were incorporated into the programs.

ESTIMATION OF DRY-WEATHER POLLUTANT DEPOSITION LOADING

Determination of where to apply sewer-sediment control alternatives requires a good prediction of the location and quantity of deposited solids that build-up during the DWF period. Based on regression analysis of field data surveyed from Boston and Fitchburg, MA (Pisano and Queiron 1977), and Cleveland, OH, (Pisano and Queiron 1984), three empirical models (i.e., Simplest, Intermediate, and Elaborate) were developed for estimating total solids (*TS*) deposition loading in CSS for different purposes (e.g., assessment, planning, or designing). Nine variables were tested in the regression analyses. The Elaborate Model represents the highest multiple-correlation coefficient value ($R^2 \geq 0.94$), and the R^2 is ≥ 0.85 for the Simplest Model. Models calibrated with field data collected from Boston and Fitchburg, MA and Cleveland, OH (Pisano and Queiron 1984) are:

Fitchburg, MA:

Simplest Model: $TS = 0.0011\ (L^{1.063})(S^{-0.436})(Q^{-0.51})$ 　　　　　　　　$[R^2 = 0.85]$

Intermediate Model: $TS = 0.0013\ (L^{1.18})(D^{0.604})(A^{-0.178})(S^{-0.418})(Q^{-0.51})$ 　　$[R^2 = 0.85]$

Elaborate Model: $TS = 0.00073\ (L^{0.814})(S_{PD}^{-0.819})(S_{PD/4}^{-0.108})(Q^{-0.51})$ 　　　$[R^2 = 0.95]$

Cleveland, OH:

Simplest Model: $TS = 0.0012\ (L^{1.065})(S^{-0.433})(Q^{-0.539})$ $\qquad$ $[R^2 = 0.88]$

Elaborate Model: $TS = 0.00017\ (L^{0.948})(S^{-0.323})(S_{PD}{}^{-0.519})(S_{PD/4}{}^{-0.148})(Q^{-0.518})$ $\quad$ $[R^2 = 0.94]$

Where:

A = service area of collection sewer system, ha

D = average sewer diameter, mm

L = total sewer length, m

L_{PD}= sewer length corresponding to 80% of the solids deposited in the sewer system, m

Q = flowrate per capita, including allowance for infiltration, L/capita-d

S = average sewer slope, m/m

S_{PD} = sewer slope corresponding to L_{PD}, m/m

$S_{PD/4}$ = sewer slope corresponding to ¼ of the percentage of sewer length (L_{PD}) below

which 80% of the solids deposit, m/m

TS = daily total wastewater solids deposition loading in collection system, kg/d

As shown above, all R^2 values of these regression models are ≥ 0.85. The differences of R^2

values between Boston and Cleveland are < 5% for the Simplest Model and < 1% for the

Elaborate Model.

The total sewer length of the CSS, 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

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Queiron 1977):

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

$$L' = 168.95 \, (A)^{0.928} \qquad\qquad (R^2 = 0.82)$$

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

$$L' = 239.41 \, (A)^{0.928} \qquad\qquad (R^2 = 0.821)$$

If data on pipe slope is not available, the average sewer slope, S' can he estimated from the average ground slope S_g using the following equation:

$$S' = 0.348(S_g) \qquad\qquad (R^2 = 0.96)$$

METHODOLOGY FOR SEWER-SEDIMENT CONTROL

For controlling sewer sediment or any other pollutants in urban sewersheds, it would be much more advantageous to use an integrated approach including solids-source management, inline and in-sewer control, and treatment facilities. Source controls are a part of the best management practices (BMPs) for reducing solids from the urban catchment that would otherwise enter the sewer system during wet-weather conditions (Willson et al. 1977). A major portion of surface-solids control can be achieved through the installation of improved catchbasins for intercepting street debris (Lager et al. 1977; Aronson et al. 1983) and application of effective soil erosion-control techniques at construction sites (US EPA 1973; White and Franks 1978; Buxton and

Caruccio 1979). Improvement of CSS design, including cross-sectional bottom configurations

for low-flow solids conveyance, steeper sewer slopes, inline storage and routing, and inline

sediment control will afford better cost effectiveness and solids-capture efficiency compared to a

comparably designed separate storm and sanitary system or conventionally designed CSS

(Sonnen 1977; Kaufman and Lai 1978).

Sonnen (1977) used his version of the "EXTRAN" water quality model to evaluate the effects of

sewer slope and shape on the transport of sewer solids using a hypothetical case. The results

indicated that the increased slopes allowed more solids to reach the wastewater treatment plant

(WWTP) so they could be removed. It was estimated that 25 and 50 % greater slopage (from

0.0008 to 0.001 m/m and from 0.0008 to 0.0012 m/m, respectively) would achieve an additional

30 and 70% solids removal, respectively. However, the simulation results of cunette-bottom-

shaped and circular-shaped cross-sections indicated that the circular pipe transported more solids

to the treatment plant and had less accumulation on the pipe bottom than the cunette-shape

conduit. This might be a function of the sizes chosen for the examples and not a general

refutation of the cunette's reputed self-cleansing properties, despite the monetary upsets in the

hydraulics results for the cunettes.

In addition, sewer-sediment-control methods (e.g., sewer flushing), should be considered as an

effective method for retrofitting existing CSS or in the design of new ones (Kaufman and Lai

1978 and 1980).

SEWER FLUSHING

The concept of sewer flushing had been applied more than 100 years ago as a maintenance measure. Today, it involves resuspension and transport of deposited solids and their associated pollutants to the WWTP during DWF, by conveying solids deposited in the upper reaches of large CSS to points closer to the WWTP where there is more flow for solids conveyance and/or to a downstream point of series flushing. The intent is to reduce depositing pollutants that may be resuspended and prevent their overflow during WWF events. Periodic sewer flushing during DWF periods can be conducted to remove accumulating material and convey it hydraulically to a WWTP. This reduces the amount of solids resuspended during WWF events and lessens the need for CSO storage and treatment and sludge removal at downstream storage facilities. Furthermore, it allows the passage of more WWF to the WWTP for treatment, by reducing sewer blockages, and if the flushing system is used, for interceptor sewer-solids resuspension.

Engineered sewer-sediment flushing systems are potentially low-cost and low-structurally-intensive controls. By creating high velocity flushing waves to resuspend deposited sediments, these methods have been used to effectively reduce sediment and debris levels. Hydraulic pilot-plant studies were initiated by the EPA predecessor agency at the FMC Central Engineering Laboratories in Santa Clara, CA to determine the feasibility of a periodic flushing system for combined-sewer cleaning (FMC 1967b, 1972). Subsequent field evaluation and modeling study results indicated that sewer-sediment flushing can significantly reduce overall costs when integrated with other upstream control practices and downstream storage tanks (FMC 1972;

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Kaufman and Lai 1978, 1980; Pisano et al. 1979).

Internal automatic flushing devices have been developed for sewer systems. An inflatable fabric dam (FMC 1972) has been used to stop flow in upstream reaches to back up volume capable of generating a flushing wave. When the appropriate volume is reached, the bag is deflated, releasing the impounded wastewater, resulting in the cleaning of the downstream sewer segment.

Field experience indicated that sewer flushing by manual means (water-tank truck) was a simple, reliable method for CSO solids removal in smaller diameter laterals and trunk sewers as the results of field investigation in Dorchester, MA (Pisano et al. 1979). A sediment-solids removal efficiency of 40% and BOD_5 removal efficiency of 60% were attained in a 300- or 380-mm sewer, respectively using a flushing volume of approximately 1.5 m^3, injected at a rate of approximately 15 L/s. These removals were effective for segment lengths of up to 305 m downstream of the flushing station. Results indicate that flushing is also an effective means for suspending and transporting heavy metals associated with light colloidal particles. Approximately 20 − 40% of heavy metals contained in sewer sediment, including cadmium, chromium, copper, lead, nickel, and zinc were transported at least 305 m by flush waves.

During the last 15 years, at least three new passive hydraulic-flushing systems have been developed and installed in sewers and/or storage tanks in more than 500 locations in Europe, the United States, and Canada (Pisano et al. 1998). During that time, two new systems (Tipping Flushers® and HYDROSELF® (flushing gate) developed in Switzerland and Germany,

respectively) have been widely used in Europe for cleaning accumulated sludge and debris in

CSO and stormwater storage-sedimentation tanks. Pisano et al. (1998) evaluated the

performance of these two technologies, i.e., the tipping flusher and the flushing gate by a

detailed examination of 18 facilities in Germany, Canada, and United States. As a result, both

the tipping flusher and the flushing gate technology appear to be the most cost-effective means

for flushing solids and debris from CSO-storage tanks. The flushing gate was found to be the

most efficient method for flushing large-diameter, flat sewers. These gates are hydraulically

operated to open quickly to release backed-up combined wastewater for flushing grit and debris

to downstream collector grit pits. A cost-effectiveness analysis conducted for an actual project

compared flushing-gate technology to conventional large, pipe-cleaning operations using

bucketing methods. The flushing-gate system was found to be more cost effective and was

selected for the project (Pisano et al. 1998).

CONCLUSIONS AND RECOMMENDATIONS

Combined sewers that are oversized to accommodate very infrequent WWF events act as

sedimentation unit processes during DWF periods. This is due to the low-flow velocities they

typically experience. As a result of these low-flow velocities, these oversized sewers fail to

maintain settleable solids in suspension. In addition to the organic solids in the sanitary

wastewater, solids that enter the CSS from roof tops, streets and highways, construction sites,

commercial and industrial parking lots, automobile maintenance yards, and lawn irrigation and

runoff contribute substantial amounts of toxic-laden solids. Aside from CSO pollution, sewer

sediments create odor problems and hazardous and corrosive conditions. The production and release of H_2S gas in CSS 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 National CSO Control Policy (EPA 1994), which requires control and treatment of all CSO, will result in CSO control compliance costs approaching 100 billion dollars. Thus, low-cost low-structurally intensive controls, e.g., sewer-sediment flushing, must be thoroughly considered in any new CSO control planning effort.

The goal of sewer flushing is to transport the resuspended sediment to strategic locations, i.e., to a point where the wastestream is flowing with sufficient velocity, to another point where flushing will be initiated, to a storage sump (trap) which allows later removal of the stored contents, or to the WWTP. This eliminates H_2S gas that causes health hazards and sewerline corrosion, reduces the amount of solids resuspended into CSO during storm events, lessens the need for CSO storage-treatment and sludge removal at downstream storage facilities, and allows the conveyance of more flow for treatment at the WWTP.

Innovative methods for cleaning accumulated solids and debris in CSS (and storage tanks) have emerged over the last 15 years. Although flushing of sewerlines was widely used around the turn of the century as a maintenance practice, it is still in its infancy regarding its use as a pollution-control alternative for CSS. Development of new and improved sewer sediment control methods will be a continuous research effort.

To control sewer sediment and its resulting problems, an integrated approach should be adopted

for the design of urban-drainage systems. A wide variety of options can be used, including

upland BMP solids removal, the sewer-system, and storage-treatment facilities. The design of

the total system should be the objective, not the individual design of its parts. A model, such as

the Sonnen's (1977) version of the "EXTRAN" water-quality model, would be able to assist in

meeting the overall objective. This sewer analysis model is a useful tool that could be applied in

a variety of field applications, both to test its relationships and inherent assumptions and to allow

sewer cleansing evaluations and designs to be performed. More research is being undertaken in

the area of sewer-sediment transport. Particularly important topics for research are the

characterization of bedload, suspended load, and washload in cohesive sediment conditions,

extension of the relationships to account for cohesiveness and armoring of deposited materials,

and the linkages between sediment solids and other constituents such as organic matter, toxic

metals, and nutrients.

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