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NUMERICAL MODELING OF PREMISE PLUMBING SYSTEM CONSIDERING DISPERSION EFFECT

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Outline

- Introduction to Premise Plumbing System
- Dispersion Modeling
- Modeling Methods
- Results
- Conclusions

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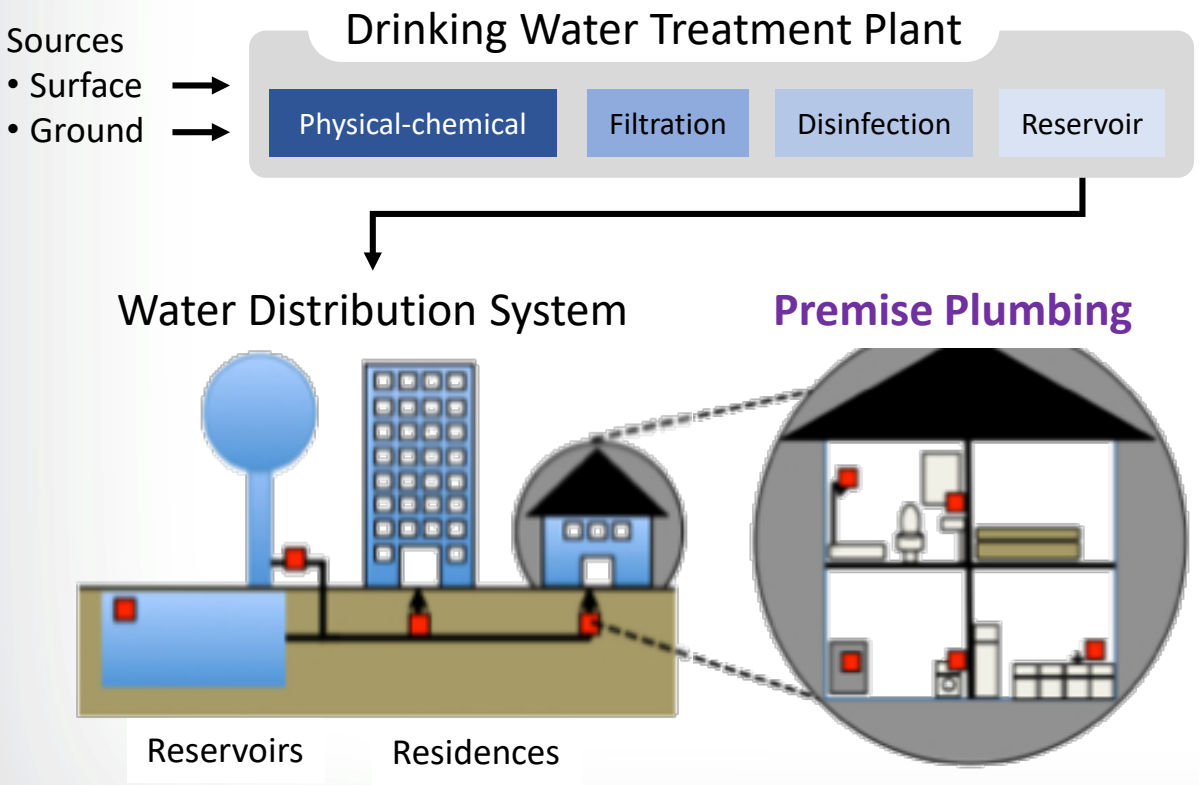
Introduction

- Water quality in premise plumbing systems (PPS)
  - Increase in public awareness of the importance of safe drinking water in homes and buildings
  - Risk of exposure to contaminants (e.g., lead or legionella) from water in homes or buildings
- Quality of water and potential exposure at the end use is affected by numerous factors:
  - Plumbing materials, dimensions and layout
  - Water chemistry
  - Number of residents and their usage patterns
  - System hydraulics

Introduction

- Premise plumbing has several unique characteristics



Hydraulic Aspects → Intermittent Uses

- High Water Age
- **Variable Velocities**

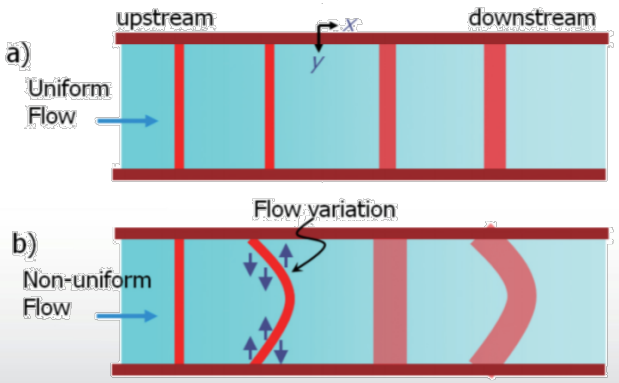
Water Quality Aspects

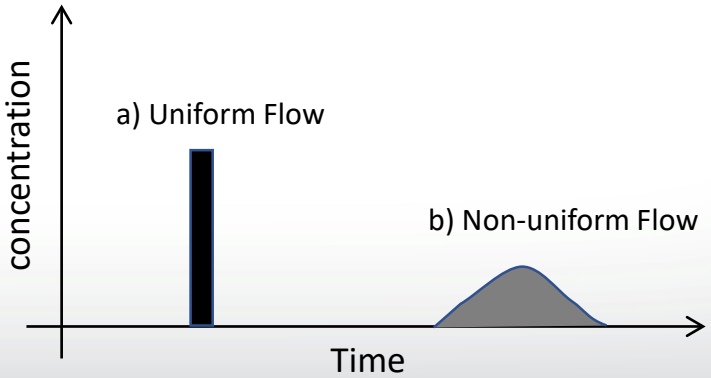
- High Surface Area to Volume Ratio
- Different Materials
- Extreme Temperatures
- Low Residual Disinfectant
- Multiple Exposure Pathways (contact, ingestion, aerosols)

https://www.nap.edu/read/11728/chapter/10

Dispersion Modeling

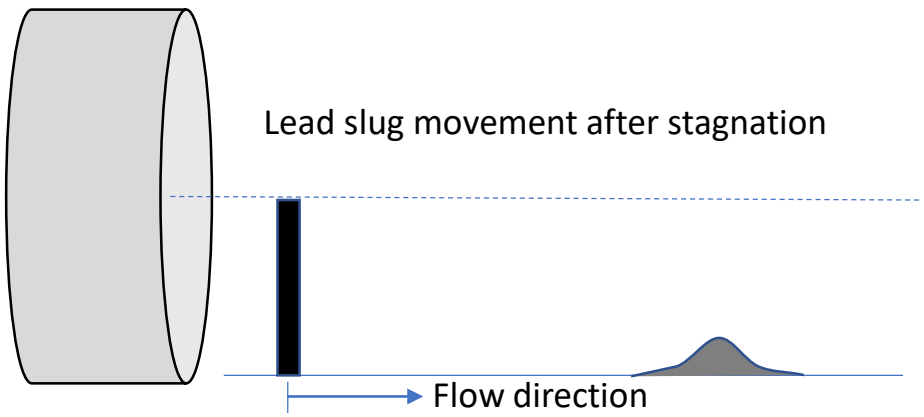
- Burkhardt et. al (2018), demonstrated the limitations of using EPANET to simulate the water quality of PPS by comparing to real data
  - EPANET does not accurately model the water quality of PPS (time alignment, peak)
  - EPANET assumes uniform flow in the pipe, solves advection and reaction equations
- Dispersion plays an important role in water quality prediction
  - Dead end, laminar flow, transition flow, chlorine decay
- Modeling of PPS also needs to consider dispersion due to the change of velocity in the pipe, specially in the laminar flow regimes





Modeling Methods

- General transport equation: Advection - Reaction - Dispersion (ARD)
  - Governing partial differential equation (PDE)



Advection Dispersion Reaction

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} - KC$$

where u = velocity, D = diffusion and dispersion coefficients, K= reaction coefficients

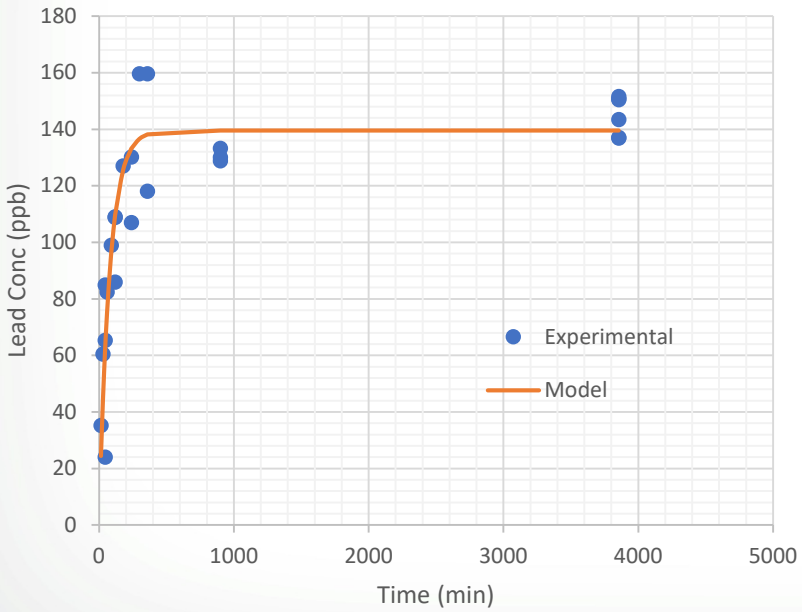
- Analytical solutions are available for special or simplified cases only.

  Ex) Stagnant or steady-state flow with special condition (continuous injection or instantaneous injection)
- Numerical solutions are available for certain conditions.
  - Transport equation is combined with two different types of PDEs

    (Advection – hyperbolic PDE, Dispersion – parabolic PDE)

Model Parameters

- Lead dissolution reaction model
  - 1st order saturation model for stagnant condition (Van Der Leer, 2002)



$$\frac{dc}{dt} = \frac{AM}{V}\frac{(E-c)}{E}$$

where
A = internal area, V = volume of pipe,
M = mass transfer rate,
E = plumbosolvency (a measure of the extent of lead dissolution)

Fig 1. Stagnation curve for a lead propensity

- Dimensionless dispersion coefficients
  - Dimensionless dispersion coefficients in premise plumbing system (Woo et al., 2018)

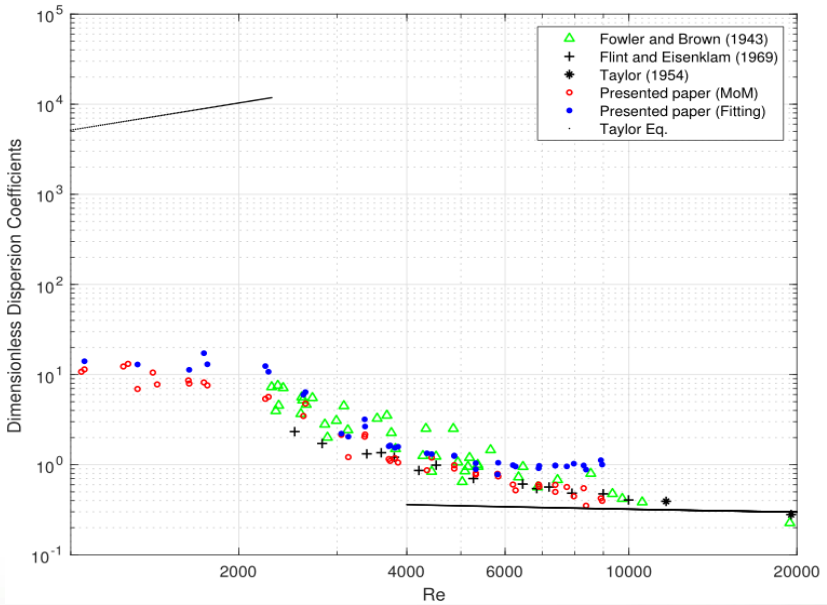


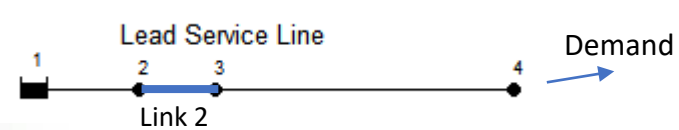
Fig 2. Comparison of the dimensionless dispersion coefficients

Numerical Solution Methods

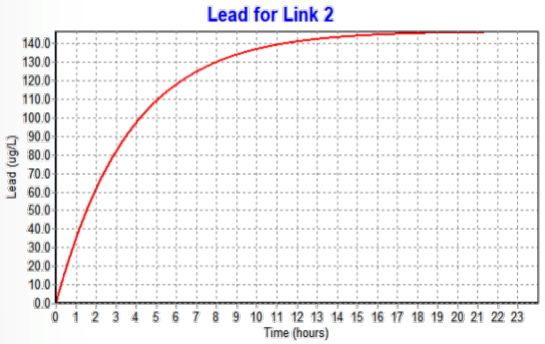
- Numerical Implementation
  - Hydraulic simulation - used the EPANET 2.2 toolkit
  - Quality simulation - used the operator splitting technique
    - Eulerian - Lagrangian splitting method: decompose unwieldy (systems of) PDEs into simpler subproblems and treat them individually using specialized numerical algorithms (Divide-and-conquer strategy)
    - Advection - Method of Characteristics (MOC)
    - Reaction – 1st order saturation growth model
    - Dispersion - Backward Time Central Space (BTCS) Finite Difference Method
    - Using C++ for calculation and Python for graphical representation

Example of Dispersion effect

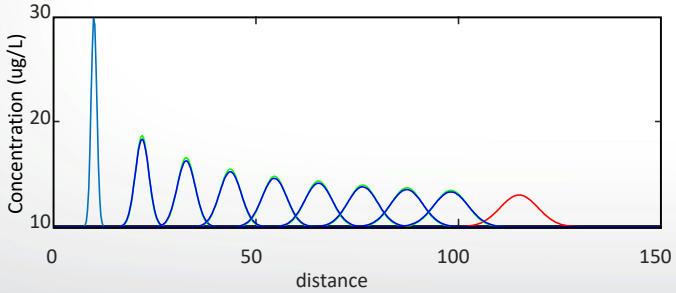
Simple Example



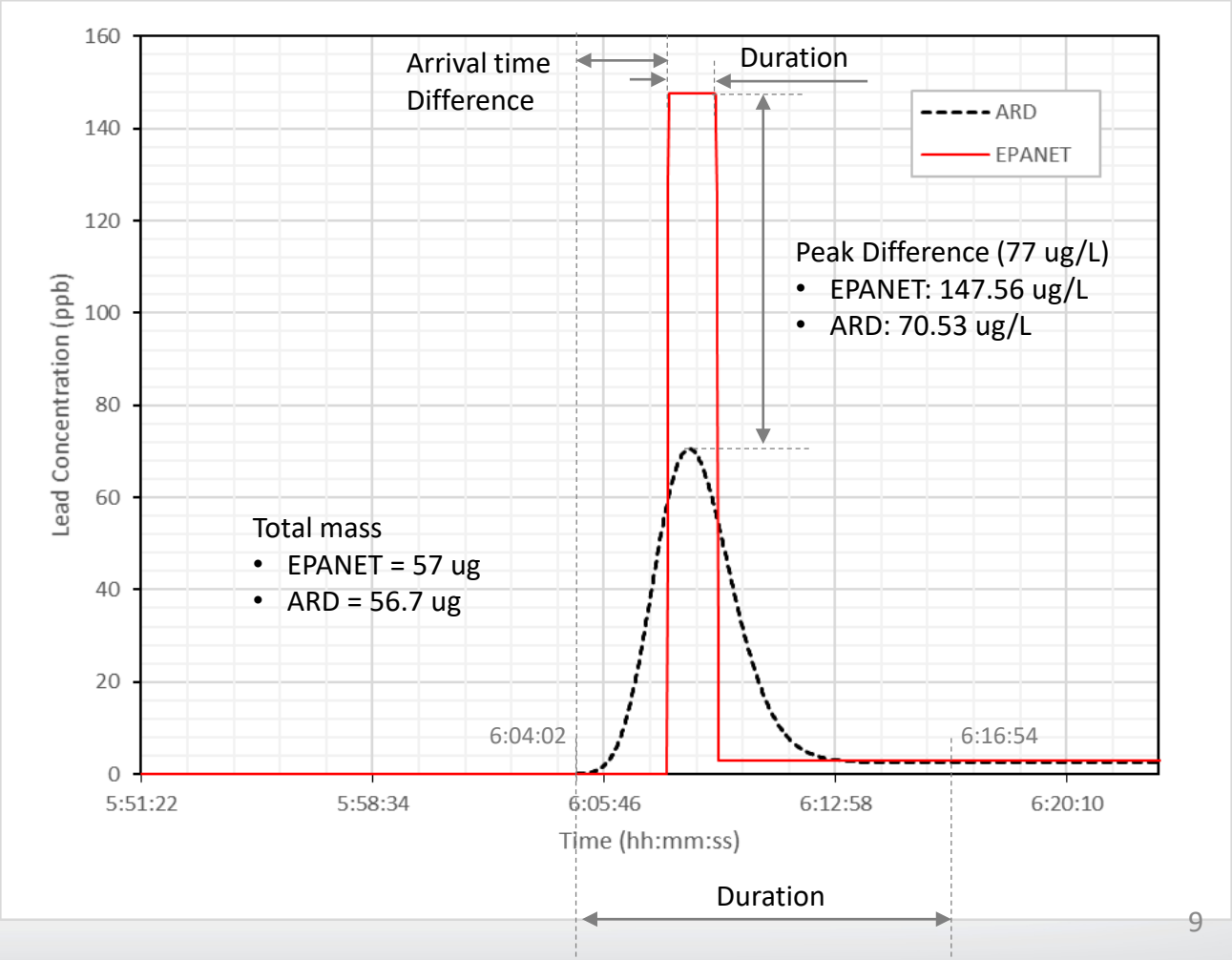
- Lead dissolution at lead service line



Contaminant transport in a pipe

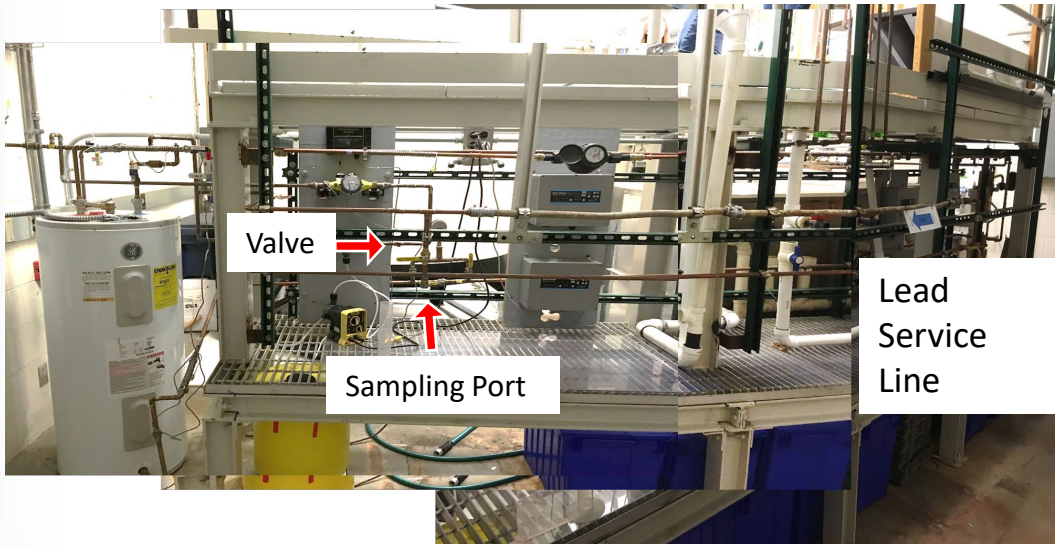


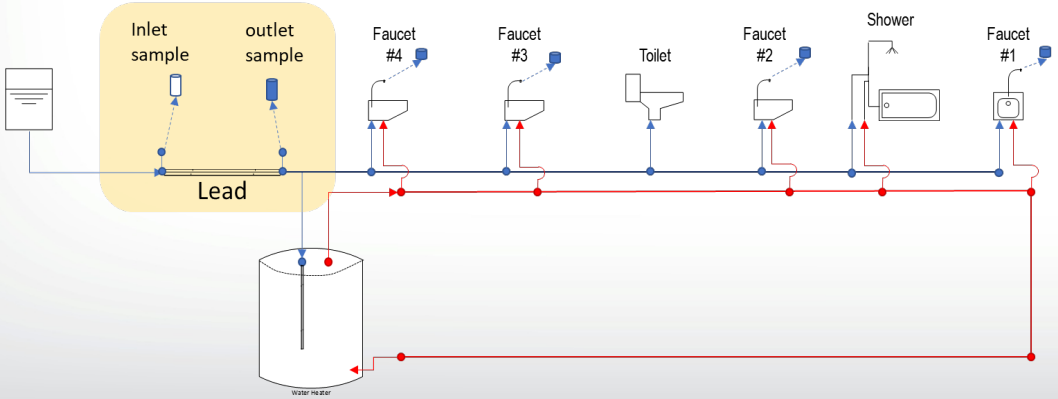
Comparison results between EPANET and EPANET-ARD model at Node 4



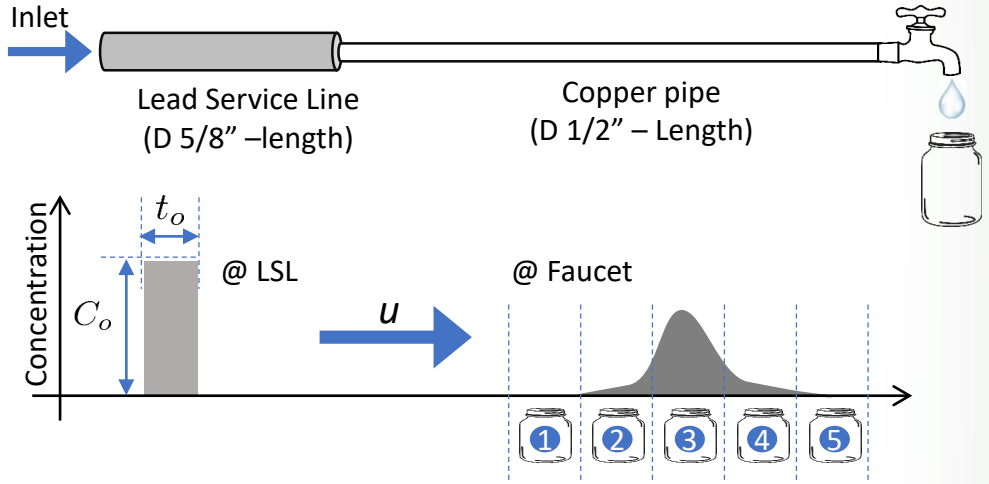
Verification of Model using Data from Home Plumbing System Simulator

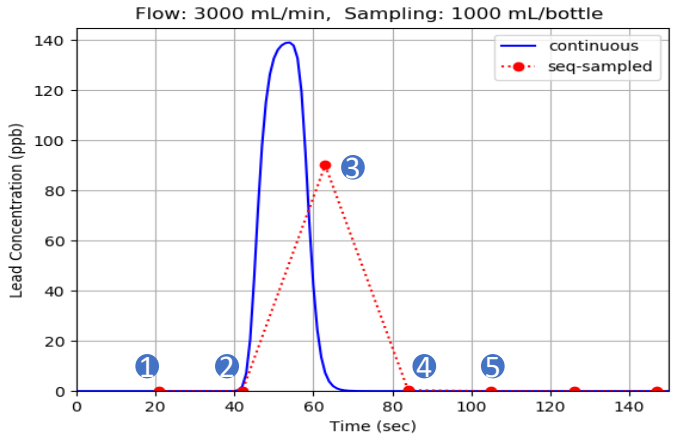
- Experimental setup
  - Home Plumbing System Simulator



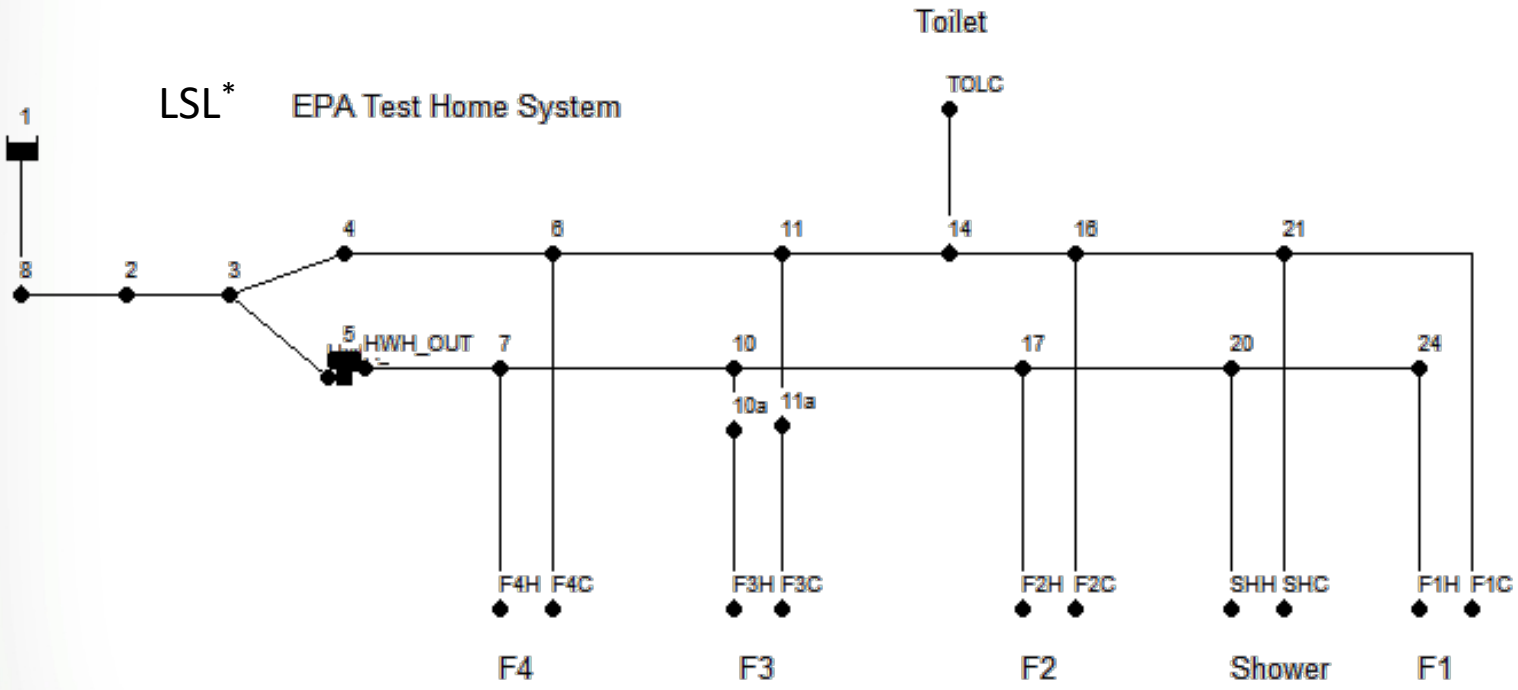


  - Sequential Sampling





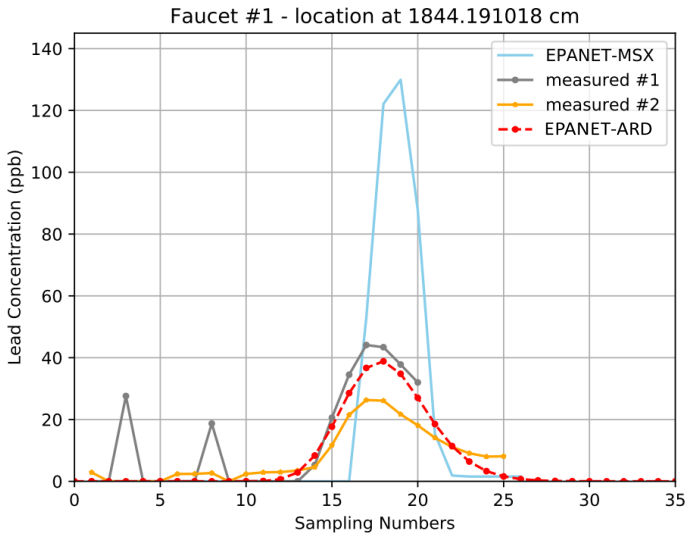
HPSS Modeling

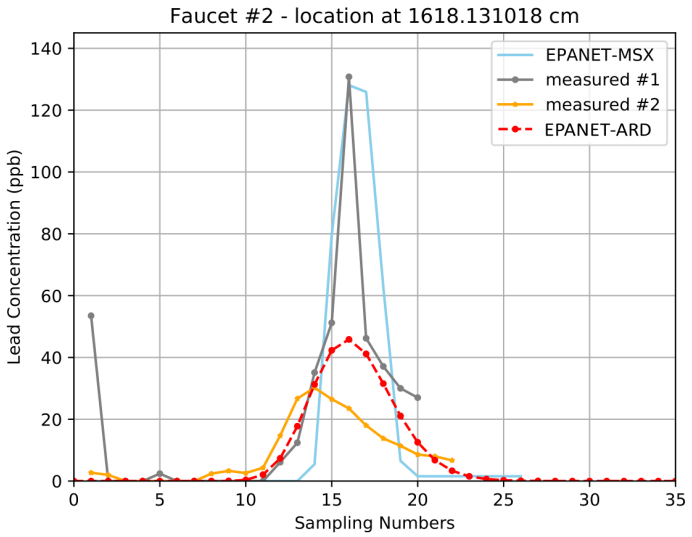


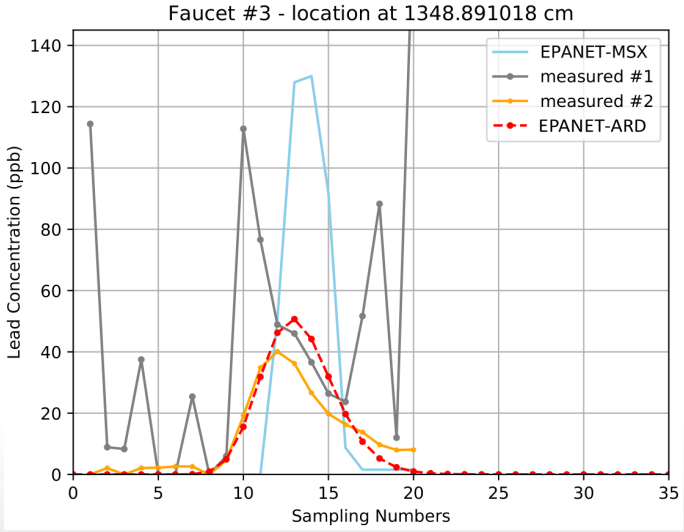
- EPANET 2.2
- Total Duration : 4 week (650 hrs)
- Hydraulic time step: 1 sec
- Quality time step: 1 sec
- Lead saturation conc: 140 ppb

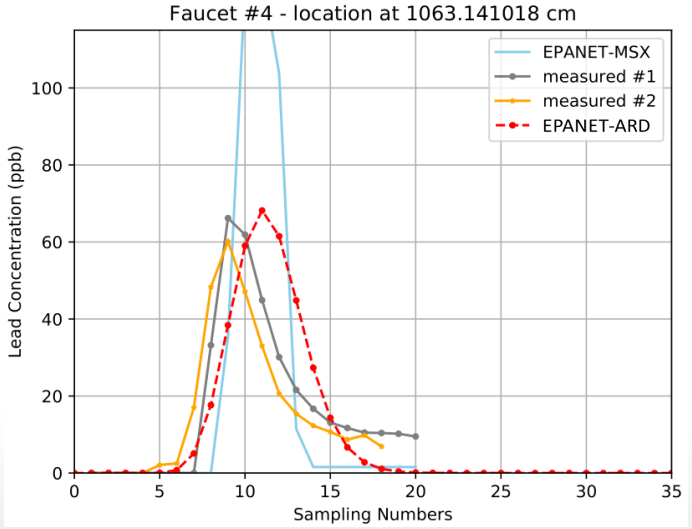
LSL: Lead Service Line

Sequential Sampling Results



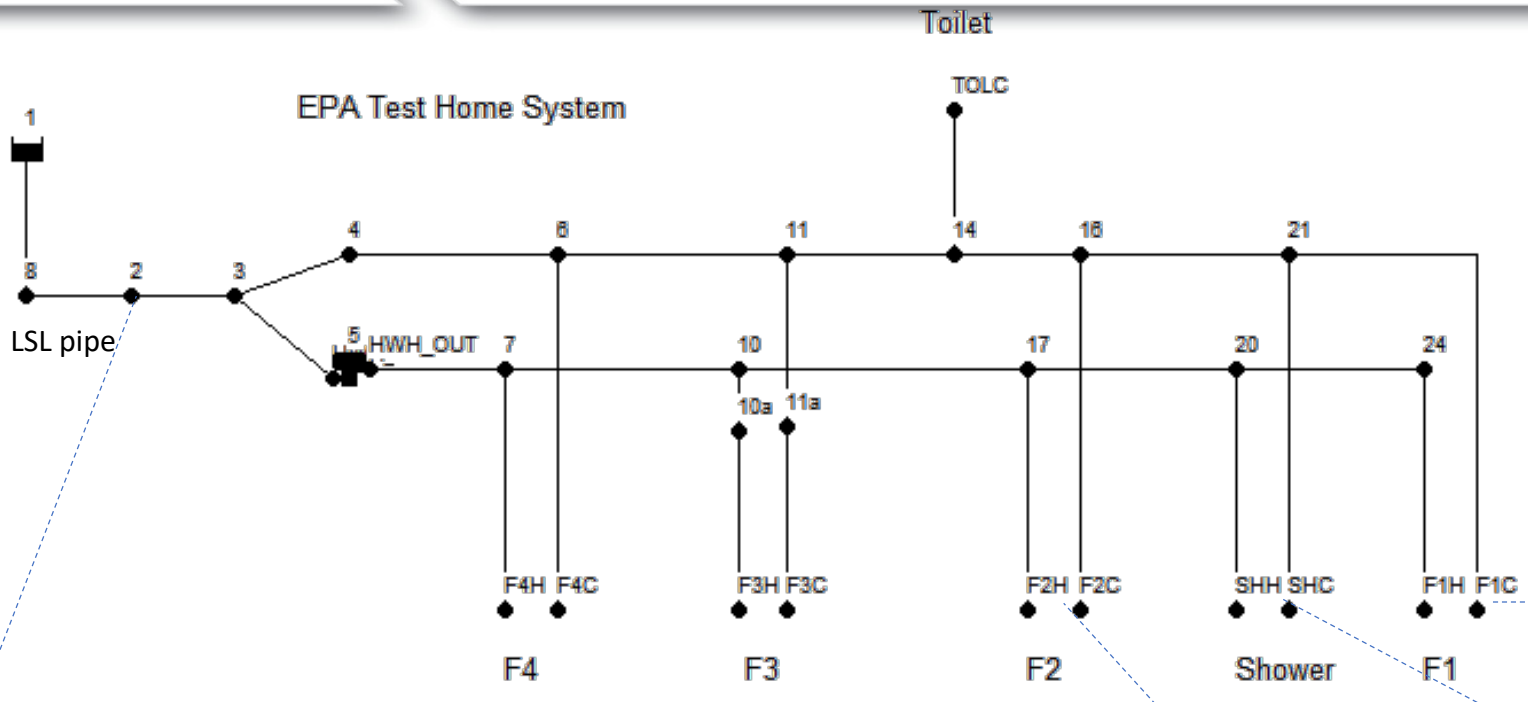




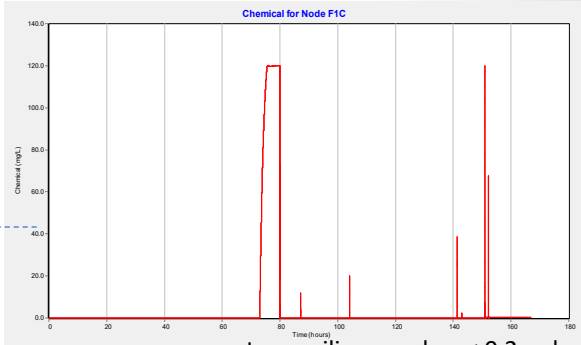


HPSS Modeling Results

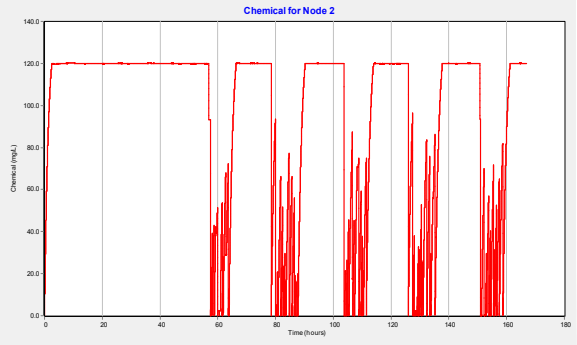
EPANET



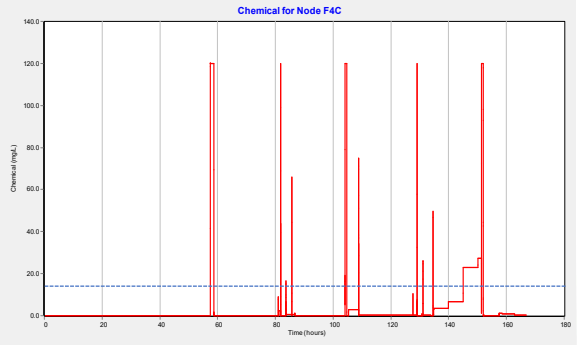
F1C: longest path from LSL



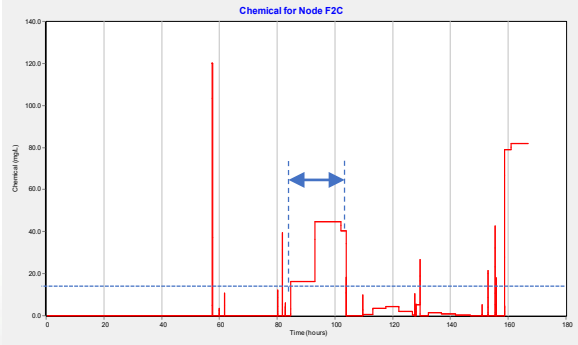
most prevailing number < 0.2 ppb



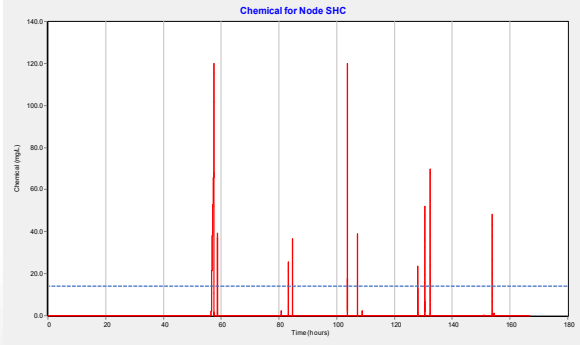
Node 2: LSL lead concentration after stagnation



F4C: closest to LSL



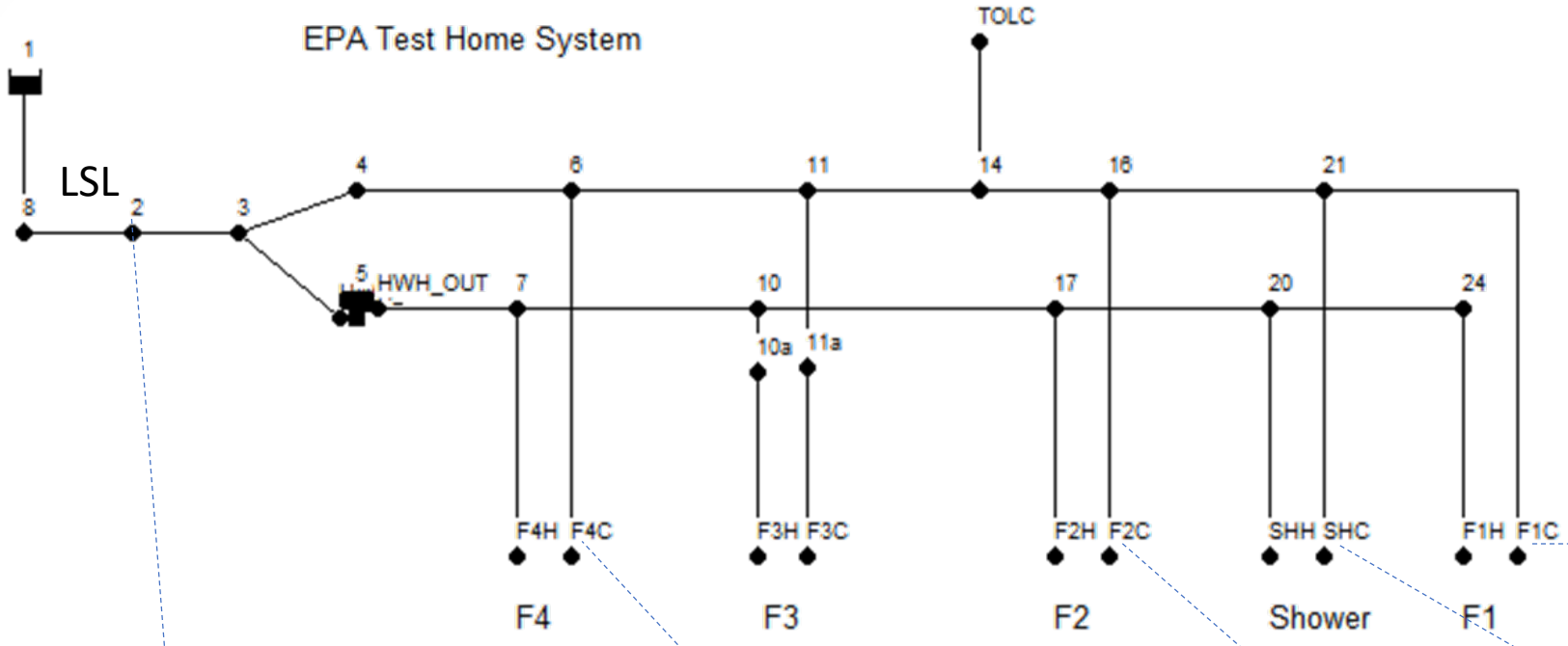
F2C



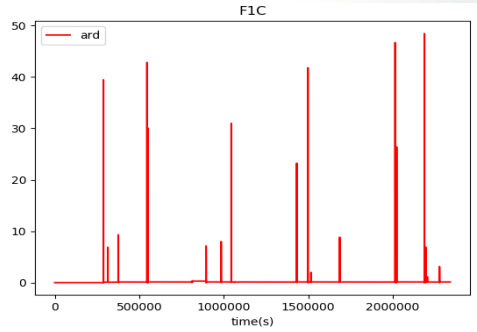
SHC: shower – highest usage

HPSS Modeling Results

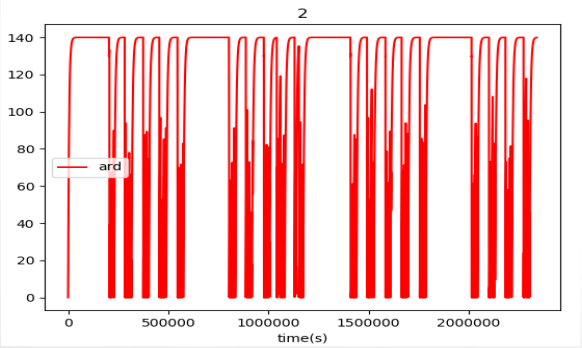
EPANET-ARD



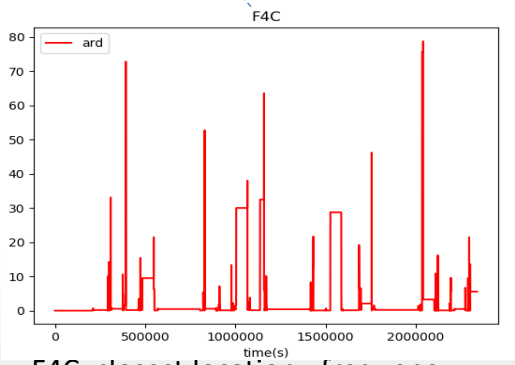
F1C: longest path



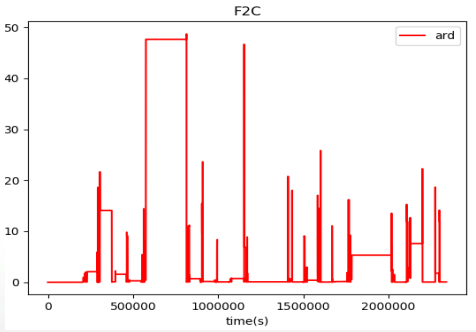
most prevailing value < 2-6 ppb



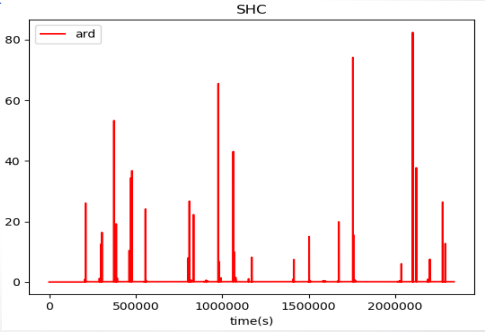
Node 2:



F4C: closest location - frequency

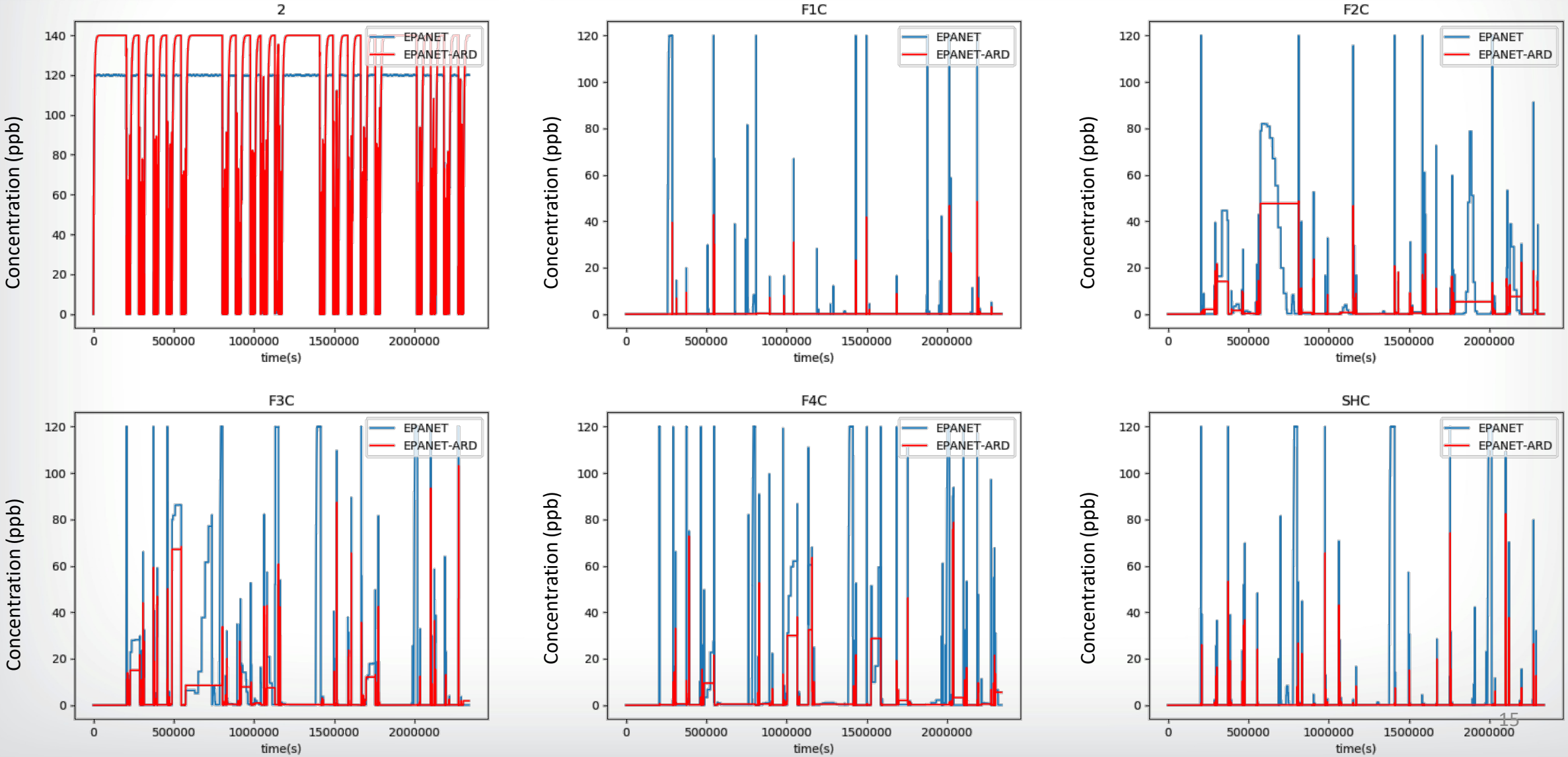


F2C



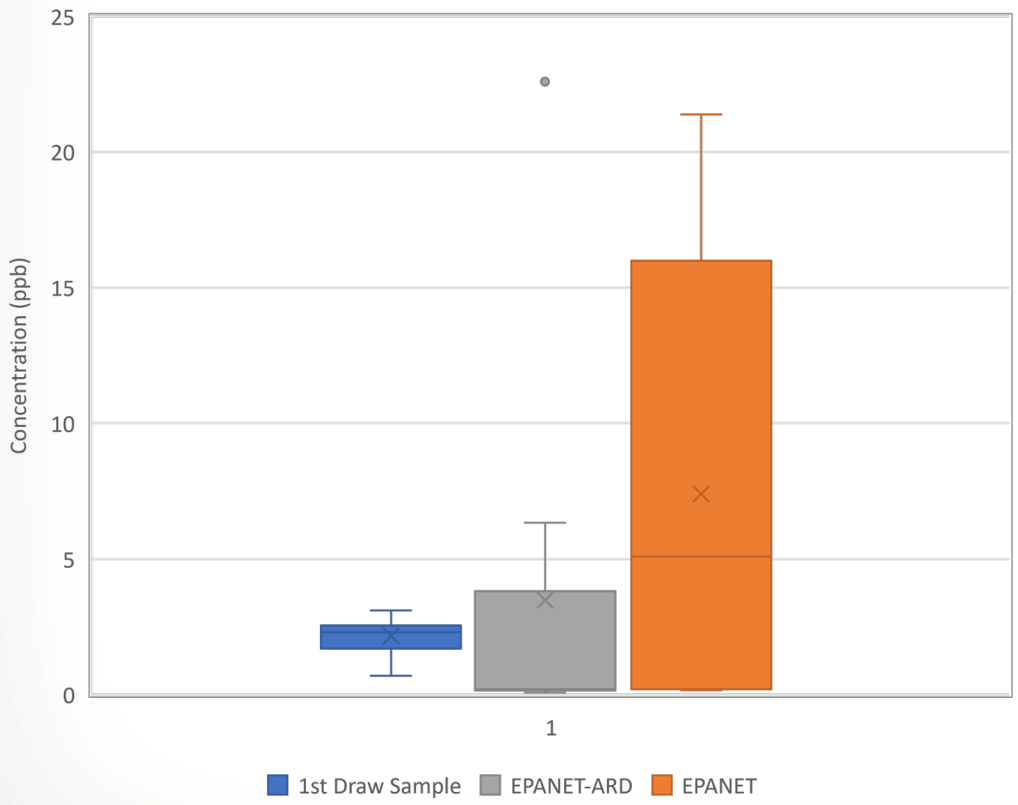
SHC: shower – highest usage

Comparison between EPANET and EPANET-ARD



Comparison to Samples

Comparison to 1st Draw Sample



- Sampling data details
  - Location: Faucet #3
  - Method: 1st draw sample with 1 Liter bottle
  - Frequency: Twice a week after 16 hours stagnation
  - Duration: 30 week periods
- EPANET-ARD has improved agreement with sampling data compared to EPANET

Conclusion

- Contaminant transport modeling of a PPS
  - PPS modeling needs to consider dispersion effects for realistic results (base concentration level, peak intensity, and duration).
- Demonstration of EPANET-ARD model
  - Lead dissolution reaction model and solute transport model were integrated with EPANET hydraulic simulation.
  - Proposed model was verified with sequential sampling data from HPSS.
- Comparison of simulation results to experimental data
  - HPSS operated to simulate a realistic usage pattern within a four-person residence.
  - EPANET-ARD model results compared favorably to HPSS sample data collected for 30 weeks of simulation.

Future Work

- Model integration to EPANET – full implementation in EPANET for PPS model
- Real home application – model application to water quality data from real home and buildings
- Further probabilistic lead exposure assessment study for public drinking water
- Application to different contaminants

Thank you !

For more information contact:

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Literature Review

- Literature Review for numerical methods for solute transport
  - 1975 Holly – numerical diffusion remains a concern for all FDM for pure advective transport
  - 1984 Baptista – dispersion dominant and advection dominant
  - 1991 Leonard – The ULTIMATE scheme and the Runge-Kutta method
  - 1994 Chaudhry and Islam – two step Lax-Wendroff scheme
  - 1996 Barry et al. - the Runge-Kutta method
  - 1998 Islam and Chaudhry – Priessman four-point implicit scheme for water quality analysis to reduce numerical diffusion.
  - 2002 Tzatchkov et al. – numerical green function
  - 2005 Zhang et al. – split-operator technique
  - 2006 Li – introduce laminar dispersion into Tzatchkov model (ADRnet)
  - 2007 Basha and Malaeb - Eulerian - Lagrangian splitting method

- Explicit finite difference technique – forward –time centered-space (FTCS)

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial X} + D\frac{\partial^2 C}{\partial X^2}$$

$$\frac{C_i^{n+1} - C_i^n}{\Delta t} = -u\frac{C_{i+1}^n - C_{i-1}^n}{2\Delta t} + D\frac{C_{i+1}^n - 2C_i^n + C_{i-1}^n}{2(\Delta x)^2}$$

- Operator Splitting Technique
  - Divide-and-conquer strategy: decompose unwieldy (systems of) PDEs into simpler subproblems and treat them individually using specialized numerical algorithms
  - Eulerian - Lagrangian splitting method (ELM)

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial X} + D\frac{\partial^2 C}{\partial X^2} \quad \rightarrow \quad \mathcal{L}(C) = C_t + uC_x - DC_{xx} = 0 \quad \rightarrow \quad \mathcal{L}(C) = \mathcal{L}_1(C) + \mathcal{L}_2(C)$$

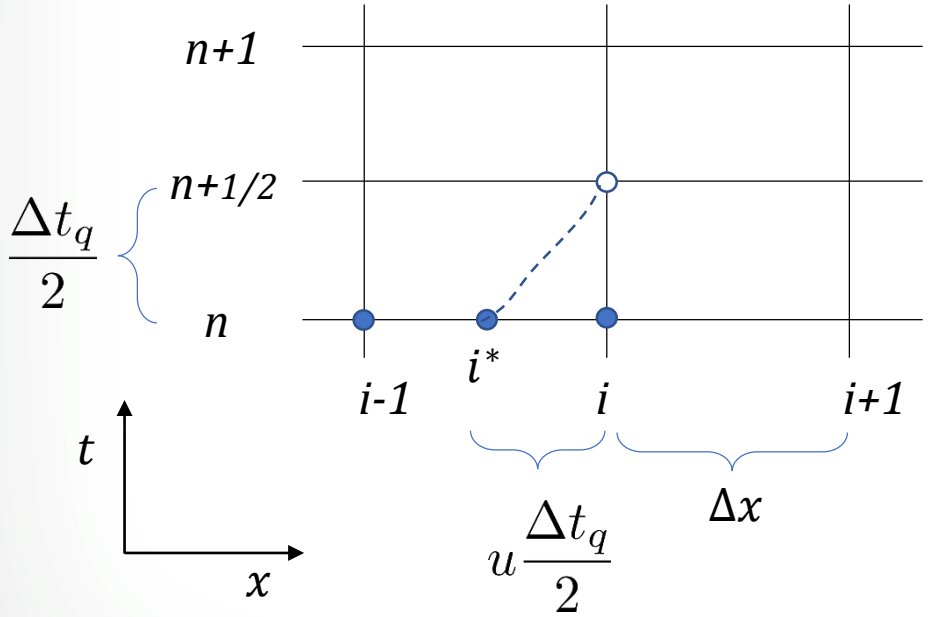
$$\frac{\partial C}{\partial t} = \frac{1}{2}\frac{\partial C}{\partial t} + \frac{1}{2}\frac{\partial C}{\partial t}$$

$$\frac{1}{2}\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} \qquad \mathcal{L}_1(C) = \frac{\partial C}{\partial t} + 2u\frac{\partial C}{\partial x} = 0$$

$$\frac{1}{2}\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad \mathcal{L}_2(C) = \frac{\partial C}{\partial t} - 2D\frac{\partial^2 C}{\partial x^2} = 0$$

Advection Step

$$\mathcal{L}_1(C) = \frac{\partial C}{\partial t} + 2u\frac{\partial C}{\partial x} = 0$$



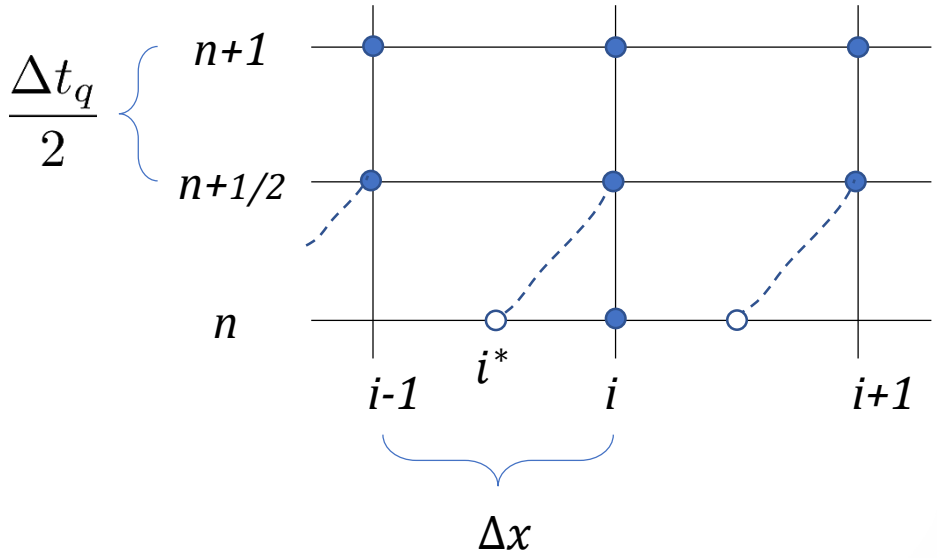
Appling Interpolation method

$$\frac{C_i^{n+1/2} - C_{i^*}^n}{\Delta t} = -u \quad \rightarrow \quad C_i^{n+1/2} = C_{i^*}^n - u\Delta t$$

u = velocity

Dispersion Step

$$\mathcal{L}_2(C) = \frac{\partial C}{\partial t} - 2D\frac{\partial^2 C}{\partial x^2} = 0$$



Appling Crank-Nicolson method

$$\frac{C_i^{n+1} - C_i^{n+1/2}}{\Delta t} = \frac{D}{2(\Delta x)^2}\left((C_{i+1}^{n+1} - 2C_i^{n+1} + C_{i-1}^{n+1}) + (C_{i+1}^{n+1/2} - 2C_i^{n+1/2} + C_{i-1}^{n+1/2})\right)$$