



**HV-Consult ApS** 

## Wastewater-Talk Sulfide Balance in Drainage Systems

Jes Vollertsen, Professor of Environmental Engineering, Aalborg University Owner of HV-Consult (Denmark) and shareholder of The WATS Guys (USA)

## Nobody (but us) loves her sewers

The public doesn't want to

- Know about them
- See them (or the wastewater)
- Smell them



The public simply wants to ignore their existence

BUT: The public wants their service, without interruption and fuss



#### That's why there are no ice cream stands, coffee shops, and people at the beach !!!









Sewer process modelling shows where and why we have the problem



## THE WALL STREET JOURNAL

## **Residents Turn Up Noses at Sewer Stink Cure**

Most San Franciscans have learned to live with foul sewer smells that come and go along the city's waterfront, Mission Bay and some other neighborhoods. But some residents are finding a growing effort by the city to combat the odors too objectionable to ignore.





#### Sewer process modelling helps finding solutions





#### Whether odor is an issue or not, depends on the quality of the neighborhood

(no taxi driver wants to pick you up where the San Francisco treatment plant is located ...)



Sewers are quite complex systems

How to keep track of the chemical, physical, and biological processes within them?



### Modelling helps keeping track of complex systems The history of sewer process modelling:



# Mega-WATS simulates whole cities for odour, corrosion, and more





#### Getting an overview (Aarhus, Denmark)



#### Zooming in on the details



## What the WATS concept covers

#### Biological processes

- Aerobic transformations (oxygen is present)
- Anoxic transformations (nitrate is present, no oxygen)
- Anaerobic transformations (sulphide, mercaptans, methane)

#### • Chemical processes

- Oxidation
- Precipitation
- Liquid-gas mass transfer
- Wastewater buffer system: pH, alkalinity

#### • Hydraulics

- Rout water through the network (semi-steady state, non-uniform flow)
- Rout air through the network (balancing water drag and pipe friction)
- Gas release to the urban atmosphere (balancing air flows)

#### Management solutions

- Ferric Iron, Ferrous Iron, Hypochlorite, Hydrogen peroxide, Nitrate, Oxygen, Magnesium hydroxide, Sodium hydroxide, Forced ventilation, and more
- Stochastic modelling for extreme event statistics and sensitivity analysis

Sewer processes are simulated by solving a large number of coupled non-linear differential equations describing processes.

This is akin to the approach of Activated Sludge models, Anaerobic Digester models, and similar engineering process models

#### The concept contains many processes and parameters

	Type of process/ Compound	8.58	Si	SA	Xir	Xire	Xisi	$\mathbf{X}_{t4}$	$X_{\mathrm{eff}(1)}$	Xetien	So	SNDI	Stupp	Stat	$s_{\mu \eta}$	S <sub>SM</sub>	5
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	10 23	Sici	$S_{A} \ast S_{S} \ast X_{\mathrm{H}} \ast X_{\mathrm{H} \mathrm{H}^{-1}} \ast X_{\mathrm{H} \mathrm{H} \mathrm{exc}} \ast X_{\mathrm{S}} \ast X_{\mathrm{SH}} \ast X_{\mathrm{SH}} \ast X_{\mathrm{SH}}$	Me	MeS	S1000	System	\$ <sub>0</sub>
Unit	00	2				а	a	
Compound #	é	13	1-5	16	17	18	19	
Ferrous and ferric precipitation of sulfide	46	-1		$\Psi_{,n}$	-Ψ <sub>,N</sub>			
Oxidation of sulfide by ${\rm H_2O_2}$	47	-1				$-\Upsilon_{H,O_{i},\mu H}$		$\frac{16}{34}\Upsilon_{H,O_{1,2}H}$
Osidation of organic matter by $H_{\rm B}\Omega_{\rm 2}$	48		-Y <sub>COD</sub> , <i>H</i> , <i>O</i> ,			-1		16 34
Oxidation of sulfide by NaOCI	49	-1					-Υ <sub>NA3,7</sub> Ν	
Oxidation of organic matter by NaOCI	50		-Y <sub>COD NOCI</sub>				-1	

	8 55	$\mathbf{S}_{[i+1]}$	$S_{A}\ast S_{F}\ast X_{11}\ast X_{10j-1}\ast X_{10jmax}\ast X_{31}\ast X_{3m}\ast X_{5n}$	PDs	FePO <sub>1</sub>	Fe(OH)1	Fe(OH) <sub>2</sub>	FeS	5 <sub>1000</sub>	Smather
Unit	000		4		e	e			а	
Compound #	e.	13	1-5				20	21	22	23
Ferrous precipitation of sulfide	51	-1					$\Psi_{_{P^N}}$	-Ψ <sub>,N</sub>		
Ferric reduction by sulfide	52									
Oxidation of sulfide by H <sub>2</sub> O <sub>2</sub>	53	-1							-Y <sub>R,O,D</sub> H	
Osidation of organic matter by H <sub>2</sub> O <sub>2</sub>	<u>54</u>		-Y <sub>COD</sub> , N, O,						-1	
Oxidation of sulfide by NaOCI	SS	-1								-Υ <sub>5402,0</sub> 9
Oxidation of organic matter by NaOCI	56		-Fanning							-1

recipitation		
us precipitation of le	<b>S</b> 7	$ if S(A) < C_{\mu A \in C} (hen instantaneous, else zero if pH < 8 hen \Psi_{\mu H} = 1.3 < 0 hen \Psi_{\mu H} = 1.3 < 0 hen \Psi_{\mu H} = 1.3 < 0 hen Henrich (henrich and henrich h$
nical exidation		
ation of sulfide by H <sub>2</sub> O <sub>2</sub>	58	$k_{i(-R)mn} S_{2i-R}^{m_{i,i} + i^{m}mm} S_{R,i,i}^{n_{i,i} + i^{m}mm} S_{R,i,i}^{n_{i,i} + i^{m}mm} \sigma_{Sachem}^{T-20}$
ation of organic matter <sub>1</sub> 0 <sub>2</sub>	59	$k_{22\beta_{\text{Ann}}0,22\beta} S_{\beta(-d)}^{\alpha=\alpha_{\text{max}}} S_{\beta(d)}^{\alpha=\alpha_{\text{max}}} \sigma_{\delta(d)_{\text{max}}}^{\beta-2\beta}$
ation of sulfide by NaOC	60	$k_{j(-l) modd} S_{j(-l)}^{n_{j(-l)}m_m} S_{Od}^{n_{j(-l)}m_m} a_{jmd,m}^{l-10}$
ation of organic matter aGCI	61	$k_{22(hand(n)}S_{[1-i0]}^{\mu_{10},\mu_{10}} \cdot S_{(E1)}^{\mu_{20},\mu_{10}} \cdot S_{(E1)}^{\mu_{20},\mu_{10}} \cdot S_{(E1)}^{\mu_{20},\mu_{10}}$

#### s phase processes and liquid-gas mass transfer

		\$ <sub>0</sub>	Sidoot	$S_{(-1)}$	Sstel	Pee	Pcaz	Pitts	Posts	SC <sub>405</sub>	SCSHWARES	SCIALISON	diarr
Unit						ь	b	ь	ь	c	c	c	đ
Compound #		9	31	13	15	24	25	26	27	28	29	30	
Oxygen mass transfer, between	62	1				$-\frac{M_{O_c}}{R_c T_X} \frac{V_{\infty}}{V_c}$							
liquid and gas	10	-		_									
between liquid and gas	63		-1				$\frac{M_{(D)}}{R_{\chi}T_{K}}\frac{V_{\chi}}{V_{\chi}}$						
H <sub>2</sub> S mass transfer	64							Marc V					
between liquid and gas				-1				$\frac{R_{E}T_{K}}{R_{E}T_{K}} \frac{V_{w}}{V_{E}}$					
Methyl mercaptane mass transfer between liquid and gas	65				-1				$\frac{M_{MM}}{R_gT_K}\frac{V_{\pi}}{V_g}$				
H <sub>2</sub> S absorbed on a pipe wall	66							-1		$\frac{R_g T_K}{M_{R,S}} \frac{A_r}{V_g}$			
H <sub>2</sub> S oxidation, concrete	67							-1		-4	$1-k_{aar}$	k	
Sulfuric acid corrosion, concrete	68											-1	$\frac{\hat{S}_{dl}}{\sigma_{out}Ak_{cl}}$

Substance	Compound #	Unit	Buffer equation
Carbonate	31	e	$CO_{2(gard)} = CO_{2(gard)} + H_2O = H_2O_3 = HCO_3^- + H^+ = CO_3^{} + 2H^+$
Sulfide $(S_{j \rightarrow j})$	13	e	$H_1S_{(per)} \square = H_2S_{(reps)} \square = HS^+ + H^+ \square = S^{2-} + 2H^+$
Acetic acid (VFA) (S <sub>8</sub> )	2a	e	$HAc \square Ac + H^+$
Propionic acid (VFA) (S <sub>8</sub> )	2b	e	$HPr^{-\frac{2}{2}}$ $HPr^{-} \neq H^{+}$
Ammonia	32	e	$\stackrel{V_{2S}}{\underset{MH_{\pm}^{+}\square}{}} MH_{\pm} + H^{+}$
Amines	33	e	$\frac{553}{RNH_1} = RNH_2 + H^+$
Phosphate	34	e	$H_1PO_4 \square H_2PO_4^+ + H^+ \square HPO_4^{2+} + 2H^+ \square PO_4^{2+} + 3H^+$
Bisulfate	35	e	$HSO_t^{-1} = SO_t^{2+} + H^+$
Carboxyl groups other than acetic and propionic acid	36	e	$R = COOH \square R = COO^{-} + H^{+}$

e of process		Process equations			
lk water growth					
robic growth in bulk ter	69	$\mu_{\alpha_k} \frac{(S_F + S_s)}{K_{s_k} + (S_F + S_s)} \frac{S_o}{K_o + S_o} X_{H} \sigma_s^{F-m} k_{H_oH}$			
oxic growth on NO <sub>3</sub> ' in Ik water	70	$\frac{\mu_{SN2}}{K_{N2} + S_{N2}} \frac{S_F + S_s}{K_{1s} + (S_F + S_s)} \frac{K_F}{K_D + S_D} X_H \Theta_s^{F-20} k_{H,sH}$			
oxic growth on NO <sub>3</sub> ' in Ik water	71	$\left[\frac{S_{92}}{\mu_{002\ell}}\frac{S_{92}}{K_{92\ell}+S_{92}} + \mu_{002\ell}\frac{K_{92}}{K_{92\ell}+S_{92\ell}}\right]\frac{S_{92}}{K_{92\ell}+S_{62\ell}}\frac{S_F + S_s}{K_{1s} + (S_F + S_s)}\frac{K_O}{K_O + S_O}X_B \sigma_s^{T-2k} K_{B,sH}$			
robic maintenance in lk water	72	$q_{-\frac{S_0}{K_0 + S_0}} \chi_R a_n^{T-m} k_{R,N}$			
oxic maintenance in Ik water when NO <sub>3</sub> is	73	$g_{=N2} \frac{S_{N2}}{K_{N2} + S_{N2}} \frac{K_{\odot}}{K_{\odot} + S_{O}} \chi_B \sigma_n^{T-2k} k_{B,sH}$			
oxic maintenance in Ik water when NO <sub>3</sub> is	74	$\left[q_{_{N}U_{0,I}}\frac{S_{U_{0}}}{K_{U_{0}}+S_{U_{0}}} + q_{_{N}U_{0,I}}\frac{K_{U_{0}}}{K_{U_{0}}+S_{U_{0}}}\right]\frac{S_{U_{0}}}{K_{U_{0}}+S_{U_{0}}}\frac{K_{O}}{K_{O}}X_{H}\alpha_{e}^{T,20}k_{_{H},H}$			
nimum total bulk wate intenance rate	75	$\chi_{\alpha}q_{\alpha}\chi_{\alpha}a_{\alpha}^{2-13}k_{\alpha,\alpha}$ if $t^{4} + t^{5} + t^{6}$ is less than the minimum maintenance rate given above, then the			
robic growth in biofilm	76	If $5_0 < 5_{0,mix}$ then $k_{\alpha\beta\gamma} \overline{S_0} \frac{Y_{\beta\beta\beta}}{1 - Y_{\beta\beta\beta}} \frac{A_f}{V_{\alpha}} \frac{(S_a + S_F)}{K_{\gamma f} + (S_a + S_F)} \sigma_f^{T-2} k_{\beta,\mu}$ else $k_{\alpha\beta} \frac{S_{0,mix}}{S_{0,mix}} \frac{T_{\beta\beta\beta}}{1 - Y_{\beta\beta\beta}} \frac{A_f}{V_{\alpha}} \frac{(S_a + S_F)}{V_{\alpha}} \frac{(S_a + S_F)}{M_{\alpha}} (S_a $	$\frac{S_s + S_F}{(S_s + S_F)} \alpha_j^{T-10} k_{H_0H}$		
	77	If SourceSources then $k = \sqrt{S_{min}} \frac{1.17T_{RND}}{M_f} \frac{A_f}{(S_A + S_F)} = K_D \frac{\sigma^{T-1/2}}{\sigma^{T-1/2}}$			
oxic growth in biofilm ND <sub>1</sub>		$\lim_{n \to \infty} \sum_{j=1}^{n} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{j=1$	Methyl mercantan		
	78	$V_{M2,\infty} = V_{M2,\infty} = V_{M30} = V_{m} K_{S} + (S_{A} + S_{F}) K_{O} + S_{O} = V_{M3} = V_{M3} + V_{M3} = V_{M$	formation	102	<ul> <li>An An An A</li> </ul>
		If $S_{ND} < S_{ADJ,max}$ then $k_{ADJ,f} = \frac{S_{ND,f}}{K_{AD} + S_{AD}} + k_{ADJ,f} \frac{K_{ND,f}}{K_{AD} + S_{AD}} = \frac{K_{ND,f}}{1 - Y_{AD}} \frac{K_{ADJ,f}}{V} \frac{K_{AD}}{K_{AD} + S_{AD}}$	Anaerobic formation	102	$\xi_{reg,hm} \left( c_{r} \neq c_{m} + c_{m} + c_{m} \right)$
oxic growth in biofilm ND-		$\begin{bmatrix} n_{30} + \sigma_{30} \\ r \end{bmatrix} = \begin{bmatrix} n_{30} + \sigma_{30$	Aerobic oxidation	103	$z_{avas}(r_i + r_i + r_i + r_i + r_i + r_i + r_i + r_i)$
10)		else $\left  k_{(M)J} \frac{S_{M}}{K_{ND} + S_{M}} + k_{(M)H} \frac{K_{M}}{K_{ND} + S_{M}} \right  \sqrt{S_{M}} = \frac{1.74_{HMD}}{1 - Y_{HMD}} \frac{A_{f}}{V_{c}} \frac{(S_{d} + S_{F})}{K_{S} + (S_{d} + S_{F})} \frac{K_{O}}{K_{O} + S_{O}} a_{f}^{T}$	H <sub>2</sub> S formation	104	( ((-t)t)) So Kenter Knowner Knowner Arme
drolysis	70		H <sub>2</sub> S formation, biofilm, on S <sub>1</sub> (+S <sub>6</sub> )		$\left k_{i_{1}\cdots i_{D}}\left[\tau_{g}+\frac{v_{i}\cdots v_{g}}{K_{i}+\tau}\right] \mathbf{\sigma}\right] \mathbf{v}_{gg} S_{g} + (1-\delta_{gg}) S_{d} \frac{\omega_{i_{1}}}{K_{i_{2}}+S_{i_{D}}} \frac{\omega_{i_{2}(i_{1}+g)}}{K_{i_{2}(i_{1}+g)}+S_{i_{0}}} \frac{\omega_{i_{2}(i_{1}+g)}}{K_{i_{2}(i_{1}+g)}+S_{i_{2}}}  \frac{\omega_{i_{2}(i_{1}+g)}}{K_{i_{2}(i_{1}+g)}+S_{i_{2}}} \frac{\omega_{i_{2}(i_{1}+g)}}{K_{i_{2}(i_{1}+g)}+S_{i_{2}}}} \frac{\omega_{i_{2}(i_{1}+g)}}{W_{i_{2}(i_{1}+g)}+S_{i_{2}}}} \frac{\omega_{i_{2}(i_{1}+g)}}{W_{i$
robic hydrolysis, X <sub>6,500</sub> , bulk water	79	$k_{b,be} \frac{X_{3,ber}  X_H}{K_{H-1} + X_{+} + X_{+} + X_{+} + K_{+} + S_{+}} X_H \alpha_n^{T-10} k_{H,\mu}$		105	$if (S_0>10^{+}K_{0,005}) \text{ or } ((S_{0,01}+S_{0,02})>10^{+}K_{0,0123}) \text{ then rate = 0}$ $\delta = S_{0,01} + \delta_{0,01} + S_{0,012} + S_{0,0$
rabic hydrolysis, X <sub>tured</sub> ,	80	$\sum_{k=1}^{N} \frac{X_{k+1} - X_{k+1} - $	water, on S <sub>F</sub> (+S <sub>A</sub> )		$\mu_{0,1,\dots} \frac{\kappa_{g,0} + (1 - \delta_{gf}) \sigma_{f}}{\kappa_{g,0} + \delta_{gf}} \frac{\kappa_{g_{0,1}}}{\kappa_{g_{0,1}} + \delta_{gg}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \delta_{gg}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \delta_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \delta_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \sigma_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \sigma_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \sigma_{g_{0,1}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}} \frac{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}}{\kappa_{g_{0,1}} + \sigma_{g_{0,1}}}}$
bulk water	81	$\kappa_{h,mol} = K_{X,mol} + X_{X,mol} - X_H - K_0 + S_0 - \kappa_{H,mol}$ $K_{L-1} - K_{L-2} - K_{L-2} - K_{L-2} - \kappa_{H-2}	H <sub>2</sub> S formation, biofilm, on	106	$\mathbf{e}_{[n_1,m_2]}\left\{k_{[n_1,m_2]}\left[\mathbf{t}_{n_1} + \frac{(1-\mathbf{t}_{n_2})\mathbf{z}}{K+\mathbf{t}}\right]\boldsymbol{\sigma}\right\}\boldsymbol{\sigma}_{[n_1,m_2]}\frac{S_{N_1}}{K_{N_1}+S_{N_2}}\frac{K_{N(N_1,m_2)}}{K_{N_1}+K_{N_2}}\frac{K_{N(N_1,m_2)}}{K_{N_1}+K_{N_2}}\frac{K_{N(N_1,m_2)}}{K_{N_1}+K_{N_2}}\frac{K_{N(N_1,m_2)}}{K_{N_2}+K_{N_1}+K_{N_2}}\frac{K_{N(N_1,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}+K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}}\frac{K_{N(N_2,m_2)}}{K_{N_2}}\frac{K_{N(N_2,m_2)}}\frac{K_{N(N_2,m_2)}}{K_{N_2}}K_{N(N_2,m_$
bulk water		$k_{i,dm} \frac{X_{i,dm}}{K_{X,dm}} + X_{X,dm} \frac{X_{H}}{X_{H}} \frac{X_{H}}{K_{0}} + S_{O} \frac{X_{H}}{K_{0}} \frac{X_{H}}{K$	xs	107	If (S <sub>1</sub> >10 <sup>+</sup> K <sub>0/05</sub> ) or ((S <sub>101</sub> +S <sub>100</sub> )>10 <sup>+</sup> K <sub>100</sub> )) then rate = 0
oxic hydrolysis, X <sub>3,5et</sub> in Ik water		$\eta_{i_1mn}k_{i_2jac} \frac{\Lambda_{X,jac}f\Lambda_H}{K_{X,jac}fX_Xg} \frac{K_O}{S_O + K_O} \frac{S_{H2} + S_{H2}}{K_{H2} + (S_{H2} + S_{H2})} \chi_H \sigma_n^{T-in} k_{H,jH}$	H <sub>2</sub> S formation, bulk water, on X <sub>1</sub>		$ x_{0,-0)0} \mu_{H,3,w} \frac{\alpha_{H}}{K_{3,w} + X_{0j}} \frac{\alpha_{H,1}}{K_{H,2w} + S_{H,2}} \frac{\alpha_{0,3j,-0,3w}}{K_{0,0j,-0,3w} + S_0} \frac{\alpha_{0,3j,-1,3w}}{K_{0,2j,-0,3w} + S_{0,2}} \frac{\alpha_{0,3j,-1,3w}}{K_{H,2,3j,-0,3w} + S_{H,2}} \frac{\alpha_{0,3j,-0,3w}}{K_{H,2,3j,-0,3w} + S_{H,2}} \frac{\alpha_{0,3j,-0,3w}}{K_{H,2,3w} + S_{H,$
oxic hydrolysis, X <sub>Synel</sub> bulk water	83	$\overline{\eta}_{h,mn} \bar{k}_{h,mnd} \frac{X_{N,mnd}   X_N - K_N - K$	Decay of sulfate reducers H <sub>2</sub> S oxidation, water	108	$b_{m(m)} X_{m(m)} \mathbf{x}_{e^{-m}}$
oxic hydrolysis, X <sub>3,dow</sub>	84	$\frac{1}{T_{1,mn}} \sum_{k,n=0}^{n,mn} \frac{K_{k}}{K_{1,n+1}} \sum_{k=1}^{m} \frac{K_{k}}{K_{k}} \sum_{k$	Sulfide oxidation, aerobic, chemical, bulk water	109	$k_{B,bar(0)} + k_{B,mr(0)} \frac{K_{+1}}{0.1} \sum_{\eta_1,\eta_2} \sum_{\eta_2,\eta_3} \sum_{\eta_3,\eta_4} \sum_{\eta_2,\eta_3} \sum_{\eta_3,\eta_4} \sum_{\eta_4,\eta_4} \sum_{\eta_4,\eta_4$
aerobic hydrolysis,	85	$\overline{\eta}_{h,m}, \overline{k}_{h,low} = \frac{X_{3,low}  X_N }{K_N} = \frac{K_{3D}}{K_{3D}} = \frac{K_D}{K_D} X_N \sigma_n^{2-2n} k_{N-N}$	Sulfide oxidation, aerobic,	110	0.1 <sup>rr</sup> k
ar, in bulk water	86	$K_{X,ford} = A_{X,ford} \int A_N - K_{NO} + (S_{NO} + S_{NO}) + S_O - S_O$ =	biological, bulk water Sulfide oxidation, aerobic,	111	$\chi_{1} = \frac{1}{2} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \sum_{j=1}^{N-1$
wee, in bulk water	87	$T_{L_{2}m\sigma^{2}L_{2}m\sigma^{2}}K_{-}K_{-}m\sigma^{-}K_{-}K_{-}M_{-}K_{-}M_{-}K_{-}M_{-}M_{-}M_{-}M_{-}M_{-}M_{-}M_{-}M$	Sulfide oxidation, anoxic,	112	$k_{\mu_1,\mu_2\Omega} = k \frac{r_{\mu_1}}{k_{\mu_1}} \frac{k_{\mu_1}}{\omega_{\mu_1}\omega_{\mu_2}} \frac{r_{\mu_2}}{\omega_{\mu_1}\omega_{\mu_2}} \frac{r_{\mu_2}}{\omega_{\mu_2}} \frac{r_{\mu_2}}{\omega_{\mu_1}}$
tow in bulk water	88	$q_{b_1aa}A_{b_1baa}K_{X_1baa} + X_{X_1baa} + X_K_{X_2} + (S_{X_2} + S_{X_2})K_O + S_O^{-X_HBA_N} + K_{H_2H}$ $X_{X_1baa} + X_H = S_O^{$	chemical, bulk water	113	$l + \frac{K_{a}}{0.1^{pt}} = 3_{11-0}, 3_{30}, \omega_{hag0}$
biofilm		$K_{b,bel} = \frac{1}{K_{X,feel}} + X_{X,feel} + X_N K_O + S_O^{-2} R_N^{-N} H V_{-}^{-2} R_{-}^{-K} K_{N,FN}$	biological, bulk water		$k_{  -1  _{100}dML} S_{  -1  _{100}dML} c_{0}^{1-20} \mathbf{a}_{   _{100}dML} k_{  -1  _{10}M}$
robic hydrolysis, X <sub>6,444</sub> , aiofilm	89	$k_{i,mel} \frac{X_{S,mel} f X_H}{K_{S,mel} + X_{S,mel} f X_H} \frac{S_O}{K_O + S_O} \mathbf{r}_H X_H \frac{A_I}{V_u} \mathbf{a}_u^{T-2k} k_{K,iH}$	Sulfide oxidation, anoxic, biofilm	114	$k_{[i-1]j_{klk}M_{2}} \sum_{n_{l}=d_{l}}^{n_{l}d_{l}M_{2}} \left( S_{N(2)} + S_{N(2)} \right)^{n_{l}(M_{2})} \frac{d_{l}}{V_{n}} \frac{d_{l}}{d_{kk}M_{k}} \frac{d_{l}}{k_{kl}-d_{l}} k_{[i-1]_{l}N_{l}}$
robic hydrolysis, X <sub>6,1800</sub>	90	$k_{k,dm} = \frac{X_{S,dm}}{V} \frac{X_H}{V} \frac{S_O}{V} \epsilon_H X_{H} \frac{A_f}{V} \alpha_n^{T-20} k_{H,H}$	H <sub>2</sub> S precipitation		187/11/a.P. Alexa Instantaneous alexan
ovir badeolusis X	91	$X_{1,low} = X_{2,low} [X_{H} = K_{0} = K_{0} = K_{0}$ , $X_{1,low} [X_{H} = K_{0} = S_{H0} + S_{H0} = \dots = A_{\ell} = r_{1}r_{\ell}$	precipitation of sulfide	115	$if_{1}p_{1} < 8$ then $\Psi_{pl} = 1.3 + 2*(8 - pH) \operatorname{cbe} \Psi_{pl} = 1.3$ (obs this is a stoichiometric parameter which did not physically fit into the table)
film		$\frac{\eta_{i,um}k_{i,jm}}{K_{X,jm}+X_{2,jm}}X_{H}\frac{\sigma}{S_{O}+K_{O}}\frac{\sigma}{K_{ND}+\left(S_{ND}+S_{ND}\right)}\sigma_{H}X_{H}\frac{\sigma}{V_{u}}\sigma_{u}^{i-i-k}k_{H,M}$	Chemical oxidation		
oxic hydrolysis, X <sub>Spante</sub>	92	$\eta_{h,m,k} k_{h,m,d} \frac{X_{N,m,d}   X_N}{K_{m-1} + X_{m-1}   X_N} \frac{K_O}{S_{m} + K_{m}} \frac{S_{M_0} + S_{M_0}}{K_{m} + (S_{m-1} + S_{m-1})} \epsilon_M X_{N_0} \frac{A_J}{V} \alpha_n^{F-10} k_{N,m}$	Oxidation of sulfide by H <sub>3</sub> O <sub>2</sub>	116	$\tilde{h}_{j_1,\dots,j_{2(n+1)(2n+1)}} \overset{A^{(n)}_{j_1}\dots\dots,J^{(n)}_{j_{n+1}}\dots\dots,J^{(n-1)}_{j_{n+1}(2n+1)}\dots\dots,J^{(n-1)}_{j_{n+1}(2n+1)}\dots\dots,J^{(n-1)}_{j_{n+1}(2n+1)}\dots$
oxic hydrolysis, X <sub>3,dow</sub> ,	93	$\frac{1}{2} \sum_{n=0}^{\infty} \frac{1}{2} \sum_{n=0}^{\infty} \frac{1}$	Oxidation of organic matter by H <sub>2</sub> O <sub>2</sub>	11/	$k_{220hauW2202}S_{2(-d)}^{h_1\cdots h_{max}}S_{K(d)}^{h_1\cdots h_{max}}=S_{K(d)}^{h_1\cdots h_{max}}S_{K(d)}^{h_1\cdots h_{max}}$
biofilm	94	$\frac{m_{abc}}{m_{abc}} = \frac{K_{abc}}{K_{abc}} + \frac{K_{abc}}{K_{abc}} X_{B} S_{0} + K_{0} K_{B0} + (S_{B0} + S_{B0})^{-m} - m V_{a}^{-m} = -m_{abc}^{-m}$	Oxidation of sulfide by NaOCI	118	$k_{[1-l]_{point}} \sum_{s_{1}-l}^{c_{1}} \sum_{s_{1}-l}^{c_{1}} \sum_{s_{1}-l}^{s_{1}} \sum_{s_{1}-l}^{s_{1}-l_{1}} \sum_{s_{1}-l_{1}}^{c_{1}-l_{1}} \sum_{s_{1}-l_{1}$
w, in biofilm		$\eta_{i_{0}m} k_{i_{0}m} \frac{1}{K_{\chi_{f}m} + X_{\chi_{f}m}} \frac{1}{K_{H}} \frac{1}{K_{HD}} + \left(S_{HD} + S_{HD} + S$	matter by NaOCI		$k_{(2)low(0)}S_{(-i)}^{low,m_n}S_{(C)}^{l_n,m_m} \mathbf{a}_{bulkm}^{l_n-2}$
aerobic hydrolysis, w4, in biofilm	33	$\eta_{i_1m_i}k_{i_1m_i}\frac{X_{i_1m_i}}{K_{i_1m_i}+X_{i_1m_i}}\frac{X_N}{K_N}\frac{K_{i_2}}{K_{i_N}+(S_{N_i}+S_{N_i})}\frac{K_O}{K_O}+S_O} \sharp_{M}X_N\frac{A_j}{V_a}a_a^{P-in}k_{N_iN}$	phases	120	$K_{,a,a} (\beta S_{a,a} - S_{a,b})$ where
aerobic hydrolysis,	96	$\eta_{i_1,,k_{k,ikm}} \frac{X_{i_1,.i_2m}}{K_{m-1} + X_{m-1}} \frac{X_{i_1}}{K_{m-1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_2}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K_{m+1} + (S_{m-1} + S_{m-1})} \frac{K_{i_1}}{K$			$K_{1}q_{1} = 24 \cdot 0.85(1+0.20F^{*})(.at)^{V} d_{-}^{-1} a_{-}^{r_{-10}}$ for a flowing sewer
mentation		$\chi_{phen} = \chi_{phen} - \chi_{phen} $	Oxygen mass transfer, between liquid and gas		For a drop KLaO2 is calculated from an empirical equation for the oxygen deficit ratio, $r_c = \frac{(C_{car} - C_c)}{(C_{car} - C_c)}$ and $\ln r_c = aH^b_{drop}Q^c_{car}h^d_{eff}$
aerobic fermentation, film, on 5;	97	$k_{\bar{p}} \sqrt{S_F} \frac{K_O}{K_O + S_O} \frac{K_{NO}}{K_{NO} + \left(S_{NO} + S_{NO}\right)} \frac{K_{RO, low, \bar{l}}}{K_{RO, low, \bar{l}} + S_{RO}} \frac{K_{OO, low, \bar{l}}}{K_{OO, low, \bar{l}} + S_{OO}} \frac{A_{\bar{l}}}{V_{u}} \sigma_u^{\bar{l} - 2k} k_{R, H}$	, ,		The oxygen deficit ratio is converted into a KLa value as $K_{\pm 0} \frac{V}{Q} = -\ln(r_c)$
aerobic fermentation, k water. on %	98	$q_{j_{ew}} \frac{S_{\mu}}{K_{\mu} + S_{\mu}} \frac{K_{\mu}}{K_{\mu} + S_{\nu}} \frac{K_{\mu\mu}}{K_{\mu} + S_{\nu}} \frac{K_{\mu\mu}}{K_{\mu\nu} + S_{\nu\nu}} \frac{K_{\mu\mu}}{K_{\mu\nu} - \dots + S_{\mu\nu}} \frac{K_{\mu\mu}}{K_{\mu\nu} - \dots + S_{\mu\nu}} \frac{K_{\mu\mu}}{K_{\mu\nu} - \dots + S_{\mu\nu}} X_{\mu\mu\nu} \sigma_{\nu}^{T-2\nu} k_{\mu\mu\nu}$	CO <sub>2</sub> mass transfer	121	For a hydraulic minor loss, the energy loss in m water column is used as H <sub>imp</sub>
aerobic fermentation,	99	$F_{-} = \frac{K_{-}}{K_{-}} \frac{K_{0}}{K_{0}} \frac{K_{00}}{K_{00}} \frac{K_{00,jm0}}{K_{00,jm0}} \frac{K_{00,jm0}}{K_{00,jm0}} \frac{4_{j}}{m} \frac{\pi^{1.0}}{m} E_{-}$	between liquid and gas H <sub>2</sub> S mass transfer	122	$\kappa_1 a_{01} a_{01} a_{01} (F_m S_{01m} - S_{01})$
film, on X <sub>1</sub>	100	$K_{ab} = K_{ab} + S_{ab} K_{ab} + (S_{B2} + S_{B2}) K_{B(0, joinj)} + S_{B(0, K_{B2})joinj} + S_{O2} V_{ab} = K_{ab} +	between liquid and gas Methyl mercaptane mass	123	<sup>ere</sup> <sup>(n</sup> g) <sup>(n</sup> m (nm <sup>*</sup> )g)m <sup>(n</sup> g) <sup>(g)</sup>
k water, on Xr		$\mathbf{c}_{j(m)l}q_{lm}\frac{q}{K_{jc}+K_{ll}}\frac{-\alpha}{K_{0}+K_{0}}\frac{-\alpha}{K_{00}}$	transfer between liquid and gas		$K_1 a_{\mu\nu} \boldsymbol{\sigma}_{\alpha\nu} \left( \boldsymbol{\beta}_{\alpha\nu} S_{\nu\nu,\nu} - S_{\nu\nu} \right)$
cay of fermenters	101	$b_{ijen} X_{ijen} \mathfrak{C}_{c}^{-d}$	Tracer gas (any type of solubility in water) H <sub>2</sub> S oxidation, gas	124	$k_1 a_{nm} \mathbf{e}_{m} \left( \mathbf{f}_m \mathbf{S}_{nmm} - \mathbf{S}_{nmr} \right)$
			H <sub>2</sub> S absorbed on a pipe wall	125	$f_{n_1 n} = k_1 p_{n_2 n}^n$ where $k_j = k_2 R e^{i \omega n}$
			H <sub>3</sub> S oxidation, concrete	126	instantaneous
			Sulfuric acid corrosion, concrete	127	Instantaneous
			-	_	

### Each pipe is simulated, meter for meter



A simulation example – 215 m of gravity pipe with backwater

## Stockholm – Smältvägen force main

Dissolved sulphide (mg/L)



## Identifying solutions

There are many tools in the toolbox

They can be tested by the model before running expensive field trials



### Mega-Vent Solves the momentum balance of the air flow Gives pressure and air velocities in all pipes



#### Blue nodes: Positive pressure Red nodes: Negative pressure







#### Forced ventilation

#### Pressure, velocities, flows





# Forecasting urban densification, climate change, etcetera

The impact of temperature



# Forecasting urban densification, climate change, etcetera

The impact of per capita water usages



## And so much more

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