Assessing Distribution System Integrity:

the case for maintaining a disinfectant residual

Mark W. LeChevallier, Ph.D.
Director, Innovation & Environmental Stewardship

Regulation of Disinfection in the US

- **Surface Water Treatment Rule**
  - Giardia and Virus CT values
  - Maintenance of disinfectant residual at 95% locations
- **Long Term II Enhanced Surface Water Treatment Rule**
  - Cryptosporidium
- **Groundwater Rule**
  - Viruses
- **Stage 1 Disinfection/Disinfection By-Product Rule**
  - maximum residual limit (based on an annual average) of 4 mg/L for free chlorine and chloramines
- **Total Coliform Rule**
  - Disinfectant residual monitoring locations

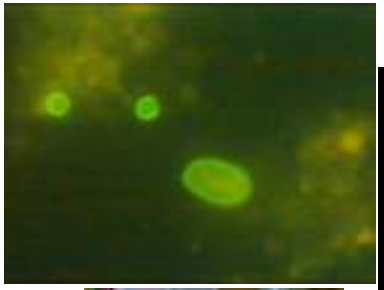
Summary of State Regulations: Disinfectant Residuals

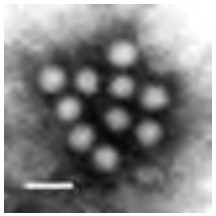
State	Minimum Distribution System Residual (mg/L)
Alabama	0.2 (free)
California	0.2 (free)
Delaware	0.3 (free)
Florida	0.2 (free), 0.6 (total)
Georgia	0.2 (free)
Illinois	0.3 (free), 0.5 (total)
Indiana	0.2 (free), 0.5 (total)
Iowa	0.3 (free), 1.5 (total)
Kansas	0.2 (free), 1.0 (total)
Kentucky	0.2 (free), 0.5 (total)

State	Minimum Distribution System Residual (mg/L)
Louisiana	0.5 (free or total)
Missouri	0.2 (total)
Nebraska	0.2 (free), 0.5 (total)
North Carolina	0.2 (free), 1.0 (total)
Ohio	0.2 (free), 1.0 (total)
Oklahoma	0.2 (free), 1.0 (total)
Tennessee	0.2 (free)
Texas	0.2 (free), 0.5 (total)
West Virginia	0.2 (total)

Water Treatment: the Multiple Barrier Concept

- **Source Water Protection**
  - Surface Water
  - Groundwater
- **Filtration**
- **Disinfection**
- **Distribution System**
  - Chlorine residual
  - Pressurized networks
  - Cross connection control





Dead-End Free Chlorine Residual

Residual mg/L	N	#Samples	# Positive	# Colonies	% Positive	Avg/100 mL
0 - 0.2	99	11,056	138	10,535	1.248	0.953
0.2 - 0.5	159	10,637	36	2,850	0.338	0.267
0.5 - 1.0	164	14,276	87	2,107	0.609	0.147
> 1.0	127	7,803	118	4,955	1.512	0.635

LeChevallier et al., 1996. *Appl. Environ. Microbiol.* 62(7): 2201-2211.

Dead-End Chloramine Residual

Residual mg/L	N	#Samples	# Positive	# Colonies	% Positive	Avg/100 mL
0 - 0.5	110	11,447	67	331	0.585	0.029
0.5 - 1.0	125	7,106	20	66	0.281	0.009
1.0 - 2.0	121	7,564	13	15	0.171	0.001
> 2.0	105	9,835	83	213	0.844	0.022

LeChevallier et al., 1996. *Appl. Environ. Microbiol.* 62(7): 2201-2211.

Relationship between Disinfection and AOC on Coliform Occurrences

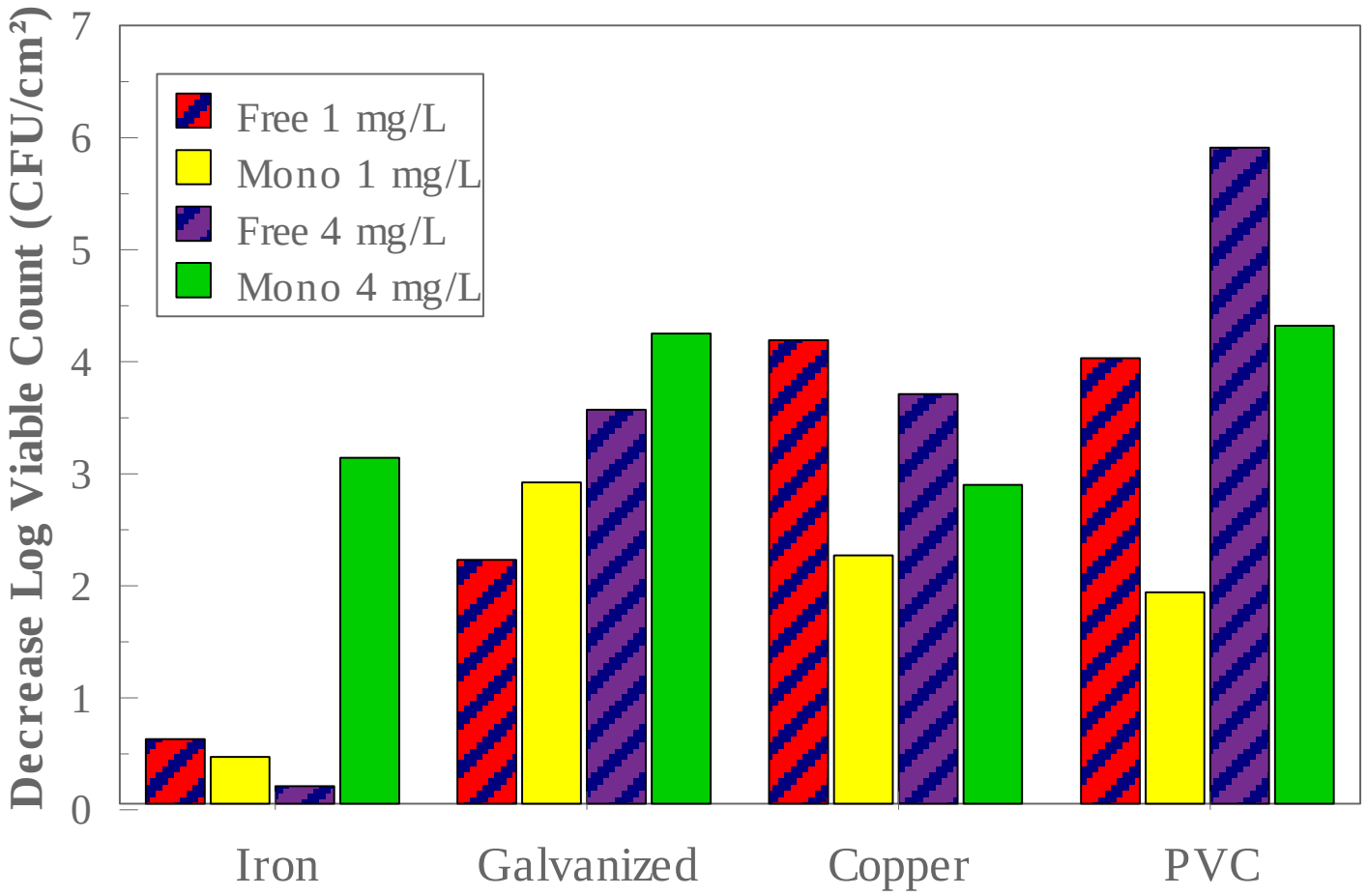
System	AOC Level (ug/L)	% Samples Positive	Avg. Coliform /100 mL
Free Chlorinated	120 - 189	1.24	1.077
Systems, N=11	50 - 93	0.68	0.058
Chloraminated	101 - 166	0.87	0.022
Systems, N=11	42 - 99	0.36	0.015

Free chlorinated systems with high AOC had 87% higher occurrence rate, and bacterial levels 19 times higher than low AOC systems.

Chloraminated systems with high or low AOC were not statistically different.

LeChevallier et al., 1996. *Appl. Environ. Microbiol.* 62(7): 2201-2211.

Impact of Pipe Surface on Disinfection of Biofilm Bacteria

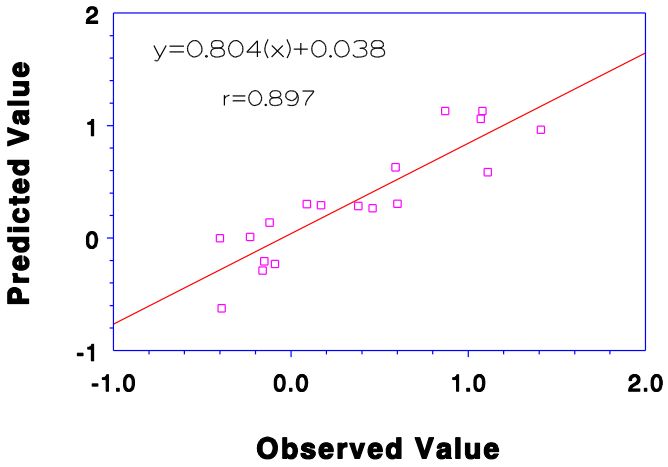


LeChevallier, Lowry, and Lee. 1990. *J. Amer. Water Works Assoc.* 82(7): 87-99.

Model for Monochloramine Disinfection of Biofilm Bacteria

	Coefficient	Standard Error	*t*-Statistic	Significance Level
Log reduction viable counts=				
Intercept	-1.0734	0.5685	-1.888	0.0816
Log Larson Index	-0.5808	0.l963	-2.958	0.0111
Log Corrosion Rate	-0.4820	0.3205	-1.504	0.1566
Log Monochloramine	2.0086	0.9226	2.177	0.0485
Phosphate Level	0.1445	0.0336	4.295	0.0009
Corrected R-Squared:	0.746	F test:	13.474	

Model is based on 18 observations

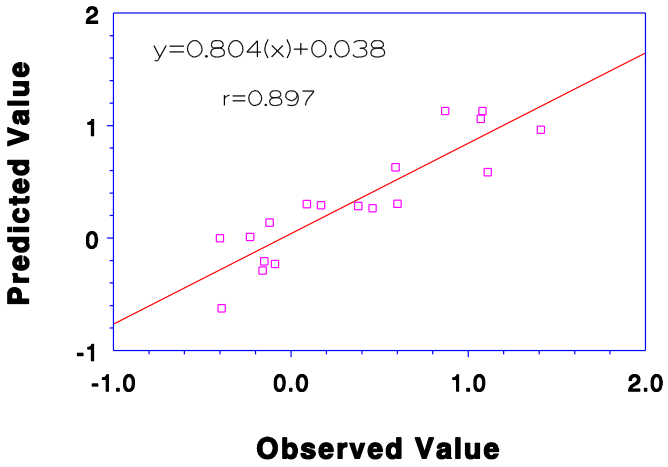


LeChevallier, Lowry, and Lee. 1990. *J. Amer. Water Works Assoc.* 82(7): 87-99.

Model for Monochloramine Disinfection of Biofilm Bacteria

	Coefficient	Standard Error	*t*-Statistic	Significance Level
Log reduction viable counts=				
Intercept	-1.0734	0.5685	-1.888	0.0816
Log Larson Index	-0.5808	0.l963	-2.958	0.0111
Log Corrosion Rate	-0.4820	0.3205	-1.504	0.1566
Log Monochloramine	2.0086	0.9226	2.177	0.0485
Phosphate Level	0.1445	0.0336	4.295	0.0009
Corrected R-Squared:	0.746	F test:	13.474	

Model is based on 18 observations



LeChevallier, Lowry, and Lee. 1990. *J. Amer. Water Works Assoc.* 82(7): 87-99.

Nosocomial Legionnaires' Disease

Kool *et al.*, *Lancet* 353: 272-277 1999

- Examined 32 nosocomial outbreaks, 1979-1997, in which drinking water was implicated
  - Examined characteristics of the hospital (size, transplant program), primary disinfectant treatment, disinfectant residual, water source, community size, pH.
- Odds of nosocomial outbreak was 10.2 (1.4-460) higher in systems that maintained free chlorine versus a chloramine residual.
- Estimated that 90% of outbreaks could be prevented if chloramines were universally sed.

Nosocomial Legionnaires' Disease

International Conference on Nosocomial Infections (www.decennial.org):

- ✓ Survey 166 hospitals. Those supplied with chloraminated water were less likely (RR=0.36, CI=0.18-0.72) to have nosocomial Legionnaires disease.

International Legionella Conference (www.uni-ulm.de):

- ✓ Monochloramine at 1.5 mg/L resulted in >99.9% inactivation of Legionella biofilms within 60 min.

Association for Professionals in Infectious Control (www.apic.org):

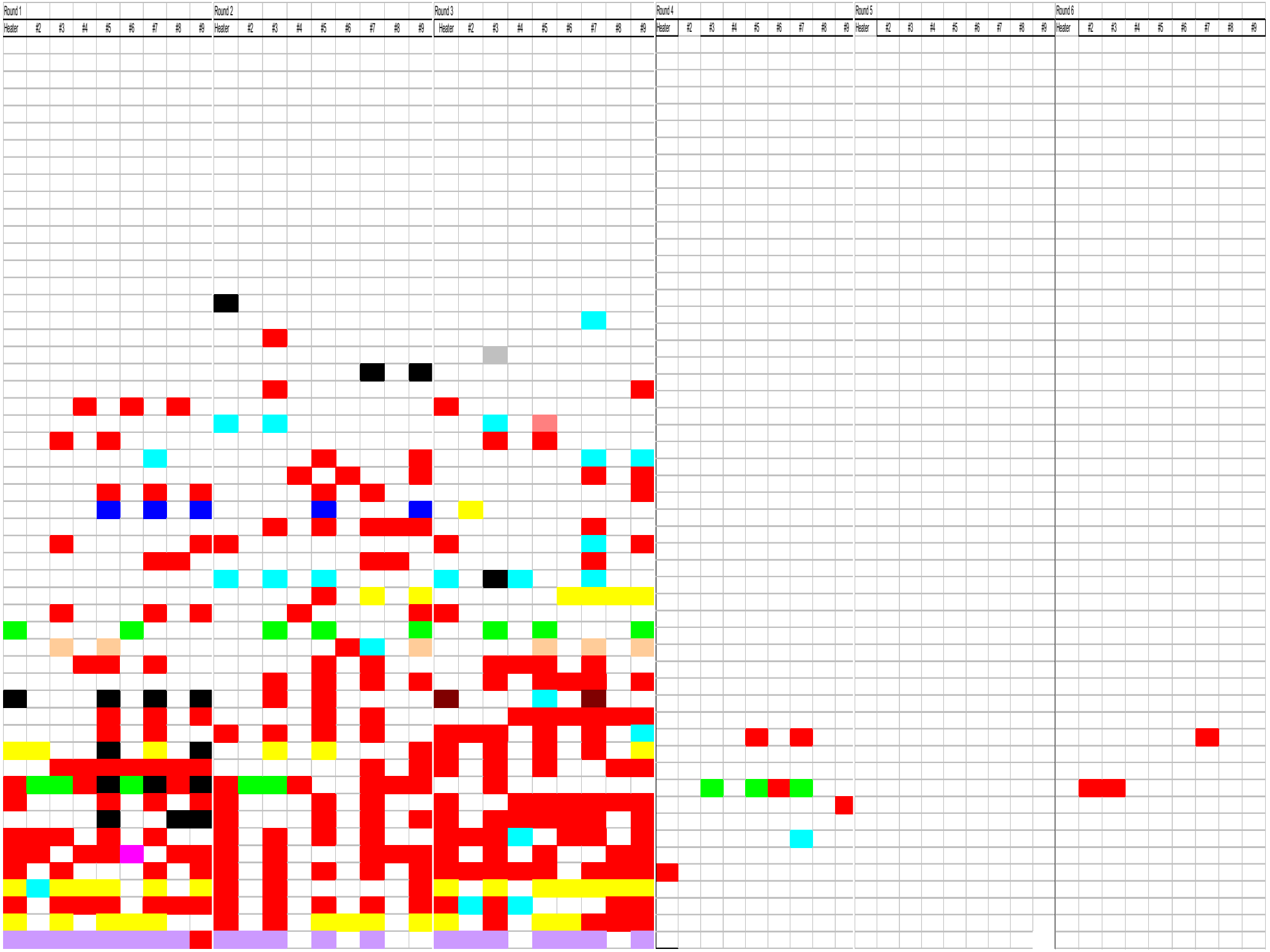
- ✓ Fed chloramines to a hospital. Legionella were 97.9 cfu/mL before (n=72), and 0.13 cfu/mL after (n=104) treatment with 0.1 mg/L chloramines.

Lessons from Real Life:
San Francisco, CA

- 53 buildings
- Sampled 3 times pre- and post-conversion to chloramines
- Sampled hot water heater and four distal sites
- Sampled swab and water from distal sites
- Surveys collected data on building age, height, type and number of hot water heaters
- pH, temperature, free or total Cl_2 residual measured for each sample

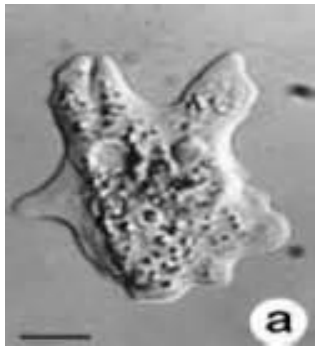
Flannery, B. et al. 2006. Reducing *Legionella* colonization of water systems with monochloramine. Emerg. Infect. Dis. 12(4): 588-596.

http://www.cdc.gov/ncidod/EID/vol12no04/05-1101.htm.

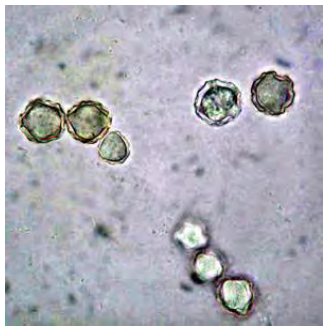

Round 1
Heater #2 #3 #4 #5 #6 #7 #8 #9
Round 2
Heater #2 #3 #4 #5 #6 #7 #8 #9
Round 3
Heater #2 #3 #4 #5 #6 #7 #8 #9
Round 4
Heater #2 #3 #4 #5 #6 #7 #8 #9
Round 5
Heater #2 #3 #4 #5 #6 #7 #8 #9
Round 6
Heater #2 #3 #4 #5 #6 #7 #8 #9

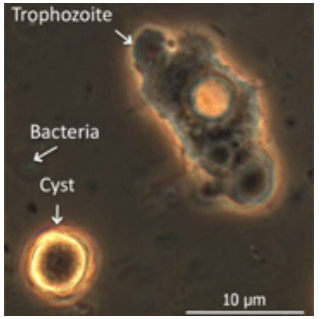
Legionella and Amoebae

- Intracellular *Legionella* in: *Acanthamoeba, Amoeba, Comandonia, Echinamoeba, Filamoeba, Hartmannella, Naegleria, Paratetramitus, Vahlkamfia, Tetrahymena, Dictyostelium*
- *Legionella* survive for months, resistant to 50 mg/L free chlorine for 18 hr
- Coated with amoebal proteins
- Increases virulence, replication
- *Legionella*-containing vacuoles expelled prior to encystation
- Trophozoite stage sensitive to disinfectants ($CT_{99.9}$ = 1.5 mg-min/L)



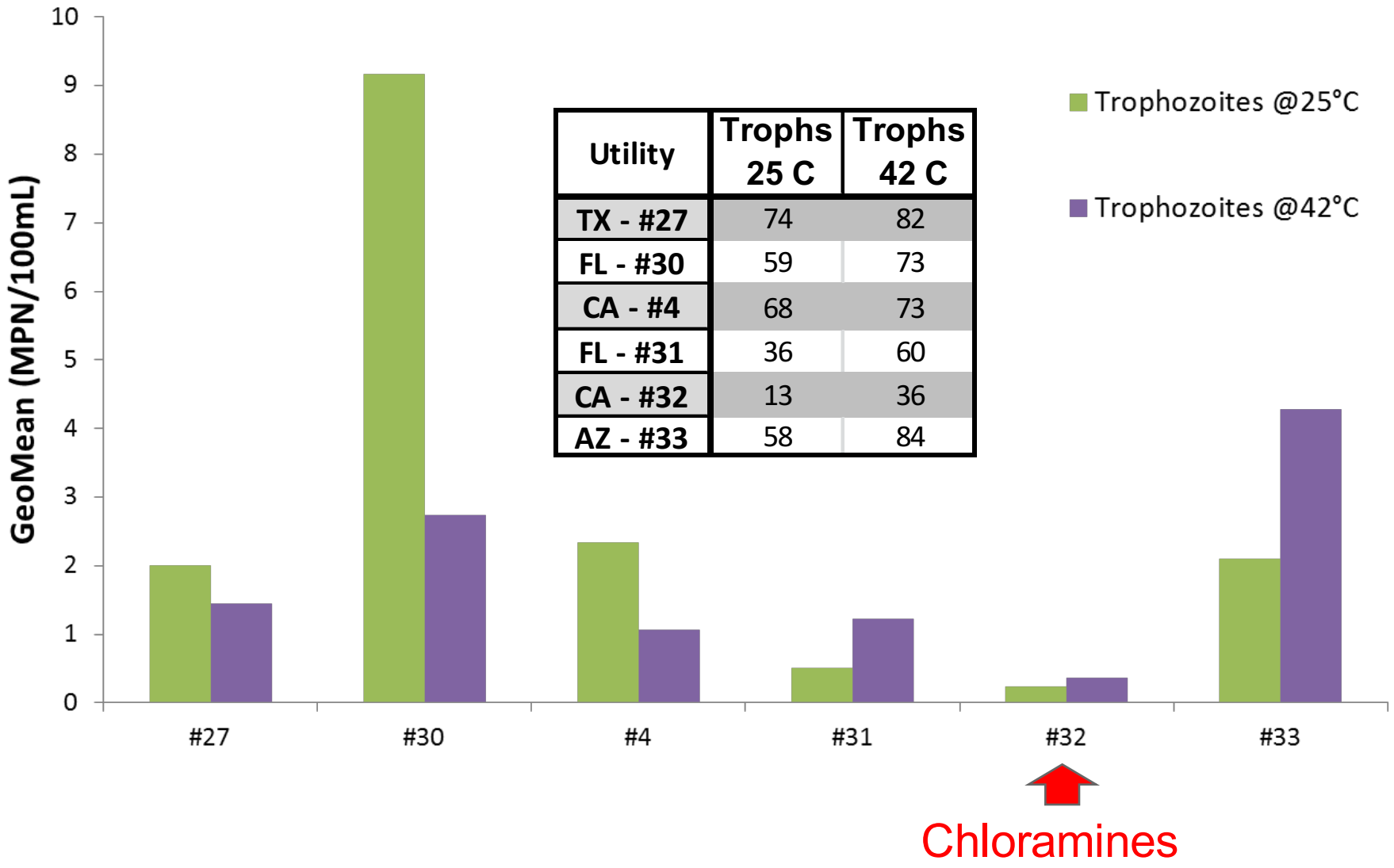
Trophozoite

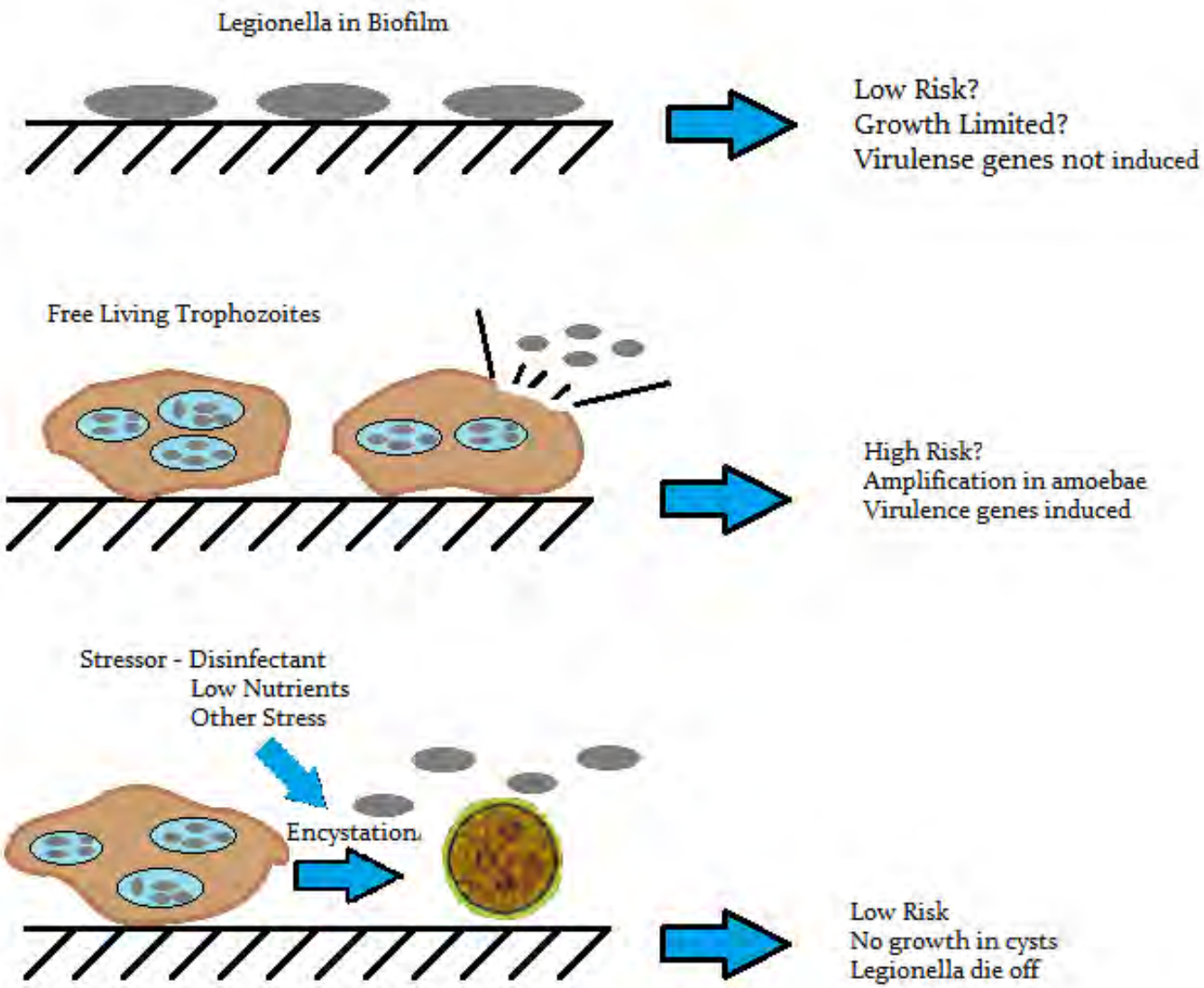

Cyst



Trophozoite Concentration

Utility	Trophs 25 C	Trophs 42 C
TX - #27	74	82
FL - #30	59	73
CA - #4	68	73
FL - #31	36	60
CA - #32	13	36
AZ - #33	58	84




Legionella in Biofilm
Low Risk?
Growth Limited?
Virulense genes not induced
Free Living Trophozoites
High Risk?
Amplification in amoebae
Virulence genes induced
Stressor - Disinfectant
Low Nutrients
Other Stress
Encystation
Low Risk
No growth in cysts
Legionella die off

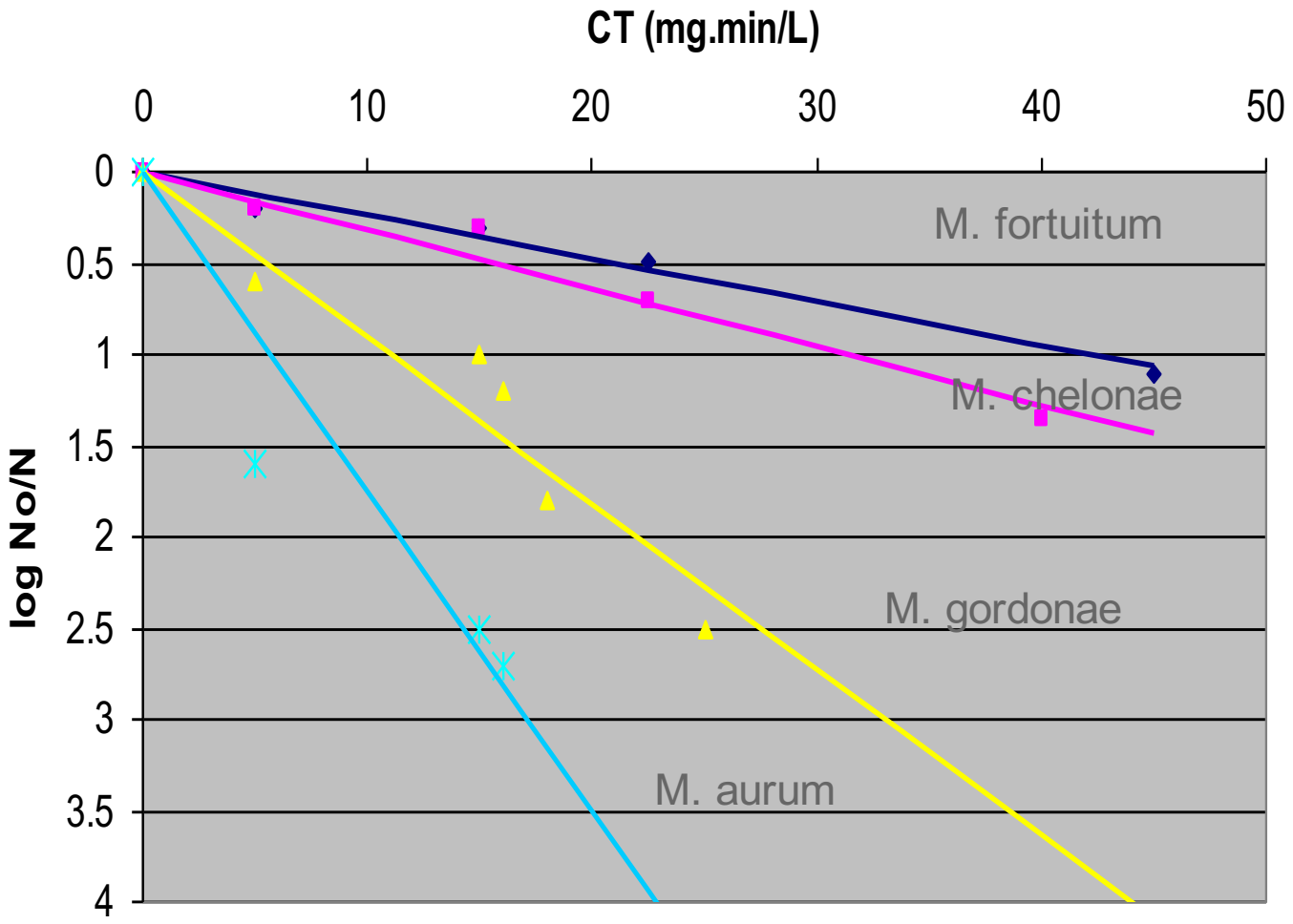
Disinfection – *M avium*

Calculated disinfection $CT_{99.9\%}$ (mg·min/l) for *E. coli* and *M. avium* strains*

Disinfectant Condition	Control E. coli	*Mycobacterium avium* Strain A5	1060	1508	5002	5502
Chlorine (M7H9)	0.088 ± 0.003	106 ± 9	204 ± 36	164 ± 28	126 ± 27	51 ± 10
Chlorine (water)	Not Done	1552 ± 403	1445 ± 238	596 ± 292	962 ± 431	551 ± 290
Monochloramine	73 ± 28	97 ± 9	458 ± 152	548 ± 62	1710 ± 814	91 ± 34
Chlorine Dioxide	0.015 ± 0.003	Not Done	8 ± 3	Not Done	11 ± 2	2 ± 0.1
Ozone	0.002 ± 0.002	Not Done	0.17 ± 0.14	Not Done	0.12 ± 0.01	0.10 ± 0.01

* Cells were exposed to the disinfectants in demand-free phosphate buffer (pH 7.0) at 23 °C
Taylor et al., 2000, *Appl. Environ. Microbiol.* 66(4): 1702-1705.

Mycobacterium Disinfection by Free Chlorine



Experimental conditions: pH 7.0, 25°C, initial free chlorine concentration 0.5 mg/l. Adapted from Le Dantec *et al.* 2002.

Impact of nutrient level, disinfectant, and pipe material on *M. avium* and HPC levels

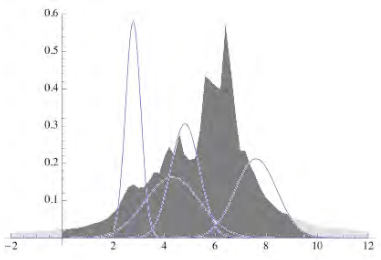
AOC Level	Disinfectant Type	Disinfectant Residual (mg/l)	Copper Pipe [1]		Iron Pipe [1]	
			HPC	*M. avium*	HPC	*M. avium*
85 µg/l AOC	Free chlorine	0.6	1.76	0.18	6.02	5.85
	Chloramine	2.2	2.44	2.38	5.21	4.92
213 µg/l AOC	Free chlorine	0.3	2.17	0.37	5.93	5.50*
	Chloramine	1.4	2.43	2.10	5.89	5.20*

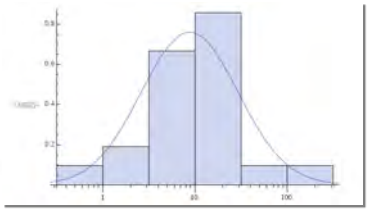
[1] Values are log CFU/cm^2, * Corrosion products interfered with these analyses

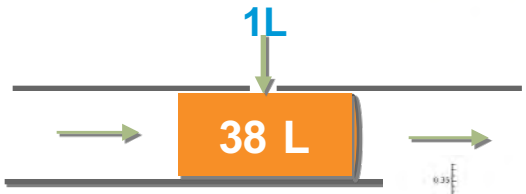
Norton, LeChevallier, and Falkinham. 2004. *Water Research*, **38**: 1457-1466.

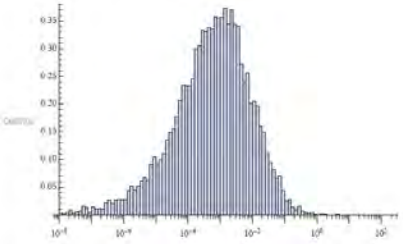
Development of QMRA

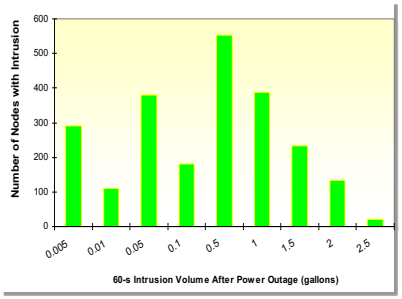
1. External virus concentration
2. Negative pressure duration
3. Intrusion volume
4. Dilution
5. Virus Transport
6. Population Exposed
7. Coincidence of exposure
8. Volume consumed
9. Dose Response
10. Risk Calculation

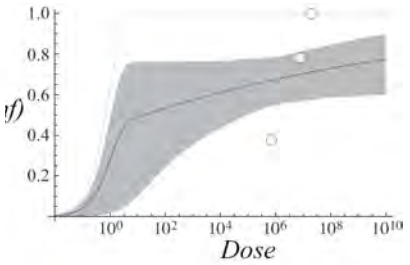


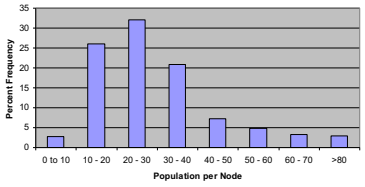


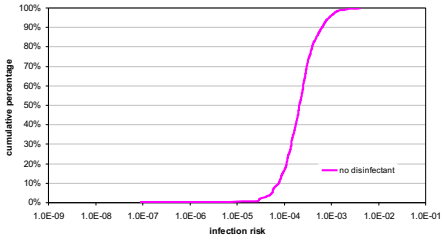


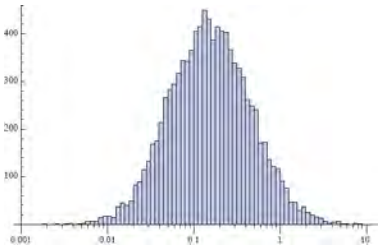






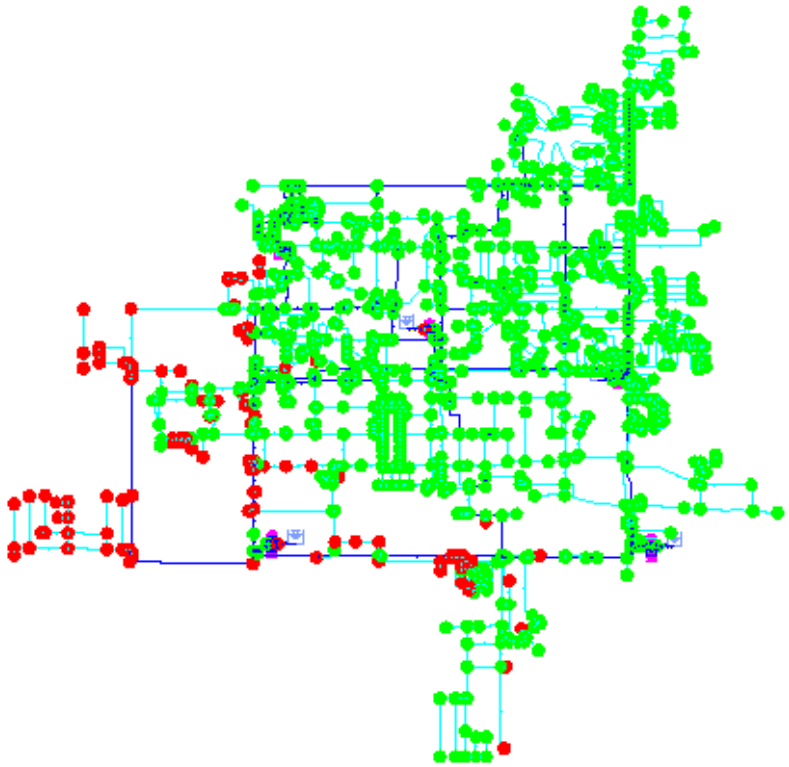




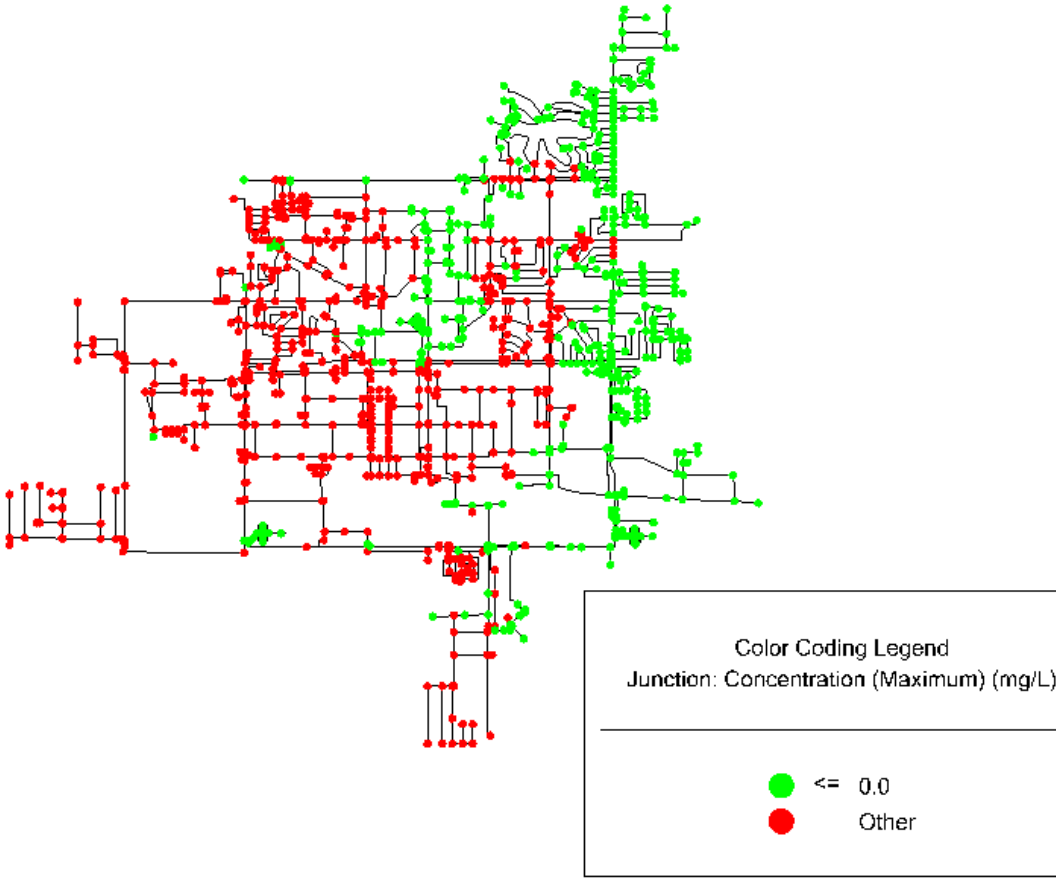


LeChevallier, M.W., Xu, M., Yang, J. Teunis, P. and K.K. Fleming. 2011. Managing Distribution System Low Transient Pressures for Water Quality. Water Research Foundation, Denver, CO.

Virus transport without a disinfectant residual



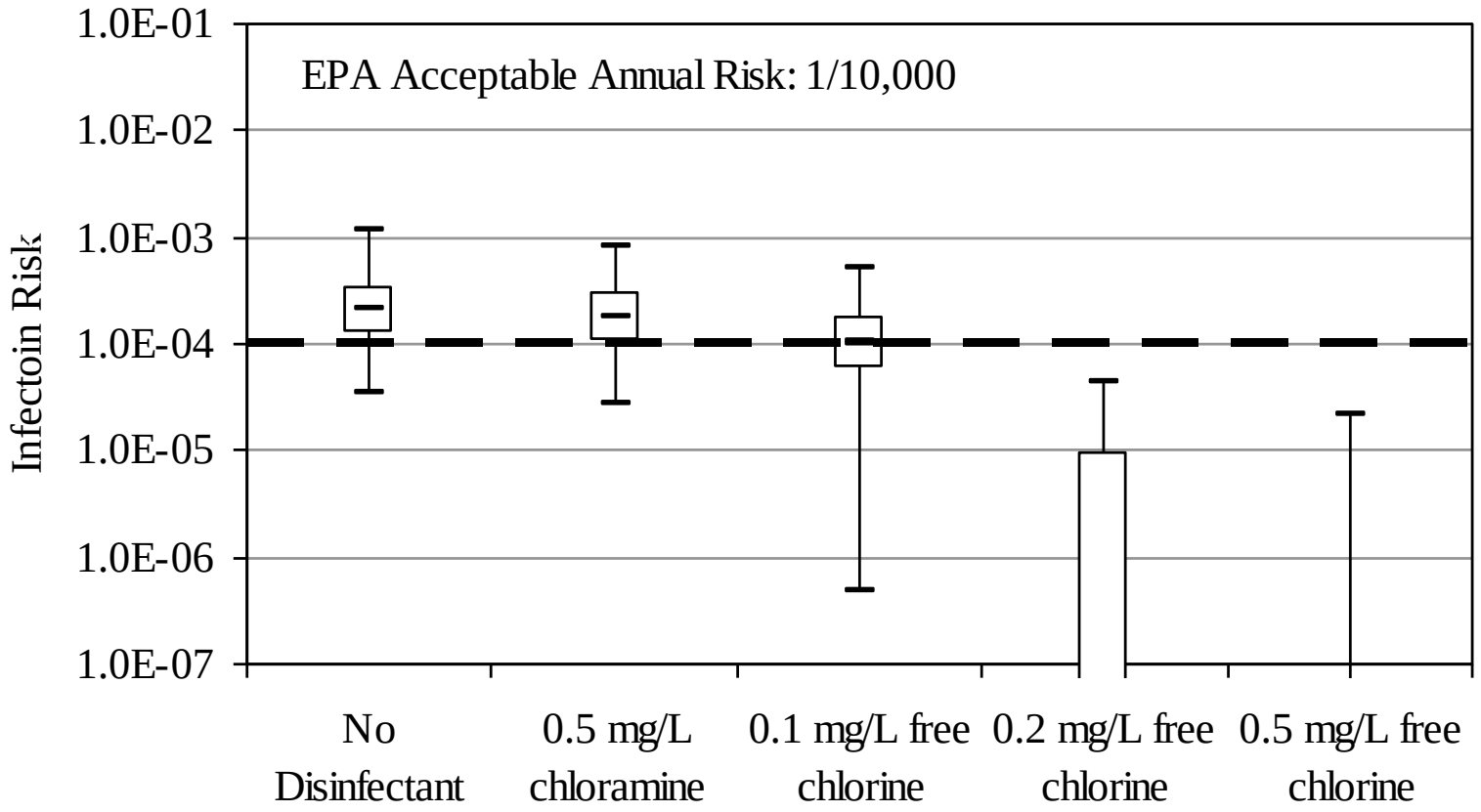
Initial points of intrusion



Virus transport after 24 h.

LeChevallier, M.W., Xu, M., Yang, J. Teunis, P. and K.K. Fleming. 2011. Managing Distribution System Low Transient Pressures for Water Quality. Water Research Foundation, Denver, CO.

Minimum Disinfectant Residual



Free chlorine residuals >0.2 mg/L eliminated Norovirus virus risk due to intrusion of 0.1% wastewater

LeChevallier, M.W., Xu, M., Yang, J. Teunis, P. and K.K. Fleming. 2011. Managing Distribution System Low Transient Pressures for Water Quality. Water Research Foundation, Denver, CO.

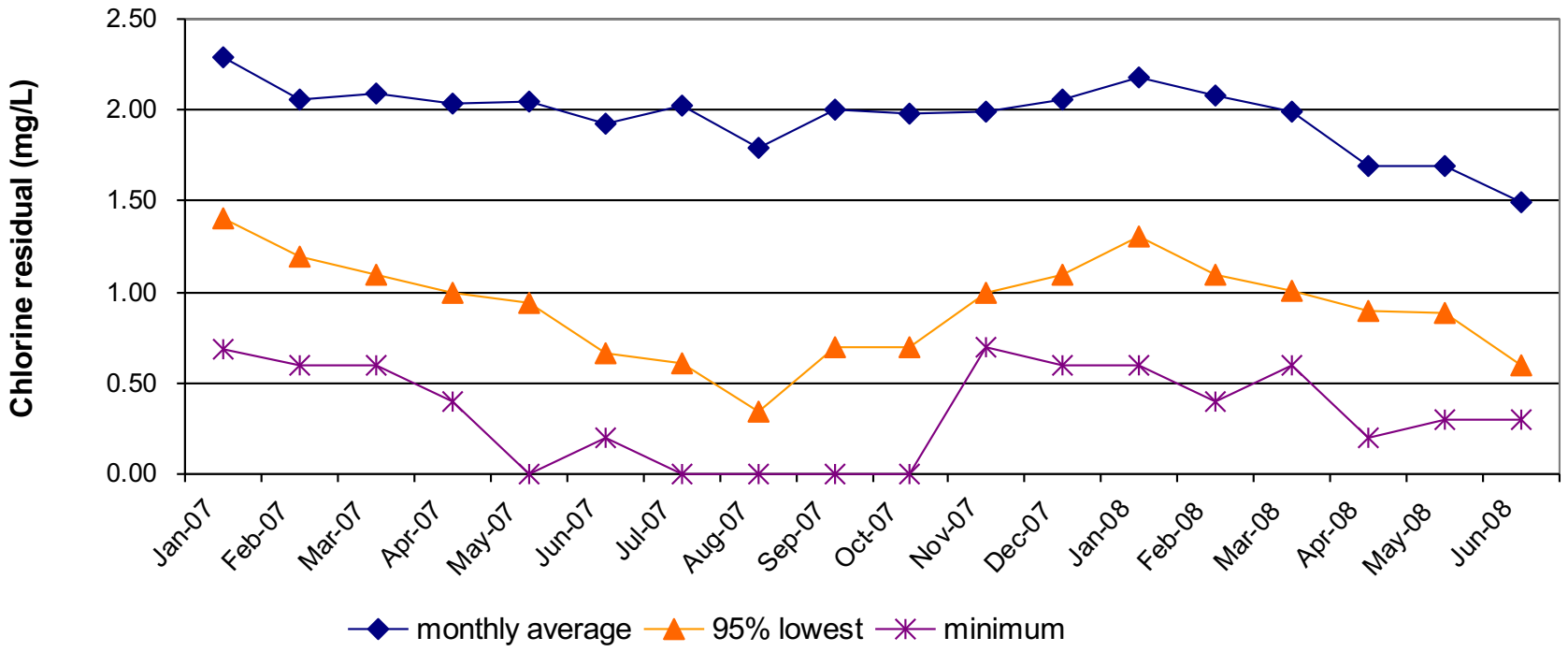
Disinfectant Residual Performance Assessment

Performance Goals:

- **Chlorine residual 95% > 0.2mg/L free chlorine or > 0.5 mg/L total chlorine (chloramine systems)**
- **Chlorine residual may not be undetectable for two consecutive months**
- **Monitoring based on a representative system wide plan consisting of key sites and compliance sites:**
  - Stage 1 & 2 DBP sites, TCR and tank sites and all pressure zones
  - The minimum number of sites should be population based
  - Monthly minimum monitoring
  - Sample taps flushed to be representative of water in the main
  - Testing conducted using colorimeter or online monitor

Friedman, M., G. Kirmeyer, J. Lemieux, M. LeChevallier, S. Seidl, and J. Routt. 2010. Criteria for Optimized Distribution Systems. Water Research Foundation, Denver, CO.

Disinfectant Residual Monitoring: example



Meets 95% >0.2 mg/L free chlorine, but not 2 consecutive months >0

Friedman, M., G. Kirmeyer, J. Lemieux, M. LeChevallier, S. Seidl, and J. Routt. 2010. Criteria for Optimized Distribution Systems. Water Research Foundation, Denver, CO.

Strategy For Managing Distribution System Integrity

Chloraminated Systems

- **Control Intrusion**
  - Pressure Management
  - Leak Detection
  - Main Break/Repair
  - Sewer Separation/Leakage
- **Nitrification Control**
  - Control Water Age
- **Cross Connection Control**
- **Corrosion Control/Material Compatibility**
- **Maintain Storage Facilities**
- **Security**

Free Chlorinated Systems

- **Control Biofilms**
  - Organic Carbon Control
  - Measure/Reduce AOC
  - Disinfectant Residuals
  - Biological Treatment
- **DBP Control**
  - Control Water Age
- **Cross Connection Control**
- **Corrosion Control/Material Compatibility**
- **Maintain Storage Facilities**
- **Security**