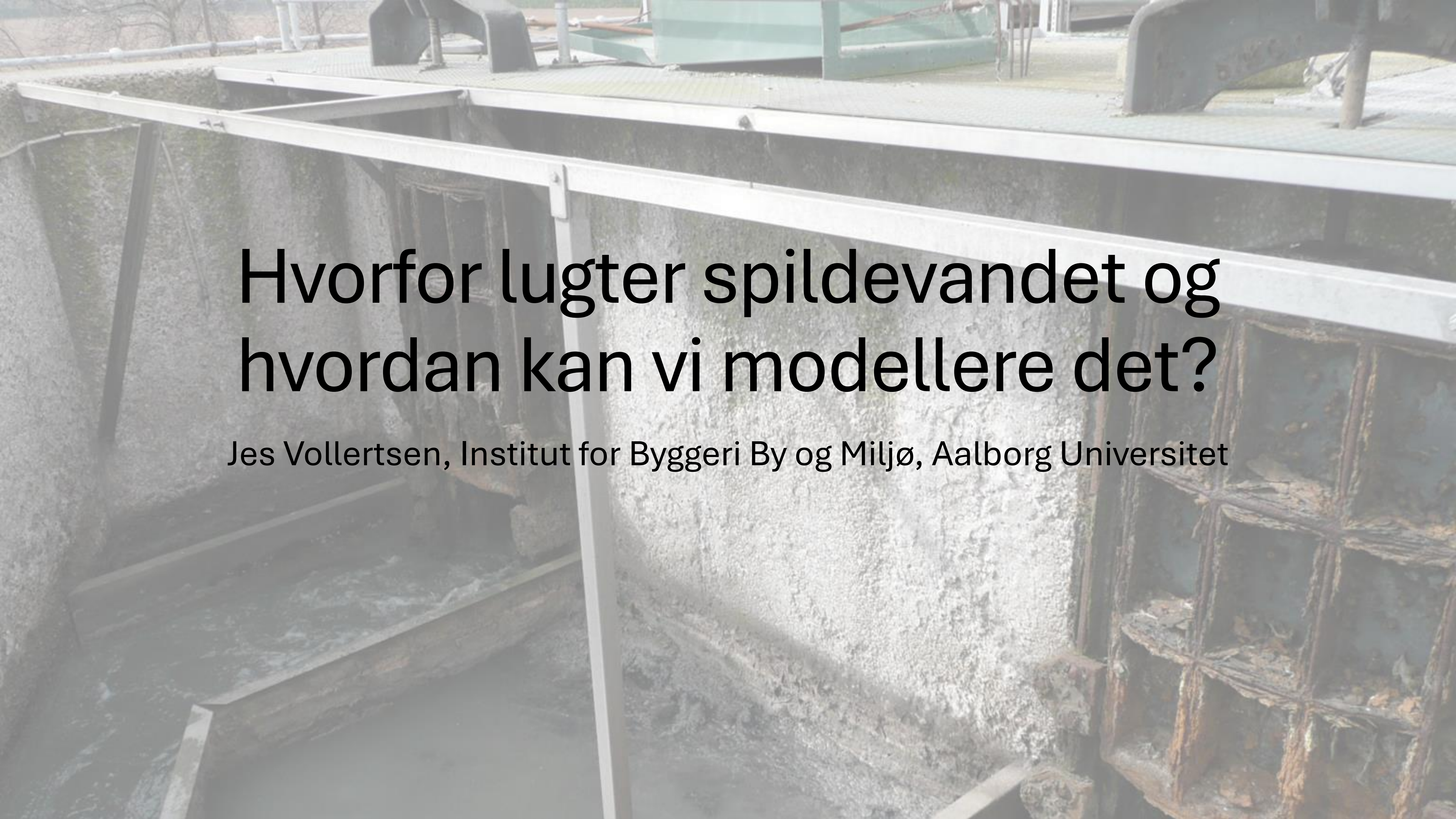


Hvorfor lugter spildevandet og hvordan kan vi modellere det?

Jes Vollertsen, Institut for Byggeri By og Miljø, Aalborg Universitet

Nobody (but us) loves the sewers

The public doesn’t want to

- Know about them
- See them
- Smell them
- The public simply wants to ignore their existence

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

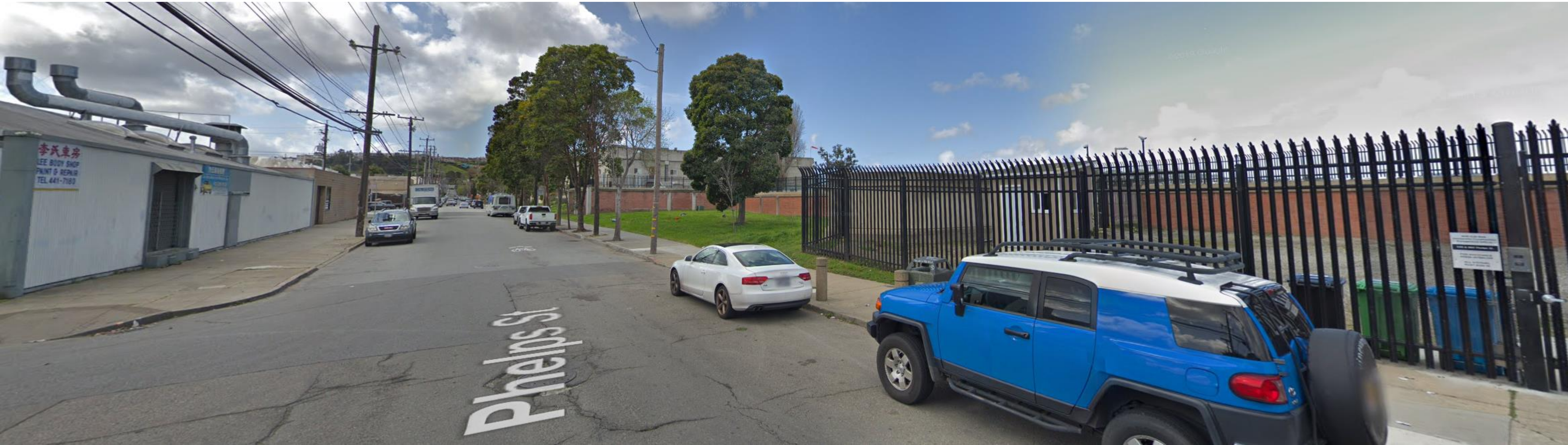
THE WALL STREET JOURNAL

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.

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

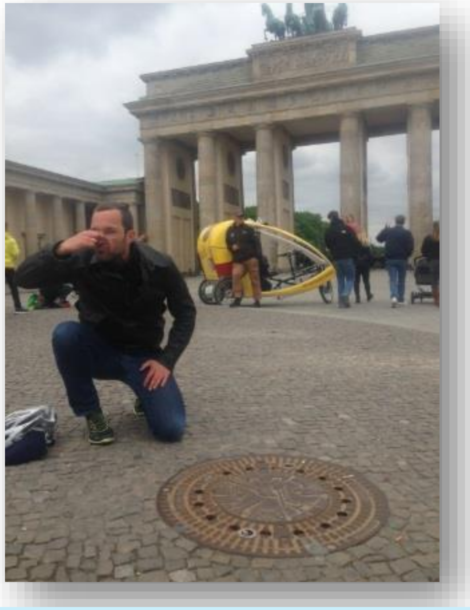
(no taxi driver wants to pick you up where the San Francisco treatment plant is located …)



Consequences of sewer processes – asset corrosion

Corroding concrete manholes and metal covers

Consequences of sewer processes - odors



Sewer odor, even in very low concentrations (0.5 ppm H_2S)

Consequences of sewer processes - safety

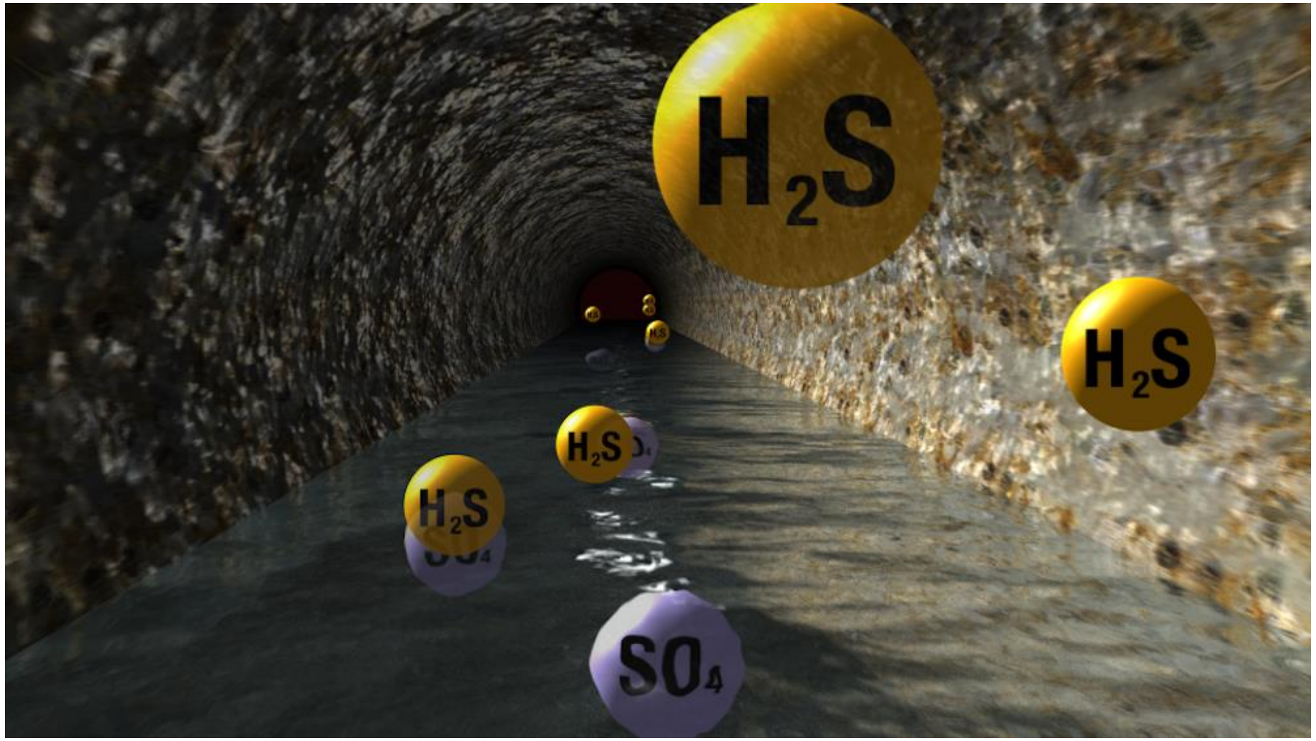
Toxic air emissions & Hazardous confined space entry (>300 ppm)

Costly mitigation techniques

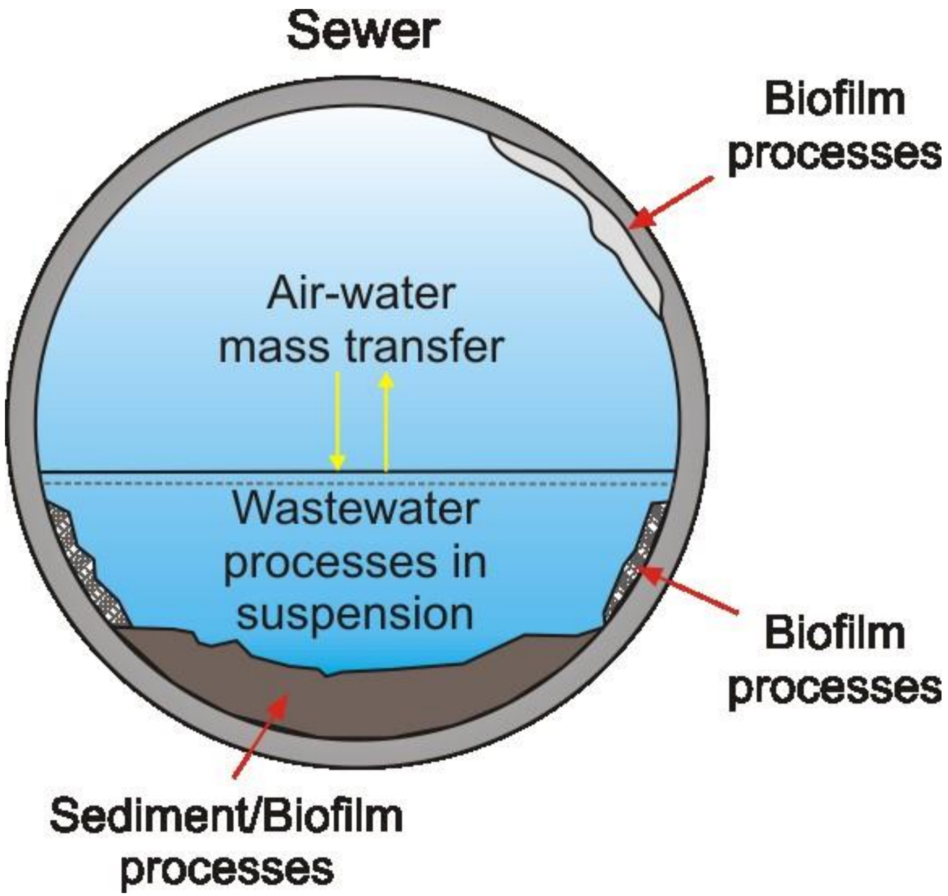
Addition of chemicals

Air filters

Get a grip on sewer process problems



The sewer as a reactor
- biological, chemical, physical processes



Biological and chemical processes take place in the wastewater, biofilm, sediments, and on moist sewer surfaces

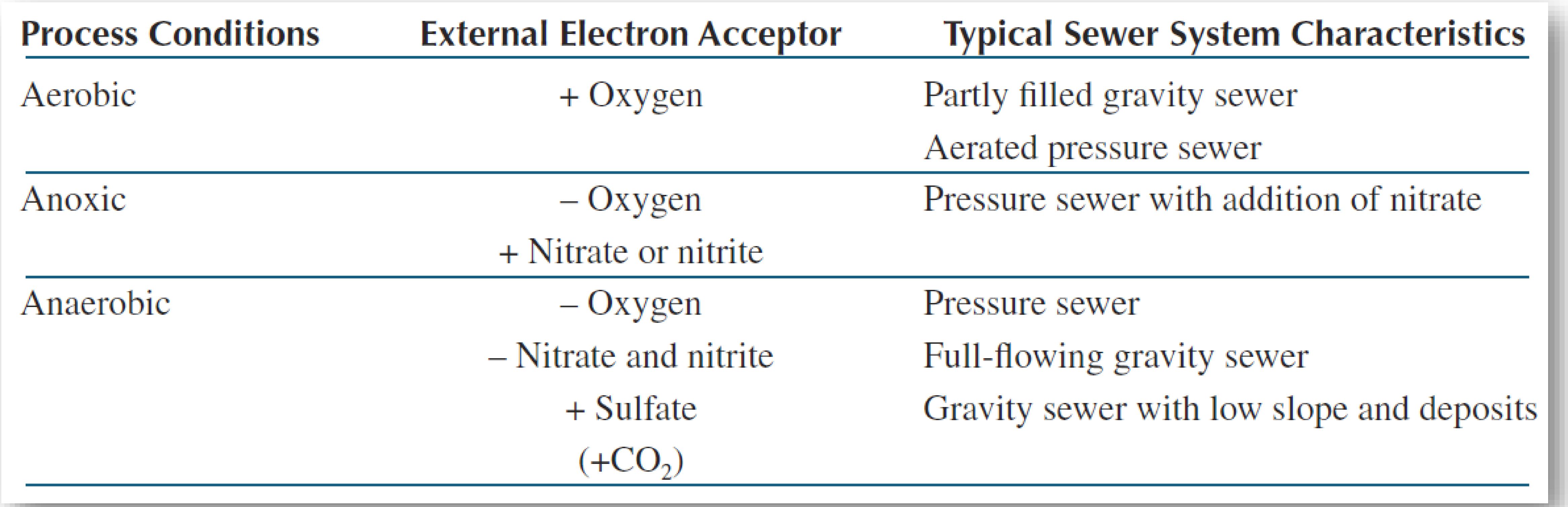
Transport takes place in the wastewater and the gas

Sewer air interacts with the urban atmosphere as the sewer continuously takes in and pushes out air

Wastewater interacts with the treatment plants

Redox reactions in sewers

- Electron acceptors and corresponding conditions for microbial redox processes (respiration processes)



Process Conditions	**External Electron Acceptor**	**Typical Sewer System Characteristics**
Aerobic	+ Oxygen	Partly filled gravity sewer Aerated pressure sewer
Anoxic	– Oxygen + Nitrate or nitrite	Pressure sewer with addition of nitrate
Anaerobic	– Oxygen – Nitrate and nitrite + Sulfate (+CO_2)	Pressure sewer Full-flowing gravity sewer Gravity sewer with low slope and deposits

Organic substrate – the most important electron donor

TOC – Total Organic Carbon (70-250 gC m^{-3})

- Combustion of organic matter coupled with a CO_2 measurement

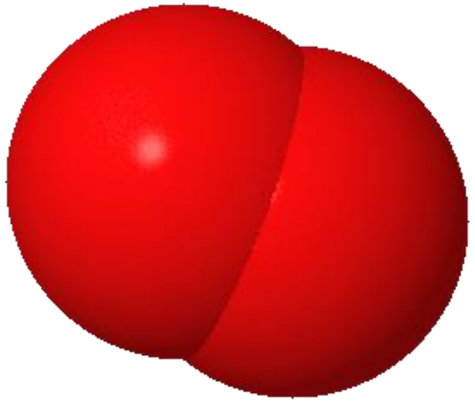
COD – Chemical Oxygen Demand (200-800 gO_2 m^{-3})

- Chemical oxidation of all organic compounds
- (+ some inorganic compounds).

BOD – Biological Oxygen Demand (150-500 gO_2 m^{-3})

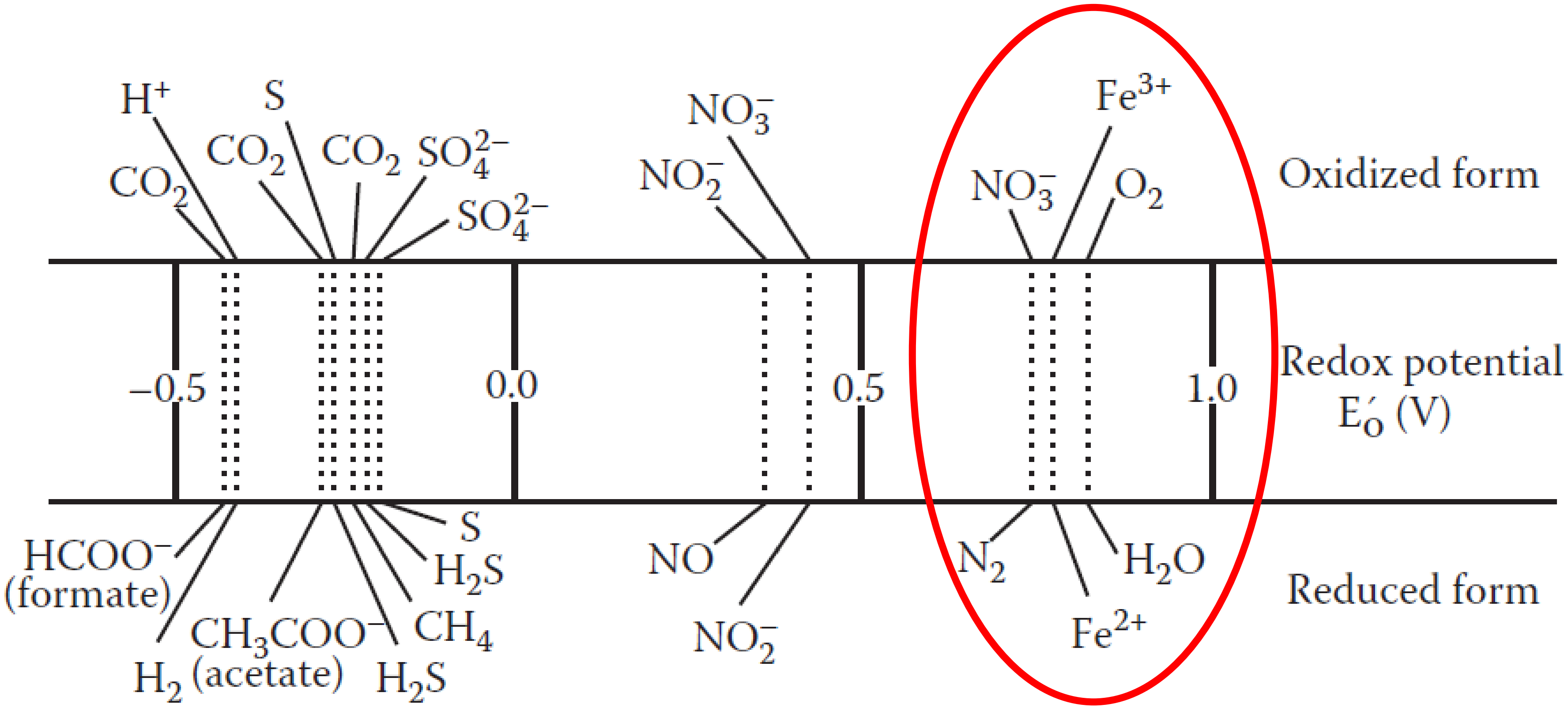
- Oxygen demand from partial breakdown of organic matter during 5 days (or 7 days)

Aerobic processes



Di-oxygen (O_2) – the terminal electron acceptor in aerobic processes

Aerobic processes = High redox potentials

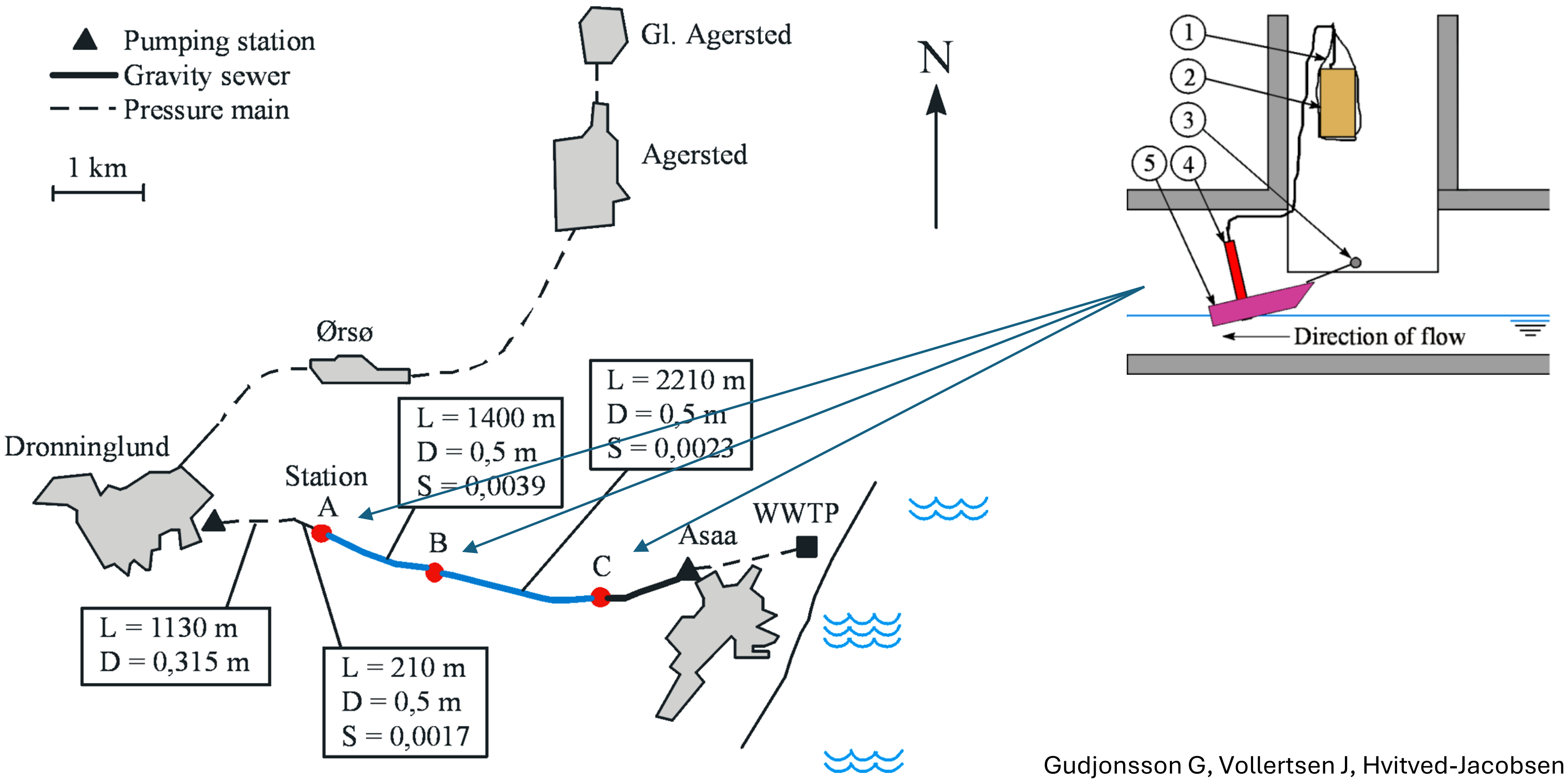


Where to find aerobic conditions?

- Gravity sewers
  - Where reaeration exceeds the potential oxygen uptake of the microorganisms in wastewater, biofilms and sediments
- The first few meters of force mains
  - If the wastewater of the pump pit is aerobic
- In force mains with air or oxygen injection
  - Air makes the force a pseudo-gravity sewer
  - Pure oxygen is dissolved in the wastewater

A case study of measuring oxygen in a sewer

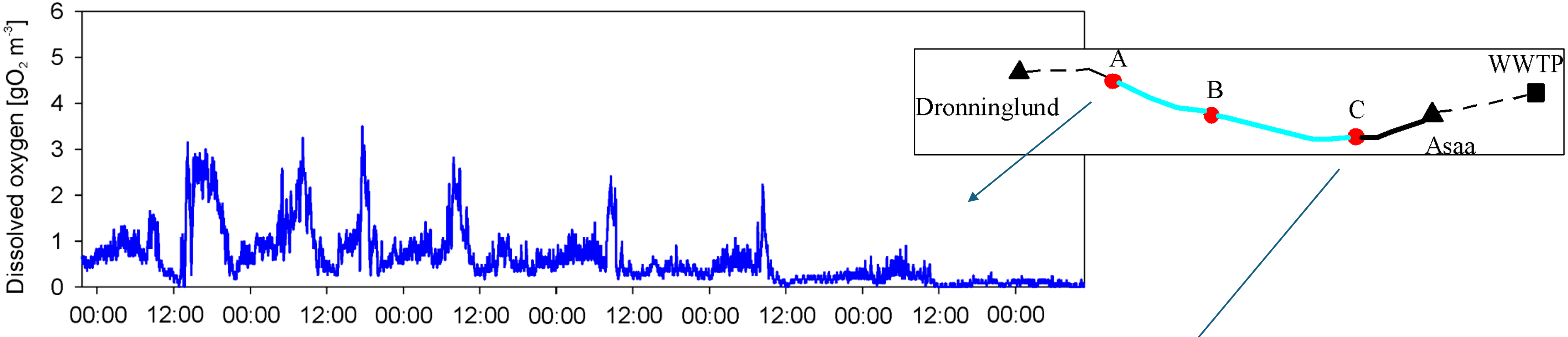
Oxygen was measured continuously in an intercepting gravity sewer



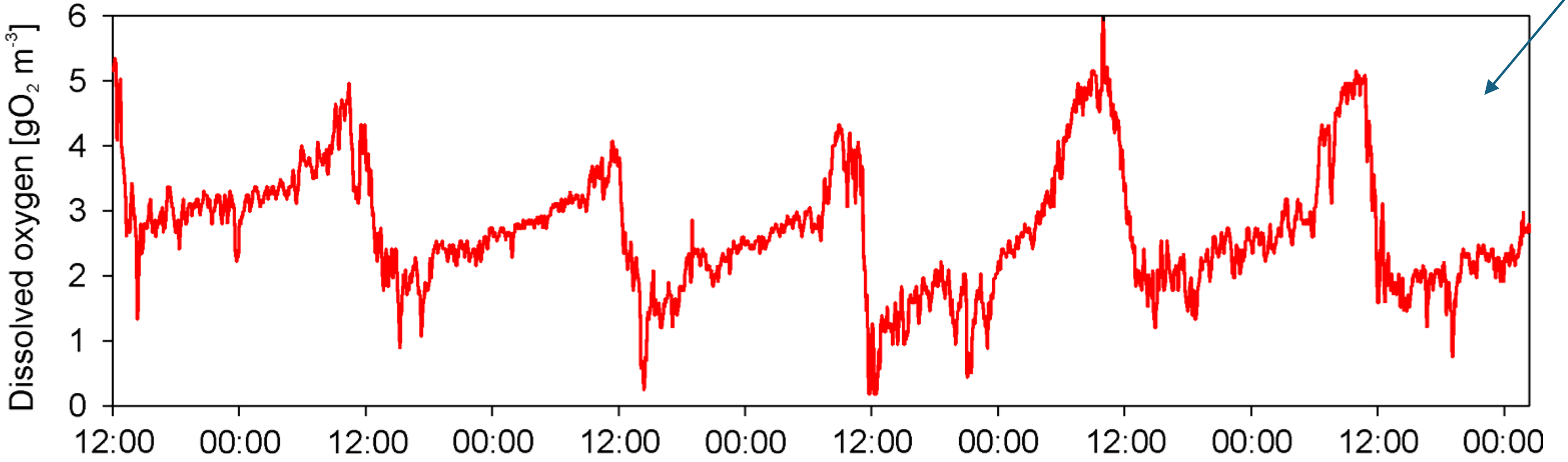
1) A bag
2) A waterproof box with electrical equipment, datalogger and batteries.
3) A steel rod
4) A DO-meter
5) A float anchored by the steel rod held the DO-meter

Gudjonsson G, Vollertsen J, Hvitved-Jacobsen T (2002). Dissolved oxygen in gravity sewers – measurement and simulation. Water Science and Technology,

Diurnal variations in the DO concentration in station A (May 25 to June 1).

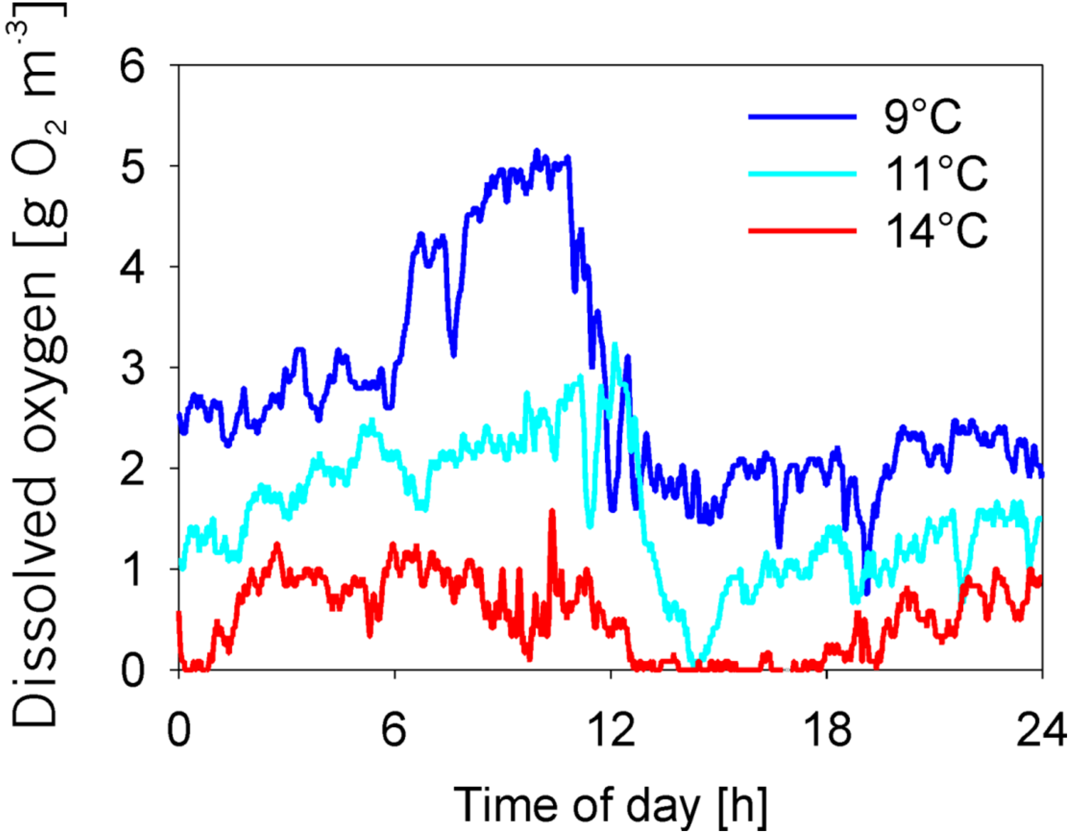


Diurnal variations in the DO concentration in station C (April 25 to May 1).

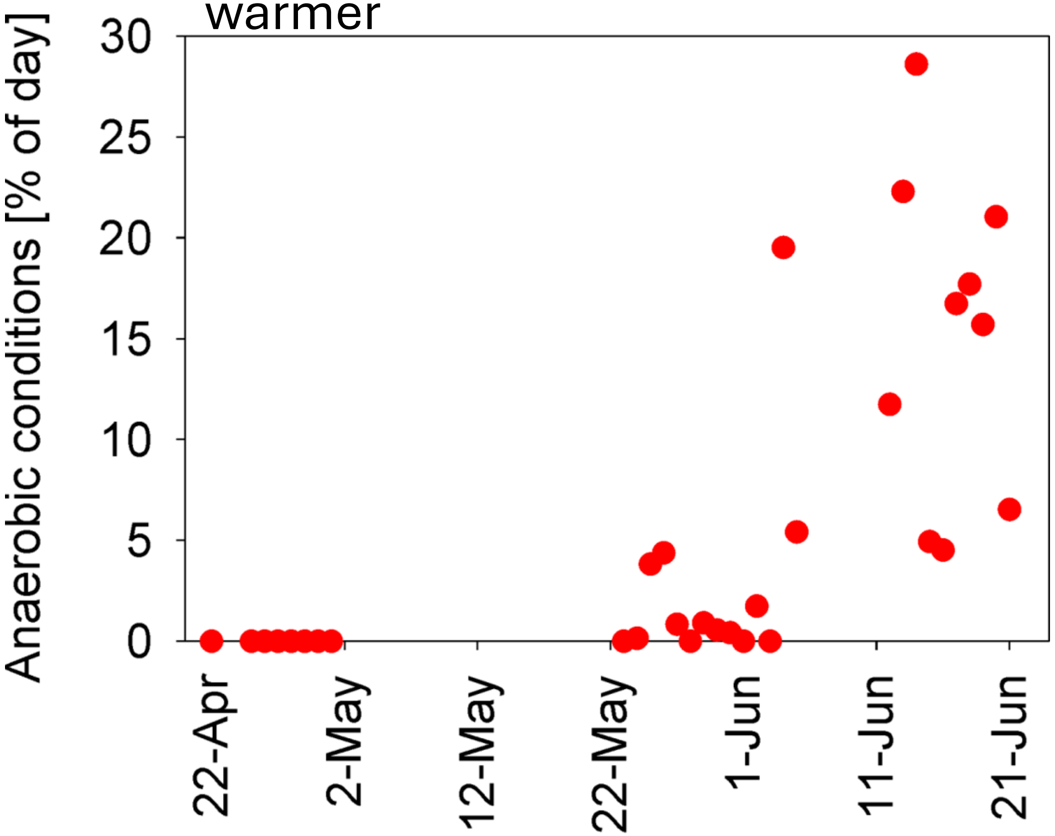


The effect of temperature on DO concentration

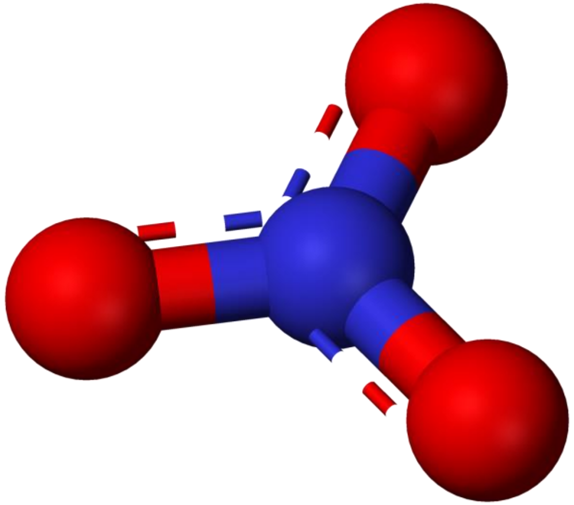
Three diurnal profiles at different wastewater temperatures



The duration of anaerobic conditions as the weather gets warmer

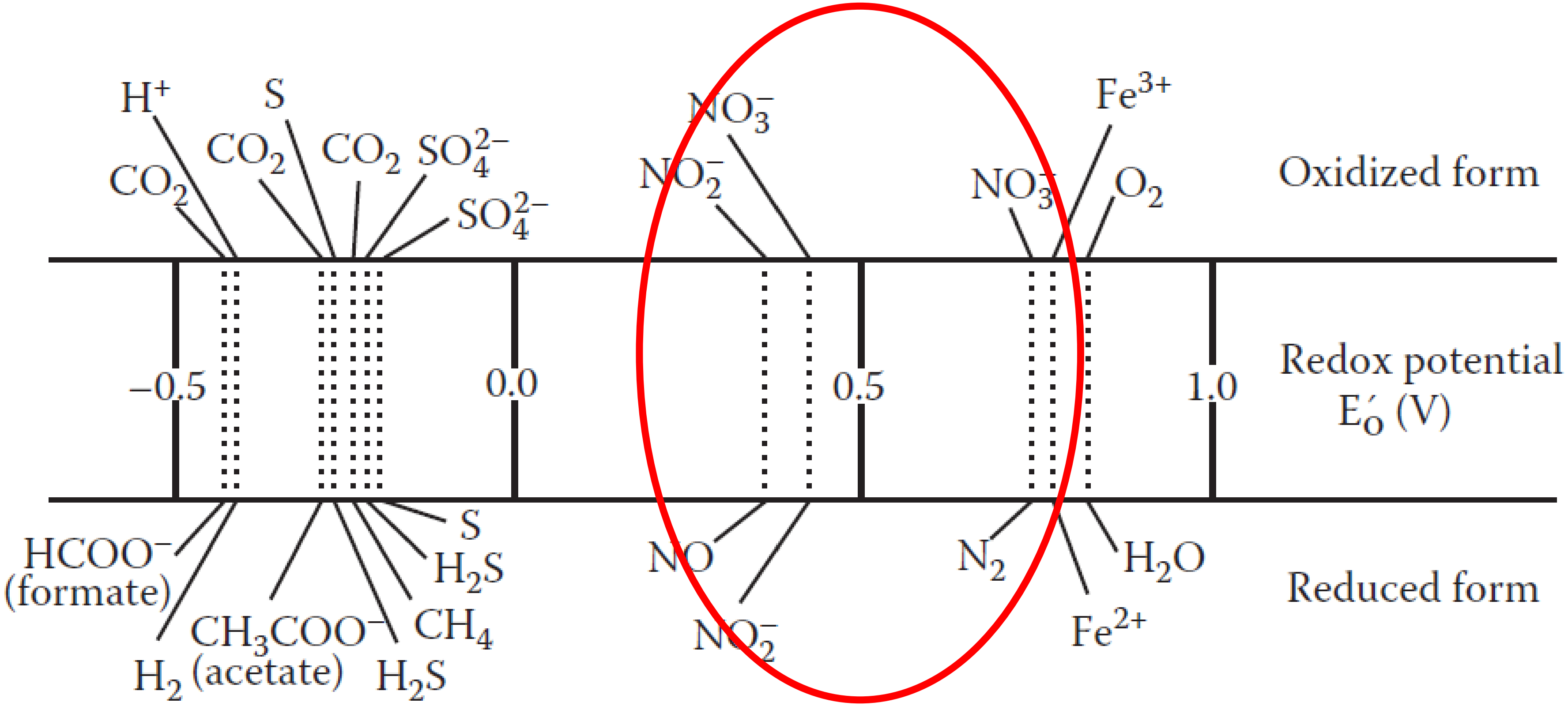


Anoxic processes



Nitrate (NO_3^-) – the terminal electron acceptor for anoxic processes

Aerobic processes = High redox potentials



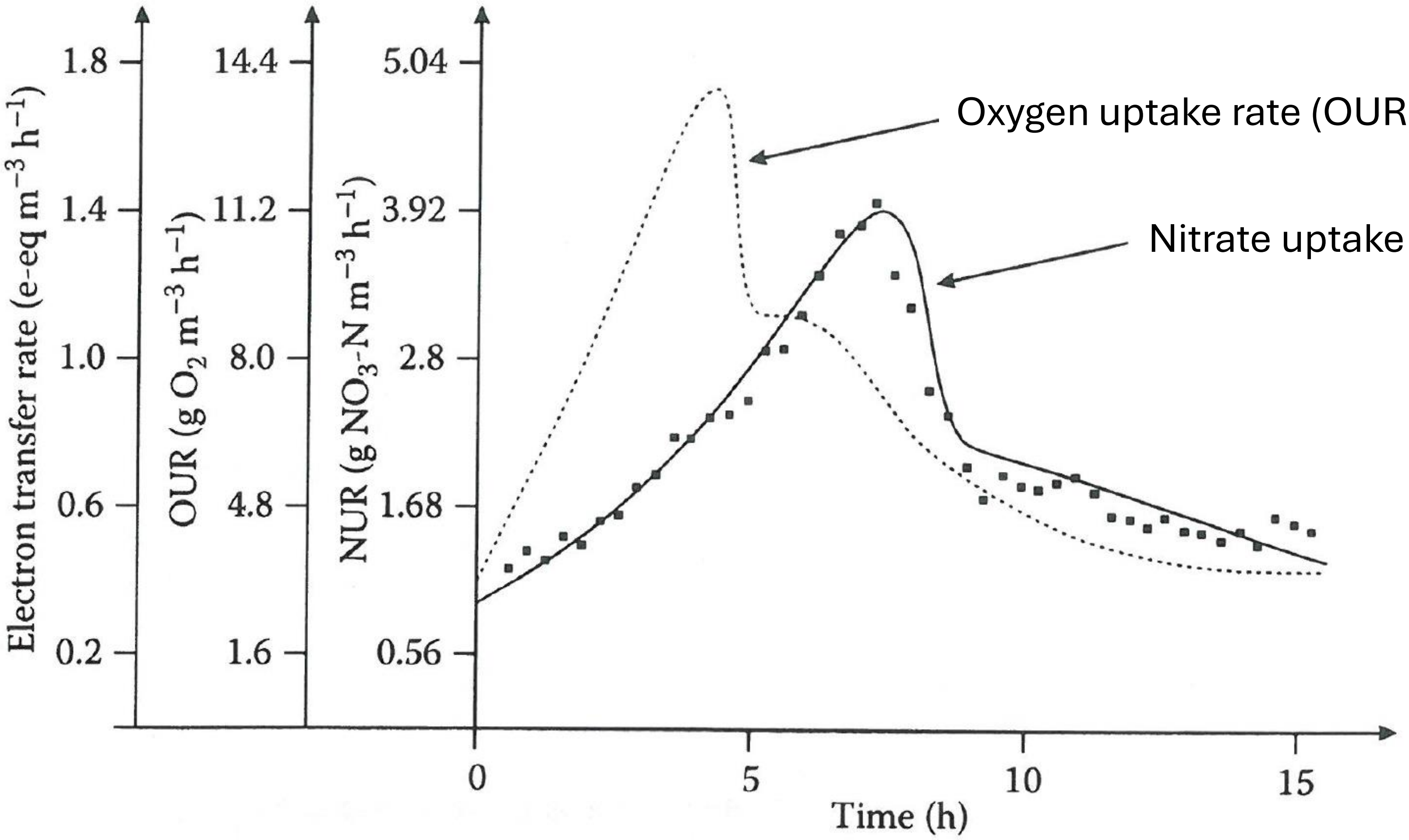
Where we find anoxic conditions

- Nitrate can come from
  - Inflow and infiltration
  - Industrial discharges
  - Injection to manage H_2S and odours

- Nitrate is NOT formed in the sewer
  - Ammonia cannot be oxidized to nitrate in sewer biofilms as the slow-growing ammonia oxidizers loose the competition for oxygen to the fast-growing bacteria that oxidize organic matter

Nitrate substitutes oxygen as electron acceptor

It is the same bacteria that do the work, they just switch from oxygen to nitrate



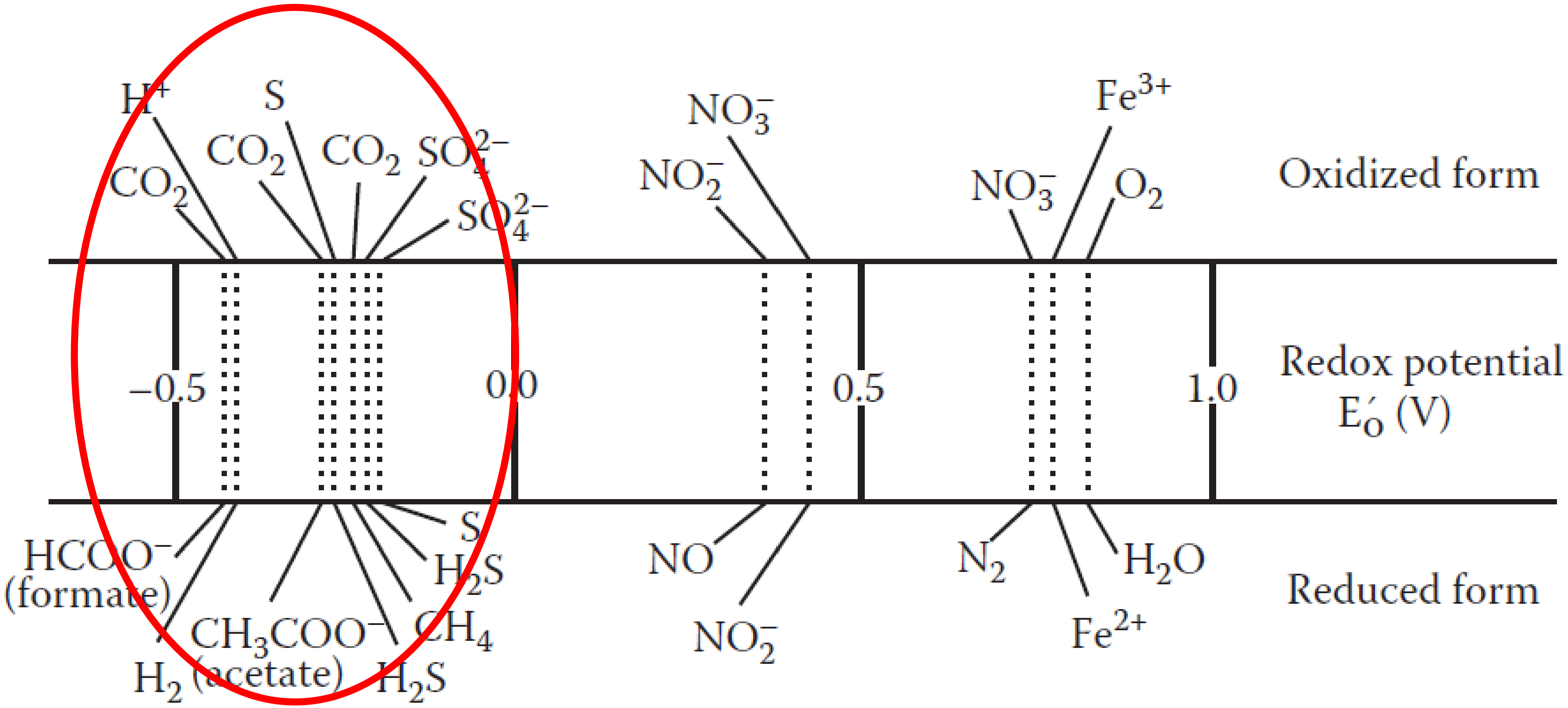
Oxygen uptake rate (OUR)

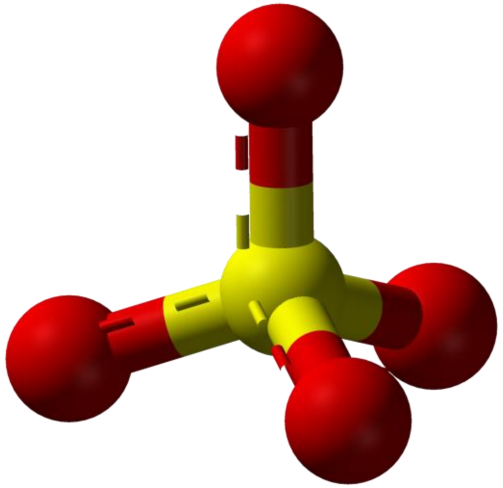
Nitrate uptake rate (NUR)

Specific process rates are slightly lower than for oxygen

Anaerobic processes

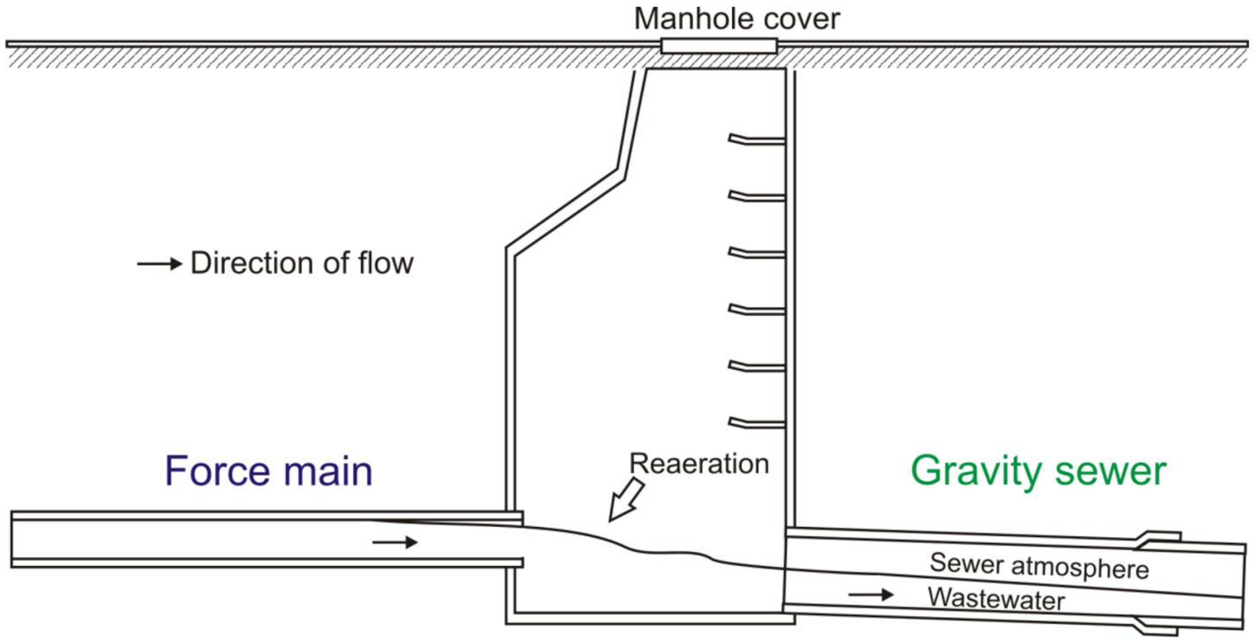
Aerobic processes = High redox potentials





Sulfate (SO_4^{2-}) – the most important terminal electron acceptor for anaerobic processes

Anaerobic sewer processes



Anaerobic conditions occur in

- Force mains of sufficient residence time
- Full-flowing gravity sewers of sufficient residence time
- Partly filled gravity sewers with poor or negative slope when temperatures are high, flow velocities low, and water depts large

Problems are typically perceived downstream of such anaerobic conditions

- Force main discharges
- Syphons
- Gravity pipes of poor slope

Relevant redox processes

Fermentation

$$\overset{\text{glucose}}{C_6H_{12}O_6} \rightarrow 2\overset{\text{ethanol}}{CH_3CH_2OH} + 2CO_2$$

$$\overset{\text{glucose}}{C_6H_{12}O_6} + 2H_2O \rightarrow 2\overset{\text{acetic acid}}{CH_3COOH} + 2CO_2 + 4H^+$$

$$\overset{\text{glucose}}{C_6H_{12}O_6} + 2H_2 \rightarrow 2\overset{\text{propionic acid}}{CH_3CH_2COOH} + 2H_2O$$

$$\overset{\text{propionic acid}}{CH_3CH_2COOH} + 2CO_2 \rightarrow \overset{\text{acetic acid}}{CH_3COOH} + CO_2 + 3H_2$$

$$\overset{\text{glucose}}{C_6H_{12}O_6} \rightarrow 2\overset{\text{lactic acid}}{CH_3CHOHCOOH}$$

Methanogenesis

$$\overset{\text{acetic acid}}{CH_3COOH} \rightarrow CH_4 + CO_2$$

$$\overset{\text{glucose}}{C_6H_{12}O_6} \rightarrow 3CO_2 + 3CH_4$$

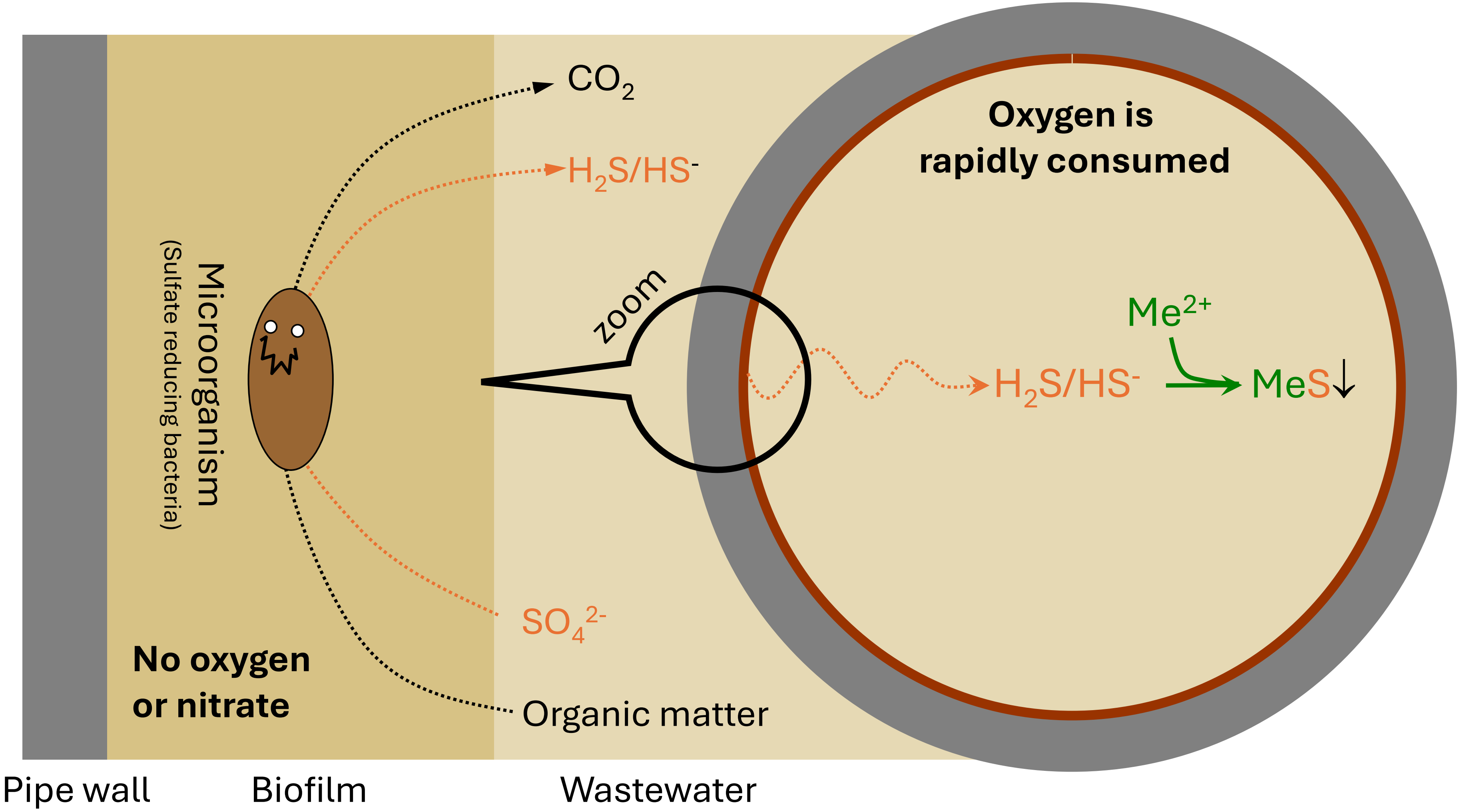
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Sulfate Respiration

$$2\overset{\text{lactic acid}}{CH_3CHOHCOOH} + SO_4^{2-} + H^+ \rightarrow 2\overset{\text{acetic acid}}{CH_3COOH} + 2CO_2 + 2H_2O + HS^-$$

$$2\overset{\text{lactic acid}}{CH_3CHOHCOOH} + 3SO_4^{2-} + 3H^+ \rightarrow 6CO_2 + 6H_2O + 3HS^-$$

Sulphide formation in sewers



Example: sulphide formation in a full flowing pipe

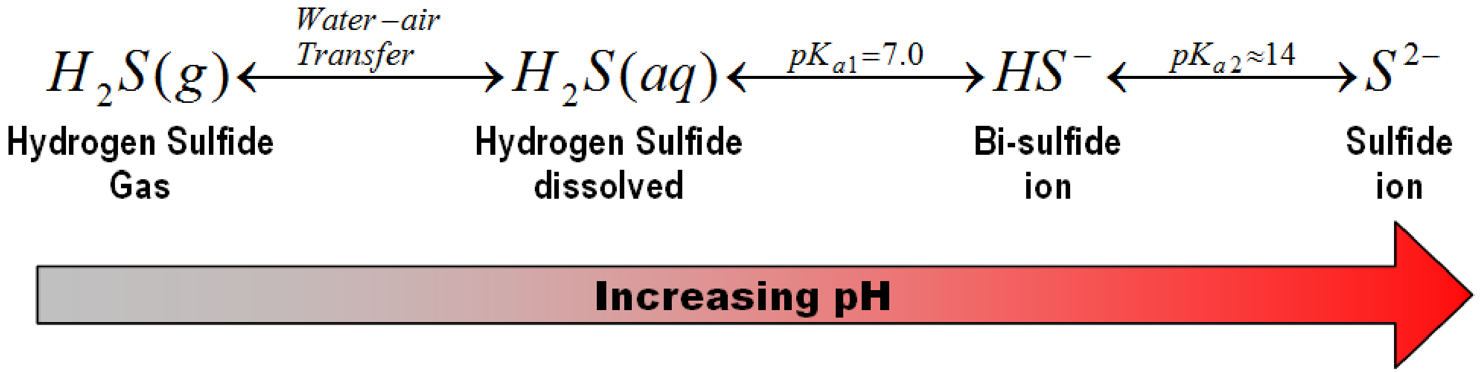
Factors affecting sulfide formation

The quality of the organic matter (the COD)	High COD (readily degradable) increases the sulfide formation rate.
The ratio between biofilm area and bulk water volume	Sulfide formation is primarily a biofilm process The higher the biofilm area to water volume ratio, the more sulfide For a full pipe, A/V = D/4 ⇒ The smaller the pipe the more sulfide per time unit
Wastewater residence time in force mains or syphons	Sulfide is only formed under anaerobic conditions The longer anaerobic conditions prevail, the more sulfide will be formed
Reaeration in gravity sewers	Gravity sewers can become anaerobic when the reaeration is low. For example, at low sewer slopes and large water depths. This can cause sulfide to be formed in the gravity sewer
Wastewater temperature	Sulfide formation is a diffusion limited biological process. Typical temperature dependency is 3% per °C. This is low compared to most biological processes (10% per °C).
Flow velocity	Sulfide formation is a diffusion limited biological process. Diffusion increases with increased shear rates. Typical flow rates do though not impede sulfide formation. When water stands still, the sulfide formation rate decreases significantly.
Sulfate content	Sulfide formation is caused by biological reduction of sulfate to sulfide. Sulfate limitation first occurs when sulfide concentrations are below 5-15 g-S/m^3, which seldom is the case in wastewater.

The release of H_2S
Why it does not want to stay in the water

A tiny bit of chemistry is needed to explain this:

Sulfide is a weak di-protic acid that dissociates as follows:



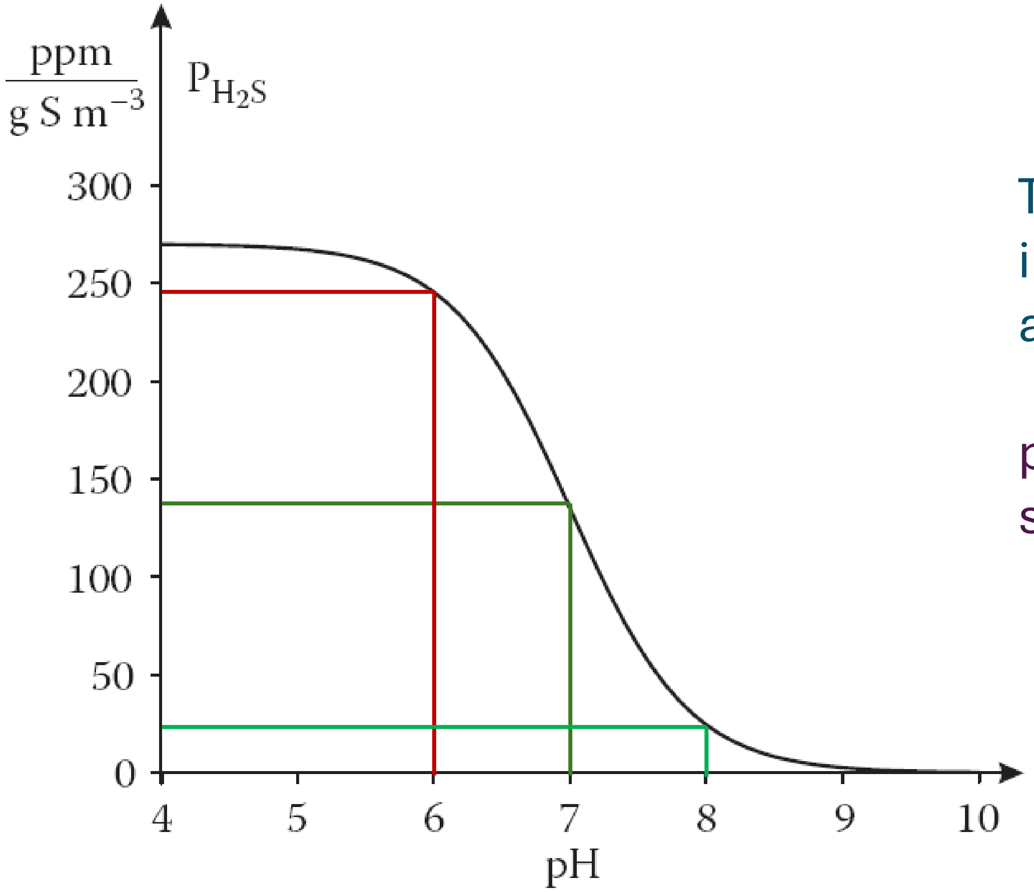
$$H_2S(g) \xleftrightarrow{Water-air\ Transfer} H_2S(aq) \xleftrightarrow{pK_{a1}=7.0} HS^- \xleftrightarrow{pK_{a2}\approx 14} S^{2-}$$

Only dissolved hydrogen sulfide, $H_2S(aq)$, can be emitted from the water

Thus, at constant total sulfide concentration the equilibrium concentration in the overlaying sewer atmosphere will be reduced with increasing pH

How pH affects the H_2S water/air equilibrium

Assume there is 1 mg/L dissolved sulfide
Assume there is equilibrium

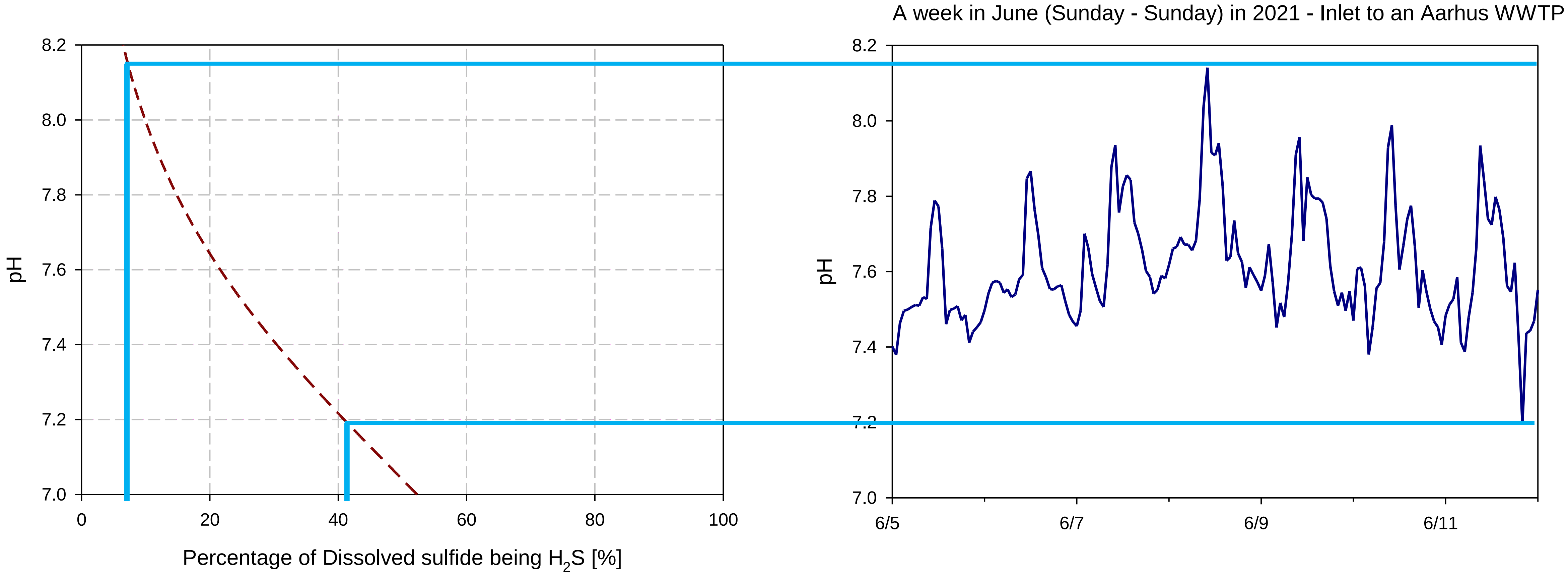


The practical consequence is that pH is highly important for how much H_2S goes into the sewer air

pH can be controlled by adding alkaline solutions such as magnesium hydroxide

How pH affects the H_2S water/air equilibrium

In this range, 7– 39% of the dissolved sulfide in the water is present as H_2S
I.e. the potential for H_2S-release is 5.6 times higher at pH 7.20 vs 8.15

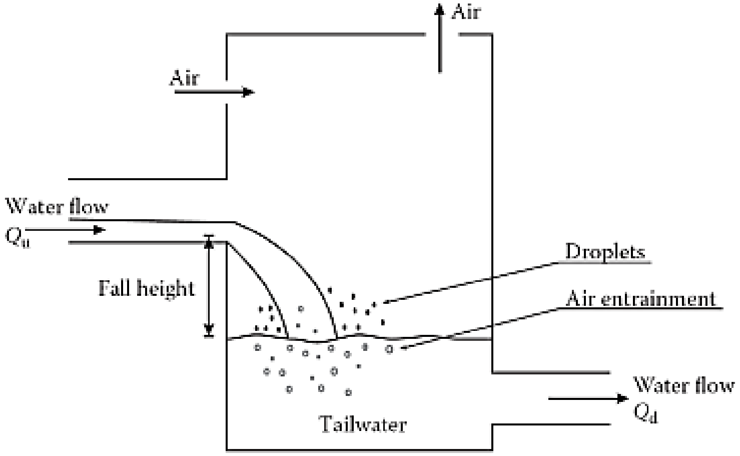

A week in June (Sunday - Sunday) in 2021 - Inlet to an Aarhus WWTP

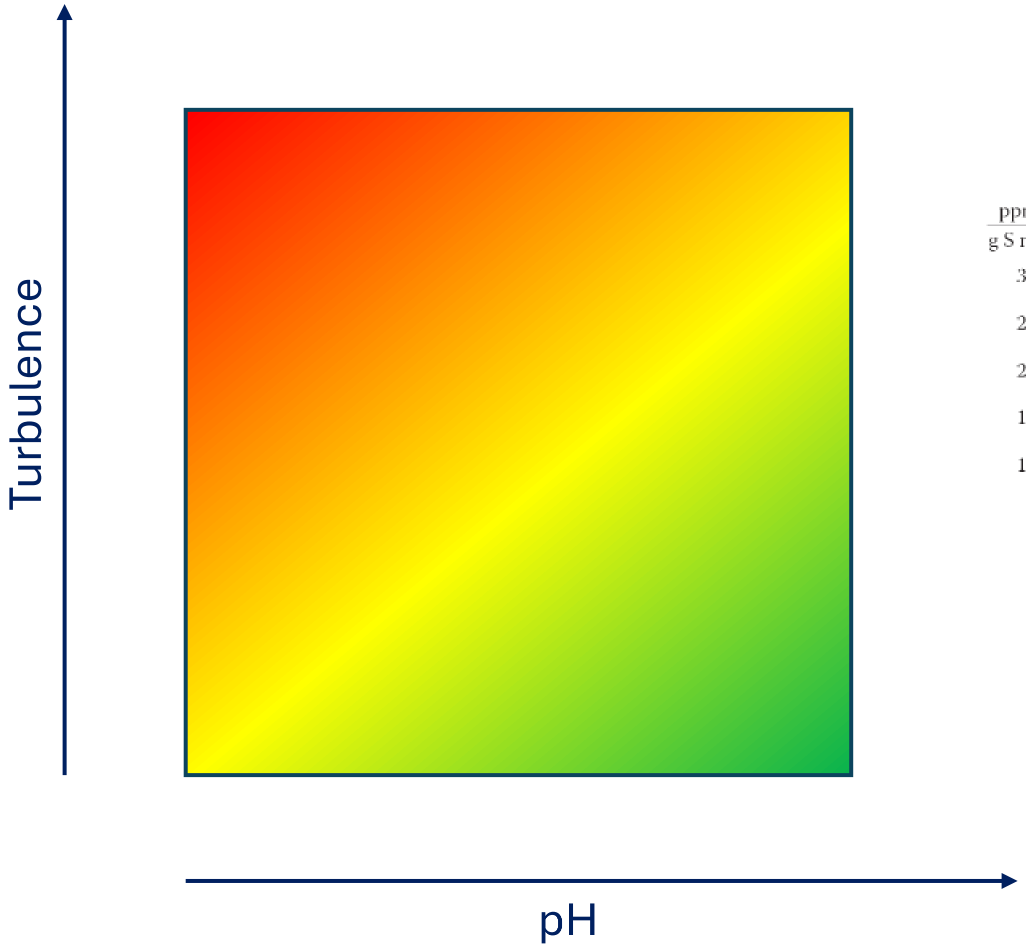
The release of H_2S why does it not want to stay in the water?

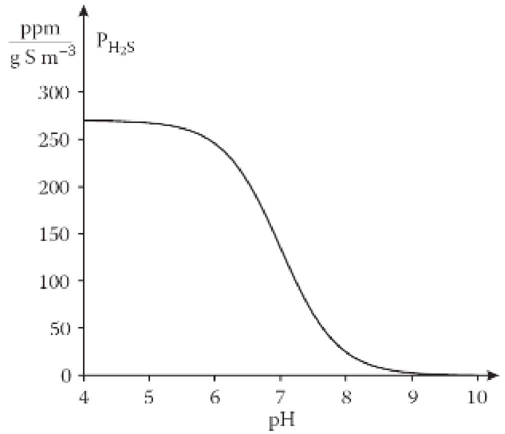
But: There is never equilibrium in a sewer system

Turbulence in the water allows H_2S to get into the air

Risk of H_2S gas release

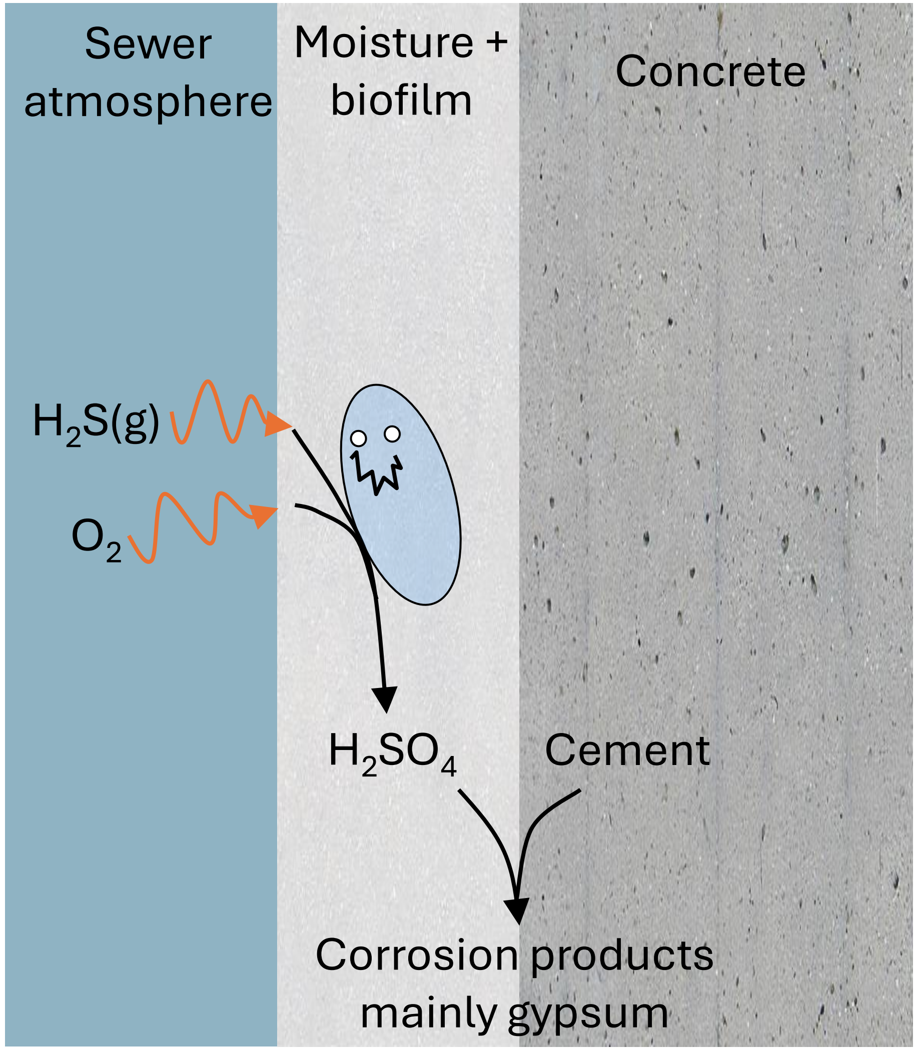






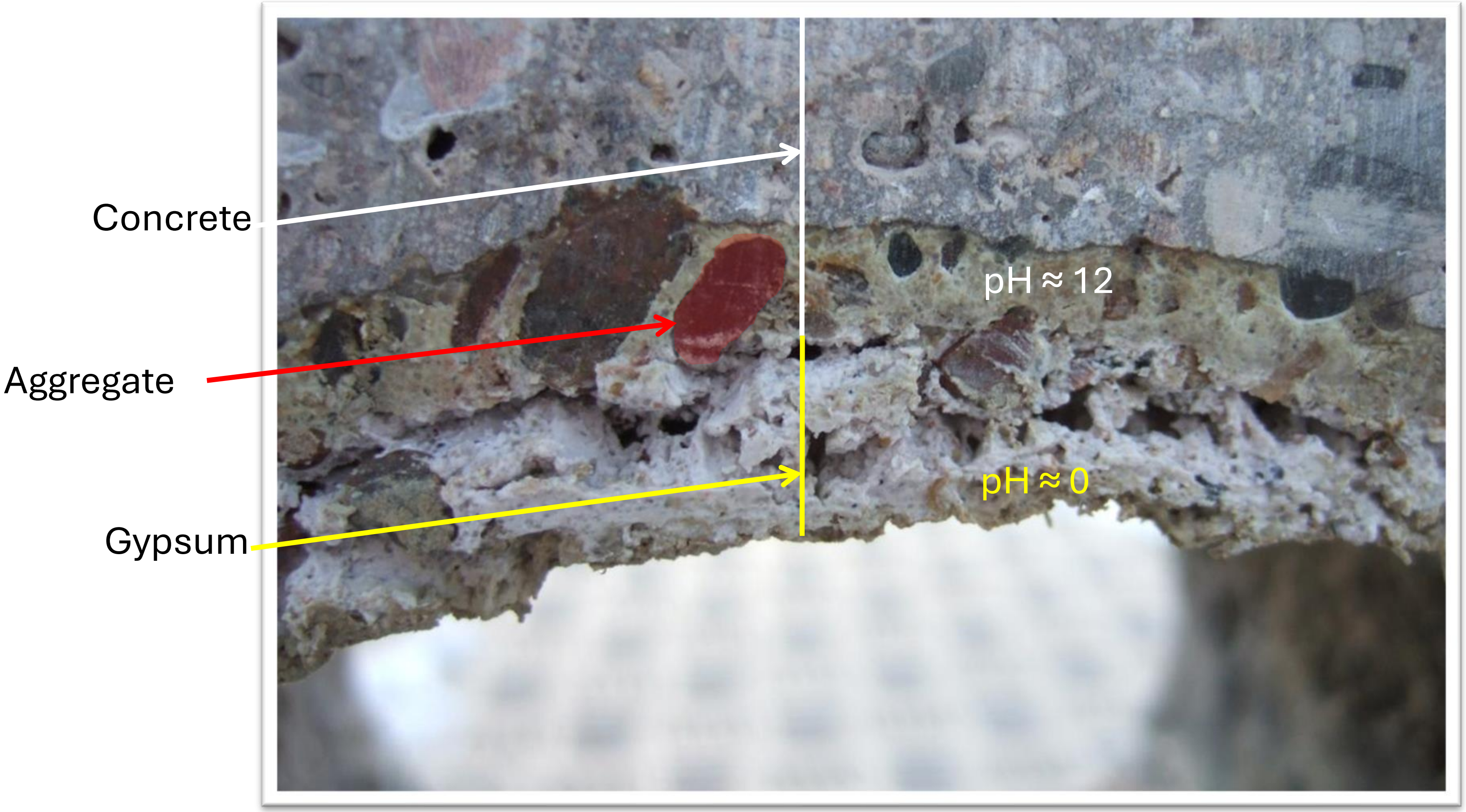
Concrete corrosion

- Processes
  - Adsorption of H_2S and O_2 on moist surface
  - H_2S is oxidized to sulfuric acid (H_2SO_4)
  - The acid reacts with the alkaline components of the concrete



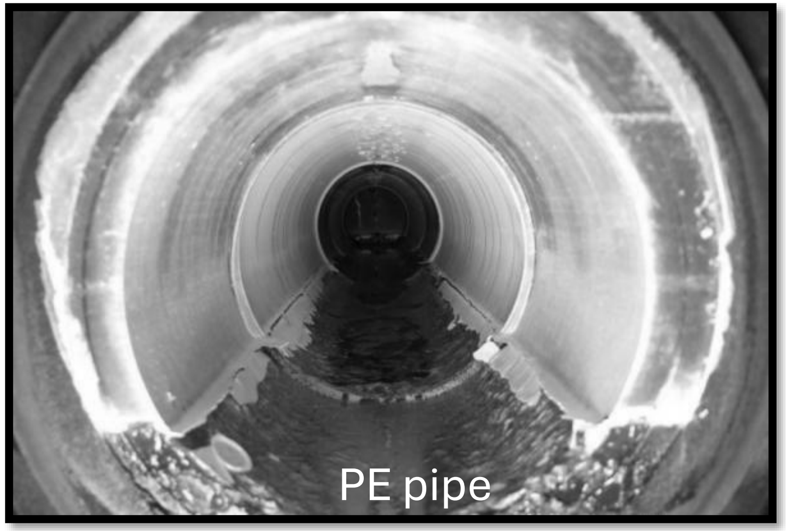
H_2SO_4 + $CaCO_3$ (cement) → H_2O + CO_2 + $CaSO_4$ (gypsum)

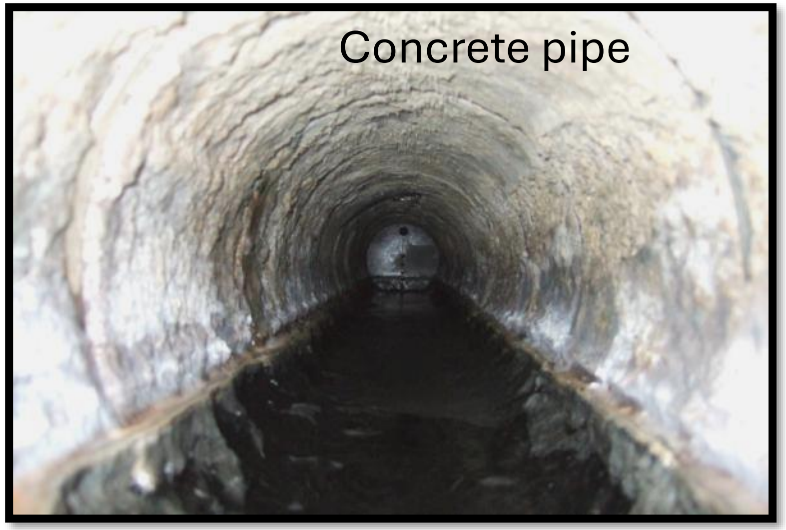
Corroding concrete – an extreme environment



Effect of pipe material

- Concrete, PE og PVC
- When using plastic pipe, the corrosion is mitigated, but what else happens?


PE pipe


Concrete pipe

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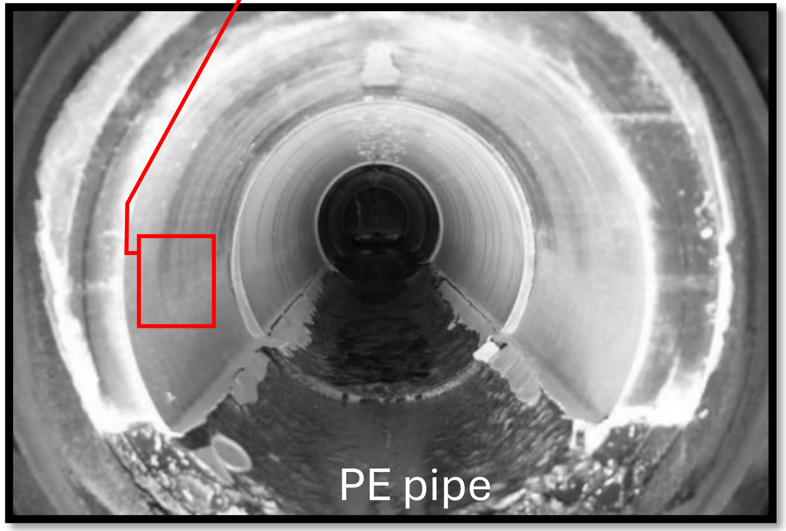

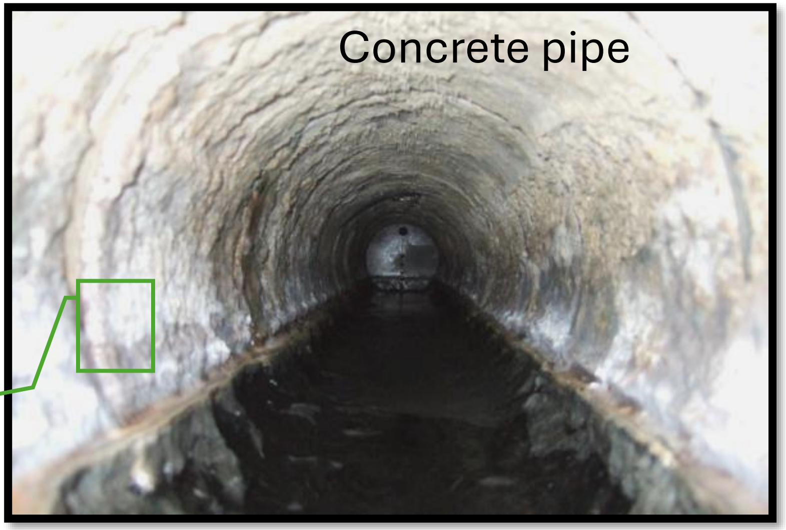

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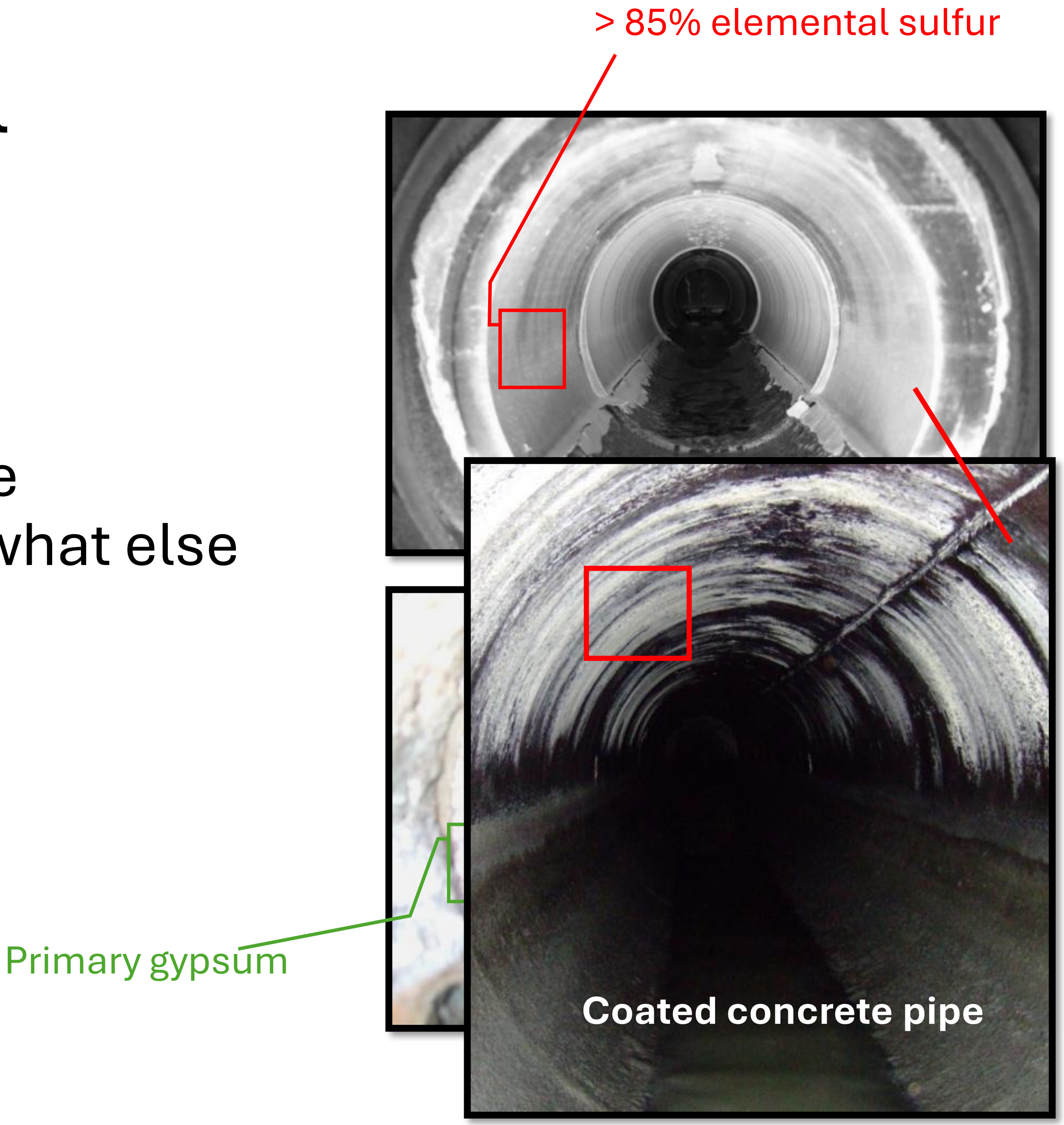
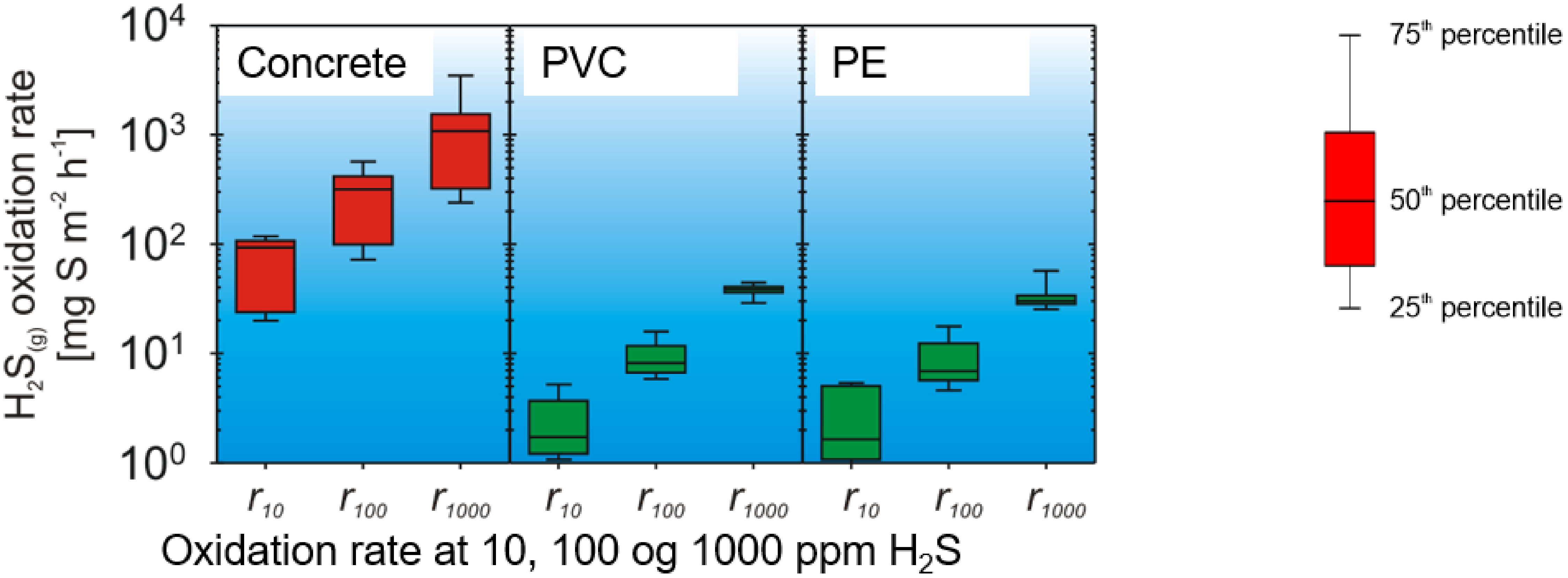


What pipe material does to sewer air H_2S

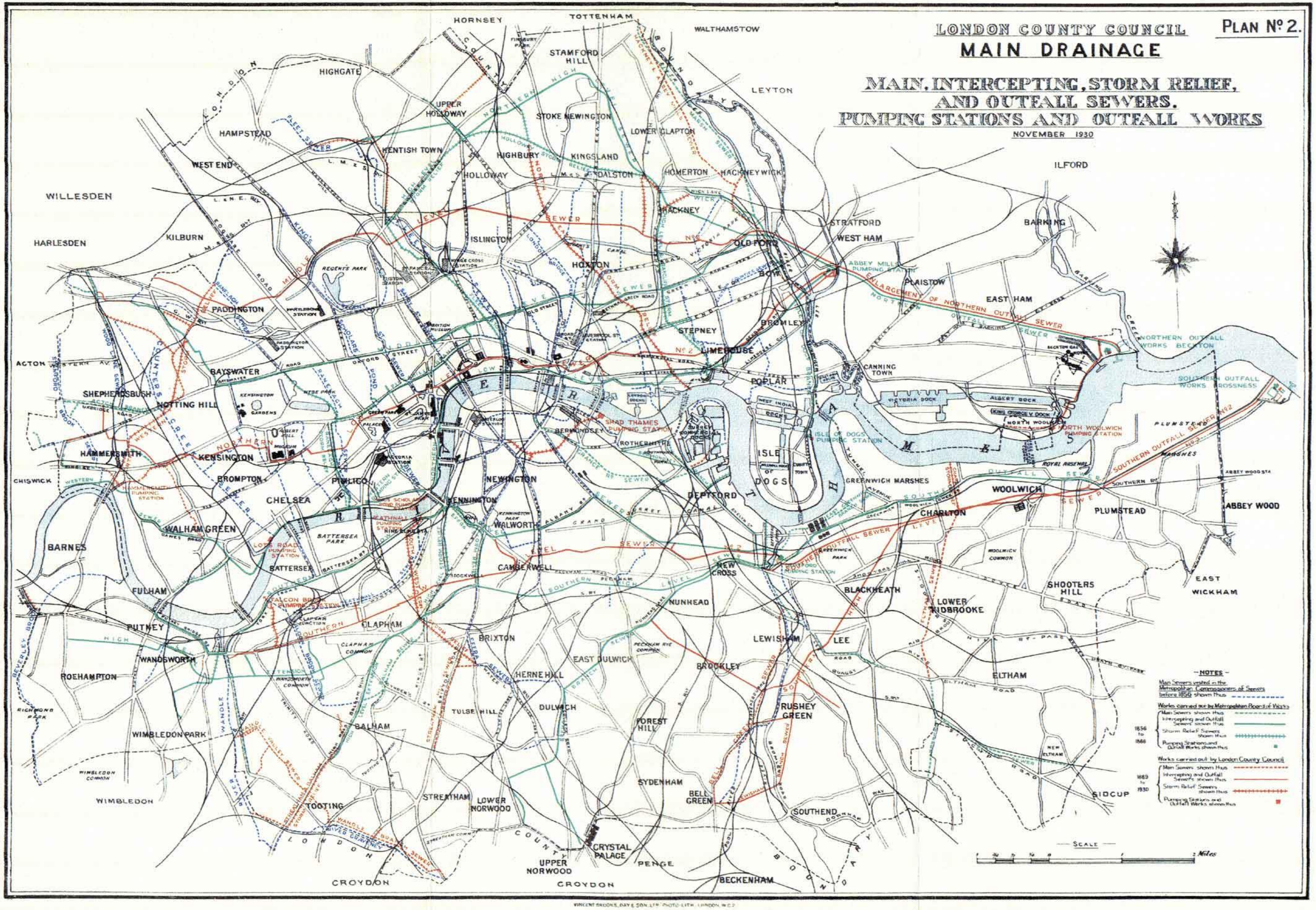
When concrete corrodes, it takes up the H_2S-gas

It hence is a sink for H_2S-gas



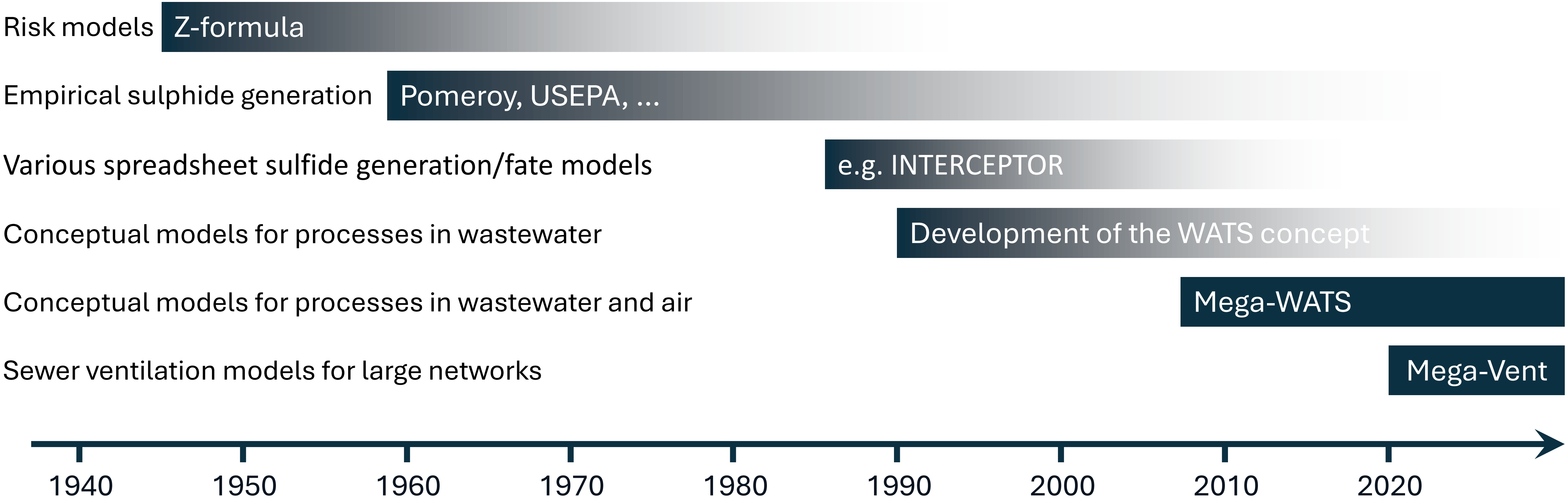
Sewers are quite complex systems

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



Modelling helps understanding complex systems

A short history of sewer process modelling



Risk models — Z-formula

Empirical sulphide generation — Pomeroy, USEPA, …

Various spreadsheet sulfide generation/fate models — e.g. INTERCEPTOR

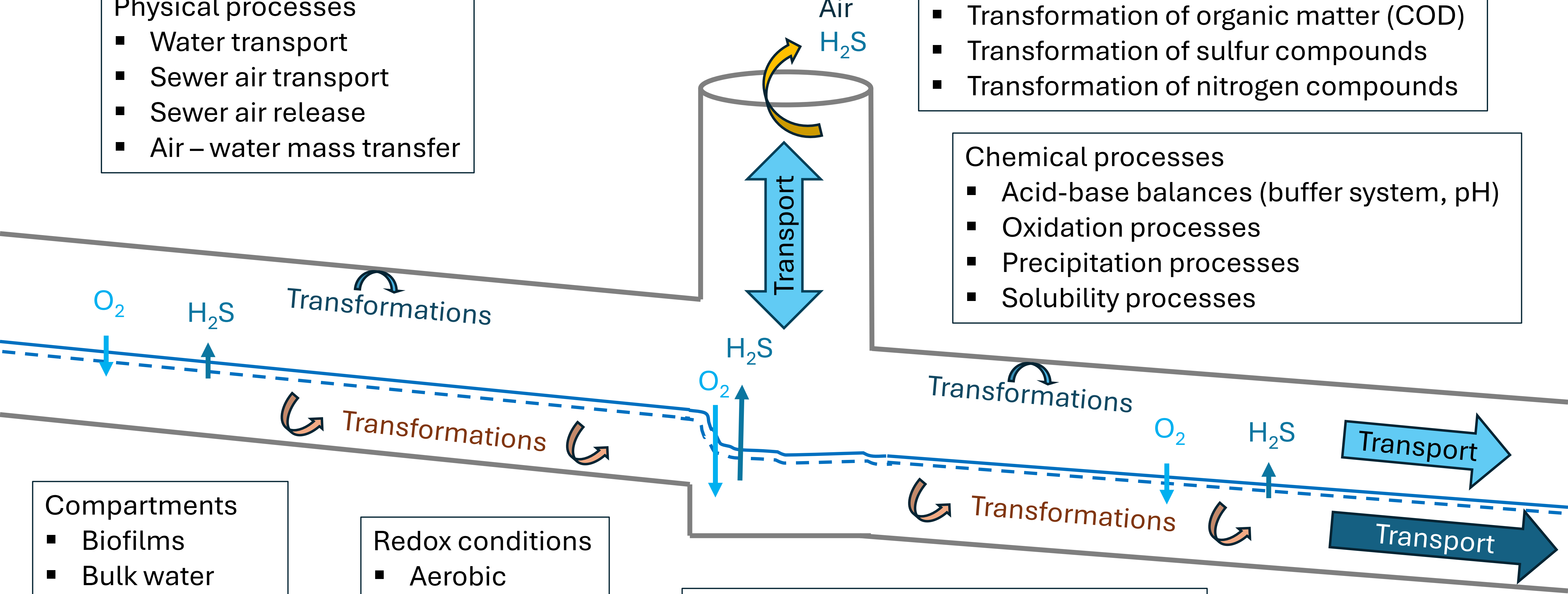
Conceptual models for processes in wastewater — Development of the WATS concept

Conceptual models for processes in wastewater and air — Mega-WATS

Sewer ventilation models for large networks — Mega-Vent

Mega-WATS was developed by Jes Vollertsen, Mega-Vent by Matthew Ward
Together Matthew and Jes founded The WATS Guys in 2020

A sewer process model must simulate all relevant in-sewer processes



Physical processes

- Water transport
- Sewer air transport
- Sewer air release
- Air – water mass transfer

Biological processes

- Transformation of organic matter (COD)
- Transformation of sulfur compounds
- Transformation of nitrogen compounds

Chemical processes

- Acid-base balances (buffer system, pH)
- Oxidation processes
- Precipitation processes
- Solubility processes

Compartments

- Biofilms
- Bulk water
- Sewer air
- Moist surfaces

Redox conditions

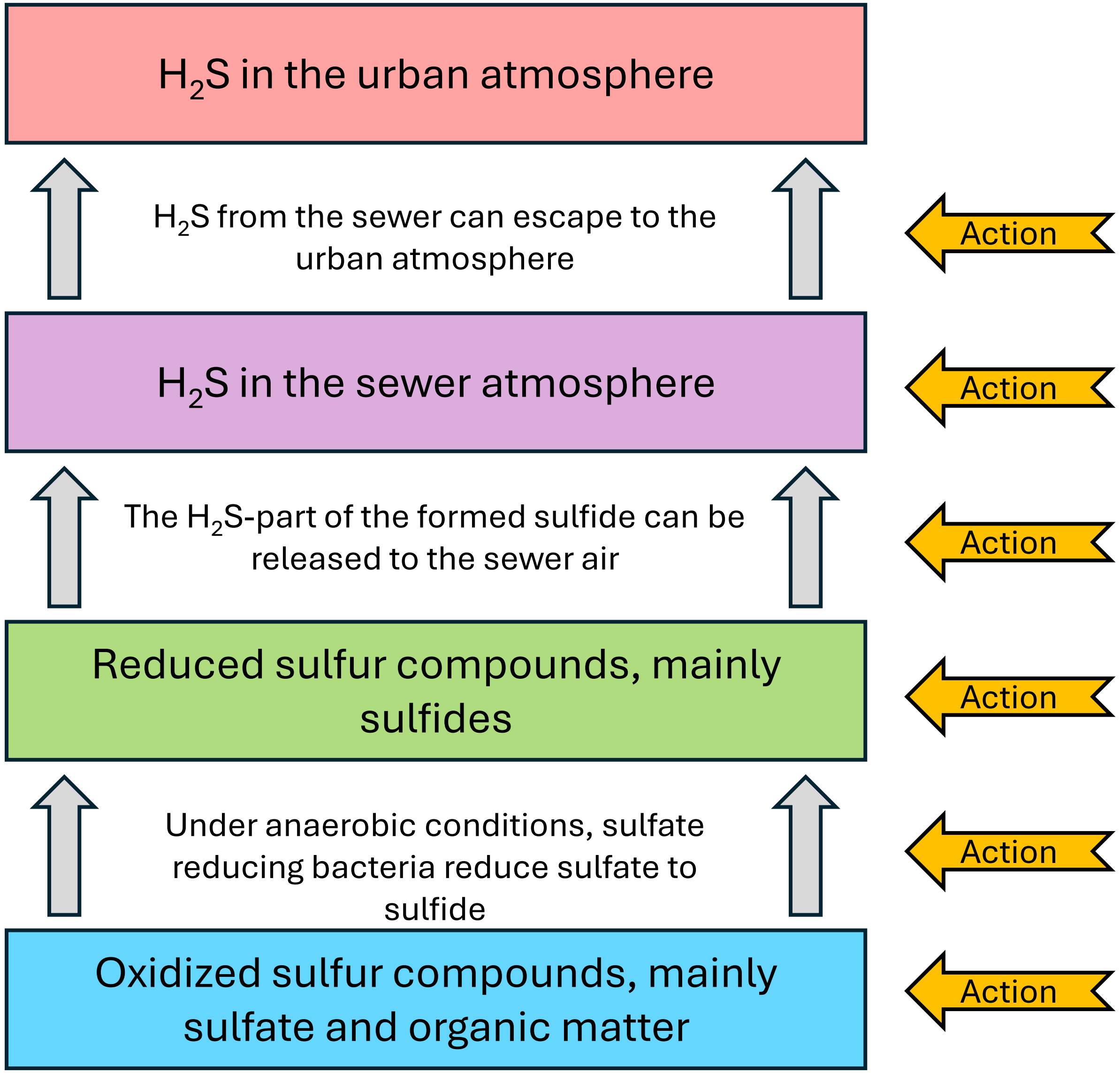
- Aerobic
- Anoxic
- Anaerobic

Elements, substances

- C, O_2, N, P, Mg, Fe, H_2O_2, NaClO, …

A sewer process model must simulate mitigation methods

The processes governing formation and fate of sulfide and other malodorous substances govern which methods can be used to mitigate issues



H_2S in the urban atmosphere

H_2S from the sewer can escape to the urban atmosphere

Action

- Avoid uncontrolled air release
- Extract and treat air

H_2S in the sewer atmosphere

Action

- Remove H_2S from the sewer air
- Biological and chemical oxidation

The H_2S-part of the formed sulfide can be released to the sewer air

Action

- Avoid turbulent conditions
- Make HS^- the dominant species

Reduced sulfur compounds, mainly sulfides

Action

- Precipitate formed sulfide
- Oxidize formed sulfide

Under anaerobic conditions, sulfate reducing bacteria reduce sulfate to sulfide

Action

- Avoid anaerobic conditions
- Reduce sulfide forming biomass

Oxidized sulfur compounds, mainly sulfate and organic matter

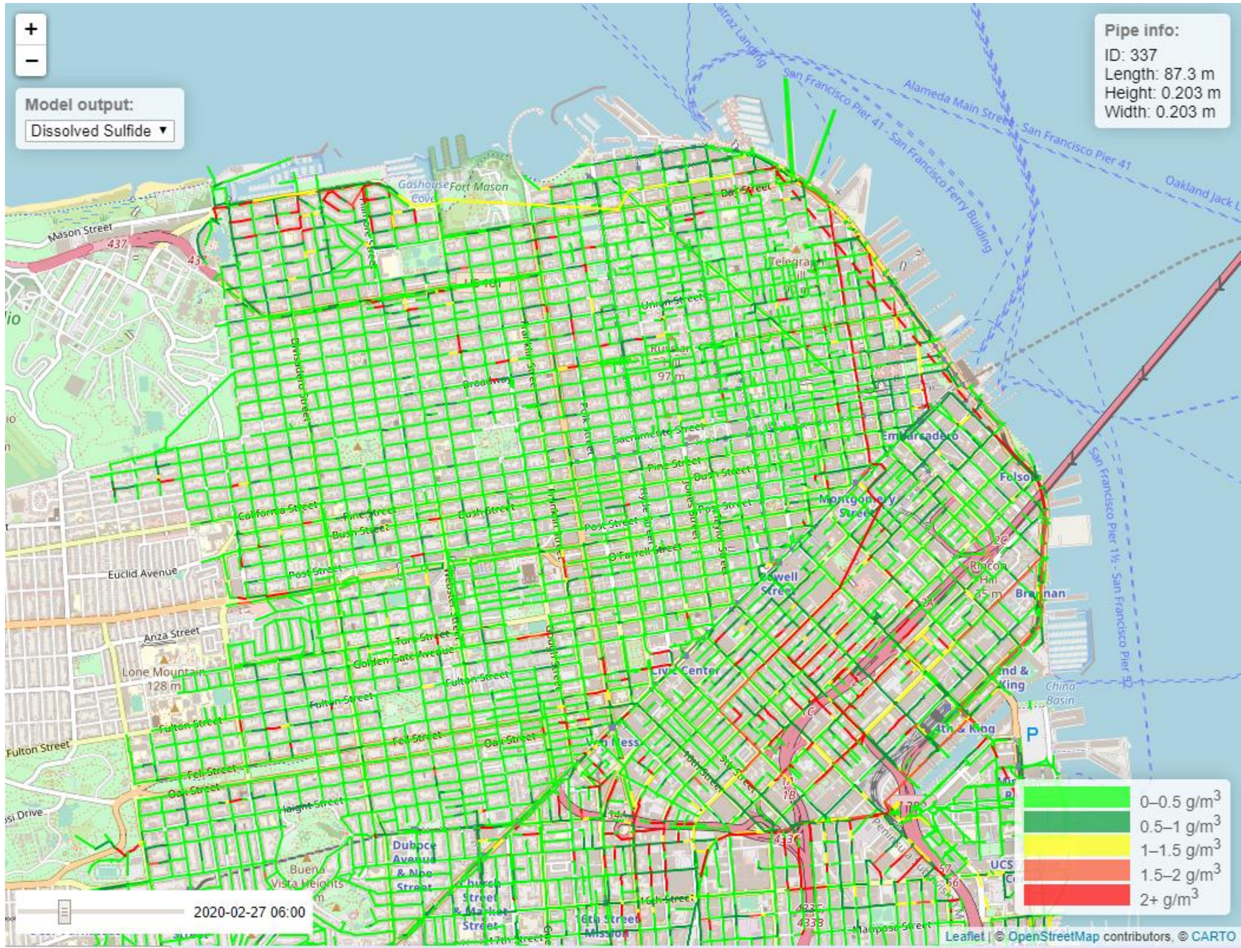
Action

Difficult to control as the purpose of the sewer is to handle them

Sewer process modelling helps you getting a better grip on the problems

- Assess
  - Odor and toxicity impacts from the collection system
  - Corrosion of the sewer assets
  - Impacts on the treatment works
- Manage
  - Odors and hydrogen sulfide in the sewer network
- Predict
  - Future developments in the sewer network

Modelling San Francisco with Mega-WATS



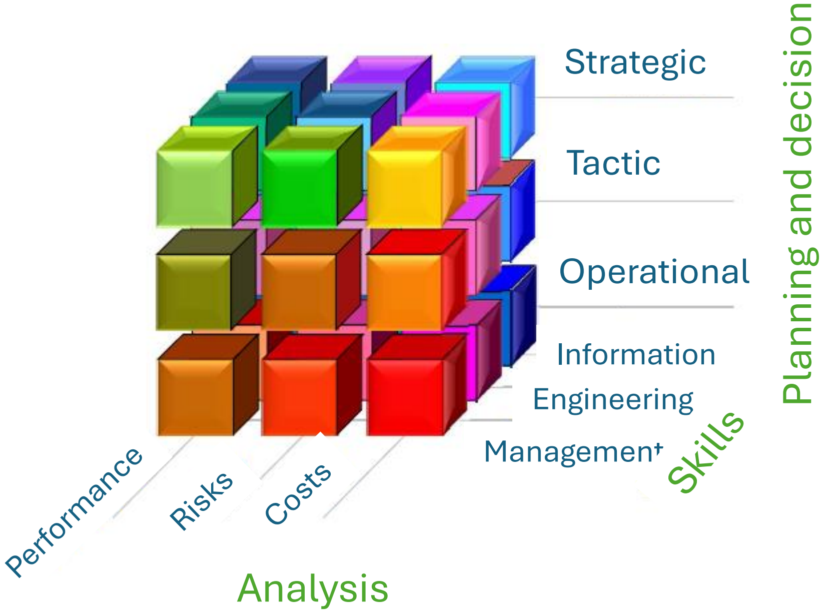
Pipe info:
ID: 337
Length: 87.3 m
Height: 0.203 m
Width: 0.203 m

Model output: Dissolved Sulfide ▾

2020-02-27 06:00

It helps you to:

- Manage complexity
- Project into the Future
- Identify Treatment Alternatives
- Screen Treatment Alternatives



Strategic

Tactic

Operational

Planning and decision

Information

Engineering

Management

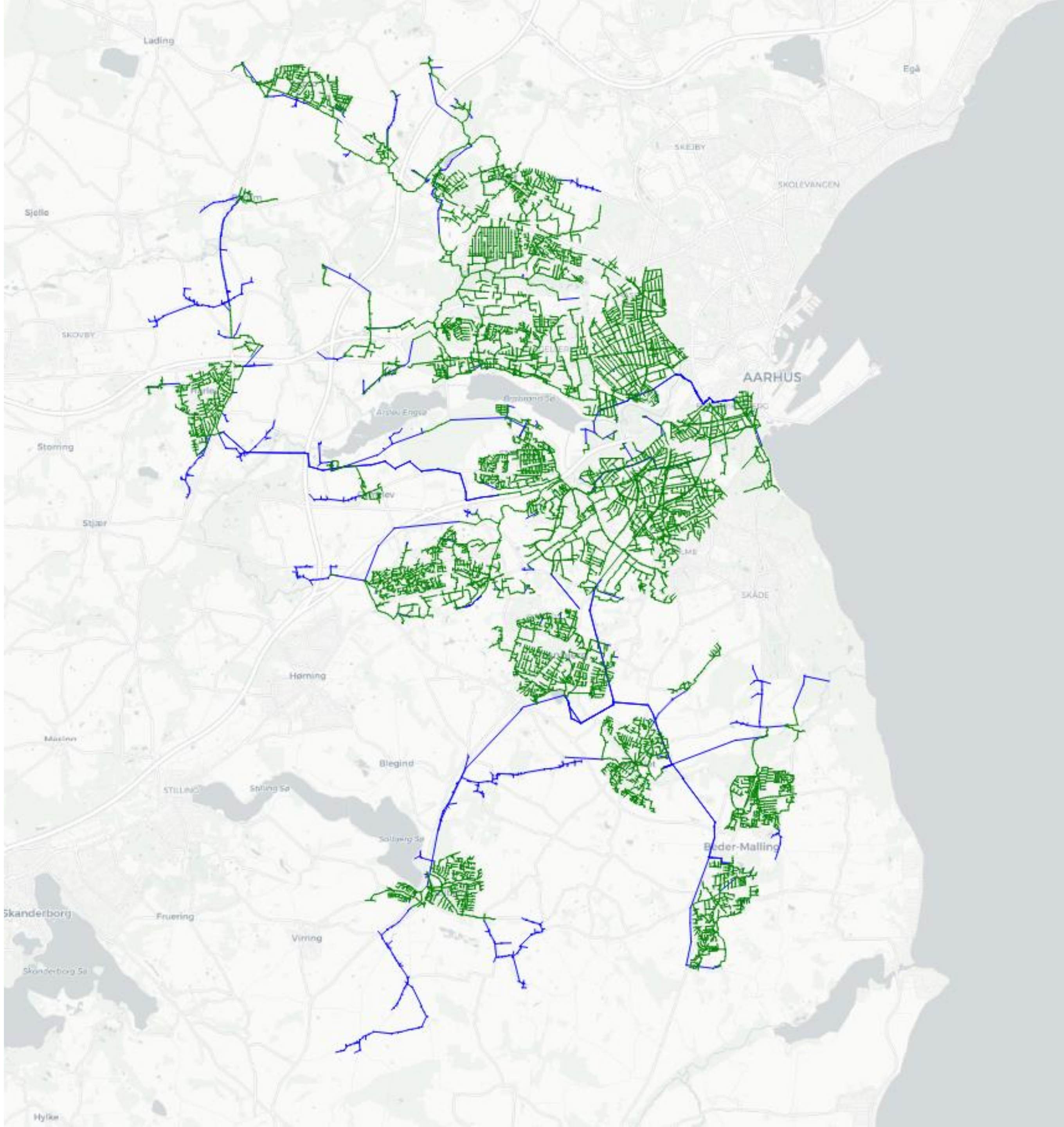
Skills

Performance

Risks

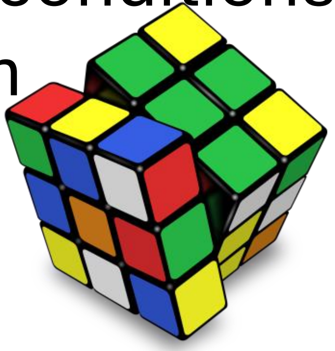
Costs

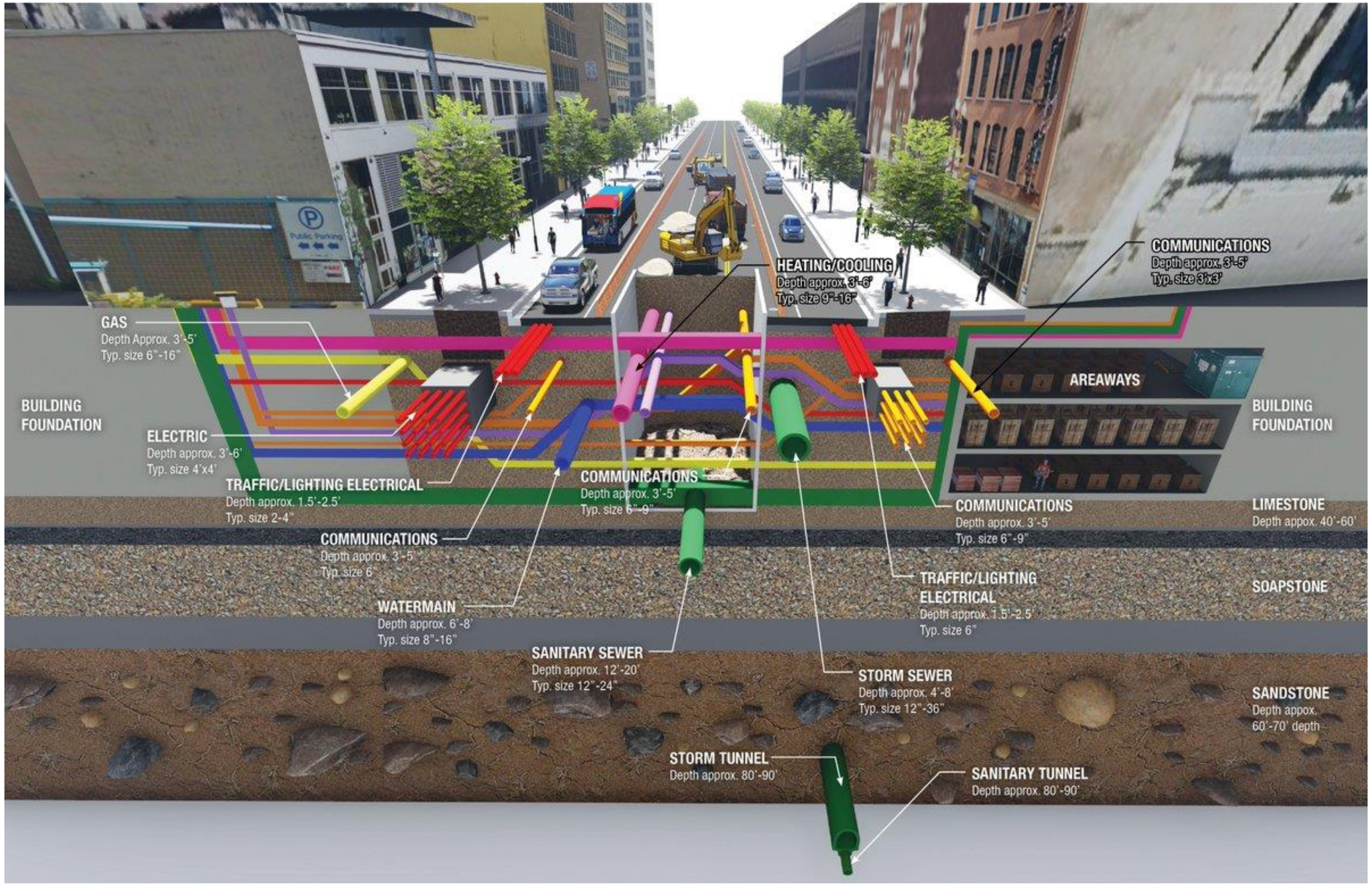
Analysis



Issues when modelling in-sewer processes

- High natural variability in wastewater composition
- Model constants are not constant
- Impossible to know the boundary conditions of the system





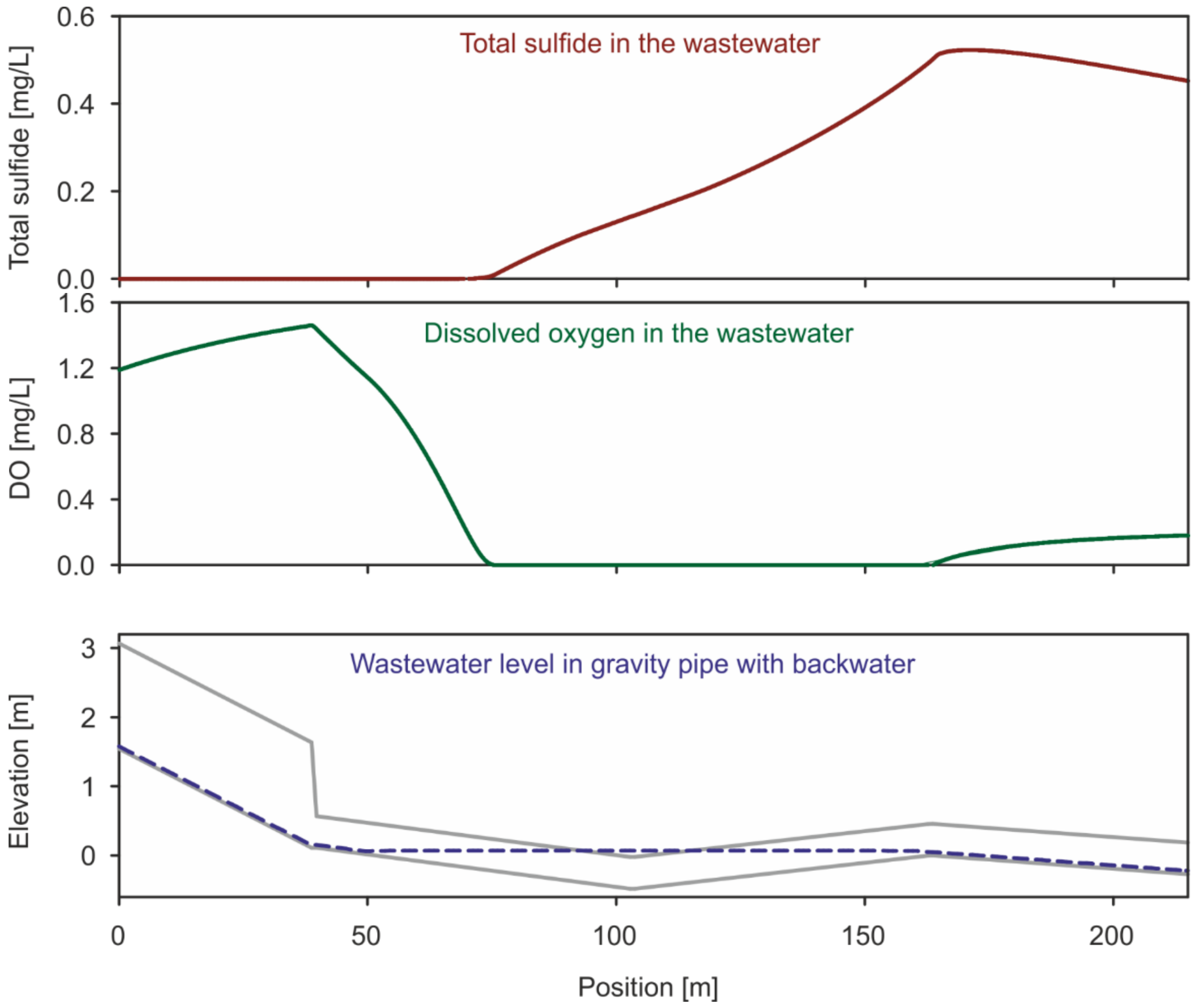
What Mega-WATS includes

- Biological processes
  - Aerobic transformations (oxygen is present)
  - Anoxic transformations (nitrate is present, no oxygen)
  - Anaerobic transformations (sulfide, mercaptans, methane, …)
- Chemical processes
  - Oxidation
  - Precipitation
  - Wastewater buffer system: pH, alkalinity
- Hydraulics
  - Rout water and air through the network
  - Gas exchange with the urban atmosphere
- 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

Sewer processes are simulated by solving many 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

Each pipe is simulated, meter for meter



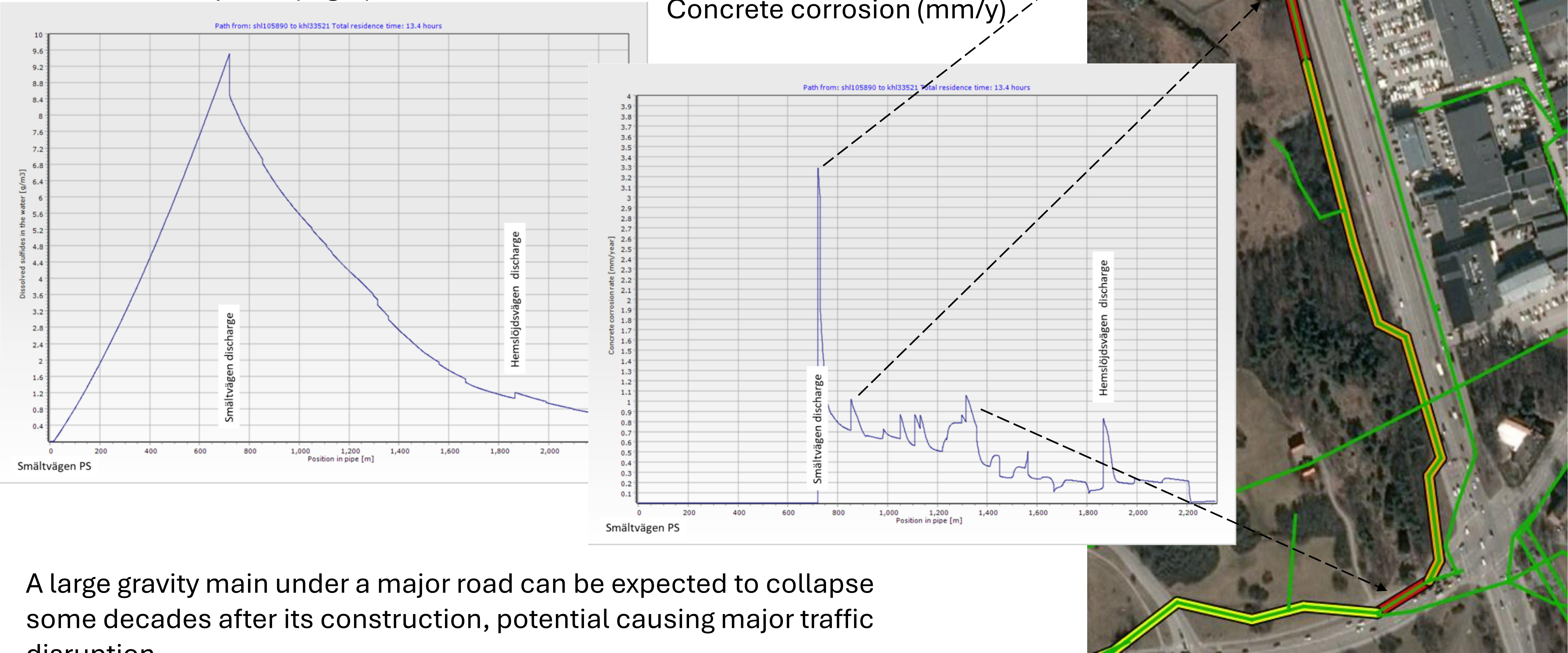
A simulation example
– 215 m of gravity pipe with backwater

An example of predicting sewer collapse risk

Stockholm – Discharge of a force main into a concrete gravity sewer

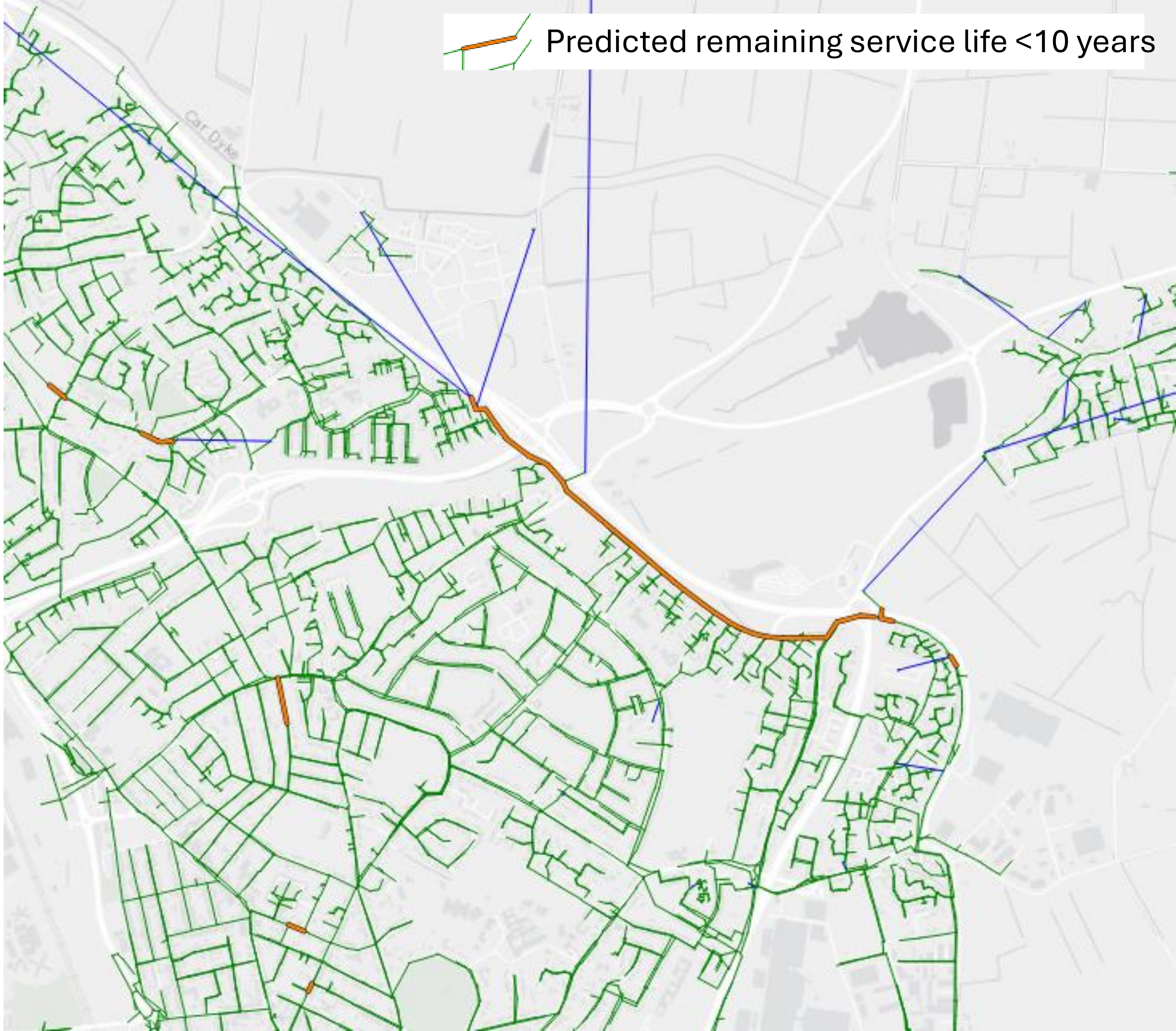
Dissolved sulphide (mg/L)

Concrete corrosion (mm/y)

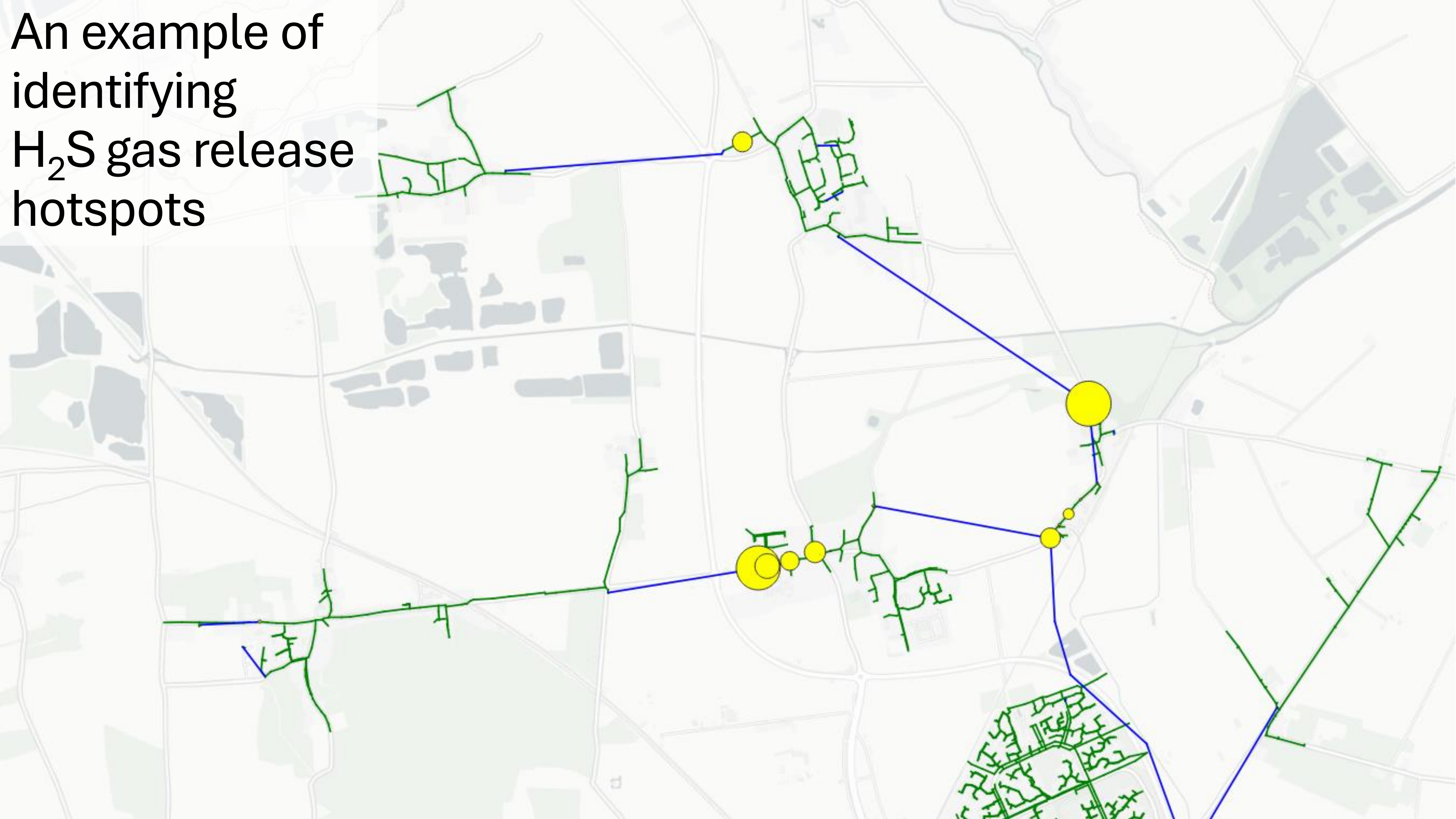


A large gravity main under a major road can be expected to collapse some decades after its construction, potential causing major traffic disruption

An example of predicting remaining service life

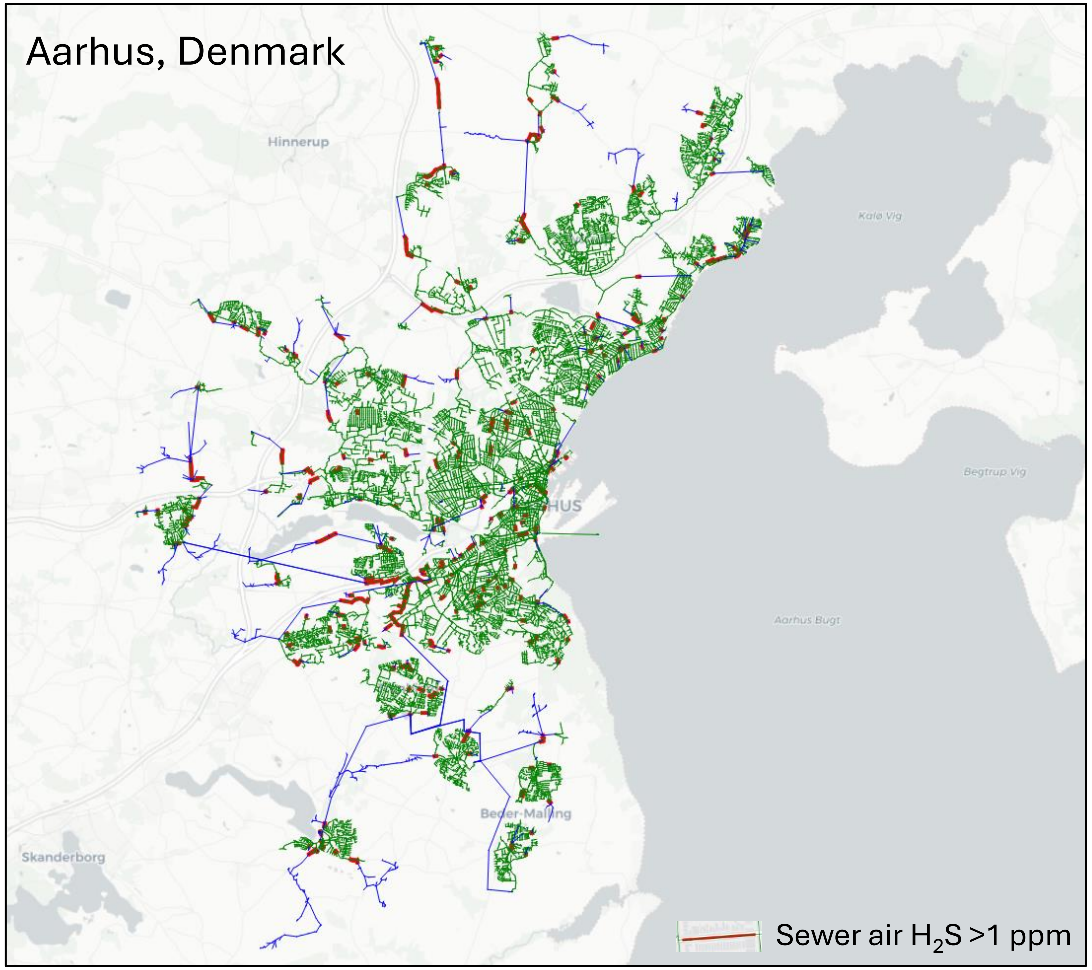


An example of identifying H_2S gas release hotspots

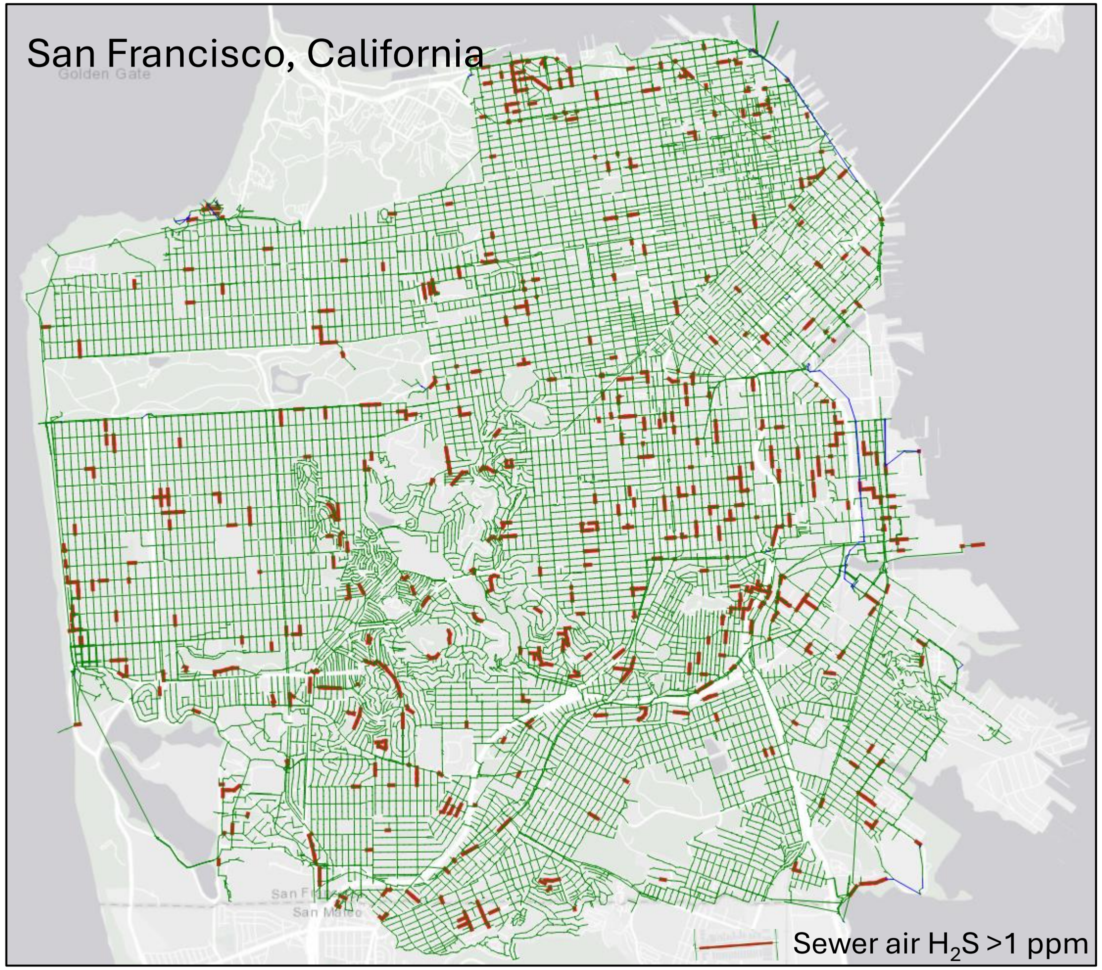


Mega-WATS is fast

1632 km of pipes
33215 individual pipes
1-2 minutes simulation time on a decent laptop



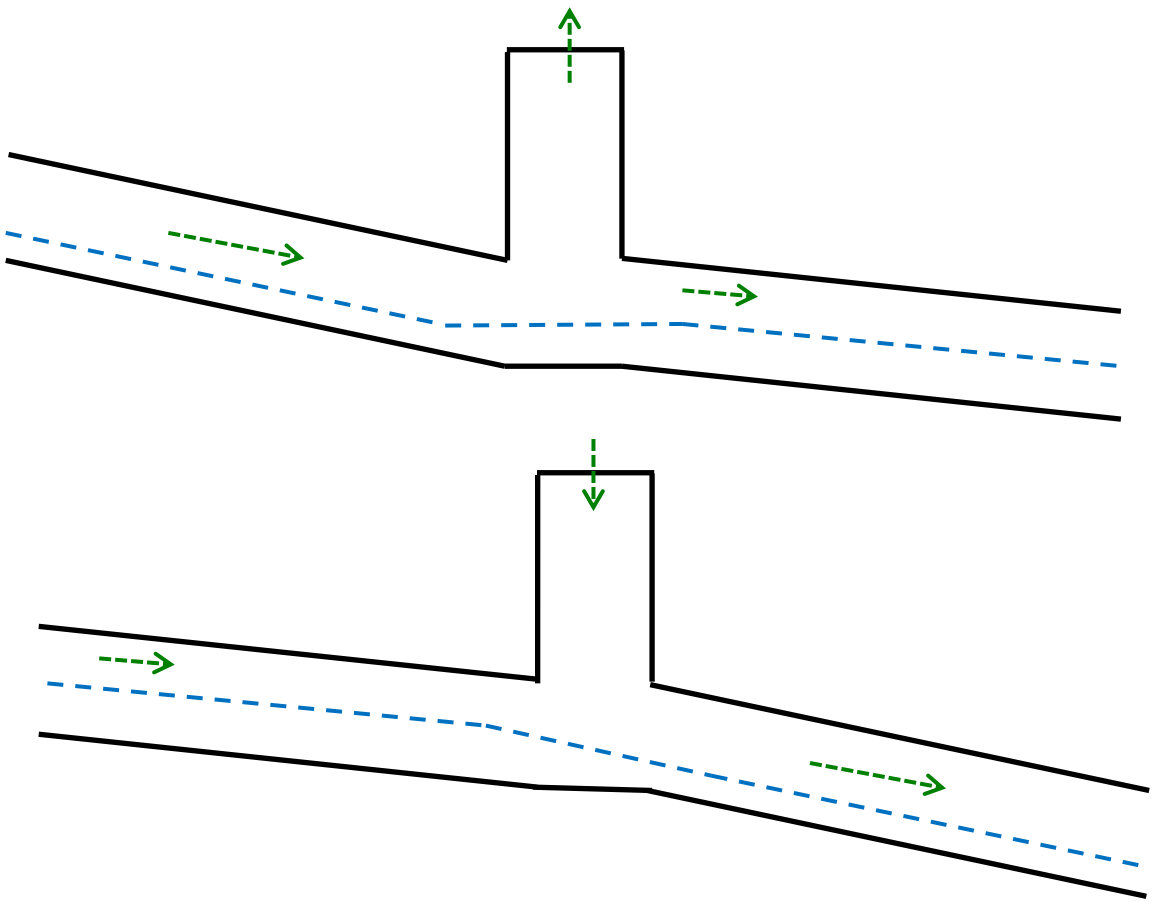
1672 km of pipes
34282 individual pipes
1-2 minutes simulation time on a decent laptop



Sewer ventilation

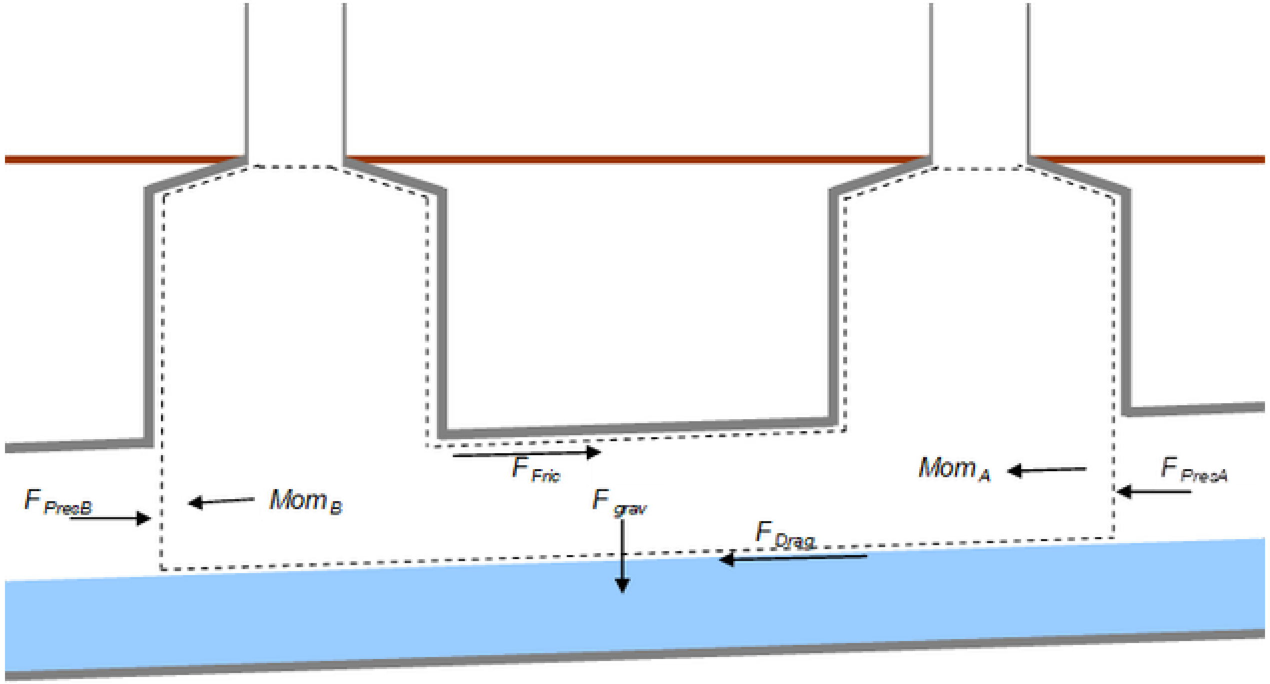
Mega-Vent

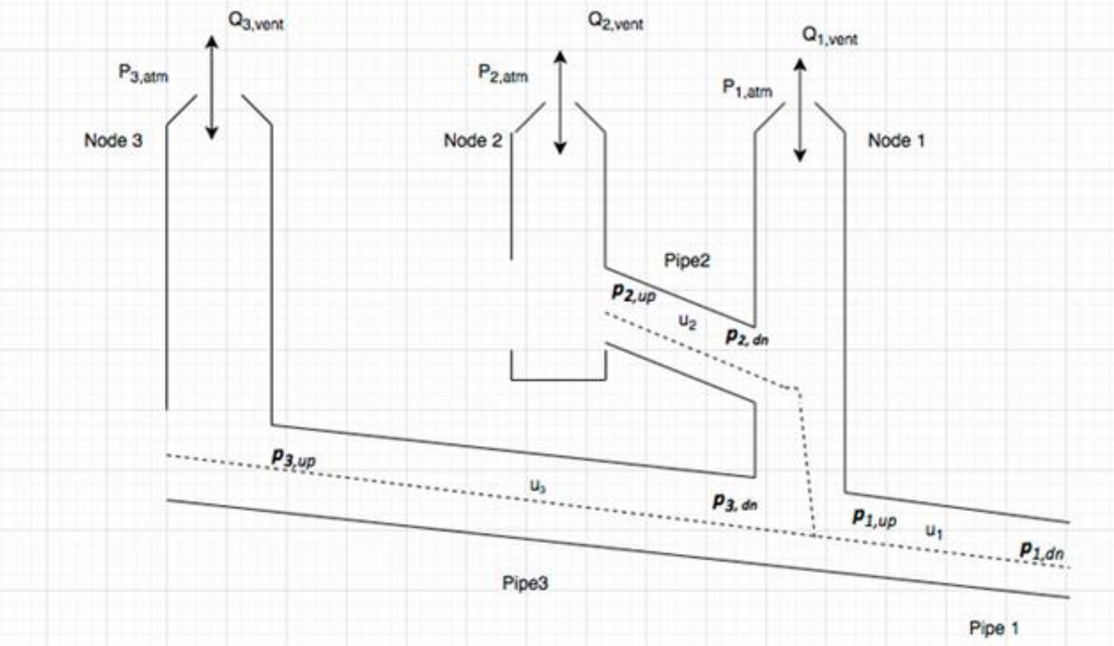
Air goes in and out of sewers all the time



Mega-Vent sewer ventilation modelling

Solves the momentum balance of the air flow
Gives pressure and air velocities in all pipes

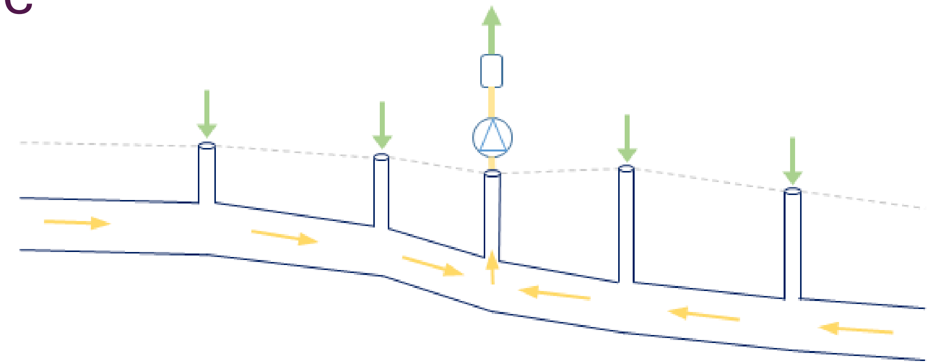




Forced ventilation – a common solution in many countries

Objective: Avoid foul air release to the atmosphere

- Fans extracting air are placed in the network
- Extracted foul air is treated and vented



Designing forced ventilation:

- Keep the area of interest in negative pressure (vacuum) relative to the ambient atmosphere
- When the sewers are in negative pressure, air can only flow in not out