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## **Technical Appendix 5 (TA-5)**

# **Description of a Model to Estimate Effects of Reductions of Influent Wastewater Flow on Wastewater Collection Systems**



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# 1 Introduction

The purpose of this model is to predict the impact of reduced flows on collections systems and extent of the associated mitigation efforts of reduced flows. It's generally accepted that reductions in flow volume can lead to negative impacts on collection systems such as - accelerated corrosion, odor complaints, and increased settling of solids. The underlying physical, chemical, and biological processes that contribute to these effects are heavily dependent on each other. While there are studies and models that examine the impact of reduced flow on one or some of these processes, nothing that predicted their combined effects on the collection system was found in literature. Furthermore, this model was developed to translate the effects of reduced flows - corrosion, odor, and sedimentation - into estimated costs of mitigation efforts. Using academic literature on general collection system influent characteristics and internal processes, an excel-based model was created that can predict the effects and cost of mitigation actions based on the characteristics of a sewer system.

## 2 Model Inputs

The model inputs can be categorized as either characteristics of the collection system or the influent flow. The collection system characteristics are user-inputs based on data that is available in the SSO Questionnaire as well as the DWR data.

Collection System Characteristics:

- Population served
- Indoor per capita use (gal/cap-d)
- Average flow (MGD)
- Total length of network (miles)
- Pipe size distribution
- Time between wide-spread flushing events (days)

Based on the population served and flow rate, the influent flow characteristics could be predicted using general values for mass loadings of common wastewater constituents provided in **Metcalf and Eddy table 3-13**.

Influent Flow Characteristics

- Temperature (°C)
- Total suspended solids (TSS) (mg/L)
- Total Chemical Oxygen Demand (COD) (mg/L)
- Readily Biodegradable COD (mg/L)
- Slowly Biodegradable COD (mg/L)
- Inert COD (mg/L)
- Biological Oxygen Demand (BOD) (mg/L)
- Total Kjeldahl Nitrogen (TKN) (mg/L)
- Ammonia (mg/L)
- Total Sulfur (mg/L)
- Sulfate Concentration (mg/L)
- Sulfide Concentration (mg/L)

## 3 Model Outputs

The model outputs can be categorized as either effects on the collection system, mitigation costs, and wastewater treatment plant influent characteristics.

Effects on the collection system:

- Average flow velocities by pipe size (ft/s)
- Average depth of accumulated sediment (in)
- Hydrogen sulfide (H<sub>2</sub>S) gas emissions (lb/day)
- Methane (CH<sub>4</sub>) gas emissions (lb/day)
- Average corrosion rate (in/year)
- Pipe life expectancies (year)

Estimated cost of mitigation actions:

- Chemical addition cost (\$/year)
- Pumping energy costs (\$/year)
- Pipe replacement cost (\$/year)

WWTP Influent Constituent Loadings:

- Total suspended solids (TSS) (mg/L)
- Total Chemical Oxygen Demand (COD) (mg/L)
- Readily Biodegradable COD (mg/L)
- Slowly Biodegradable COD (mg/L)
- Inert COD (mg/L)
- Biological Oxygen Demand (BOD) (mg/L)
- Total Kjeldahl Nitrogen (TKN) (mg/L)
- Ammonia (mg/L)
- Total Sulfur (mg/L)
- Sulfate Concentration (mg/L)
- Sulfide Concentration (mg/L)

In order to estimate the outputs previously discussed, the model incorporates a variety of physical, chemical, and biological processes. The model combines equations and other modeling efforts from technical and academic literature. Some of the internal processes modeled are well-studied while others have limited information available. For example, pipe corrosion caused by hydrogen sulfide emissions has been studied for decades and there are multiple well-established equations and modeling approaches available. However, studies on methane emission in collection systems are less prevalent. Consequently, the model relies on emerging literature for these calculations.

### 3.1 Physical Processes

All of the chemical and biological processes in this model rely on flow velocity or sediment deposition.

#### 3.1.1 Flow Velocity

The flow velocity determines retention time in sewers, turbulence, the amount of deposition, as well as many other factors that impact the internal processes. Flow velocity was calculated for different pipe diameters for both gravity sewers and pressure sewers. Gravity sewers were assumed to be flowing partially full and continuously. The partial velocity in gravity sewers was calculated based on methods described in Metcalf and Eddy's *Collection and Pumping of Wastewater*. Pressure sewers were assumed to be flowing full but not continuously. The slope's used in calculations are the minimum design slope associated with a pipe diameter from the City of West Sacramento's collection system master plan. The velocity in pressure sewers was determined using the volumetric

flow rate calculated from Manning's equation for flow in a full pipe. A more detailed explanation of the equations used and sample calculations can be found below.

**Partial flow velocities in gravity sewers**

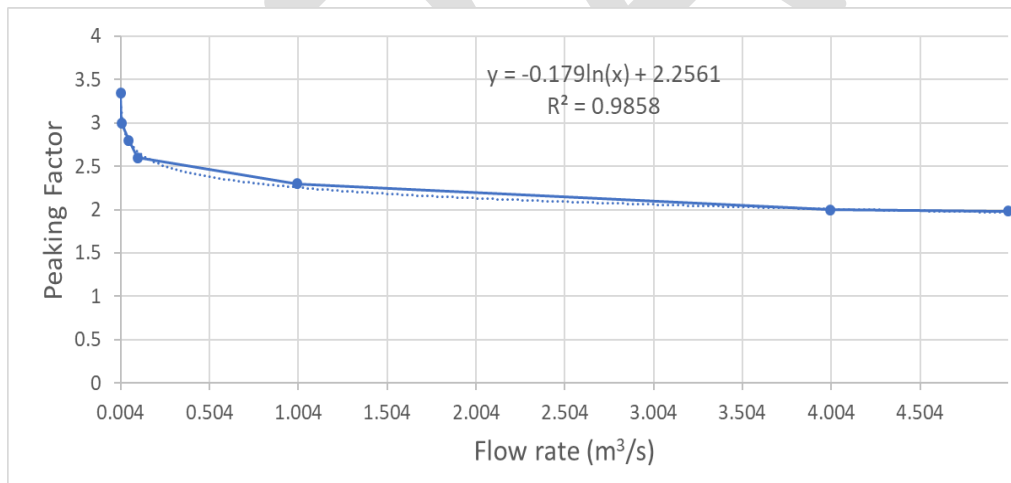
1. Estimate flow distribution

In order to more accurately calculate flow velocity, a method to estimate how much of the total daily flow was flowing through each pipe was developed. Based on the branched structure of collections systems it was assumed that the smaller pipes would feed into the larger pipes. Each pipe diameter was associated with a "Contributing Population". These were based on values available in **M&E** as well as the total population served. The fraction of total flow in a pipe was calculated dividing the contributing population by the total population served and multiplying by the total flow. The number of pipe segments was also calculated by dividing the total population served by the contributing population of each pipe size.

$$Q_{avg} = \frac{\text{Contributing Population}}{\text{Total Population Served}} * Q_{total}$$

2. Calculate and apply peaking factor

The flow rate calculated in the previous step was an average flow rate. The peak flow rate was needed for many of the following calculations. In order to determine the peaking factor, an equation was fitted to the plot in figure 3-4 in **M&E** that is then used to calculate the peaking factor based on the average volumetric flow rate.



$$\text{Peaking Factor} = -0.79\ln(Q_{avg}) + 2.2561$$

$$Q_{peak} = \text{Peaking Factor} * Q_{avg}$$

3. Calculate partial velocity in gravity sewers

Using the following equations, the peak flow was used to calculate the factor K' and subsequently the depth and cross-sectional area of the flow using tables 2-4 and 2-5 in **M&E**.

$$K' = \frac{Q * n}{D^{2/3} * S^{1/2}}$$

- $K' = \text{????}$
- $Q = \text{peak flow (m}^3/\text{s)}$
- $n = \text{mannings constant}$
- $D = \text{pipe diameter (m)}$
- $S = \text{slope (m/m)}$

$$V_p = \frac{Q}{a_p}$$

- $V_p = \text{partial flow velocity (m/s)}$
- $Q = \text{peak flow (m}^3/\text{s)}$
- $a_p = \text{cross – sectional area of partial flow (m}^2\text{)}$

### *Flow rate calculations in pressure sewers*

1. Calculate flow rate of pipe flowing full

$$Q_{full} = \frac{A * R^{2/3} * S^{1/2}}{n}$$

- $Q = \text{peak flow (m}^3/\text{s)}$
- $A = \text{cross – sectional area (m}^2\text{)}$
- $n = \text{mannings constant}$
- $R = \text{pipe radius (m)}$
- $S = \text{slope (m/m)}$

### **3.1.2 Sediment Deposition**

Increased solids build-up in pipes not only contributes to blockages but also H<sub>2</sub>S production and methane production. Deposited solids provide an anaerobic environment for sulfate reducing bacteria and methanogens. The process model uses a procedure for estimating dry weather solids deposition presented in a 1981 study to estimate the amount of solids deposited in a collection system as flow is reduced<sup>1</sup>. After calculating the mass of sediment deposited, the surface area of the deposited solids are calculated in order to estimate the sediment contributions to sulfate reduction and methane production. A more detailed explanation of the calculations follows.

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<sup>1</sup> Pisano, William C., Celso Queiroz, Gerald L. Aronson, Frederic C. Blanc, and James C. O'Shaughnessy. "Procedures for Estimating Dry Weather Pollutant Deposition in Sewer Systems." Water Pollution Control Federation 53, no. 11 (November 1981): 1627–36.



## Equations

1. Calculate total daily solids deposition in the system using equation developed in Pasano et. al.

$$TS = 10.91 * 10^{-4} * L^{1.180} * A^{-0.178} * S_{Avg}^{-0.418} * D_{Avg}^{0.604} * q^{-0.510}$$

$$A = \frac{L}{169.99} - e^{0.928} \text{ (high population density)}$$

$$A = \frac{L}{119.25} - e^{0.928} \text{ (low population density)}$$

- $TS$  = total daily solids deposition,  $\frac{kg}{d}$
- $L$  = total length of pipes,  $m$
- $A$  = estimated basin area,  $m^2$
- $S_{Avg}$  = average slope,  $m/m$
- $D_{Avg}$  = average pipe diameter,  $m$
- $q$  = per capita use,  $\frac{m^3}{d*capita}$

2. Calculate solids deposition in a pipe segment.

$$TS_{seg} = TS * \left( \frac{L_{DX}}{L} \right) \div (\# \text{ of Segments})$$

- $TS_{seg}$  = daily solids deposition in a segment of pipe,  $\frac{kg}{d}$
- $TS$  = total daily solids deposition,  $\frac{kg}{d}$
- $L_{DX}$  = total length of pipes with a specific diameter,  $m$
- $L$  = total length of pipes,  $m$
- # of Segments = number of pipe segments of a specific diameter

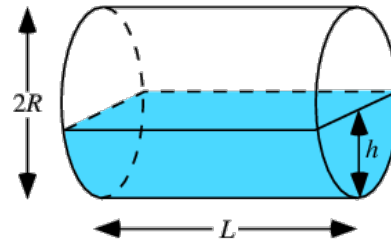
3. Calculate fraction of pipe volume occupied by solids.

$$\% \text{ vol} = \frac{TS_{seg} * t_{storm}}{\rho_{sed} * V_{pipe}}$$

- $\% \text{ vol}$  = the fraction of volume occupied by sediment
- $TS_{seg}$  = total solids deposited per day in a segment of pipe,  $\frac{kg}{d}$
- $t_{storm}$  = time since the last storm event, days
- $\rho_{sed}$  = density of sewer sediment
- $V_{pipe}$  = volume of pipe segment

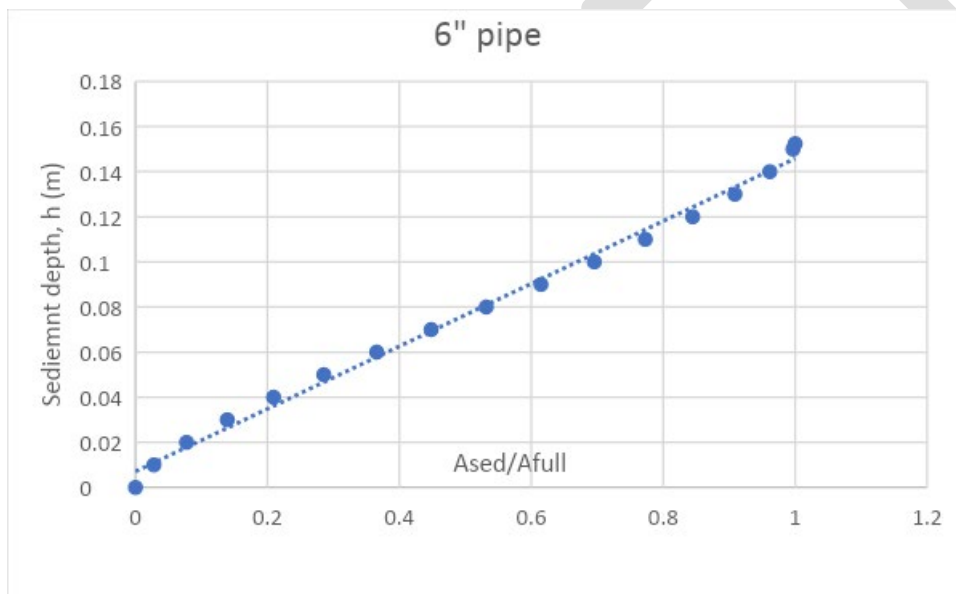
- Calculate the depth of sediment:

$$\frac{V_{sed}}{V_{full}} = \frac{A_{sed} * L}{A_{full} * L} = \frac{A_{sed}}{A_{full}}$$



$$\frac{A_{sed}}{A_{full}} = \frac{R^2 * \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h) * \sqrt{2Rh - h^2}}{\pi R^2}$$

4. Graph  $\frac{A_{sed}}{A_{full}}$  for  $h$  values from 0 to  $2R$  and fit a polynomial equation. Use an equation to calculate depth of sediment,  $h$ , from the fraction of volume occupied by sediment.



5. Calculate surface area of sediment

Find angle:

$$\theta = 2 * \cos^{-1}\left(\frac{R - h}{R}\right)$$

Find chord length:

$$b = 2R * \sin\left(\frac{\theta}{2}\right)$$

- $\theta$  = angle created by sediment surface and center of circle
- $R$  = pipe radius, m
- $h$  = depth of sediment deposit, m
- $b$  = length of sediment deposit across pipe, m

Find surface area of sediment:

$$SA_{sed} = b * L_{seg}$$

- $SA_{sed}$  = surface area of sediment deposited in a pipe segment,  $m^2$
- $b$  = length of sediment deposit across pipe, m
- $L_{seg}$  = length of pipe segment, m

Sample calculations:

1. Calculate total daily solids deposition in the system

$$L = 290,000 \text{ m}$$

$$A = \text{estimated basin area, } m^2$$

$$S_{Avg} = 0.003 \text{ m/m}$$

$$D_{Avg} = 0.27 \text{ m}$$

$$q = 0.21 \frac{m^3}{d * \text{capita}}$$

$$A = \frac{290000}{169.99} - e^{0.928} = 3040 \text{ m}^2$$

$$TS = 10.91 * 10^{-4} * (290000)^{1.180} * (3040)^{-0.178} * (0.003)^{-0.418} * (0.27)^{0.604} * (0.21)^{-0.510}$$

$$TS = 8140 \frac{kg}{d}$$

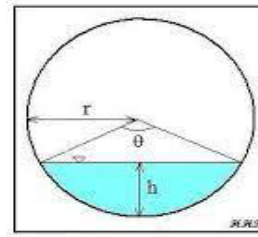


Figure 1. Partially Full Pipe Flow Parameters (Less than Half Full)

$$r = \frac{D}{2} \quad h = y$$

$$\theta = 2 \arccos\left(\frac{r-h}{r}\right)$$

$$A = \frac{r^2(\theta - \sin\theta)}{2}$$

$$P = r\theta$$

$$R_h = A/P$$

2. Calculate solids deposition in a pipe segment

$$TS_{seg} = 8140 \frac{kg}{d} * \left( \frac{68,600 m}{408,400m} \right) \div (100) = 13.7 \frac{kg}{d}$$

- Calculate fraction of volume occupied by solids

$$t_{storm} = 180 \text{ days}$$

$$\rho_{sed} = 1510 \text{ kg/m}^3$$

$$V_{pipe} = 5.21 \text{ m}^3$$

$$\% \text{ vol} = \frac{13,7 \frac{kg}{d} * 180d}{1510 \frac{kg}{m^3} * 5.21 \text{ m}^3} = 0.313$$

- Calculate the depth of sediment:

$$\frac{V_{sed}}{V_{full}} = \frac{A_{sed}}{A_{full}} = 0.313$$

$$h = 0.004 * (0.673)^2 + 0.1347 * (0.673) + 0.0076 = 0.05 \text{ m}$$

- Calculate surface area of sediment

Find angle:

$$\theta = 2 * \cos^{-1} \left( \frac{0.1524/2 - 0.05}{0.1524/2} \right)$$

$$\theta = 139.8^\circ$$

Find chord length:

$$b = 0.1524m * \sin \left( \frac{139.8}{2} \right) = 0.108m$$

Find surface area of sediment:

$$L_{seg} = 686 \text{ m}$$

$$SA_{sed} = 0.108 \text{ m} * 286 \text{ m} = 73.9 \text{ m}^2$$

## 3.2 Chemical and Biological Processes

### 3.2.1 Reaeration in Gravity Sewers

The rate of biological processes in gravity sewers depends on the dissolved oxygen concentration. As the flow rate decreases the turbulence and rate of reaeration will decrease. A more detailed explanation of how the reaeration rate and dissolved oxygen concentration in gravity sewers follows.

#### Equations for estimating reaeration in gravity sewers:

1. Calculate the reaeration coefficient

$$KLa = 0.86 * (1 + 0.2 * Fr^2) * (s * V_{Avg})^{\frac{3}{8}} * d_m^{-1}$$

$$Fr = \frac{V_{Avg}}{(g * d_m)^{0.5}}$$

- $KLa$  = reaeration coefficient,  $h^{-1}$
- $Fr$  = froude number
- $s$  = slope,  $m/m$
- $V_{Avg}$  = average flow velocity,  $m/s$
- $g$  = gravitational acceleration,  $m/s^2$
- $d_m$  = depth of flow,  $m$
- Calculate the rate of reaeration

$$r_{ro} = KLa * (S_{OS} - S_o)$$

$$S_{OS} = \frac{468}{31 + T}$$

- $r_{ro}$  = rate of reaeration,  $\frac{mg}{L \cdot h}$
- $KLa$  = reaeration coefficient,  $h^{-1}$
- $S_{OS}$  = saturation concentration for oxygen,  $\frac{mg}{L}$
- $S_o$  = initial dissolved oxygen concentration,  $\frac{mg}{L}$
- $T$  = temperature,  $^{\circ}C$

2. Calculate final dissolved oxygen concentration

$$\Delta DO = r_{ro} * t_r$$

$$DO_f = DO_0 + \Delta DO$$

- $r_{ro}$  = rate of reaeration,  $\frac{mg}{L \cdot h}$
- $t_r$  = residence time,  $h$
- $DO_0$  = initial dissolved oxygen concentration,  $mg/L$
- $\Delta DO$  = change in dissolved oxygen concentration,  $mg/L$
- $DO_f$  = final dissolved oxygen concentration,  $mg/L$

### Sample Calculations:

1. Calculate the reaeration coefficient

$$s = 0.005$$

$$V_{Avg} = 0.5 \text{ m/s}$$

$$g = 9.81 \text{ m/s}^2$$

$$d_m = 0.061 \text{ m}$$

$$Fr = \frac{0.5 \frac{m}{s}}{\left(9.81 \frac{m}{s^2} * 0.061 \text{ m}\right)^{0.5}} = 0.646$$

$$KLa = 0.86 * (1 + 0.2 * (0.646)^2) * (0.005 * 0.5)^{\frac{3}{8}} * (0.061)^{-1}$$

$$KLa = 1.62 \text{ h}^{-1}$$

2. Calculate the rate of reaeration

$$S_o = 1 \frac{mg}{L}$$

$$T = 25 \text{ }^\circ\text{C}$$

$$S_{os} = \frac{468}{31 + 25} = 8.36 \text{ mg/L}$$

$$r_{ro} = 1.62 \text{ h}^{-1} * \left(8.36 \frac{mg}{L} - 1 \frac{mg}{L}\right) = 11.9 \frac{mg}{L * h}$$

3. Calculate final dissolved oxygen concentration

$$t_r = 0.41 \text{ h}$$

$$\Delta DO = 11.9 \frac{mg}{L * h} * 0.41 \text{ h} = 4.89 \frac{mg}{L}$$

$$DO_f = 1 \frac{mg}{L} + 4.89 \frac{mg}{L} = 5.89 \frac{mg}{L}$$

### 3.2.2 COD Transformation

The retention time in collection systems impacts both the degradation of COD and the fractionation of COD. As flow remains in collection systems longer, not only will more biodegradable COD be oxidized but slowly biodegradable particulate matter will be hydrolyzed into readily biodegradable matter. Altering the ratio of fast degrading to slow degrading COD can impact processes at the wastewater treatment plant. Furthermore, methane production depends on the concentration of readily biodegradable COD available for fermentation.

#### Rate of Hydrolysis (aerobic conditions):

$$r_{hyd,ae} = \frac{k_{hn} X_{Sn} S_O \left( X_{BW} + \varepsilon X_{Bf} \frac{A}{V} \right)}{X_{BW} \left( K_{Xn} + \frac{X_{Sn}}{X_{BW}} \right) (K_O + S_O)} \alpha^{(T-20)}$$

- n=1 for fast biodegradable fraction, n=2 for slow biodegradable fraction

#### Rate of Hydrolysis (anaerobic conditions):

$$r_{hyd,an} = \eta_{an} \frac{k_{hn} X_{Sn} K_O K_{NO3} \left( X_{BW} + \varepsilon X_{Bf} \frac{A}{V} \right)}{X_{BW} \left( K_{Xn} + \frac{X_{Sn}}{X_{BW}} \right) (K_O + S_O) (K_{NO3} + S_{NO3})} \alpha^{(T-20)}$$

- n=1 for fast biodegradable fraction, n=2 for slow biodegradable fraction

#### Example calculations:

Constants		Units	Description
$k_{h1} =$	4	d <sup>-1</sup>	hydrolysis rate constant for fast biodegradable substrate
$K_{X1} =$	0.5	$\frac{g}{D}$ COD/gCO	saturation constant for soluble biodegradable substrate
$K_O =$	0.1	g O <sub>2</sub> /m <sup>3</sup>	saturation constant for dissolved oxygen
$\alpha_w =$	1.07		temperature coefficient in the water phase
$\varepsilon =$	0.15		efficiency coefficient for biofilm biomass under aerobic conditions
$X_{BW} =$	60	g O <sub>2</sub> /m <sup>3</sup>	heterotrophic active biomass in the bulk phase
$X_{Bf} =$	10	g COD/m <sup>3</sup>	heterotrophic active biomass in the biofilm <sup>2</sup>
Variables		Units	Description
$X_{S1} =$	720	g COD/m <sup>3</sup>	fast biodegradable hydrolysable substrate
$S_O =$	4	g O <sub>2</sub> /m <sup>3</sup>	dissolved oxygen concentration
$t_r =$	0.41	H	residence time
$A/V =$	26.2	m <sup>-1</sup>	area to volume ratio

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1. Rate of hydrolysis for fast-hydrolyzing fraction under aerobic conditions (gravity sewers)

$$r_{hyd,ae} = \frac{4d^{-1} * \left(720 \frac{g \text{ COD}}{m^3}\right) * \left(4 \frac{g \text{ O}_2}{m^3}\right) * \left(60 \frac{g \text{ COD}}{m^3} + 0.15 * 10 \frac{g \text{ COD}}{m^3} * 26.2 \text{ m}^{-1}\right)}{60 \frac{g \text{ O}_2}{m^3} * \left(0.5 + \frac{720 g \text{ COD}/m^3}{60 g \text{ COD}/m^3}\right) \left(0.1 \frac{g \text{ O}_2}{m^3} + 4 \frac{g \text{ O}_2}{m^3}\right)} 1.07^{(27-20)}$$

$$r_{hyd,ae} = 597.4 \frac{g}{m^3 d}$$

Change in COD concentration in a segment of pipe

$$\Delta[\text{COD}] = -r_{hyd,ae} * t_r$$

$$\Delta[\text{COD}] = -597.4 \frac{g}{m^3 d} * 0.309 h * \frac{d}{24 h} * \frac{1000 L}{1000 mg} = -7.69 \text{ mg/L}$$

2. Rate of hydrolysis for slow-hydrolyzing fraction under anaerobic conditions (pressure sewers)

Constants		Units	Description
$k_{h2} =$	1	$d^{-1}$	hydrolysis rate constant for slow biodegradable substrate
$K_{X2} =$	0.2	$\frac{g \text{ COD}}{g \text{ CO}}$ D	saturation constant for particulate biodegradable substrate
$K_O =$	0.1	$g \text{ O}_2/m^3$	saturation constant for dissolved oxygen
$\alpha_w =$	1.07		temperature coefficient in the water phase
$\epsilon =$	0.15		efficiency coefficient for biofilm biomass under aerobic conditions
$X_{BW} =$	60	$g \text{ O}_2/m^3$	heterotrophic active biomass in the bulk phase
$X_{Bf} =$	10	$g \text{ COD}/m^3$	heterotrophic active biomass in the biofilm <sup>2</sup>
$\eta_{an} =$	0.15		efficiency coefficient for anaerobic fermentation
$K_{NO3} =$	0.75	$g \text{ NO}_3/m^3$	saturation coefficient for nitrate
Variables		Units	Description
$X_{S2} =$	360	$g \text{ COD}/m^3$	slow biodegradable hydrolysable substrate
$S_O =$	4	$g \text{ O}_2/m^3$	dissolved oxygen concentration
$S_{NO3} =$	15	$g \text{ NO}_3/m^3$	dissolved nitrate concentration
$t_r =$	0.24	H	residence time
$A/V =$	26.2	$m^{-1}$	area to volume ratio

$$r_{hyd,an} = 0.15 \frac{1d^{-1} \left( 360 \frac{g\ COD}{m^3} \right) \left( 0.1 \frac{g\ O_2}{m^3} \right) \left( 0.75 \frac{g\ NO_3}{m^3} \right) \left( 60 \frac{g\ COD}{m^3} + 0.15 * 10 \frac{g\ COD}{m^3} * 26.2\ m^{-1} \right)}{60 \frac{g\ O_2}{m^3} \left( 0.5 + \frac{360g\ COD}{60\ g\ COD} \right) \left( 0.1 \frac{g\ O_2}{m^3} + 4 \frac{g\ O_2}{m^3} \right) \left( 0.75 \frac{g\ NO_3}{m^3} + 15 \frac{g\ NO_3}{m^3} \right)} 1.07^{(27-20)}$$

$$r_{hyd,ae} = 0.0256 \frac{g}{m^3 d}$$

*Change in COD concentration in a segment of pipe*

$$\Delta[COD] = -r_{hyd,ae} * t_r$$

$$\Delta[COD] = -0.0256 \frac{g}{m^3 d} * 0.24h * \frac{d}{24h} * \frac{1000L}{1000mg} = -0.000256mg/L$$

### 3.2.3 Corrosion Rate

#### Equations for estimating corrosion rates

**Sulfide Balance:**

$$\Delta[H_2S] = [H_2S]_{Bf} + [H_2S]_{sed} - [H_2S]_{Emit} - [H_2S]_{Ox}$$

- $\Delta[H_2S]$  = accumulation of sulfide in wastewater
- $[H_2S]_{Bf}$  = sulfide produced in biofilm
- $[H_2S]_{sed}$  = sulfide produced in sediment
- $[H_2S]_{Emit}$  = sulfide emitted to sewer atmosphere
- $[H_2S]_{Ox}$  = sulfide reoxidized in wastewater

#### 1. Rate of $H_2S$ Production in Biofilm (1):

$$r_a = 0.5 * 10^{-3} * V_{Avg} * [BOD]^{0.8} * [SO_4]^{0.4}$$

- $r_a$  = areal rate of flux from biofilm, gS/m<sup>2</sup>/h
- $V_{Avg}$  = average flow velocity, m/s
- $[BOD]$  = concentration of BOD, mg/L
- $[SO_4]$  = concentration of sulfate, mg/L

#### 2. Rate of $H_2S$ Flux from Sewer Sediment (2):

$$r_{S2-} = 1.989 * [SO_4]^{0.5}$$

- $r_{S2-}$  = rate of flux from H<sub>2</sub>S from sewer sediment, gS/m<sup>2</sup>/d
- [SO<sub>4</sub>] = concentration of sulfate, mg/

### 3. Rate of sulfide emitted

- see sulfide emissions calculations

### 4. Rate of sulfide reoxidized in the water phase

$$r_{SO} = K * 0.96 * C_A * (S * V)^{\frac{3}{8}} * D_O * d_m^{-1} * S_T$$

$$D_O = S_{OS} - S_O$$

$$S_{OS} = \frac{468}{31 + T}$$

- $r_{SO}$  = rate of sulfide oxidation,  $\frac{g}{m^3 \cdot h}$
- $C_A$  = turbulence factor (see sulfide emissions calculations)
- $V$  = average flow velocity, m/s
- $S$  = slope, m/m
- $D_O$  = oxygen deficit in the water, g/m<sup>3</sup>
- $d_m$  = mean hydraulic depth, m
- $S_T$  = total soluble sulfides, g/m<sup>3</sup>
- $S_{OS}$  = dissolved oxygen saturation concentration, g/m<sup>3</sup>
- $S_O$  = dissolved oxygen concentration, g/m<sup>3</sup>
- $T$  = temperature, °C

### 5. H<sub>2</sub>S contributions from Biofilm (3):

$$\Delta[H_2S]_{bf} = \frac{A}{V} * r_a * t_r$$

- $\Delta[H_2S]_{bf}$  = change in sulfide concentration from biofilm contributions, mg/L
- $\frac{A}{V}$  = area to volume ratio of pipe, m<sup>2</sup>/m<sup>3</sup>
- $r_a$  = areal rate of flux from biofilm, gS/m<sup>2</sup>/h
- $t_r$  = residence time, h

### 6. H<sub>2</sub>S contributions from Sediment:

$$\Delta[H_2S]_{sed} = \frac{SA_{sediment} * r_{S2-}}{Q_{avg}}$$

- $\Delta[H_2S]_{sed}$  = change in sulfide concentration from sediment contributions, mg/L
- $SA_{sediment}$  = surface area of sediment in pipe, m<sup>2</sup>
- $r_{S_2-}$  = rate of flux from H<sub>2</sub>S from sewer sediment, gS/m<sup>2</sup>/d
- $Q_{avg}$  = average flow rate, m<sup>3</sup>/s

7. *H<sub>2</sub>S removed via oxidation:*

$$\Delta[H_2S]_{ox} = r_{SO} * t_r$$

- $\Delta[H_2S]_{ox}$  = sulfide loss due to oxidation, mg/L
- $r_{SO}$  = rate of sulfide oxidation, g/(m<sup>3</sup> \* h)
- $t_r$  = residence time, h

8. *Calculate the limiting value of soluble sulfide in a segment of gravity sewer (4):*

$$(S_T)_{lim} = \frac{M}{m} * [BOD] * (s * V_{Avg})^{-\frac{3}{8}} * \frac{p}{b}$$

- $M$  = observed flux coefficient,  $\frac{m}{h}$
- $m$  = empirical coefficient
- $[BOD]$  = BOD concentration,  $\frac{mg}{L}$
- $s$  = slope, m/m
- $V_{Avg}$  = average flow velocity, m/s
- $b$  = length of stream surface (m)
- $p$  = submerged perimeter of pipe

9. *Flux of H<sub>2</sub>S at wall (4):*

$$\varphi_{aw} = 0.69 * C_A * (s * V_{avg})^{\frac{3}{8}} * j * [H_2S] * \left(\frac{b}{p'}\right)$$

- $\varphi_{aw}$  = flux of H<sub>2</sub>S to the pipe wall
- $C_A$  = turbulence factor
- $s$  = slope, m/m
- $V_{Avg}$  = average flow velocity, m/s
- $j$  = fraction of H<sub>2</sub>S at a specific pH
- $[H_2S]$  = sulfide concentration, mg/L
- $b$  = length of stream surface (m)
- $p'$  = exposed perimeter of pipe

10. Average rate of Corrosion (5):

$$C_{Avg} = \frac{11.5 * k * \varphi_{aw}}{A}$$

- $C_{Avg}$  = average rate of corrosion, mm/year
- $k$  = coefficient of efficiency
- $\varphi_{aw}$  = flux of H<sub>2</sub>S to the pipe wall, gm<sup>2</sup> – h
- $A$  = alkalinity of concrete,

11. Calculate pipe life expectancy (6):

$$\text{Pipe Life} = \frac{z}{C_{Avg}}$$

- Pipe Life = life expectancy of pipe, years
- $z$  = maximum depth of corrosion
- $C_{Avg}$  = average rate of corrosion, in/year

Sample Calculations:

1. Rate of H<sub>2</sub>S Production in Biofilm:

$$V_{Avg} = 0.5 \text{ m/s}$$

$$[BOD] = 350 \text{ mg/L}$$

$$[SO_4] = 30 \text{ mg/L}$$

$$r_a = 0.5 * 10^{-3} * 0.5 * [350]^{0.8} * [30]^{0.4}$$

$$r_a = 0.106 \text{ g/m}^2/\text{h}$$

2. Rate of H<sub>2</sub>S Flux from Sewer Sediment:

$$r_{S2-} = 1.989 * [30]^{0.5}$$

$$r_{S2-} = 10.9 \text{ g/m}^2/\text{d}$$

3. Rate of sulfide emitted

- see sulfide emissions calculations

4. Rate of sulfide reoxidized in the water phase

$$K = 0.05$$

$$C_A = 1.74$$

$$V = 0.5 \text{ m/s}$$

$$S = 0.005$$

$$d_m = 0.061 \text{ m}$$

$$S_T = 2.76 \text{ g/m}^3$$

$$S_O = 4.5 \text{ g/m}^3$$

$$S_{Os} = \frac{468}{31 + 25} = 8.36 \text{ g/m}^3$$

$$D_O = 8.36 - 4.5 = 3.86 \text{ g/m}^3$$

$$r_{SO} = 0.05 * 0.96 * 1.76 * (0.005 * 0.5)^{\frac{3}{8}} * 3.86 * (0.061)^{-1} * 2.76$$

$$r_{SO} = 1.56 \frac{\text{g}}{\text{m}^3 * \text{h}}$$

5.  $H_2S$  contributions from Biofilm:

$$D = 0.1524 \text{ m}$$

$$L = 540 \text{ m}$$

$$t_r = 0.41 \text{ h}$$

$$\frac{A}{v} = \frac{\pi * 0.1524 \text{ m} * 540 \text{ m}}{\pi * \left(\frac{0.1524 \text{ m}}{2}\right)^2 * 540 \text{ m}} = 26.2/\text{m}$$

$$\Delta[H_2S] = \frac{26.2}{\text{m}} * 0.106 \frac{\text{g}}{\text{m}^2 \text{ h}} * 0.41 \text{ h}$$

$$\Delta[H_2S] = 1.14 \text{ g/m}^3$$

6.  $H_2S$  contributions from Sediment:

$$SA_{\text{sediment}} = 5.4 \text{ m}^2$$

$$Q_{\text{avg}} = 94.6 \text{ m}^3/\text{d}$$

$$\Delta[H_2S] = \frac{5.4 \text{ m}^2 * 10.9 \frac{\text{g}}{\text{m}^2 \text{ d}}}{94.2 \text{ m}^3/\text{d}} = 0.622 \text{ g/m}^3$$

7.  $H_2S$  removed via oxidation:

$$\Delta[H_2S]_{\text{ox}} = 1.56 \frac{\text{g}}{\text{m}^3 * \text{h}} * 0.41 \text{ h} = 0.640 \text{ g/m}^3$$

8. Calculate the limiting value of soluble sulfide in a segment of gravity sewer (4):

$$M = 0.32 * 10^{-3} \frac{m}{h}$$

$$m = 0.64$$

$$[BOD] = 350 \text{ mg/L}$$

$$s = 0.005$$

$$V_{Avg} = 0.50 \text{ m/s}$$

$$b = 0.106 \text{ m}$$

$$p = 0.269 \text{ m}$$

$$(S_T)_{lim} = \frac{0.32 * 10^{-3} \frac{m}{h}}{0.64} * \left(350 \frac{mg}{L}\right) * \left(0.005 * 0.5 \frac{m}{s}\right)^{-\frac{3}{8}} * \frac{0.269}{0.106} = 4.20 \frac{mg \text{ H}_2\text{S}}{L}$$

9. Compare calculated H<sub>2</sub>S concentration to (S<sub>T</sub>)<sub>lim</sub>

$$[H_2S]_0 = 1 \text{ mg/L}$$

$$[H_2S]_{Bf} = 1.14 \text{ mg/L}$$

$$[H_2S]_{sed} = 0.622 \text{ mg/L}$$

$$[H_2S]_{ox} = 0.640 \text{ mg/L}$$

$$\Delta[H_2S] = 1.14 \frac{mg}{L} + 0.622 \frac{mg}{L} - 0.640 \frac{mg}{L} = 1.12 \frac{mg}{L}$$

$$[H_2S]_{aq} = 1 \frac{mg}{L} + 1.12 \frac{mg}{L} = 2.12 \text{ mg/L}$$

10. Flux of H<sub>2</sub>S at wall:

$$s = 0.005$$

$$[H_2S]_0 = 1 \text{ mg/L}$$

$$b = 0.106 \text{ m}$$

$$p' = 0.269 \text{ m}$$

$$j = 0.5$$

$$[H_2S] = \frac{1 \text{ mg}}{L} + 1.14 \frac{\text{mg}}{L} + 0.622 \frac{\text{mg}}{L}$$

$$[H_2S] = 2.76 \text{ mg/L}$$

$$\varphi_{aw} = 0.69 * (1.74) * (0.005 * 0.50)^{\frac{3}{8}} * 0.5 * [2.12] * \left(\frac{0.106}{0.269}\right)$$

$$\varphi_{aw} = 0.053 \text{ g} * \text{m}^2 - \text{h}$$

11. Average rate of Corrosion:

$$k = 0.7$$

$$A = 0.18$$

$$C_{Avg} = \frac{11.5 * 0.7 * 0.053}{0.18}$$

$$C_{Avg} = 2.37 \text{ mm/year}$$

$$C_{Avg} = 0.0602 \text{ in/year}$$

12. Calculate pipe life expectancy (6):

$$z = 2 \text{ in}$$

$$\text{Pipe Life} = \frac{2 \text{ in}}{0.0602 \text{ in/year}} = 33.3 \text{ years}$$

### 3.2.4 Odor Production

Equations for calculating H<sub>2</sub>S Emissions:

1. Turbulence Factor (1)

$$C_A = \frac{1 + 0.17 * V_{Avg}^2}{g * d_m}$$

- $C_A$  = turbulence factor
- $V_{Avg}$  = average flow velocity, m/s
- $g$  = gravitational acceleration, m/s<sup>2</sup>
- $d_m$  = depth of flow

2. H<sub>2</sub>S Emitted from Aqueous Phase (1)

$$r_{se} = 0.69 * j * [H_2S]_{aq} * C_A * (s * V_{avg})^{\frac{3}{8}} * \frac{1 - q}{d_m}$$

- $r_{se}$  = H<sub>2</sub>S emitted into gas phase,  $\frac{mg}{L * h}$
- $j$  = fraction of H<sub>2</sub>S at a specific pH
- $[H_2S]_{aq}$  = aqueous H<sub>2</sub>S concentration, mg/L
- $C_A$  = turbulence factor



- $s = \text{slope, m/m}$
- $V_{Avg} = \text{average flow velocity, m/s}$
- $q = \text{ratio of H}_2\text{S saturation in air to equilibrium concentration}$

### 3. Convert to Pounds of H<sub>2</sub>S per Day

$$[H_2S]_{emitted\ total} = [H_2S]_{emitted} * Q_{avg} * \# \text{ of pipe segments}$$

- $[H_2S]_{emitted\ total} =$   
amount of H<sub>2</sub>S emitted in all pipes of a specific diameter, lb/d
- $[H_2S]_{emitted} = \text{H}_2\text{S emitted into gas phase, } \frac{mg}{L}$
- $Q_{avg} = \text{the average flow rate through one segment of pipe, m}^3/d$
- $\# \text{ of Pipe Segments} = \text{number of pipe segments of a specific diameter}$

#### Example Calculations:

##### 1. Turbulence Factor:

$$V_{Avg} = 0.50 \text{ m/s}$$

$$g = 9.81 \text{ m/s}^2$$

$$d_m = 0.061 \text{ m}$$

$$C_A = \frac{1 + 0.17 * (0.50 \frac{m}{s})^2}{9.81 \text{ m/s}^2 * 0.061 \text{ m}} = 1.74$$

##### 2. H<sub>2</sub>S Emitted from Aqueous Phase

$$m = 0.96$$

$$[H_2S]_{aq} = 2.76 \text{ mg/L}$$

$$s = 0.005 \text{ m}$$

$$j = 0.5$$

$$q = 0.10$$

$$r_{se} = 0.96 * 0.5 * \left(2.76 \frac{g}{m^3}\right) * 1.74 * \left(0.005 * 0.5 \frac{m}{s}\right)^{\frac{3}{8}} * (1 - 0.1)$$

$$r_{se} = 0.219 \frac{mg}{L}$$

##### 3. Convert to Pounds of H<sub>2</sub>S per Day

$$Q_{avg} = 0.00109 \text{ m}^3/\text{s}$$

$$\# \text{ of Pipe Segments} = 100$$

$$[H_2S]_{emitted} = 0.219 \frac{\text{mg}}{\text{L}} * 94.6 \frac{\text{m}^3}{\text{d}} * \frac{1000\text{L}}{\text{m}^3} * \frac{2.205\text{lb}}{10^6\text{mg}} * 100 = 4.58 \text{ lb/day}$$

### 3.2.5 Methane Production

Equations for calculating methane production:

#### 1. Rate of CH<sub>4</sub> Production in Biofilm (1):

$$r_{CH_4 \text{ bf}} = 6 * 10^{-5} * 1.05^{T-20} * \frac{A}{V} * t_r + 0.0015$$

- $r_{CH_4 \text{ bf}}$  = rate of CH<sub>4</sub> production in biofilm, kg/m<sup>3</sup>
- $T$  = temperature, °C
- $\frac{A}{V}$  = area to volume ratio of pipe, m<sup>2</sup>/m<sup>3</sup>
- $t_r$  = residence time, h

#### 2. Rate of CH<sub>4</sub> Production in Sewer Sediment (2):

$$r_{CH_4 \text{ sd}} = k_{CH_4} * [COD]^{0.5}$$

- $r_{CH_4 \text{ sd}}$  = rate of methane production in sediment,  $\frac{\text{g}}{\text{m}^2 \text{d}}$
- $k_{CH_4}$  = rate constant for methane production,  $\left(\frac{\text{g CH}_4}{\text{m}}\right)^{0.5} / \text{d}$
- $[COD]$  = concentration of fermentable COD, g/m<sup>3</sup>

#### 3. CH<sub>4</sub> contributions from Biofilm:

$$Q_{CH_4 \text{ bf}} = r_{CH_4 \text{ bf}} * Q_{avg} * \# \text{ of pipe segments}$$

- $Q_{CH_4 \text{ bf}}$  = total CH<sub>4</sub> production in biofilm from pipes of a specific diameter, lb/d
- $r_{CH_4 \text{ bf}}$  = rate of CH<sub>4</sub> production in biofilm, kg/m<sup>3</sup>
- $Q_{avg}$  = the average flow rate through one segment of pipe, m<sup>3</sup>/d
- # of Pipe Segments = number of pipe segments of a specific diameter

#### 4. CH<sub>4</sub> contributions from Sediment:

$$Q_{CH_4sd} = r_{CH_4sd} * SA_{sd} * \# \text{ of pipe segments}$$

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- $Q_{CH_4 sd}$  = total  $CH_4$  production in sediment from pipes of a specific diameter, lb/d
- $r_{CH_4 sd}$  = rate of methane production in sediment,  $\frac{g}{m^2 d}$
- $SA_{sd}$  = surface area of sediment in a segment of a pipe,  $m^2$
- # of Pipe Segments = number of pipe segments of a specific diameter

Example calculations:

1. *Rate of  $CH_4$  Production in Biofilm:*

$$T = 27^\circ C$$

$$\frac{A}{V} = 26.6 \text{ m}^2/\text{m}^3$$

$$t_r = 0.41 \text{ h}$$

$$r_{CH_4 bf} = 6 * 10^{-5} * 1.05^{27-20} * 26.2 * 0.41 + 0.0015 = 0.00241 \text{ kg}/\text{m}^3$$

2. *Rate of  $CH_4$  Production in Sewer Sediment:*

$$k_{CH_4} = 0.224 \left( \frac{g \text{ } CH_4}{m} \right)^{0.5} /d$$

$$[COD] = 700 \text{ g}/\text{m}^3$$

$$r_{CH_4 sd} = 0.224 * [700]^{0.5} = 5.93 \frac{g}{m^2 d}$$

3.  *$CH_4$  contributions from Biofilm:*

$$Q_{avg} = 94.6 \text{ m}^3/d$$

$$\# \text{ of Pipe Segments} = 100$$

$$Q_{CH_4 bf} = 0.00241 \frac{kg}{m^3} * 94.6 \frac{m^3}{d} * 100 * \frac{2.205 lb}{kg} = 50.3 \text{ lb}/d$$

4.  *$CH_4$  contributions from Sediment:*

$$SA_{sd} = 540 \text{ m}^2$$

$$Q_{CH_4 sd} = 5.93 \frac{g}{m^2 d} * 5.42 \text{ m}^2 * 100 * \frac{2.205 lb}{1000g} = 7.06 \text{ lb}/d$$

### 3.3 Mitigation Activities

#### 3.3.1 Pumping Energy

The annual pumping energy costs were modeled using two characteristic pump stations, designed to support less than 75,000 gpd or over 75,000 gpd. Pump stations designed for under 75,000 gpd were assumed to have two 15 horsepower (HP) pumps each with a capacity of 500 gallons per minute (gpm). These smaller pump stations were assumed to provide lift for the smaller diameter pipes (6"-18"). Pump stations designed for over 75,000 gallons per day were assumed to have three 50 HP pumps with capacities of 5,000 gpm. The model assumes these provide lift for the 27"-36" diameter pipes. The number of each pump station type was predicted based on the population served. These assumptions and thresholds were based on pump station data reported in the SSO questionnaire and design specifications provided in the City of West Sacramento's sewer master plan. Below is a more detailed explanation of how pumping energy costs were calculated.

1. Calculate the time each pump runs per day

$$t = \frac{Q}{\# \text{ of pumps} * \text{pump capacity}}$$

- $t$  = time pumps are running per day, hour/d
- $Q$  = total flow received by pump station, gal/d
- # of pumps = number of pumps at a pump station
- pump capacity = volume pumped per minute, gpm

2. Calculate the total power used by a pump station per day

$$E_{PS,x} = \text{power output} * t$$

- $E_{PS,x}$  = total energy used by a pump station, kW \* h /d
- power output = power output of pump station, kW converted from HP
- $t$  = time pumps are running per day, hour/d

3. Calculate the annual cost of pumping energy

$$APE \text{ Cost} = [ \# PS_{\text{under}} * (E_{PS,\text{under}}) + \# PS_{\text{over}} * (E_{PS,\text{over}}) ] * 365 \text{ d} * \text{Cost}$$

- APE Cost = annual cost of pumping energy, \$/year
- #  $PS_{\text{under}}$  = number of pump stations designed for under 75,000 gpd
- #  $PS_{\text{over}}$  = number of pump stations designed for over 75,000 gpd
- $E_{PS,\text{under}}$  = energy requirement of pump station under 75,000 gpd, kW \* h/d
- $E_{PS,\text{over}}$  = energy requirement of pump station over 75,000 gpd, kW \* h/d
- Cost = average cost of 1 kW \* h in California as of October 2021, \$/kW \* h

#### 3.3.2 Odor Control Chemical Costs

There are a variety of chemical treatment strategies for H<sub>2</sub>S related available. Following a study from the City of San Diego on the potential impacts of reduced flows, bioxide was used as a

surrogate for chemical treatment costs. Bioxide is typically dosed as needed to address odor complaints in populated areas. According to manufacturer instructions, bioxide should be dosed to keep aqueous HS<sup>-</sup> concentrations under 1 mg/L. The manufacturer instructions also recommend a dose of 2.4 lb calcium nitrate (0.7 gal of bioxide) for each pound of sulfide present. In order to mimic typical application strategies, the model assumes that bioxide addition only occurred in the 6” and 8” pipes which are more likely to be collection pipes in residential areas. Below is a more detailed explanation of how annual chemical costs were calculated.

1. Calculate daily bioxide usage

$$Q_{bx} = Q_{Pipe} * ([HS^-] - 1 \text{ mg/L}) * 8.34 \frac{\text{lb} * \text{L}}{\text{mg} * \text{MGD}} * 0.7 \frac{\text{gal bioxide}}{\text{lb } [HS^-]}$$

- $Q_{bx}$  = volume of bioxide, gal/d
- $Q_{Pipe}$  = flow through pipe of a specific diameter, MGD
- $[HS^-]$  = aqueous sulfide concentration, mg/L

2. Calculate annual cost of bioxide use

*Annual Bioxide Cost*

$$= [ \# \text{ 6" pipe segments} * (Q_{bx,6"}) + \# \text{ 8" pipe segments} * (Q_{bx,8"}) ] * 365 \text{ day} * \$2.15/\text{gal}$$

- $Q_{bx,6"}$  = estimated bioxide use in 6" pipes
- $Q_{bx,8"}$  = estimated bioxide use in 8" pipes

### 3.3.3 Pipe Replacement Costs

Annual pipe replacement costs were estimated by calculating the cost to replace the full length of each pipe size and dividing by the life expectancy estimated during the corrosion rate calculations. The costs of pipe replacement came from the following equation in the City of West Sacramento’s sewer master plan:

$$\text{Cost of pipe replacement} = \$10 - \$14/\text{inch diameter}/\text{feet of pipe replaced}$$

An average cost of 12\$ per inch of diameter and feet of pipe replaced was used. The estimated yearly cost of replacement was calculated for each pipe size and summed for the entire system. For pipes that were reported as a range of diameters the average diameter was used (e.g. pipes reported as 9”-18”, used a diameter of 13.5” in all calculations).

$$APR_X = (L_X * D_X * \$12)/(LE_X)$$

Where:

- $APR_X$  = annual cost of pipe replacement for pipes of diameter  $X$  inches, \$/year
- $L_X$  = total length of pipes of diameter  $X$ ", ft
- $D_X$  = pipe diameter, ft
- $LE_X$  = life expectancy of pipes of diameter  $X$ , years

$$\text{Total APR} = APR_{6"} + APR_{8"} + APR_{9-18"} + APR_{19-27"} + APR_{27-36"}$$