EPA
United States
Environmental Protection
Agency

Monitoring and Operating Internal Building Drinking Water Distribution Systems to Maintain Drinking Water Quality

Darren A. Lytle, PhD, PE, and
Simoni Triantafyllidou, PhD

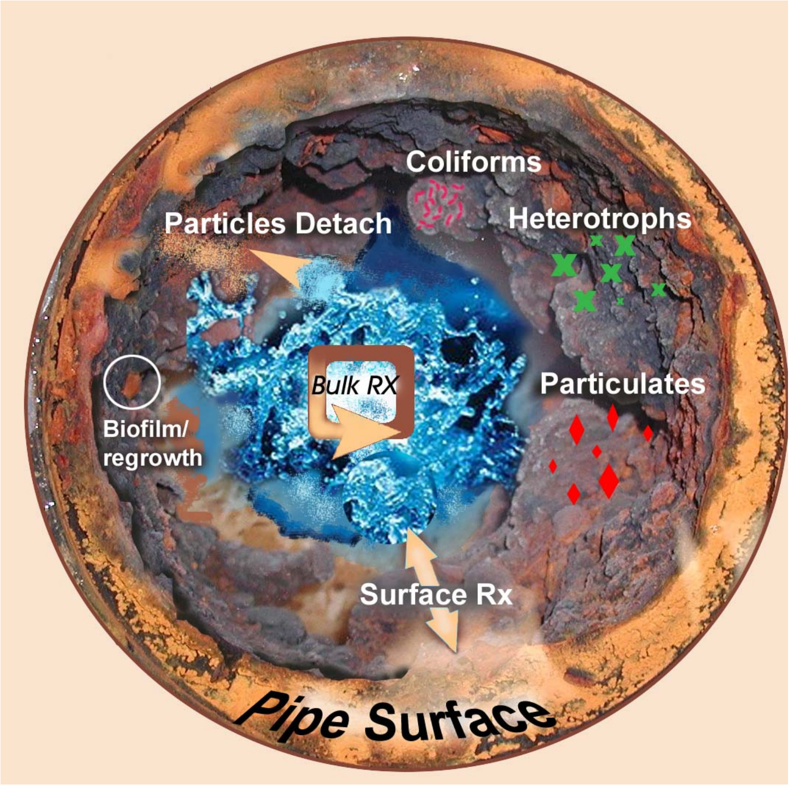
U.S. Environmental Protection Agency

United States Environmental Protection Agency

EPA Region 3 RARE Project
Monitoring and Operating Building Water Plumbing Systems to Maintain Drinking Water Quality

- ✓ Establish adequate sampling points for hot and cold water collection (faucets and shower heads) that represent spatial variability in water.
- ✓ Develop sampling protocol to monitor water quality from the targeted sampling points.
- ✓ Identify critical water quality parameters to be monitored for chemical and microbiological analyses in water.
- Apply water quality and flow models such as EPANET to building plumbing systems.
- ✓ Develop practical guidance on the application of copper-silver ions to premise plumbing for *Legionella* control (unintended consequences)
- ✓ Perform field sampling of a large buildings, and conduct targeted bench-scale copper solubility and disinfection studies.

Plumbing in Buildings can be Very Complex



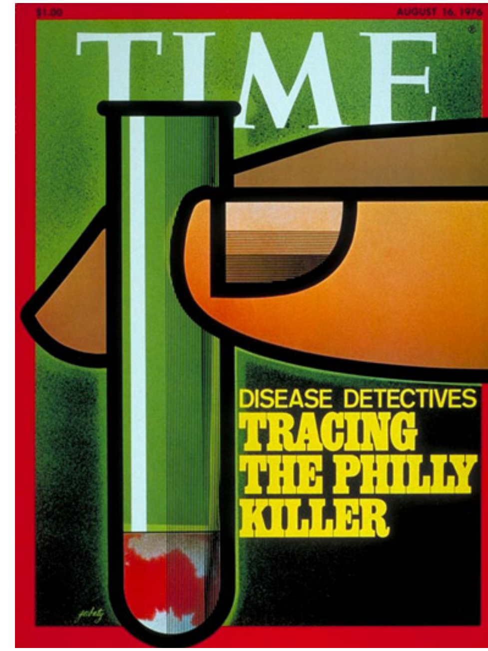
- Complicated plumbing networks
- Multiple plumbing materials
- Hot and cold water
- Dead ends
- Storage reservoirs
- Long residence time
- Dead zones
- Difficulty maintaining disinfectant residual
- Water quality changes
- Expansion

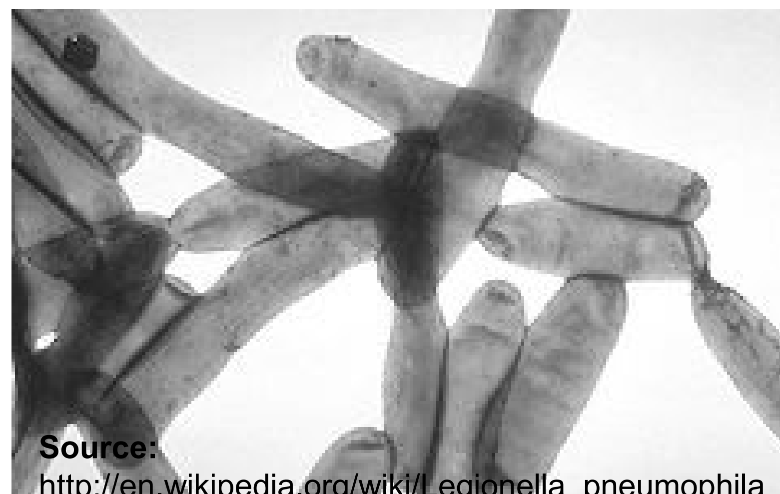
EPA United States Environmental Protection Agency

Legionella is an Opportunistic Pathogen

Legionella pneumophila Serogroup 1

- Legionellosis, Pontiac fever, Legionnaires' disease
- Pneumonia, and can even lead to death of susceptible individuals with risk factors
- Primary cause of waterborne disease in the United States
- No enforceable regulations
  - MCLG=0, TT, listed on CCL3
- No consensus on endpoints for remediation





Source: http://en.wikipedia.org/wiki/Legionella_pneumophila

Secondary Treatment Options for Legionella Control in Buildings

- Chlorine
- Chlorine dioxide
- Monochloramine
- UV Light
- Copper/Silver Ionization

- Ozone Addition
- Heat and Flush
- POU
- Hyperchlorination
- Superheating

  (Usually only during outbreak)

United States Environmental Protection Agency

Preventative and Remediation Strategies
Monochloramine

- Formed from mixing ammonia and chlorine
- Normally dosed between 1 and 1.4 mg/L
- Monochloramine forms at pH 7.5-9
- Often used as a secondary disinfectant to chlorine
- Laboratory studies showed wide range of inactivation under varying water quality conditions
- Efficacy increases with increased temperature
- Several studies concluded chloramine is more effective at penetration of biofilms than chlorine

United States Environmental Protection Agency

Pros and Cons: Monochloramine

- Pros
  - Relatively inexpensive
  - Effective against most bacteria/ virus
  - Fewer DBPs than chlorine
  - Provides residual disinfection; less reactive oxidant and hangs around, stable
  - Penetrates biofilm better
- Cons
  - Generated on site and may be complicated, dosing control, ammonia
  - Even less effective than chlorine against protozoa
  - Nitrification potential (nitrite, pH drop, corrosion, taste, odor)
  - Not effective against some other bacteria; increased populations in *Mycobacterium* numbers
  - Potential disinfection by-products (nitrosamines [NDMA]); Maximum Residual Disinfectant Level (MRDL) of 4.0 mg Cl_2/L
  - Taste and odor, corrosion, downstream interactions (plastics)

Ohio Hospital Case Study 1

Monochloramine Treatment

EPA United States Environmental Protection Agency

Monochloramine System

Ohio Regulatory Requirements

- **Monochloramine:** Monitor the level of monochloramine collected at the entrance to the distribution system on a weekly basis (<4 mg Cl_2/L).
- **Nitrate/nitrite** (Entry Point): Monitor the level of nitrate/nitrite weekly when water temperatures are equal to or greater than 18 degrees Celsius and quarterly when water temperatures are less than 18 degrees Celsius (< 1 mg N/L NO_2 and < 10 mg N/L NO_3).
- **Lead and Copper** (Tap Monitoring): The number of lead and copper collected depends on the daily population served (20 locations).
- **Disinfection By-Products (DBPs):** TTHM and HAA5 (Distribution): Routine monitoring for TTHMs and HAAS.

Monochloramine System
USEPA Study and Self-Monitoring

Self-Monitoring and USEPA Study Analyses. In addition to OEPA requirements, the Hospital identified additional water quality monitoring needs.

Distribution system off-site analysis (US EPA):

- Metals (ICP-MS/AES)
- Phosphate, Ammonia, Nitrite, Nitrate, Total organic carbon, Total nitrogen
- Alkalinity, Chloride
- Legionella, Pseudomonas aeruginosa
- Heterotopic plate counts, Nucleic acid based molecular analysis

Distribution system on-site analysis (Hospital operator):

- Ammonia
- Nitrite
- Nitrate
- Monochloramine

Monochloramine System
USEPA Study and Self-Monitoring

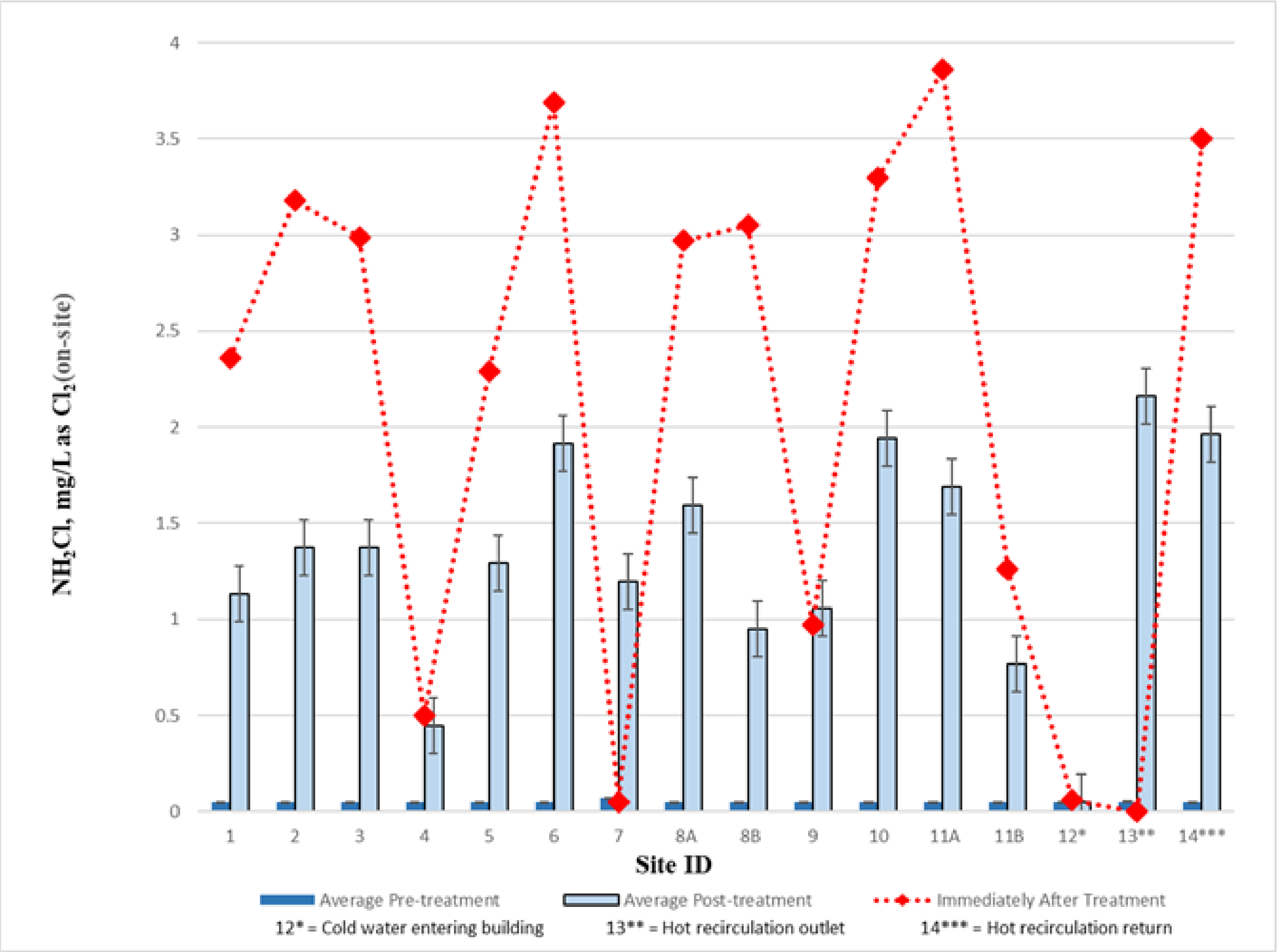
- **Heterotrophic Plate Count (HPC) monitoring:** Distribution point once per month for 6 months in the distribution system then reduced to quarterly.
- **Free Available Ammonia:** Monitor the level of free available ammonia collected at the entrance to the distribution system daily.
- **Chlorine to Ammonia Ratio (bench scale study):** The chlorine to ammonia feed ratio shall be established based on a bench scale study using WRF Optimization of Chloramination Treatment.

Monochloramine System
USEPA Sampling Plan

16 sites (entry to building, hot water after treatment, hot water return, 11 hot water faucets, 2 shower heads) were sampled on a monthly basis without flushing in the following order:

- 0.5L –Collected for onsite analysis of temp, DO, pH, NH_4, NO_2, FCl_2, NH_2Cl, and remaining volume for offsite analysis (Metals, organic Carbon, Nitrogen, NH_4, NO_2, NO_3, PO_4, TTHM, ALK)
- ~15mL --ORP, pH, Temp, Conductivity measured at sampling site
- 1L –Collected for microbial culture (*Legionella*, HPC, *Pseudomonas*)
- 1L –Collected for microbial culture (NTMs)
- 1L –Collected for DNA
- 1L –Collected for DNA
- ~15mL --ORP, pH, Temp, Conductivity measured at sampling site

Monochloramine



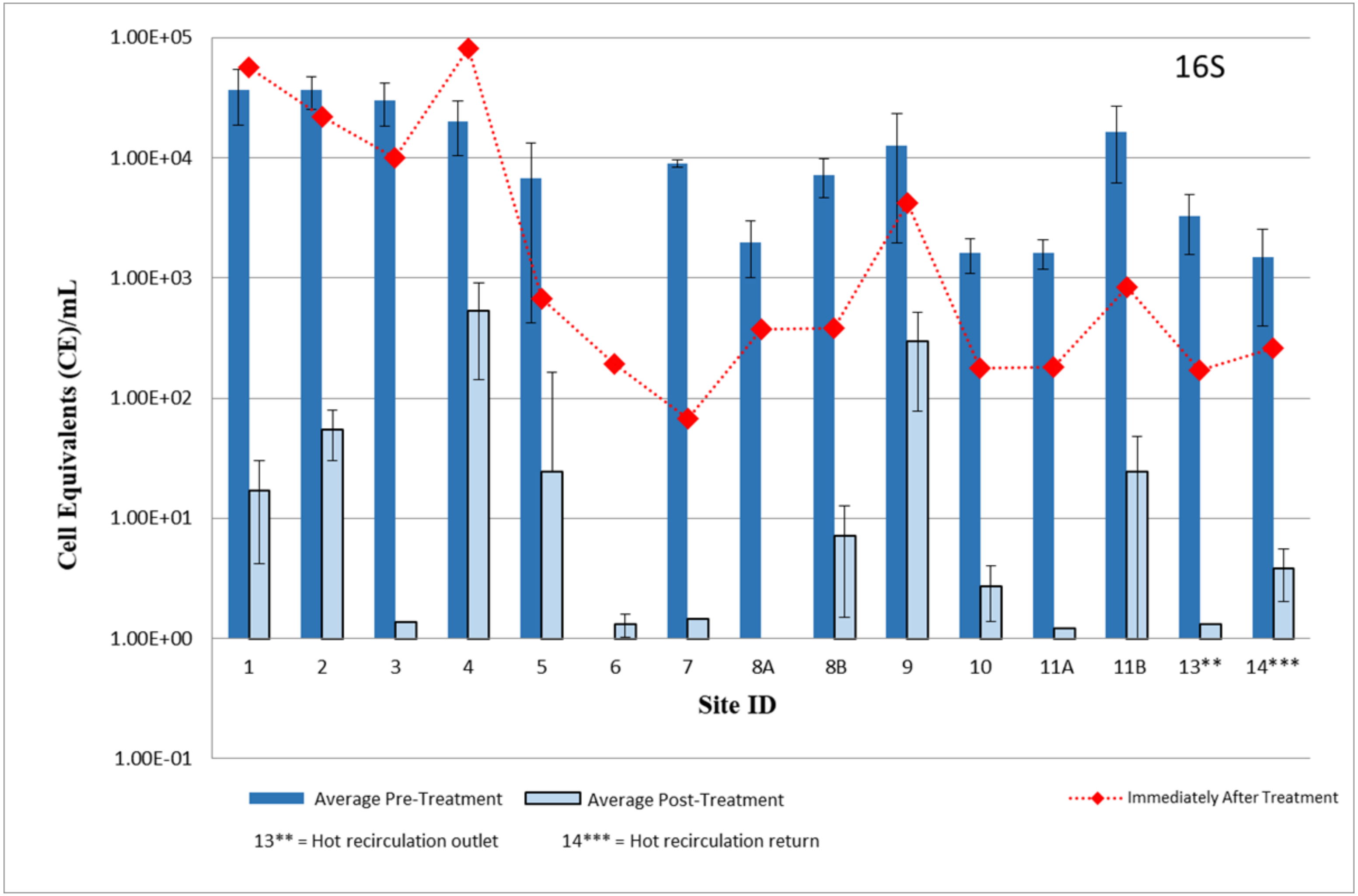
United States Environmental Protection Agency

Legionella Culture Results

	Legionella Culture	
Sampling Site ID	Positives Pre-chloramination	Positives Post-chloramination
1	6/6 (100)	0/7 (0)
2	5/5 (100)	1/6 (17)
3	7/7 (100)	0/7 (0)
4	6/6 (100)	1/7 (14)
5	6/7 (86)	0/7 (0)
6	2/7 (29)	0/6 (0)
7	0/6 (0)	0/7 (0)
8A	4/7 (57)	0/7 (0)
8B	3/7 (43)	0/7 (0)
9	1/5 (20)	1/7 (14)
10	5/7 (71)	0/5 (0)
11A	3/6 (50)	0/7 (0)
11B	6/6 (100)	3/6 (50)
13	6/7 (86)	0/7 (0)
14	5/7 (71)	0/7 (0)
Totals	65/96 (68)	6/100 (6)

Legionella spp.*

qPCR results

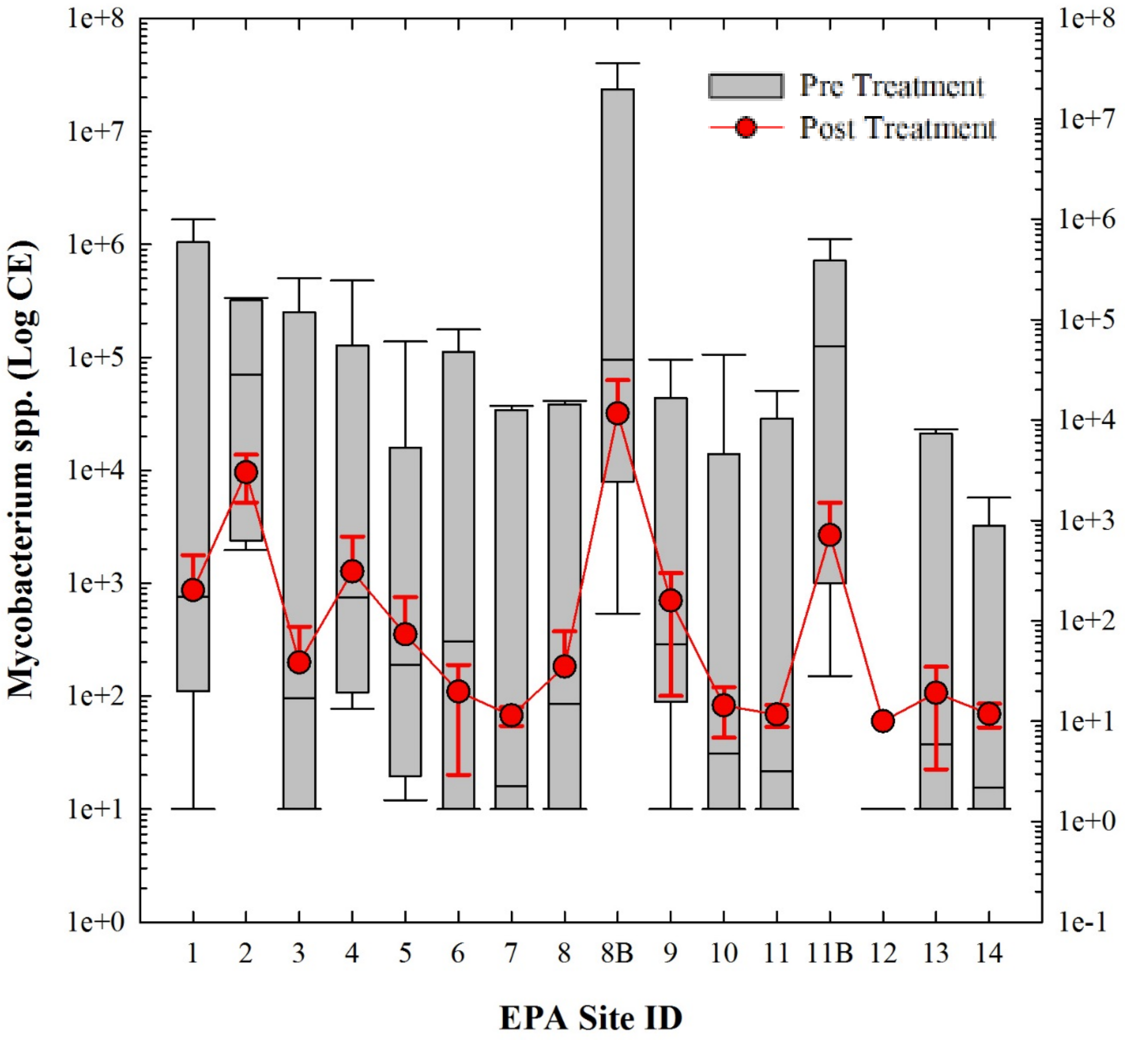


* Legionella pneumophila SG1

Case Study: NTM by Site

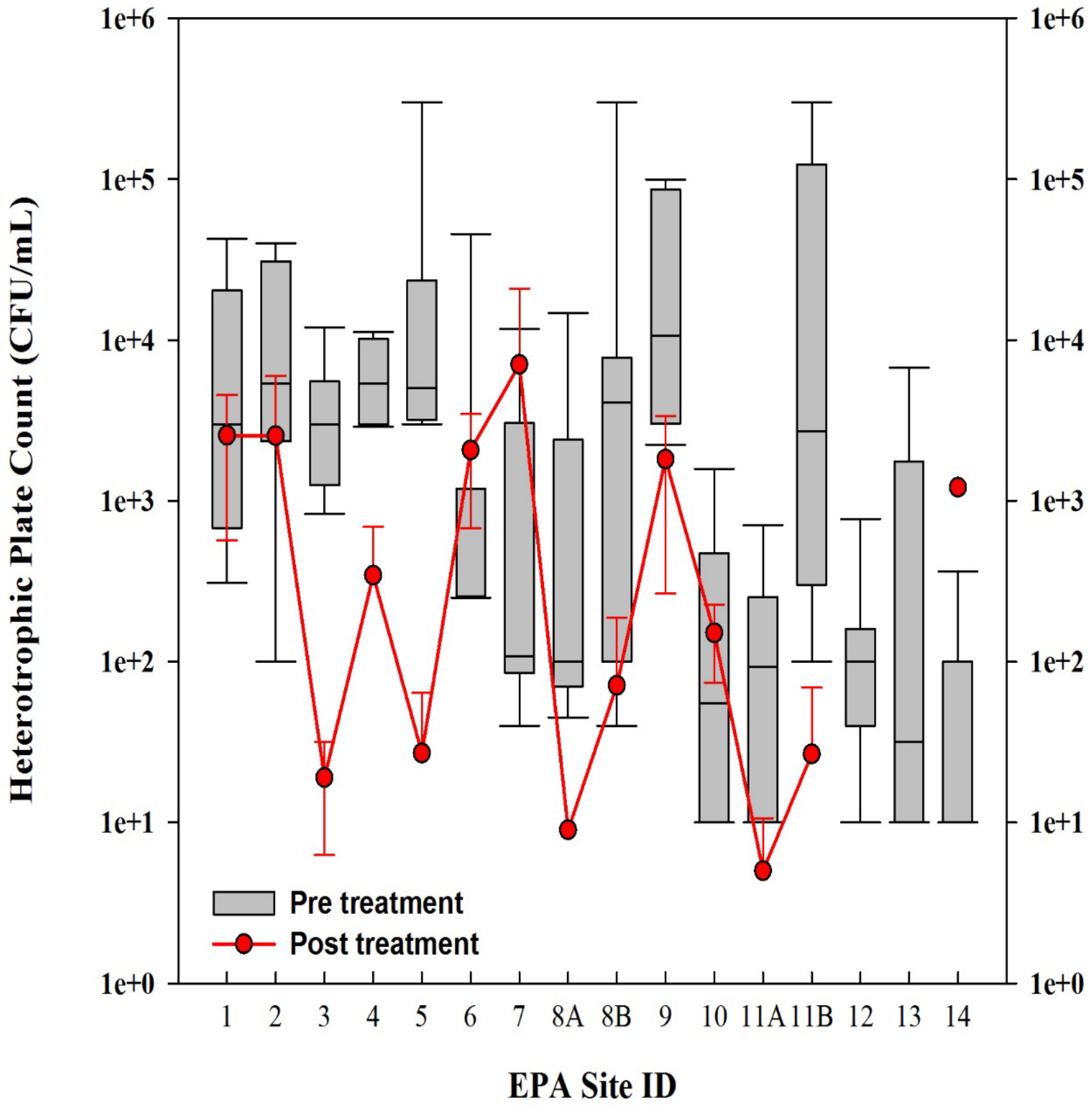
Monochloramine Site

- Cold water levels very low
- Distribution system shower heads were consistently higher
- MA/MI qPCR assays were negative



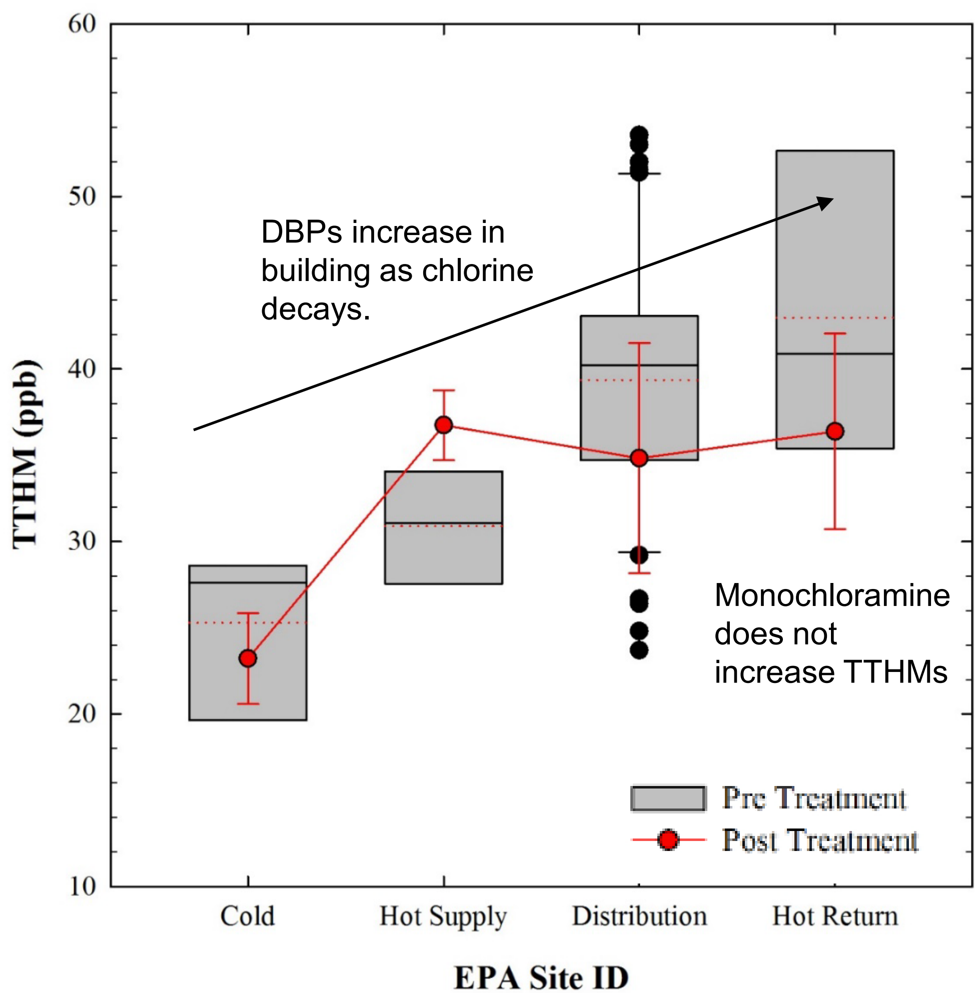
HPCs

- Sites 1-5
- Showers
- Generally lower overall
- Hot supply and cold influent BDL

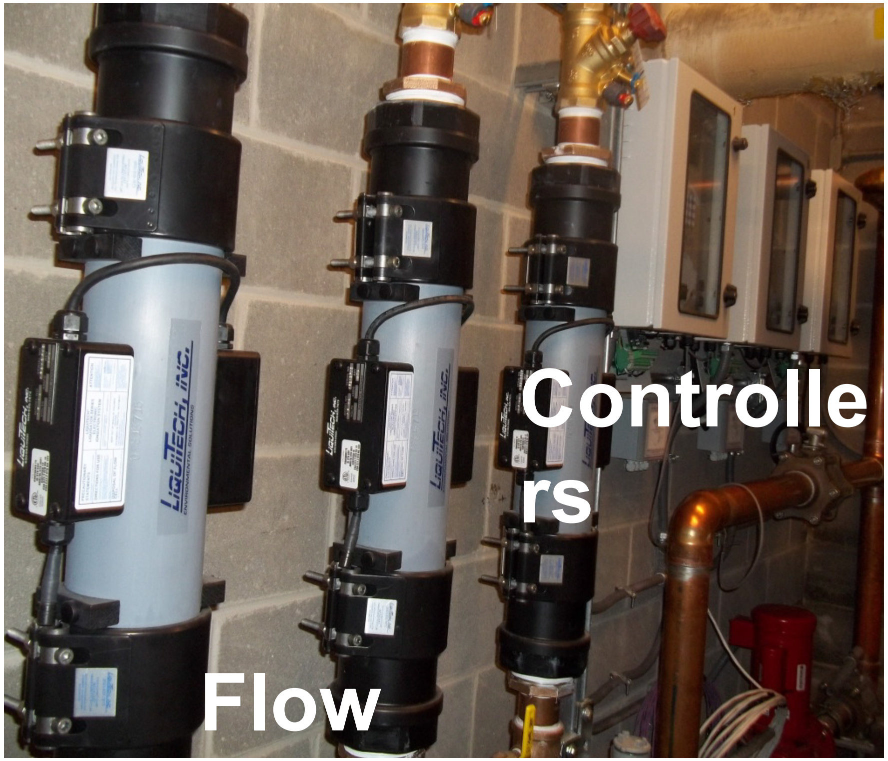


Disinfection By-Products:TTHMs

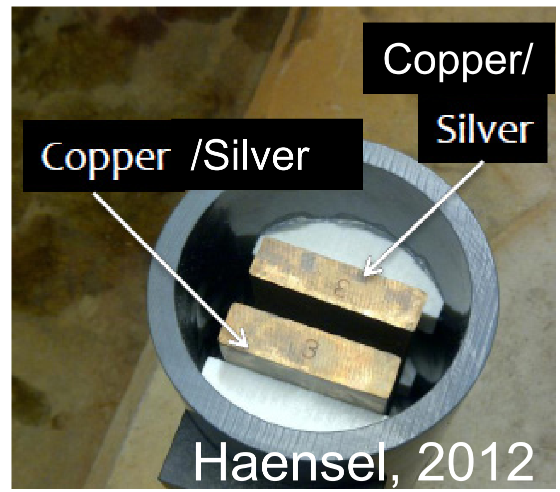
- Increase in TTHM through the heat exchanger and distribution system
- 0.080 mg/L MCL
- Free chlorine versus monochloramine



Ohio Case Study 2: Copper-Silver Ionization (CSI)



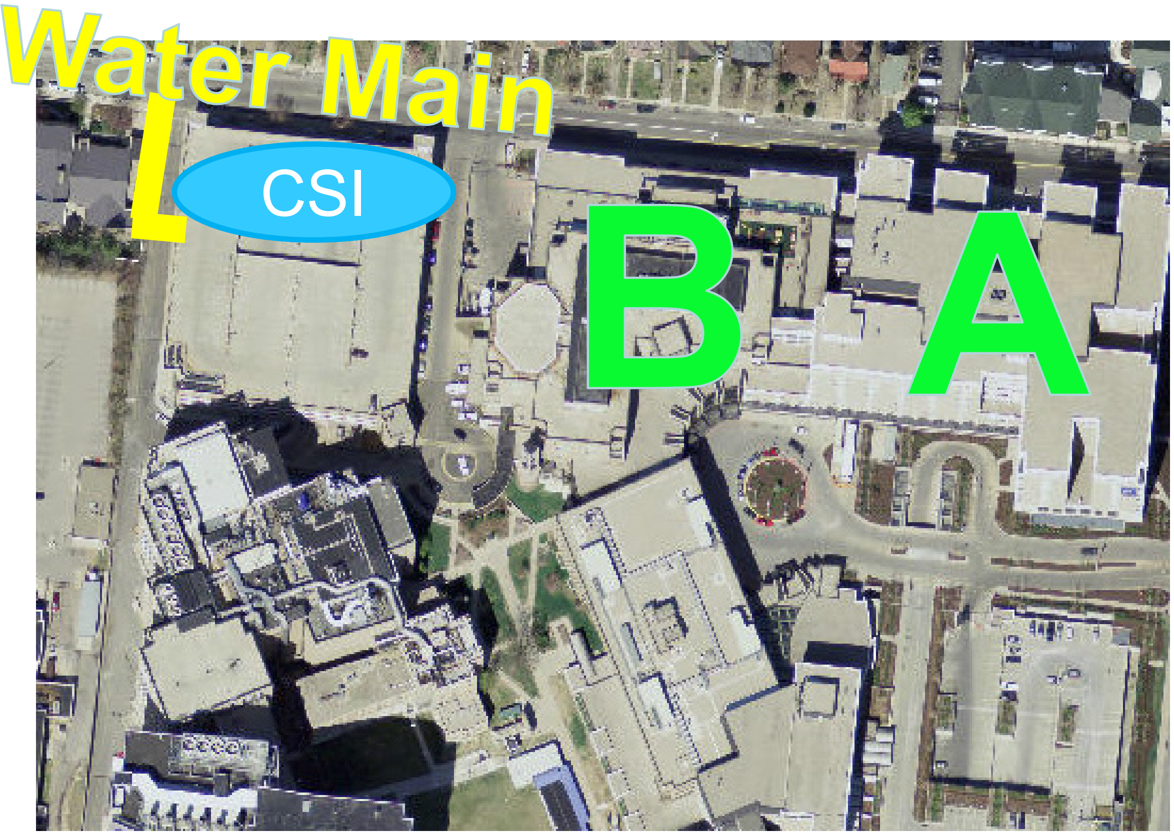
Unused Flow cell



Used Flow Cell

- Adds copper ions (Cu^{+2}) and silver ions (Ag^{+}) to water →biocides
- Only a fraction of copper and silver will remain in free ionic form depending on water chemistry

Case Study 2: Large Hospital in Ohio



Treated surface water

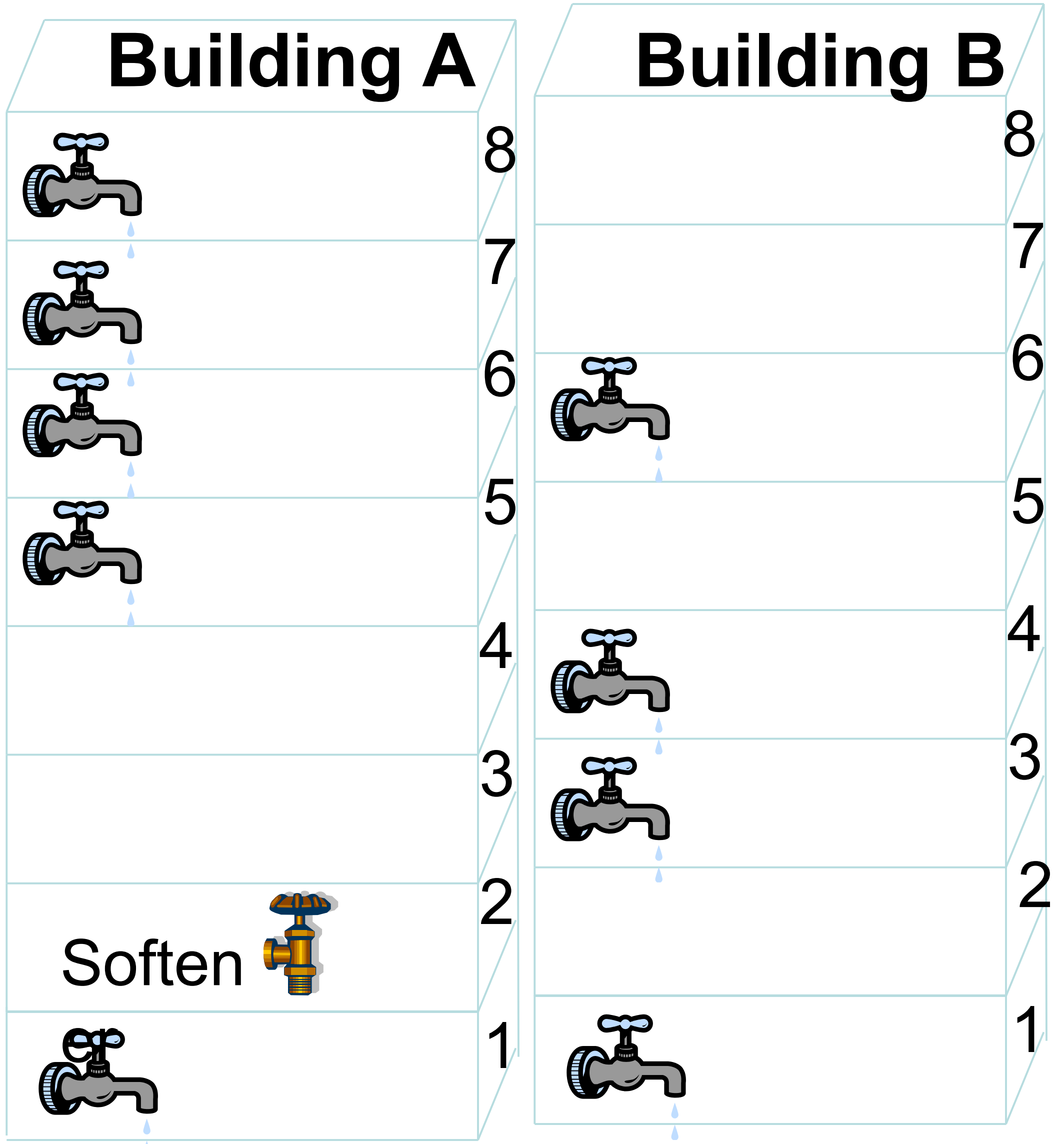
- pH 8.6
- Alkalinity 75 mg/L as $CaCO_3$
- Free chlorine 1 mg/L

- A & B are patient buildings supplied with the CSI-treated water
- First hospital in Ohio to be regulated under the Safe Drinking Water Act due to in-building water treatment installed in 2014
- Sampling study before/after CSI start-up (1.5 years total)

Sampling - Water Chemistry/ Inorganics

General
- pH
- Temp.
- Chlorine

Inorganics
- Cu
- Ag



Variability in bulk water:

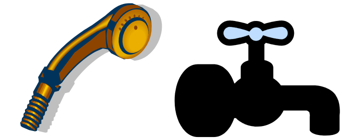
Buildings

Floors

First Draw vs Flushed Water

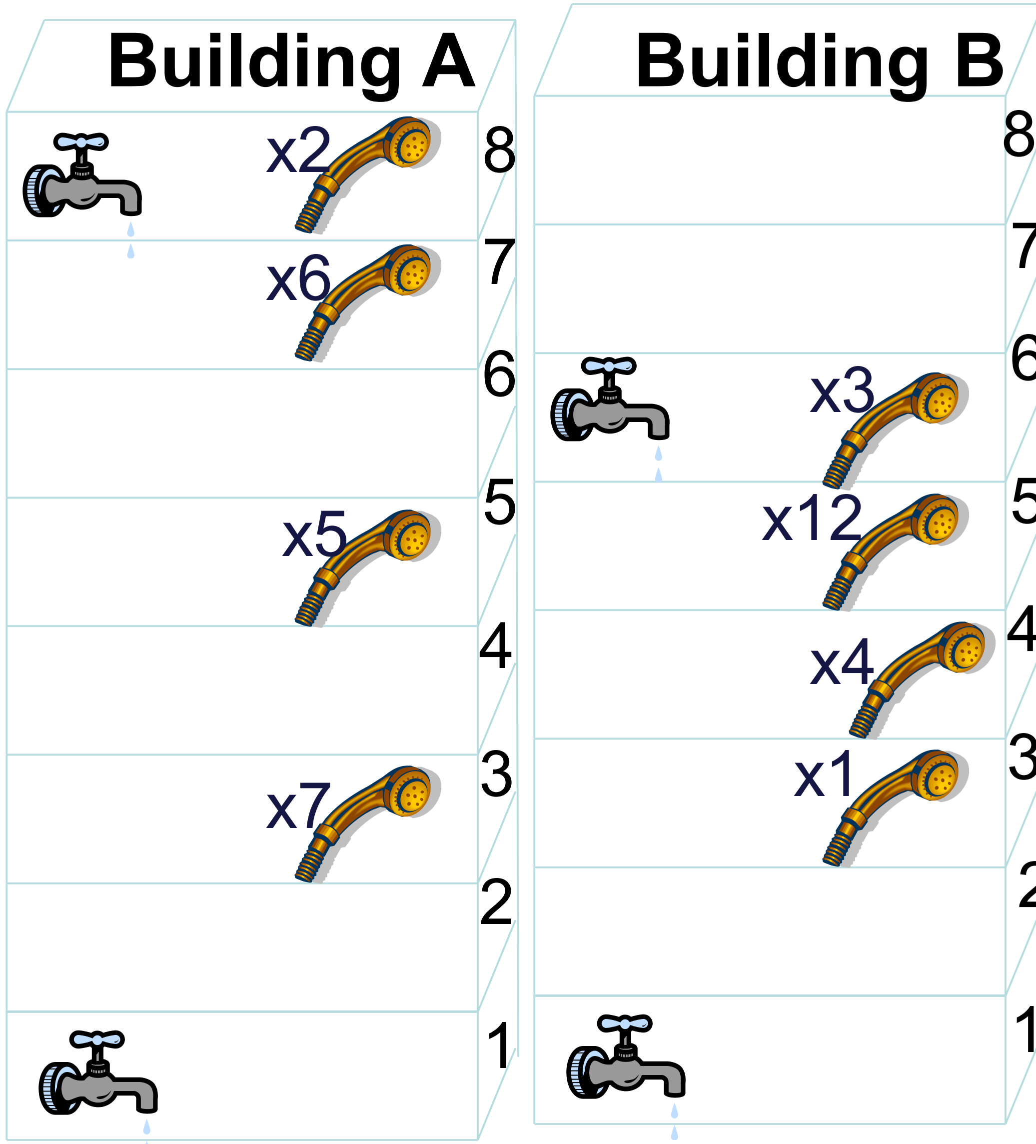
Hot vs Cold Water

Sampling – Microbiology



Microbes

- *Legionella pneumophila* sg1 qPCR
- Biofilm community composition



Variability in biofilm and bulk water between:

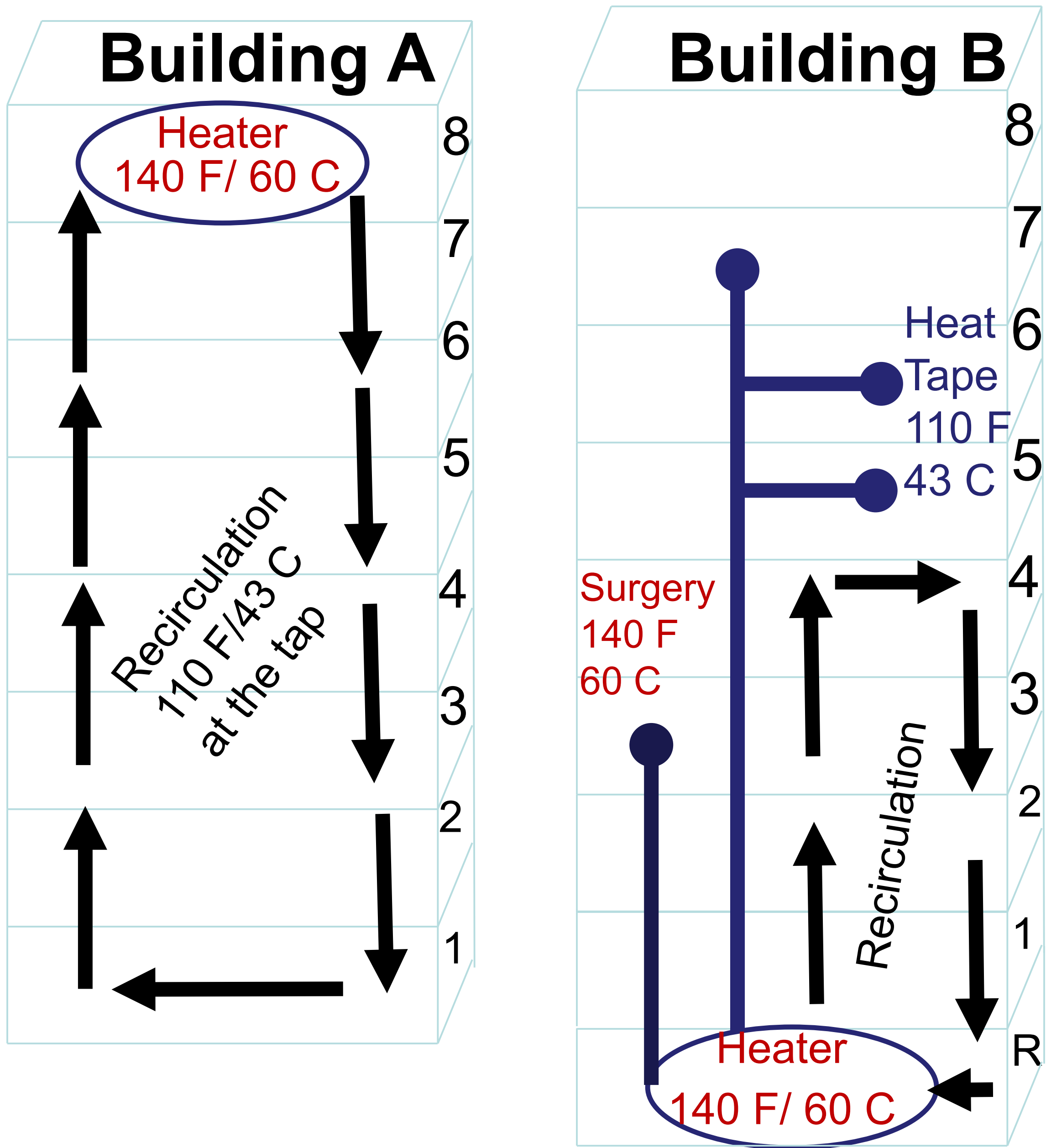
Buildings

Floors

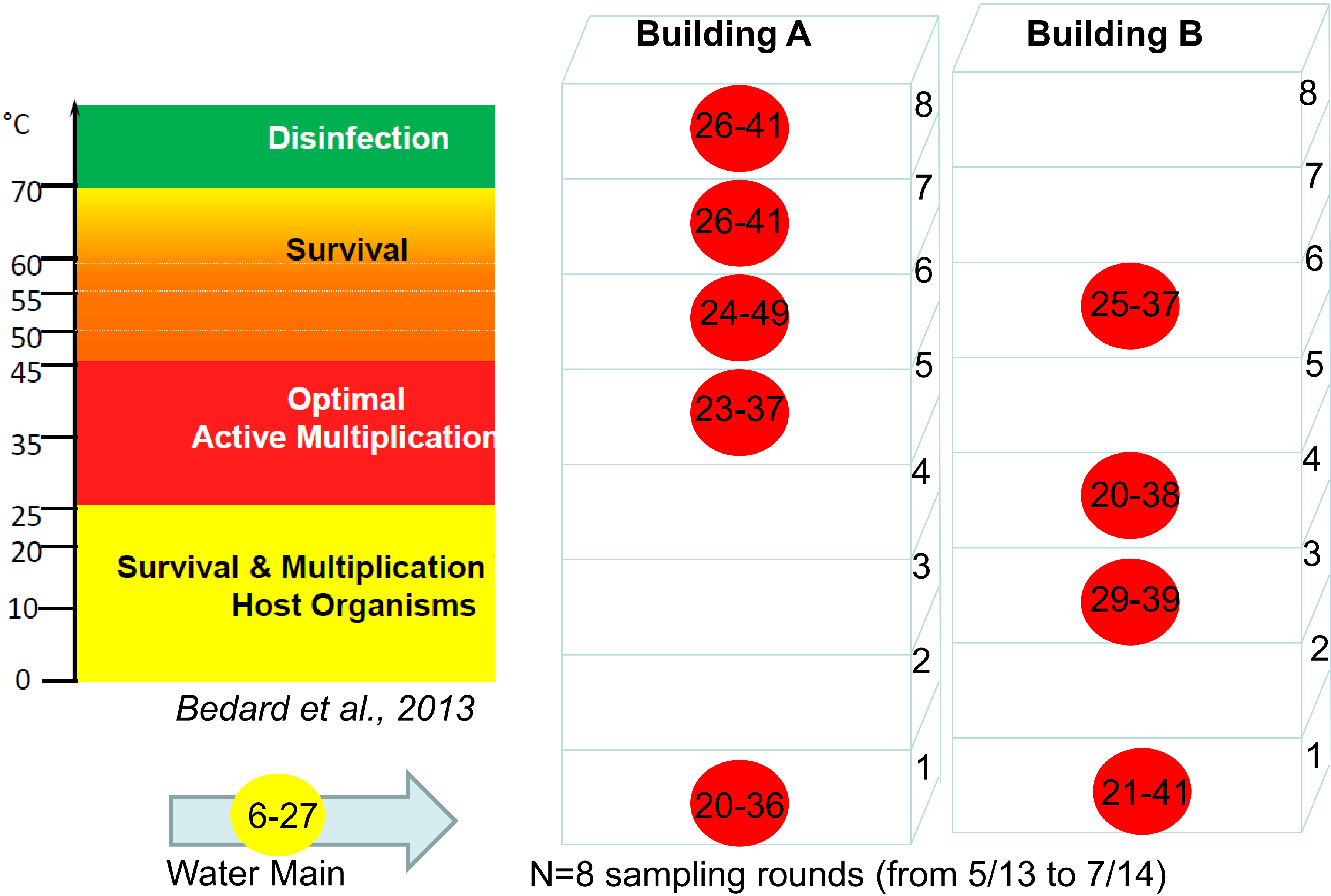
First Draw vs Flushed Water

Hot vs Cold Water

Hot water temperature goals from Plumbing Code

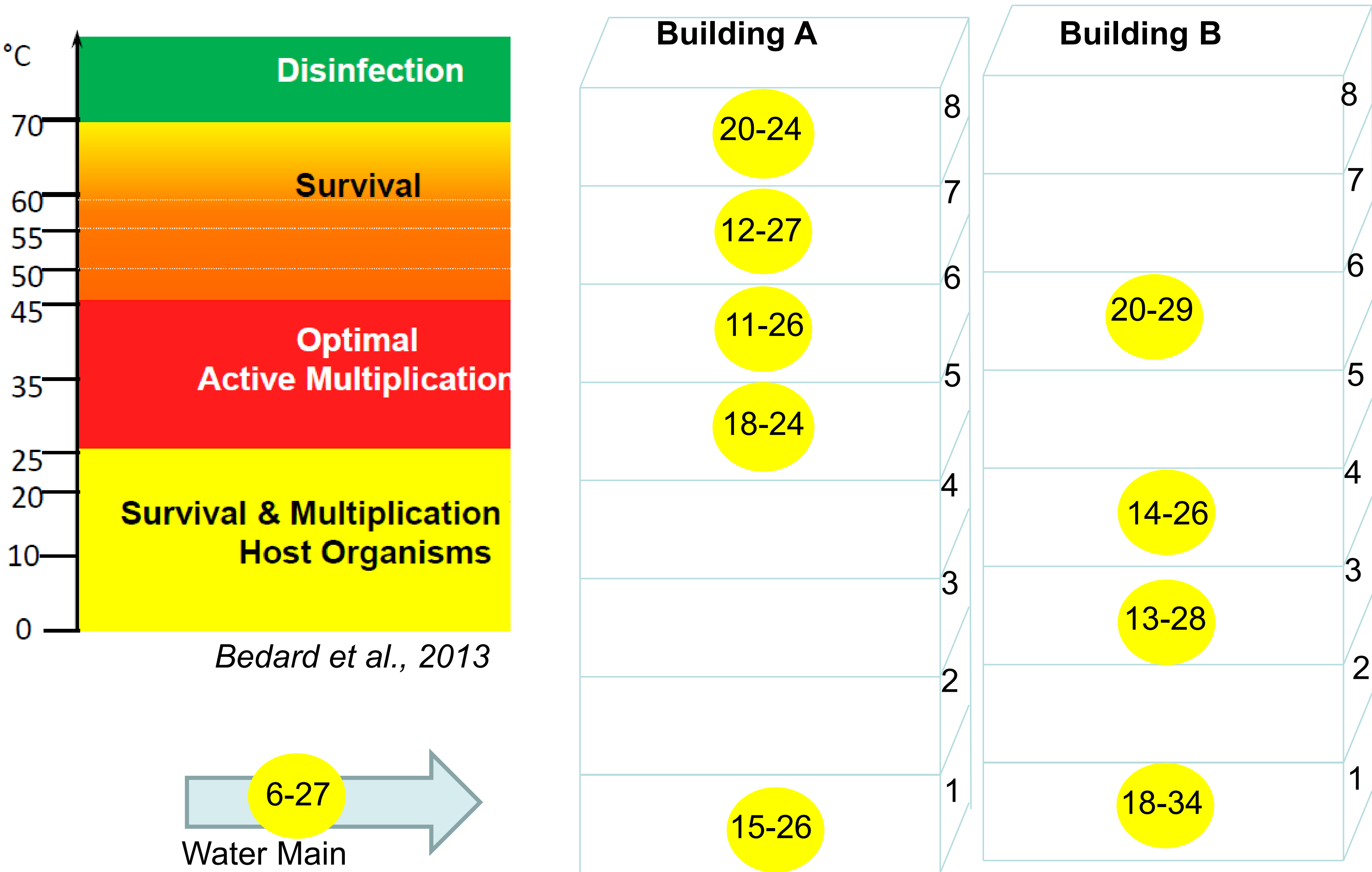


Temperature (° C) in First-Draw **Hot Water**



N=8 sampling rounds (from 5/13 to 7/14)

Temperature (° C) in First-Draw Cold Water



Free Chlorine in First Draw Hot Water

Reported as:
Average (Min-Max)

Floor	Building A	Building B
8	0.1 (0.0-0.1)	
7	0.3 (0.0-0.8)	
6	0.1 (0.0-0.2)	0.1 (0.0-0.2)
5	0.0 (0.0-0.1)	
4		0.4 (0.2-0.6)
3		0.1 (0.0-0.3)
2		
1	0.2 (0.0-0.6)	0.2 (0.0-0.6)

1.0 mg/L (0.7-1.2)
Water Main

N=8 sampling rounds (from 5/13 to 7/14)

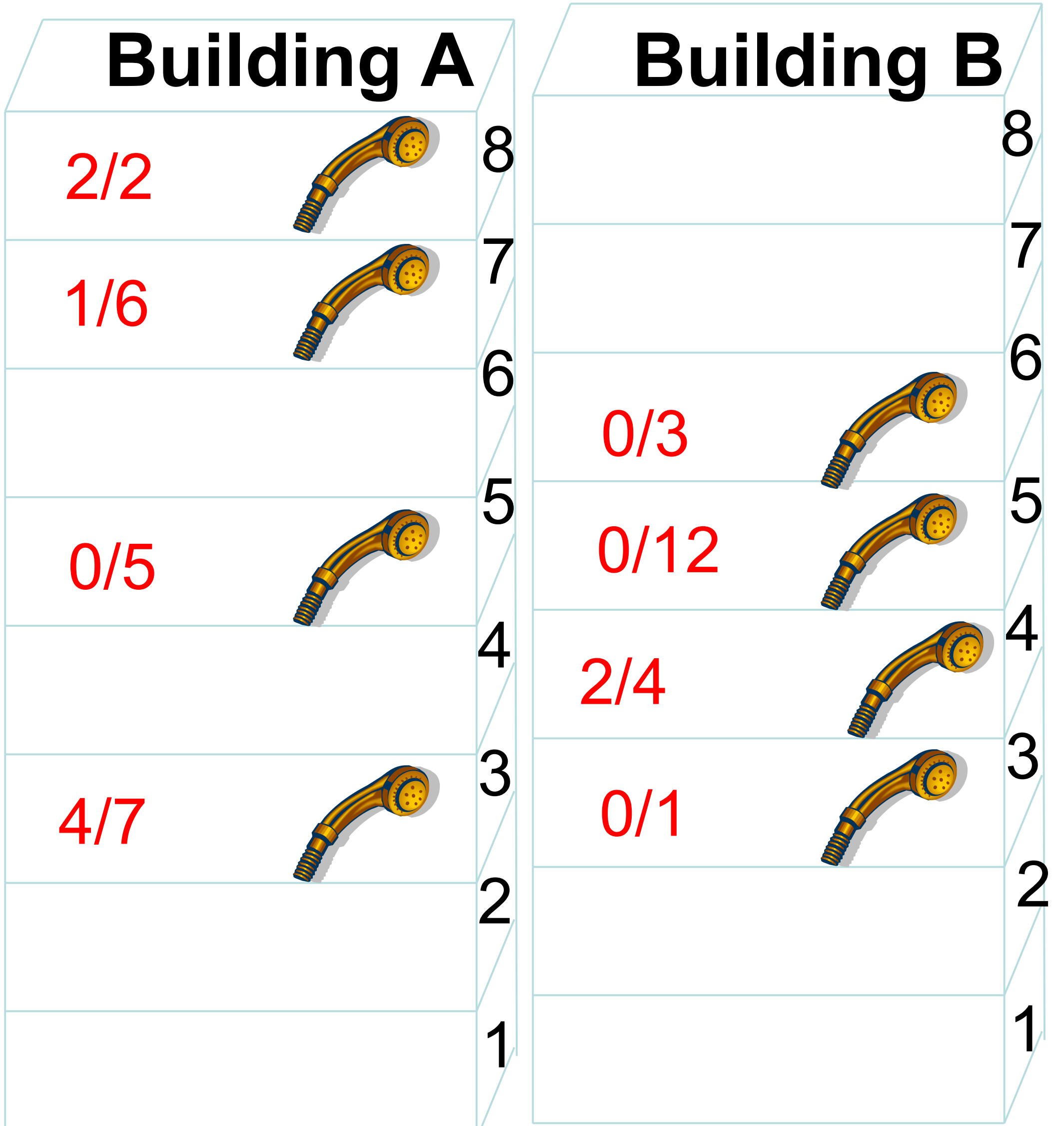
Free Chlorine (mg/L) in First-Draw Cold Water

Reported as:
Average (Min-Max)

Floor	Building A	Building B
8	0.2 (0.0-0.4)	
7	0.6 (0.0-0.9)	
6	0.8 (0.7 -1.0)	0.4 (0.2-0.9)
5	0.3 (0.0-0.6)	
4		0.8 (0.7-0.9)
3		0.6 (0.0-0.9)
2	0.7 (0.4-0.9)	
1	0.6 (0.4-0.8)	0.3 (0.0-0.8)

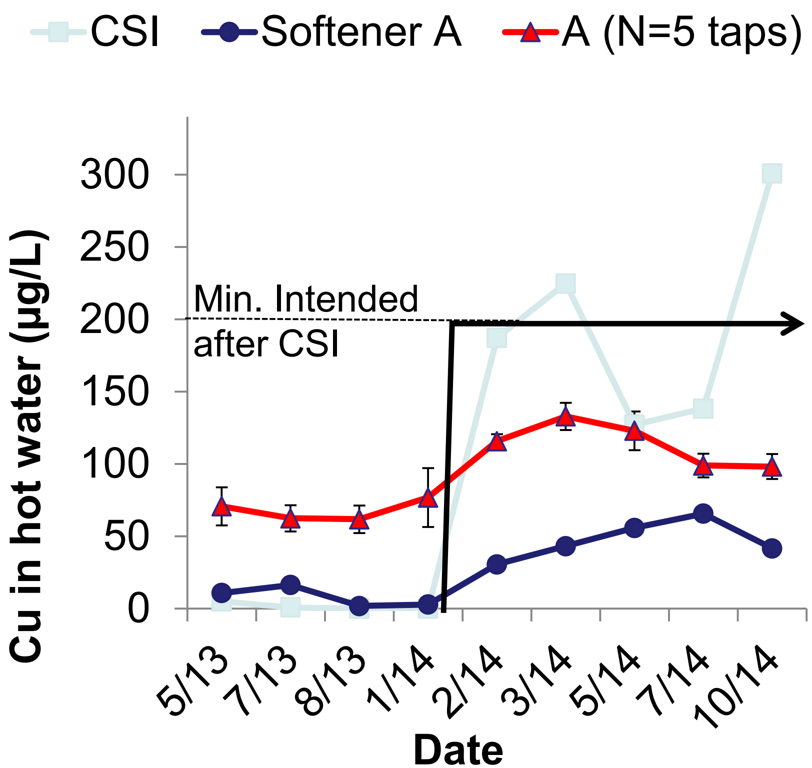
1.0 (0.7-1.2)
Water Main

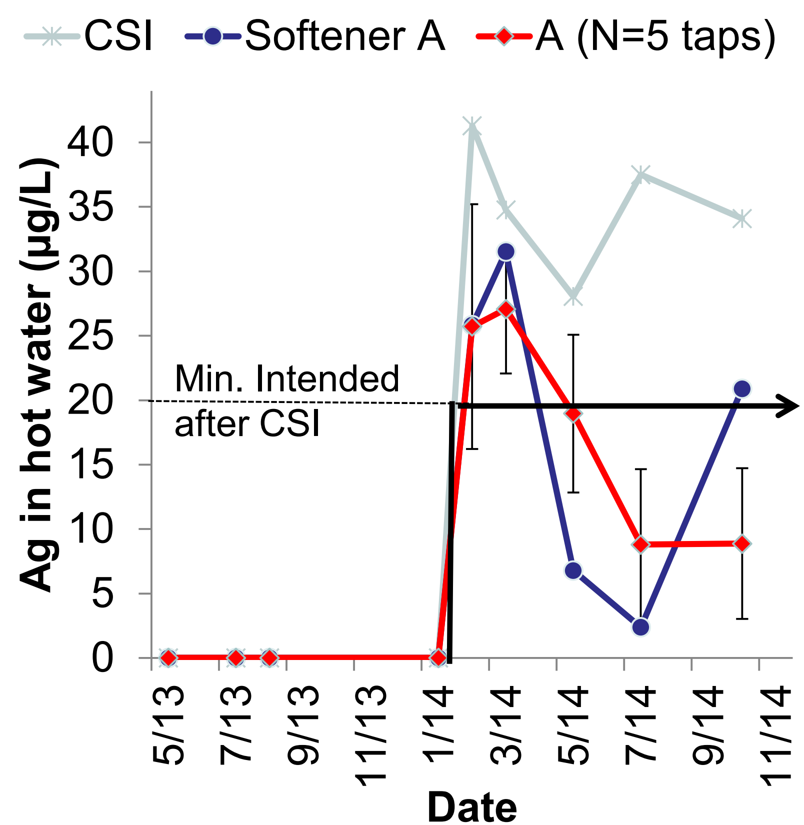
L. pneumophila serogroup 1 Positives qPCR



Donohue et al, 2013; Rodgers et al., 2014

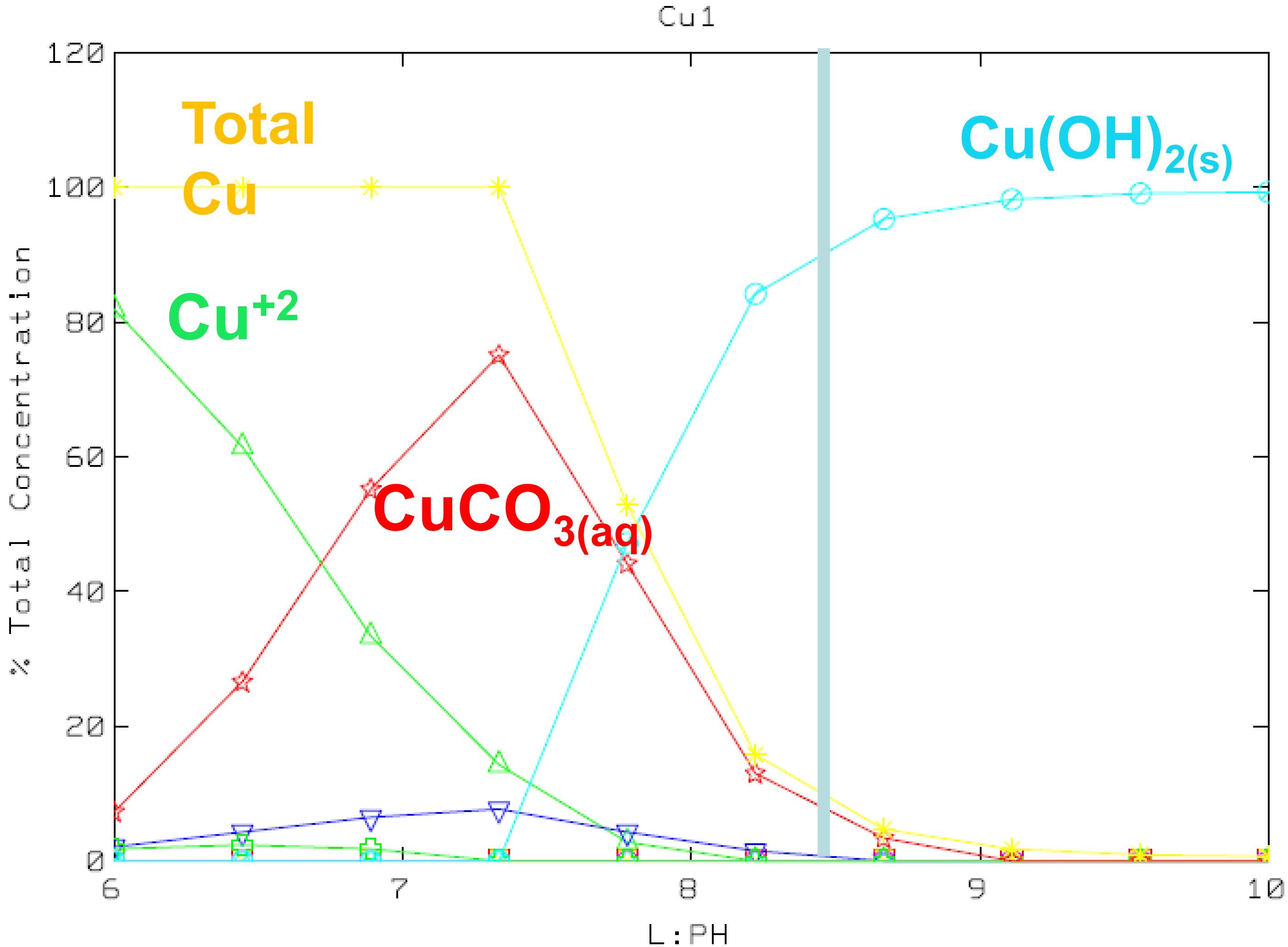
Insufficient Cu and Ag levels reaching hospital taps





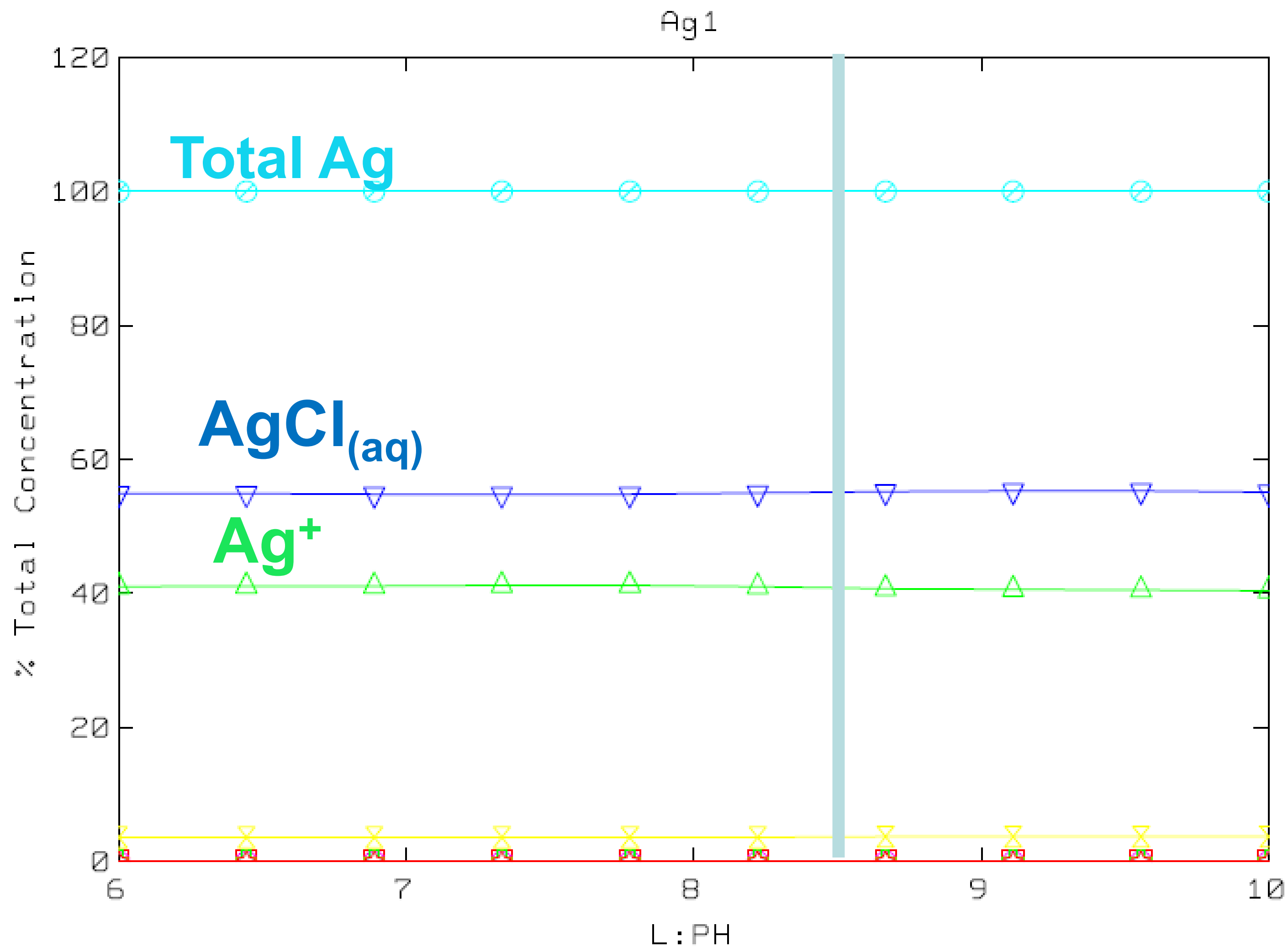
Triantafyllidou et al., 2016

Solubility modeling (Mineql+) for Cu



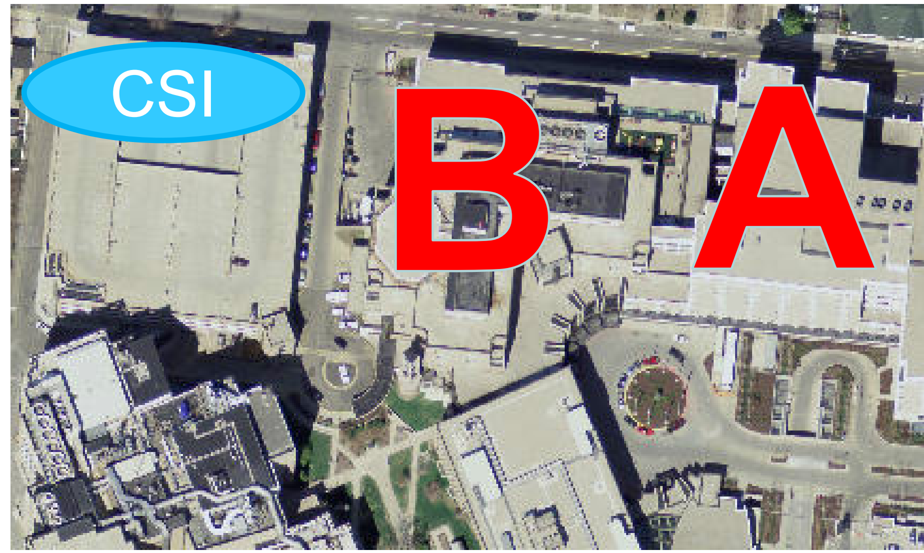
Total Cu = Cu^{+2} + $CuCO_{3(aq)}$

Solubility modeling (Mineql+) for Ag



Total Ag = $AgCl_{(aq)}$ + Ag^{+}

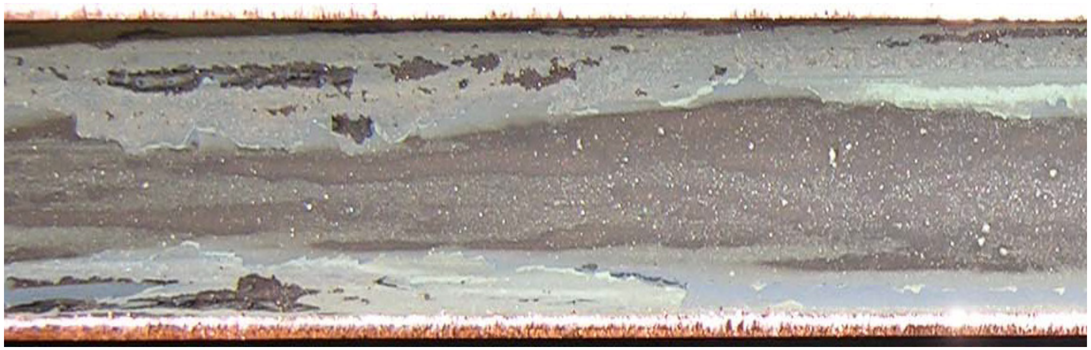
Aesthetic problems

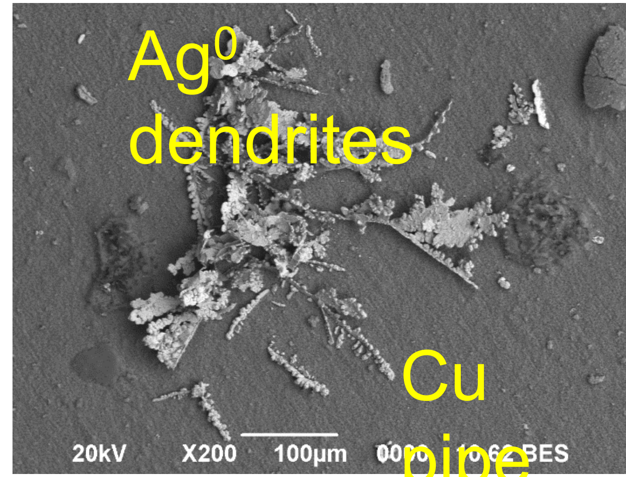


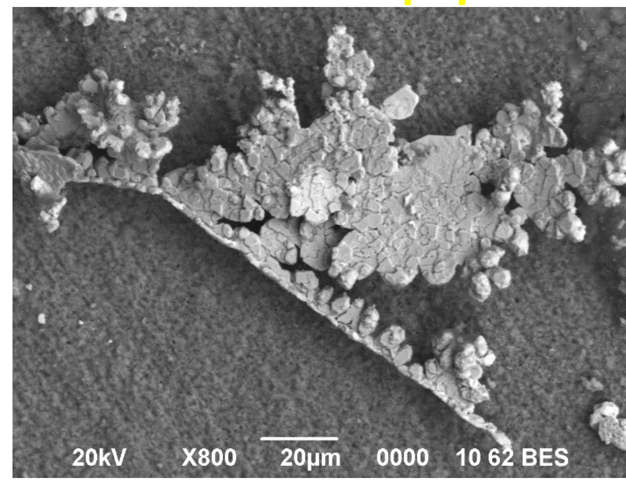
- Grey/purple staining in bathroom porcelain throughout buildings A and B
- Caused temporary inactivation of CSI
- XRD analysis identified precipitate as $AgCl_{(s)}$

$Ag^{+} + Cl^{-} \leftrightarrow AgCl_{(s)}$ $\quad$ $K = 5.62 \times 10^{9}$ at 25 °C

Plating of reduced silver onto copper pipes







Reaction	Potential, V	Implication
$Ag^+ + e^- \leftrightarrow Ag^0$	+0.799	More Noble (Cathodic)
$Cu^{+2} + 2e^- \leftrightarrow Cu^0$	+0.342	More Active (Anodic)

- Implications on silver disinfecting ability for bulk water and for biofilms
- Possibility of deposition corrosion for Cu pipe

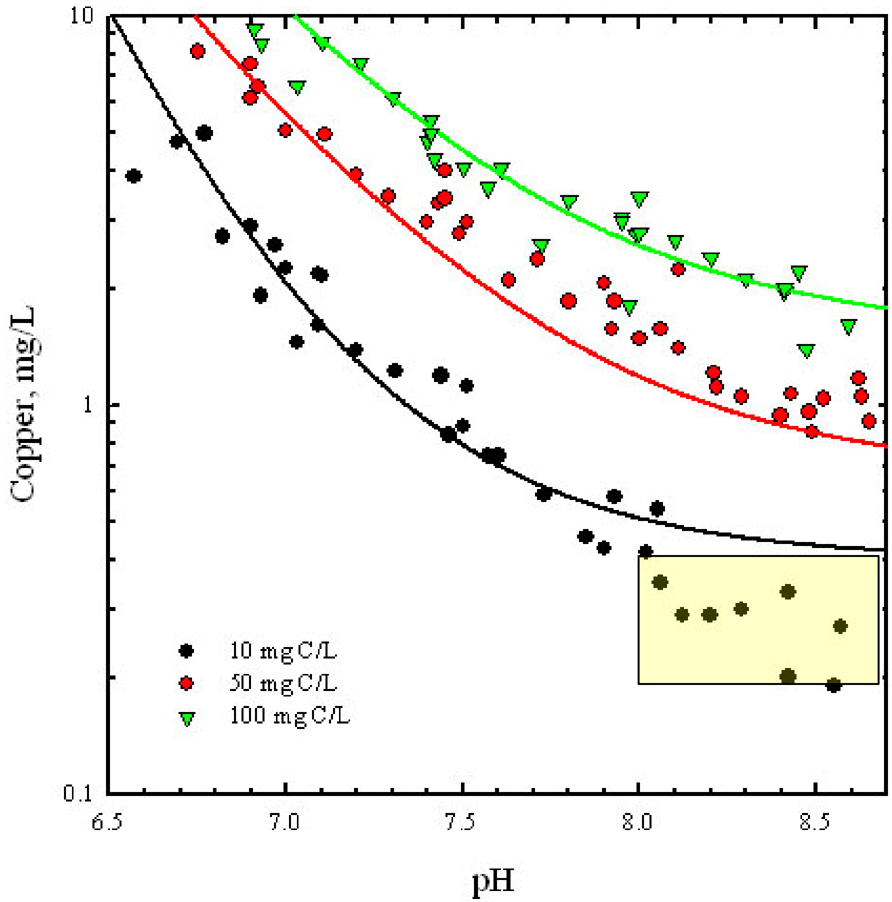
Summary

- *Legionella* detected in hospital showerheads
- Disinfectant residual and hot water temperature as lines of defense not sufficient
- Variability between first-draw and flushed water, hot and cold water, different floors and different buildings
- CSI ionization intended to control *Legionella* caused undesirable staining of porcelain
- Yet Cu and Ag levels in hot and cold water were mostly below manufacturer recommended levels (cation exchange softener countered the CSI treatment, metallic silver deposited onto copper pipes after CSI activation)
- Although the primary aspect of CSI is the effect on controlling *Legionella* and other pathogens in water, non-microbiological implications deserve exploration to holistically evaluate in-building drinking water disinfection

Copper (and Silver) Chemistry and Copper/Silver Ionization Treatment

- Aqueous metal solubility limits set upper bounds on the amount of ions that can be added to water
- Water variables including DIC, pH, PO_4, etc. impact solubility
- Adding metal ions to water above the solubility limit can result in precipitation of metals
- Water variables control the nature of aqueous soluble ions
- The technique used to introduce metal ions to water does not dictate the chemistry of the metals in the water
- You need to know your water chemistry

Effect of Dissolved Inorganic Carbonate and pH on Copper Solubility (23°C) (freshly formed copper*)

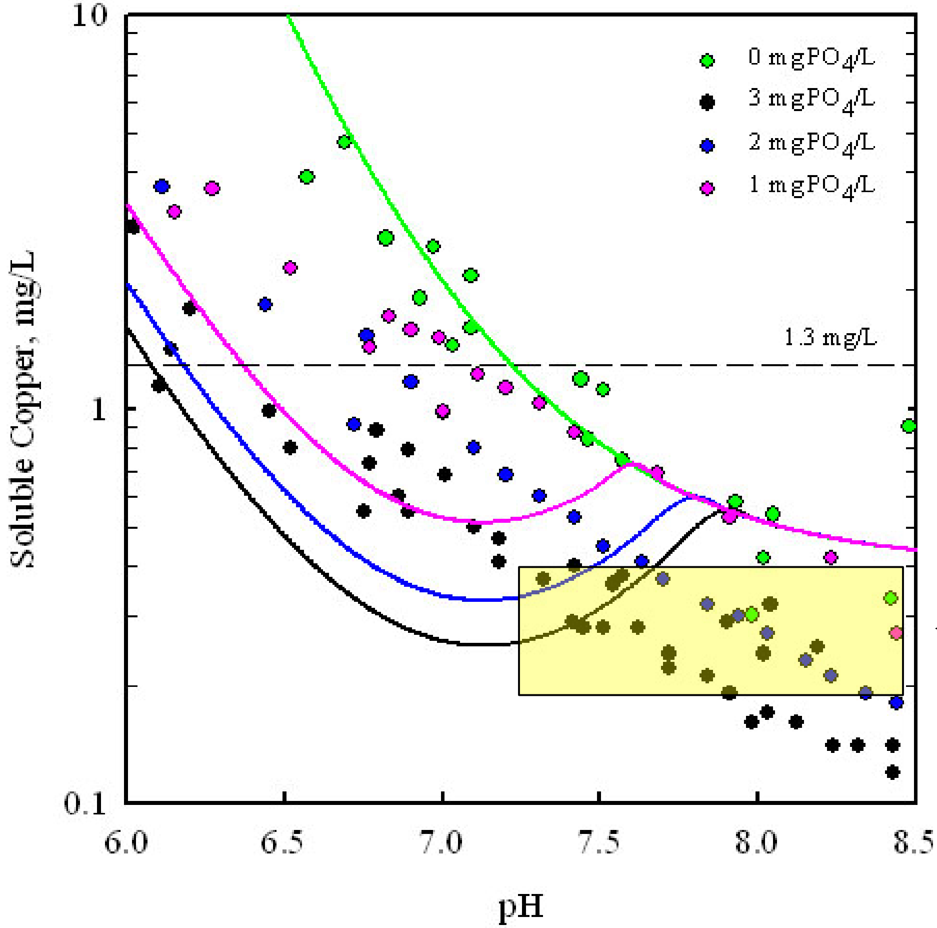


Recommended copper dose:
200 µg/L to 400 µg/L

*Model predictions based on $Cu(OH)_2$

EPA United States Environmental Protection Agency

Effect of Orthophosphate and pH on Copper Solubility (23°C, 10 mg C/L) (freshly formed copper*)

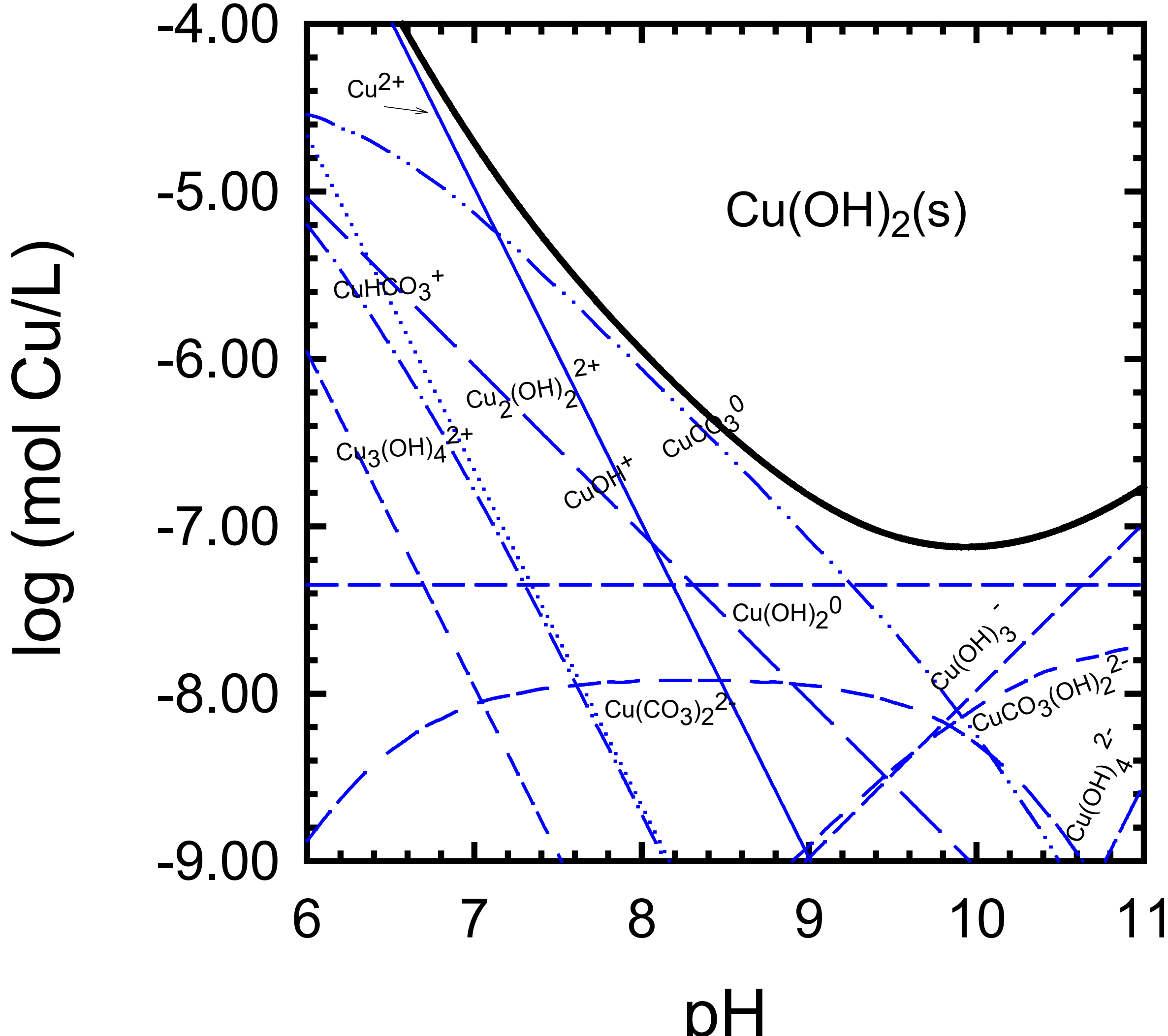


Recommended copper dose: 200 µg/L to 400 µg/L

*Model predictions based on $Cu_3(PO_4)_2 \cdot 2H_2O$ and $Cu(OH)_2$

EPA United States Environmental Protection Agency

Aqueous Chemistry of Cu(II) is Very Complicated



EPA United States Environmental Protection Agency

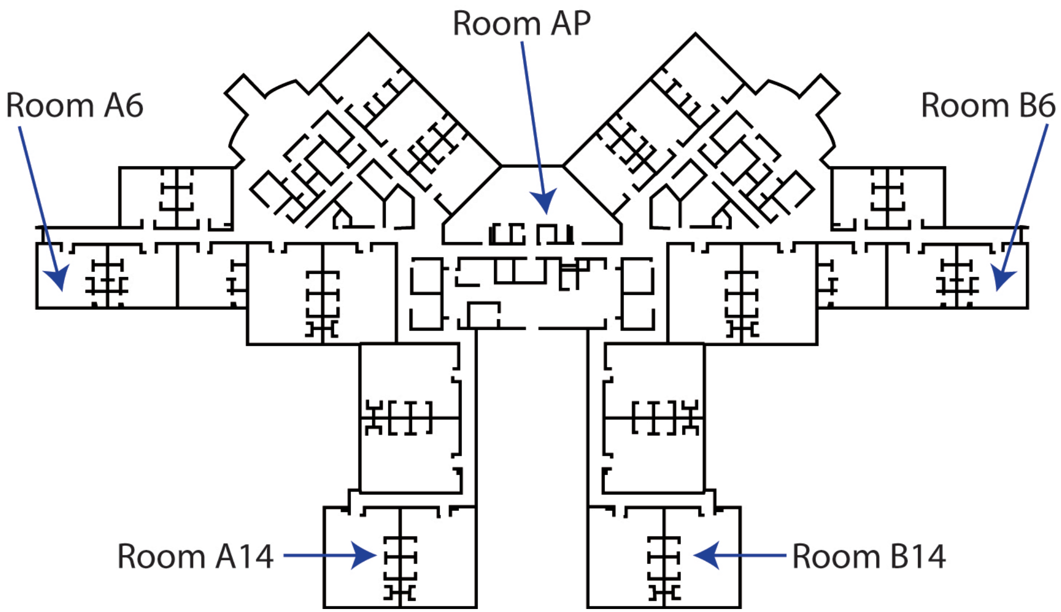
Corrosion Control in a Building and Disinfectant Residual

- The success of supplemental disinfection in reducing microbial risks depends on the residual reaching drinking water outlets
- Disinfectant will decay in a building as it reacts with organics, biofilms, etc..
- Disinfect will decay as it oxidizes (corrodes) metal pipes or reacts with metal corrosion by-products
- Good corrosion control can reduce disinfectant demand associated with corroding metal materials in a building

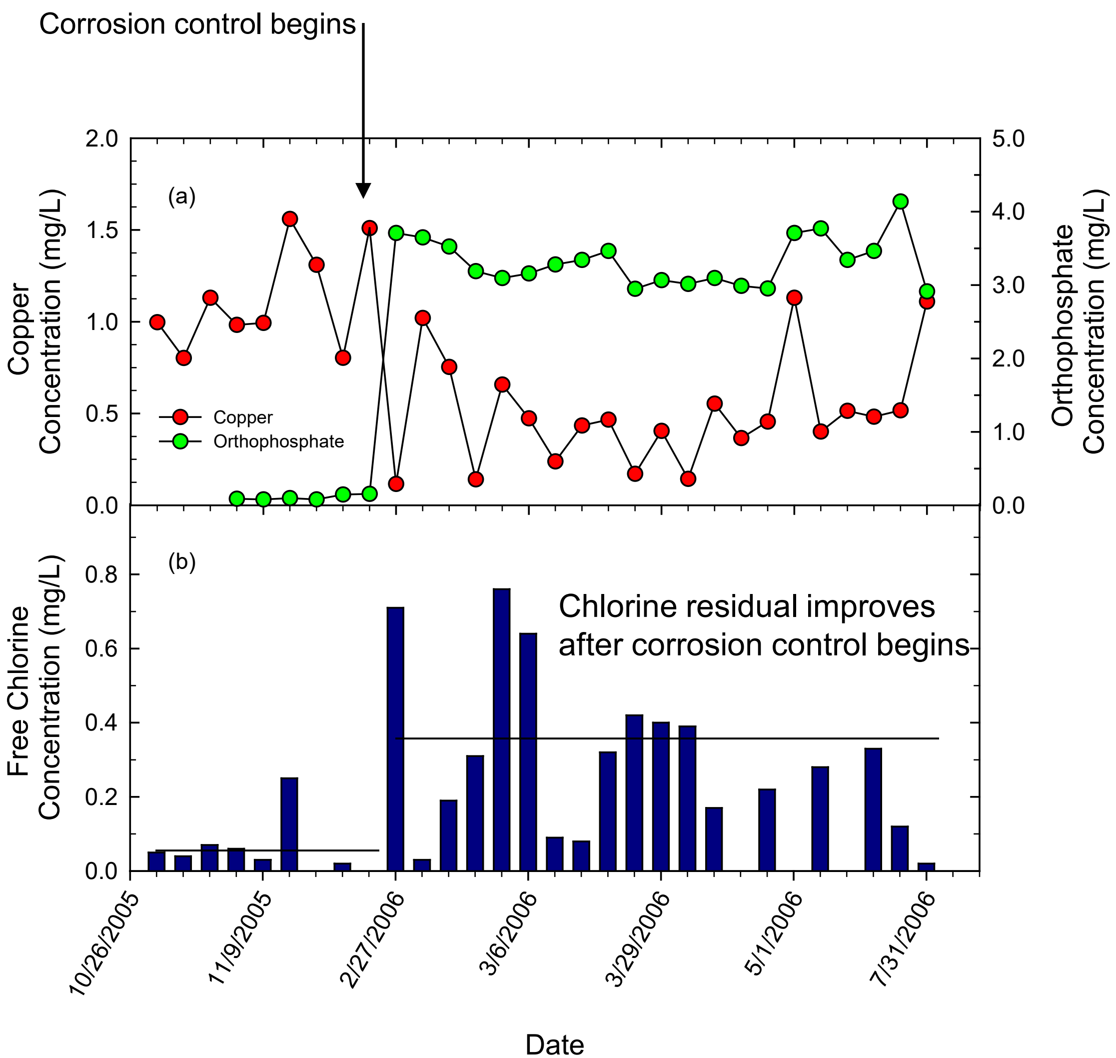
EPA United States Environmental Protection Agency

Treating Water in Buildings

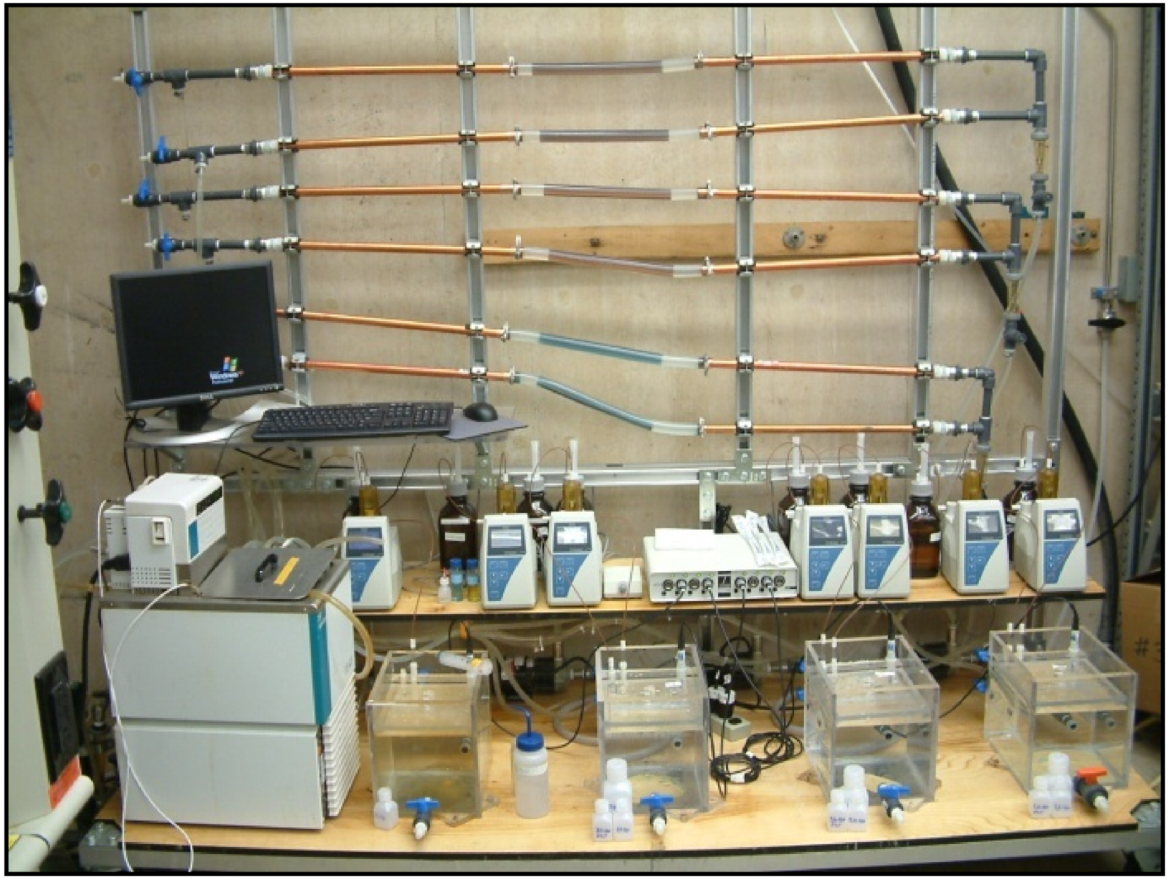
Benefit of Corrosion Control



Relationship Between Corrosion Control (Orthophosphate) of Copper and Chlorine Residual

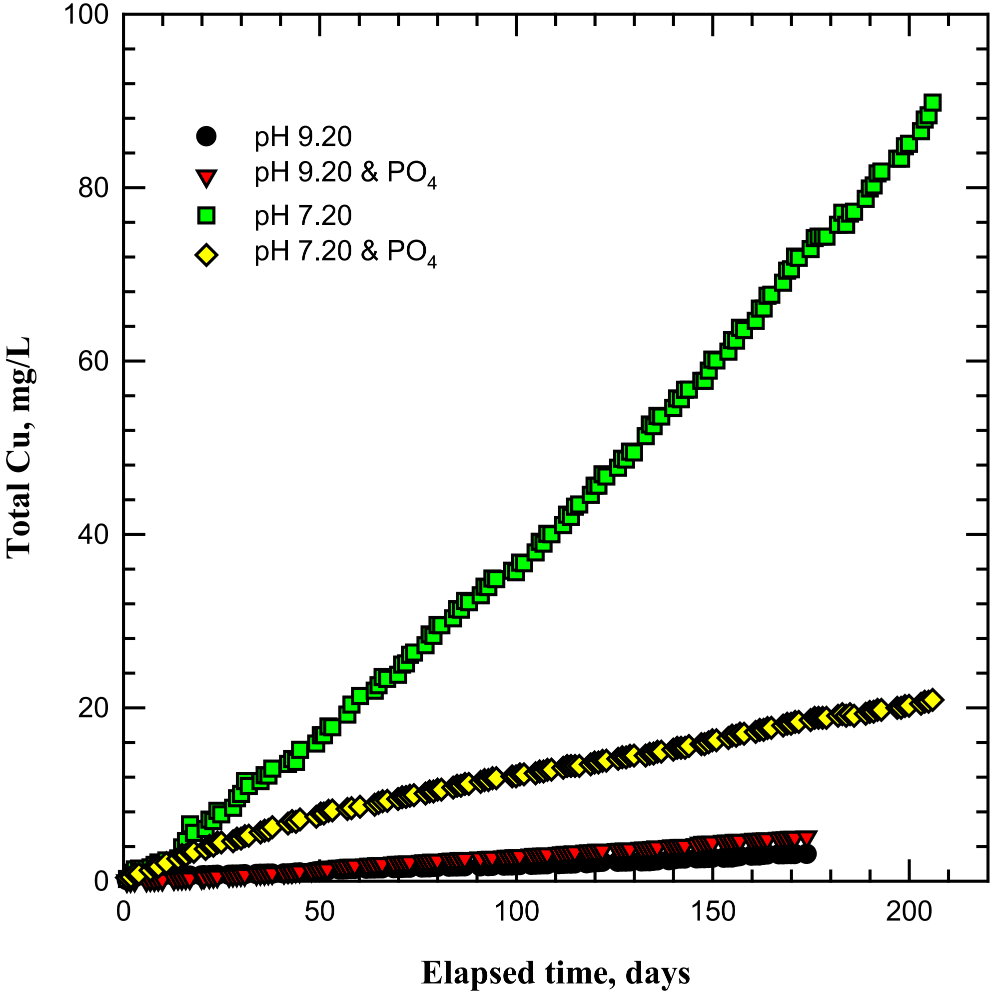


Copper Corrosion Control and Chlorine Demand



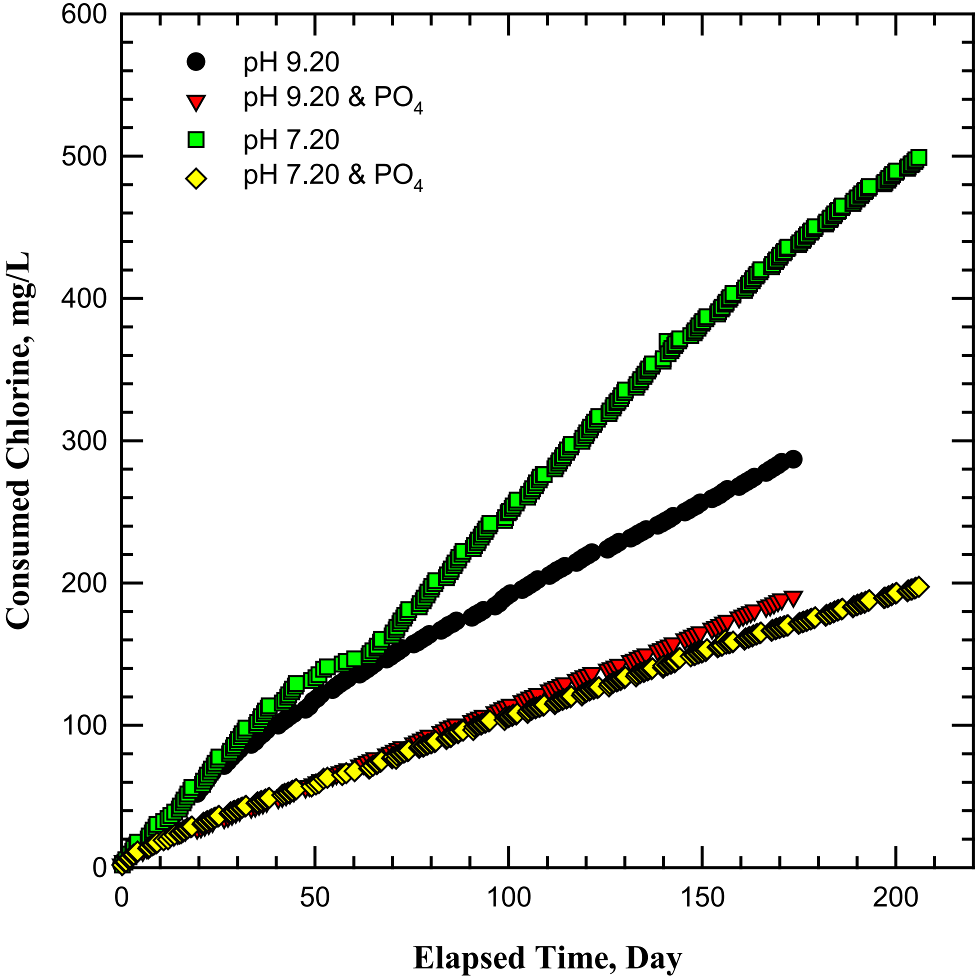
Total Copper Release over Time: Impact of Orthophosphate

(3 mg PO_4/L, 10 mg C/L, 100 mg Cl^-/L, 100 mg SO_4/L, 2 mg Cl_2/L)



Total Chlorine Consumption over Time: Impact of Orthophosphate

(10 mg C/L, 100 mg Cl^-/L, 100 mg SO_4/L, 2 mg Cl_2/L)



Acknowledgments

- Michael DeSantis & Michael Schock (USEPA)
- Keith Kelty & Maily Pham (USEPA)
- Mark Rodgers (USEPA)
- Jeff Swertfeger (GCWW)
- Hospital management and staff

Questions?

Darren Lytle
EPA
513-569-7432
lytle.darren@epa.gov

Simoni Triantafyllidou
triantafyllidou.simoni@epa.gov

United States Environmental Protection Agency

Notice

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the author (s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.