AMERICAN WATER

Risk Modeling of Microbial Control Strategies for Main Breaks and Depressurization

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Industry Standards
AWWA C651-05 Disinfecting Water Mains

- **Three disinfection methods for both new construction and repairs:**
  - Tablet method
    - Typical for new construction
    - Places calcium hypochlorite tablets at intervals along the pipe crown
    - Dose 25 mg/L with a detectable chlorine residual at the end of 24 hours
  - Continuous feed method
    - The water main filled water at a dosage of at least 25 mg/L 24 hours
    - Should have a residual of at least 10 mg/L
  - Slug method
    - Flow water through the pipeline with at least 50 mg/L for three hours

- **Preliminary flushing (>2.5 ft/sec) for the continuous feed and slug methods**
  - To eliminate air pockets and remove particulates
  - For 24-in or larger mains, a flushing alternative is to broom-sweep the main

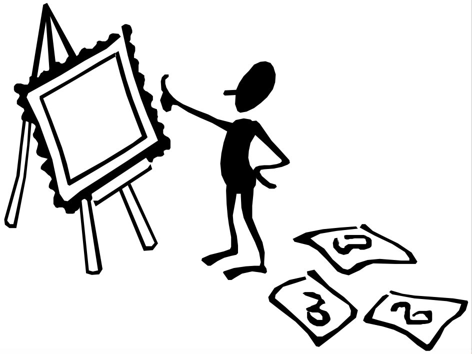
- **Verification of disinfection requires two clean coliform samples taken 24 hr apart, Turbidity, pH, and HPC samples may also be collected.**

Project Objectives

1. To improve utility responses to main breaks and depressurization events to better protect public health.

2. To evaluate the effectiveness of disinfection and flushing practices to mitigate risks.

3. To identify parameters to quantify the level of risk control achieved.



Project Tasks

Task 1: Define Terminology and Establish the Baseline of Practice

Task 2: Conduct Laboratory, Pilot Studies and Risk Modeling

1. Microbial Risk Modeling
2. Flushing Effectiveness
3. Disinfectant Decay and Microbial Inactivation

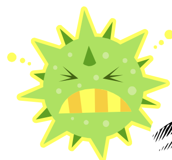
Task 3: Identify/Pilot Test Field and Monitoring Activities

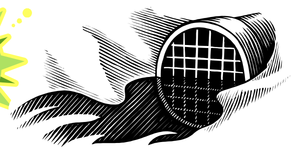
Task 4: Develop Tiered Risk Management Strategy Including Multiple Barriers

Task 5: Prepare Work Products and Final Report

Microbial Risk Modeling (Concept)

1. Pathogen levels in sewage (Meta-analysis of occurrence levels from literature)





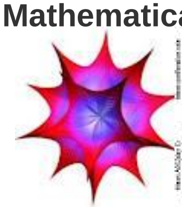
2. Main breaks and depressurization (Sewage intrusion and dilution)

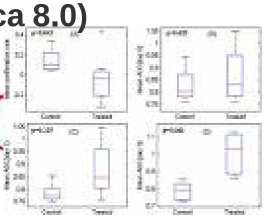
3. Main break repairs and back to service: a) Flushing; b) Disinfection

4. Individual water intake

5. Dose-response models (Collected from literature)

6. Risk characterization (Monto-Carlo simulations in Mathematica 8.0)

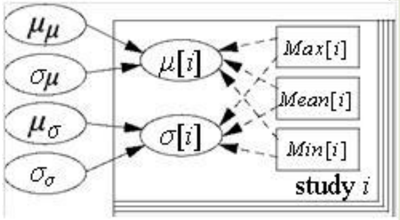




7. Risk management options
a) Compare with an acceptable annual risk of 10^{-4}
b) Flushing, disinfection, boil water advisory, etc.

Risk Model (1) Source of Contamination

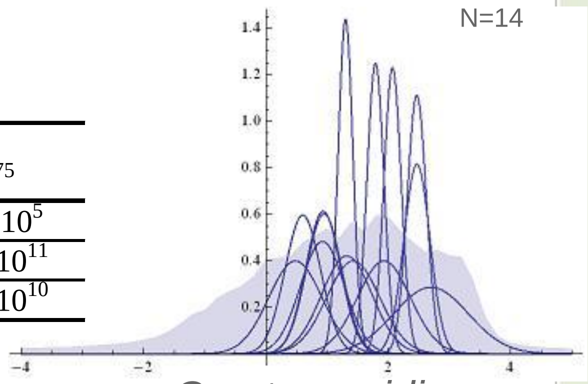
Overall 56% (18/32) of samples near water pipes were positive for viruses: enteroviruses, Norwalk, and Hepatitis A virus (Karim et al. 2003, *JAWWA*)



Sewage Pathogen Levels

- **Meta-analysis of occurrence levels in literature**

Pathogens/Indicator	Geometric Mean	$Q_{0.025}$	Median	$Q_{0.0975}$
Cryptosporidium	2.58×10^{1}	2.03×10^{-3}	2.84×10^{1}	2.41×10^{5}
E coli O157:H7	3.19×10^{3}	1.57×10^{-7}	5.21×10^{3}	2.47×10^{11}
Norovirus	1.59×10^{4}	1.98×10^{-4}	2.38×10^{4}	1.39×10^{10}



Cryptosporidium

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Risk Model (2-4)

(2) Intrusion Dilution

- 300 feet pipe depressurized
- Intrusion of 0.1 - 100 gal of sewage
- Dilutions of 99 to 99.99%

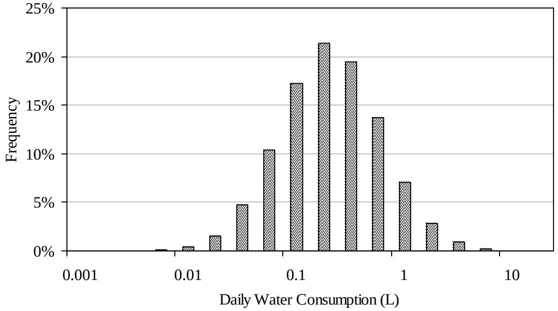
	Invtrusion Vol (gal)			
Diameter	**0.1**	**1**	**10**	**100**
4	0.05%	0.51%	5.11%	51.06%
6	0.02%	0.23%	2.27%	22.69%
8	0.01%	0.13%	1.28%	12.76%
10	0.01%	0.08%	0.82%	8.17%
12	0.01%	0.06%	0.57%	5.67%
16	0.00%	0.03%	0.32%	3.19%
24	0.00%	0.01%	0.14%	1.42%
36	0.00%	0.01%	0.06%	0.63%
72	0.00%	0.00%	0.02%	0.16%

(3) Pathogen Levels after Main Break Repairs

- Removed by flushing
- Inactivated by disinfection
- Determined by lab studies shown in later slides

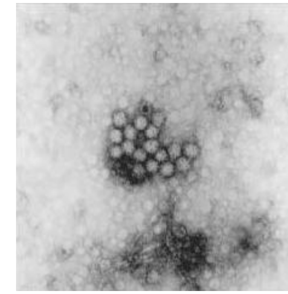
(4) Individual Water Intake

- Unheated tap water intake from a population survey (Teunis et al. 1997)
- Lognormal distribution with a median water consumption of 0.18 liter

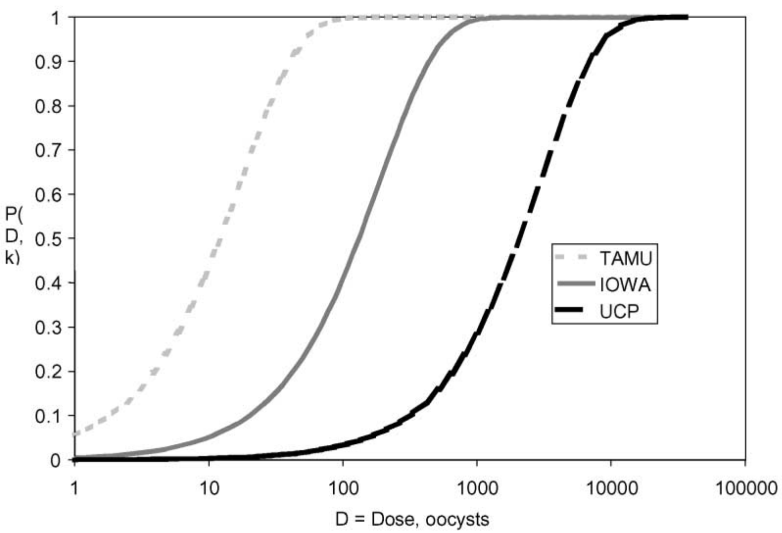


Risk Model (5) Dose Response Models

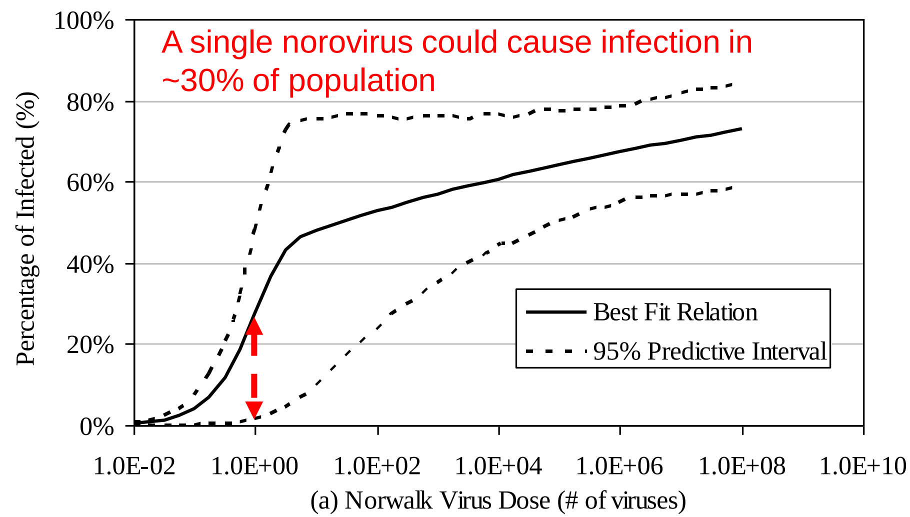
- Collected from literature
- Human feeding studies for various pathogens
- Determined the probability of infection



ID_{50} of18 viruses (dispersed)

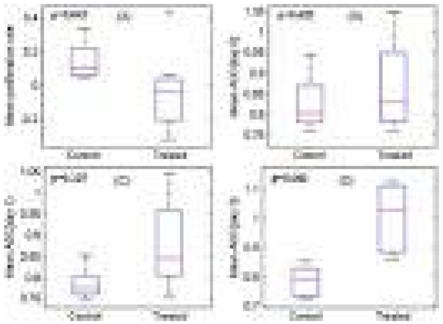


A single oocyst could cause infection in 2.8% of population



Risk Model (6-7)

(6) Risk Characterization



- Monto-Carlo simulations (10,000 repetitions or more)
- During each repetition, random generated
  - External pathogen levels
  - Pathogen reduction by dilution, flushing, or disinfection
  - Individual water intake
  - Pathogen infectivity

(7) Risk Management Options

- Baseline risk levels (dilution only)

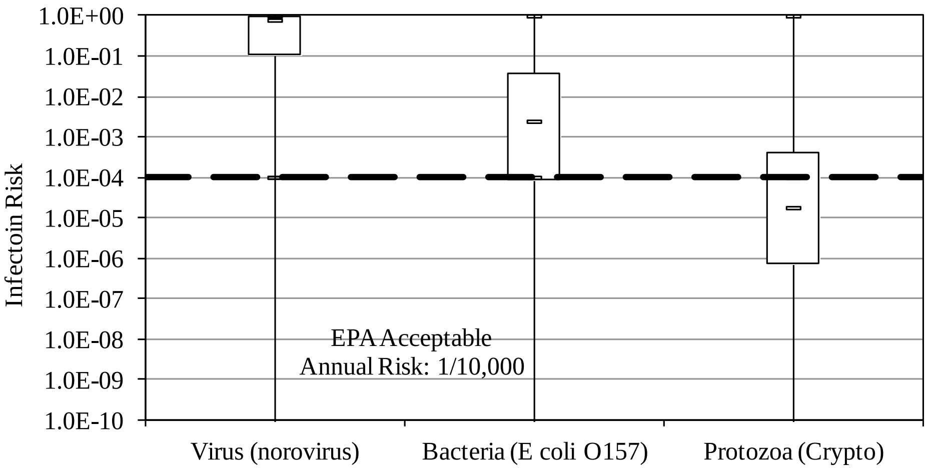
- Risk levels after dilution + flushing

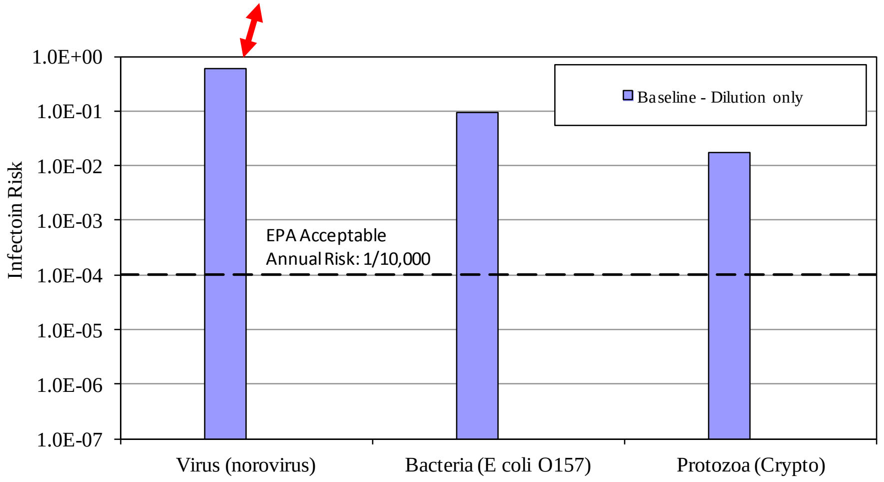
- Risk levels after dilution + flushing + disinfection

What are the baseline risk levels?

- Main break and depressurized
- Sewage intrusion 0.01-1.0% (i.e., 2-4 log of dilution)
- No flushing or disinfection

Significant risks, especially from virus (Mean risk of 0.59)

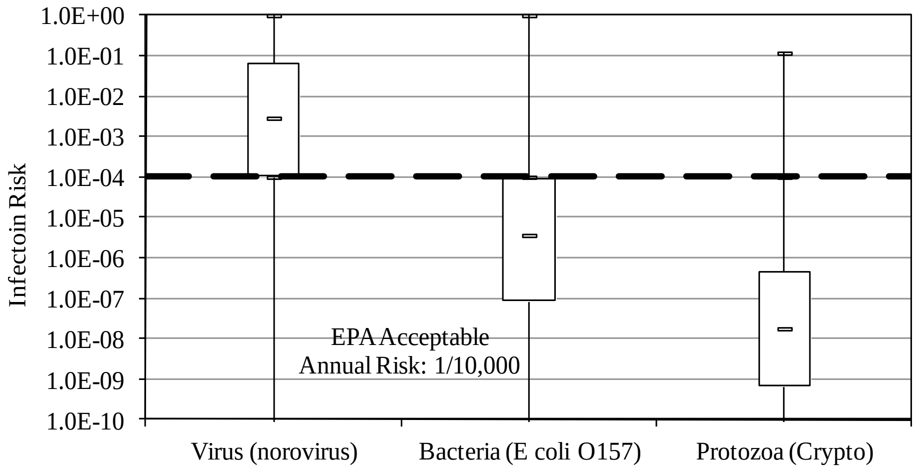


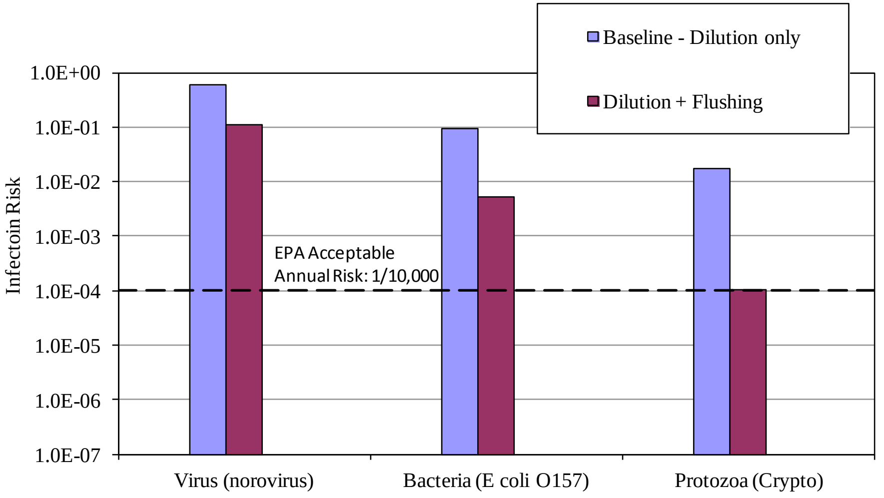


Randomness of infection risks

How effective is flushing to reduce the risks?

- **Pathogens attached to soil particles**
  - **All suspended pathogens removed by flushing**
  - **Assume flushed at a velocity above the threshold velocity and achieved 2-3 log removal**



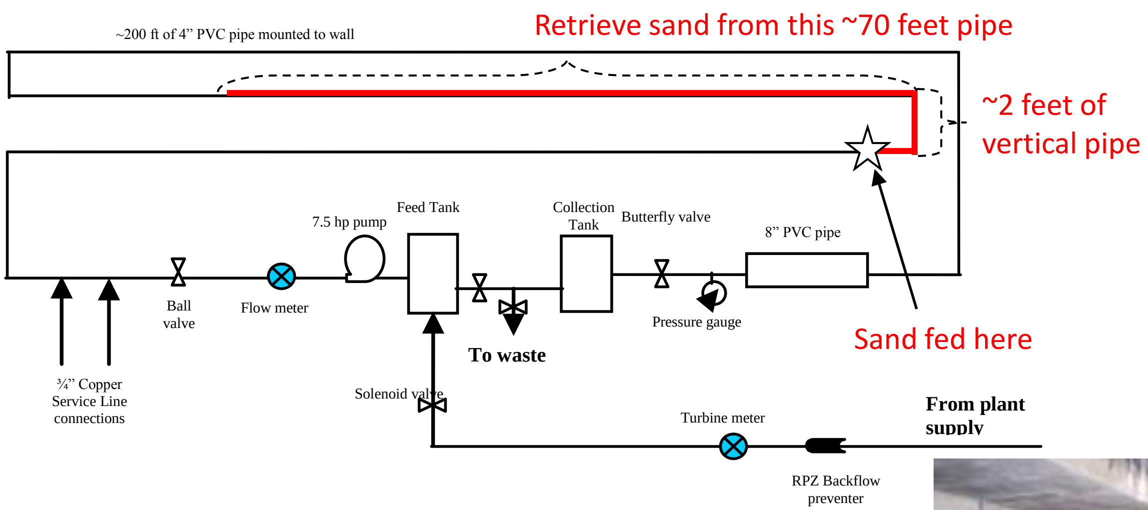


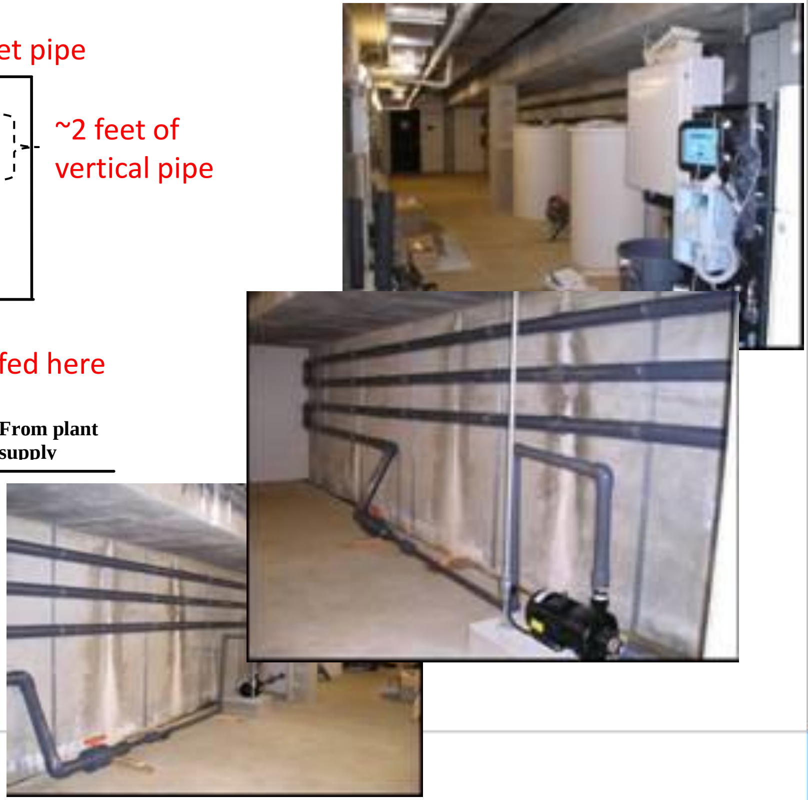
Infection risks reduced by 2-3 logs

Flushing is effective, some risk may still remain high (e.g. mean risk of 0.11 for virus).

Flushing Experiments

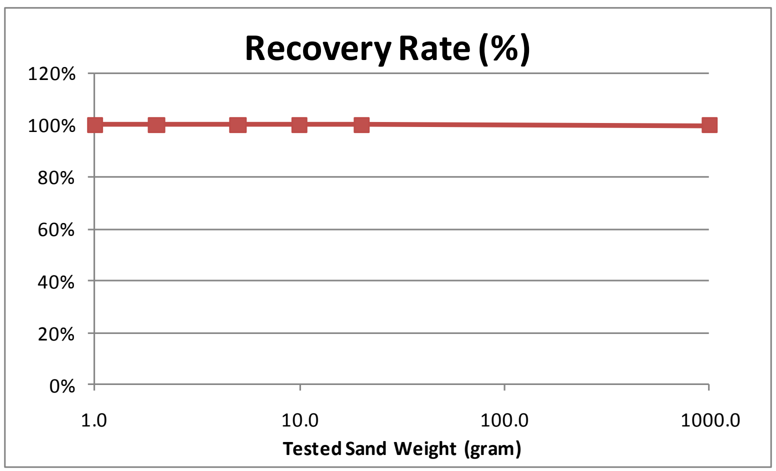
- **Evaluate flushing effectiveness on particle removal**
  - Using sand as surrogate for soil particles (conservative)
  - Flushing velocity and duration
  - Particle size, biofilm, and tuberculation





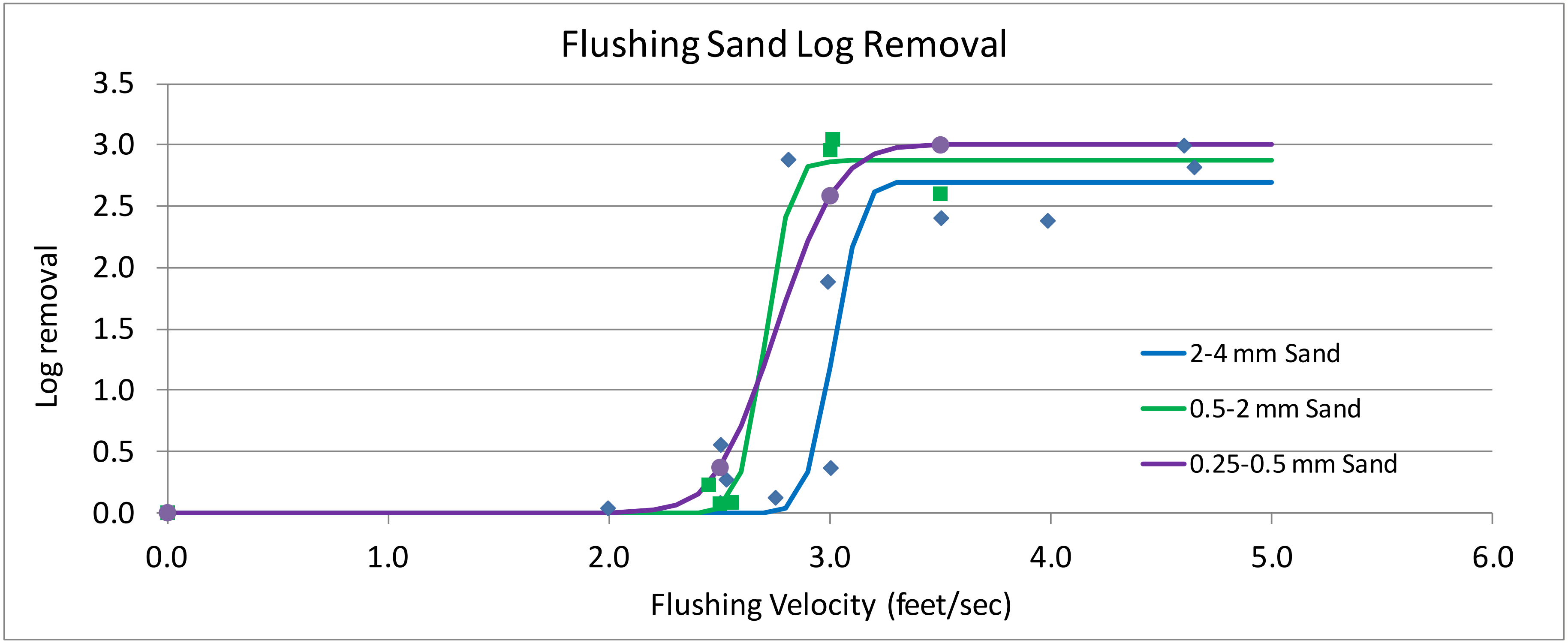
Flushing Results – Recovery Test

- **Residual sand retrieved by double “U” wash**
  - 2-4 mm sand from 1 to 1,000 grams
  - 99.9% to 100% recovery



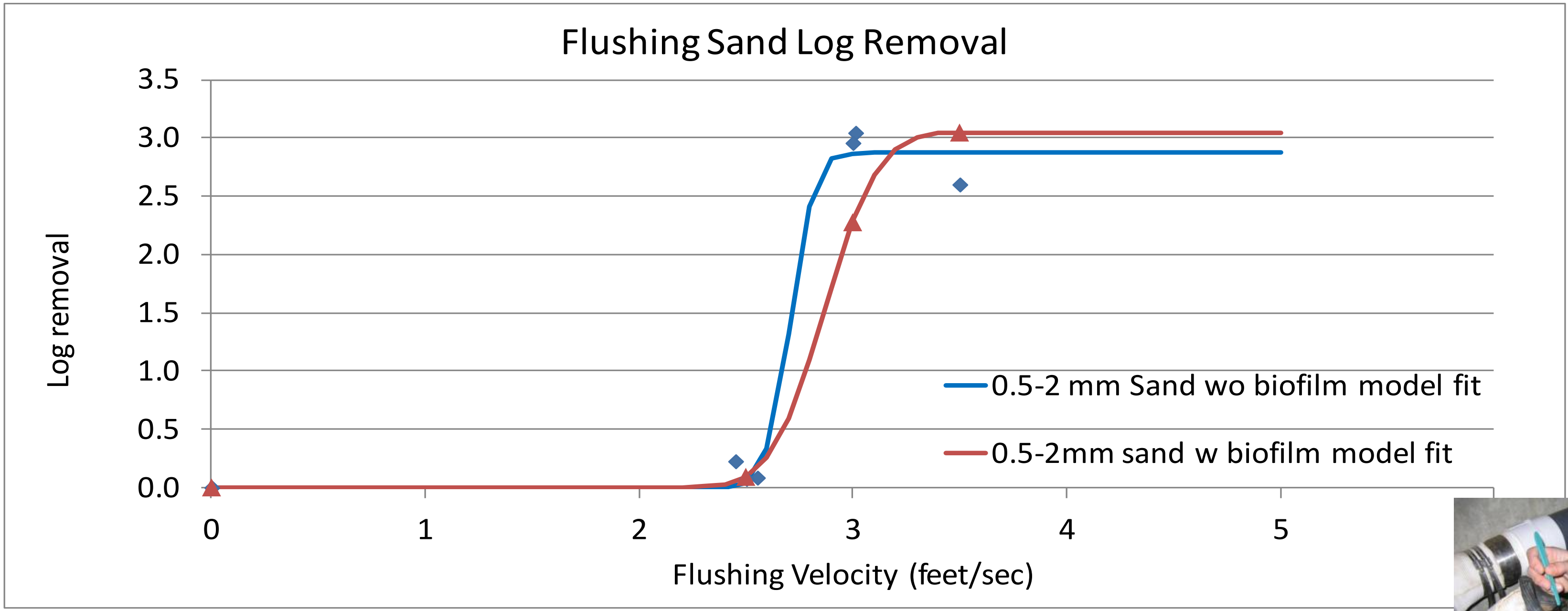
Flushing Results – Sand Size

- **Flushing 1 kg of sand of difference sizes**
  - 2-4 mm; 0.5-2 mm; and 0.25-0.5 mm;
  - Similar threshold velocities (2.5-3.0 ft/sec) and removals (2.5-3.0 log);



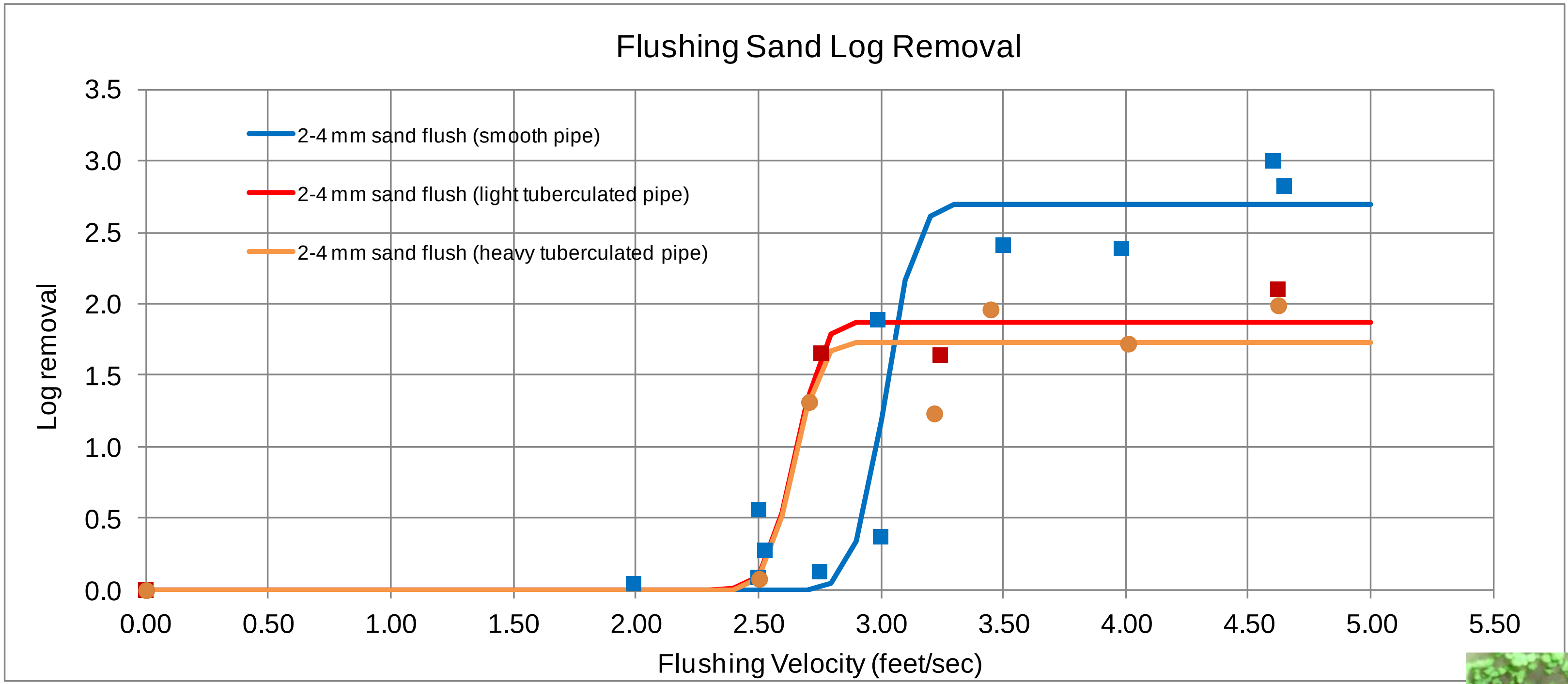
Flushing Results – Impact of biofilm

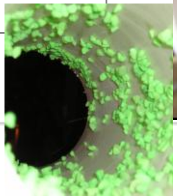
- **Biofilm cultivated for two weeks using 0.1% TSB nutrient broth**
  - ATP levels measured 0.29-1,400 pg/cm^2 and HPC measured 3.4x10^7-3.8x10^7 HPC/cm^2, typical biofilm densities in water distribution systems;
  - No impact on flushing;



Flushing Results – Impact of Tuberculation

- **PVC pipe inside glued with small gravels to simulate tubercles**
  - Smooth, light tuberculation, and heavy tuberculation
  - Sand removal reduced by 1-log (from ~2.7 to 1.7 log);





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Flushing Result Implications

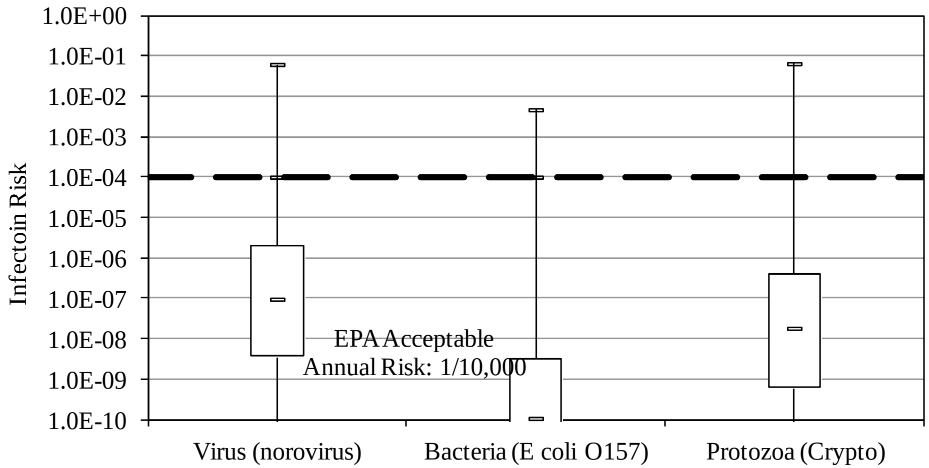
- **Flushing >3.5 ft/sec may remove soil-attached pathogens by 2.5-3.0 log (using sand as surrogate for soil particles).**

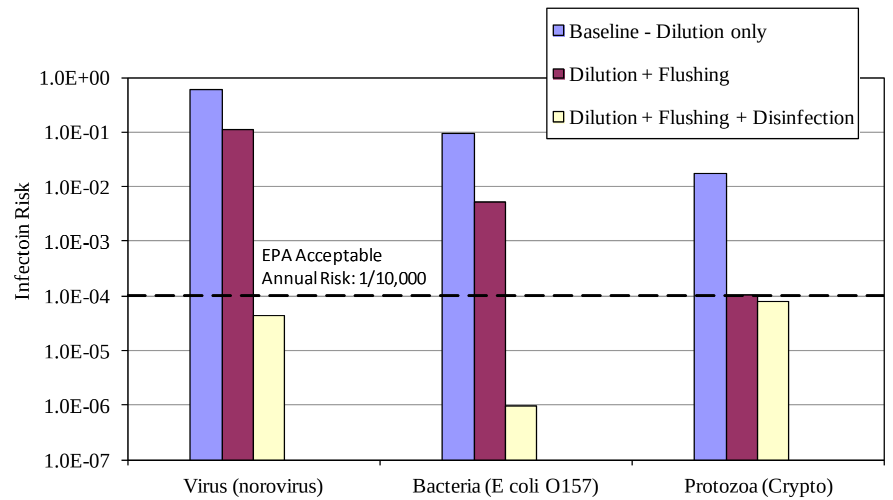
- **For heavily tuberculated or larger diameter (>16-in) pipes, flushing may not be as effective. More disinfection may be necessary. The *Crypto* infection risk may become the controlling risk.**

Flushing Metrics				
Diameter (inch)	Volume per 100 Feet Pipe (gal)	Minimum Required Flow Rate (gpm) 3 feet/sec	Minimum Required Flow Rate (gpm) 4 feet/sec	Minimum Required Flow Rate (gpm) 5 feet/sec
4	60	120	160	200
6	140	270	360	450
8	260	480	630	790
10	400	740	980	1,300
12	580	1,100	1,500	1,800
14	790	1,500	2,000	2,400
16	1,040	1,900	2,600	3,200
18	1,320	2,400	3,200	4,000
20	1,630	3,000	4,000	4,900

How effective is disinfection to reduce the risks?

- What levels of disinfection will be needed for risk reduction?
  - Disinfection had no reduction on the *Crypto* levels
  - Need 4-5 logs of inactivation of virus and bacteria





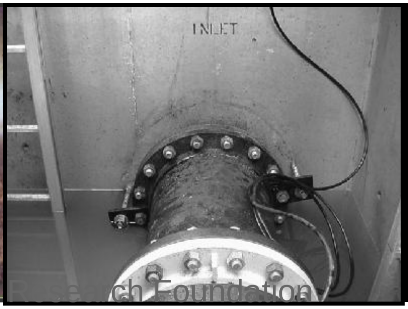
Virus and bacteria infection risks reduced by 4-5 logs, *Crypto* infection risk remained the same

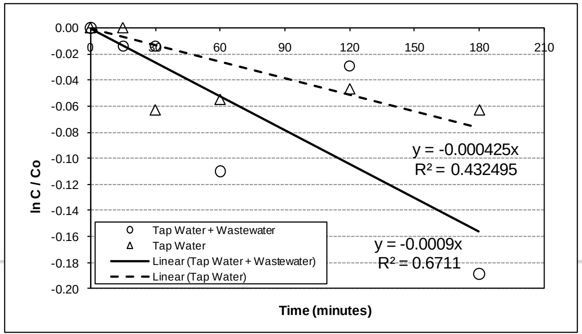
Mean risks of all three pathogens are below the 1/10,000 level.

Disinfection Studies

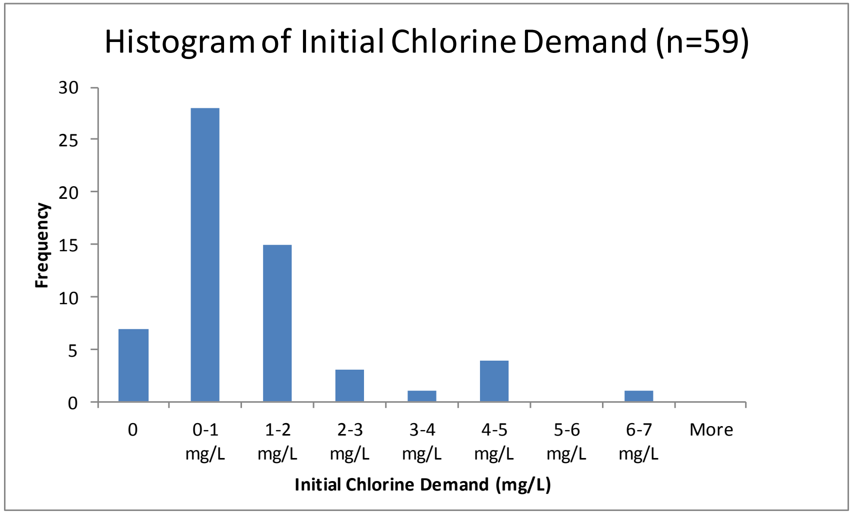
Batch disinfection kinetics studies to be conducted in continuously-mixed glass reactors (maintained at 10ºC)

- Each conducted using at least three reactors per run, each containing 1,000 mL tap water.
- While two reactors are maintained as controls (disinfectant and microbe), water from pits or wastewater influent/effluent will be added to the other reactor at 0.01, 0.1%, or 1% of the water volume.
- 5 samples were collected from 4 sample types (sewage, valve boxes, meter chambers, excavation pits).
- Chlorine or chloramine residuals monitored over three hours with data collected at 0, 5, 15, 30, 60, 120, and 180 minutes.
- Compare disinfectant demand in the test reactor to the control.

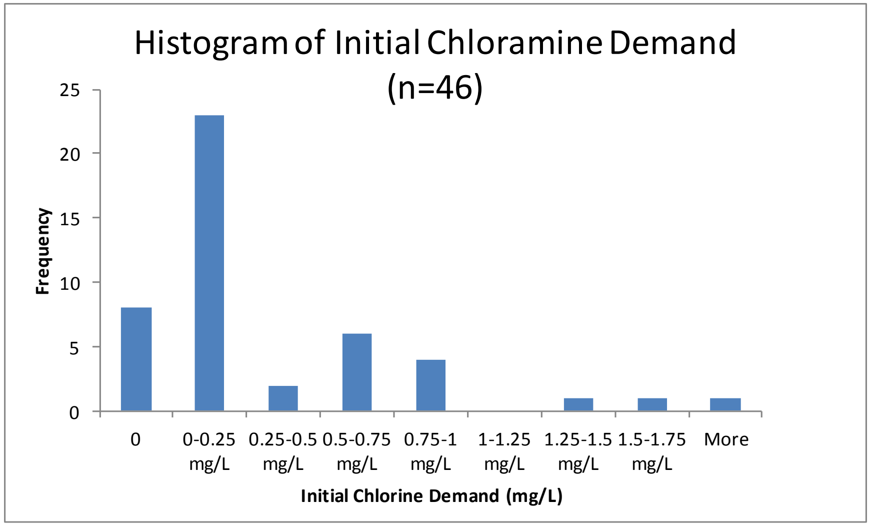



Disinfectant Decay



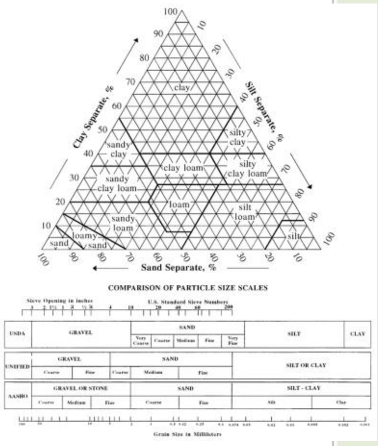
- Initial chlorine demands mostly 0-2 mg/L, up-to 7 mg/L
- Initial chloramine demands mostly less than 1 mg/L
- N = 105 decay tests

Loss of a chlorine residual could be an indicator of water contamination after main break depressurization, while chloramine residuals may be equivocal.



Impact of Particle Shielding from Disinfection

- **Suspended pathogens removed by flushing (no risk), soil-attached pathogens control the risk**



- **Soil particles include**
  - Coarse-grained soils (e.g. sand, specific weight about 2.7)
  - Fine-grained soils (e.g. silts and clays)
  - Highly organic soils or “peat” (lightest of the three)

- **Inactivation experiment of soil-attached pathogens**
  - *Crypto* resistant to free chlorine and chloramines
  - Chloramine disinfection not effective for virus
  - Experiments focused on chlorine disinfection of soil-attached virus and bacteria

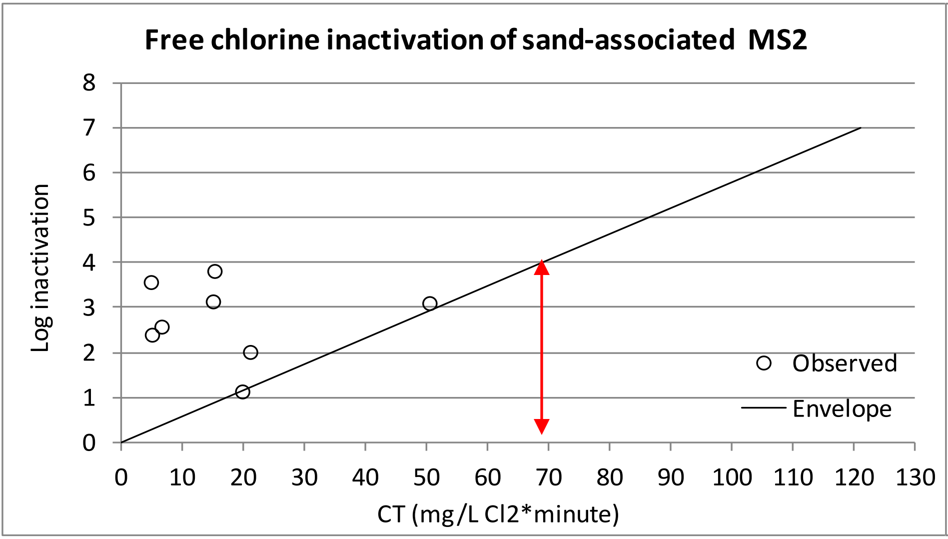
Experimental Approach

- Ten (10) reactors: One control (no chlorine), triplicate reactors for 5, 15, and 60 minute disinfection
- Free chlorine residual boosted to 1-25 mg/L (*CT* up to 1,500 mg/L Cl_2*min)
- Inclusion of particles (bentonite clay, quartz sand, or fine grain peat)
- Incubate *E. coli* (1mL) and coliphage MS2 (1mL) with the filter effluent and the particles overnight on a shaker at room temperature $22 \pm 2^{o}C$ (to attach microbes)
- Washed three times with 100 ml of phosphate buffer, and re-suspended in the phosphate buffer before the disinfection
- After disinfection for 5, 15, or 60 minutes, quenched with sodium thiosulfate, centrifuged at 1120 rcf (4 minutes), and re-suspended in 30 mL biofilm buffer.
- The suspension was homogenized at 13,000 rpm for 30 sec.
- Plated on m-Endo LES agar for *E. coli* and the double layer agar for MS2

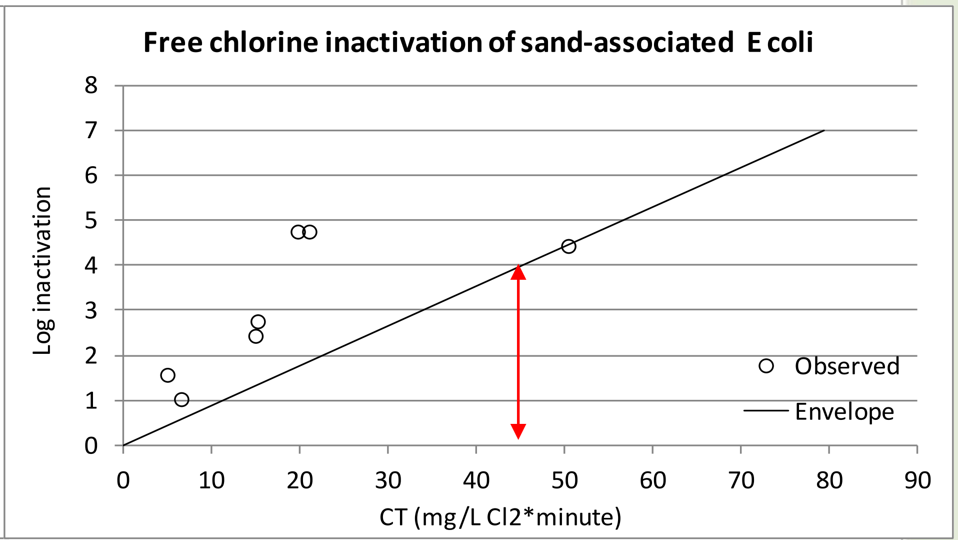
Camper, A.K., M.W. LeChevallier, S.C. Broadaway, and G.A. McFeters, 1985. Evaluation of procedures to desorb bacteria from granular activated carbon, J. Microbiol. Methods. (3): 187–198.

Inactivation of Sand-Attached MS-2 and *E Coli*

Virus (MS-2)



Bacteria (*E Coli*)



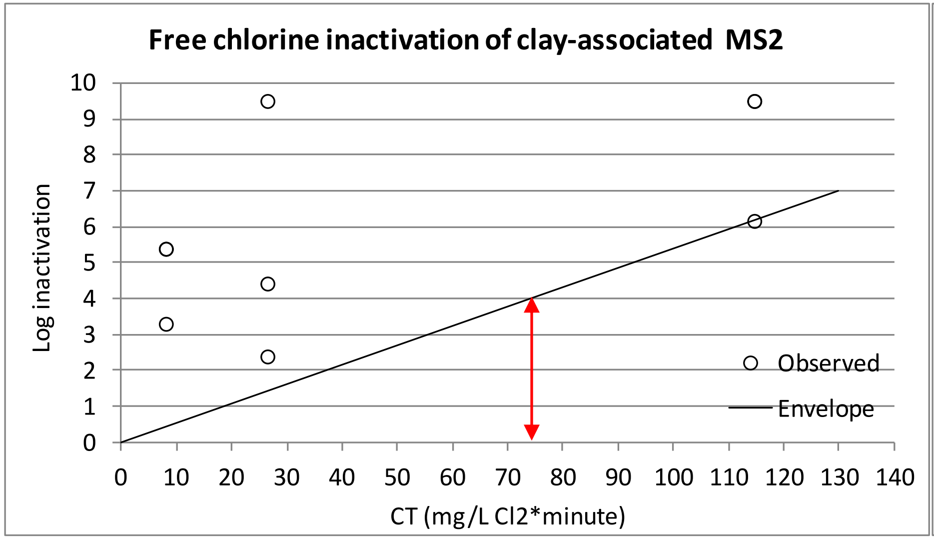
- **Significant data variations, envelop used (conservative)**
- **The effectiveness of chlorine disinfection slightly reduced**
  - 4-Log inactivation of sand-associated MS-2 and *E coli* need a higher *CT* of 69 and 45 mg/L Cl_2*min

Inactivation of Clay-Attached MS-2 and *E Coli*

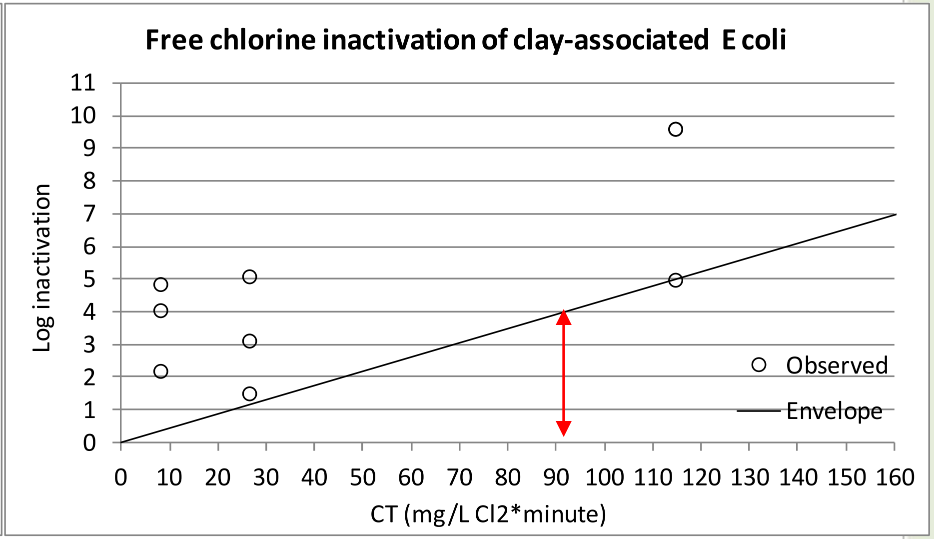
- **The effectiveness of chlorine disinfection slightly reduced**
  - 4-Log inactivation of clay-associated MS-2 and *E coli* need a higher *CT* of 74 and 92 mg/L Cl_2*min

Clay provided slightly more protection from chlorine disinfection compared with sand.

Virus (MS-2)

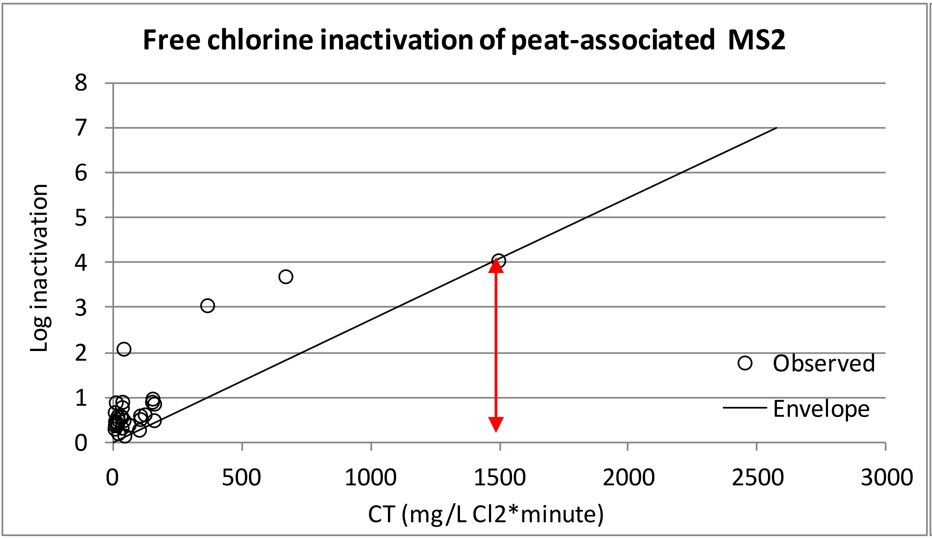


Bacteria (*E Coli*)

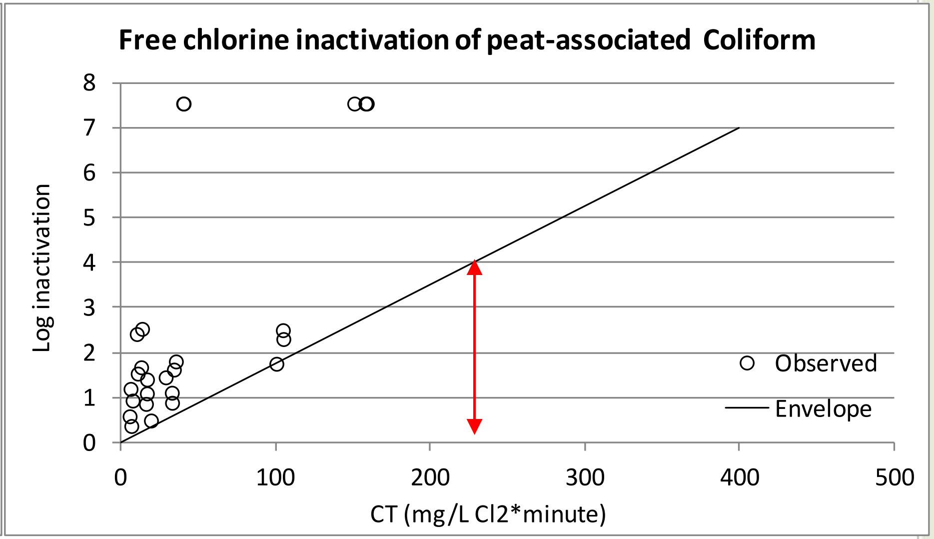


Inactivation of Peat-Attached MS-2 and *E Coli*

Virus (MS-2)



Bacteria (*E Coli*)



Peat particles appeared to provide the most protection compared with clay and sand particles.

- ***E Coli***
  - 4-Log inactivation with a *CT* of 230 mg/L Cl_2*min
- **MS-2**
  - 4-Log inactivation with a *CT* of **1,500** mg/L Cl_2*min (e.g., 100 mg/L Cl_2 for 15 minutes)

Overall Main Break Risk Assessment (Conservative)

Intrusion of raw sewage

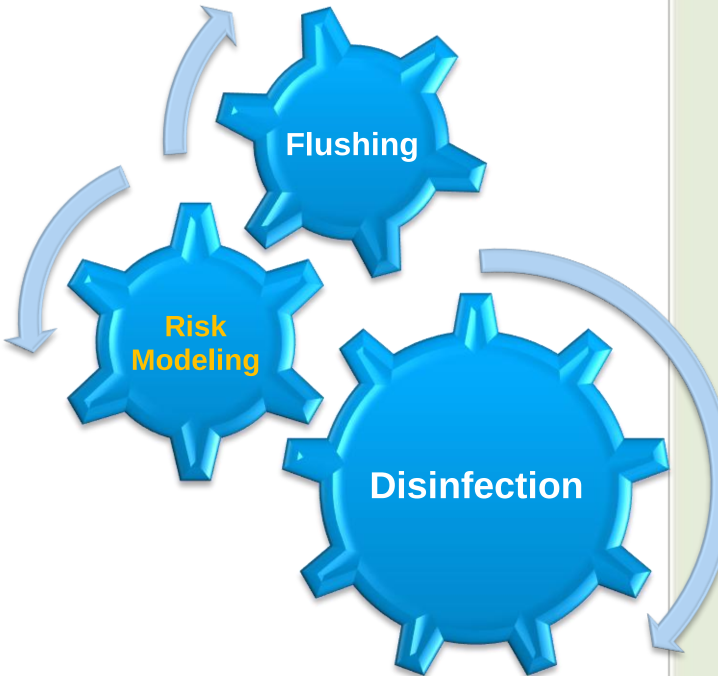
- Leaking sewage nearby, worst scenario (compared with pit waters)

Using sand as surrogate for flushing

- Sand is more difficult to flush, but provides minimal shielding from disinfection
- Lighter soil particles (e.g. peat) provide most protection, but easier to flush out.

Using the *CT* of peat-attached virus for disinfection

- Sand or clay: 4-log inactivation *CT* values for free chlorine up to 92 mg/L Cl_2*min
- Peat: 4-log inactivation *CT* values for chlorine up to 1,500 mg/L Cl_2*min



Effective Microbial Control Strategies for Main Breaks and Depressurization

Most breaks can be repaired without risk of contamination

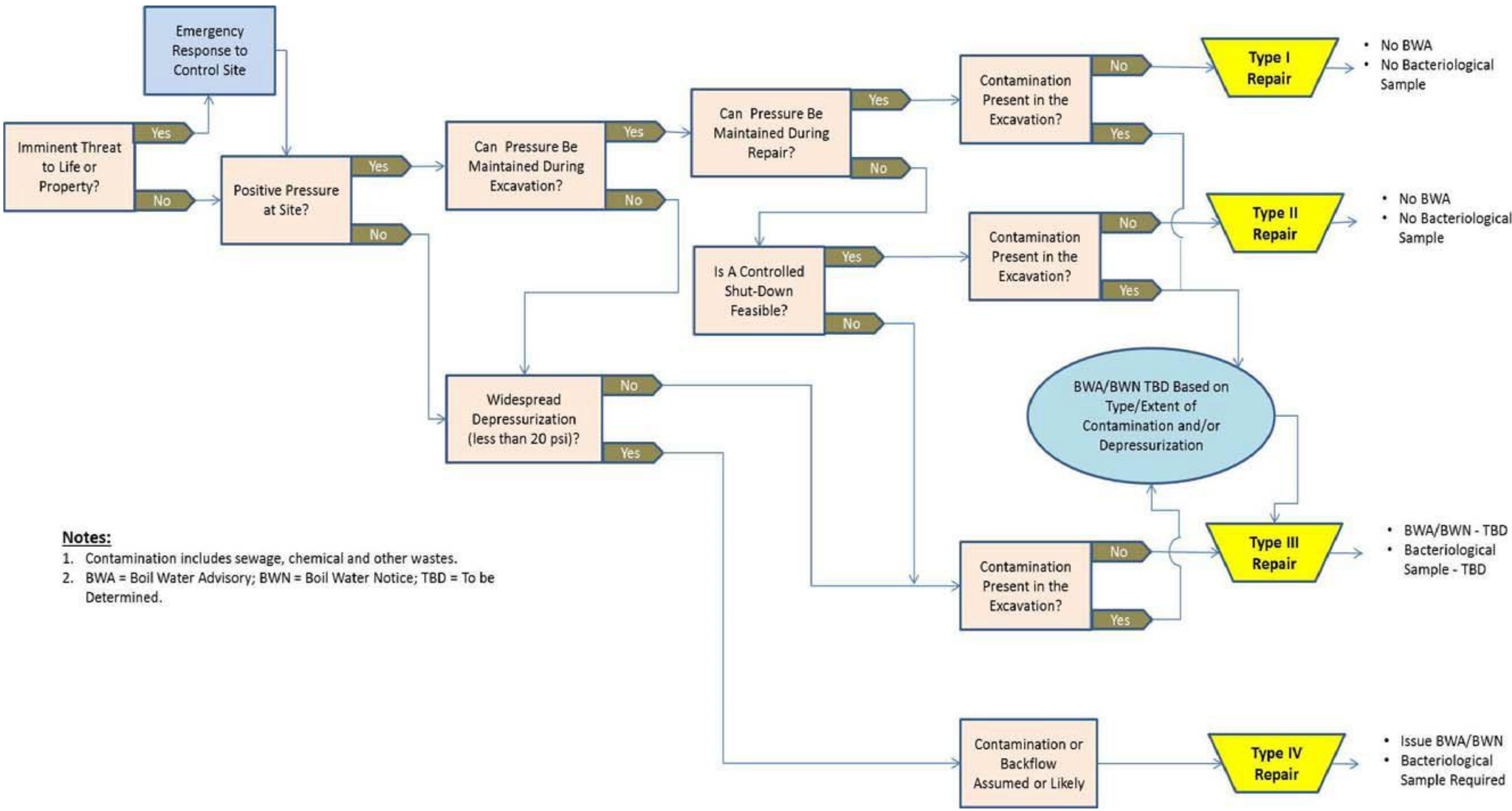
For severe breaks, procedures recommended to address and reduce risk

Type I Break	Type II Break	Type III Break	Type IV Break
• Positive pressure maintained during break	• Positive pressure maintained during break	• Loss of pressure at break site/ depressurization elsewhere in system	• Loss of pressure at break site/ depressurization elsewhere in system
• Pressure maintained during repair	• Pressure maintained until break exposed	• Partially or un-controlled shutdown	• Widespread depressurization
• No signs of contamination intrusion	• No signs of contamination intrusion	• Possible contamination intrusion	• Possible/ actual contamination intrusion

Main Break Repairs

Type I Break	Type II Break	Type III Break	Type IV Break
Excavate to below break	Excavate to below break	Uncontrolled shutdown	Catastrophic failure response
Maintain pit water level below break Repair under pressure	Maintain pit water level below break Controlled shutdown	Document possible contamination Disinfect repair parts	Document possible contamination Shut-off customer services in affected area
Disinfect repair parts Check residual disinfectant level in distribution system No Boil Water Advisory (BWA)	Disinfect repair parts Conduct low velocity flush (flush three pipe volume) Check residual disinfectant level in distribution system	Conduct scour flush (3 ft/sec) Conduct slug chlorination (CT of 100 mg/L-min) Check residual disinfectant level in distribution system	Disinfect repair parts Conduct scour flush (3 ft/sec) Conduct slug chlorination (CT of 100 mg/L-min)
No bacteriological samples	No Boil Water Advisory (BWA)	Instruct customers to flush premise plumbing upon return to service	Instruct customers to flush premise plumbing upon return to service
	No bacteriological samples	No BWA unless extent of depressurization is outside repair area No bacteriological samples unless depressurization is outside repair area	Check residual disinfectant level in distribution system Issue BWA/ Boil Water Order Bacteriological sampling required

Main Break Triage



Notes:
1. Contamination includes sewage, chemical and other wastes.
2. BWA = Boil Water Advisory; BWN = Boil Water Notice; TBD = To be Determined.

Summary

- **Site conditions and main break repair practices vary widely in the industry**
  - Age of infrastructure, rural versus inner city congestion, weather, soils, etc.
- **There is a lack of a technical basis and risk management structure for assessing the effectiveness of mitigations such as flushing and disinfection**
- **Lab studies were conducted to evaluate pathogen removal efficacies by flushing and disinfection**
  - Background disinfectant residuals may either be overcome by water contaminations (free chlorine) or not provide adequate inactivation of pathogens (chloramines).
- **A microbial risk model was developed to evaluate customer’s infection risks after a main break and depressurization event**
  - Virus is the controlling risk (7-log reduction needed).
  - Effective flushing would remove ~3-log particles and control the *Crypto* infection risk.
  - Additional 4-log virus inactivation (disinfection) is needed to control the virus infection risk.
  - Soil particles may protect virus from disinfection and 4-log inactivation *CT* values for free chlorine increase up to 100 mg/L Cl_2*min.

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Questions??

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