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Water Quality in the Distribution System

Thursday December 11, 2025; 1 – 2:00 EST

- Daryl Gotham PE, Senior Research Engineer

This program is made possible under a cooperative agreement with US EPA.

Water Quality in the Distribution System

- Overview of the Topic
- System Flushing
- Cross Connection Control
- Disinfection
- Monitoring

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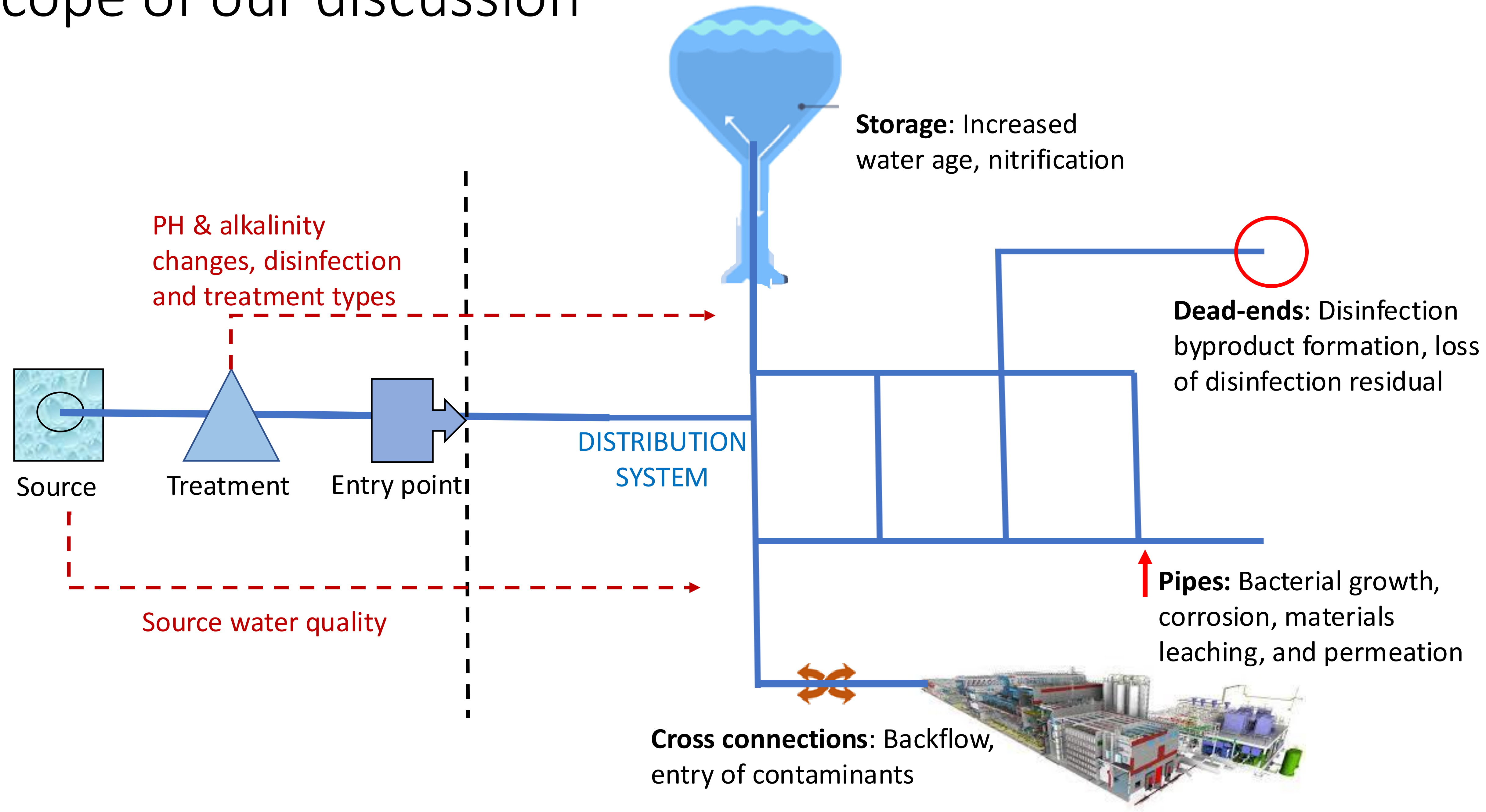
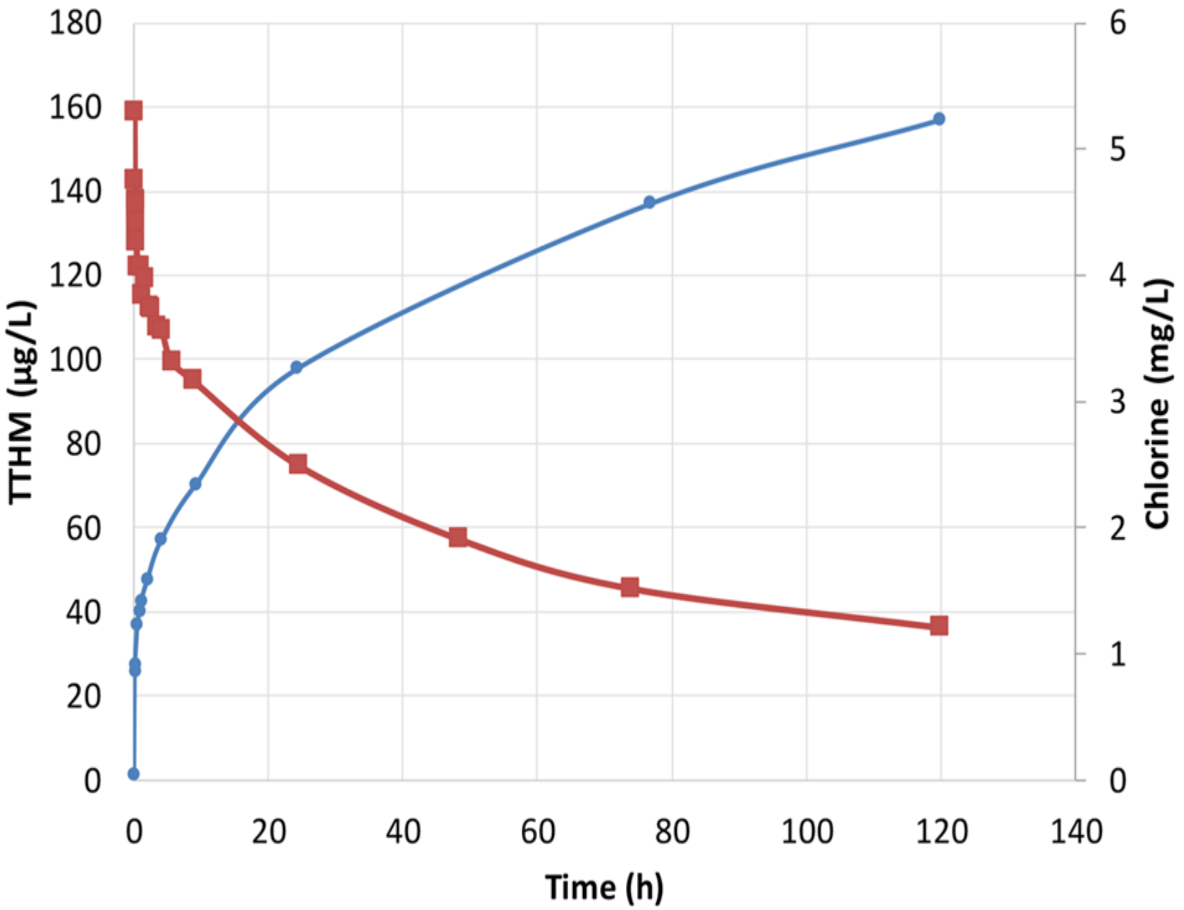
Scope of our discussion



Water age management

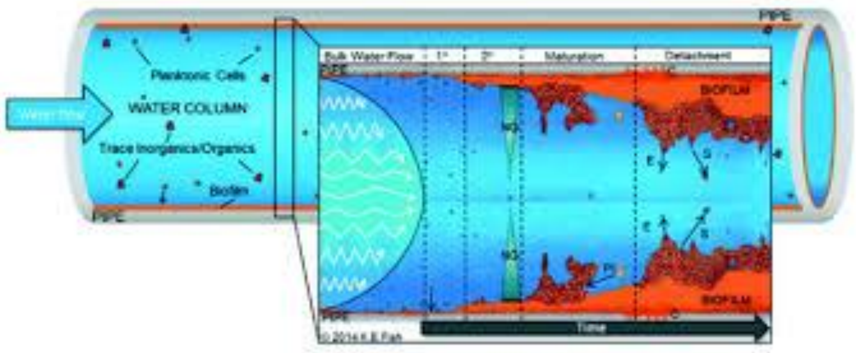
Management Practices

- Ensuring sufficient turnover in tanks
- Flushing and eliminating dead ends



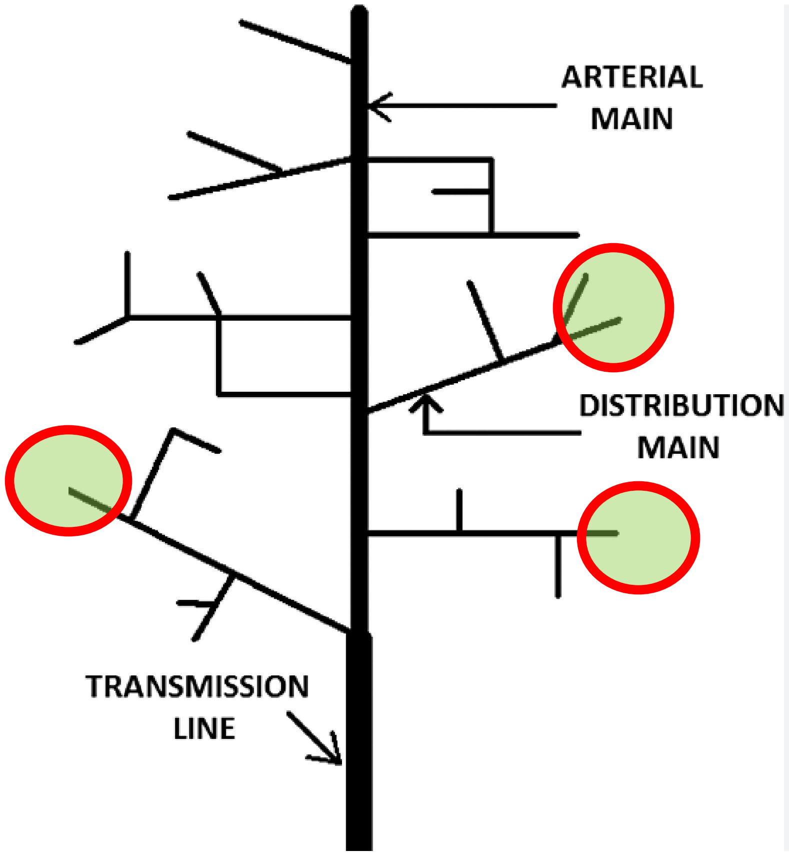
Factors associated with increased water age:

- Loss of disinfection residual
- Increased microbial activity
- Formation of disinfection byproducts
- Increased corrosion and tuberculation
- Nitrification in tanks and dead-ends



Water 2021, 13(18), 2574; https://doi.org/10.3390/w13182574
Monteiro, L. et al

Dead-ends



LeChevallier et al. (1996) found that distribution systems that have dead-ends with free chlorine residuals less than 0.2 mg/L had substantially more coliform occurrences (system-wide) than systems maintaining higher residuals.

Storage tank turnover

The time (in days) it takes for all the water in the tank to be exchanged with fresh water.

- For optimal performance it is recommended that turnover be less than 5 days.

A 0.5 MG storage tank receives an average flow of 175,000 gal/day. Calculate the turnover for this tank in days.

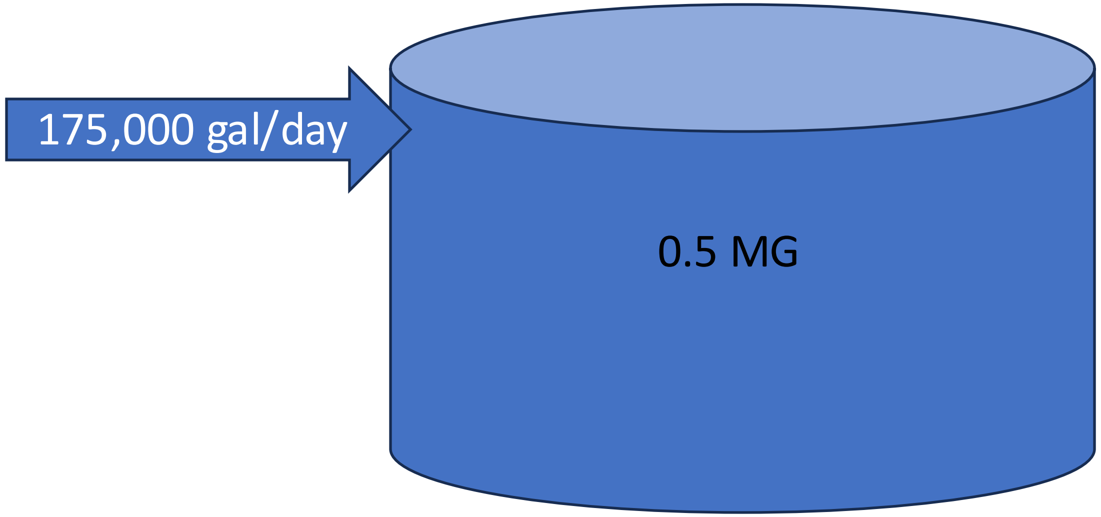
Solution:

Step 1: Convert 0.5 MG to gallons

0.5 MG x 1,000,000 gal/MG = 500,000 gallons

Step 2: Divide volume by flow

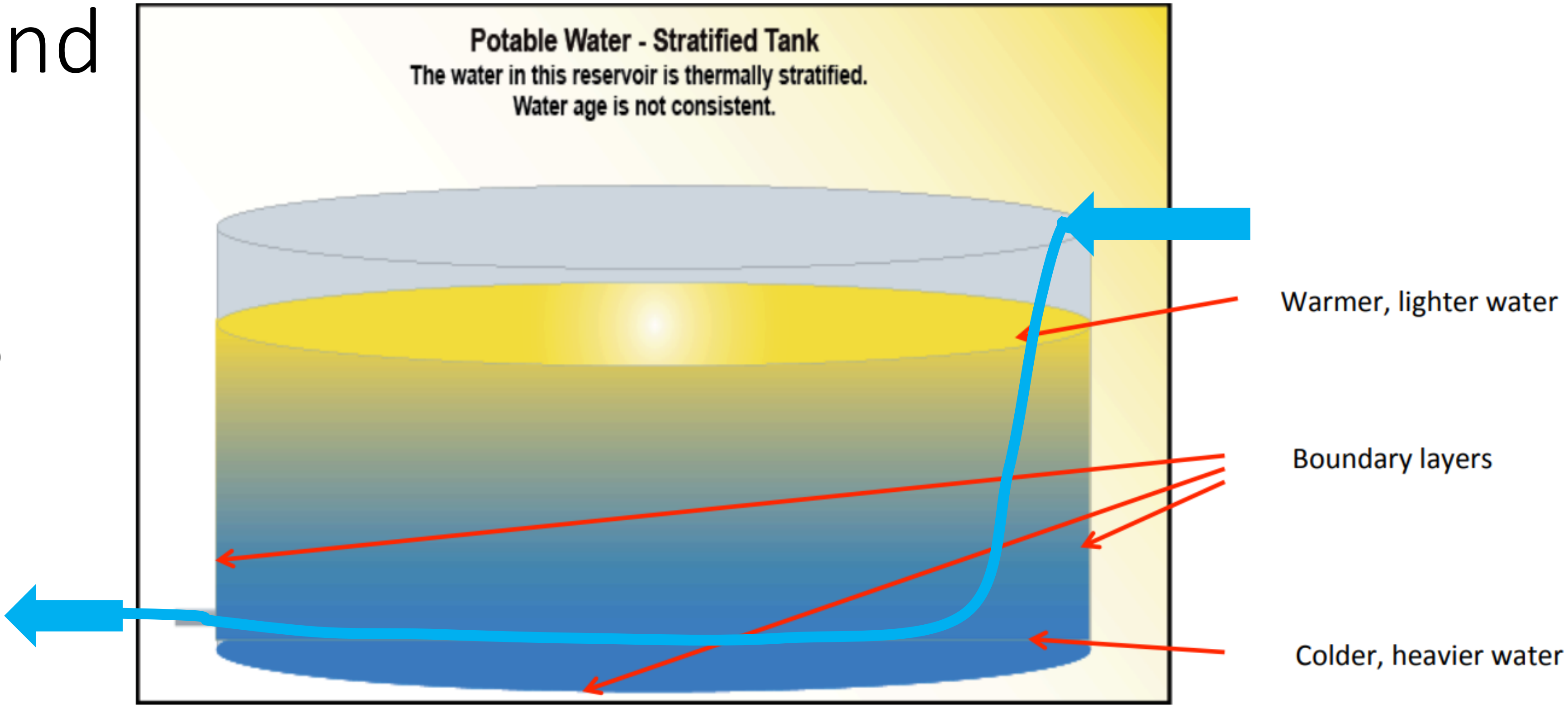
500,000 gal ÷ 175,000 gal/day = **2.86 days**

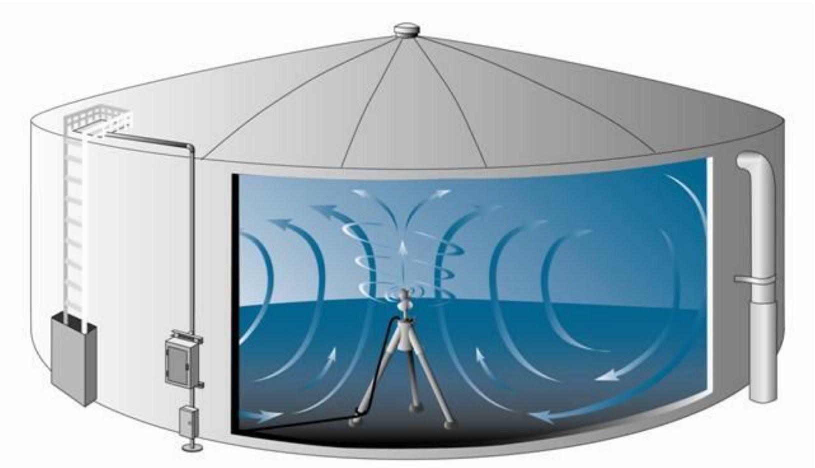


Short circuiting and tank mixers

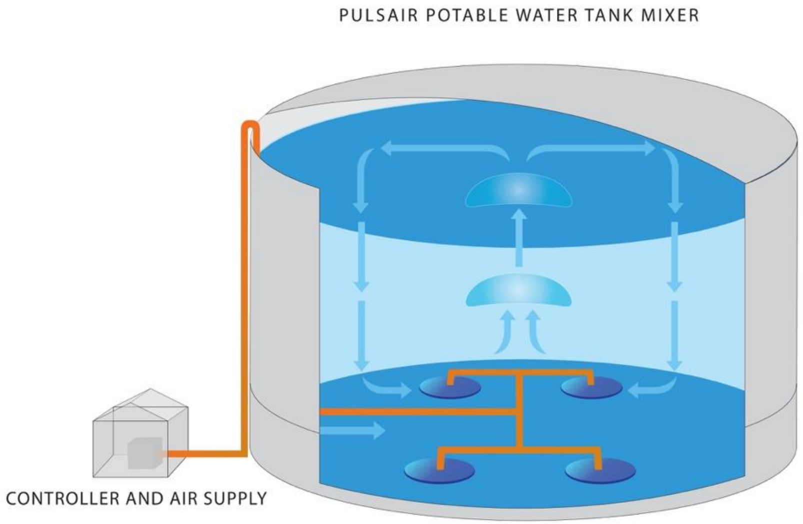
Short-circuiting in Tanks

Tank design can cause currents to flow too quickly from the inlet to the outlet. In thermal short circuiting, warmer water remains in tank longer while colder water short circuits from inlet to outlet quickly





Propeller type mixer



Aeration type mixer

Tank mixers reduce extreme differences in water age and help to limit DBP production

Water Quality Benefits of System Flushing

- Reduces water age
- Brings in new fresh chlorine residual to dead ends
- Reduces microbial growth
- Removes sediment from water mains
- Reduces disinfection byproduct formation

A flushing program also functions as a form of preventative maintenance because operators can confirm that hydrants and valves are operational and exercise them.

Flushing velocity and scouring

For distribution system cleaning it is recommended to attain a water velocity of between 2.5 and 5.0 feet per second to attain a scouring action.

Normally water moves relatively slowly through water mains, but during flushing the velocity is increased to dislodge and remove accumulated sediment, rust, and other deposits (such as iron and manganese, biofilms, & portions of scales).

Manganese in pipe

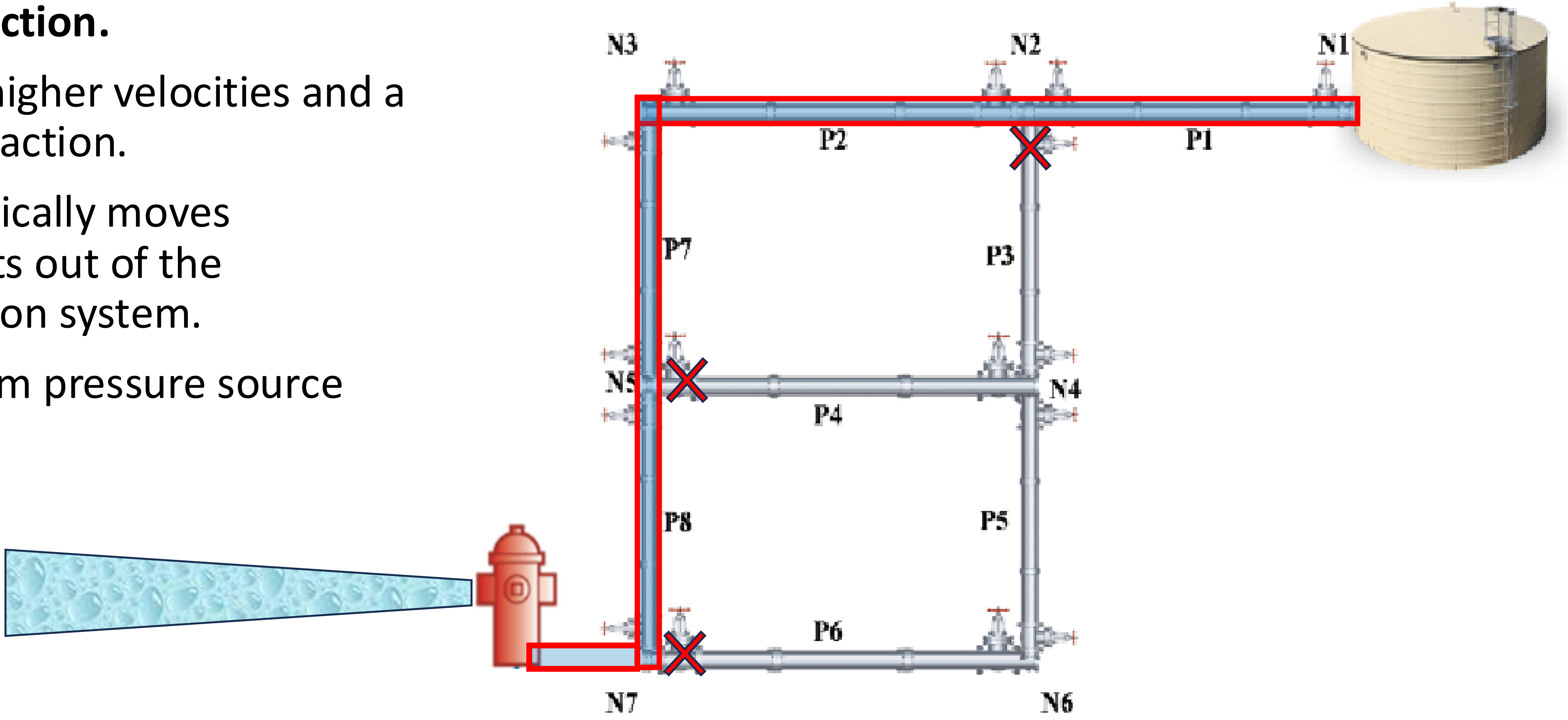
Rusty iron slime in pipe

biofilm in pipe

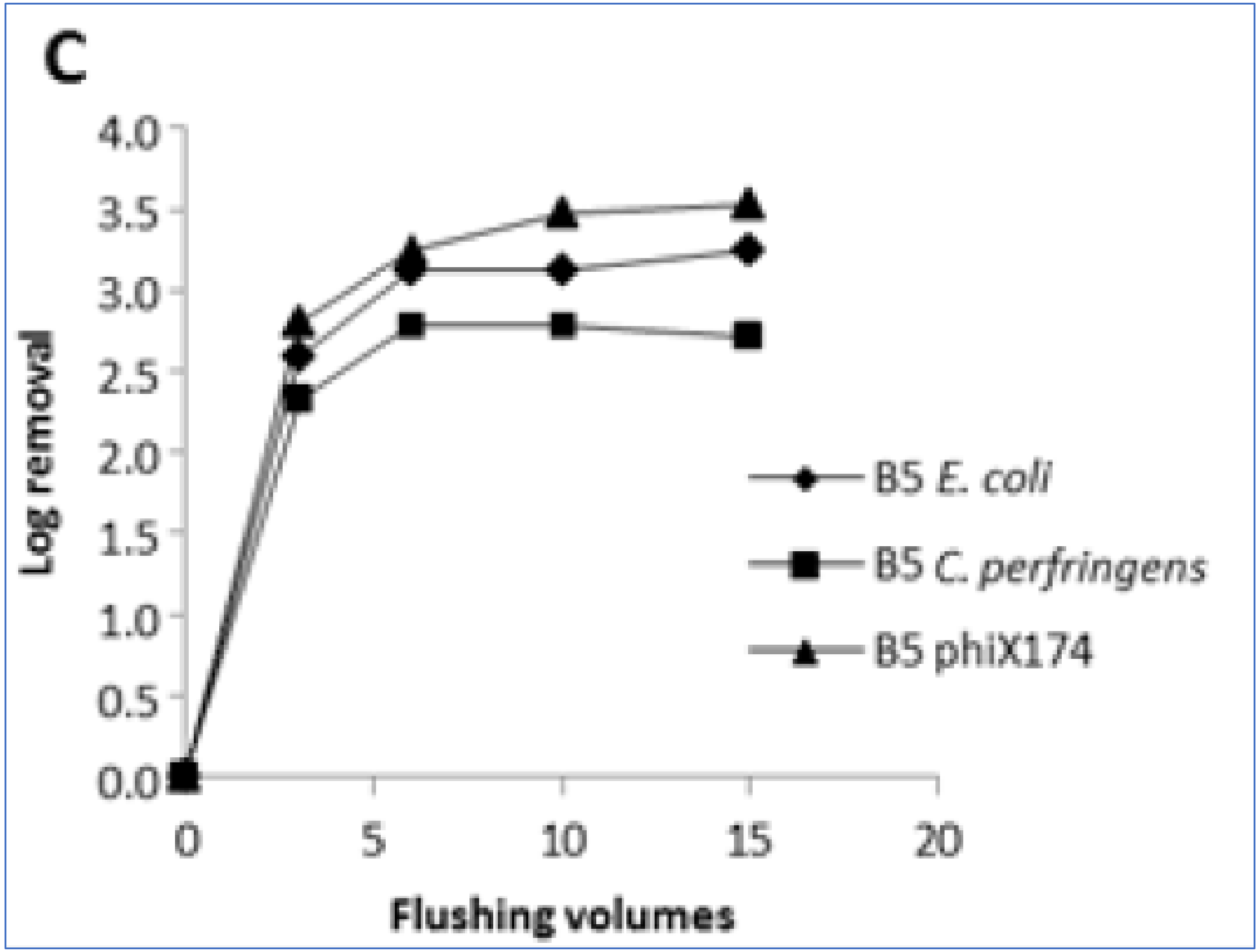
Unidirectional Flushing

Valves are closed to direct flow in one direction.

- Creates higher velocities and a scouring action.
- Systematically moves sediments out of the distribution system.
- Work from pressure source outward.



Flushing volume removal efficiency



- Three pipe volumes of flushing at 5 fps velocity gave the most benefit.
- Extended flushing with up to 15 volumes yielded an extra 0.4–0.7 log removal (diminishing returns)

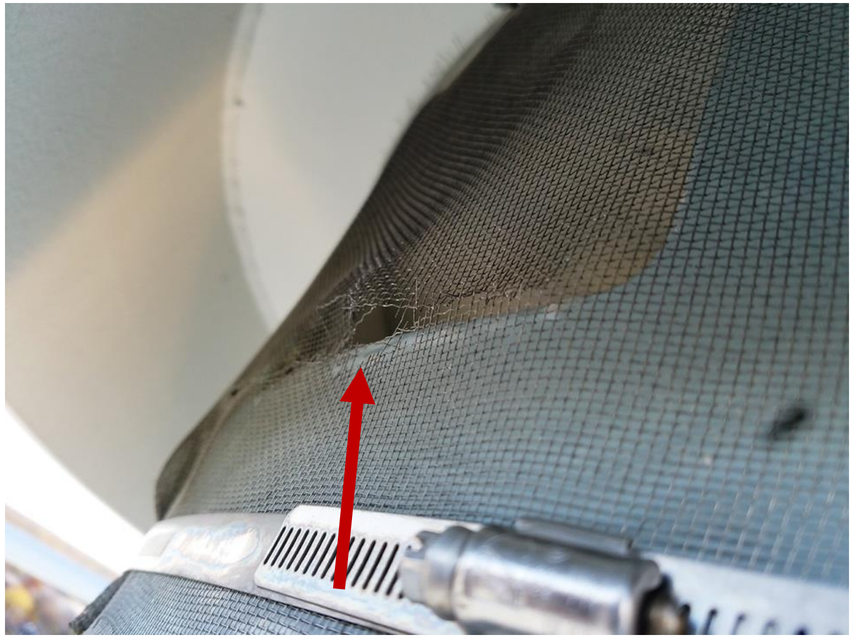
Efficacy of Flushing and Chlorination in Removing Microorganisms from a Pilot Drinking Water Distribution System (Van Bel, 2019). https://www.mdpi.com/2073-4441/11/5/903

Sanitary deficiencies

Sanitary deficiencies are defects that could allow contaminants to enter the drinking water system.

Wells should have a secure sanitary seal.

Tank overflow pipe should be 12 to 24 inches above grade.

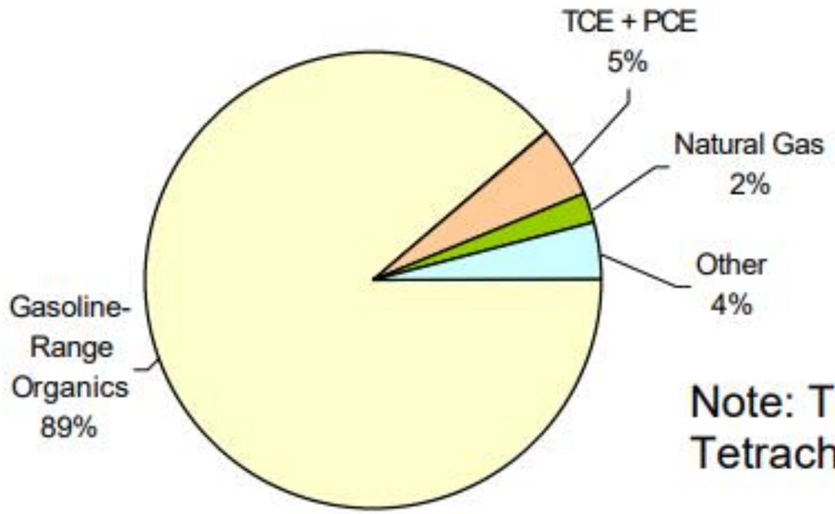


A tear in a tank vent screen could allow dust and insects in.

Pipe material factors

Permeation: the process where external contaminants pass through pipe material into the drinking water.

Leaching: the dissolution of metals, solids, and chemicals into drinking water.



Note: Trichloroethene (TCE), Tetrachloroethylene (PCE),

Table 4
Analytical Results from a Gasoline Permeation Incident

Contaminant	MCL (µg/L)	Water Sample (µg/L)
Benzene	5	1,300
Toluene	1,000	4,300
Ethylbenzene	700	< 500
Xylene	10,000	< 500

USEPA (2015 Permeation and Leaching
https://www.epa.gov/sites/default/files/2015-09/documents/permeationandleaching.pdf

NSF/ANSI 61
https://www.nsf.org/knowledge-library/nsf-ansi-standard-61-drinking-water-system-components-health-effects

Over 100 known permeation contamination events studied in 1992. Most(89%) were due to release of gasoline related products

In 1991 a 10-gallon gas tank which leaked onto a road resulted in benzene and toluene levels over the mcl in a permeated PE pipe.

Leaching can result in metals from metallic pipes, cement pipes and linings, asbestos, and organic chemicals from PE pipe and linings entering water.

Main breaks and repairs

Main breaks or leaks that do not result in a pressure loss throughout the repair may not require disinfection of the inside of the main.

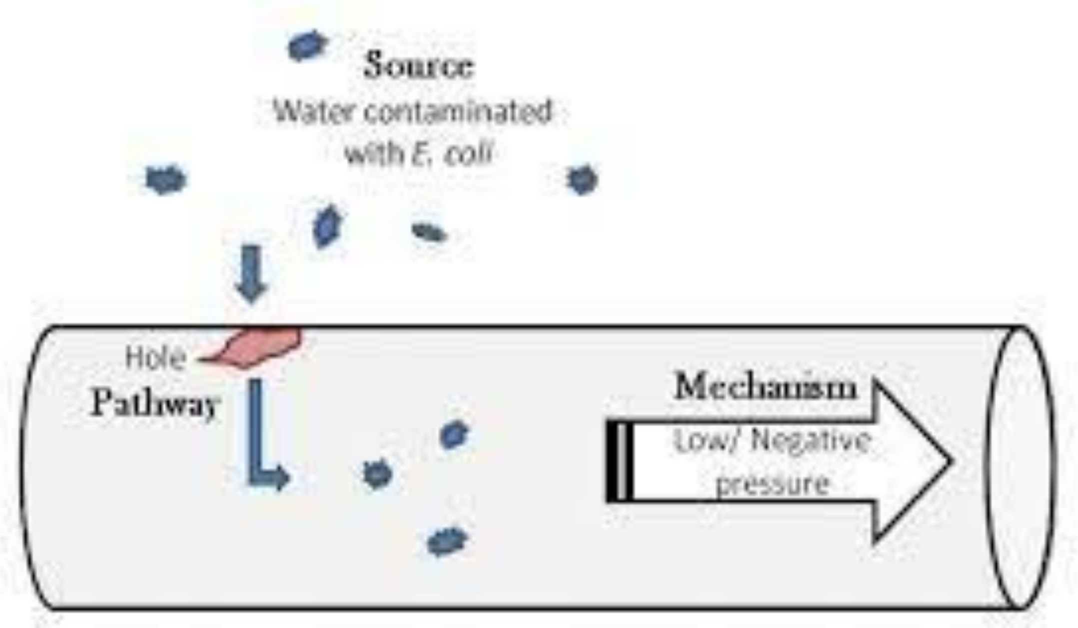
Main breaks can result in the entrance of pathogens from the surrounding trench soil or shallow groundwater. Trench must be dewatered and main must be flushed and disinfected.

Repairs or breaks with a pressure drop below 20 psi should result in a boil water notice – until negative bacti testing confirms the water is safe.

Distribution protection

Two most important control measures

1. Continuous positive water pressure
2. Physical integrity of the system



Even small cracks can provide a pathway for pathogens to enter the distribution system during a low-pressure event.

- A free chlorine residual is a final backup barrier, however once the residual is used up, there is no more disinfecting power.

A 2017 study found that households were 1.9 times more likely to report acute gastrointestinal illness after a pipe break or repair in the distribution system (Save-Soderbergh et al., 2017).

Operational practices

Table 1 Summary of Water Quality Issues Associated with Construction and Repair of Water Mains		
Microbiological Issues	**Physical Issues**	**Chemical Issues**
Pathogen Contamination*	Turbidity Color	Harmful Chemical Contamination* Exposure to Excess Chlorine* Loss of Disinfectant Residual Taste and Odor pH Stability

*Associated with the potential for direct public health impact.

Table 2 Summary of Microbial Occurrences at Main Repair Sites		
Microbe	**Presence in Trench Water Samples**	**Presence in Soil Samples**
Total Coliform	18 of 31 samples	23 of 33 samples
Fecal Coliform	12 of 18 samples	15 of 30 samples
Clostridium perfringens	9 of 30 samples	8 of 32 samples
Bacillus subtilis	24 of 30 samples	31 of 32 samples

(Adapted from: Kirmeyer et al, 2000)

An outbreak of E. coli 157 occurred in Cabool, MO in 1990 that resulted in 240 cases of illness and 4 deaths. It was concluded that the illness was caused by waterborne contamination from two major pipe breaks. Operators flushed the pipe after repair but did not disinfect the repaired main.

Sanitary practices

1. Isolate
2. Flush
3. Disinfect

USEPA (2015) New and Repaired Water Mains.
https://www.epa.gov/sites/default/files/2015-09/documents/neworrepairedwatermains.pdf

Poll 1

How can operators protect water quality when repairing main breaks?

a) Isolate the repair site using valves

b) Flush the line after making the repair

c) Disinfect the water main

d) All of the above

Backflow

A backflow event requires two elements to occur:
(1) The existence of a cross connection; and
(2) A pressure differential that causes reversal of flow through the cross connection.

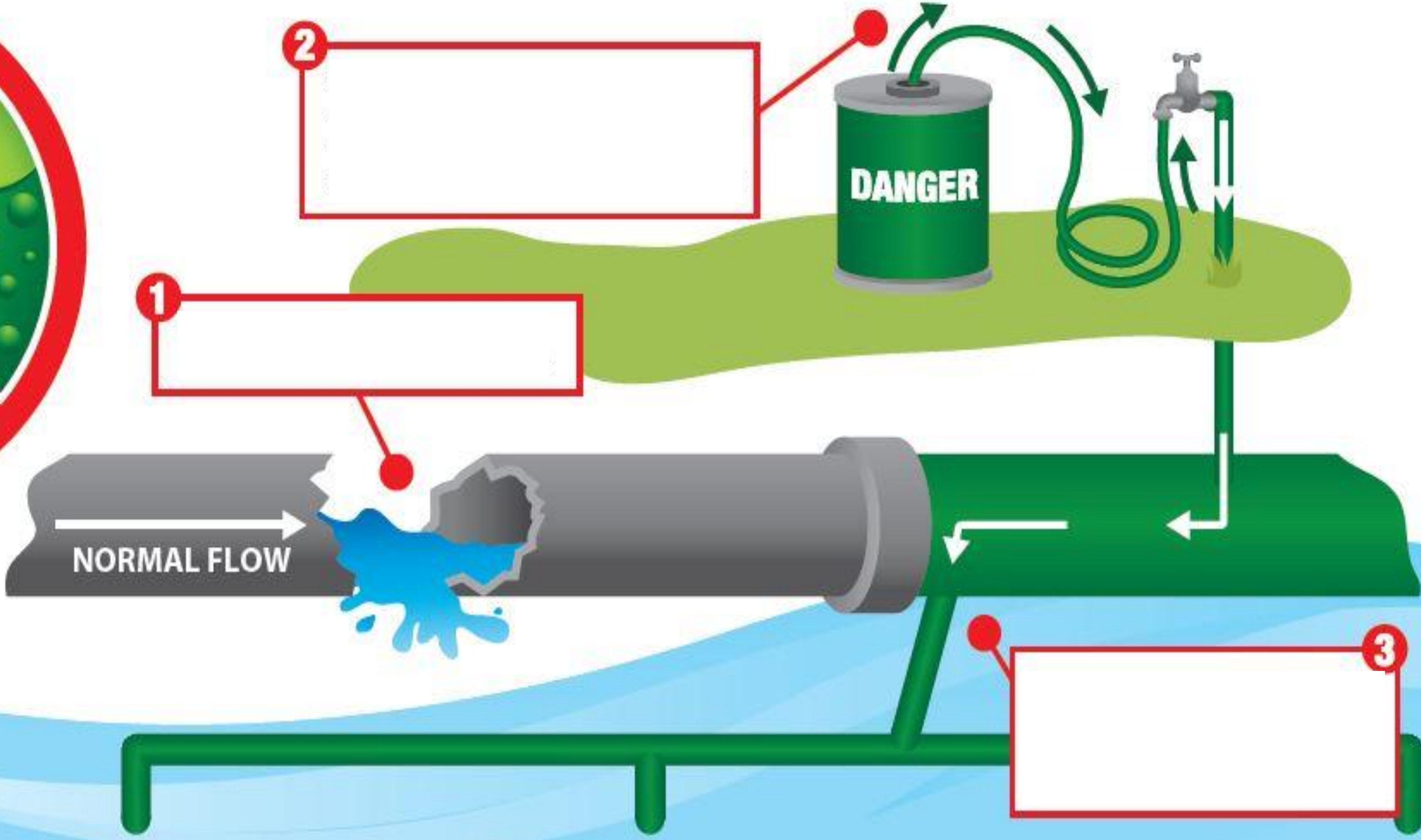
Types of backflow

Backsiphonage – A loss of system pressure (main break, fire flow, outage) creates a vacuum that draws in non-potable water

Backpressure - customer pressure exceeds system pressure – and non potable water is forced into the water supply

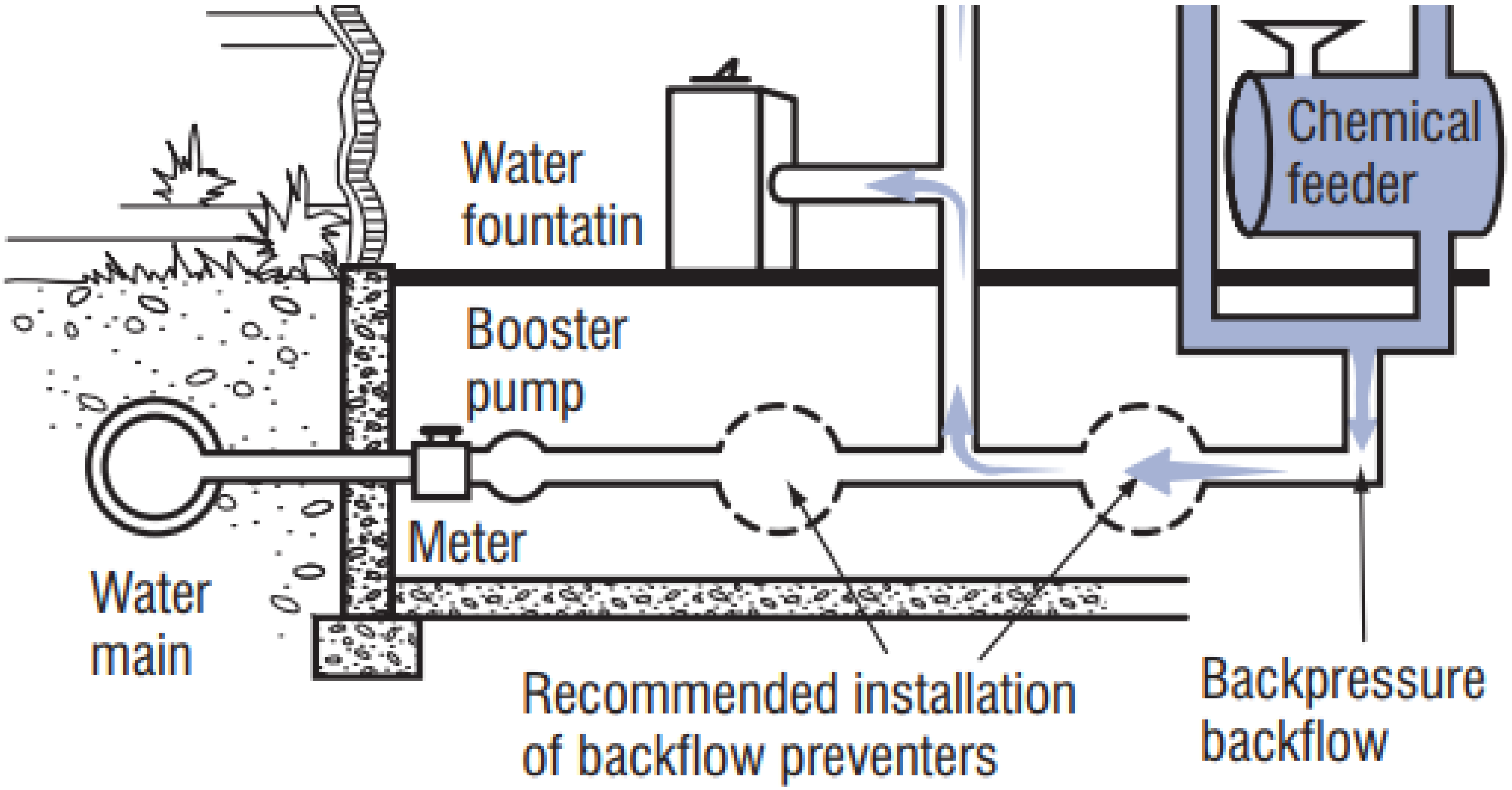
Cross-connection: A plumbing arrangement that makes it possible for a nonpotable substance to enter the potable drinking water supply.

Cross Connections and Backflow



Backflow of chemicals into drinking water from backpressure.

A plant with a chemical pump or boiler could develop a pressure that exceeds water system pressure resulting in a backflow due to overpressure.

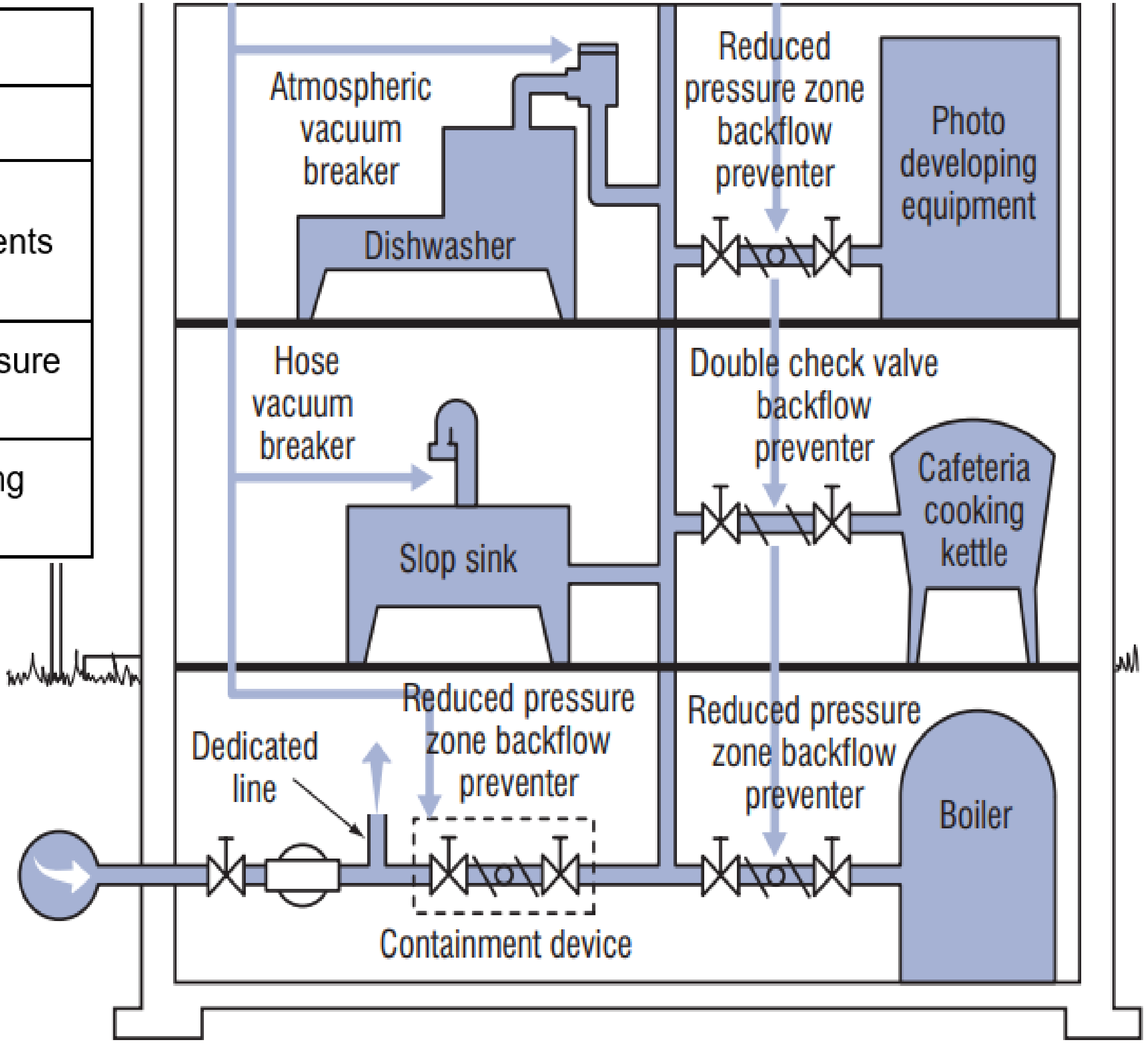


Source: EPA Cross Connection Control Manual.

Website:https://www.epa.gov/sites/production/files/2015-09/documents/epa816r03002_0.pdf

Degree of hazard

Backflow Device	Hazard Level	Function
Air Gap	Very High health hazards.	Completely separates systems.
Reduced Pressure Zone	Presence of moderate Health hazards.	Stops backflow from both over pressure and siphonage - also vents contaminant to outside.
Double Check	Low to moderate health hazards.	Stops backflow due to back pressure with two redundant checks.
Vacuum Breaker	Varied health hazards - used mainly for faucets.	Stops back siphonage by breaking vacuum.

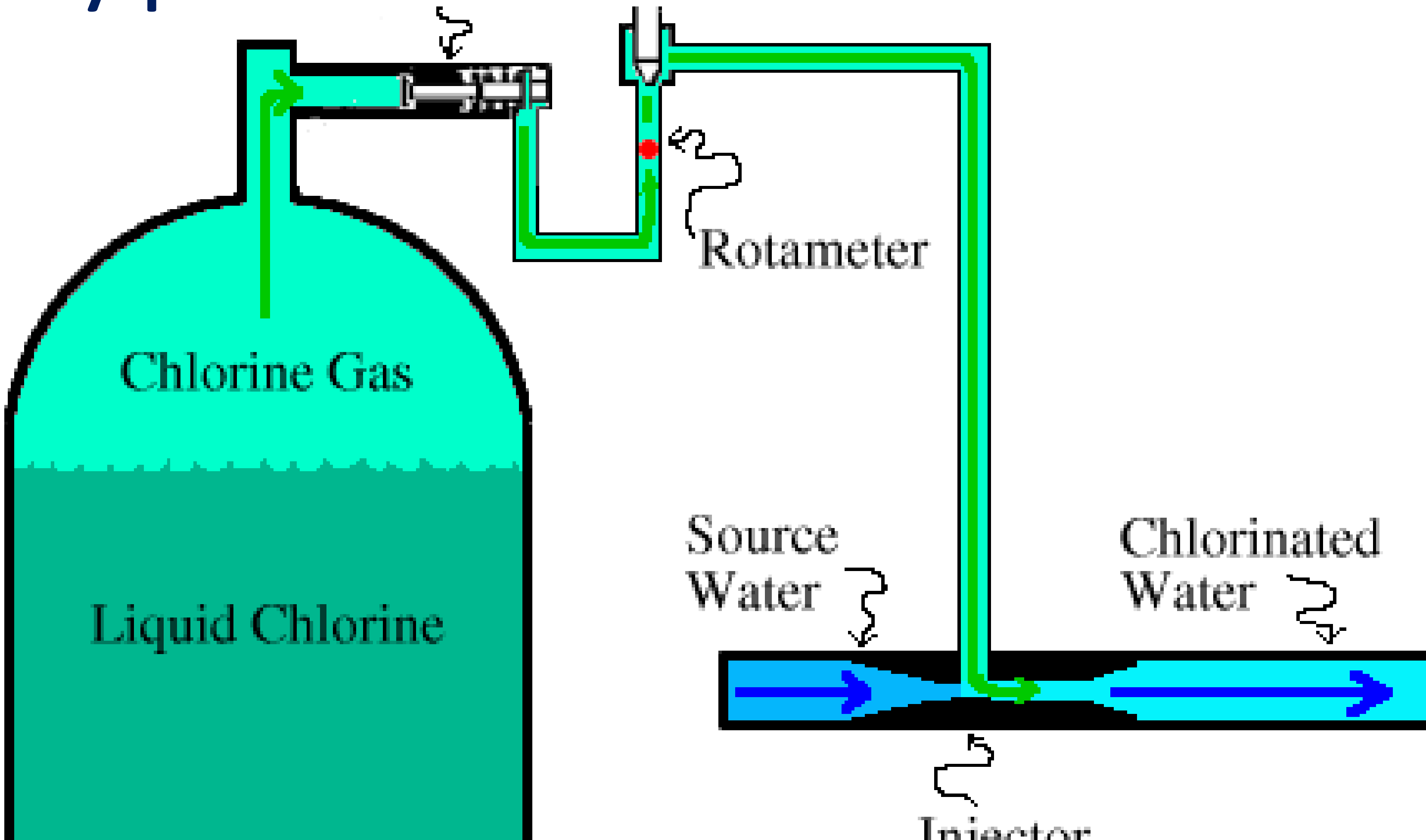


Poll 2

Which backflow prevention device would allow the minimum necessary protection from backflow when providing water under pressure to a chemical facility?

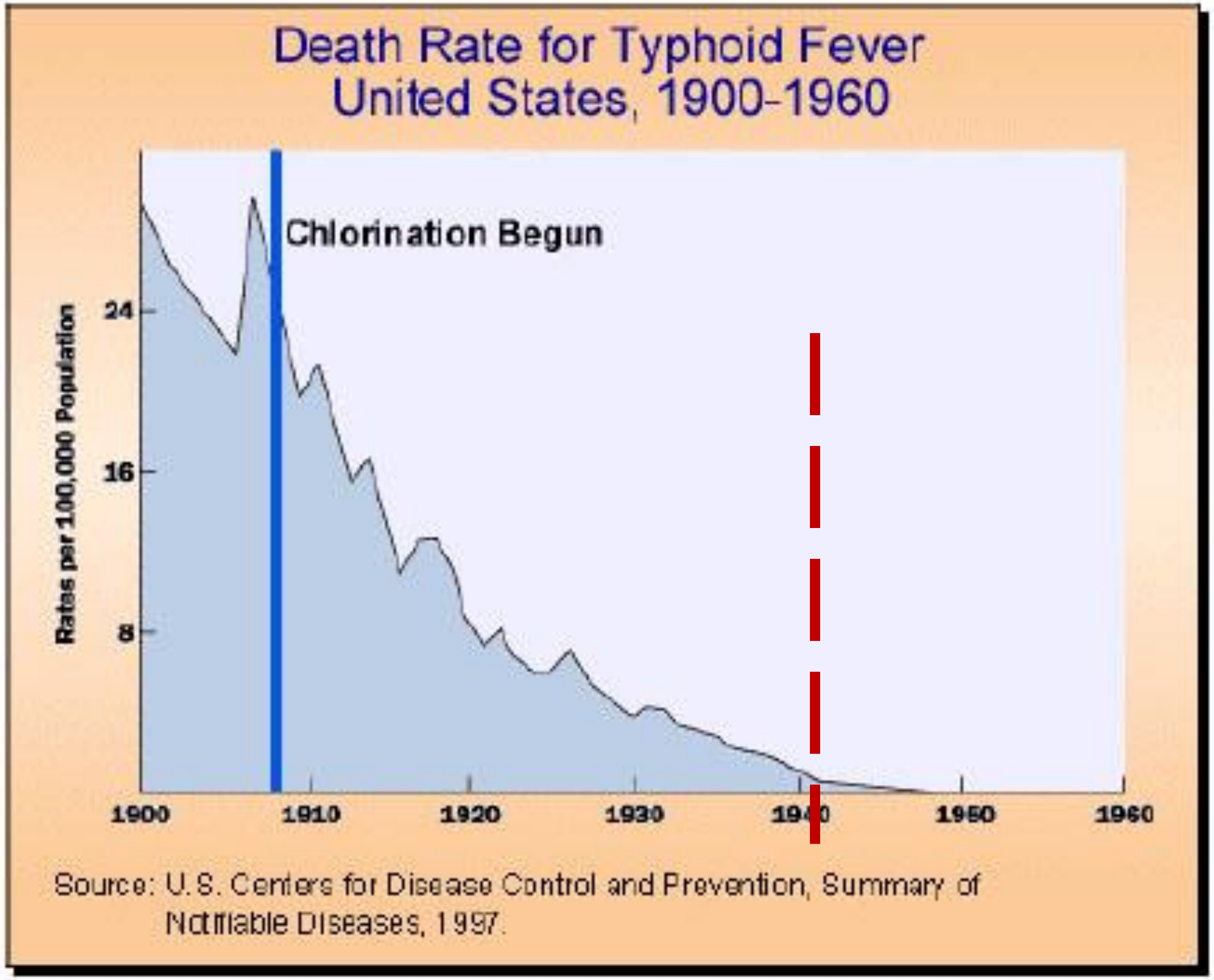
a) Reduced pressure zone assembly
b) Double-check valve
c) Vacuum breaker
d) Air gap

Chlorine Disinfection and Disinfection Byproducts



Health impact of chlorine disinfection

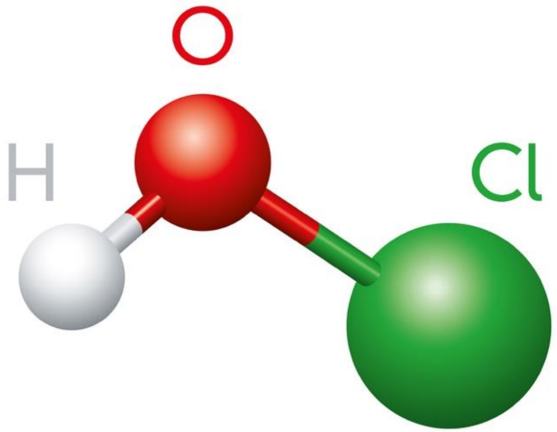
- 1,000s of deaths due to water borne diseases - but no one understood the cause
- 1670s Antonie van Leeuwenhoek first observes microbes using a microscope
- 1854 John Snow figured out that cholera was a cause of a waterborne disease epidemic
- 1860s Germ Theory developed by Louis Pasteur (microbial infection)
- 1908 New Jersey- first system in US to chlorinate drinking water
- The US water industry achieves less than 1 death per 100,000 around 1945



Disinfectant Types

Chlorine

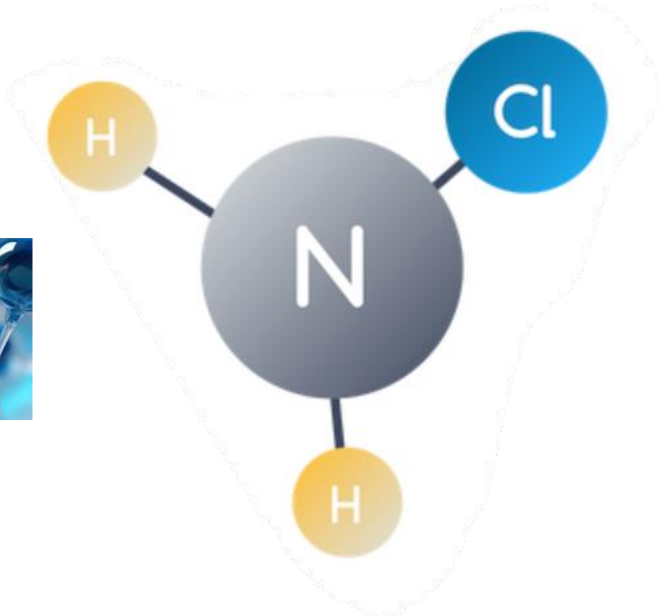
- Results in a free residual (hypochlorous acid) More reactive, inactivates pathogens
- Primary disinfectant in water treatment
- Can lead to disinfection byproducts



Hypochlorous Acid (HOCl)

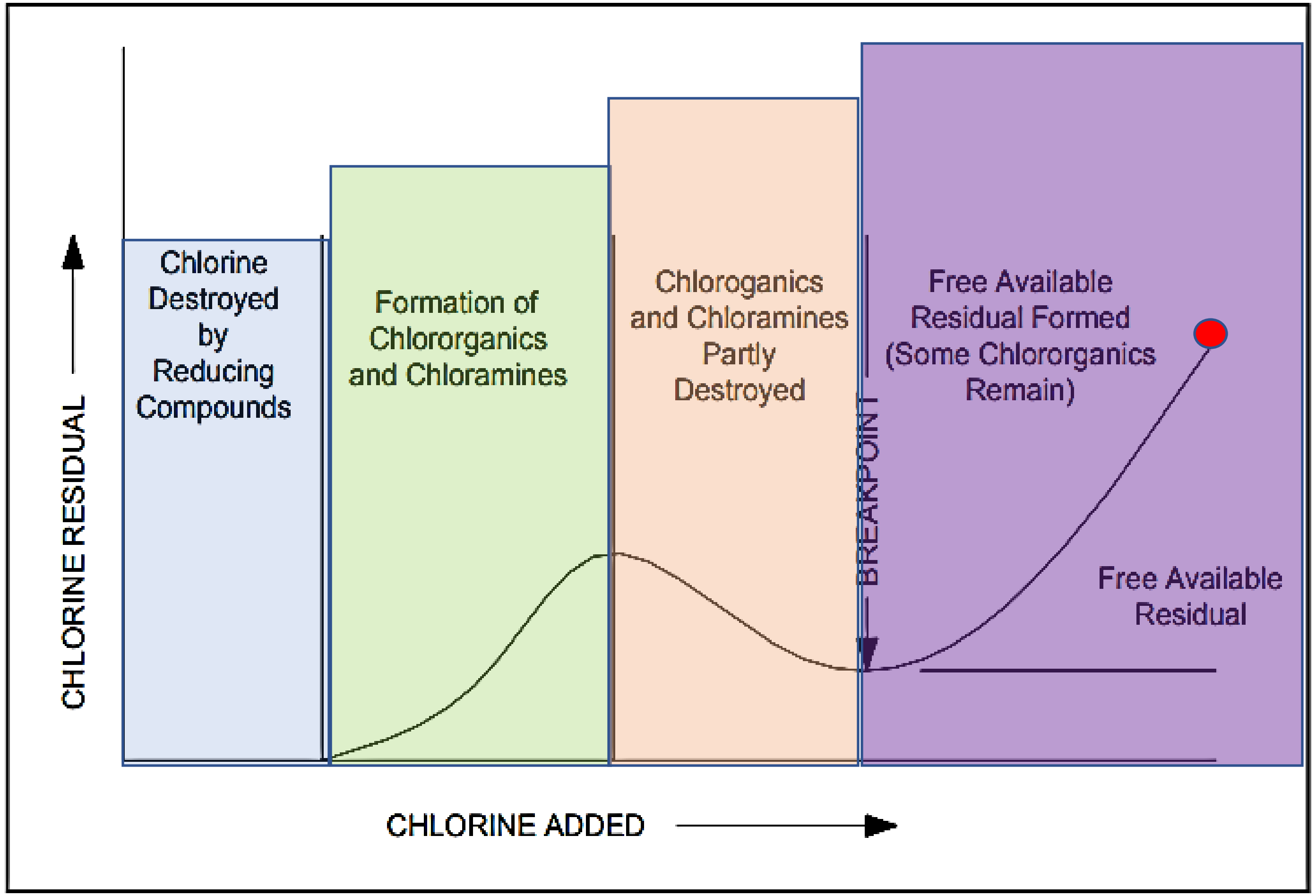
Chloramine

- Measured as a total residual. More stable.
- Chlorine (Cl2) and Ammonia (NH4) are combined in a 5 to 1 ratio (Monochloramine)
- Often used for secondary disinfection - does not produce disinfection byproducts
- Nitrification can occur in tanks with high water age – nitrifying bacteria convert ammonia to nitrate (NH4 → NO3)



Monochloramine (NH2Cl)

Residual as chlorine is added



Legend:

A: Reducing compounds use up chlorine.

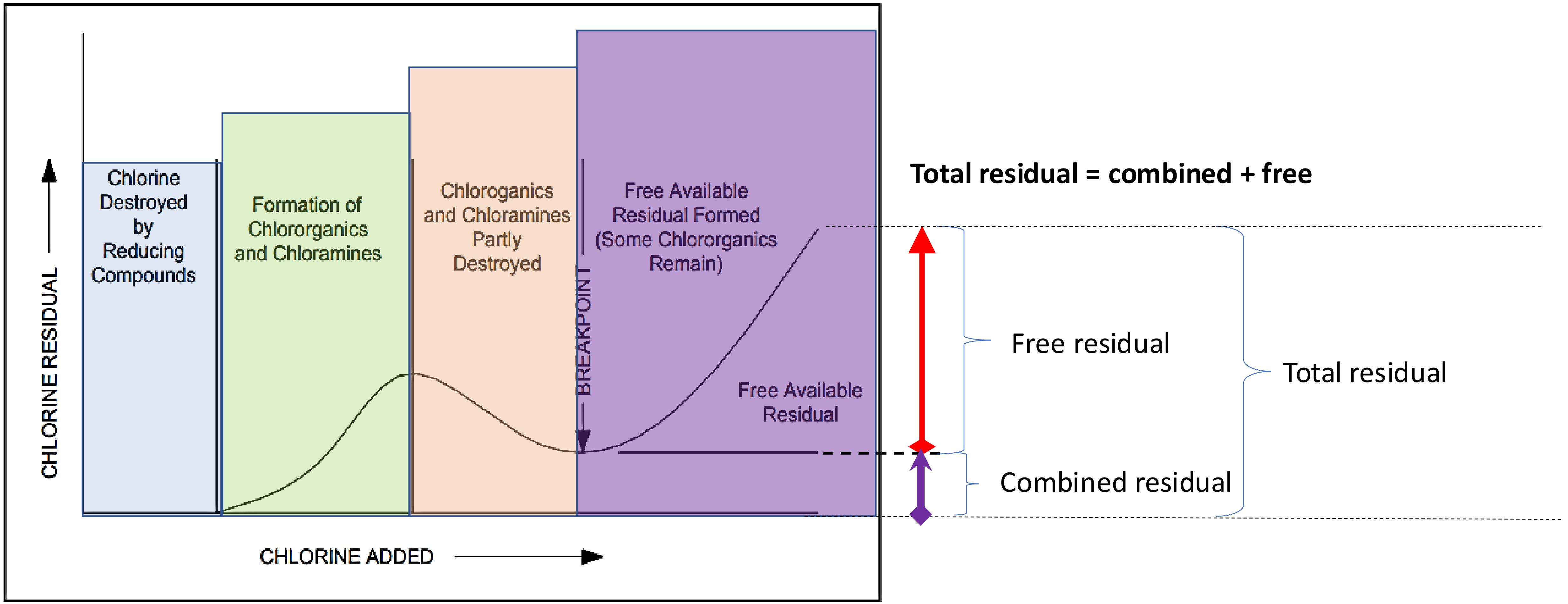
B: Chloramines produced

C: Chloramines destroyed

D: After the "breakpoint" all demand is satisfied and free residual begins to build

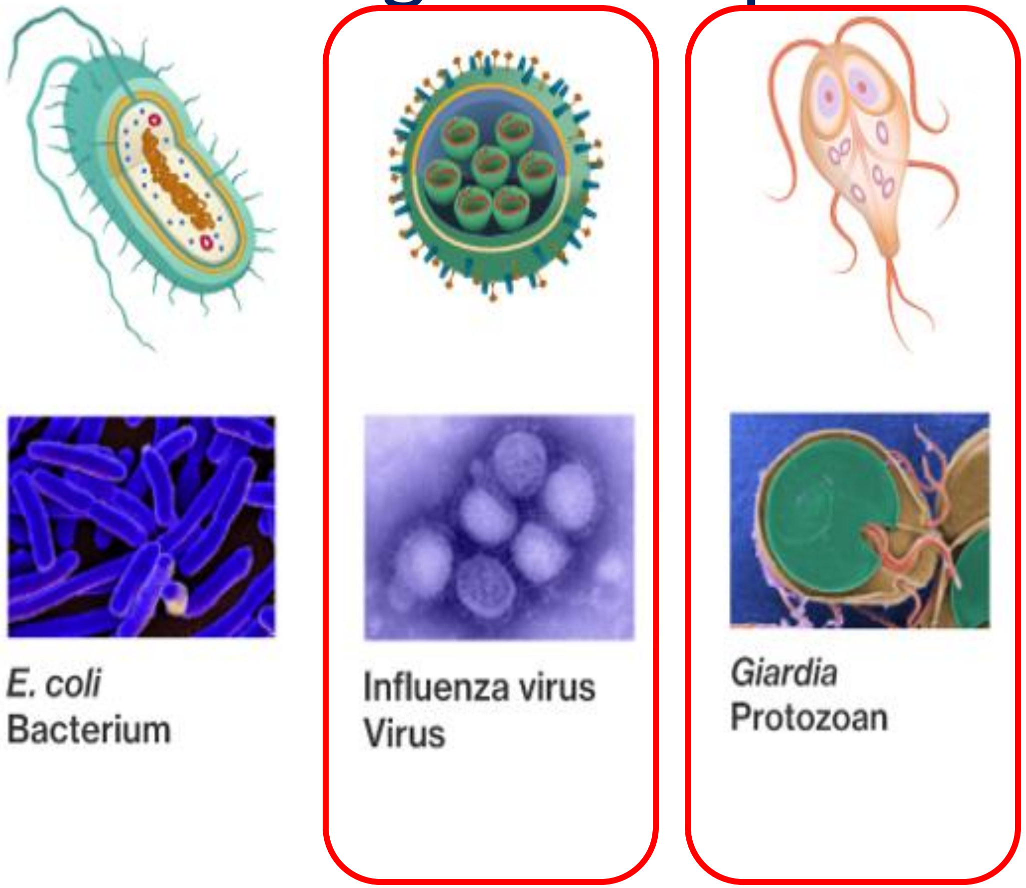
What do we learn from this graph?

1. The effect of reducing compounds
2. The effect of organic compounds such as ammonia to form combined chlorine
3. Dose = demand + residual
4. Total residual = combined + free



Residual as chlorine is added

Pathogen Groups



Viruses and protozoa are inactivated when rendered incapable of replicating or reproducing. Bacteria are destroyed

The effectiveness of chlorine disinfection depends primarily on:

1. Residual concentration
2. Contact time

Disinfection of Distribution System Components

Disinfection of different components of the water distribution system typically requires the use of highly concentrated chlorine.

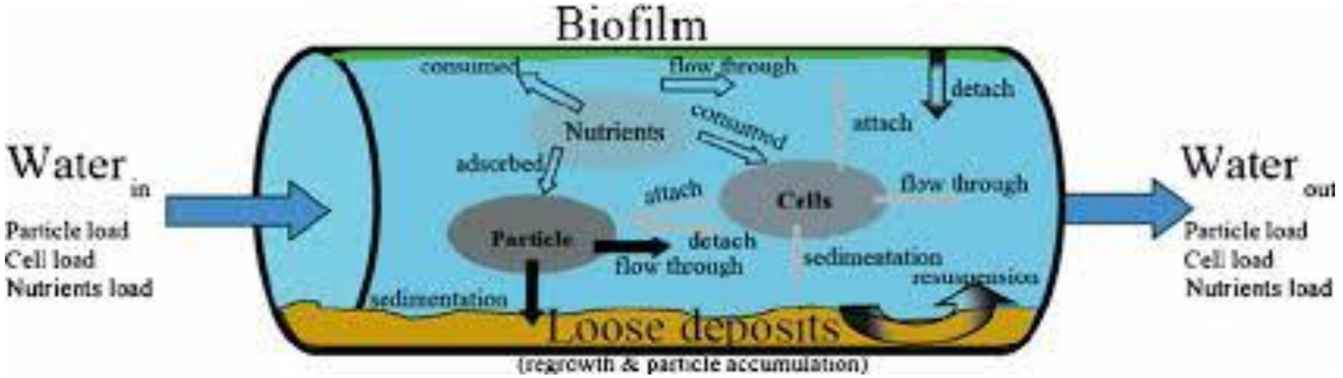
Disinfection of water mains: Follow the guidelines identified in the American Water Works Association (AWWA) Standard C651-23. There are three different approved methods (Continuous Feed, Tablet/Granule and Slug)

Disinfection of Storage tanks: Follow the guidelines identified in the AWWA Standard C652-19. The tank should be cleaned prior to adding chlorine and thoroughly rinsed afterwards.

Disinfection of Wells: Follow the guidelines identified in the AWWA Standard C654-21. The volume of the well casing should be calculated to determine the proper amount of chlorine.

After disinfection, the chlorinated water should be dechlorinated and flushed to waste.

Reasons to Monitor Chlorine Residuals



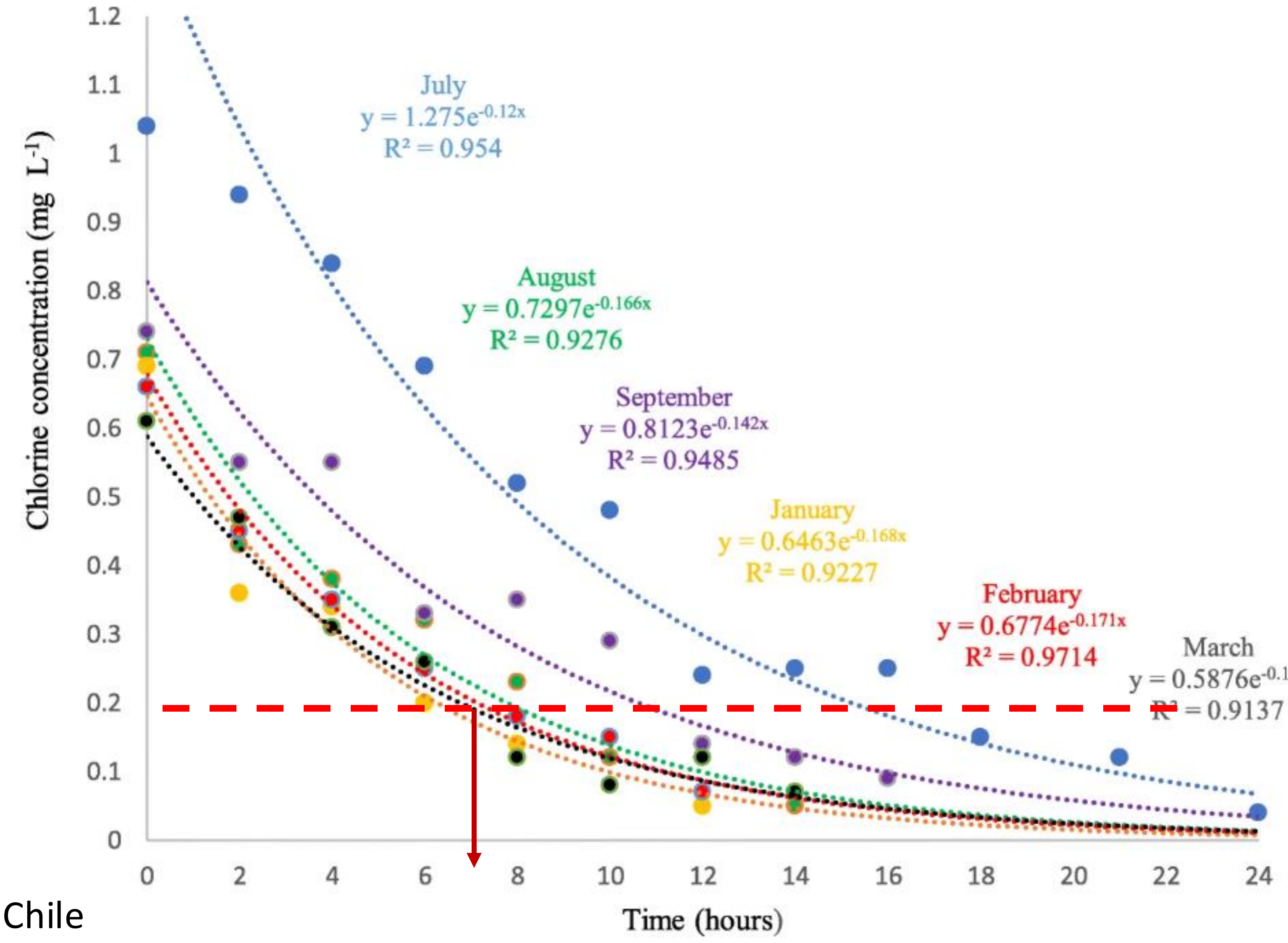
Maximum Residual Disinfectant Level (MRDL): 4.0 mg/L

Minimum recommended residuals
- 0.2 mg/L for Chlorine
- 0.5 mg/L for Chloramine

1. Ensure protection against pathogenic organisms
2. Inhibit biofilm growth in pipes
3. Provides an early warning if contamination occurs
4. Ensure chlorine residual of at least 0.2 mg/L in remote sections and dead ends.

Chlorine residual decay

- **Chlorine decay** is largely a function of time, temperature and chlorine demand. In a normal system, residuals can be expected to last at least a few days up to a couple of weeks.
- **Chlorine demand** can be reduced by flushing sediment from pipelines at scouring velocities, cleaning storage tanks, and replacing or lining corroding cast iron pipes.
- **Water age** can be reduced by gently flushing dead ends and ensuring adequate storage turnover



Rapid chlorine decay in a distribution system study in Chile

https://sustainenvironres.biomedcentral.com/articles/10.1186/s42834-021-00084-w

Disinfection byproduct formation

Total Trihalomethanes (TTHM)

- Chloroform
- Bromodichloromethane
- Dibromochloromethane
- Bromoform

Trihalomethanes are the 4 volatile organic compounds found in drinking water that pose a cancer risk over the **MCL of 0.080mg/L**

They are formed from a reaction between naturally occurring organic matter (NOM) and chlorine.

Haloacetic Acids (HAA5)

- Monochloroacetic acid
- Dichloroacetic acid
- Trichloroacetic acid
- Bromoacetic acid
- Dibromoacetic acid

HAA5 are weak acids that pose a cancer risk when over the **MCL of 0.060 mg/L**.

Both TTHM and HAA5 compounds are the result of reactions with NOM and the decay products of plant and animal materials (humic and fulvic acids.)

Prevention of TTHMs and HAA5

Distribution System

- Adding mixing to storage tanks
- Ensure tank turnover 5 days or less
- Use chloramines for a disinfectant residual
- Gentle flushing of dead-ends and high retention areas
- Regular tank cleaning and water main flushing to remove debris

Disinfection Profiling and Benchmarking Technical Guidance Manual (USEPA, 2020).
https://www.epa.gov/system/files/documents/2022-02/disprof_bench_3rules_final_508.pdf

Impacts of Nitrification

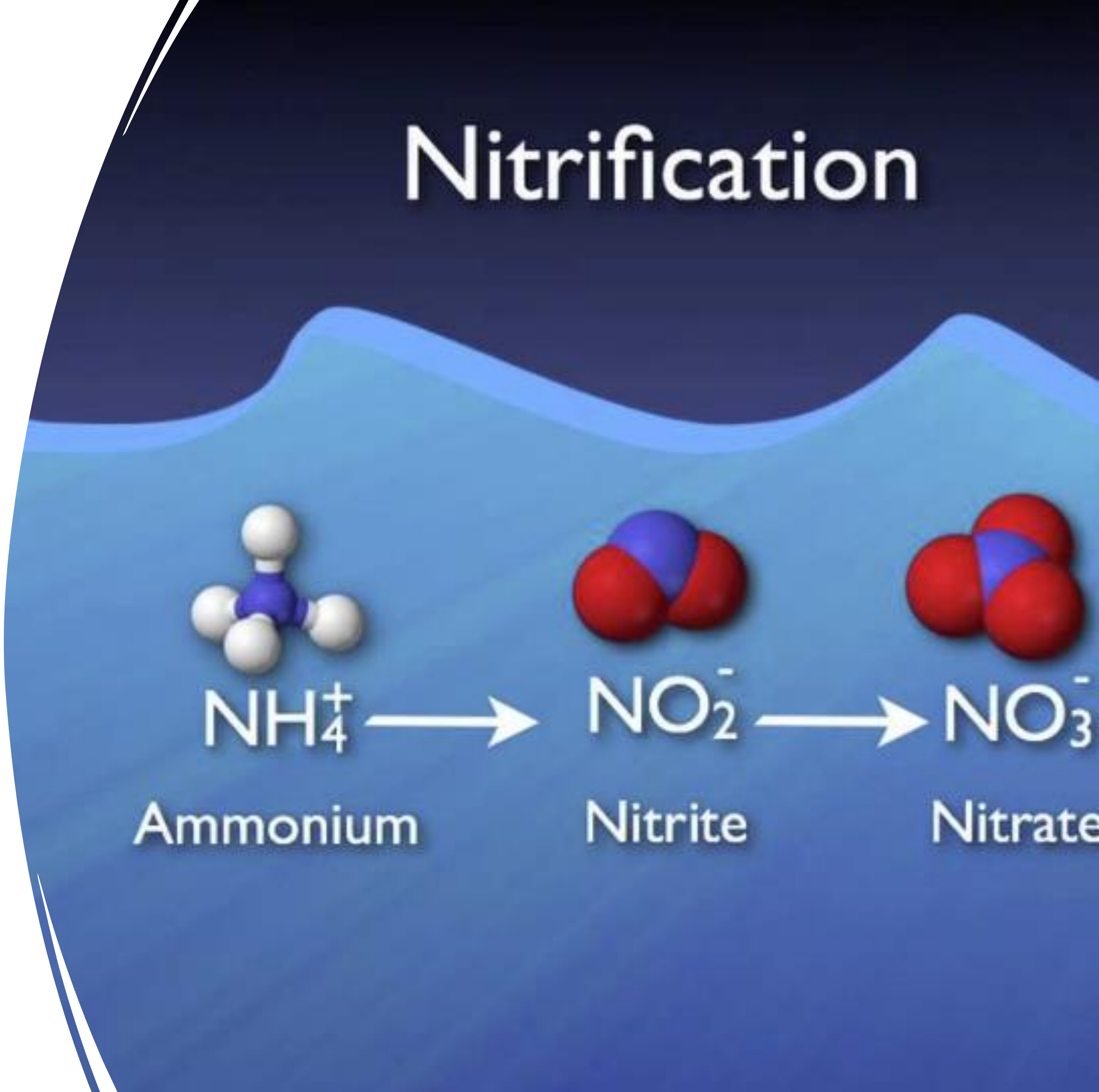
1. High Nitrate Levels
2. Loss of disinfection residual
3. Bacterial growth

Factors that lead to nitrification

- Use of chloramines
- Ammonia as a food source (bacteria)
- Warmer temperatures and lack of sunlight
- Sediments that harbor bacteria
- Significant drop in pH and alkalinity

Solutions

- Increase disinfection residual
- Tank mixing and cycling
- Tank cleaning

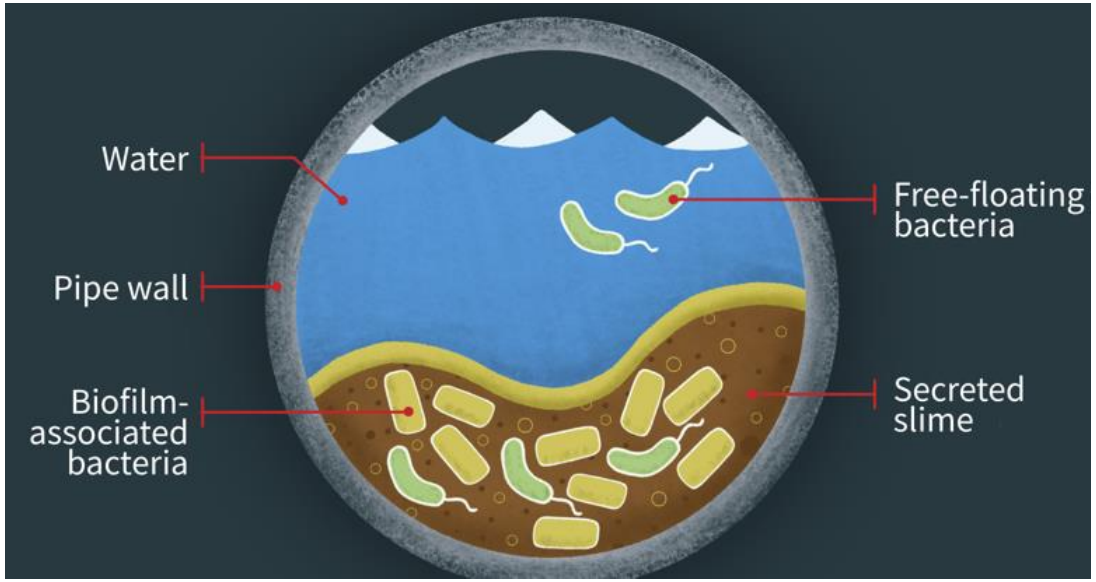


Disinfection and biofilm study findings

Free chlorine followed by chloramines is the most effective disinfection strategy to reduce biofilms. (Momba and Binda, 2002).

Flushing followed by disinfection is the most effective sequence
High velocity flushing removes the biofilm protective layer, allowing disinfection to be more effective.

Warning: Changes in disinfection strategy should be thoroughly investigated and pilot-tested.



USEPA Disinfection Profiling and Benchmarking: Technical Guidance Manual:
https://www.epa.gov/system/files/documents/2022-02/disprof_bench_3rules_final_508.pdf

Disinfection byproducts rule

	Stage 1 DBPR		Stage 2 DBPR	
Regulated Contaminants	MCL (mg/L)	MCLG (mg/L)	MCL (mg/L)	MCLG (mg/L)
TTHM	0.080		Unchanged[2]	
Chloroform		-		0.07
Bromodichloromethane		Zero		Unchanged[2]
Dibromochloromethane		0.06		Unchanged[2]
Bromoform		Zero		Unchanged[2]
HAA5	0.060		Unchanged[2]	
Monochloroacetic acid		-		0.07
Dichloroacetic acid		Zero		Unchanged[2]
Trichloroacetic acid		0.3		0.2
Bromoacetic acid		-		-
Dibromoacetic acid		-		-
Bromate (plants that use ozone)[1]	0.010	Zero	Unchanged[2]	Unchanged[2]
Chlorite (plants that use chlorine dioxide)	1.0	0.8	Unchanged[2]	Unchanged[2]
Regulated Disinfectants	MRDL[3] (mg/L)	MRDLG[3] (mg/L)	MRDL (mg/L)	MRDLG (mg/L)
Chlorine	4.0 as Cl_2	4	Unchanged[2]	Unchanged[2]
Chloramines	4.0 as Cl_2	4	Unchanged[2]	Unchanged[2]
Chlorine dioxide	0.8	0.8	Unchanged[2]	Unchanged[2]

[1]A new analytical method for bromate was established with the Stage 2 DBPR.

[2]Stage 2 DBPR did not revise the MCL or MRDL for this contaminant/disinfectant.

[3]Stage 1 DBPR included MRDLs and MRDLGs for disinfectants, which are similar to MCLs and MCLGs.

DBPR Compliance is based on the Locational Running Annual Average

Trihalomethanes (TTHM) and **Haloacetic Acids (HAA5)** form when **chlorine** reacts with organic compounds in water

Bromate forms from the reaction of **Ozone** with naturally occurring Bromide in water

Chlorite forms as a result of reactions between **chlorine dioxide** and organics

DBPR Rule Quick Reference Guide: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt

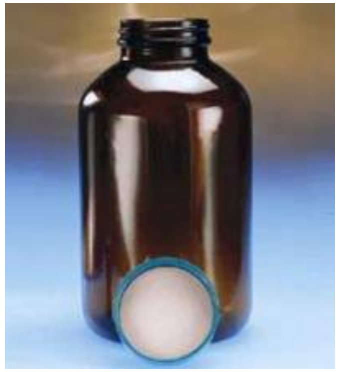
Disinfection byproduct compliance and sampling

Compliance

- The MCL for Total Trihalomethanes (TTHM) is **0.080 mg/L**
- The MCL For Haloaecetic acids is HAA5 is **0.060 mg/L**
- Compliance is based on the locational running annual average (**LRAA**)

Sample locations

Sample locations are based on an **Initial Distribution System Evaluation (IDSE)** – which is a study used to determine locations most likely to facilitate disinfection byproduct formation. In general disinfection byproducts form in part of the distribution system with the longest retention times and in the warmest time of the year.



HAA5 samples use a glass bottle with ammonium chloride as a preservative. Wear gloves and eye protection. Do not rinse the bottle. Fill to within 2 inches of the top. Place in cooler w/ice.

TTHM samples use clear or amber volatile organic analysis (VOA) glass bottles with Teflon septum-cap containing an acid preservative. Wear hand and eye protection and fill slowly until there is a meniscus on the top. Cap, ensure there are no bubbles. Place in cooler w/ice.

Poll 3

What are factors that can lead to increased DBP production and loss of chlorine residual?

a) tank turnover less than 5 days and excessive flushing
b) tank turnover greater than 5 days and sediment build-up
c) Use of chloramines and system flushing
d) All of the above

Sampling and Monitoring

Total coliform rule (TCR)

The two most prominent aspects of the TCR are repeat sampling requirements and the required number of samples based on population. (Refer to the quick reference guide below)

Required Repeat samples
When a routine sample test is **positive** at least 3 repeat samples are taken within 24 hours at the following locations:

a) the original routine site,
b) within 5 service connections upstream, &
c) within 5 service connection downstream.
d) A fourth sample is required for systems that collect 1 routine sample per month (These are systems serving a population of 1,000 or less and are taken at a point representative of the DS).

Number of samples is based on population

- The number of samples required each month is roughly 1 sample for every 1,000 persons served, but the details can be seen in the chart on the next screen.
- Systems that serve 4,900 persons or fewer can collect all routine samples on the same day while larger systems must space the sampling at regular time intervals throughout the month.

Total Coliform Rule Quick Reference Guide:
https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=3000663W.txt

Public Water System ROUTINE Monitoring Frequencies

Population	Minimum Samples/ Month	Population	Minimum Samples/ Month	Population	Minimum Samples/ Month
25-1,000*	1	21,501-25,000	25	450,001-600,000	210
1,001-2,500	2	25,001-33,000	30	600,001-780,000	240
2,501-3,300	3	33,001-41,000	40	780,001-970,000	270
3,301-4,100	4	41,001-50,000	50	970,001-1,230,000	300
4,101-4,900	5	50,001-59,000	60	1,230,001-1,520,000	330
4,901-5,800	6	59,001-70,000	70	1,520,001-1,850,000	360
5,801-6,700	7	70,001-83,000	80	1,850,001-2,270,000	390
6,701-7,600	8	83,001-96,000	90	2,270,001-3,020,000	420
7,601-8,500	9	96,001-130,000	100	3,020,001-3,960,000	450
8,501-12,900	10	130,001-220,000	120	≥ 3,960,001	480
12,901-17,200	15	220,001-320,000	150		
17,201-21,500	20	320,001-450,000	180		

Coliform sampling

Coliform samples are collected at **representative** points throughout the distribution system.

A **Site Sampling Plan** (SSP) identifies

- **Routine** sampling locations (representative of the distribution system service area)
- **Repeat** sampling locations (within 5 connections upstream and downstream)

Representative concepts

- *different types of population centers served*
- *different pressure zones*
- *geographic portions of the distribution system.*
- *Different sources*

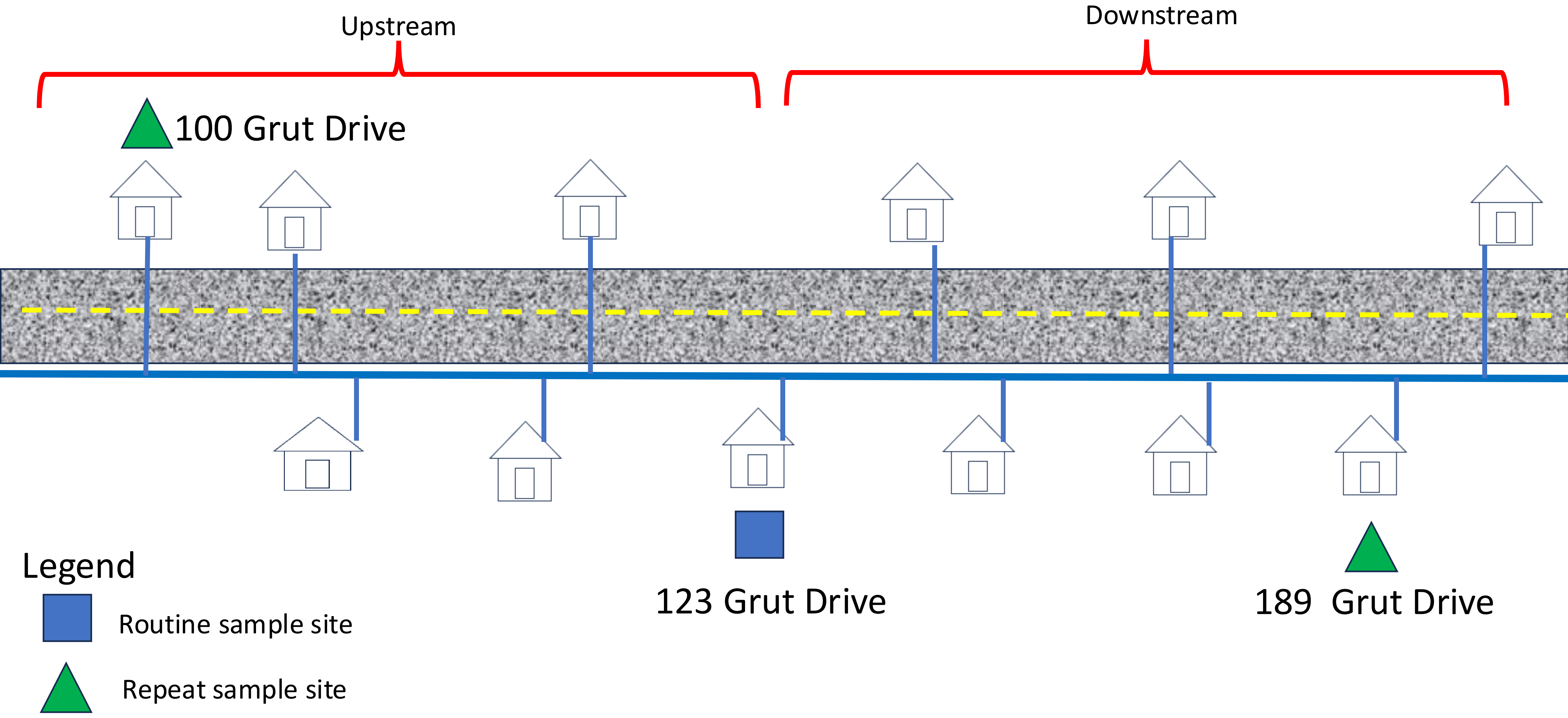
RTCR SAMPLE SITING PLAN

RTCR Sample Siting Plan - Avengertown WY5600000

Updated 04/25/2019

Month	Routine Sample Site	Repeat Sample Site	Source
January	**1.** 123 Grut Dr.	(same as routine)	WL01
		189 Grut Dr.	
		100 Grut Dr.	
February	**2.** 562 Pepper Way	(same as routine)	WL01
		500 Pepper Way	
		575 Pepper Way	
March	**3.** 2014 Thanos Blvd.	(same as routine)	WL01
		2000 Thanos Blvd.	
		2050 Thanos Blvd.	
April	**1.** 123 Grut Dr.	(same as routine)	WL01
		189 Grut Dr.	
		100 Grut Dr.	
May	**2.** 562 Pepper Way	(same as routine)	WL01
		500 Pepper Way	
		575 Pepper Way	

Routine and repeat sites example



Lead and copper rule

Establishes action levels (AL)

- 0.015 mg/L for Lead (Pb)
- 1.3 mg/L for Copper (Cu)

- Based on 90th percentile level of tap water samples
- Sample is “first draw” from a tap that has set unused for at least 6 hours.
- Standard sampling frequency is every 6 months unless accelerated or reduced.

An AL exceedance is not a violation but can trigger other requirements: water quality parameter (WQP) monitoring, corrosion control treatment (CCT), source water monitoring/treatment, public education, and lead service line replacement (LSLR).

Lead and Copper Rule Quick Reference Guide:
https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=60001N8P.txt

Lead and Copper Rule Revisions
https://www.epa.gov/dwreginfo/lead-and-copper-rule-implementation-tools#LCRR%20Imp%20FS

LCR sampling and tiers

Table 1: Lead and Copper Tap and WQP Tap Monitoring					
Size Category	System Size	Number of Pb/Cu Tap Sample Sites[3]		Number of WQP Tap Sample Sites[4]	
		Standard	Reduced	Standard	Reduced
Large	> 100K	100	50	25	10
	50,001 - 100K	60	30	10	7
Medium	10,001 - 50K	60	30	10	7
	3,301 - 10K	40	20	3	3
Small	501 - 3,300	20	10	2	2
	101 - 500	10	5	1	1
	≤ 100	5	5	1	1

[3] With written State approval, PWSs can collect < 5 samples if all taps used for human consumption are sampled.
[4] Two WQP tap samples are collected at each sampling site.

- **Tier 1**: **Single family** with copper w/lead solder (CLS) (constructed between 1983-1988), lead pipes including lead goosenecks or pigtails (LP), or lead service lines (LSL).
- **Tier 2**: **All building types** with copper w/lead solder (constructed between 1983-88) lead pipes including lead goosenecks or pigtails or lead service lines (LSL).
- **Tier 3**: **Single Family** Structures that have copper w/lead solder (CLS) constructed before 1983.
- **Other:** If all Tier 1 through 3 Are exhausted, a system can use other sites that are representative.

Samples sites should use tier 1 sites first, and if needed add tier 2 and then tier 3

Poll 4

What factor needs to be taken into consideration when selecting routine total coliform sample locations in the distribution system?

a) Availability of repeat sites within 5 locations upstream and downstream

b) Different pressure zones

c) Different water sources

d) All of the above

Our brains can only hold **3 to 5** things at once before they start tuning out.

So how do we get the important stuff to stick?

DISTILL IT DOWN to 3.

Main Takeaways

If you remember nothing else, remember these 3 key points...

01

Flushing

Water age management is most effective at a velocity of 5ft/sec for 3 pipe volumes and is part of water main repair procedures, water age control, and biofilm management to improve water quality.

02

Breakpoint Chlorination

Breakpoint Chlorination requires the application of enough chlorine to destroy the chloramines and allow for additional chlorine added to be free chlorine, available to kill pathogens.

03

Cross Connections

Cross Connection Control involves protecting public health by ensuring adequate separation or isolation between contaminants and drinking water

Thank you for participating

Please share one thing you enjoyed learning about today in the chat.

Great Lakes Environmental Infrastructure Center

https://gleic.org/

Daryl Gotham P.E. | djgotham@mtu.edu

National EFC Network

www.efcnetwork.org