Sulfide Modeling as a Practical Asset Management Tool

Prabhu Chandrasekeran, PE

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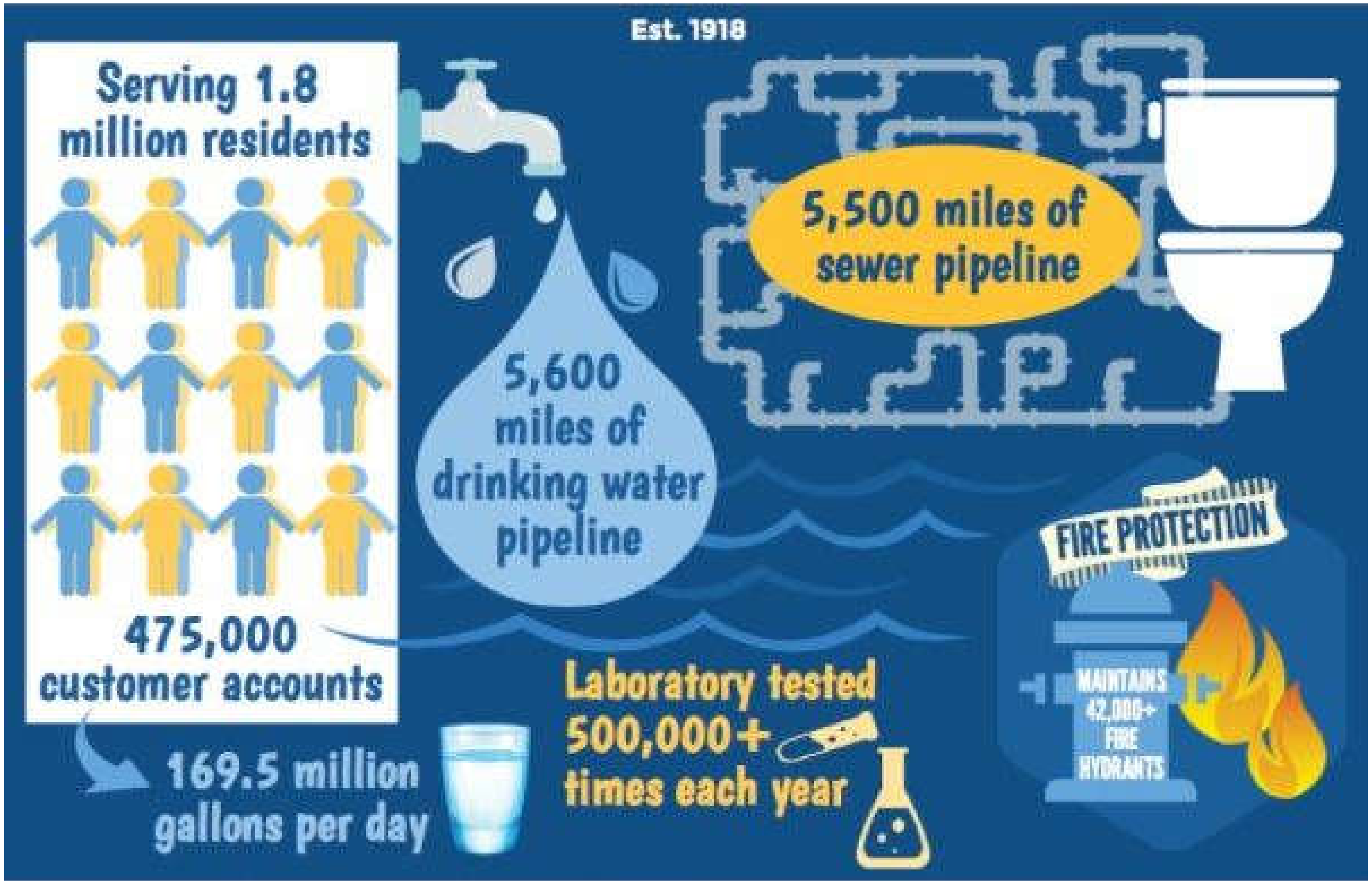
Introduction



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WSSC's Collection System

- Collection System Evaluation Program
  - Consent Decree requirements
  - Currently in Phase-III
- Critical Asset Condition Assessment
  - Anacostia Sewer (102")
  - Trunk Sewers
  - Microbial Induced Corrosion (MIC) issues
  - How can we predict and be proactive?

This Presentation Describes The Sewer Sulfide Modeling As A Practical Asset Management Tool

- Sulfide generation and corrosion mechanisms
  - How does sulfide generate within collection system?
  - How does corrosion occur?
  - How does hydraulics affect corrosion?
  - What is sulfur cycle?
- How can we predict corrosion within sewer system?
  - Basic approaches and complex modeling tools
  - Limitation of various approaches
- Application of Model
  - What factors were found to affect corrosion?
  - How can a model be used as a predictive tool?

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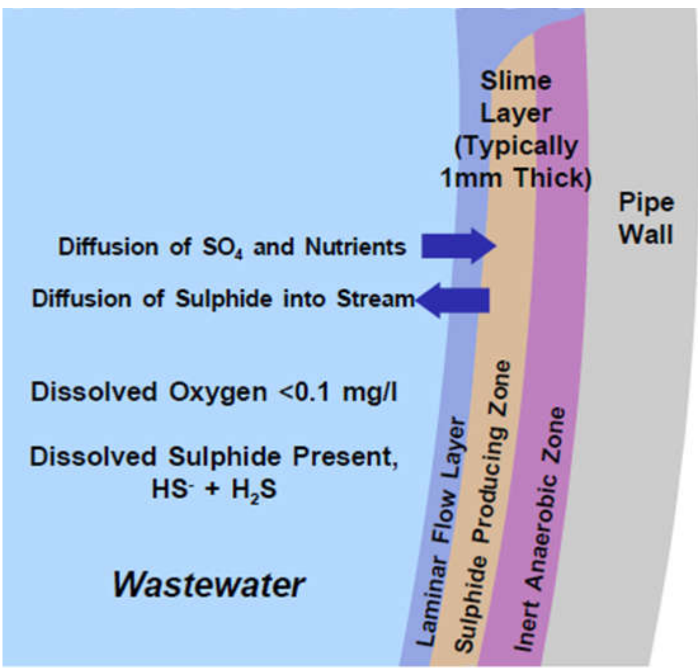
Sulfide Generation, Sulfide Transfer and Corrosion Mechanisms



- High Sulfates High H_2S
- High BOD High H_2S
- Low DO High H_2S (Anaerobic conditions)
  - Non-limiting O_2 (<1.0 mg/L)
  - Flat sewers (Trunk Sewers)
- More Surface area More slime layer More H_2S
  - Debris increases surface area
- High temperature High H_2S
- High Detention Time High H_2S
- SRBs can exist between pH 5.5 to 9

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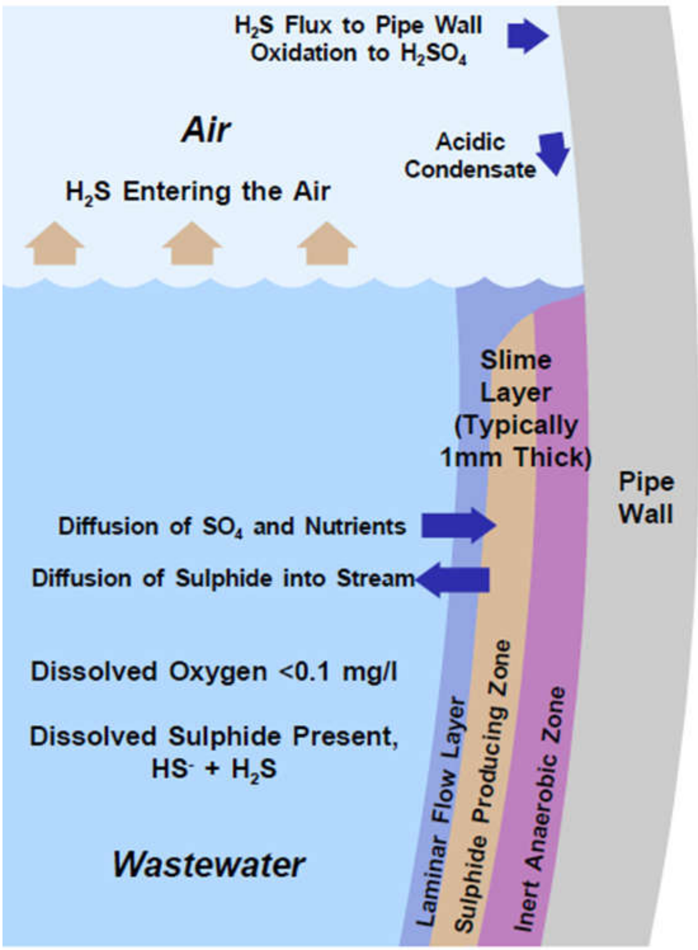
Sulfide Generation, Sulfide Transfer and Corrosion Mechanisms

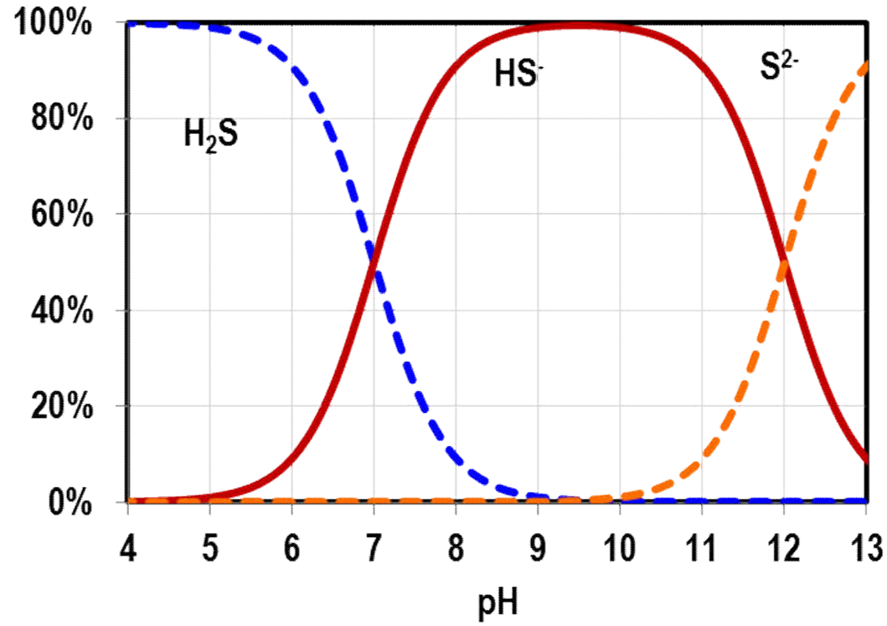


- DO concentration and sulfide oxidizing bacteria
- Liquid/Gas phase H_2S equilibrium (Henry's Law)
- Higher the dissolved H_2S, higher the headspace H_2S
- Higher the temperature higher the concentration of H_2S in headspace

Sulfide Generation, Sulfide Transfer and Corrosion Mechanisms

- Sulfide is a weak-acid and pH dependent
- Only the unionized H_2S is a soluble gas

Fraction of Total Sulfur in Each Form



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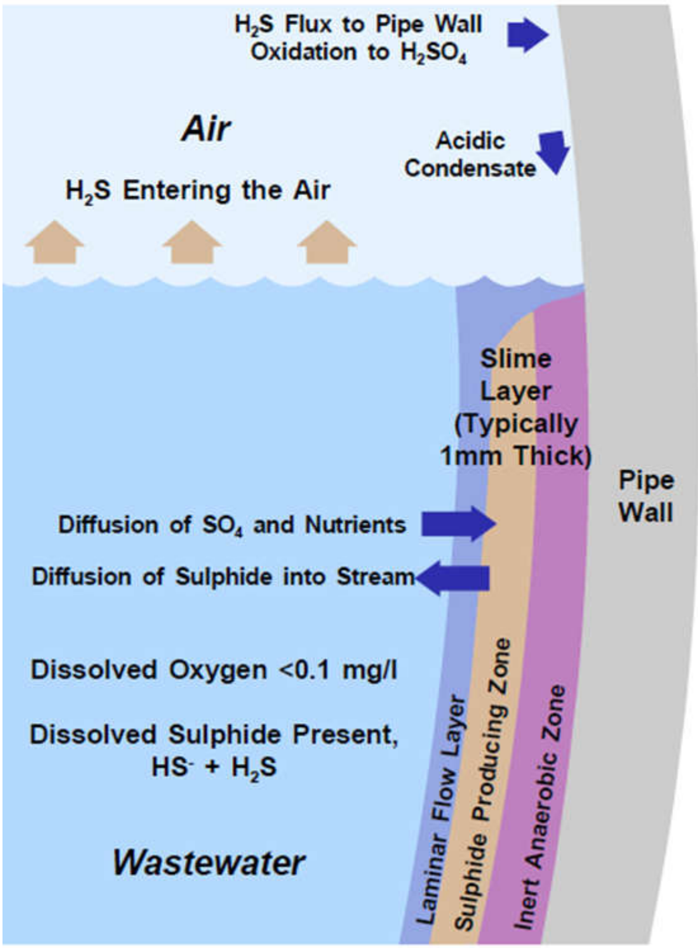
Sulfide Generation, Sulfide Transfer and Corrosion Mechanisms



- Gaseous H2S is oxidized to sulfuric acid
- Impact to different pipe materials
- pH of Concrete
- Sulfuric acid runs back into the sewage
- Depletes alkalinity and become sulfates
- CYCLE STARTS AGAIN

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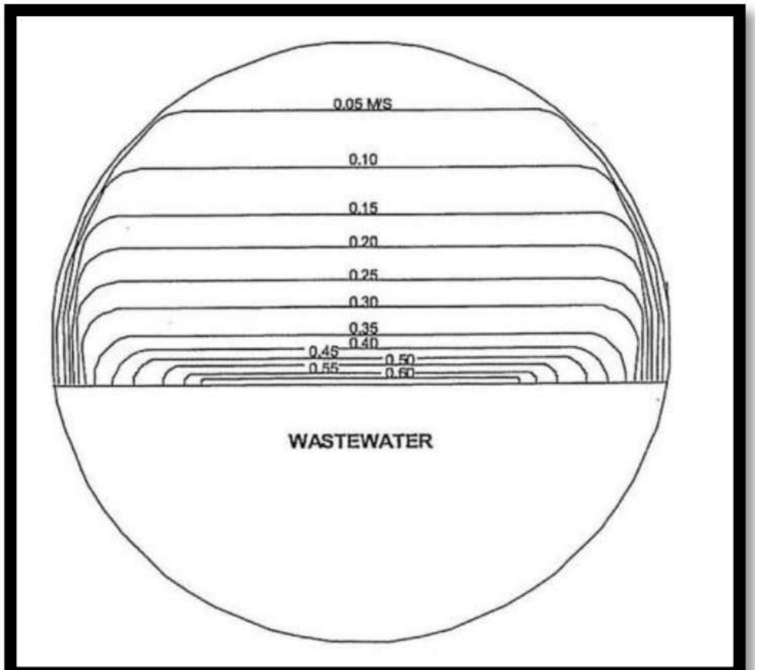
Sulfide Generation, Sulfide Transfer and Corrosion Mechanisms



From Pescod & Price (1982)

- Air velocity profile within a sewer
- Air moves at different velocities based on the distance from the wastewater
- Point of H_2S release is not necessarily the point of corrosion

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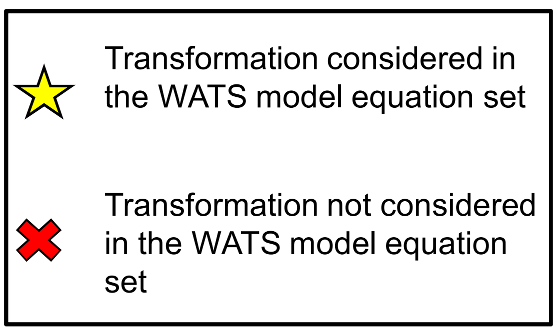
  - What is sulfur cycle?
- **How can we predict corrosion within sewer system?**
  - **Basic approaches and complex modeling tools**
  - **Limitation of various approaches**
- Application of Model
  - What did we find about factors affecting corrosion?
  - How can we use the model as a predictive tool?

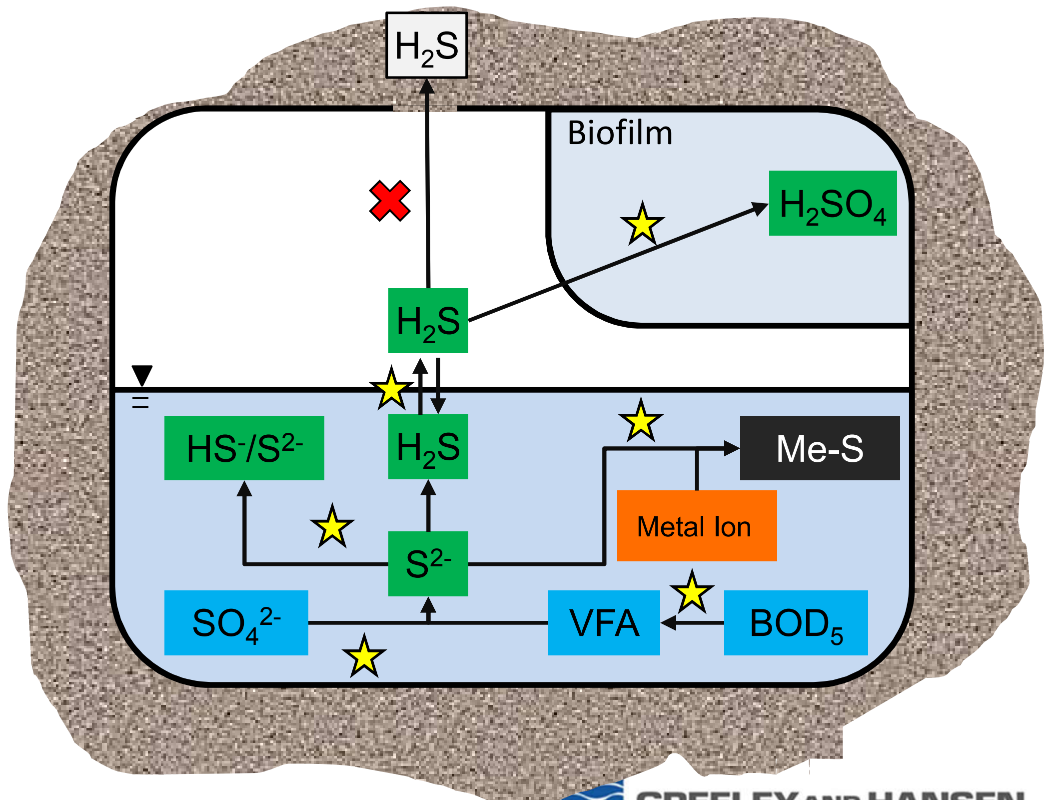
Prediction of Sulfide Generation And Corrosion In Sewer Networks

- Empirical Equations
  - Yes-or-No Answers
- Qualitative Indicators
  - Pomeroy Method for Pressure Sewers
  - Pomeroy and Parkhurst Method for Gravity Sewers
  - Z-Formula
- Mechanistic Modeling
  - WATS – Wastewater Aerobic/Anaerobic Transformations in Sewers
  - Adaptation of the WATS Model

Mechanistic Modeling Is Akin To Biological Process Modeling, Reflecting As Many Important Transformations As Practical

- Mechanistic Modeling
  - WATS – Wastewater Aerobic/Anaerobic Transformation in Sewers
  - Akin to IWA's ASM No. 1 for Activated Sludge





Mechanistic Modeling Requires Significant Computational Power And Expertise Of A Software Operator/Programmer

Processes	$X_{S(-II)}$	$S_{S(-II)}$	S_O	pH_2S	Process rate
Sulfide production		1			Equation 1
Sulfide precipitation*	1	-1			
Water phase sulfide oxidation, chemical		-1	-1.2		Equation 2
Water phase sulfide oxidation, biological		-1	-0.5		Equation 3
Biofilm sulfide oxidation		-1	-0.5		Equation 4
Reaeration			1		Equation 5
Sulfide emission		-1		1	Equation 6
Adsorption on moist sewer walls				-1	Equation 7

* Sulfide precipitation is assumed instantaneous

WATS in Peterson Matrix Notation

Process rate equations are described as follows (Nielsen et al., 2005):

Equation 1: $k_{S(-II),\,p}(S_F + S_A + X_{S1})^{0.5}(K_O/(S_O + K_O))(A/V)1.03^{(T-20)}$

Equation 2: $k_{S(-II),\,o,c}S_{S(-II)}S_O^{0.1}1.07^{(T-20)}$

Equation 3: $k_{S(-II),\,o,b}S_{S(-II)}S_O^{0.1}1.07^{(T-20)}$

Equation 4: $k_{S(-II),\,o,f}S_{S(-II)}^{0.5}S_O^{0.5}(A/V)1.03^{(T-20)}$

Equation 5: $K_L a_{S_O} 24(S_{OS} - S_O)$

Equation 6: $K_L a_{S(-II)} 24(\gamma S_{S(-II)} \quad S_{S(-II),eq})$

Equation 7: $k_{s(-II)gas,o,w}\,((pH_2S)/(K_{pH2S} + pH_2S))(A_c/V_g)1.03^{(T-20)}$

Source: Nielsen *et al.* (2003)

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Mechanistic Modeling Tells Us That Hydraulics Matter Intensely When Predicting Corrosion Potential

- **Assumed That Sulfate and Organics Exist in Sufficient Quantities to be a Potential Problem**
- **Mass Transfer is Critical:**

$$K_L a_{H_2S} = (1.736 - 0.196\,\mathrm{pH})\,K_L a_{O_2} \quad (4.5\ \mathrm{pH}\ 8.0,\ \mathrm{at}\ 20°\mathrm{C}) \qquad (1)$$

$$K_L a_{O_2} = 0.86(1 + 0.2F^2)(su)^{3/8} d_m^{-1} \alpha \qquad (2)$$

where u = mean flow velocity ($\mathrm{m\,s^{-1}}$)
s = slope of sewers ($\mathrm{m\,m^{-1}}$)
d_m = mean hydraulic depth, i.e., the water cross-sectional area divided by the width of the water surface (m)
F = Froude number = $u(gd_m)^{-0.5}$
g = gravitational acceleration ($\mathrm{m\,s^{-2}}$)
α_r = temperature coefficient for reaeration = 1.024
T = temperature (°C).

Source: Nielsen *et al*. (2005)

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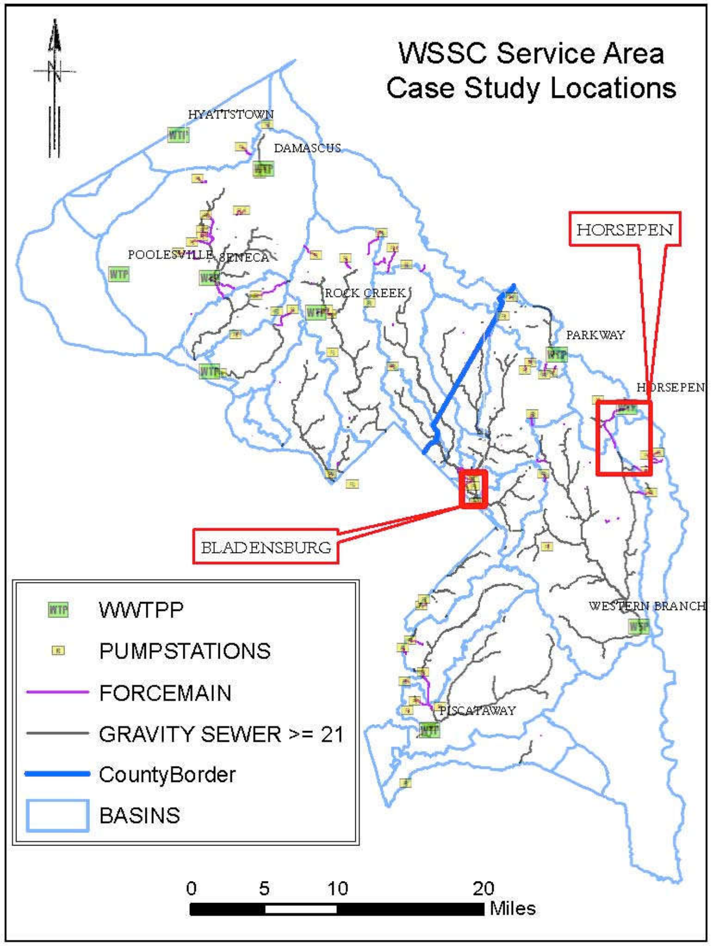
Case Study Areas and Sulfide Modeling



- Anacostia Trunk Sewer (102”)
- Horsepen Trunk Sewer (18”, 24” and 27”)
- Known corrosion problems
- How can we model these corrosion locations using the Mechanistic model?
- Data collected on H2S (liquid/gas), wastewater characteristics (ph, temp…)

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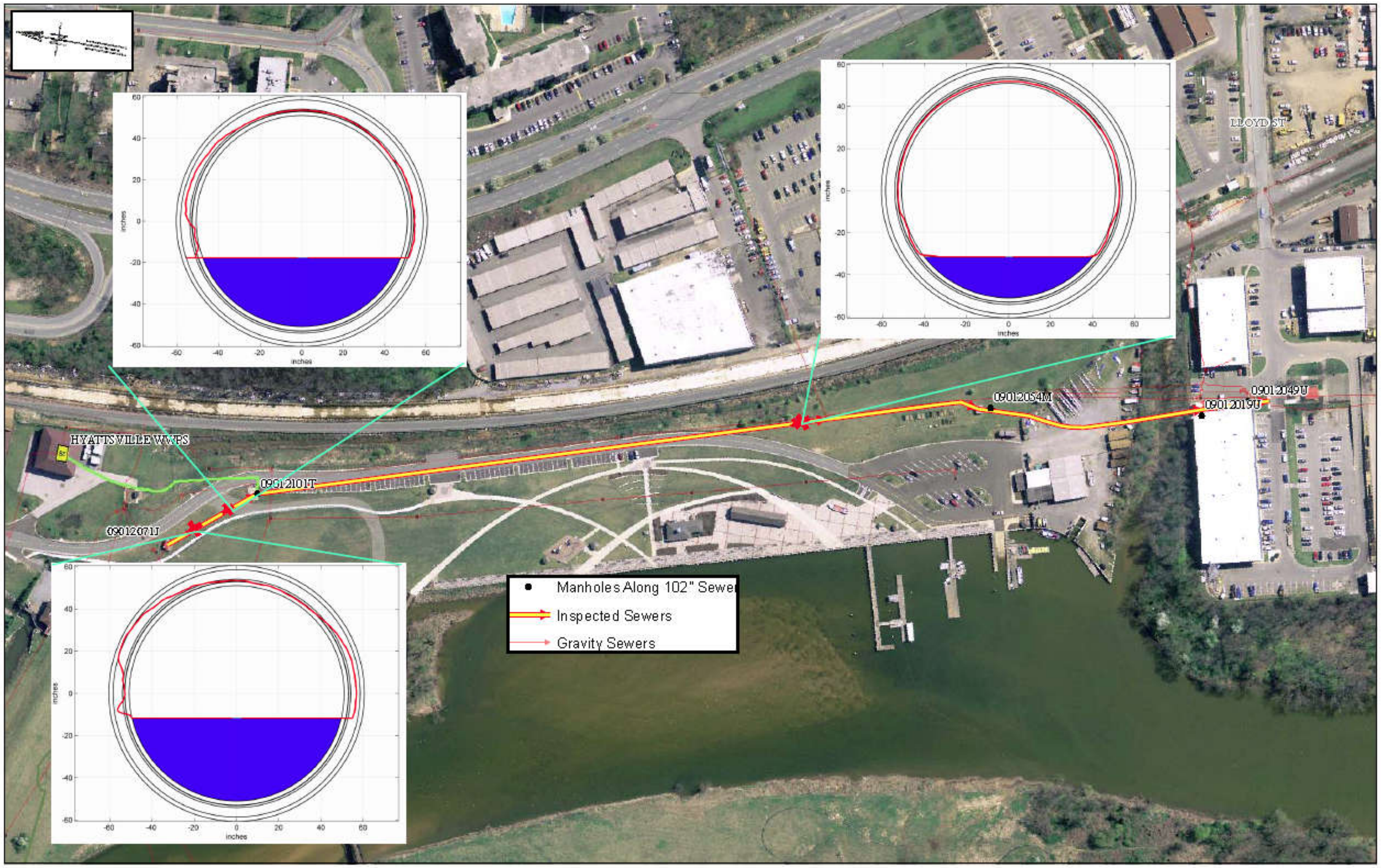
Anacostia Trunk Sewer (102”)



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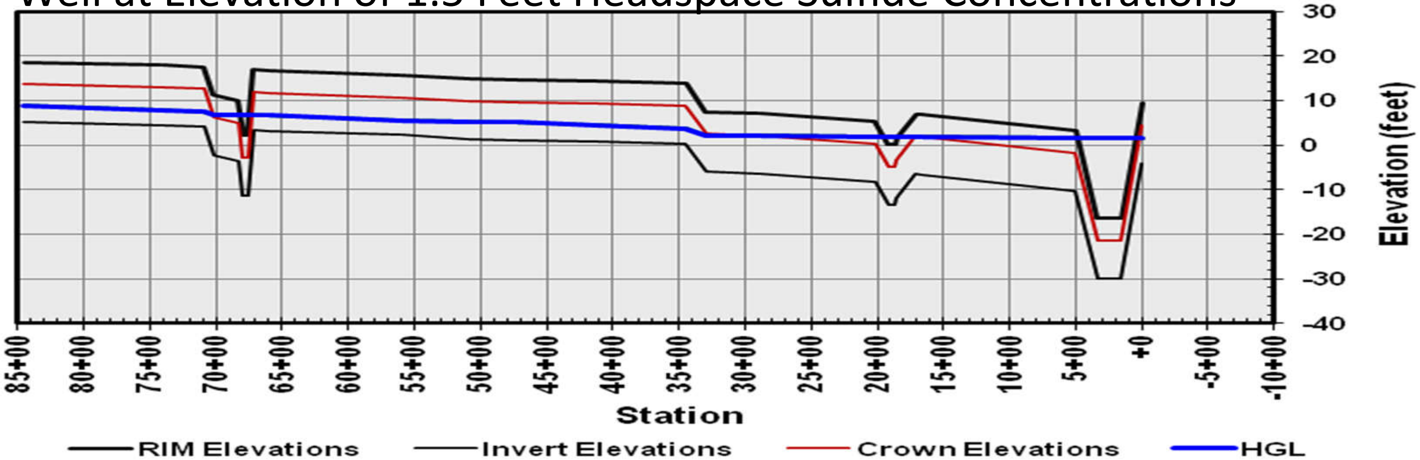
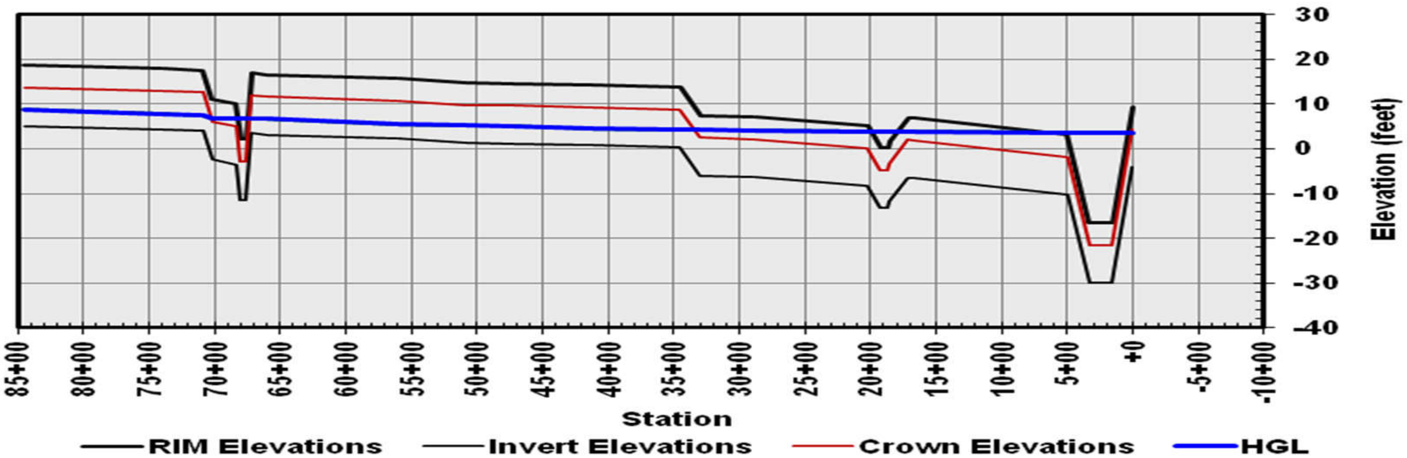
Anacostia Trunk Sewer (102”)

Well at Elevation of 1.5 Feet Headspace Sulfide Concentrations



Well at Elevation of 5.0 Feet Headspace Sulfide Concentrations



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Anacostia Trunk Sewer (102")

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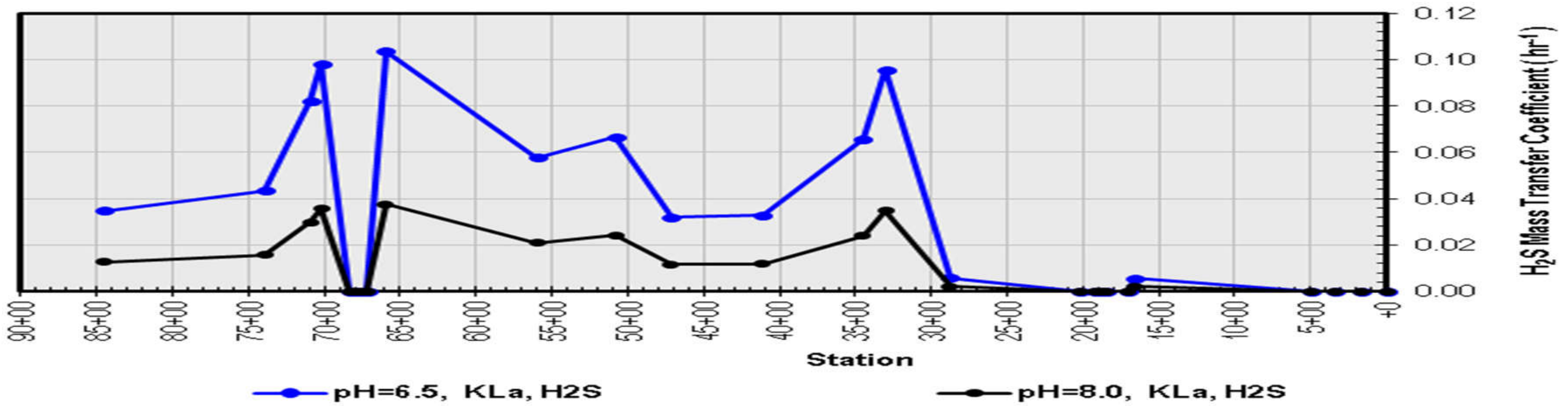

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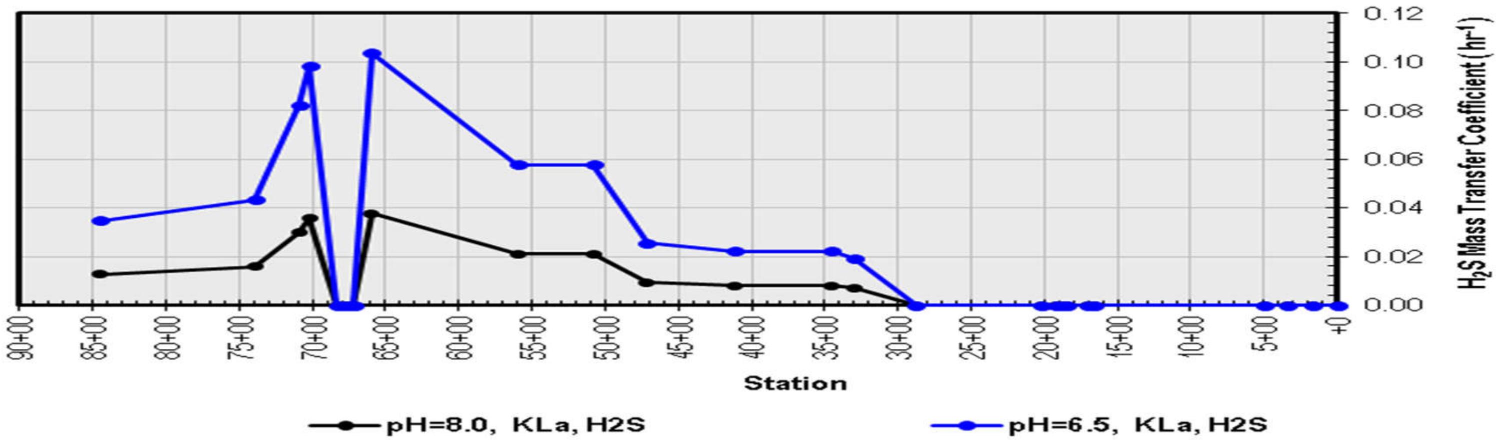

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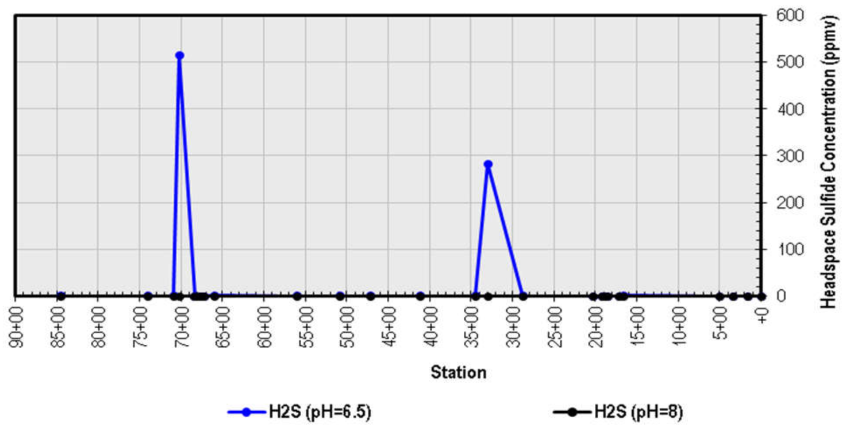
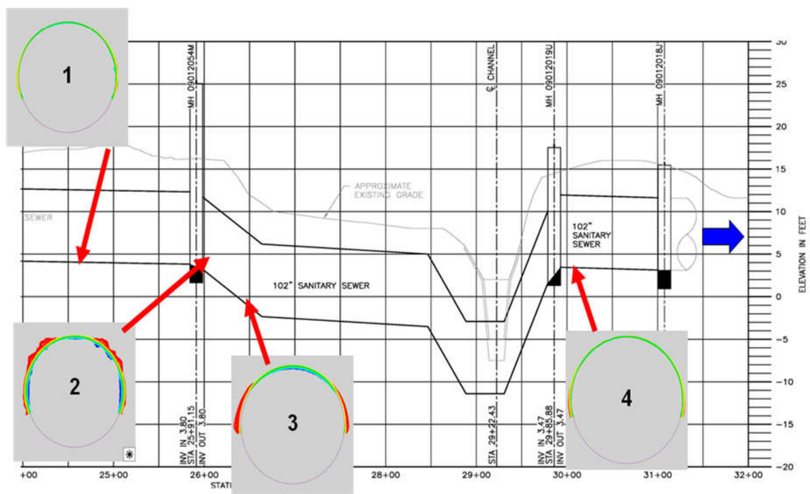
Model Results – 102” Sewer





- Most significant concrete loss has occurred at the location where crown has becomes submerged upstream of the siphon and the corresponding whitewater locations

Positives and Negatives Of Mechanistic Sewer Sulfide Modeling

- Applicability of Mechanistic Modeling
  - No Limitations on Size of System
  - Can be Calibrated to Specific System
    - Ongoing headspace sulfide monitoring
  - Broad Tool Across Collection System
  - May be Deployed to Predict Corrosion Rates

Positives and Negatives Of Mechanistic Sewer Sulfide Modeling

- **Limitations**
  - Requires More Data Inputs than Other Approaches
    - Hydraulic modeling: Froude number, hydraulic mean depth, pipe geometry
    - Chemical parameters: BOD_5 , pH, temperature
  - Requires Computational or Programming Expertise to Solve Multiple Simultaneous Differentials
  - Application is a Blend of Experience and Science
    - Venting is not included in model, nor is gas transport
    - Understanding of system needed to pair sulfide emission with local hydraulics

There Are Reasonable Ways To Simplify This Approach And Retain The Benefits Of Mechanistic Vs. Qualitative Prediction

- **Some Processes are Important for Predicting Aqueous Sulfide Concentration**
  - Important to Calculate Headspace Concentrations
  - The Good News is We Can Measure This Directly and it is Reasonably Predictable for a Point in a Sewer!!!

Processes	Role in Proposed Simplified Model
1. Sulfide production	Omit – Impacts dissolved sulfide concentration
2. Sulfide precipitation*	Omit – Serves as sink for dissolved sulfide
3. Water phase sulfide oxidation, chemical	Omit – Serves as sink for dissolved sulfide
4. Water phase sulfide oxidation, biological	Omit – Serves as sink for dissolved sulfide
5. Biofilm sulfide oxidation	Omit – Serves as sink for dissolved sulfide
6. Reaeration	Omit – Serves as brake on sulfide production
7. Sulfide emission	**RETAINED**
8. Adsorption on moist sewer walls	**RETAINED**

There Are Reasonable Ways To Simplify This Approach And Retain The Benefits Of Mechanistic Vs. Qualitative Prediction

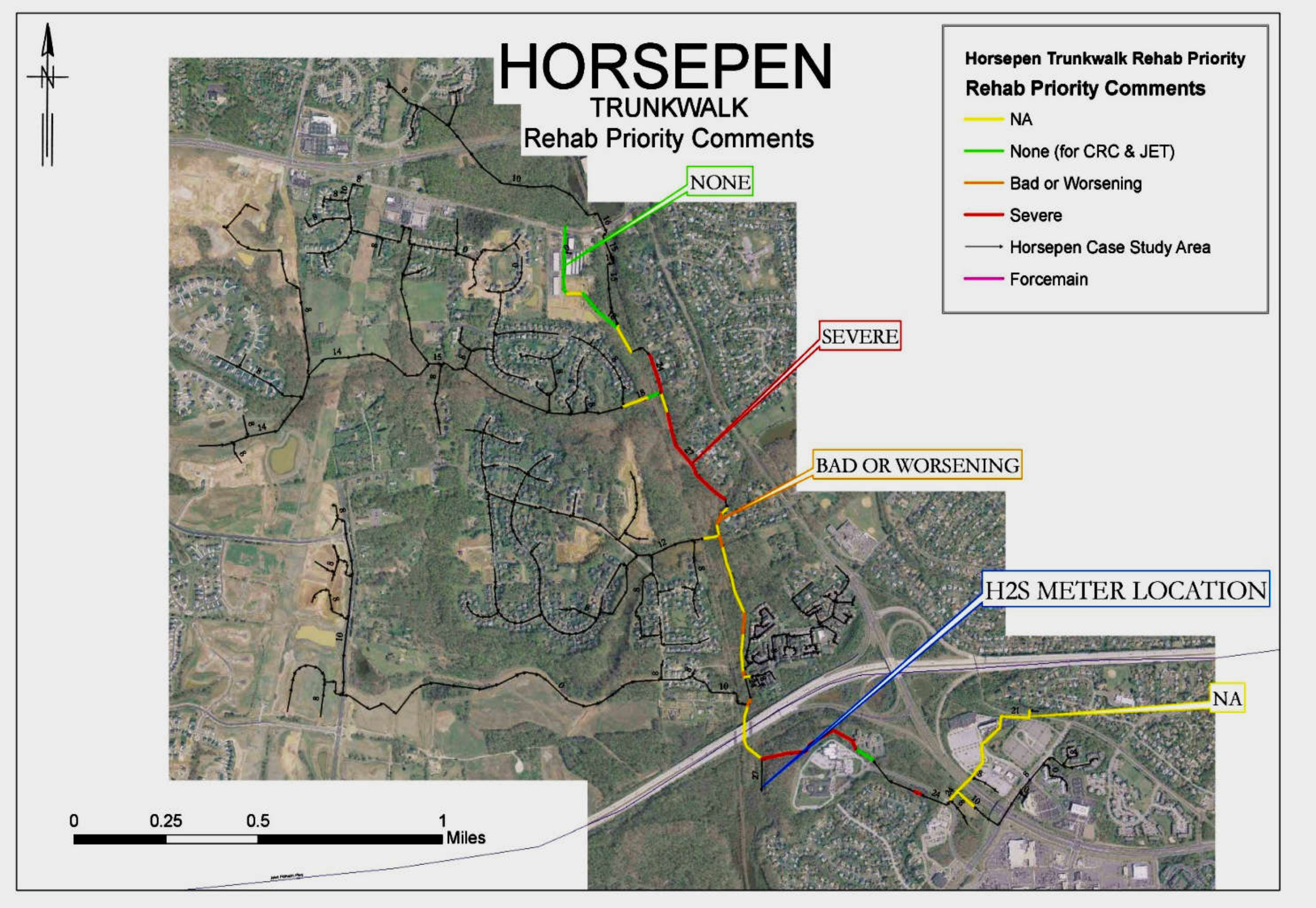
- **Predictive Tool is Very Simple at Steady State:**

Sulfide Emission: $K_L a_{S(-II)} 24(\gamma S_{S(-II)} \quad S_{S(-II),eq})$

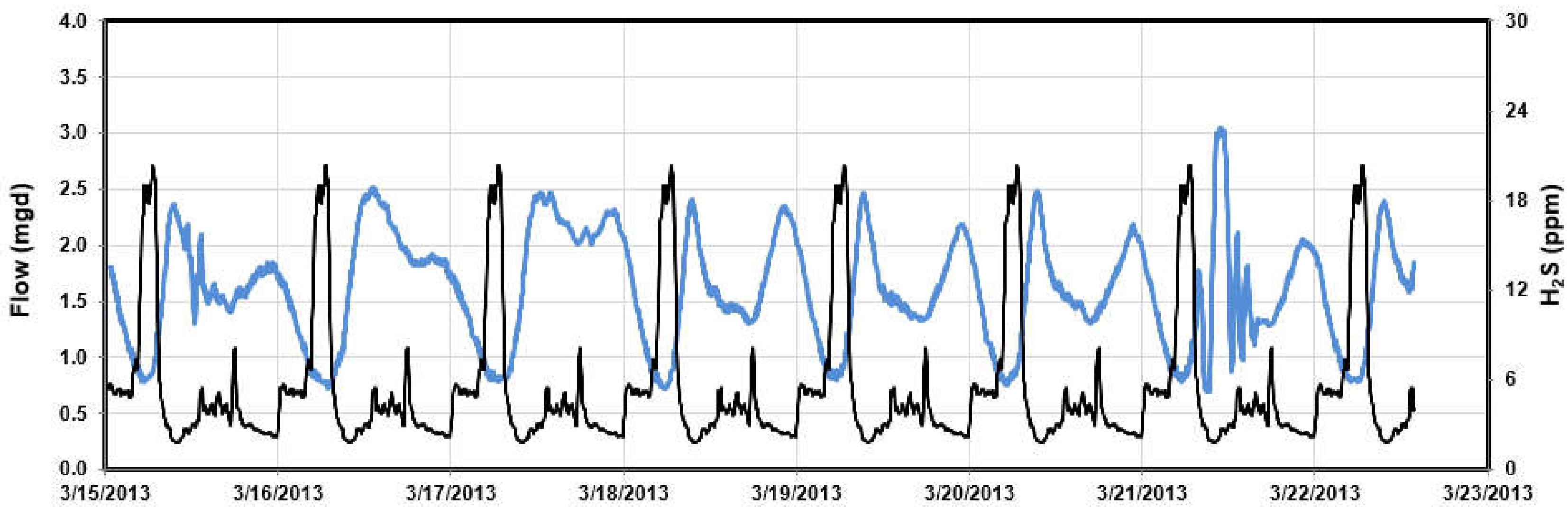
Adsorption: $\frac{\Delta p_{H2S}}{dt} = 0 = -1 \times k_{s(-II)gas,o,w}((pH_2S)/(K_{pH2S} + pH_2S))(A_c/V_g)1.03^{(T-20)}$

- **Set these Equations Equal to One Another and Solve for pH_2S**
  - We Know by Literature, Assumption, or Measurement Every Other Parameter in These Equations
  - Now it is a Suitable Job for a Spreadsheet ☑

Horsepen Trunk Sewer



Hydraulics Of This Pipe Section Drive Specific Areas Of Concrete Corrosion (Horsepen Trunk Sewer)



- Hydrogen Sulfide Concentrations More or Less Track Inverse of Diurnal Flow Pattern in Pipe
- Can This be Described by Simplified Model?

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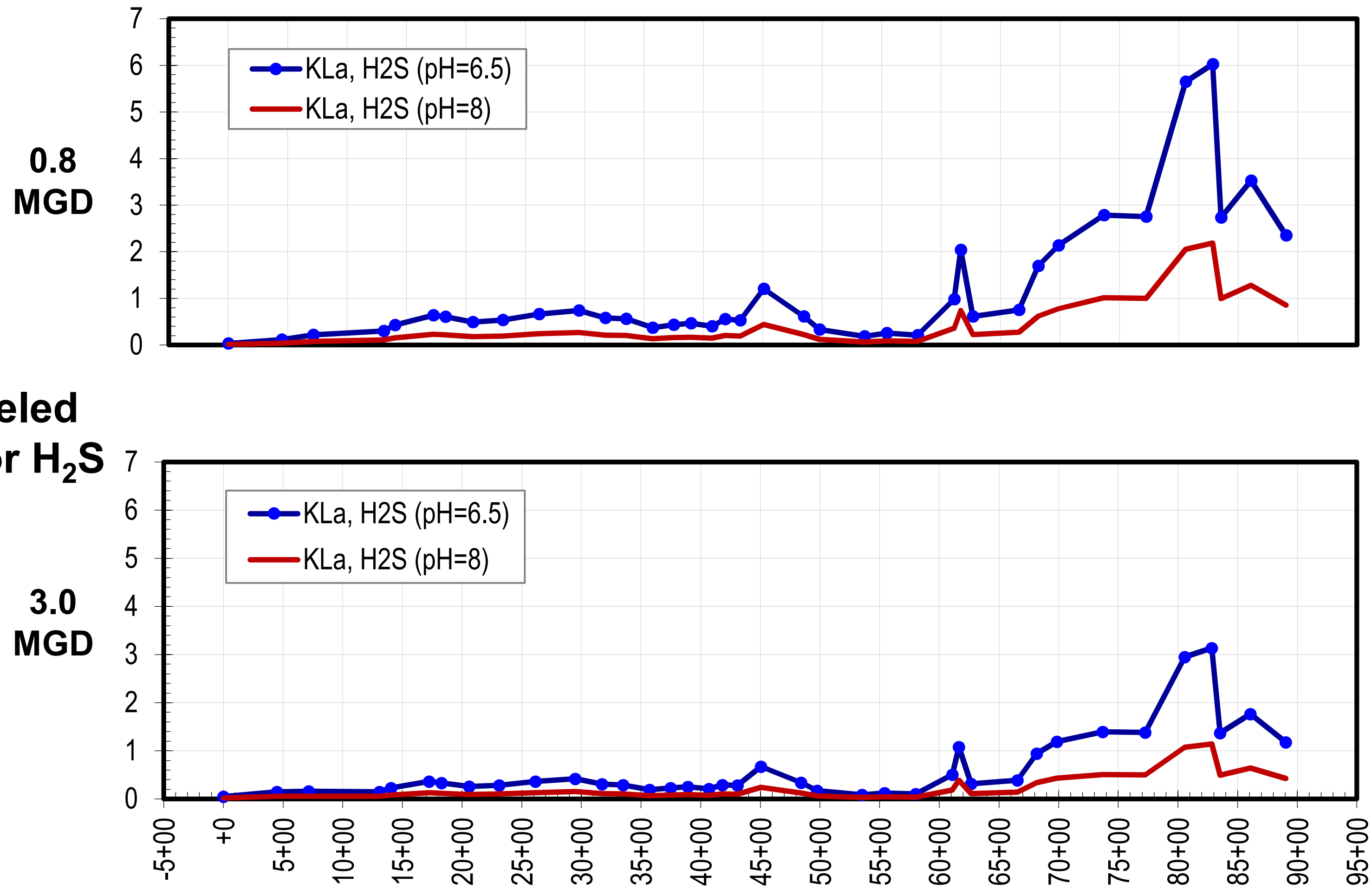
Hydraulics Of This Pipe Section Drive Specific Areas Of Concrete Corrosion

Modeled K_La for H_2S



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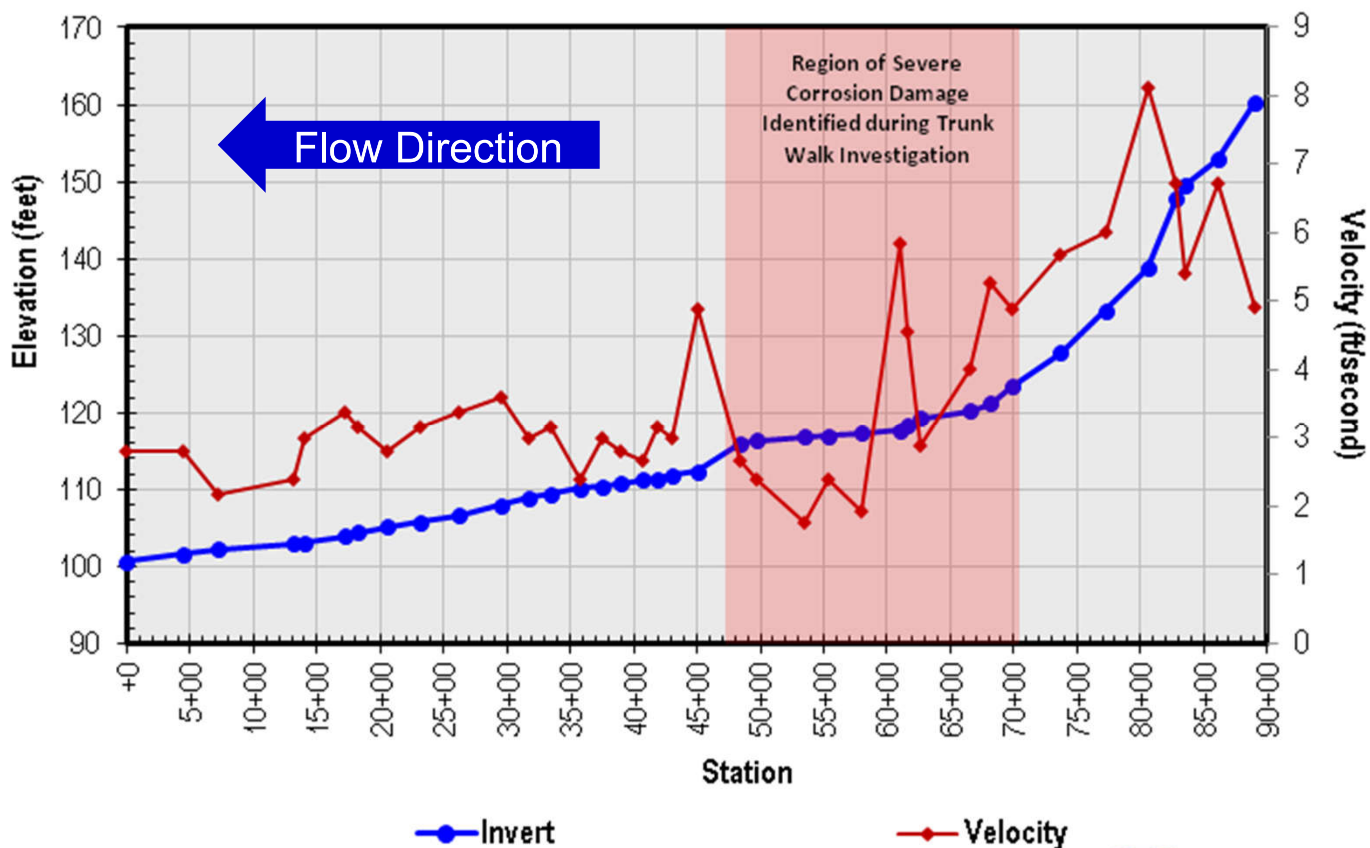
Velocity Profile In Pipe Shows Maximum Corrosion Occurs Where Pipe Flattens And Water Slows Down



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What did we learn? Factors controlling headspace H_2S

- **Sulfide Generation**
  - H_2S was generated upstream of case study in both cases
  - H_2S generated within the case study was not an important factor for headspace H_2S
- **Sulfide Transport**
  - Pipe hydraulics played a significant role in headspace H_2S
  - 102" headspace H_2S increased with diurnal flow increase
  - Horsepen headspace H_2S decreased with diurnal flow increase
- **Corrosion**
  - Confirmed by prior inspection results

What did we learn?
Sulfide modeling as a predictive tool

- WATS Mechanistic Model
  - Biological and H_2S phase transformation
  - Model proved to be:
    - comparable to the monitored data
    - sensitive to mechanisms controlling headspace H_2S
- Integrated Hydraulic/Sulfide model
  - Enables user to run sensitivity analysis on sulfide generation and emission
    - Pipe flow rate
    - ph and temperature

Take Home: A Simplified Mechanistic Approach Can Provide Useful Prescriptive Information About Sulfide Corrosion

- Sulfide in Itself is Not Evil – It is Ubiquitous
- Sulfide Acts by Volatilizing, Adsorbing, and Oxidizing on the Moist Sewer Wall
- Prior Qualitative Methods of Predicting Corrosion Ignore the Complex Hydraulics of Real Sewer Networks
- Fully Mechanistic Methods Can be Cumbersome
- Useful Information Can be Obtained From a Simplified Method Focusing on the Point of Action of Sulfide
  - Volatilization
  - Adsorption
- Simplified Approach Can be Used for Targeted Field Investigations in Areas With High Headspace Sulfide

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WSSC
Where Water Matters

THANK YOU

Water is Life

cwea
Chesapeake Water Environment Association

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