American Water Works Association

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Association of State Drinking Water Administrators

COURSE 3
PERFORMING A CORROSION CONTROL EVALUATION

Purpose

Protecting Public Health is the purpose of drinking water treatment. To support this purpose this course presents information on the following:

- Why corrosion occurs and how to control it
- How to determine if a corrosion control evaluation is needed
- How to perform a corrosion control evaluation
- How to use a corrosion control evaluation to help meet LCRR

LEARNING OBJECTIVES

As a result of this section, you will be able to:

Explain	Methods and tools for evaluating CCT
Describe	Differences and considerations in demonstration testing methods
Identify	Additional criteria when selecting CCT
Define	Steps for implementing CCT
Recall	Tools and considerations for evaluating CCT effectiveness

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MODULE 1
METHODS AND TOOLS FOR EVALUATING CORROSION CONTROL TREATMENT

LEARNING OBJECTIVES

Explain

- What methods and tools are available for evaluating CCT?
- Overview of various methods and tools
- Typical elements of a desktop
- Considerations when selecting initial targets and chemicals

LEARNING OBJECTIVES

Interpret	How extensive an analysis might be needed? What evaluation methods are available Details on Desktop Studies

Various Tools are Available for Evaluating CCT

Desktop

- Comprehensive water quality evaluation
- Treatment process models
- Solubility curves
- Pourbaix diagrams
- Corrosion literature and industry guidance
- Analogous systems

Specialty

- Scale analysis
- Jar testing

Demonstration

- Bench-scale testing
- Pilot-scale testing (e.g., harvested pipe study)

Field

- Partial-system test
- Full system test
- Profile sampling
- Sentinel sites

CCT Studies Always Start with a Desktop

Desktop studies are basis for determining:

- If more data are needed and which data are needed to support a decision
- What impacts a change in source or treatment may have on water quality and if that water quality is likely to significantly alter corrosion
- Which CCT methods are applicable and what initial treatment targets should be considered
- If additional study or testing is needed and what type

Traditional Desktop Studies

- Summarized existing data
- Used indices and flowcharts to evaluate theoretical corrosion control relationships
- Reviewed performance of analogous systems
- Evaluated and propose corrosion control alternatives

EPA has a specific list of review items in LCR desktop studies

EPA guidance has emphasized flowcharts to guide alternative analysis

EPA Guidance to States

Source, Treatment and Water Quality Information	• Review treatment and water quality for each source • Summarize raw, entry point, and distribution system data • Evaluate key WQPs, including differences between the POEs and distribution system
Tap Monitoring Data	• Review 90^{th} percentiles for Pb and Cu • Assess available supplemental Pb and Cu data
Materials and Customer Complaints	• Determine primary sources of Pb and Cu in water • Identify other materials that may impact CCT
Analogous Systems	• Ensure systems are similar in size, water quality, and materials profile
Evaluate Causes of Elevated Pb / Cu	• Apply corrosion theory with information available
Potential CCT Alternatives	• Compare abilities to reduce Pb and / or Cu • Evaluate effects of CCT on WQPs • Evaluate effects on water quality treatment processes

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Source: EPA, OCCT Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems

KNOWLEDGE CHECK

1. What topics should be considered by a Desktop Study?
    a. Observed lead concentrations
    b. Distribution system water quality data
    c. Characteristics of typical household plumbing within the service area
    d. Answers a and b
    e. Answers a, b, and c

Improving Desktop Studies

Traditional approaches have short-falls to avoid

- Analogous Systems - Often not analogous but can look for similarities
- Corrosion Indices - Don’t predict Pb or Cu stability
- Limitations with flow diagrams - One size doesn’t fit all

Improving Desktop Studies

Traditional approaches have short-falls to avoid

- Analogous Systems - Often not analogous
- Corrosion Indices - Don't predict Pb or Cu stability
- Limitations with flow diagrams - One size doesn't fit all

Analogous Systems

Lead and Copper Rule

“systems of similar size, water chemistry, and distribution system configuration ”

Analogous Systems

Parallels to Look For	Point of Comparison	Useful Objectives for Comparison
• Raw source water (e.g., nearby water systems relying on same aquifer or surface water supply) • Water treatment processes • Distribution system • Source water usage	• Corrosion control strategy performance	• pH, alkalinity, DIC finished water should match • TOC in finished water • CSMR • Similar locations on solubility curves • History of any previous water use that may have impacted scales

Improving Desktop Studies

Traditional approaches have short-falls to avoid

- Analogous Systems - Often not analogous
- Corrosion Indices - Don’t predict Pb or Cu stability
- Limitations with flow diagrams - One size doesn’t fit all

Corrosion Control Indices

- **Should not be used to assess lead and copper solubility**
- A useful tool and an important step in a desktop evaluation
- Helps understanding of scales and potential impacts of a change
- Can be useful for iron pipe and cement lined pipe considerations

Refer to Course 1 for a more comprehensive review of indices.

Corrosion Control Indices - Illustration

Water	CCPP (mg/L)	LSI	Pb (µg/L)	Cu (mg/L)
1	-4.32	-0.65	3.8	50.6
2	-0.55	-0.05	1.0	**75.8**
3	1.05	0.12	**6.4**	52.7
4	1.35	0.15	**4.1**	49.0
5	3.45	0.35	4.3	**65.6**
6	1.95	0.27	3.6	**67.4**

Source: Hill (2017). Importance of Corrosion Indices and How to Use Them. Presented at the AWWA Water Quality and Technology Conference, Portland, OR

See AWWA Water Dictionary for LSI and CCPP equations

KNOWLEDGE CHECK

2. Corrosion control indices should be used to predict lead and copper solubilities.

   a. True

   b. False

Improving Desktop Studies

Traditional approaches have short-falls to avoid

Analogous Systems - Often not analogous

Corrosion Indices - Don’t predict Pb or Cu stability

Limitations with flow diagrams - One size doesn’t fit all

EPA Flow Charts


EPA

Optimal Corrosion Control
Treatment Evaluation Technical
Recommendations for Primacy
Agencies and Public Water Systems

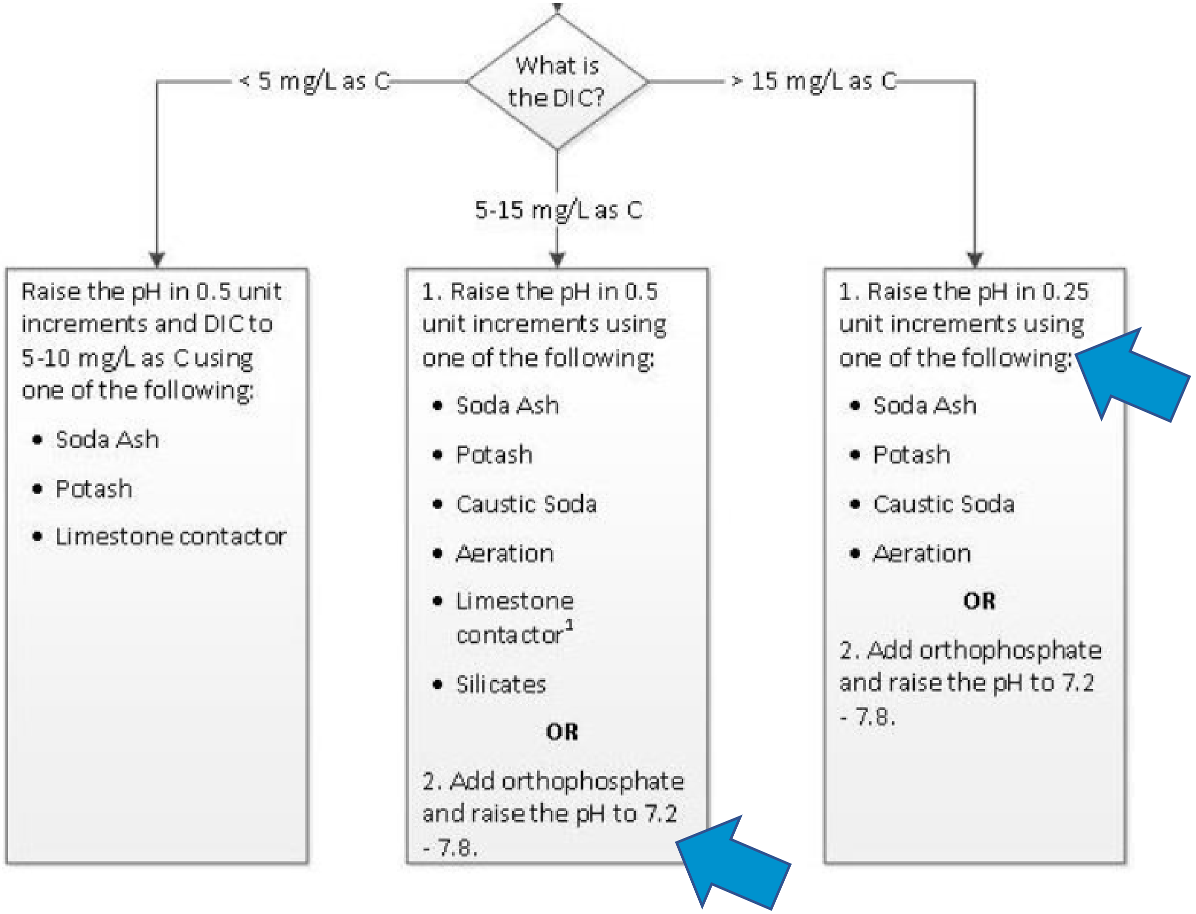
Can be used to identify initial treatment strategies or targets for further consideration

Coupling flow charts with a desktop study can help avoid conflicts and inappropriate decisions

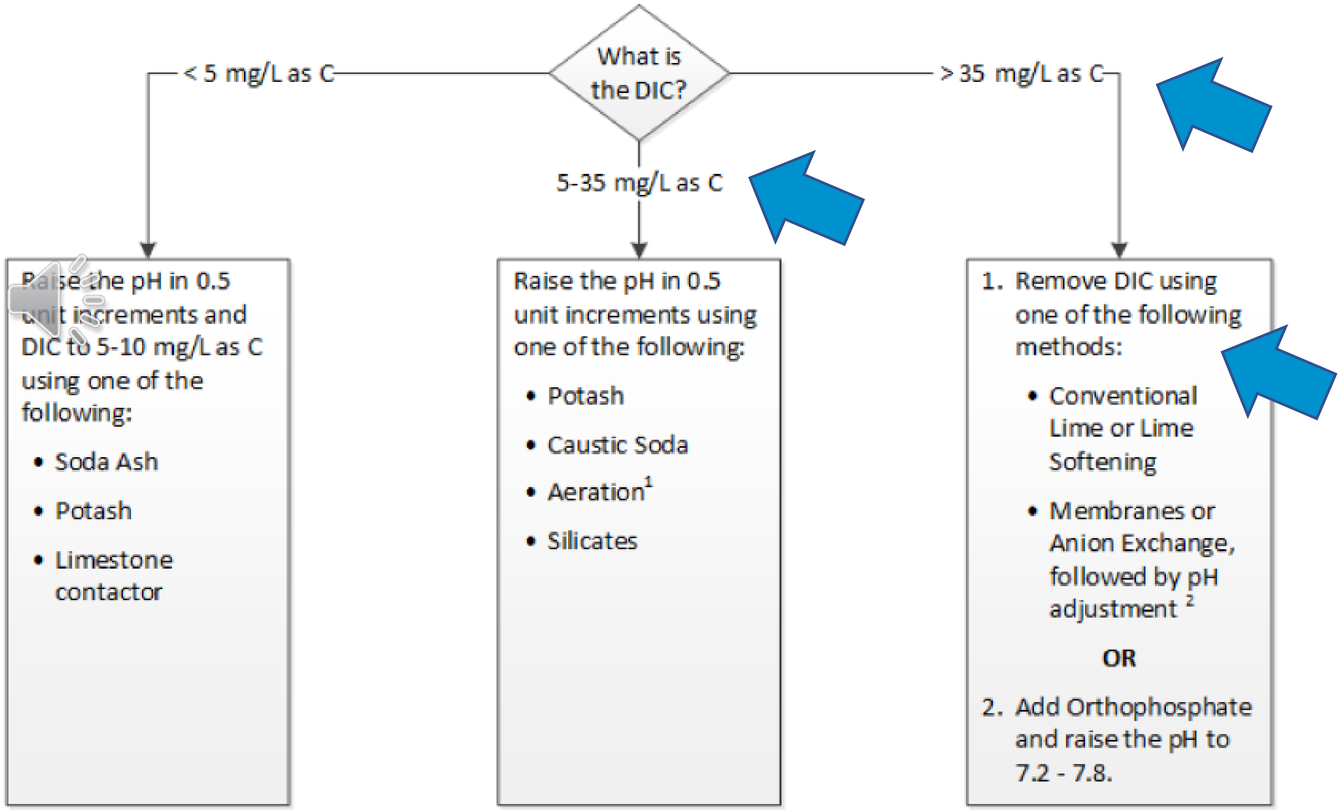
Flow charts must be used with care to support informed decision-making

Example Flow Charts: pH < 7.2 – Pb and Cu

Flowchart 1a: Selecting Treatment for Lead only or Lead and Copper



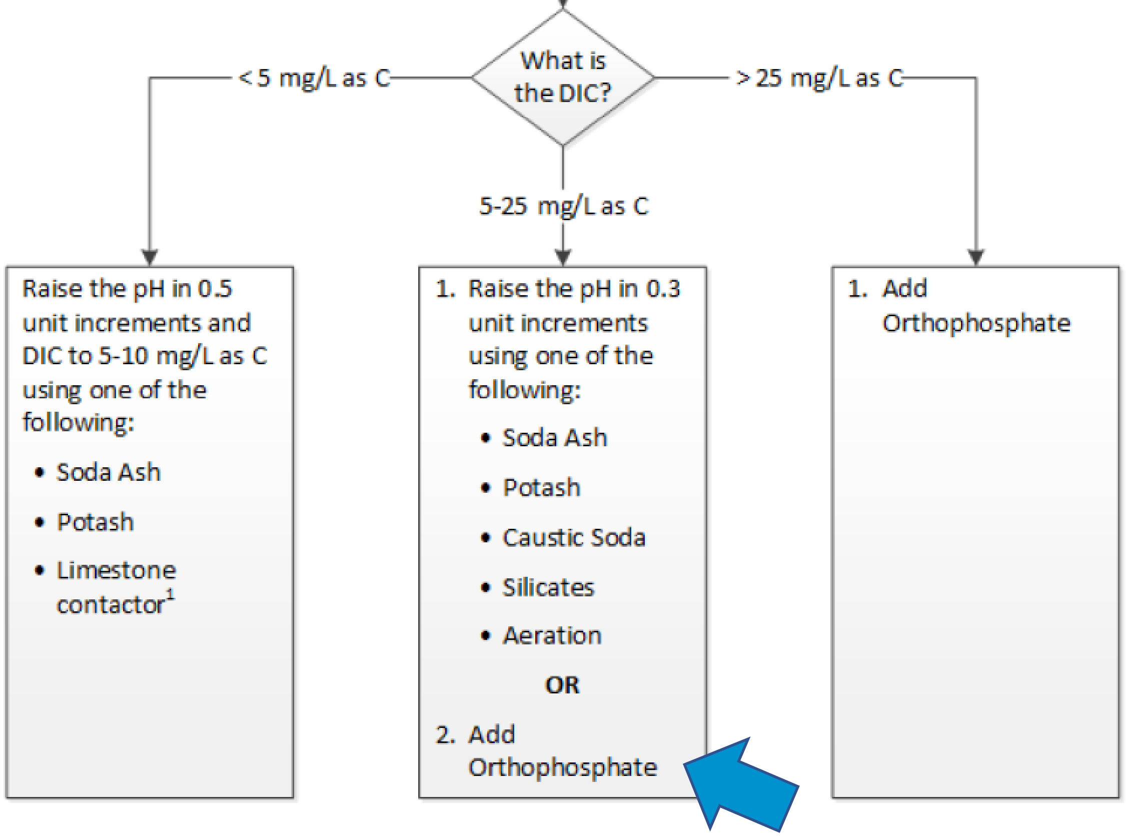
Flowchart 2a: Selecting Treatment for Copper Only



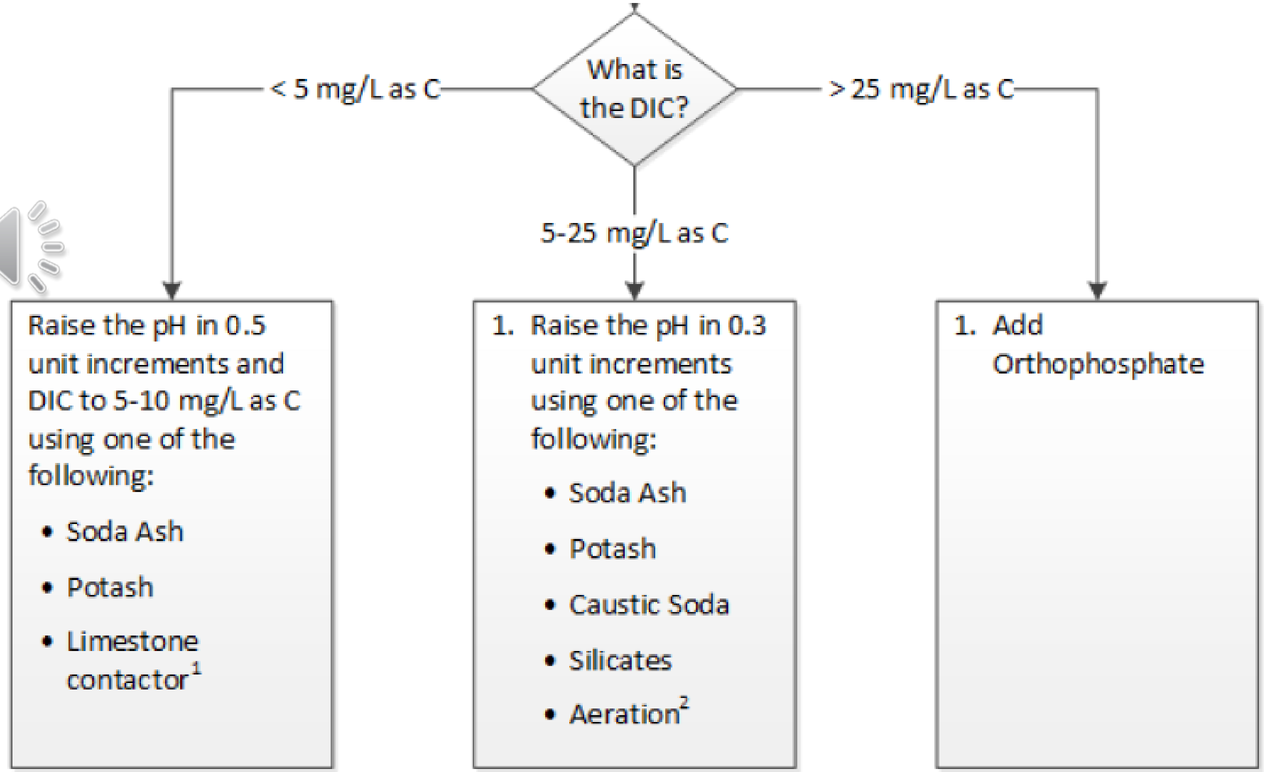
Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

Example Flow Charts: pH from 7.2 to 7.8 –Pb and Cu

Flowchart 1b: Selecting Treatment for Lead only or Lead and Copper



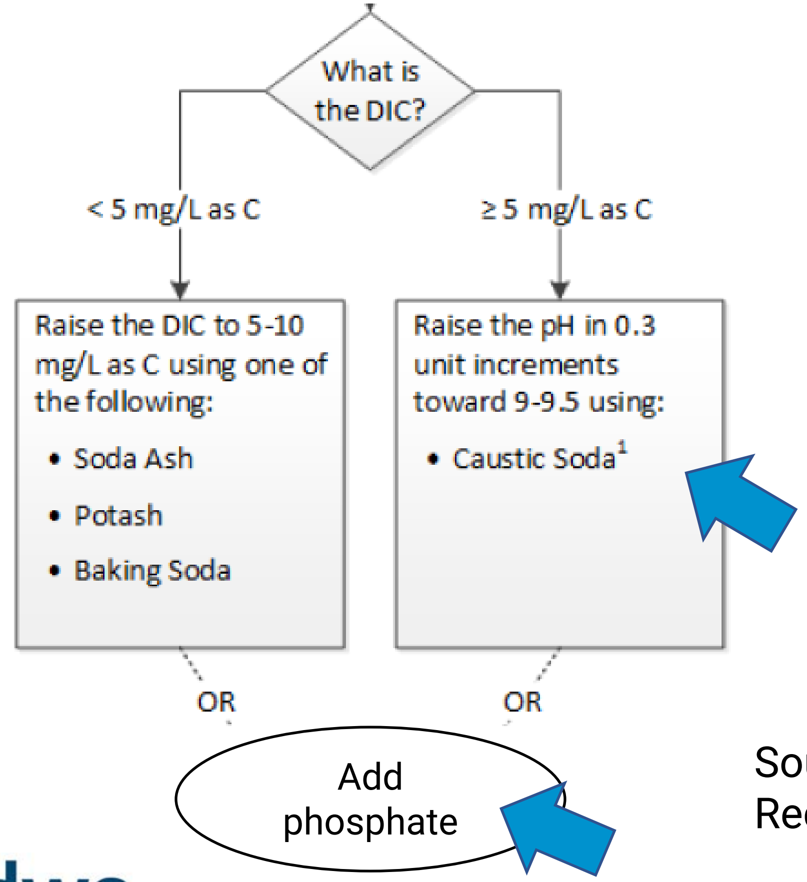
Flowchart 2b: Selecting Treatment for Copper Only



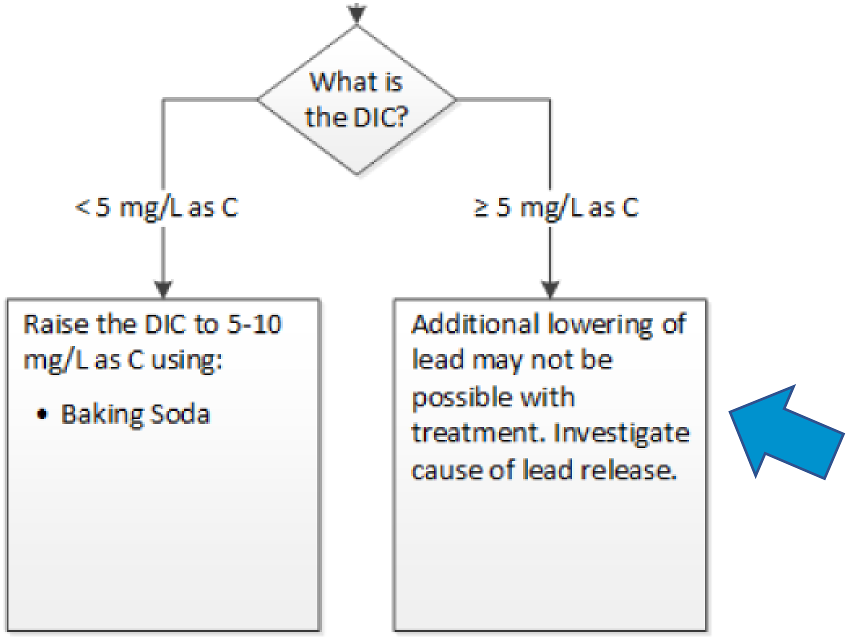
Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

EPA Flow Charts– Higher pH for Pb or Pb and Cu

Flowchart 1c: Selecting Treatment for Lead only or Lead and Copper with pH > 7.8 to 9.5



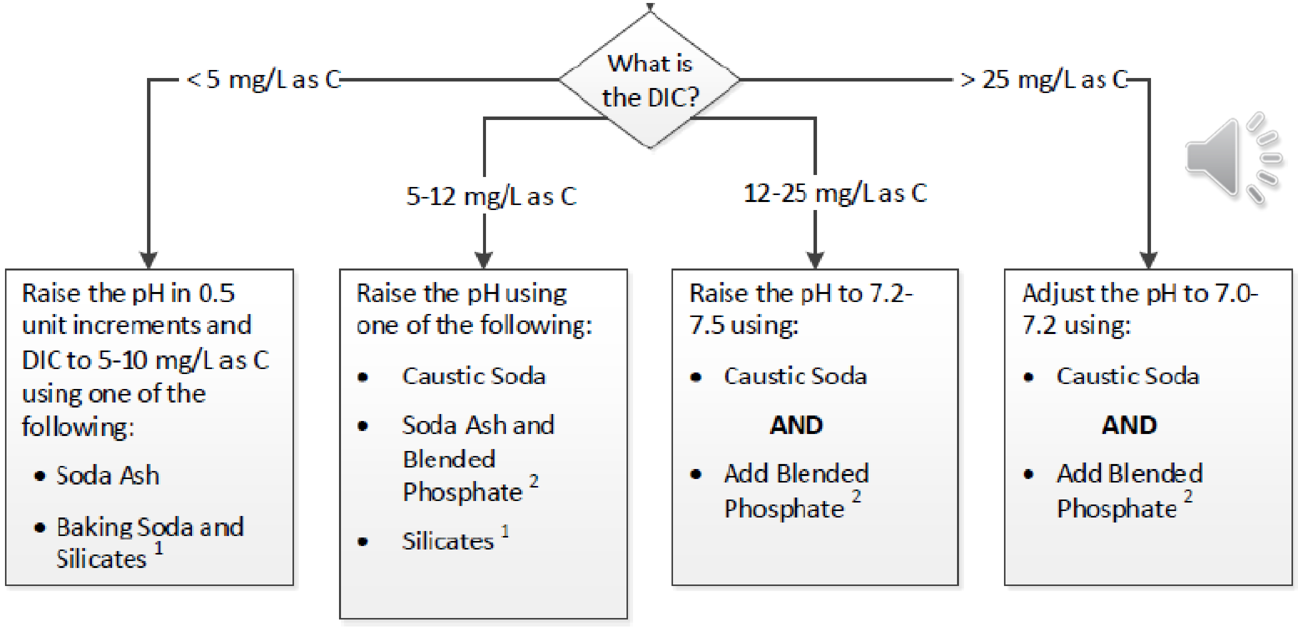
Flowchart 1d: Selecting Treatment for Lead only or Lead and Copper with pH > 9.5



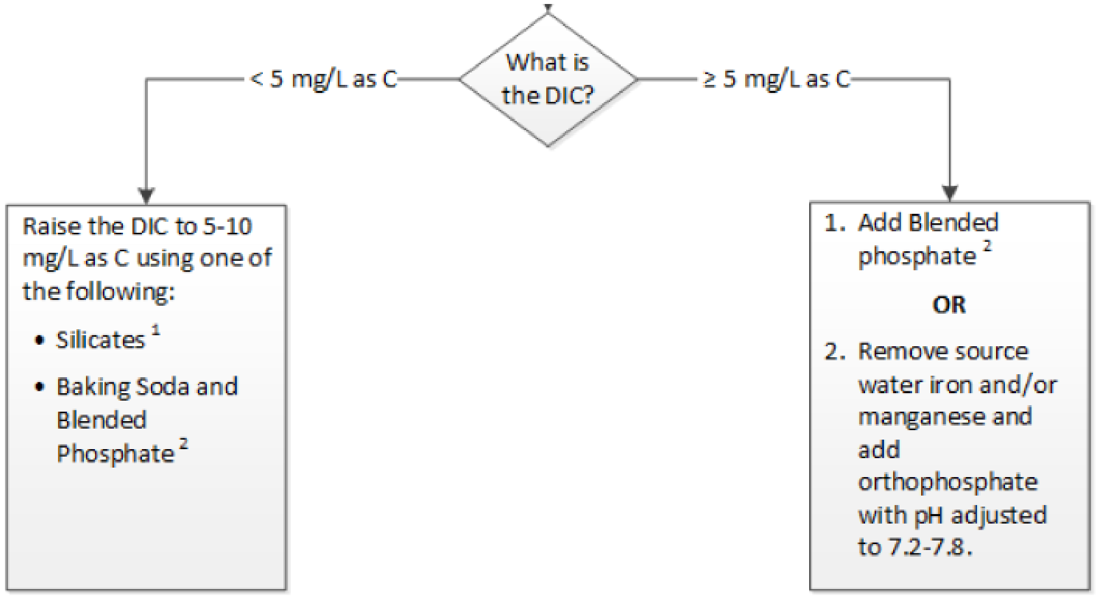
Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

EPA Flow Charts – Pb and/or Cu with Fe or Mn

Flowchart 3a: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH < 7.2



Flowchart 3b: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH ≥ 7.2



Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

KNOWLEDGE CHECK

3. Which of the following is not a required input when evaluating CCT using the EPA Flow Charts?

   a. 90th percentile lead level
   b. pH
   c. DIC
   d. Iron

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Cautionary Examples

- Applying flow charts based on inappropriately collected data
- Applying wrong controlling variable in decision-making
- Recognizing conflicting objectives
  - Soluble Pb levels vs aesthetics and contribution to particulate Pb
  - Soluble Cu levels vs excessive scaling

Inappropriately Collected Data – Example with pH

- Scenario: Groundwater supply with high CO_2
- pH is central to the EPA flow charts
- Typical data collected
  - Using a grab sample and properly calibrated pH probe or
  - Brought back to the lab for analysis
- Needed data
  - Collected using in-line pH meter or using a headspace free sampling device

Groundwater that has been newly exposed to the atmosphere releases CO2 quickly changing the observed pH

See Course 2

Wrong Controlling Variable – Example with CCPP

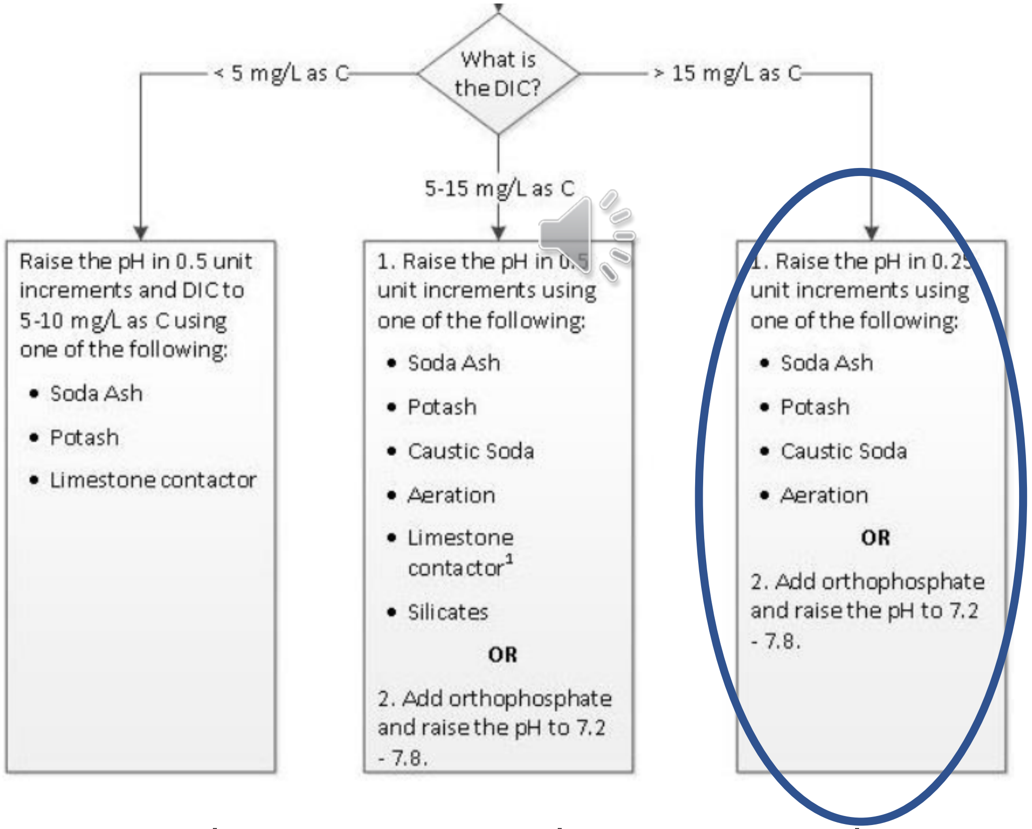
- Scenario: Applying a flow chart to a groundwater supply in limestone aquifer
- pH is central to the flow charts
- Calcium carbonate precipitation potential requires consideration

Example well conditions: pH = 7.0, Alkalinity = 300 mg/L as $CaCO_3$, Hardness=200

pH	CCPP
7	~0
7.1	+7
7.2	+16

Wrong Controlling Variable – Example with CCPP

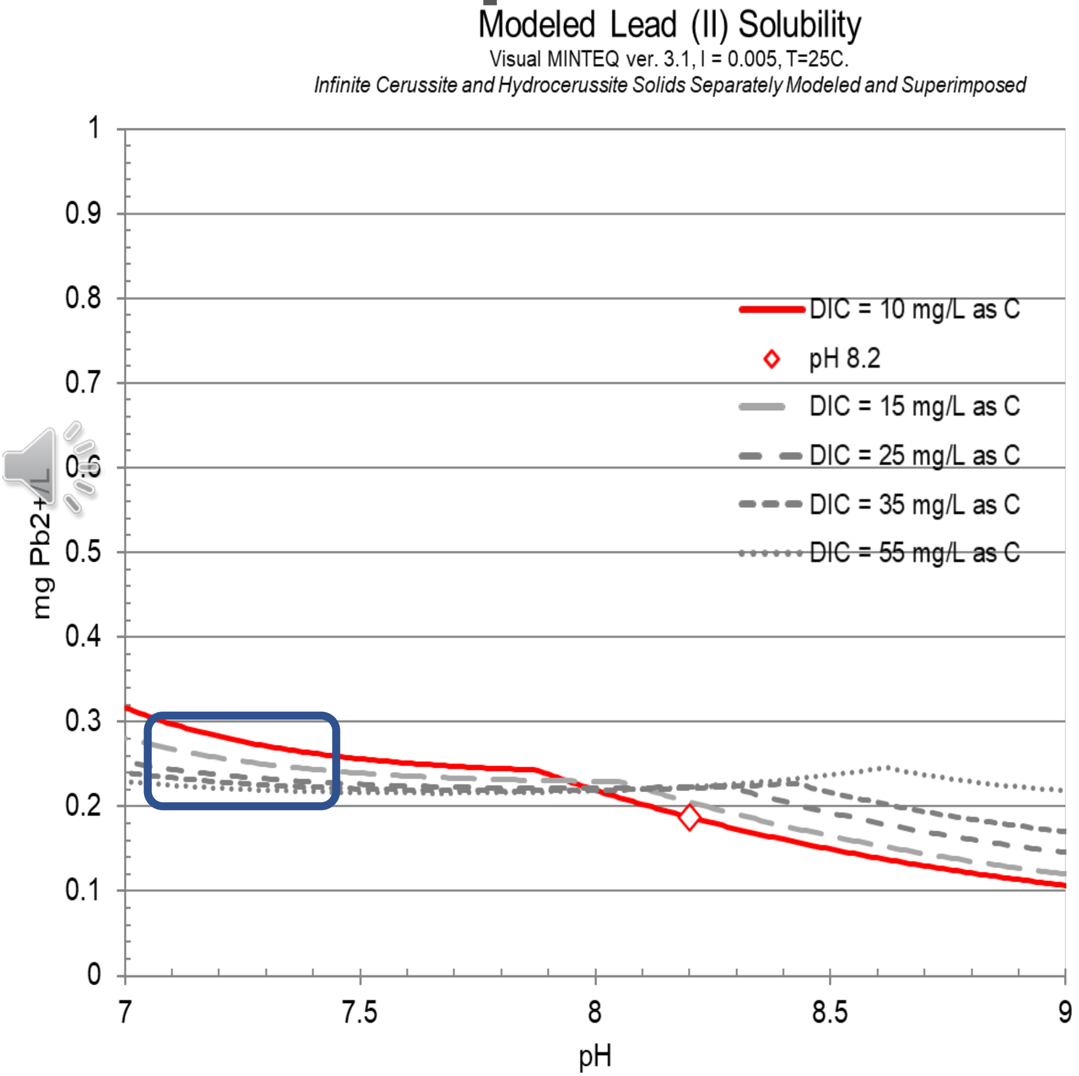
Flowchart 1a: Selecting Treatment for Lead only or Lead and Copper



Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

Wrong Controlling Variable – Example with CCPP

- Raising pH in 0.25 increments poses the same risk of calcium carbonate precipitation in high alkalinity, hard waters
- In this pH range, little incremental improvement at high DIC

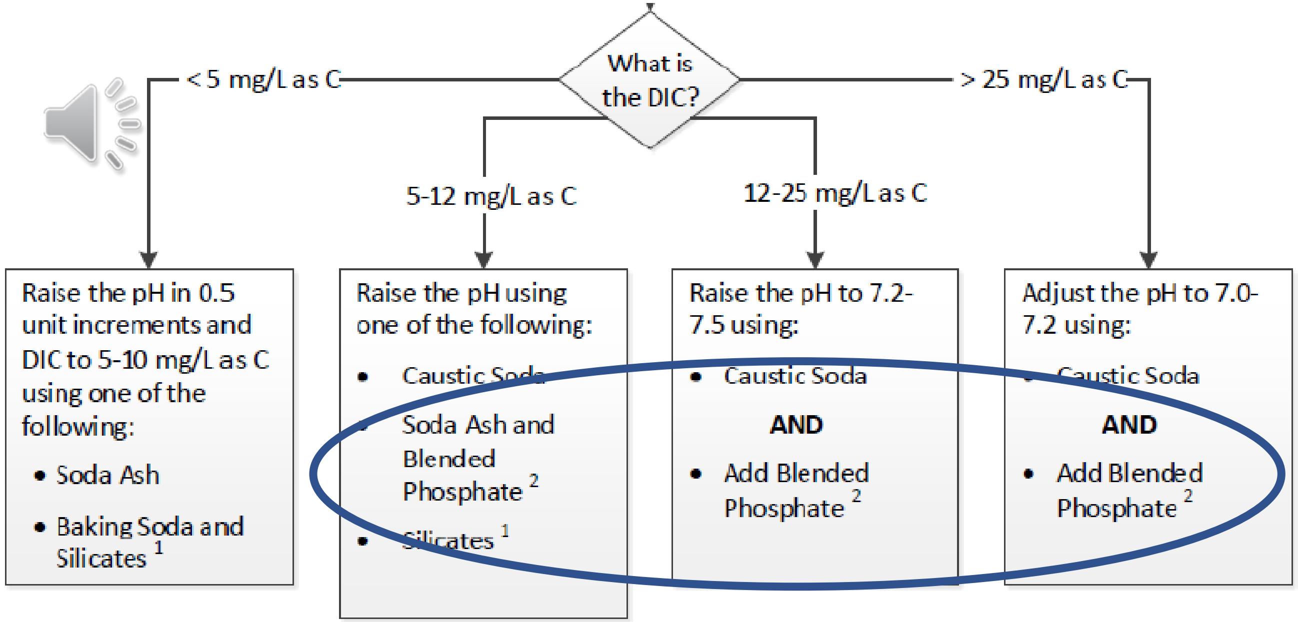


Source: Cornwell Engineering Group, 2020

Recognizing Conflicting Objectives – Example with Blended Phosphate

- When Fe and Mn are present, blended phosphate addition is a frequent option
- Blended phosphates can be very poor for Pb control and even increase observed Pb
- Adding a blended phosphate when Mn is present can release high Pb

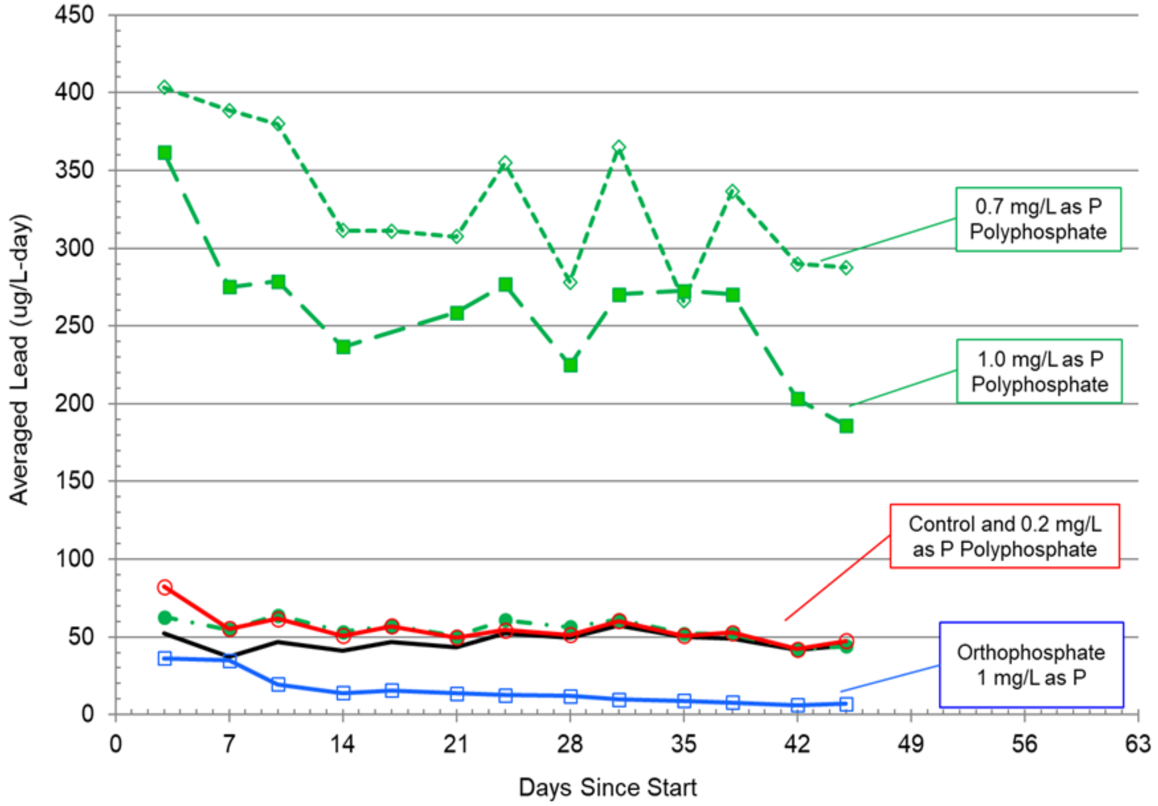
Flowchart 3a: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH < 7.2



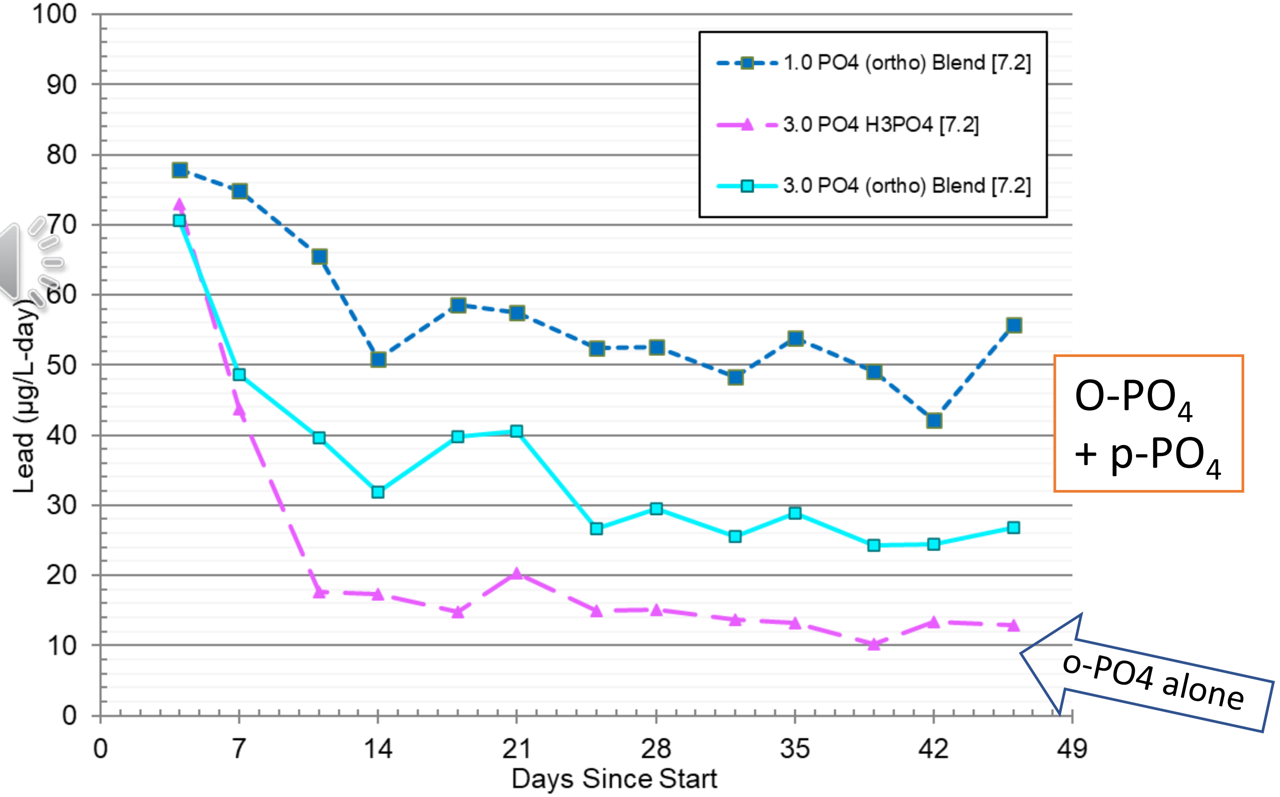
Source: EPA, Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems, 2016

Recognizing Conflicting Objectives – Example with Blended Phosphate

Polyphosphate Alone



50/50 Blended: o-PO_4 target is 1 mg/L



Source: Cornwell Engineering Group, 2020

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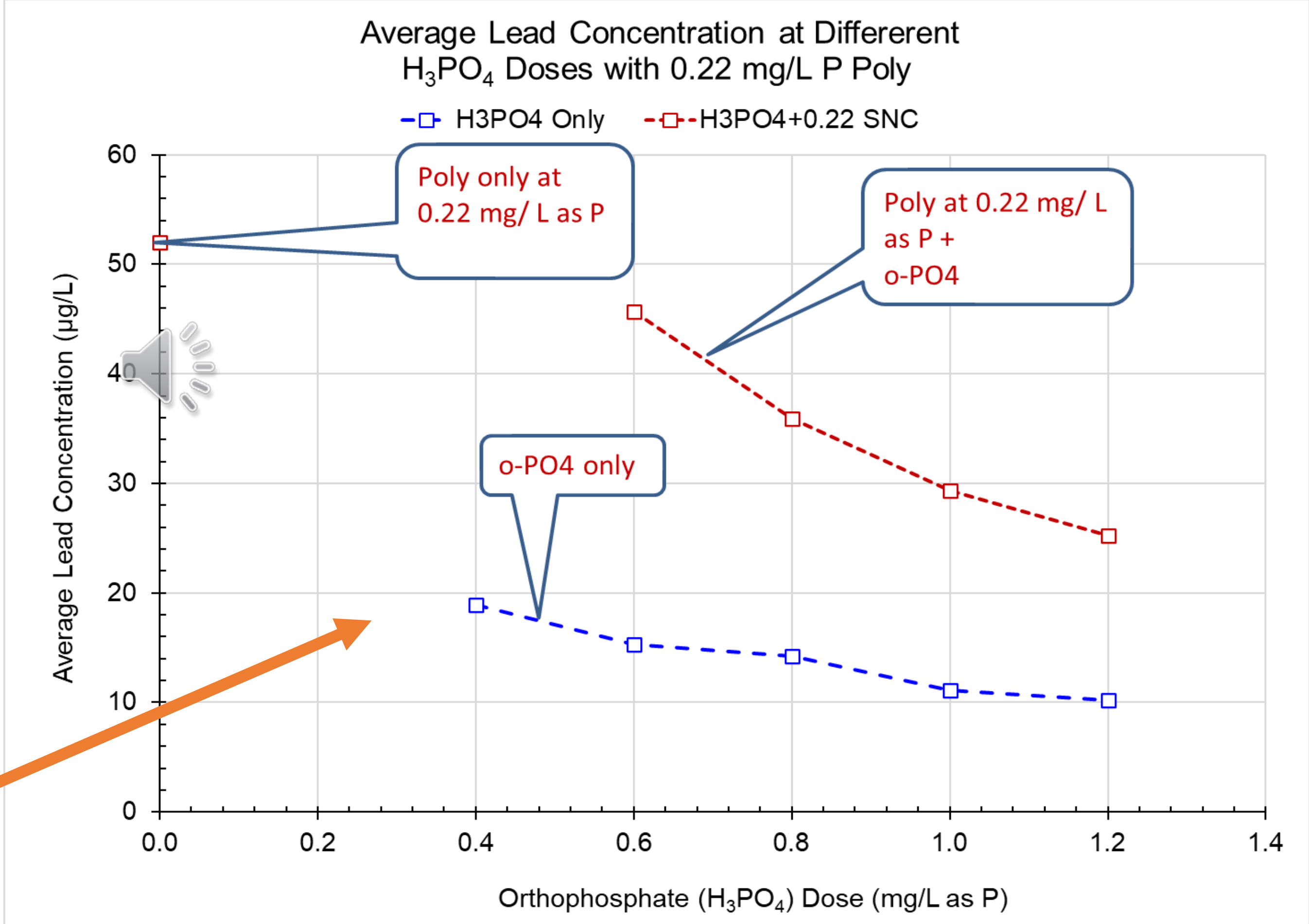
Recognizing Conflicting Objectives – Example with Blended Phosphate

- Adding ortho-PO_4 to a poly-PO_4 at high ortho-PO_4 can overcome the poly-PO_4 effect
- Very water specific—requires testing

Even 0.4 mg/L o-PO_4-P is better than 1.2 mg/L o-PO_4-P + 0.22 mg/L p-PO_4-P



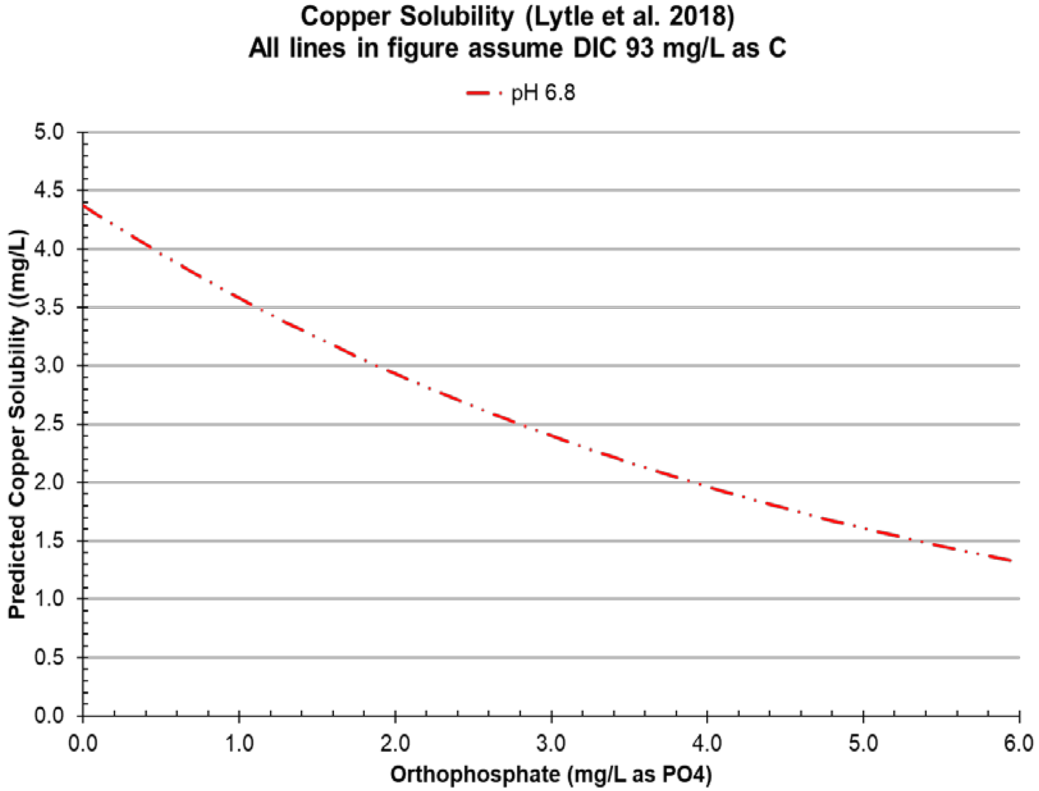
Source: Cornwell Engineering Group, 2020

Recognizing Conflicting Objectives – Example with Copper and Low pH

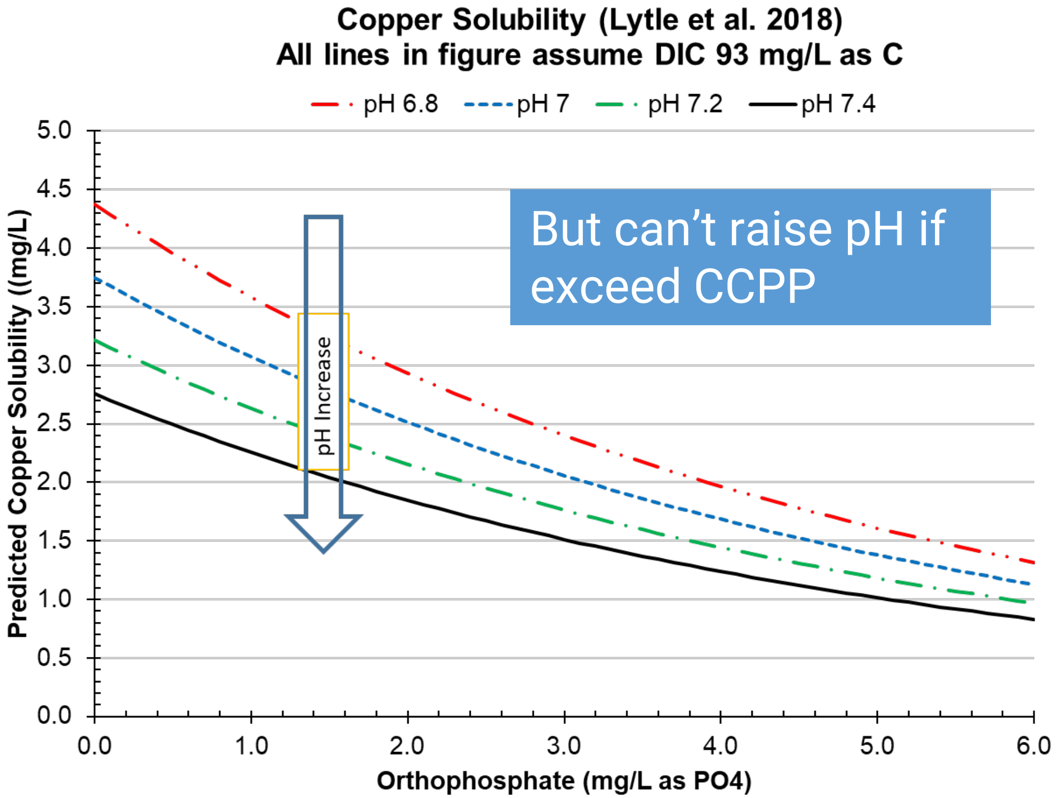
- Many small system wells are prone to copper corrosion
- Flow charts call for
  - Raising pH
  - Adding orthophosphate

Recognizing Conflicting Objectives – Example with Copper and Low pH

o-PO_4 required at pH 6.8



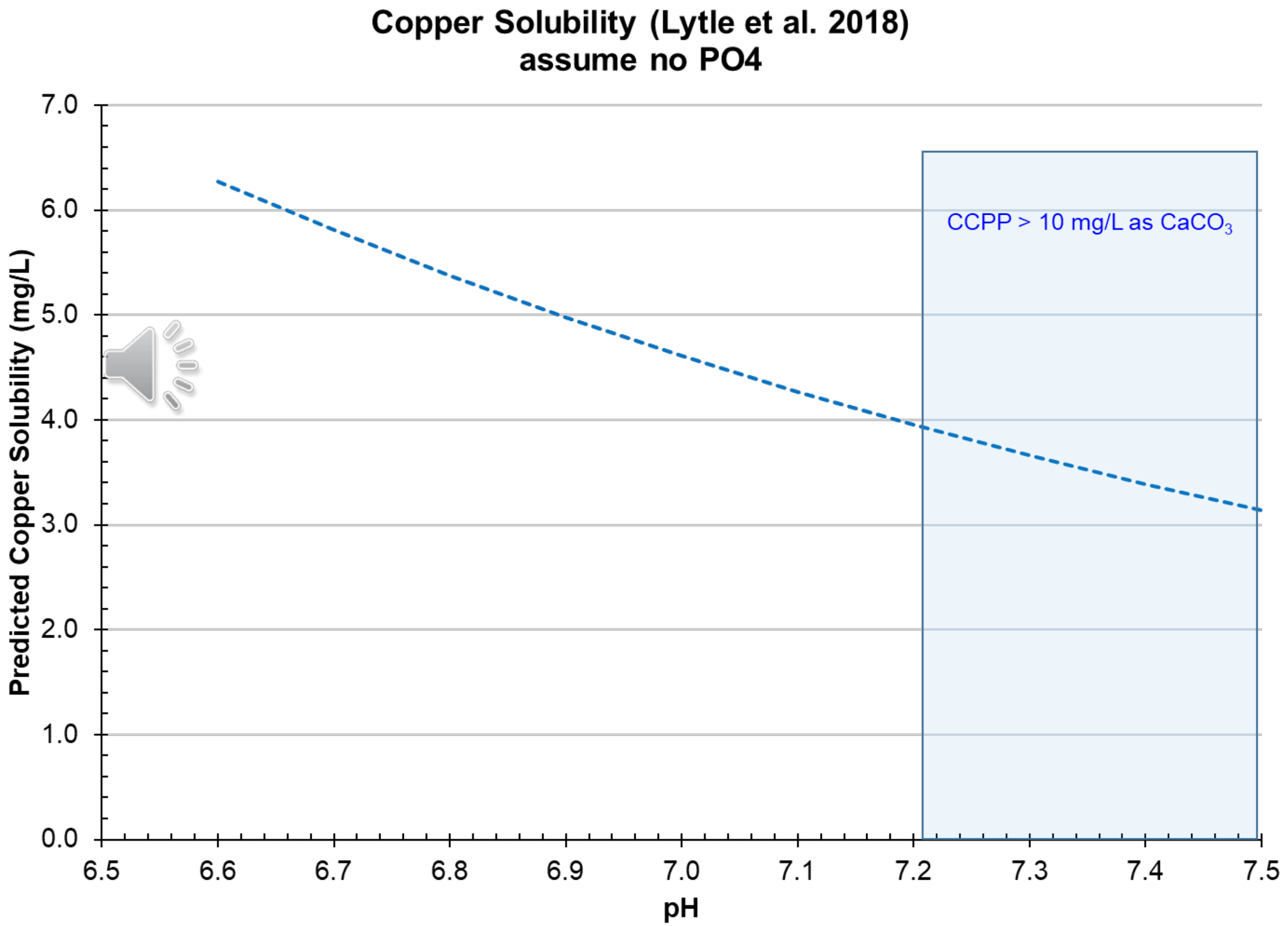
o-PO_4 required if raise pH



Source: Modified Lytle et al., 2018

Recognizing Conflicting Objectives – Example with Copper and low pH

- When have high alkalinity , hard waters
- Target conditions to control Cu release are not reached
  - With or Without o-PO_4



Source: Modified Lytle et al., 2018

KNOWLEDGE CHECK

4. Impacts to calcium carbonate precipitation potential should be evaluated when considering increased pH for corrosion control treatment.

    a. True

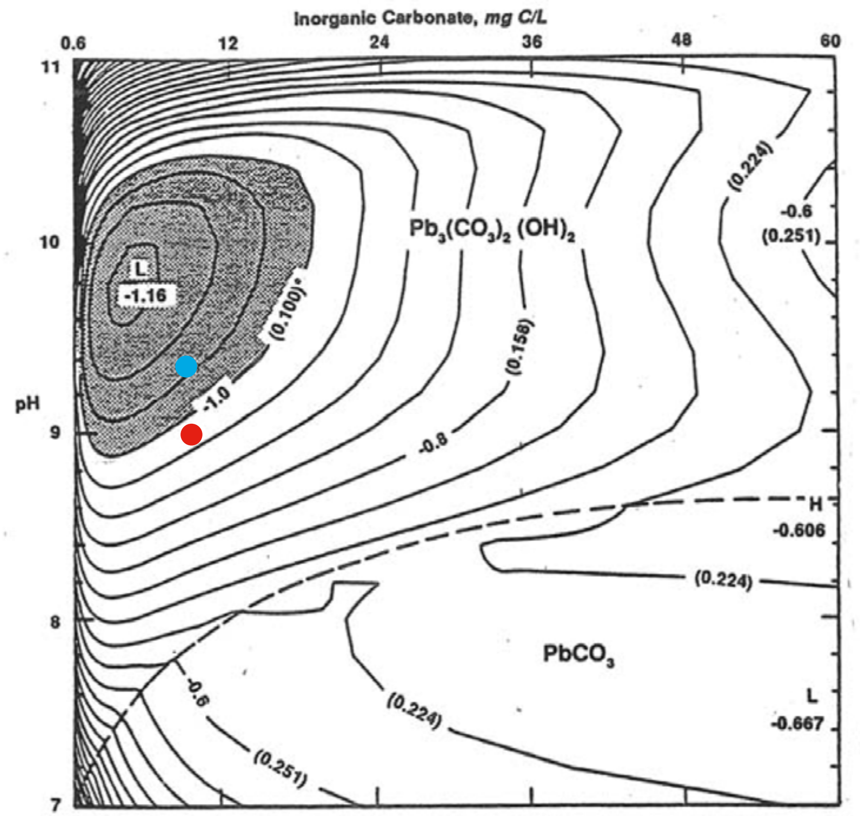
    b. False

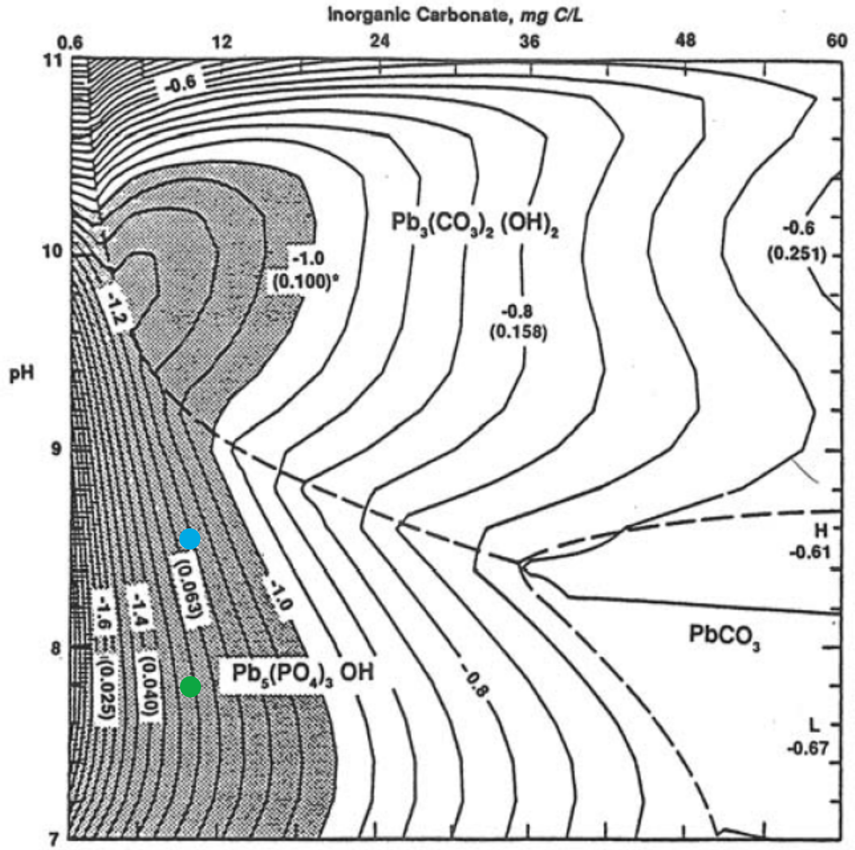
Improving Desktop Studies

Additional tools to include or couple with a desktop:

- Water quality / Solubility models
- Jar Testing
- Scale Analysis
- Profile Sampling

Existing Theoretical Solubility Diagrams





- *Existing Conditions, pH 9.0* *(Pb = 0.112)*
- *Alterative #1: Increase pH to 9.3* *(Pb = 0.089)*

- *Alternative #2: 0.5 mg/L as PO4, pH 8.6 (Pb = 0.070)*
- *Alternative #3: 0.5 mg/L as PO4, pH 7.8 (Pb = 0.056)*

Source: AWWARF & DVGW-TZW (1996).
Impact on Lead(II) solubility, assuming no orthophosphate present (left), 0.5 mg/L as PO4 present (right)

Modeling Tools for Assessing Water Chemistry

Desired information	Tool	Type
Aquatic equilibrium chemistry • Calculate solubilities of mineral species • Calculate saturation indices • Plot effects of pH and Eh on metal speciation and impacts	Mineql$^+$ Visual MINTEQ Geochemist's Workbench	Purchase required Free Purchase required
Aquatic geochemical equilibrium • Chemical and mineral speciation	PHREEQC Geochemist's Workbench	Free Purchase required
Calculation of water quality conditions • Chemical dose calculation • Calculation of water quality parameters	RTW Model WaterPro	Purchase required Purchase required
Simple calculations • pH, DIC, Alkalinity, TDS	aqion	Free

Caution: Many software packages are available to assist in water chemistry analysis. Care should be taken in treating any software package as a 'black box'. Often experience is needed to appropriately set up an analysis and accurately interpret results.

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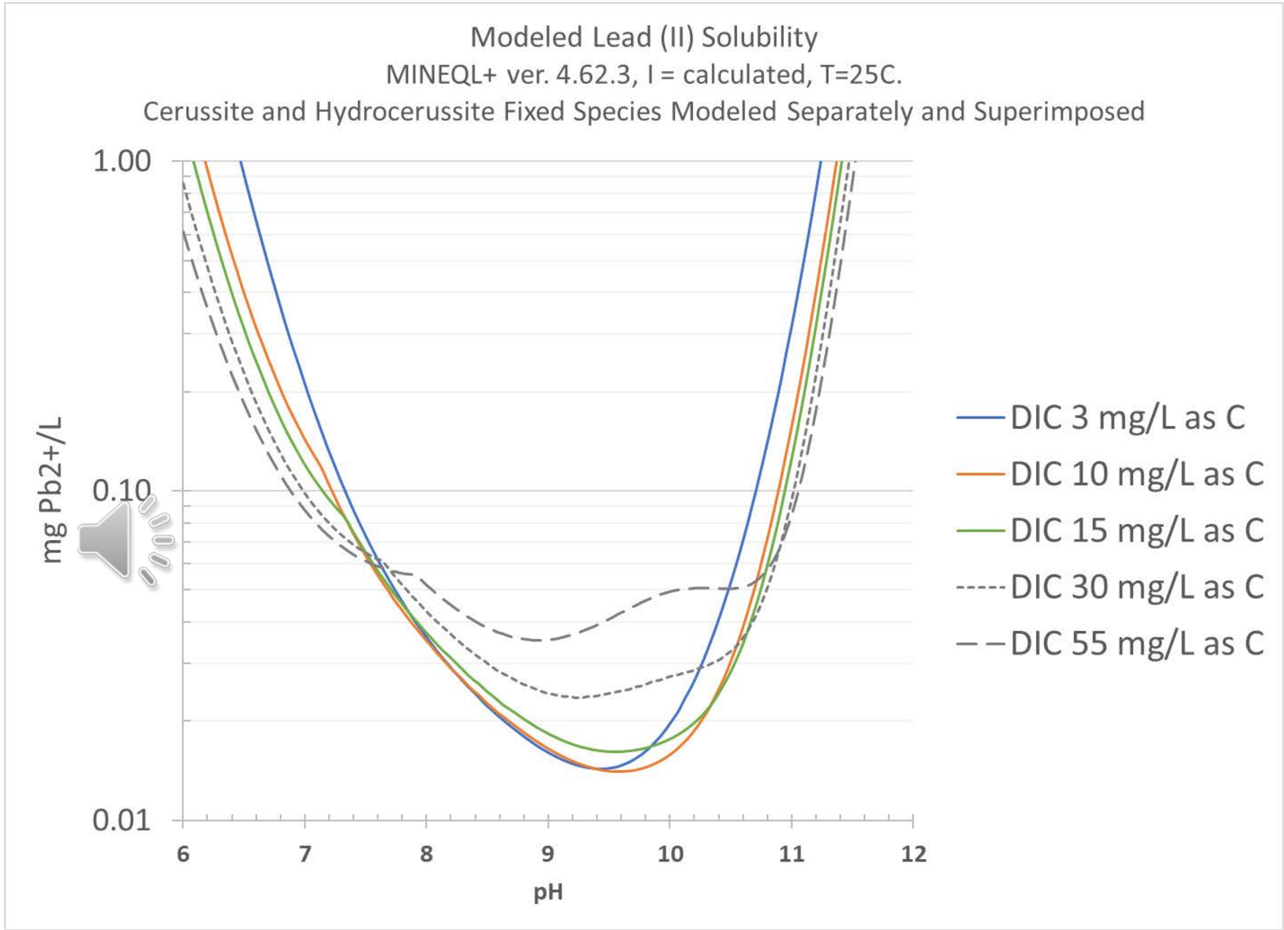
Solubility Models

Observed Pb solubility may vary from theoretical prediction. Different assumptions can lead to different conclusions, so caution is needed.

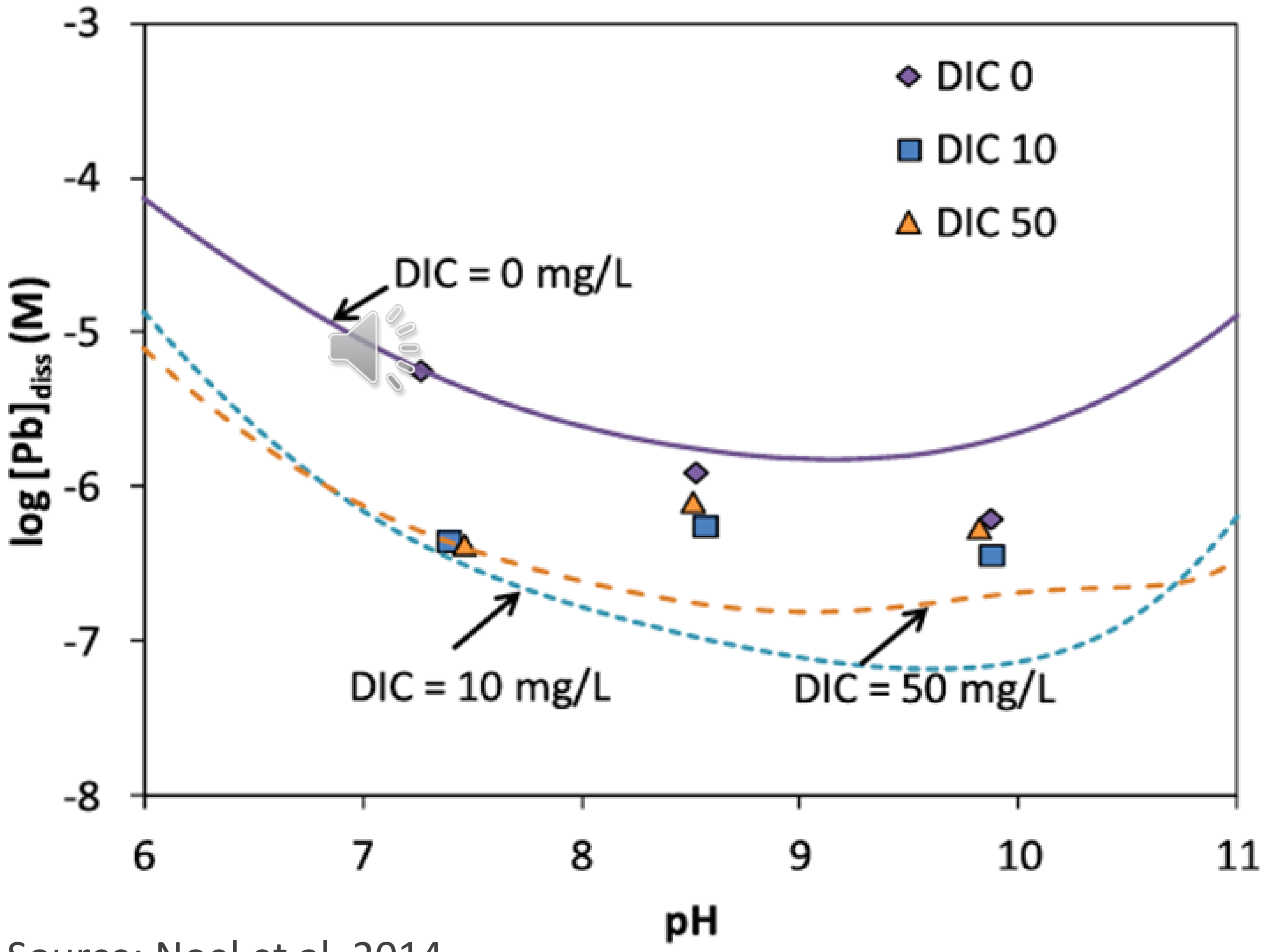


Theoretical Lead Solubility

Source: Cornwell Engineering Group

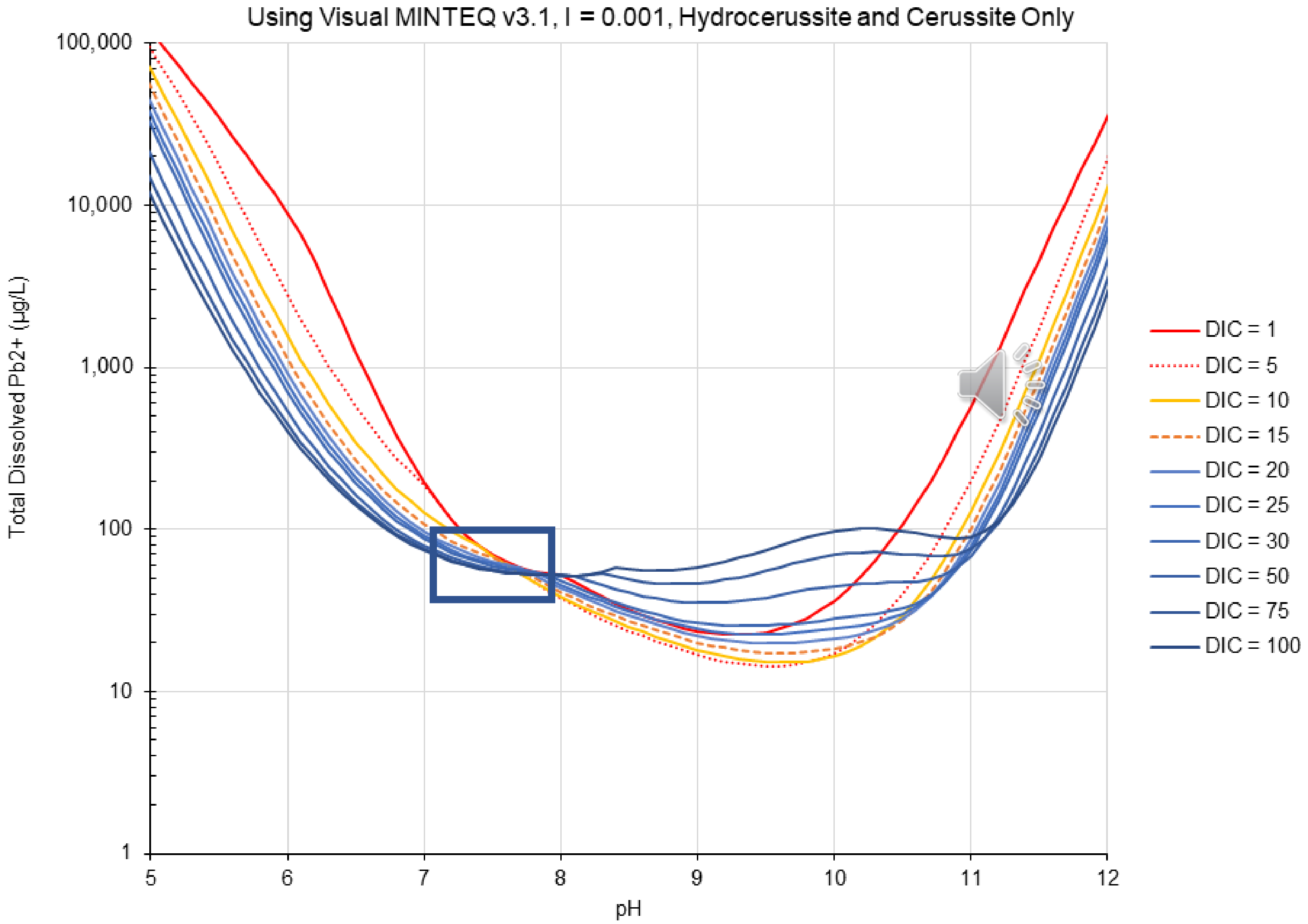
Solubility Models

Comparison of measured and predicted hydrocerrusite solubility (Minteq)



Source: Noel et al. 2014

Using Solubility Models to Compare Alternatives

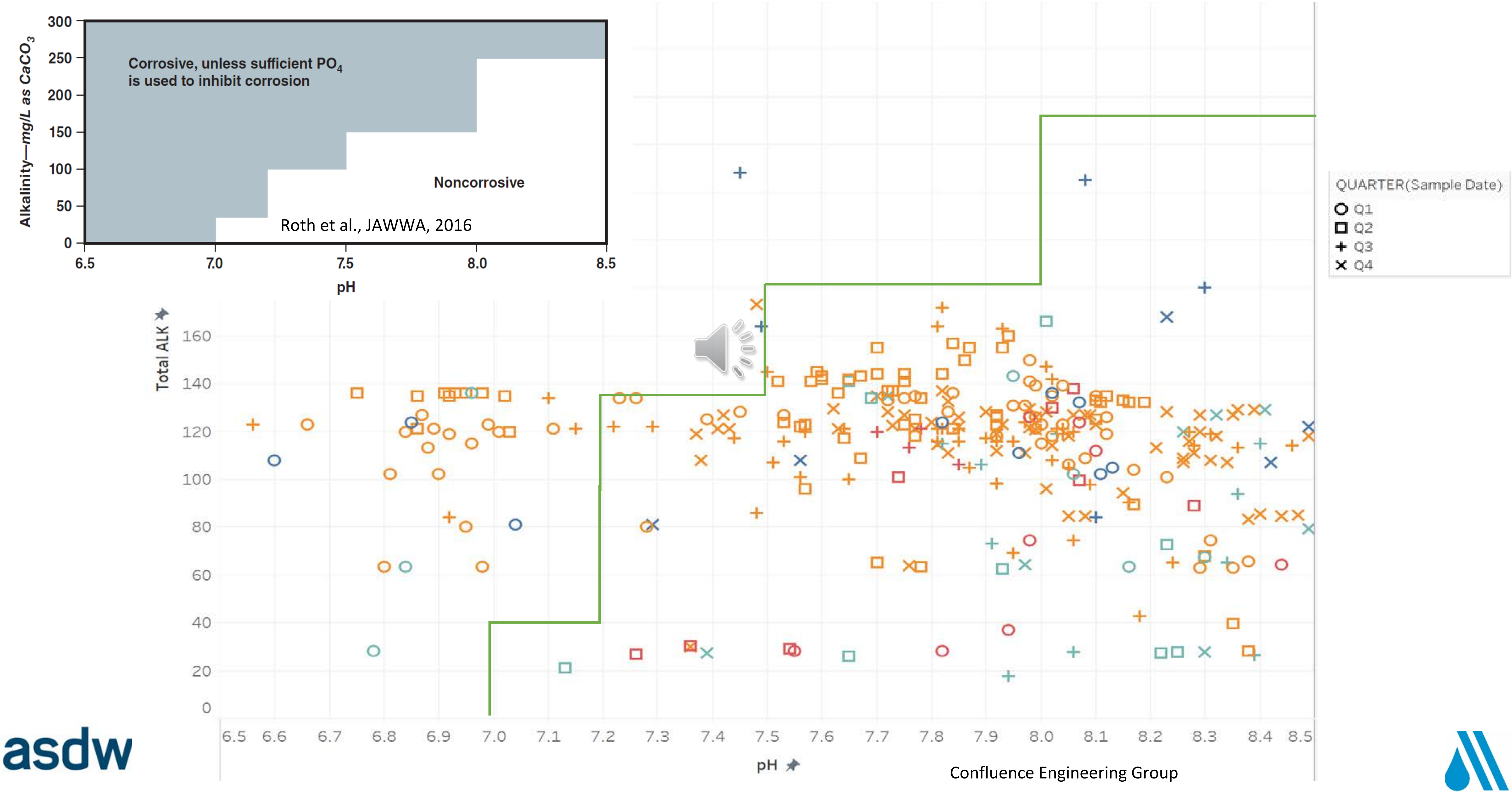


Example: For higher DIC waters, a pH change in this region would theoretically not affect Pb Could confirm with lead solubility study

Solubility Models

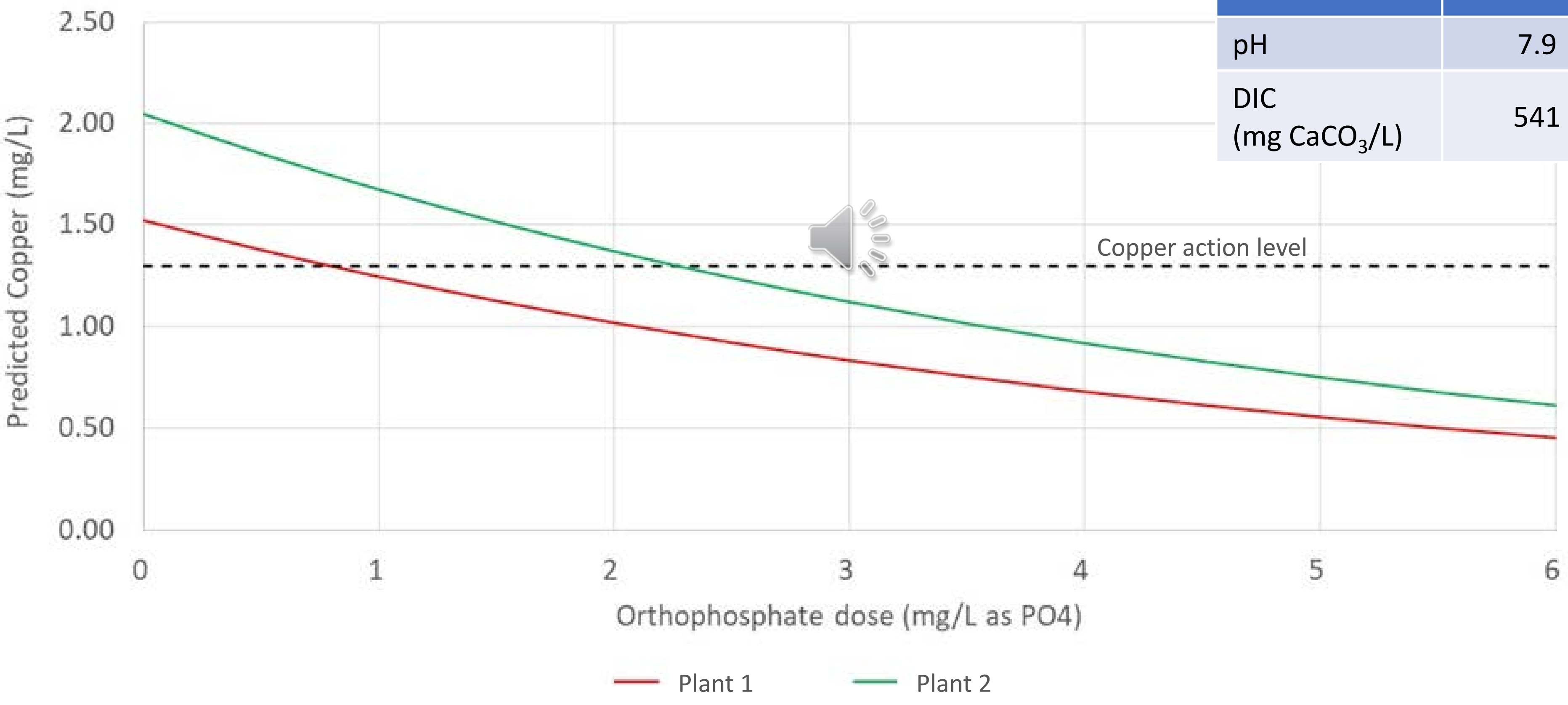
- Different constants give different results (Course 2)
- Should be created for specific water quality
- Often do not predict actual scales formed
- Should not be used to predict actual lead numbers
- BUT, they are still very useful
  - Can indicate the possible impacts of a pH or DIC change
  - Can help set testing strategies
  - Can indicate issues with treatment of souse or blending changes

Evaluating WQPs for Copper Corrosivity



Confluence Engineering Group

Using Solubility Models to Estimate Orthophosphate Dose



	Plant 1	Plant 2
pH	7.9	7.4
DIC (mg $CaCO_3$/L)	541	466

Modified from: Lytle (2017)

KNOWLEDGE CHECK

5. Which of the following is a limitation of solubility models?
    a. They cannot identify potential impacts from a pH change
    b. They often do not predict actual scales formed
    c. They are only available for lead
    d. None of the above

Common Corrosion Control Treatment Options for pH and/or Alkalinity Adjustment

pH and/or Alkalinity Adjustment	Inhibitors
• Sodium bicarbonate • Carbon dioxide • Sodium hydroxide • Potassium hydroxide • Calcium hydroxide • Calcium oxide • Sodium carbonate • Potassium carbonate • Aeration	• Phosphoric Acid • Sodium or potassium phosphate • Zinc Orthophosphate • Blended phosphates • Silicates (mixtures of soda ash and silicon dioxide)

More information for each can be found in
AWWA M58: Internal Corrosion Control in Water Distribution Systems, 2nd ed.

Considerations for Chemical Selection

Effectiveness	Secondary impacts (scaling, pH, etc.)	Operability	Operator preference & experience
Worker and Community Safety	Cost (Capital, O&M, Lifecycle)	Availability	Reliability of the technology
Flexibility	Public Opinion	Ease of implementation	Timeline for implementation

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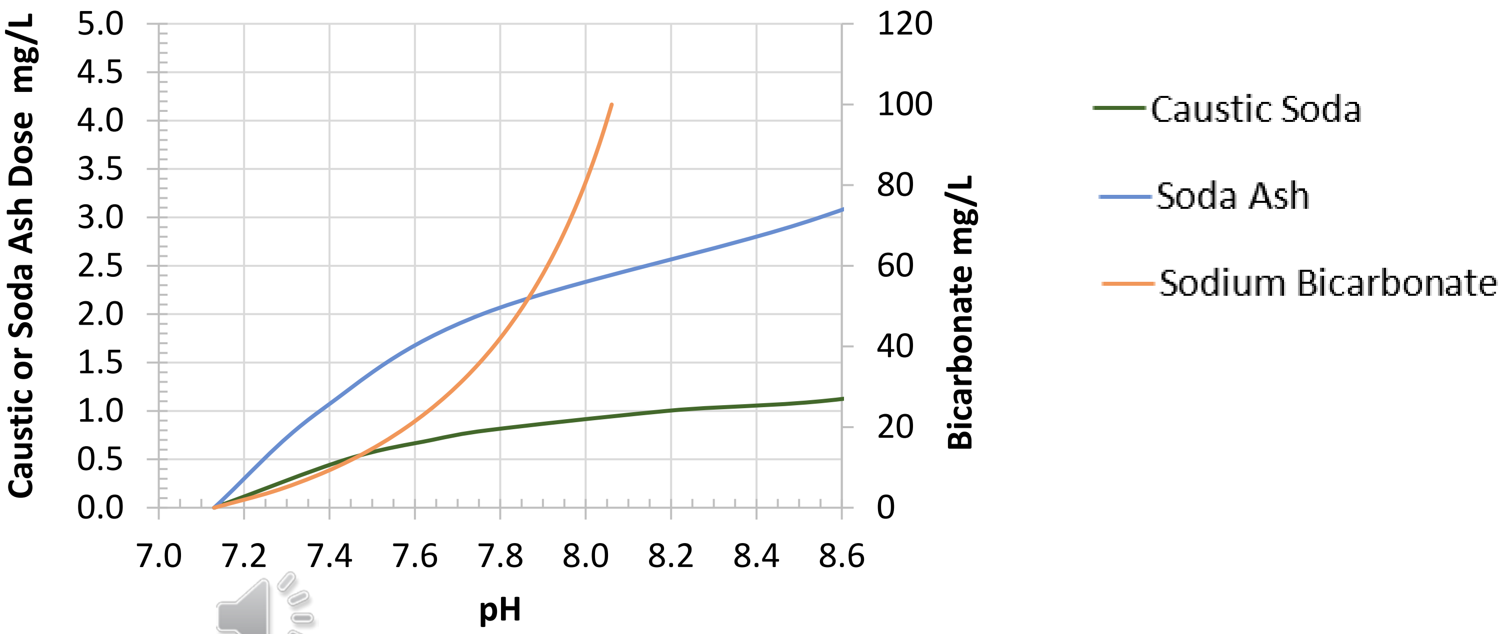
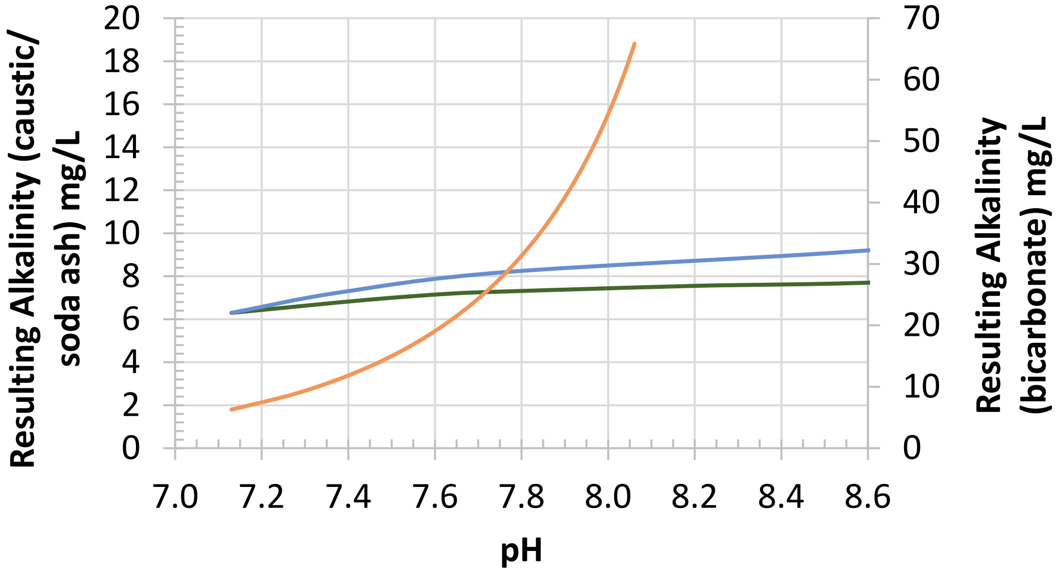
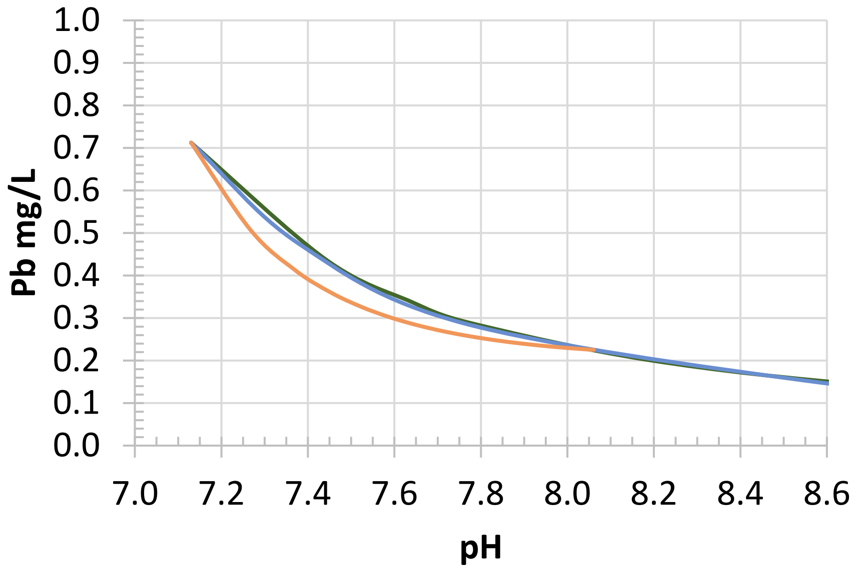
Using Modeling for Chemical Selection: Example performance for low alkalinity surface water



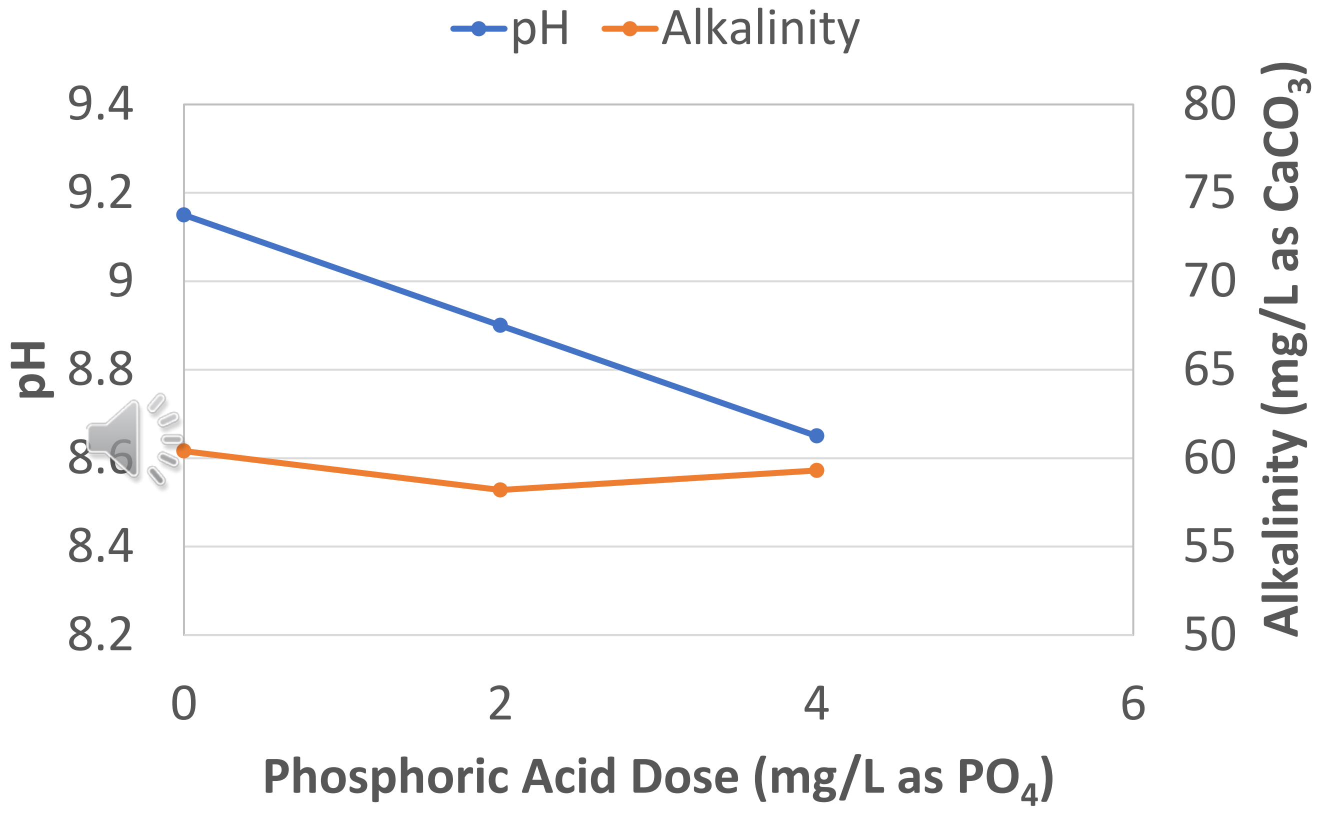




Source: Confluence Engineering Group LLC

Jar Testing to Assess Dose and/or Water Quality Impacts

- Assess pH impacts from phosphoric acid
- Confirm chemical doses for pH adjustment under various water quality conditions



Source: Arcadis

KNOWLEDGE CHECK

6. Which of the following is not a tool that can help assess impacts to finished water quality from a specific corrosion control treatment chemical include:
    a. Water treatment/chemistry process models
    b. Pourbaix diagrams
    c. Jar testing

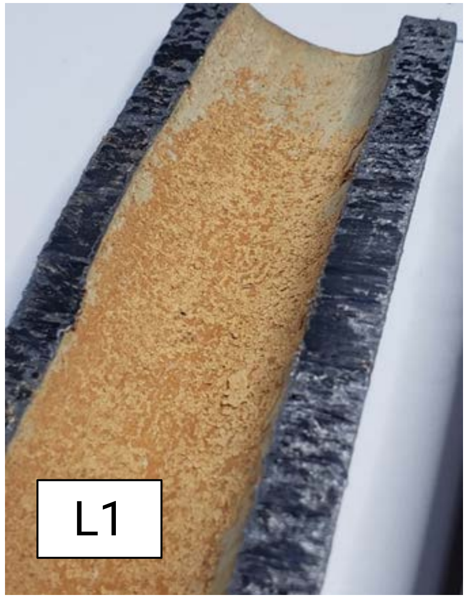
Pipe Scale Analysis Techniques

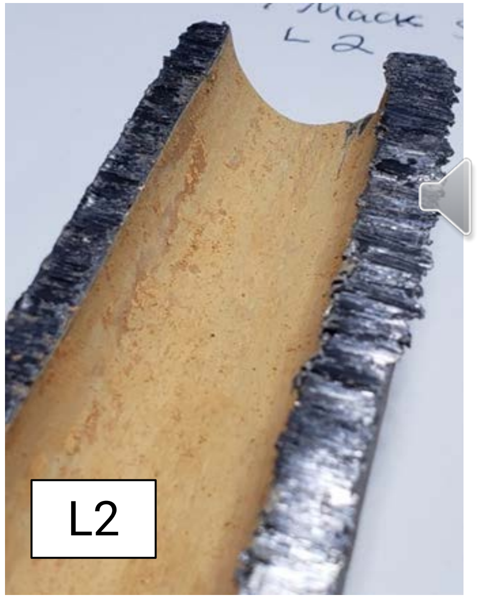
Technique	Information Provided	Usefulness	How it works
X-Ray Diffraction (XRD)	Mineralogical forms present in sample	Identify specific mineral forms in scale sample (example hydrocerussite vs. cerussite)	X-ray measures angles at which x-rays deflect
X-Ray Fluorescence (XRF)	Elemental composition of sample	Identify elements in scale sample (Example – weight % of Pb, Al, Fe Mn, As, Zn, etc.)	X-ray bombardment causes element to fluoresce
Scanning Electron Microscopy (SEM)	Micrographic image of sample	Pictorial representation of scale (Example – observe porosity of scale)	Surface scanned by electron beam
Energy-Dispersive Spectrometry (EDS)	Elemental composition of sample	In conjunction with SEM, provides elemental map of sample (Example – elemental composition of scale layers imaged by SEM)	Detects x-rays emitted when sample is bombarded by electron beam

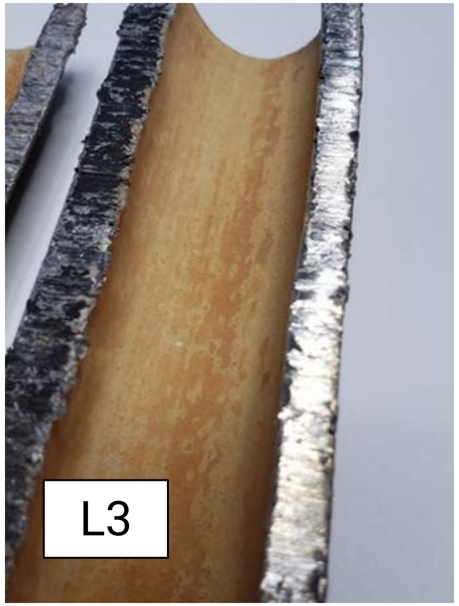
When You Might Consider Pipe Scale Analysis

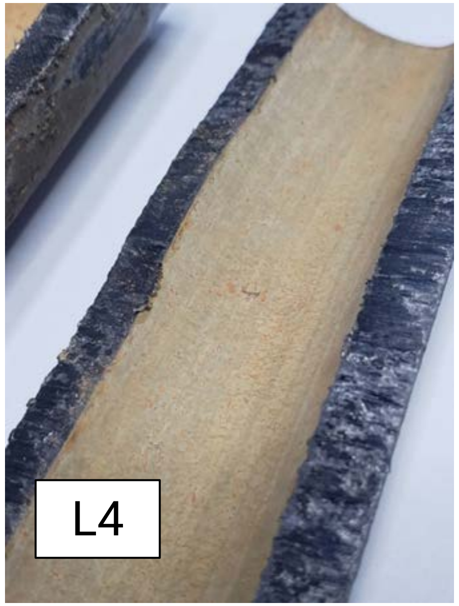
- Free chlorine systems – is lead(IV) present
- Systems with potential legacy metals (Al, Fe, Mn)
- Systems with multiple sources
- Before making a change in source/treatment (refer to Course 2 for additional information)

When You Might Consider Pipe Scale Analysis





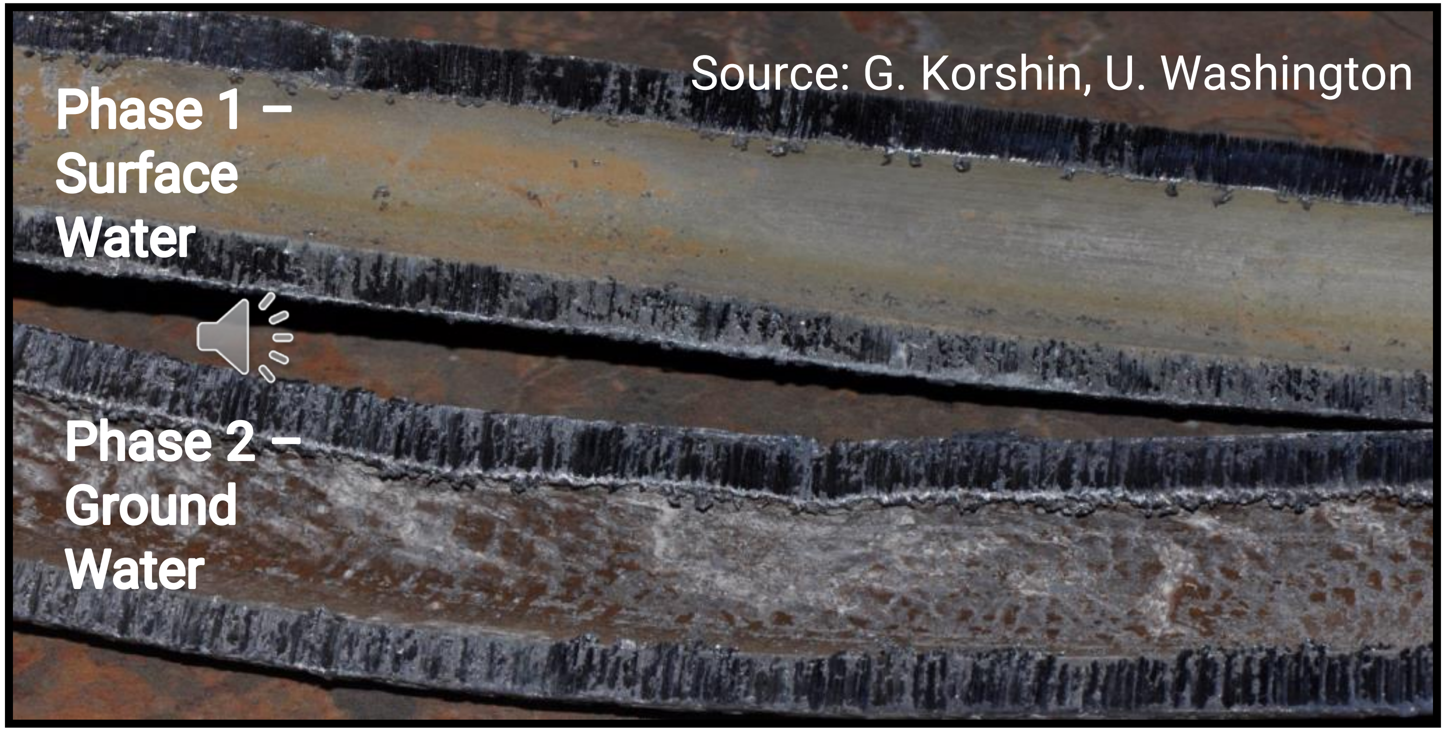




Source: Cornwell Engineering Group

Example Pipe Scale Analysis

SEM and visual examination used to verify the formation of different scales when goosenecks were exposed to surface water versus ground water



Source: Friedman. (2020). Presented at the USEPA 17th Annual Drinking Water. Workshop

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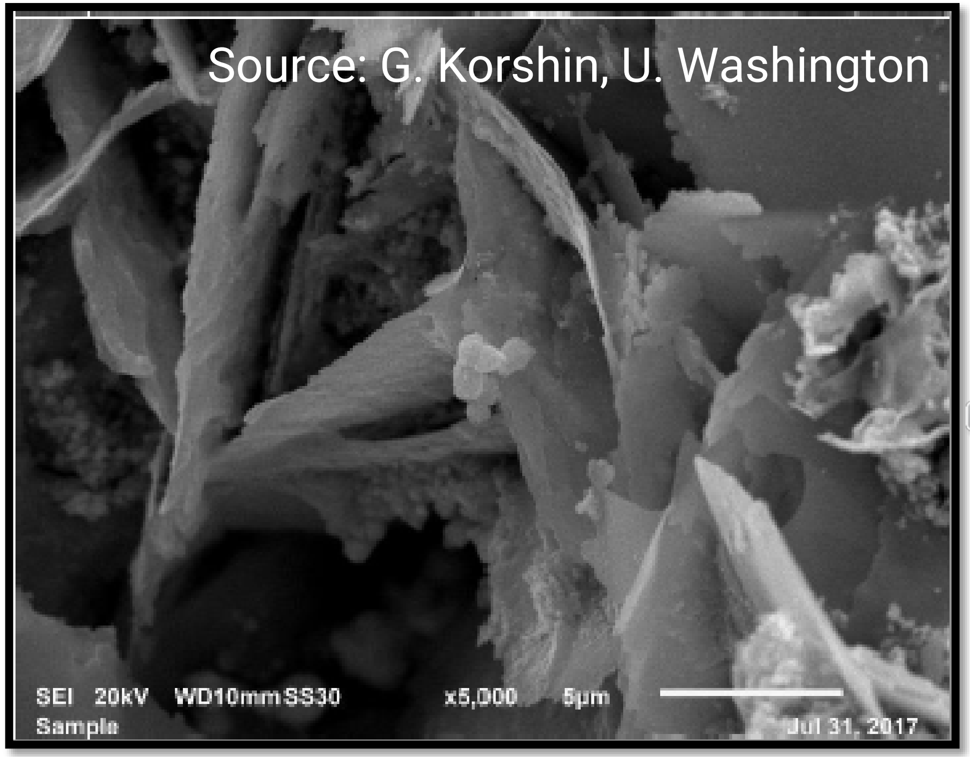
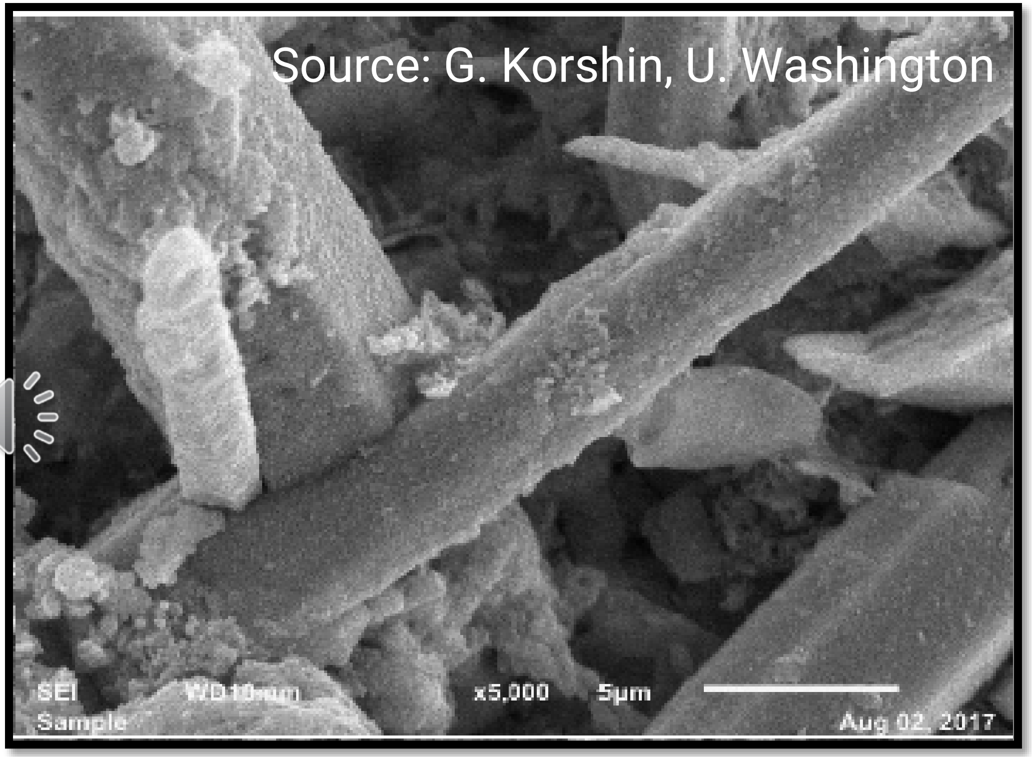
Example Pipe Scale Analysis



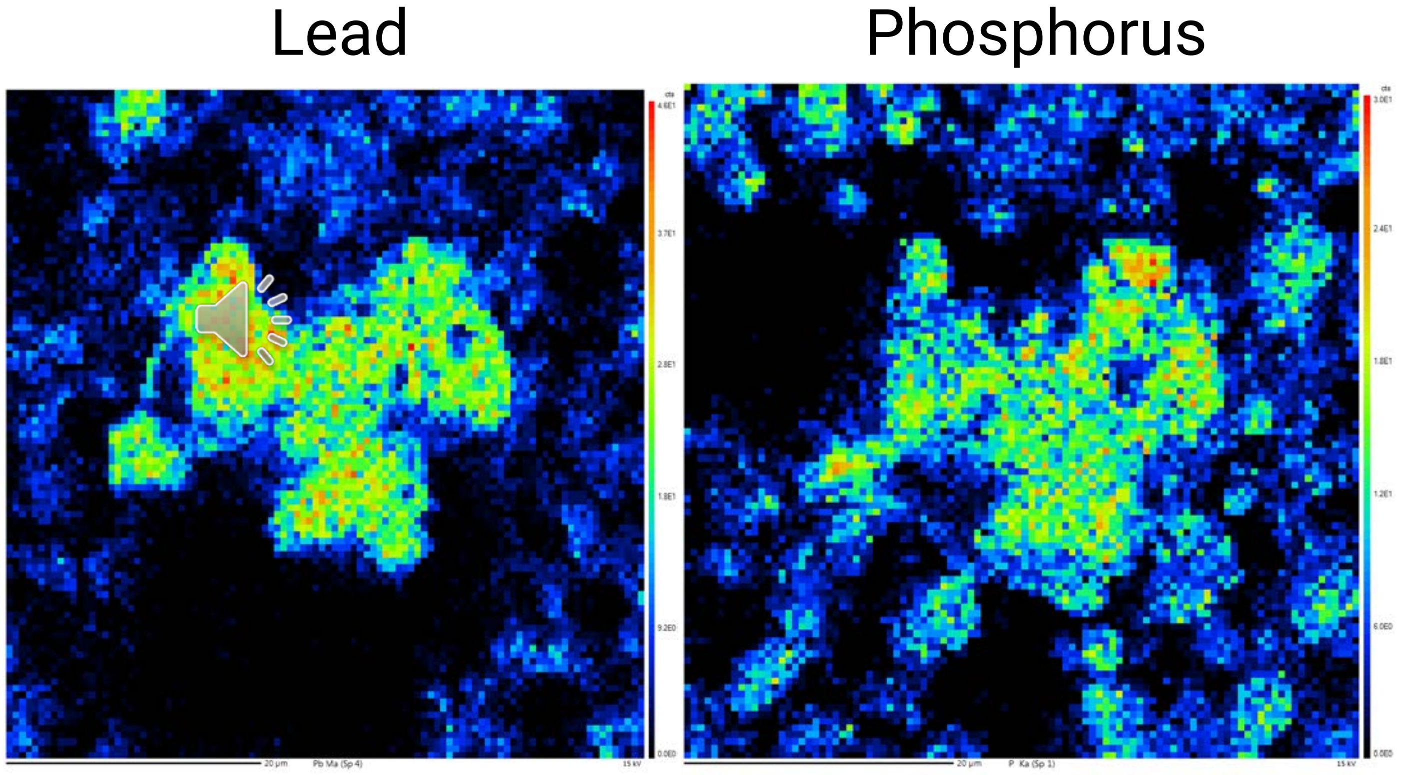
Lead Gooseneck Phase 1 – Surface Water
Scale dominated by Pb(II) hydrocerussite with some Pb(IV)



Lead Gooseneck Phase 2 - Groundwater
Scale dominated by Pb(II) cerussite with some Pb(IV)

Example Pipe Scale Analysis

Heatmaps showing the lead particle is highly associated with the phosphorus—good coverage



Source: Cornwell Engineering Group

KNOWLEDGE CHECK

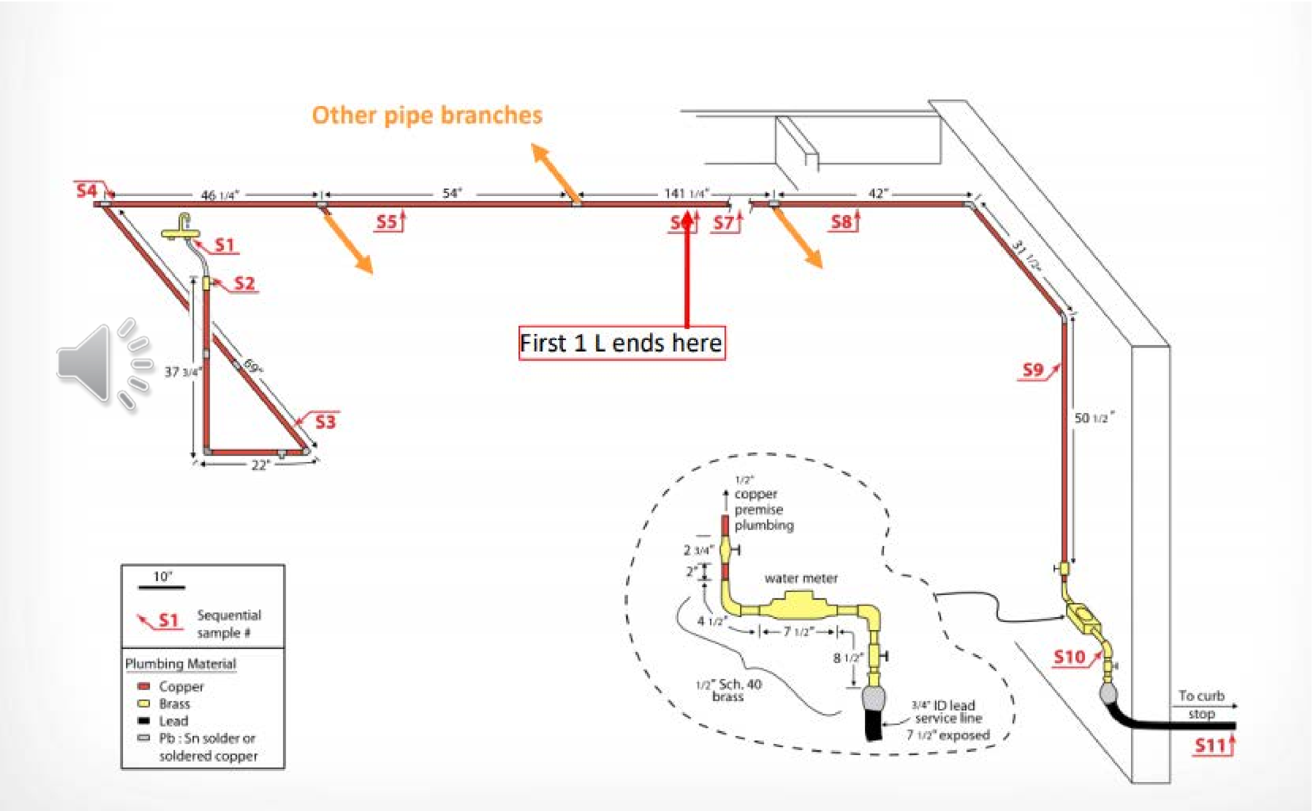
7. Pipe scale analysis can be used to:
    a. Identify specific mineral forms present
    b. Identify scale dissolution rates
    c. Determine if lead and phosphorus are associated
    d. Both (a) and (c)

Profile Sampling Considerations

- Flow rate
- Sample volume
- Stagnation time
- Aerator removal
- Pre-flush
- Temperature
- Additional metals (Zn, Cu, Sn, Fe) and WQPs (pH, chlorine, etc.)
- Total and dissolved

Typical Profile Sampling Procedure

- Conduct plumbing survey from tap to main
- Calculate the total volume of water
- Test flow rate and remove aerator, if applicable
- Allow water to stagnate for 6 hours minimum
- Hold bottle #1 under faucet and turn on cold water at a normally used flow rate
- With water flowing continuously at the same rate, fill each subsequent bottle, not allowing water to go down the drain between bottles
- Once all are filled, turn off tap



Source: Lytle et al. Sequential Sampling as a Diagnostic Tool for Assessing Lead

KNOWLEDGE CHECK

8. Profile sampling requires only the first and fifth-liter sample volumes to be collected and analyzed.

    a. True

    b. False

Summary

- CCT selection requires careful evaluation – one size rarely fits all
- Desktop studies should always be a first step in the CCS process and often includes a combination of tools or techniques
- Many testing approaches are available and the right one needs selected from the desktop study
- Caution should be exercised when using analogous systems and CCT flow charts

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MODULE 2 DEMONSTRATION & FIELD STUDIES

LEARNING OBJECTIVES

Describe

- Key considerations and differences in demonstration testing options
- Testing configurations
- Types of testing materials

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Common Sources of Lead and Copper

Material	Considerations
Lead service lines	• Often the primary source of lead at the tap, when present
Galvanized pipe	• Can act as both a direct and indirect source of lead • May have a hard time obtaining a lead signal
Lead solder	• Pre-1986 lead solder often contained 50% lead and 50% tin, which can result in elevated lead tap levels • May have varying amounts of solder / leaching characteristics
Brass	• Until January 2014, purchased brass materials could contain up to 8% lead by weight • May have challenges obtaining a lead signal • May need to test multiple in series to obtain the needed sample volume / signal
Copper pipe	• New copper piping can require years to achieve passivation

Comparison of New and Harvested Testing Materials

Type	Mechanism	Pros	Cons	Common Materials
New	Represents theoretical solubility/ corrosion prior to passivation	• Can reduce variability between specimens • Relatively easy to obtain	• Lacks scales • Can take long time to acclimate	• New lead pipe/coupons/plates • New copper pipe/coupons/plates • New brass pipe/coupons • Non-potable brass faucets
Harvested	Represents actual corrosion/ metals release from existing scales/ materials	• Represents complexity of existing scales	• Disruption of existing scales during excavation and transport • Must be preserved to maintain scale integrity • High variability • Challenge to obtain enough specimens of similar size/volume, age, leaching characteristics • Requires significant coordination and time to obtain • Can take long time to acclimate	• Lead service lines • Galvanized service lines • Copper pipe with leaded solder • Brass meters

Galvanic Corrosion

Considerations

- Highly accelerates corrosion of less noble material
- Occurs with new material; may not occur with harvested materials due to passivation or lack of remaining solder

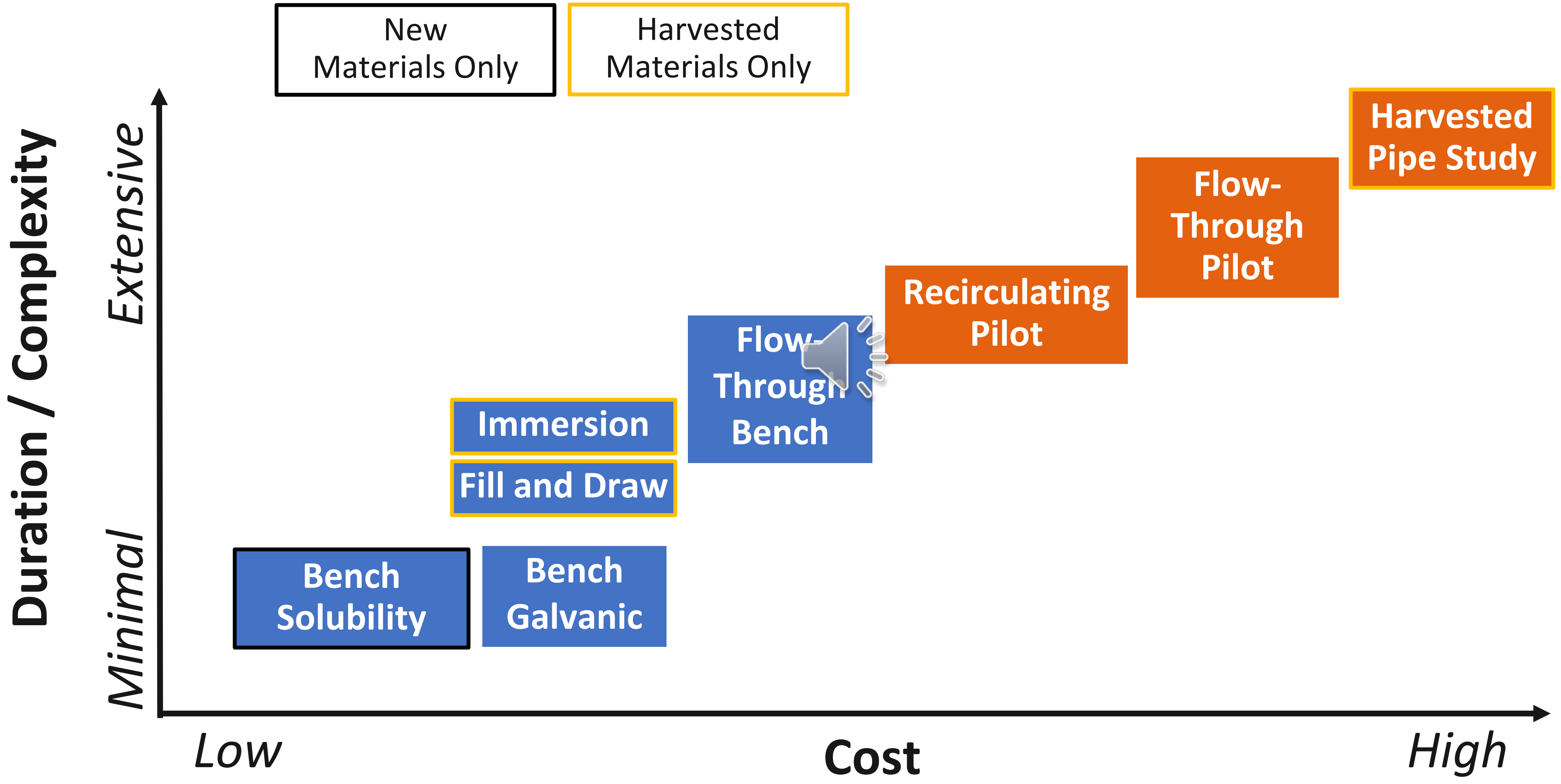
Materials of Concern

- Lead solder-copper coupons
- Lead pipe directly connected to copper pipe
- New copper pipe containing lead solder
  - Melted
  - Dipped

KNOWLEDGE CHECK

1. Which of the following is not an advantage of using new materials in a demonstration test?
   a. Easier to obtain
   b. Can be purchased in large quantities
   c. Short acclimation period
   d. May have less variability among replicates

Demonstration Testing Configurations



Comparison of Testing Requirements

Study	Site Requirements	O&M Needs
Stagnant (or Batch) Testing	• Counter space • Lighting • HVAC • Water storage	• Water quality adjustments and changes • Sample collection and analysis • QA/QC
Flow-Through Testing	• Water supply and drainage • Power • Space • Lighting • HVAC • Minimal vibration • Sink/lab space (if possible)	• Pressure, flow and leak checks • Sample collection and analysis • Chemical addition monitoring and adjustment • QA/QC

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Traditional Coupon Study Methodology

- Metal coupons placed in system (flowing)
- Coupons weighed before test and after a defined period of time, typically 90 to 180 days
- Weight loss used to determine corrosion rate and “remaining useful life” based on wall thickness

Traditional Coupon Studies

Considerations

- Challenging to determine precise weight loss
- Higher corrosion rates when first exposed
- Hard to correlate specific water quality characteristics, including lead and copper levels

Appropriate Applications

- Copper pitting assessments
- To help assess long-term metal loss for iron pipes and steel components

Improved Static Coupon Test Method Referred to as Solubility Testing

- Developed specifically for evaluating lead, copper other metal solubility in water
- Key differences from traditional coupon test practice in
  - Water preparation
  - Testing protocol

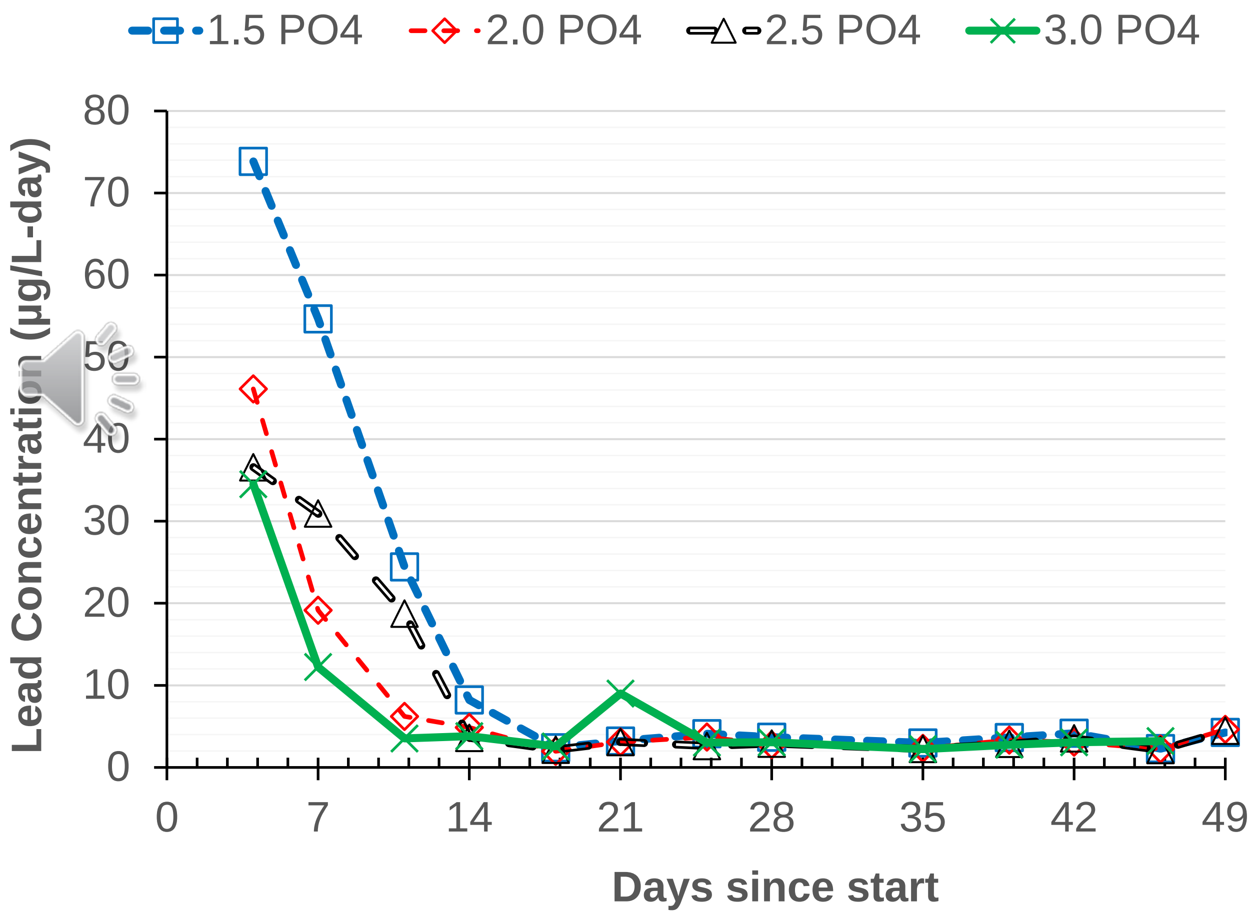
Source: Cornwell and Wagner, Journal AWWA, Volume: 111, Issue: 10, , Pages: 12-24, First published: 04 October 2019, DOI: (10.1002/awwa.1377)

Source: Cornwell Engineering Group

Source: Confluence Engineering Group

Example Bench Solubility Study

- Study overview
  - New lead coupons
  - Four orthophosphate doses (as mg/L as o-PO_4) tested in triplicates
  - Water changes 3-4 days
- Acclimation - initial period of high corrosion rates and resulting metals concentrations
- Solubility results assessed post-acclimation



Stagnant Study Considerations

- Stagnation time
- Water quantity and quality adjustment
- Minimize headspace and disruption

Measure metals levels in water that has been in contact with the selected testing material

Example Bench Solubility Studies

New Lead Coupons

Source: Cornwell Engineering Group

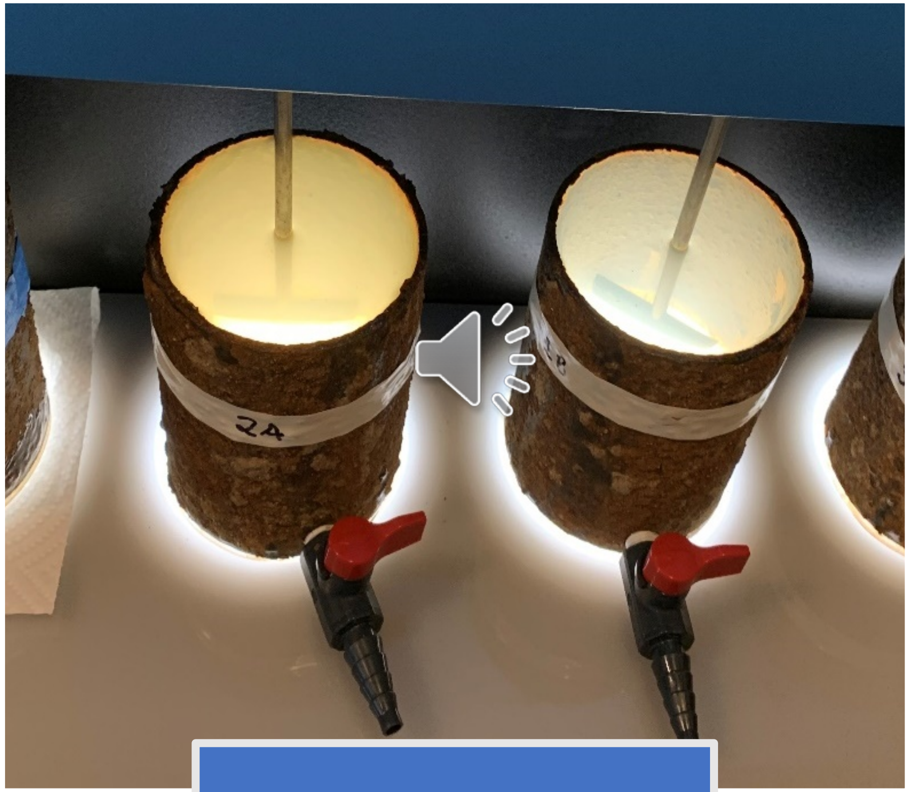
New Pipe Coupons
(Copper with dipped lead solder, lead, and brass)

Source: Confluence Engineering Group

Example Stagnant Studies with Harvested Materials

Epoxied Copper Joints with Lead Solder

Source: Arcadis



Cast Iron Mains

Source: Confluence Engineering Group

Lead Pipe

Source: Cornwell Engineering Group

KNOWLEDGE CHECK

2. Measuring weight loss in metal coupons is often a good indicator of lead release.
   a. True
   b. False

Flow-Through, Pilot Study Considerations

Study Plan

- Goals
- Drivers
- Sources / blending

Design

- Configuration
- Equipment
- Test Piece Materials and Quantity
- Testing location
- Water supply flow and pressure
- Drain capacity

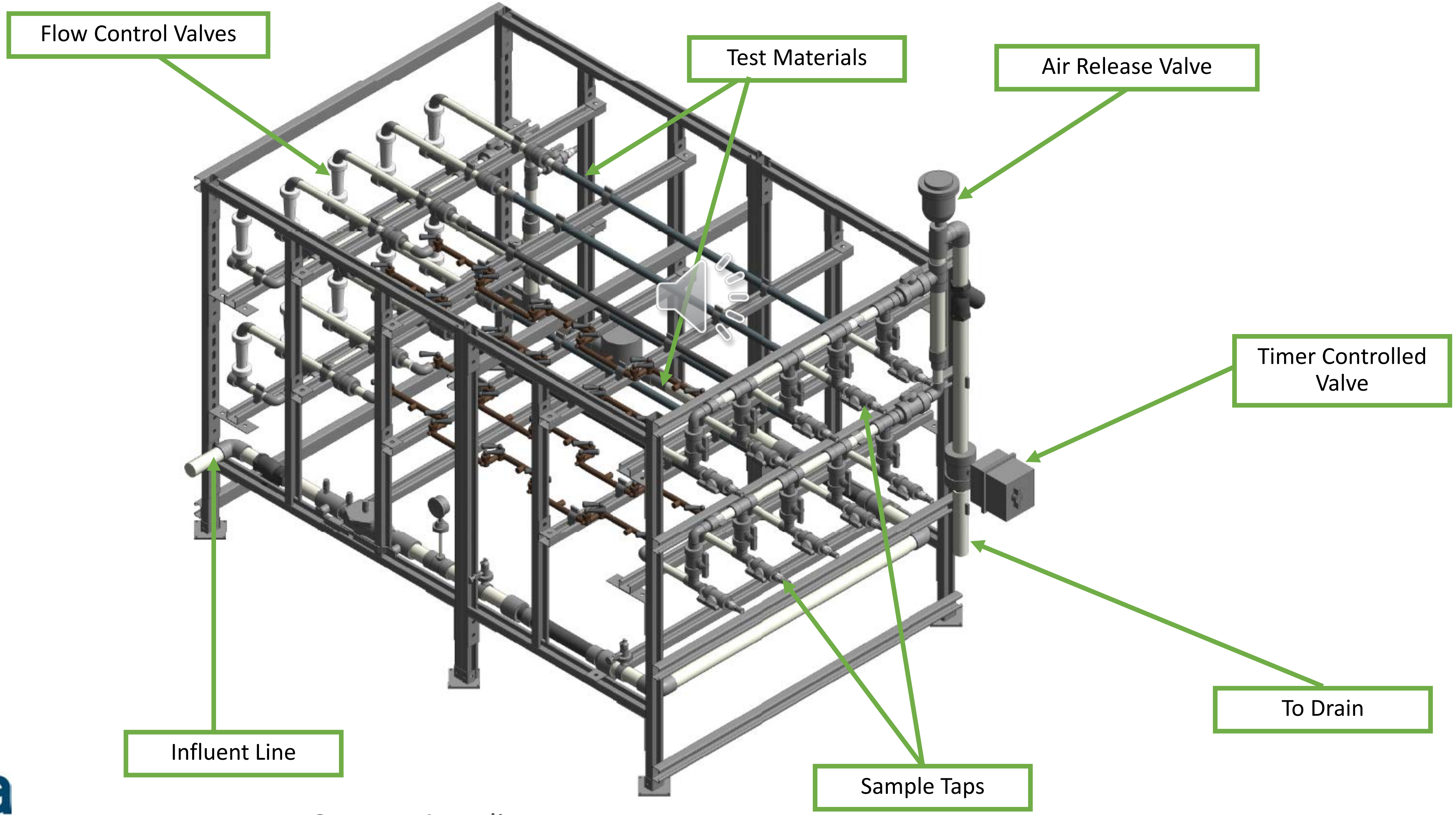
Operations

- Startup
  - Integrity Testing
  - Harvesting and/or Installation
- Routine
  - Flushing / Stagnation Schedule
  - Chemical Dosing
  - Water Quality Sampling and Collection
- QA/QC

Data Analysis

- Data quality and quantity
- Normality tests
- Paired tests

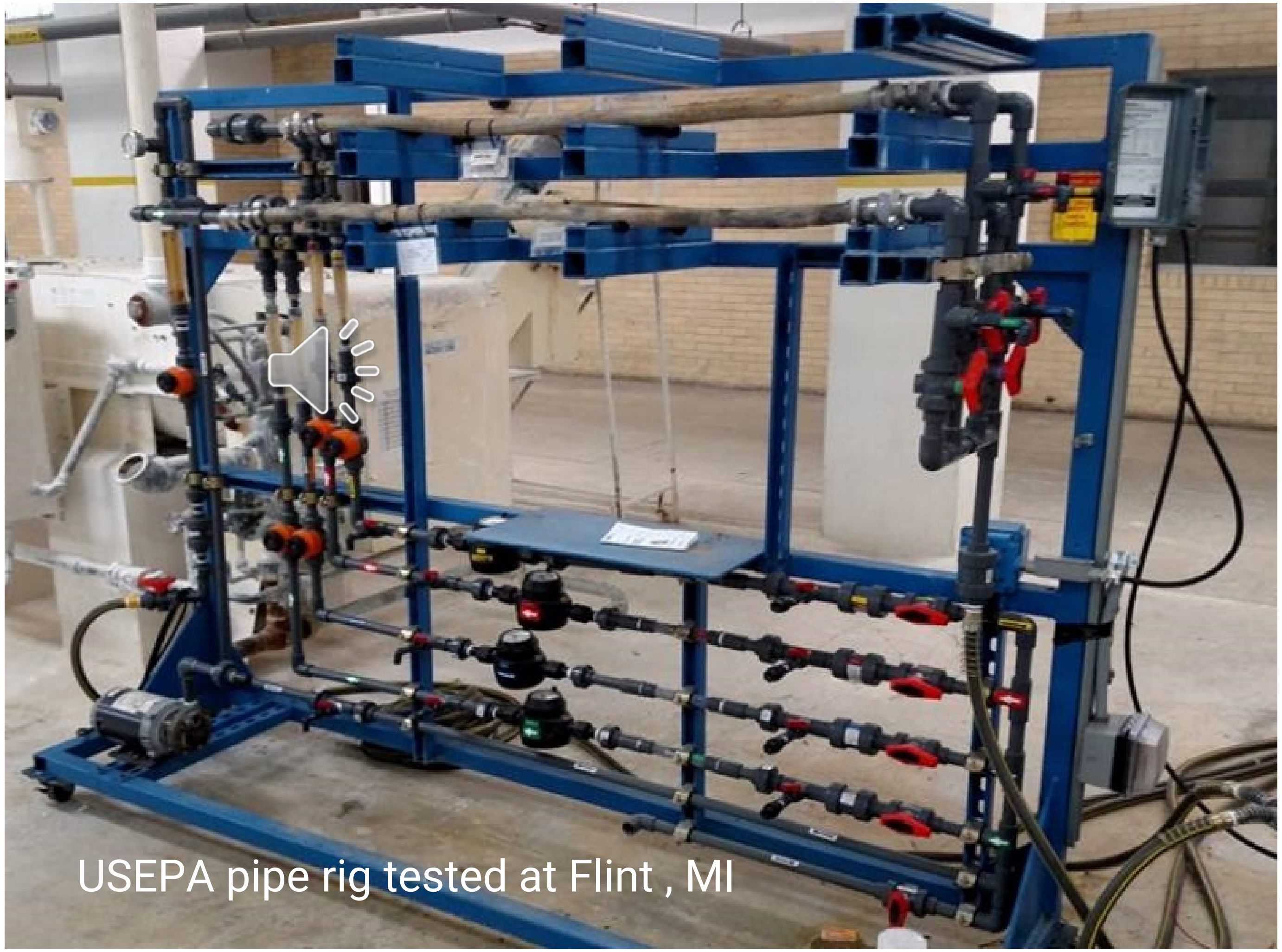
Typical Pilot Testing Rig Components



Source: Arcadis

Flow-Through, Pilot Study with Harvested Pipe

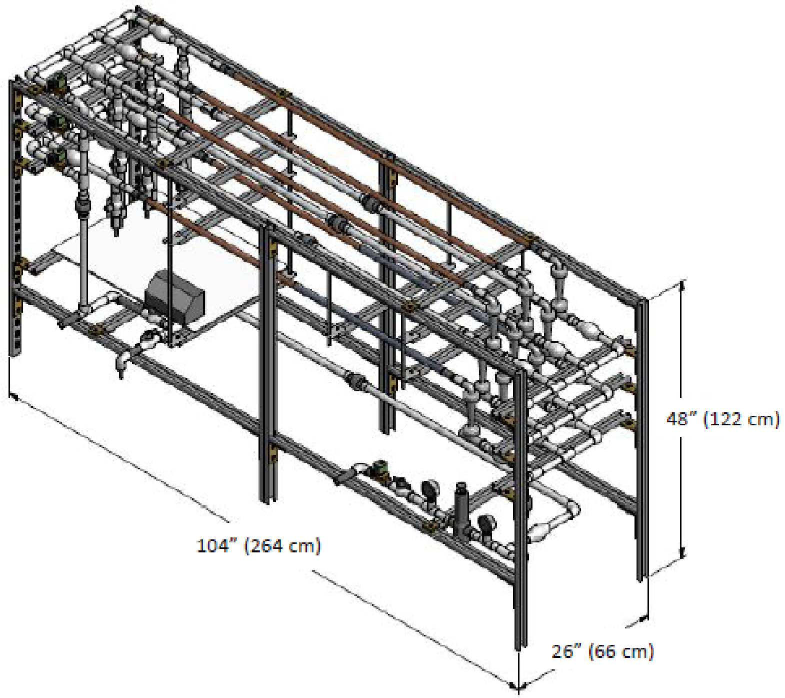
- Flow-through pilot apparatus
- Pipes and/or fixtures taken **from the distribution system**



USEPA pipe rig tested at Flint , MI

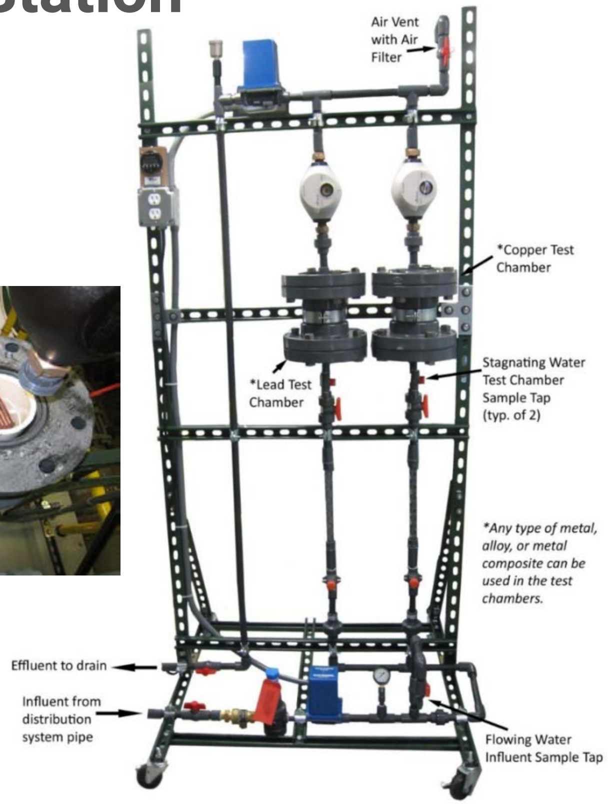
Example Pilot Testing Rigs

WRF #4317 Pipe Loop Rig



Source: Parks, Edwards & Attasi, 2014

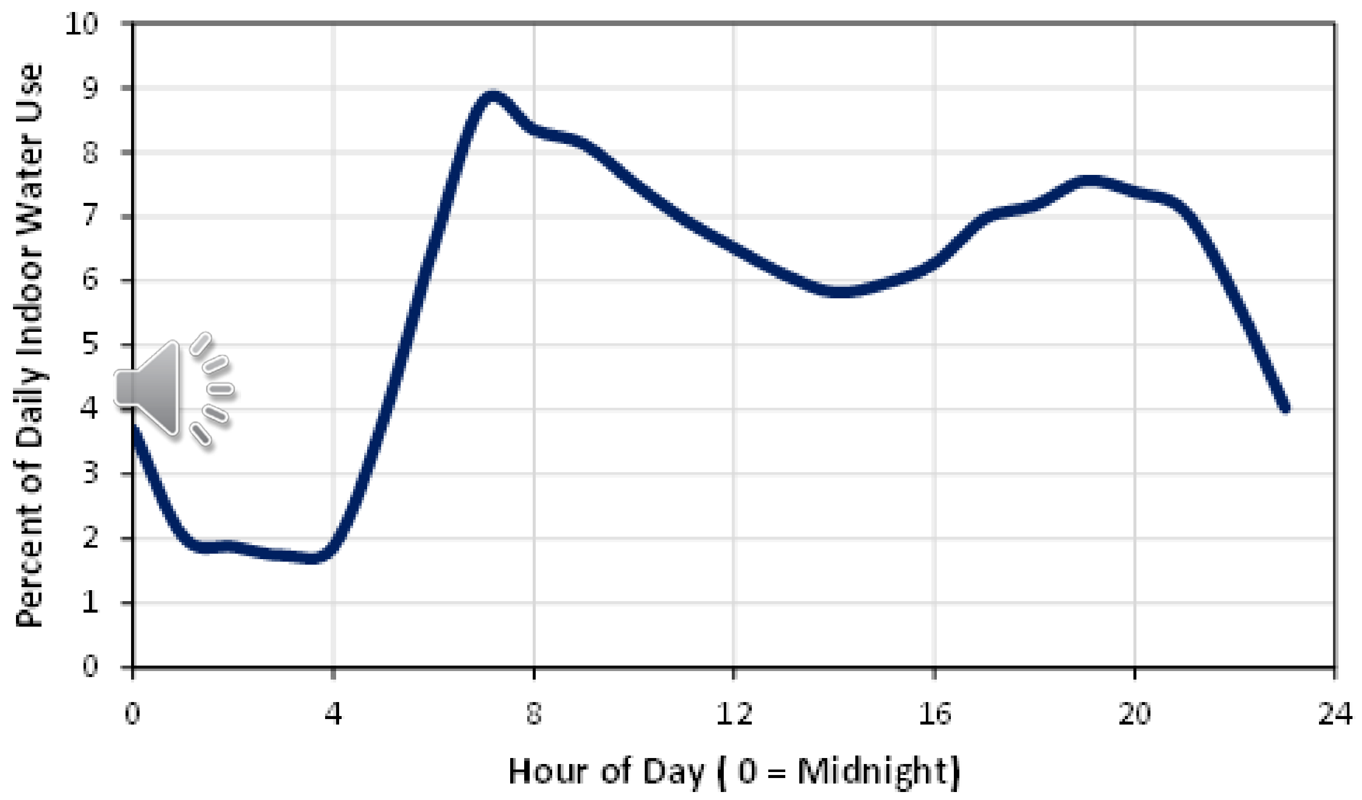
Process Research Solution (PRS) Monitoring Station



Source: Cantor, Hill, & Giani, 2011

Simulating Residential Demands During Pilot Testing

- Develop a flushing / stagnation schedule to represent typical residential usage
- Flow Rate – mimic residential flow through a service line (1.5 – 3 gpm)



Modified from DeOreo et al. (2016). Residential End Uses of Water. Water Research Foundation

Identifying Potential Pilot Testing Locations

- Site selection for loops must consider:
  - Water source(s) incl. appropriate flows and pressures
  - Appropriate utilities (i.e., drainage, power, HVAC, lighting)
  - Space for testing rig, chemical feed pumps, etc.
  - Laboratory space (counter, sink)
  - Ease of access for operators and chemical deliveries
  - Minimal disturbances
  - Water quality (note: plants represent controlled conditions not often observed in customer's homes, pipes may need to re-equilibrate)
- Often a balance of source availability versus practicality

Example Flow-Through Pilot Studies

Harvested Galvanized Pipe and New Brass Faucets

Source: Cornwell Engineering Group

Harvested Lead Pipe and Lead Solder Melted on New Copper Pipe

Source: Arcadis

Other Example Flow-Through Studies

Bench-Scale
Lead Pipe

Source: Cornwell Engineering Group

Harvested Cast Iron and
New Ductile Iron Mains

Source: Arcadis

KNOWLEDGE CHECK

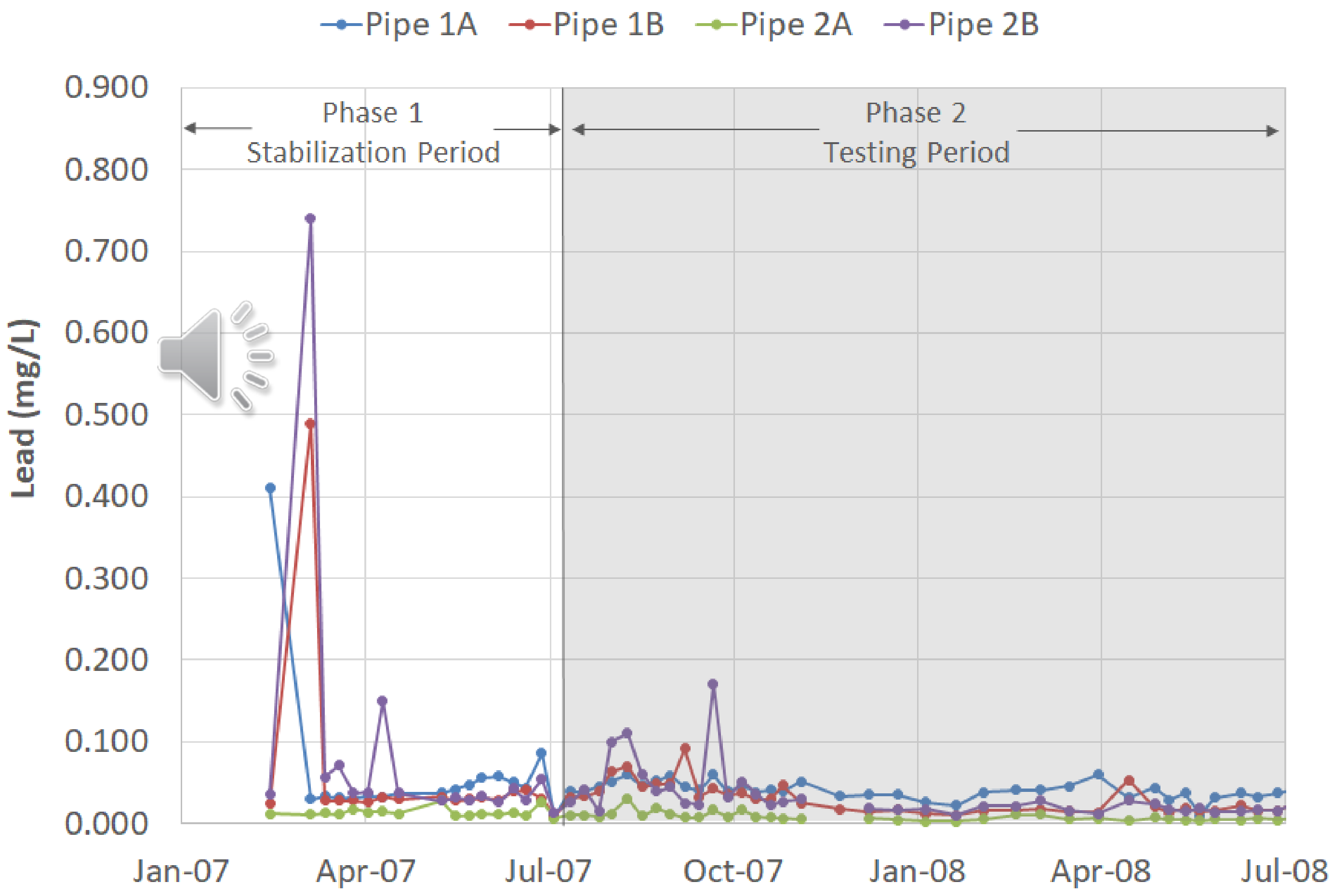
3. An optimal flow-through, pilot scale testing location should have all of the following characteristics, except:
   a. Proper drainage
   b. Easy access
   c. Internet access
   d. Available water supply

Time Required to Stabilize Test Conditions

- It is generally necessary to stabilize the test first on the existing conditions and then change the conditions and restabilize
- Studies must be planned with stabilization in mind
  - True for both harvested and new materials
  - Significant time may be needed for these stabilization periods
- Visual confirmation or statistical analysis can be used to determine samples have stabilized

Acclimation of Harvested Materials

- Phase 1: Stabilization Period
  - Allows harvested materials to re-equilibrate prior to testing phase
  - Time to reach stabilization
    - ~2 to 4 months for bench studies
    - ~4 to 9 months for pilot studies
- Phase 2: Testing Period
  - Testing of alternate conditions
  - Requires confirmation with water quality monitoring
  - Duration
    - ~2 to 4 months for bench studies
    - ~12 months for pilot studies



Harvesting Considerations

- Use open cut method to excavate service line, avoid pull method
- Label pipe
  - Address/site ID
  - Vertical orientation (top or bottom), flow direction (arrow)
  - Connection points at each end (i.e., meter, house, main, curb stop, etc.)
- Use pipe shears
- Prevent debris from entering the pipe
- Minimize impact, bending, vibration when removing the pipe from the trench
- Analyze water quality, if possible

Source: DC Water

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Preservation Considerations

- Carefully drain water from pipe
- Soak sponges in water sample and insert into pipe ends
- Wrap ends with parafilm and rubber band
- Wrap pipe in bubble wrap to protect during transportation
- Various options for long-term preservation
  - Install with flowing supply (preferred)
  - Perform periodic fill and dump

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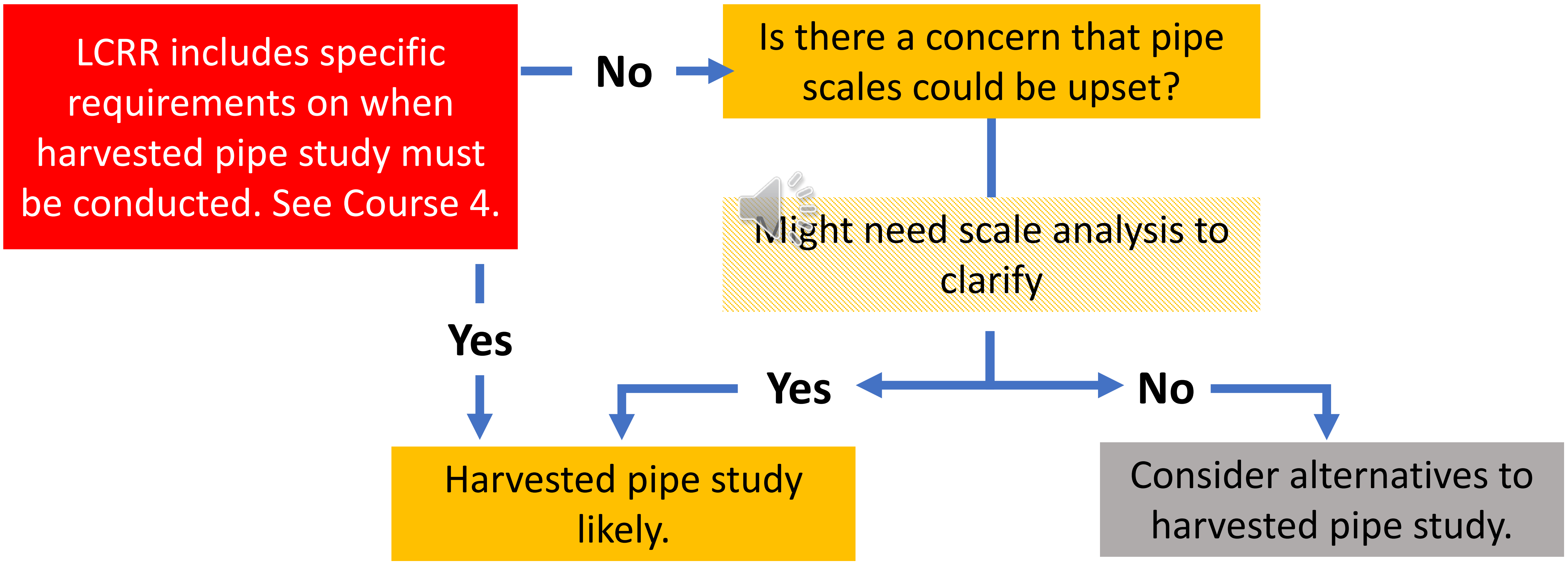
When is harvested pipe study appropriate?



Examples of When Might Harvested Pipe Studies Be Needed

LSLs	Copper Pipe with Lead Solder	Galvanized Iron Pipe

• Where select scales are present
  • Free chlorine systems where lead(IV) may be present
  • Presence of amorphous scales
• Select source/treatment changes, such as
  • Change/addition of polyphosphate-containing product
  • Major change in pH/Alk/DIC
	• CSMR increase of concern
	• Change/addition of polyphosphate-containing product
	• Major change in pH/Alk/DIC
		• Change from surface water to ground water or vice versa
		• Change of chlorine to or from chloramine
		• Change/addition of polyphosphate-containing product
		• Major change in pH/Alk/DIC

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Partial System Tests

- Testing corrosion control approach on a hydraulically isolated portion of distribution system
- Must be coupled with water quality monitoring (WQPs and tap monitoring), pre- and post-change
- Appropriate for small changes to CCT (i.e., slightly higher dose in orthophosphate, small increase in pH)

Consumer awareness and acceptance is a consideration when utilizing full-scale demonstration studies.

Partial System Tests

Advantages

- Represents actual CCT performance in the distribution system
- Opportunity to evaluate unintended consequences

Considerations/Limitations

- Isolated area / control
- Chemical feed addition (location, size, instrumentation & controls)
- Number and location of sentinel sites (see later slide)
- Increased number of variables (water use, mixture of plumbing materials)
- May be unable to return to original CCT strategy
- Public communications

KNOWLEDGE CHECK

4. When might a harvested pipe study be warranted?
   a. When changing from a groundwater source to a surface water source
   b. When increasing orthophosphate dose
   c. When changing orthophosphate vendors
   d. When adding a new coagulant aid

LEARNING ACTIVITY

Match the characteristic or consideration below to the most appropriate type of study.

- Simulates residential demands
- Typically performed in a laboratory setting
- Applies to only small changes in CCT
- A harvested pipe study is a specific subcategory of one of these
- Typically requires least amount of resources/time to complete

Bench-Scale Study	Pilot-Scale Study	Partial System Test

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Summary

- There are various types of demonstration studies, each requires careful planning and execution
- Bench scale studies can often be completed in a shorter time frame than pilot studies
- Pilot studies include several periods of flowing water to simulate residential demands
- New and/or harvested materials can be tested
  - Harvested pipe studies assess impacts to existing pipe scales and may be required in certain circumstances
- Partial system tests are typically appropriate when making small changes to CCT

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MODULE 3
SELECTING AND IMPLEMENTING CCT

LEARNING OBJECTIVES

Identify	Considerations when selecting CCT Potential unintended consequences associated with CCT
Define	Key components of an implementation plan Considerations for preparing the distribution system for change

Selection Should Consider a Holistic Evaluation

LSLR Goals

Compatibility with Connected Systems

CCT Effectiveness

Operations and Maintenance

Unintended Consequences

Ease of Implementation

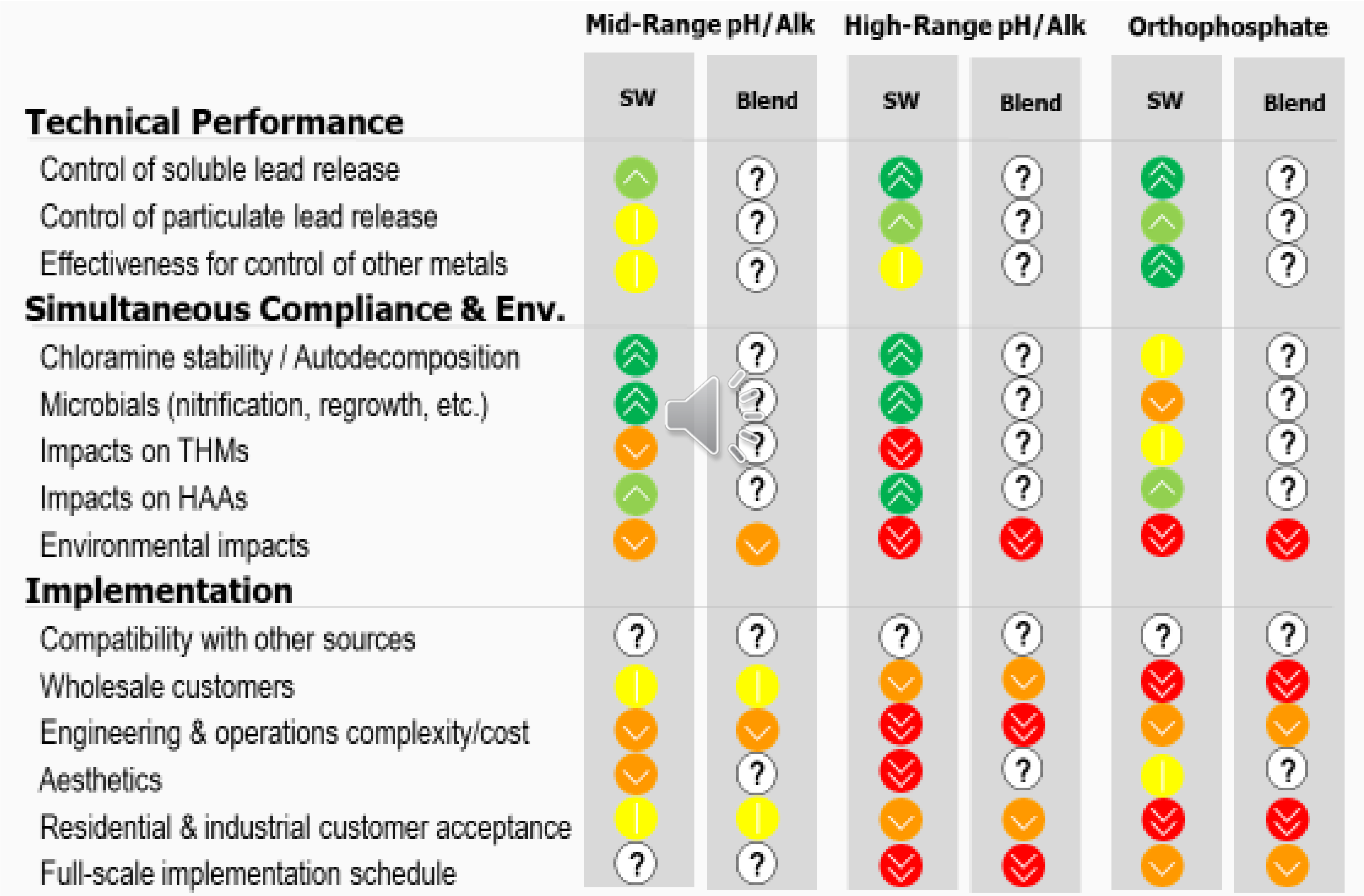
Affordability

Cost

Potential unintended consequences associated with corrosion control treatment

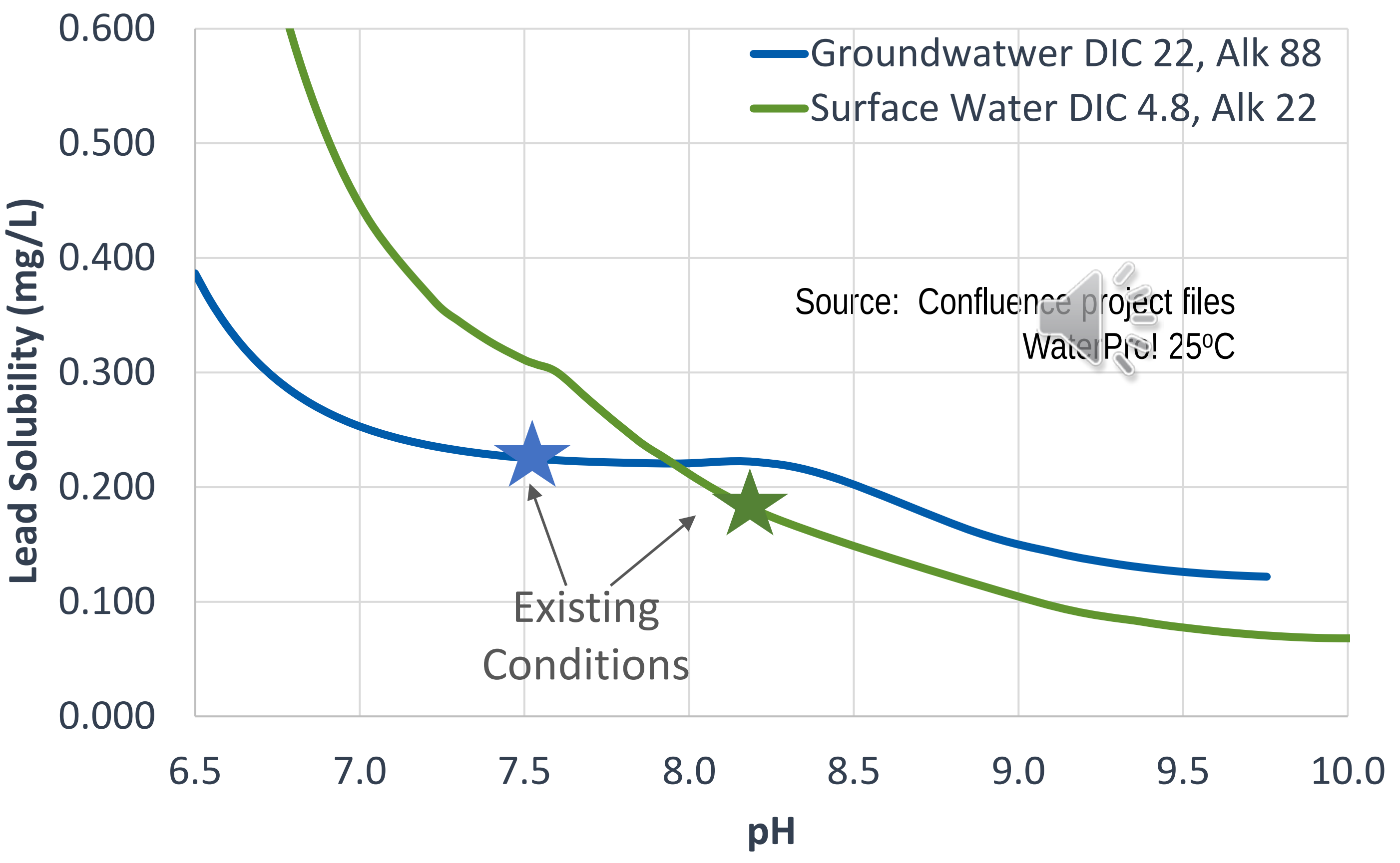
Description of Potential Unintended Consequence	Corrosion Control Treatment Strategy	
	pH/Alkalinity Adjustment	Phosphate Addition
Increased scaling resulting in loss of hydraulic capacity or additional system maintenance	✓	✓
Reduced distribution system disinfection performance (> pH 9)	✓	
Increased microbial activity in the distribution system		✓
Change in disinfection byproduct speciation/concentrations	✓	✓
Required joint Stage 2 DBPR and LCRR compliance	✓	✓
Increased phosphorus loading at wastewater treatment plants		✓
Need for additional operator certification/staffing	✓	✓

Example ranking of factors for CCT selection



Source: Friedman et al. WQTC 2017

Compatibility of Sources Case Study – Surface Water and Groundwater



Theoretical Pb Solubility of SW and GW Supplies

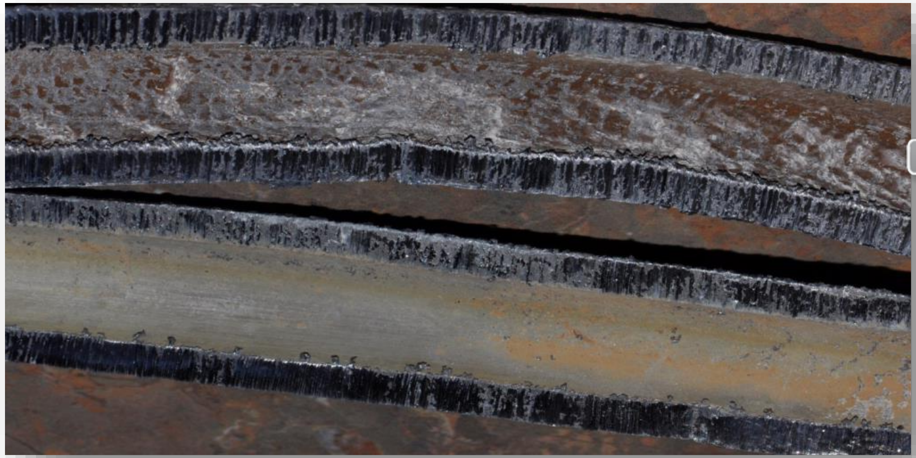
- GW less corrosive below pH 8
- SW less corrosive above pH 8
- Because of DIC, actually different dominant lead species
    - GW dominated by cerussite
    - SW dominated by hydrocerussite

Source: Confluence Engineering Group LLC

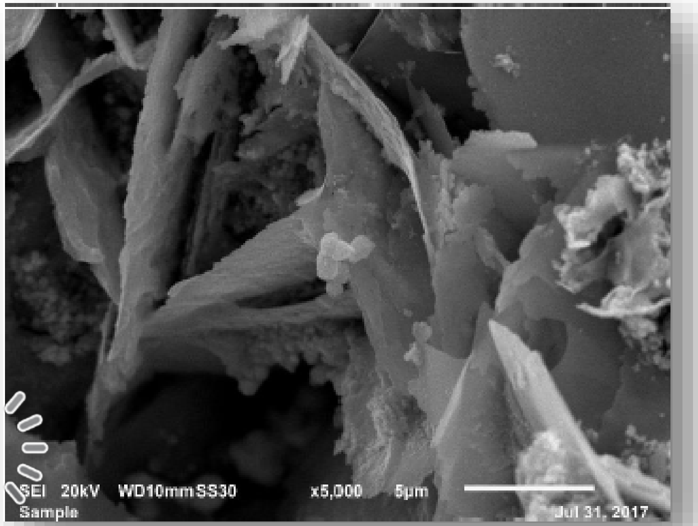
Water Quality Changes Can Impact the Types of Scales Formed

Phase 1 – Surface Water

Phase 2 – Ground Water



Source: Friedman, 17th Annual EPA Drinking Water Workshop, 2020. Photos courtesy of G. Korshin, UW and HDR Engineering"



Lead Gooseneck Phase 1 – Surface Water
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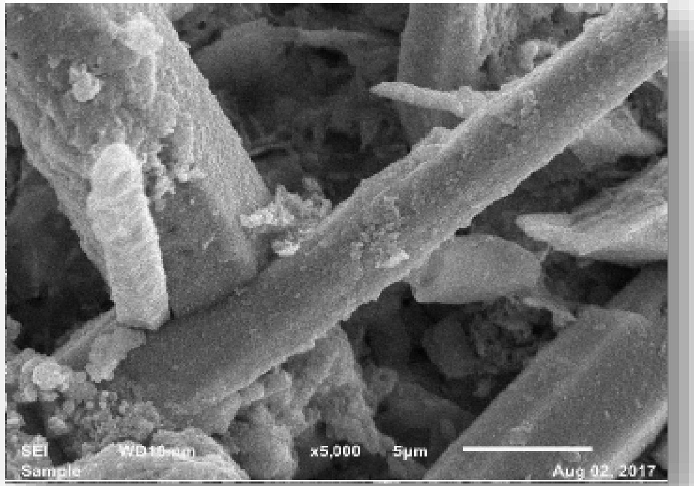
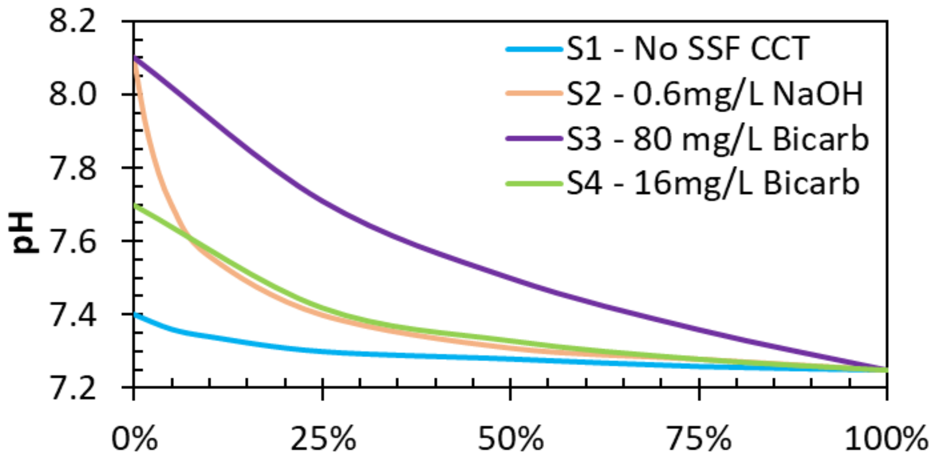


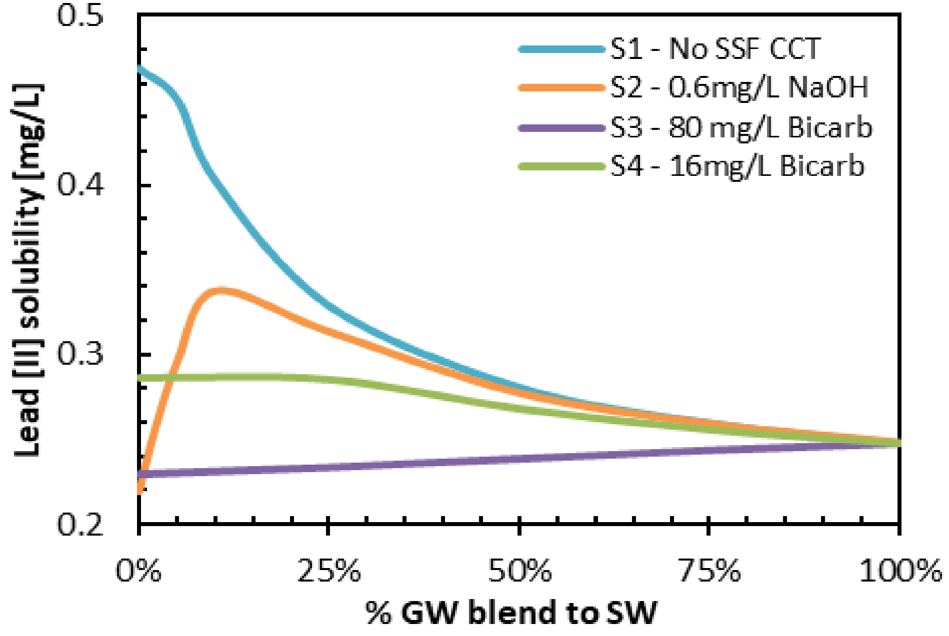
Lead Gooseneck Phase 2 - Groundwater
Scale dominated by Pb(II) cerussite with some Pb(IV)

Blending Impacts

- Blending of different SW end points with existing GW supply to assess impacts in the distribution system
- Blends of water may be more corrosive than either source alone!

	S1	S2	Not graphed	S3	S4
Treatment	No CCT	0.6mg/L NaOH	1.3 mg/L Soda ash	80 mg/L Bicarb	16mg/L Bicarb
pH	7.4	8.1	8.1	8.2	7.7
Alkalinity	6.9	7.5	8.1	54.5	16.4
DIC	1.8	1.8	2.0	13.3	4.1





Source: Confluence Engineering Group LLC

KNOWLEDGE CHECK

1. Potential unintended consequences of changing corrosion control treatment include:
   a. Increased phosphorus loading at wastewater facilities
   b. Increases in total trihalomethanes
   c. Improved disinfection
   d. (a) and (b)
   e. All of the above

Preparing for CCT Implementation Takes Time

- Chemical feed system modifications
- Continued communication with the state
  - Designation of CCT
  - WQP monitoring
- Preparing distribution system for chemistry changes

Recommended Preparation Steps and Tools for CCT Implementation

1 Assess finished water stability and compatibility
- Monitoring
- Desktop modeling
- Coupon studies
- Pipe rigs

2 Assess hydraulic impacts
- Hydraulic modeling
- Flushing trials to characterize hydraulically-mobile deposits

3 Assess legacy deposits and pipe materials
- Pipe pulls
- Swabbing
- Pipe coupons
- Pipe rigs
- Identify Unlined CI pipe areas

4 Review O&M strategies
- Water age management
- Flow direction/ velocity control
- Main cleaning practices
- Controlled blending
- Purposeful source selection/minimize changes

5 Identify and prioritize risks
- Monitoring
- Desktop modeling
- Coupon studies
- Pipe rigs

6 Develop and implement risk mitigation plan
- Monitoring
- Finished water quality goals
- Main cleaning
- Hydraulic modifications
- Pipe rigs
- Communications

Source: Confluence Engineering Group LLC

Implementation Plan Components

Design Criteria	• Product, target dose and pH (if applicable), application point • Chemical delivery, storage, metering, instrumentation and controls
Performance Monitoring	• Locations, analyses, and frequencies • Interim water quality targets
Troubleshooting	• Potential issues and solutions • Examples: feed disruptions, residual loss, colored water
Approach	• Implementation schedule • “Low and slow” mindset is common
Distribution System Preparation	• Identify, minimize, and manage risks of potential distribution system upset • Monitor and respond

KNOWLEDGE CHECK

2. Implementing a change in corrosion control should consider:
   a. System demands
   b. Legacy deposits
   c. Hydraulic impacts
   d. (a) and (c) only
   e. (b) and (c) only
   f. All of the above

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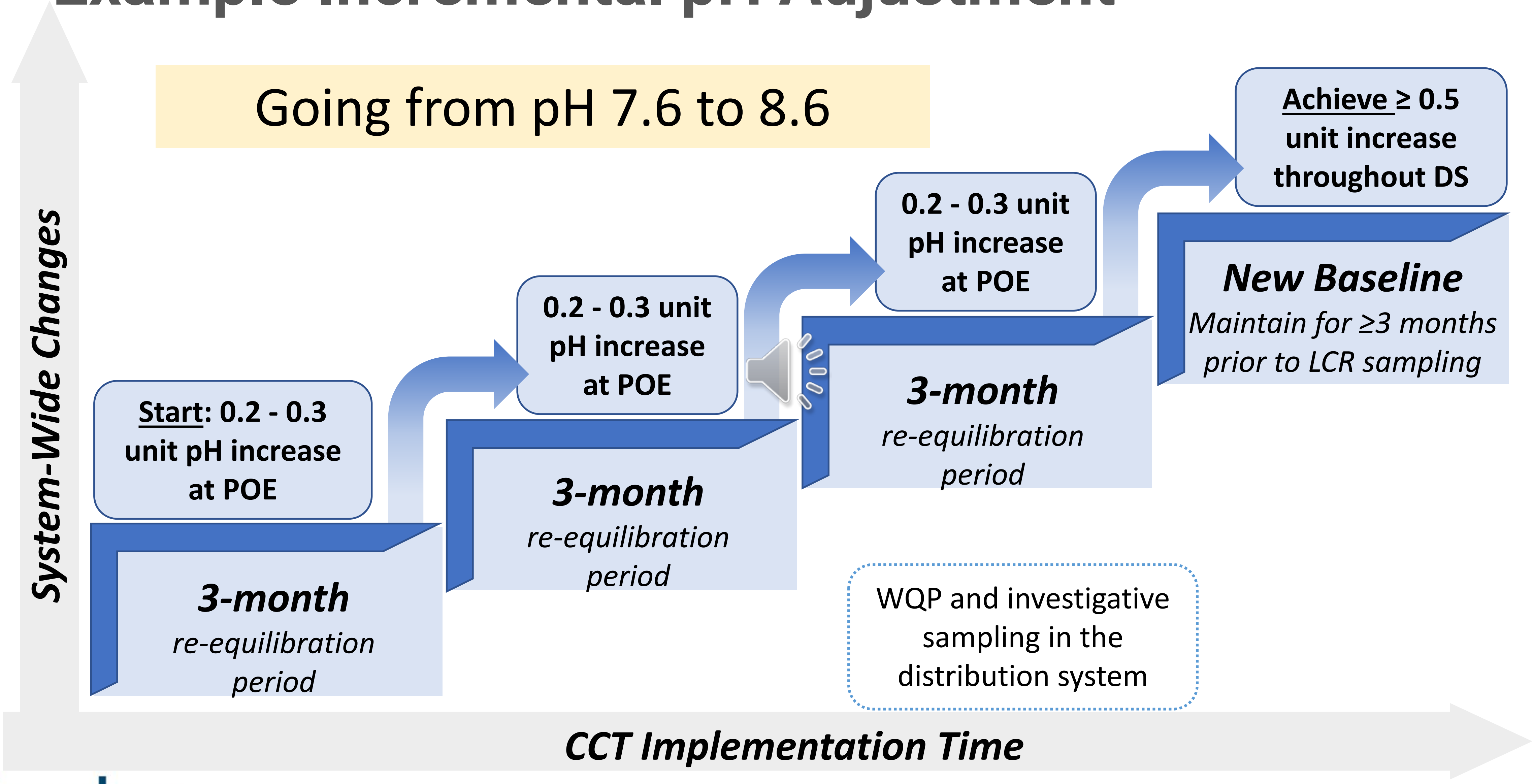
Considerations for Timing CCT Implementation

- Water temperature
- Water age / system demands
- Number of chemical feed locations
- Magnitude of change
- Gradual vs immediate

Example Incremental pH Adjustment

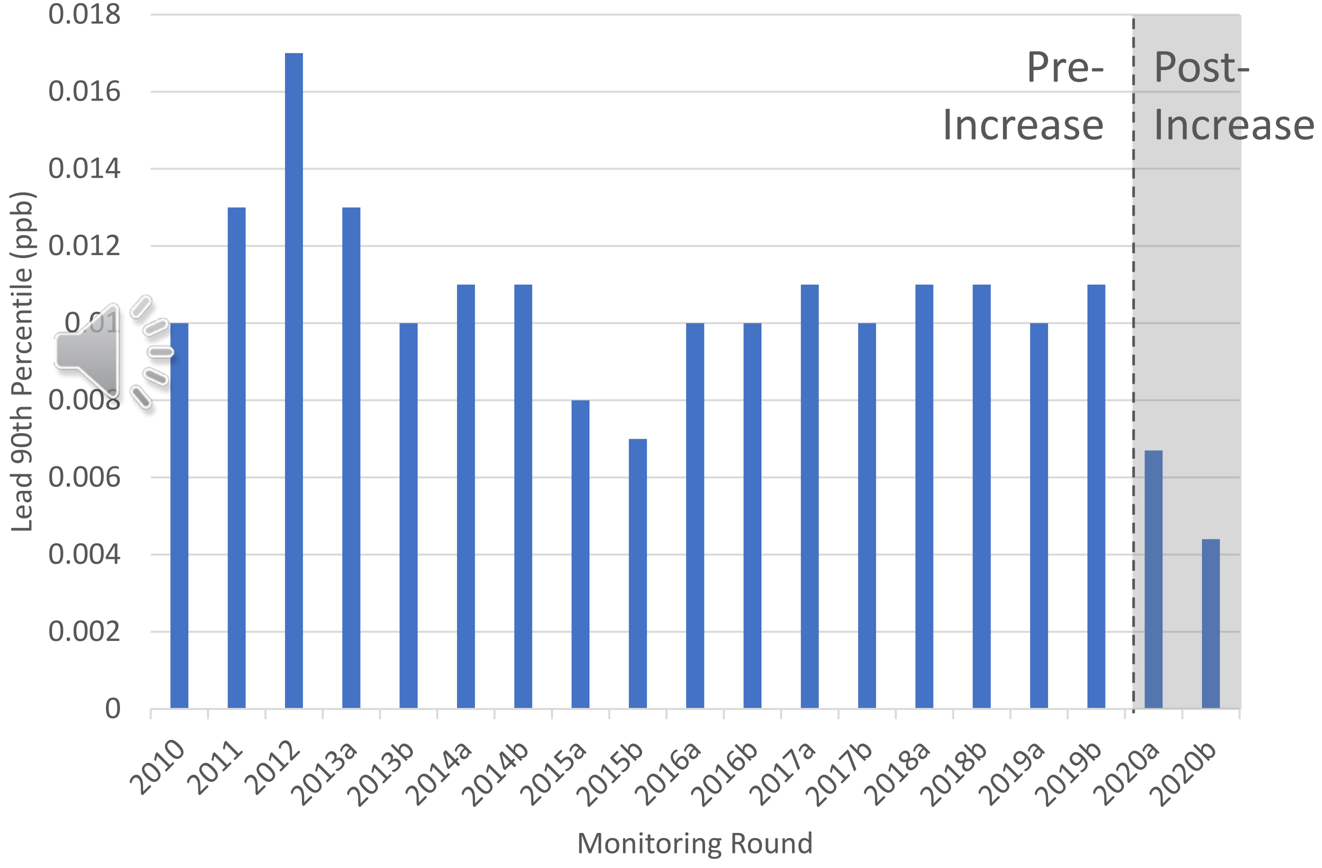


Source: Confluence Engineering Group LLC

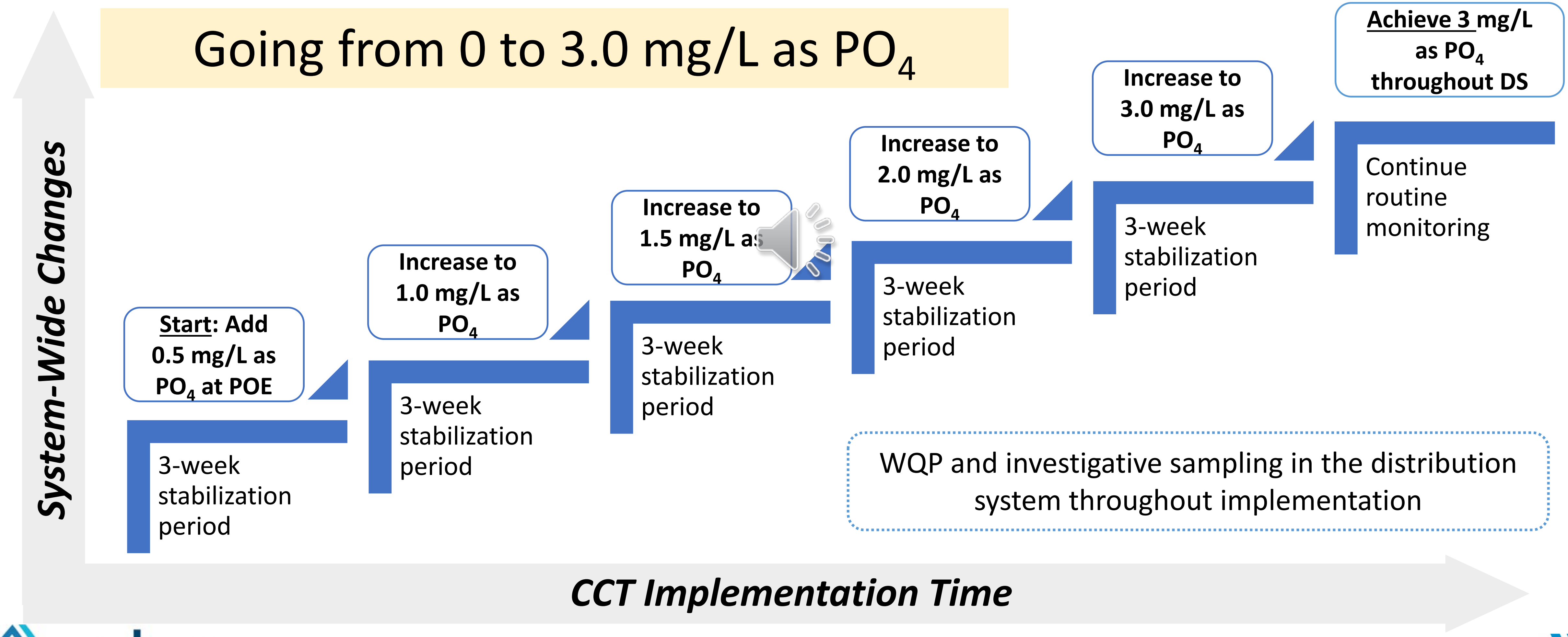
Example Rapid pH Increase

- Initial finished water pH of 7.8
- Increased pH to 8.8 (8.6 - 9.0) within a 24-hour period

Caution: Slow, incremental CCT changes are typically preferred. However, rapid changes may be considered where elevated lead or copper levels are present.



Example Incremental Orthophosphate Introduction

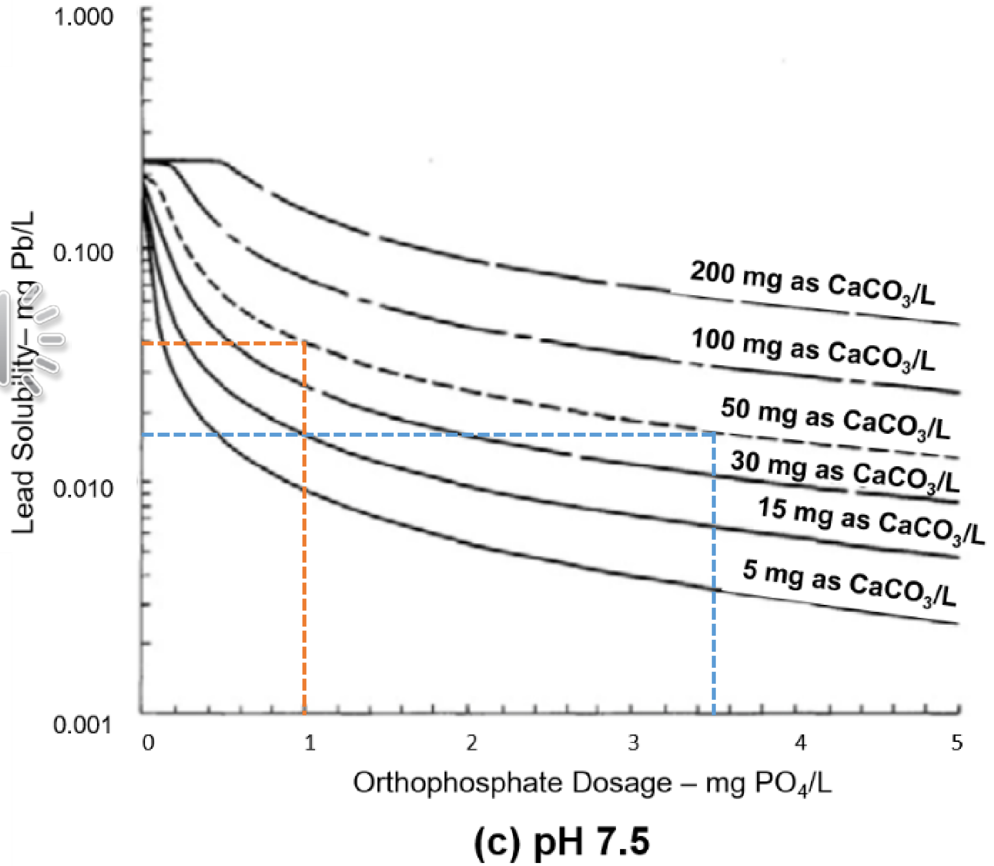


Source: Arcadis

Example rapid orthophosphate increase

- Initial finished water quality
  - pH 7.4
  - Alkalinity 72 mg/L as $CaCO_3$
  - DIC ~47 mg/L as $CaCO_3$
  - Orthophosphate dose of 1.0 mg/L as PO_4
- Increased orthophosphate dose from ~1 to 3.5 mg/L as PO_4 based on theoretical lead(II) solubility curves
  - No incremental increases

Caution: Slow, incremental CCT changes are typically preferred. However, rapid changes may be considered where elevated lead or copper levels are present.



Source: Schock (1989) as shown in Brown, McTigue & Cornwell (2015)

Long-Term Considerations for Tapering Phosphate Dose

- Impact to theoretical solubilities
- Impact to 5th liter results; may need to be coupled with removal of LSLs
- Demonstration testing recommended to identify optimal dosing
- Extremely gradual reduction with enhanced monitoring
- State approval

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KNOWLEDGE CHECK

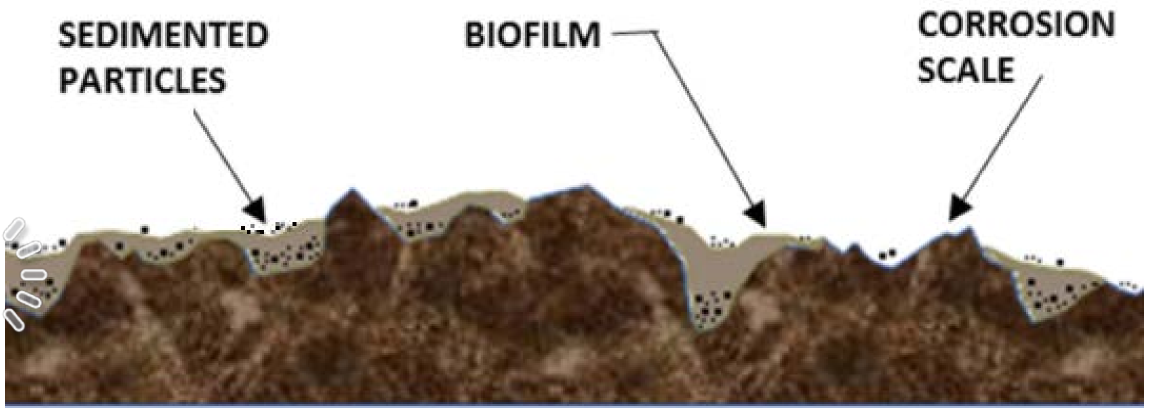
3. A new or modified corrosion control treatmentt strategy should be implemented gradually, where possible.

   a. True

   b. False

Must Consider Legacy Deposits

- Over time, all water mains accumulate a deposit/biofilm complex – **Legacy deposits**
- Legacy deposits exist in "dynamic equilibrium" with the water
- Their presence is often benign … until system changes occur
- Changes can cause destabilization and release of legacy deposits
- May or may not result in public health concerns
- Almost always results in customer complaints



Source: Hill et al., WRF 4653, 2018

Old Pipes + Change = Re-Equilibration

Potential Distribution Impacts during CCT Implementation

- Phosphate addition
  - Cloudy precipitates due to complexes with high aluminum
  - Biofilm instability
- pH increase
  - Arsenic release
- Potentially exacerbated with a rapid transition

Effects of excess aluminum on phosphate

Source: DC Water (top): Jacobs (bottom)

What Comes Out During Flushing is Only a Fraction of the Story (the hydraulically-mobile fraction)

UDF at 6 fps Velocity

Swabbing (Pass #1 of 4)

Swabbing Pass #1 to #4 Samples

Source: Confluence Engineering Group LLC

KNOWLEDGE CHECK

4. Cloudy precipitates may be the result of which of the following?
   a. Aluminum carryover from the coagulation process
   b. High orthophosphate concentrations
   c. Lead service line replacements

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LEARNING ACTIVITY

From the list below, identify all possible potential unintended consequences for a system that is considering increasing their orthophosphate dose from 1.5 to 3.0 mg/L as PO4, while maintaining the current pH and alkalinity.

a) Increase in trihalomethane concentrations

b) Reduced disinfection performance in the distribution system

c) Increased operator licensing requirements

d) Increased microbial activity in the distribution system

e) Change in disinfection byproducts species

f) Increased phosphorus loading at wastewater treatment plants

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Summary

- Implementation requires extensive planning
  - Goal is to understand and control changes prior to implementation.
  - It can take many months or years to adequately prepare distribution systems for change.
  - Never too early to start!

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MODULE 4
MONITORING AND EVALUATING CCT EFFECTIVENESS

LEARNING OBJECTIVES

Recall

- Monitoring program components and data analysis tools from Course 2
- Considerations when assessing initial CCT targets

Key Water Quality Data Needs – All Systems

Level 1[¥] (Priority)	Level 2 (Supplemental)	Level 3 (Diagnostic)
pH	Temperature	Bacterial speciation
Total alkalinity	Dissolved oxygen	Sulfide
DIC (measured or calculated)	Lead (total and dissolved)	Nitrite/nitrate
Disinfectant residual	Copper (total and dissolved)	DBPs
Lead	Iron (total and dissolved)	
Copper	HPC	
Hardness (total and calcium)	ATP	
Conductivity or TDS	Color (apparent)	
Chloride[#]	TOC	
Sulfate[#]	Turbidity	
Iron[#]		
Manganese[#]		

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[#] Could reduce monitoring frequency pending baseline / event.
[¥] Raw, finished and distribution data if available.

Source: Adapted from AWWA M58: Internal Corrosion Control in Water Distribution Systems, 2nd ed. , 2017

Additional Level 1 Parameters: System Specific

- Phosphate (total and ortho), *systems introducing or using phosphate-based inhibitor or sequestrant*
- Silica, *systems introducing or using silica-based inhibitor*
- Ammonia (total and free), *chloraminated systems or where present in source*
- Oxidation reduction potential (ORP), *chlorinated systems*
- Aluminum, *systems where aluminum may be present in the finished water*

Source: Adapted from AWWA M58: Internal Corrosion Control in Water Distribution Systems, 2nd ed. , 2017

Lead and Copper Monitoring Recommendations

- Compliance Locations
- Sentinel homes
  - Regularly monitored for lead/copper and select WQPs
  - Representative set of homes receiving "new" water quality; consider
    - Source water
    - Service line and premise plumbing materials
    - Water age (in system and home)
  - Number of sites is system specific (typ. minimum of 3)
  - Confirm reporting requirements with State

Don't wait 6 months for LCRR monitoring!

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Monitoring Procedures to Assess CCT Effectiveness

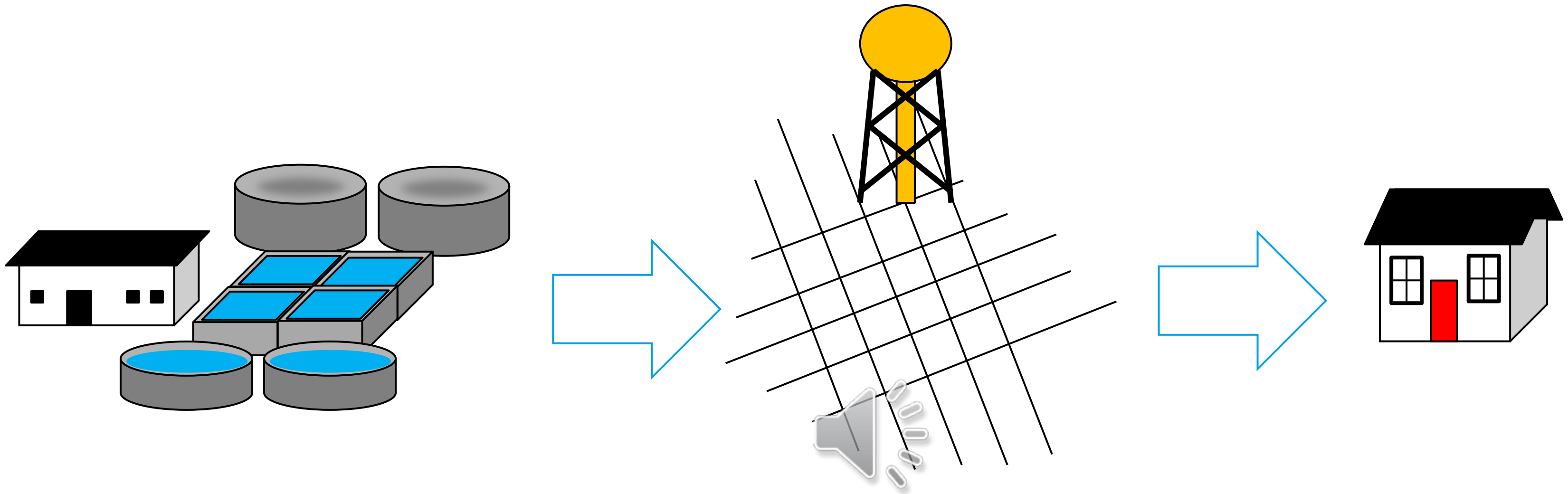
Sampling Method	Considerations
First-Draw (First Liter)	• Reliably samples premise plumbing but does not capture water from the service line
Fifth Liter Sampling	• Likely to capture water from the service line • Can be combined with above to also capture water from the premise plumbing
Timed Sampling	• Often involves multiple samples to capture water in contact with premise plumbing (ex. time 0), service line (ex. 2 mins), and main (ex. 5 mins); can be tailored to typical home configuration in system • Can be collected by the customer
Sequential Sampling ("profiling")	• Most robust method, allows for more detailed assessment • A plumbing survey must be conducted for each sample site • Requires detailed instructions and often training; typically performed by utility staff • Could be performed as follow up to elevated lead or copper

- Can be conducted at sentinel homes
- Assess impact on total and dissolved lead levels

See Course 4 for information on compliance sampling requirements

Source: Modified from Arcadis (2014). AWWA WITAF 303.

Example Monitoring Program



Entry Point
- Level 1 – daily, if practical
- Level 2/3 – weekly, if practical

Distribution System
- At WQP sites
- Level 1 – Weekly, if practical
- Level 2/3 – Monthly, if practical

Customer Tap
- Compliance monitoring, as required
- Monthly at sentinel sites, if practical

Increase monitoring frequency prior to and following changes in source, treatment, or distribution practice until return to baseline

Source: Arcadis

KNOWLEDGE CHECK

1. Which of the following should be monitored during implementation of a new CCT strategy?
   a. pH
   b. Lead and copper tap levels
   c. Turbidity
   d. None of the above
   e. (a) and (b)

Data Evaluation and Interpretation

Goals are to:

1. Verify CCT targets are being met and maintained,
2. Assess impacts to or reductions in lead/copper levels
3. Identify unintended consequences

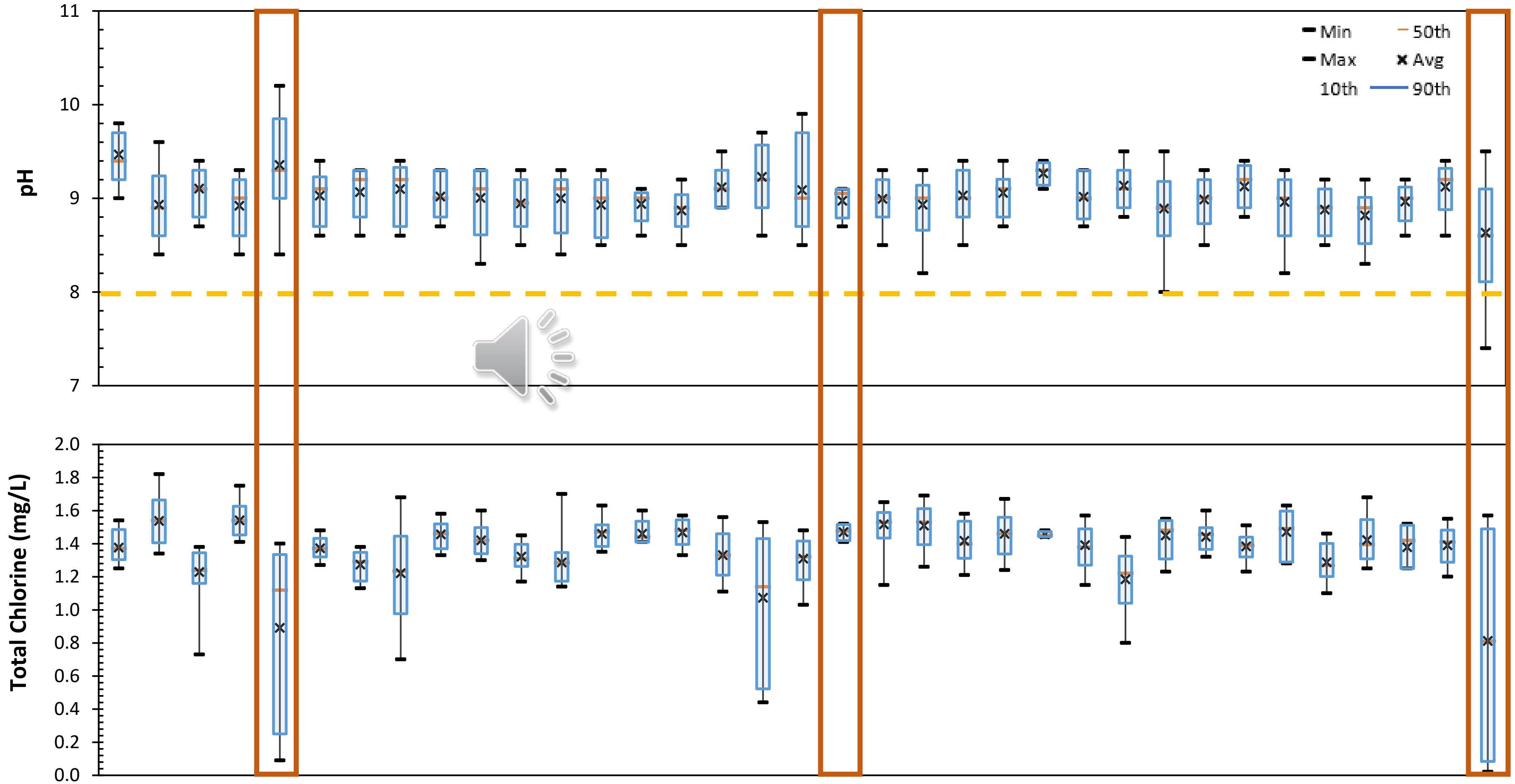
Data Visualization and Analysis

	Level 1 (Routine)	Level 2 (Supplemental)
Per POE	Plot on a time series chart (pH, alkalinity, disinfectant residual, orthophosphate, CSMR) Calculate ranges and percentiles / create box and whisker plot	Create control charts for each POE
Distribution	Create box and whisker plots of WQP/ tap data by monitoring round	Create box and whisker plots and/or control charts of key WQPs by site Map WQP / tap data (*integrate with materials inventory*

Sample size (n) and time period over which data are available may influence the type of visualization or analysis performed.

Example Water Quality Data Analysis

- Example of aggregate analysis of distribution data by location
- Importance of paired results

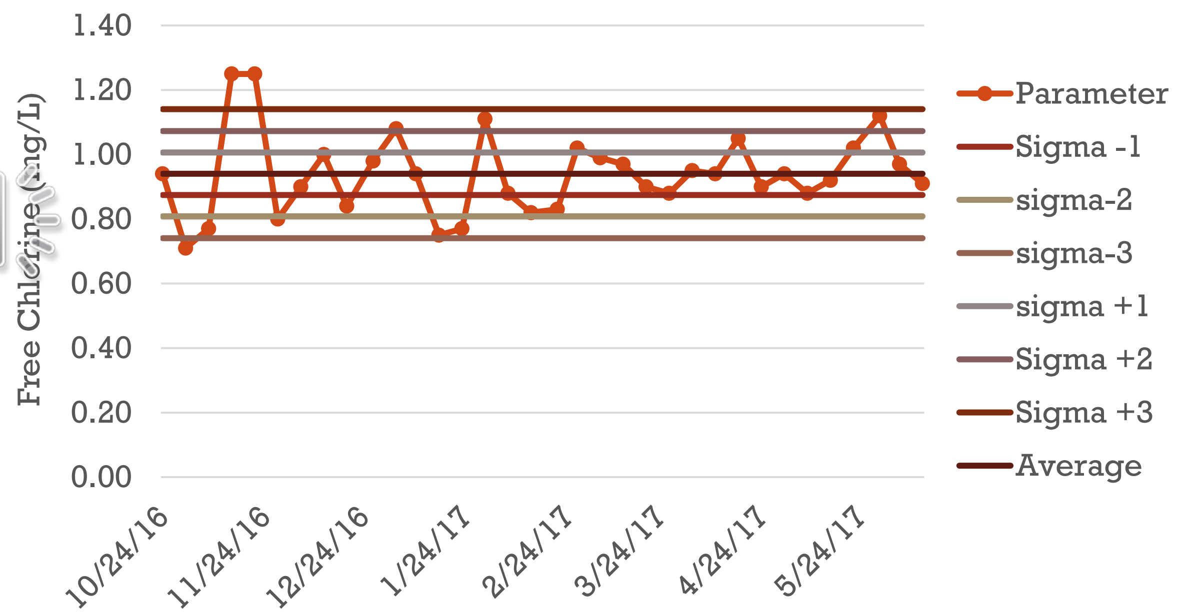


Source: Confluence Engineering

Apply Control Charts to Optimize Chemical Feed and Maintain Distribution System Stability

Tips

- Develop charts for each key parameter (chlorine, pH, orthophosphate, iron, manganese) and site
- Additional water quality investigation in the distribution system may be necessary
- Understand control limits - Set appropriate control limits for each parameter / site



Refer to Course 2 for further information

KNOWLEDGE CHECK

2. During implementation of a new corrosion control treatment, it is only important to graph finished water quality data.
   a. True
   b. False

Establish targets and variability goals

- Phosphate uptake, where applied
- pH drift
- Alkalinity impacts
- Chlorine loss
  - Water age
  - Nitrification

Additional targets (CSMR, aluminum, etc.) may be necessary depending on system-specific water quality and treatment

Example Finished Water and Distribution System Water Quality Goals to Minimize Chemistry-Based Releases

Parameter	Example Goal
pH	Avoid changes ±0.2 units or decreases of 0.5 units especially if pH ≤8.0
ORP	No decreases > 100mV (esp. if below 400mV)
Chlorine	Maintain free chlorine ≥0.5 mg/L or monochloramine residual ≥ 1 mg/L
Alkalinity/DIC	Provide adequate alkalinity for buffering Avoid major changes that affect metal speciation (e.g., cerussite vs. hydrocerussite)

(Source: Friedman and Hill, ACE 2017)

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Orthophosphate Residual Goals

- Typically stable (≤ 0.2 mg/L drop)
- Can see an initial uptake by scale- drifts down in DS
  - Complexation with aluminum – milky water
  - Complexation with calcium
  - Complexation with iron
- Optimal range is system specific
  - Typical doses in U.S. from 1 to 3.5 mg/L as PO_4
  - Depends on complexation, materials of interest, discharge limitations, other issues

Possible Causes of pH Variability with Distribution System

Contributing factor	pH Increase	pH decrease
Poor buffer capacity	✓	✓
Reaction with cement-lined pipe	✓	
Biofilm/microbial activity		✓
Reservoirs open to atmosphere	✓ (GW)	✓ (SW)
Supply blending	✓	✓
Analytical and sampling technique	✓	✓

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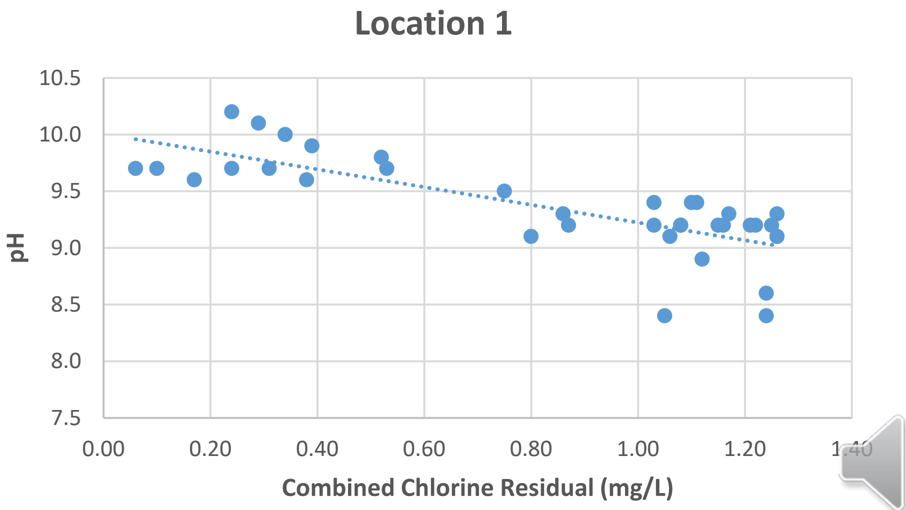
Impacts of Nitrification on CCT

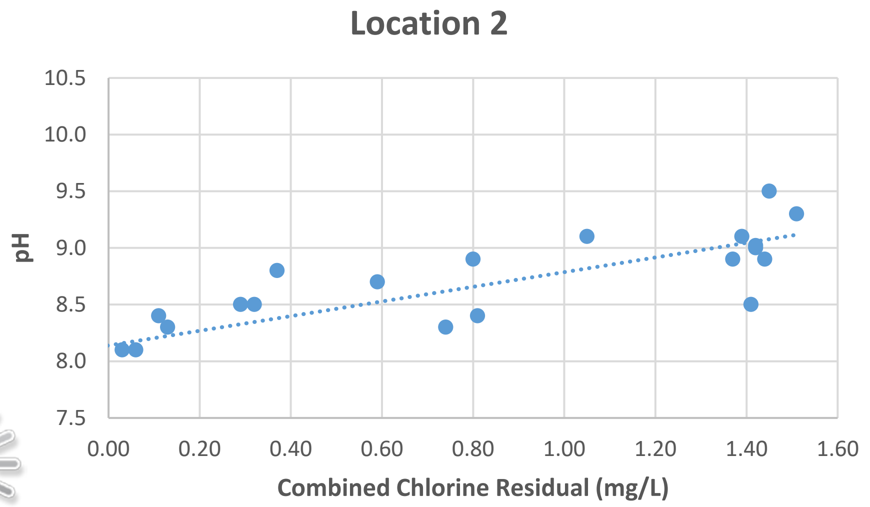
Chloramine demand/decay → Release of free ammonia → Biological oxidation to nitrite and nitrate

Disinfectant residual loss
Decreased dissolved oxygen
Decreased alkalinity
Decreased pH

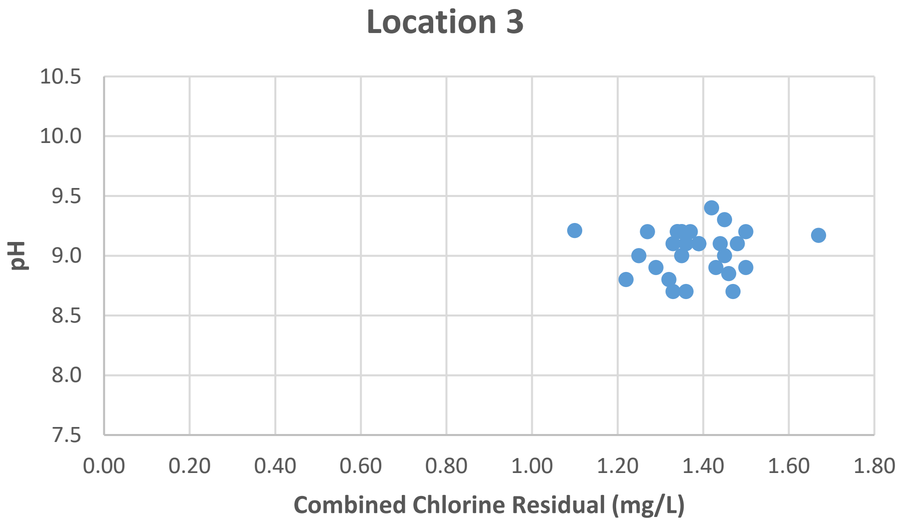
What is Causing pH Drift in This System? Nitrification, Water Age, Other ?



pH drifts up and chlorine decreases, may indicate excessive water age, in contact with cement lined pipes



pH drifts down and chlorine decreases, may indicate nitrification



Both pH and chlorine are stable, this is the goal!

Seasonal assessment also important!

Source: Confluence Engineering

KNOWLEDGE CHECK

3. pH drift in the distribution system may be caused by:
   a. Microbial activity
   b. Analytical or sampling errors
   c. Poor buffer capacity
   d. (a) and (c) only
   e. All of the above

LEARNING ACTIVITY

A system is implementing orthophosphate at a dose of 2.0 mg/L as PO_4 while maintaining their current pH target of 7.6. The proposed distribution system monitoring frequencies and water quality targets are listed in the below. For each parameter below, note whether or not both the monitoring frequency and target range are appropriate.

Parameter	Monitoring Frequency	Target
Orthophosphate	Monthly	1.8 – 2.2 mg/L as PO_4
pH	Weekly	7.0 – 9.0
Free Chlorine	Weekly	> 0.5 mg/L

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Summary

- When making a change, systems must monitor beyond requirements in LCRR – both in frequency and parameters – to assess performance and impacts
- Systems should establish clear targets and acceptable ranges when implementing a new CCT strategy
  - Potential problems and corrective actions should be identified prior to implementation