

Impacts of Source Water Blending on Lead Release

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Historically, corrosion control in the United States for Lead and Copper Rule compliance has focused on treatment to reduce the distributed water's plumbosolvency. Corrosion control treatment (CCT) typically focuses on either control of pH and alkalinity, development and maintenance of Pb(IV) scale under oxidized conditions, or use of orthophosphate-based corrosion inhibitors. These CCT methods are influenced by source water quality parameters such as pH and dissolved inorganic carbon; thus, CCT can potentially be affected when source waters with different

water qualities blend in the distribution system. If portions of the distribution system are exposed to blends of source waters with disparate water qualities, testing may be warranted to determine whether optimal CCT is being maintained where and when blending occurs, especially in transitional periods. This article discusses the theoretical impacts of blending source waters with different water qualities and presents research that was conducted on waters from two utilities to illustrate the potential impacts that source water changes can have on CCT.

Keywords: *blending, corrosion, lead, source water*

Lead (Pb) in potable water is not generally attributable to naturally occurring lead levels in surface water or groundwater supplies (EES 1990). Therefore, corrosion control in the United States for Lead and Copper Rule (LCR) compliance has focused on treatment to reduce the distributed water's plumbosolvency, or capacity to dissolve lead from lead-containing materials in the service lines or premise plumbing (Brown et al. 2015, EES 1990, Schock 1989). Brown et al. (2013) identified three treatment strategies that generally encompass the corrosion control treatment (CCT) used by utilities for LCR compliance:

- Control of pH and alkalinity
- Development and maintenance of insoluble Pb(IV) scale under oxidized conditions
- Use of orthophosphate-based corrosion inhibitors

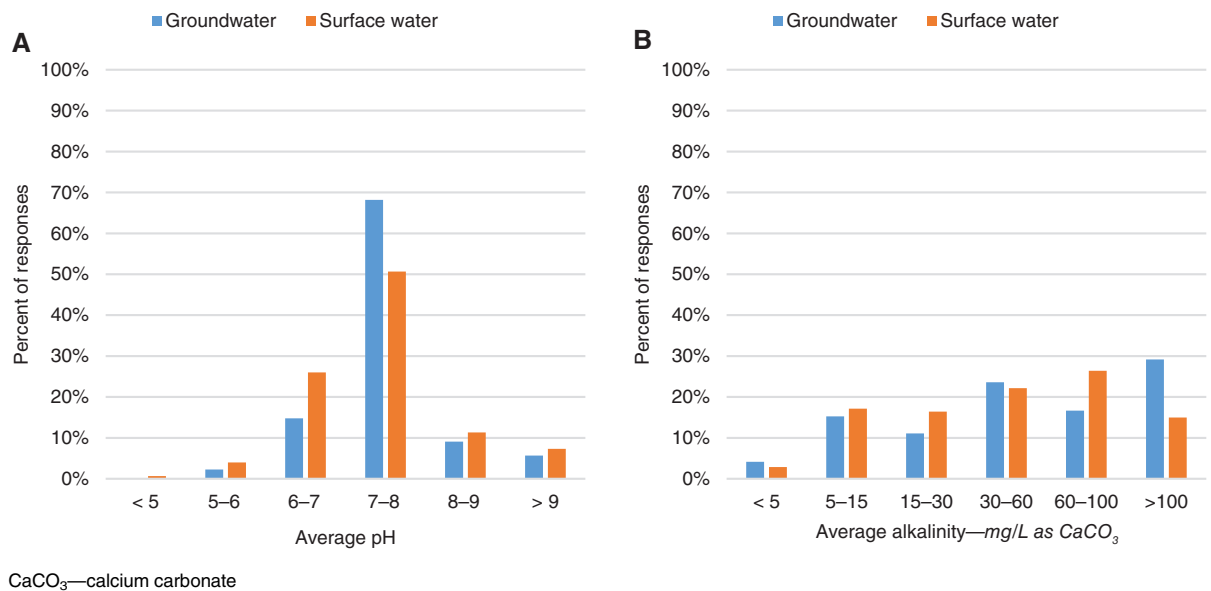
Systems that control lead corrosion through the control of pH and alkalinity seek to achieve water qualities that are amenable to the formation of passivating scales containing compounds such as PbCO_3 (cerussite), $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$ (hydrocerussite), and/or $\text{Pb}_{10}(\text{CO}_3)_6(\text{OH})_6\text{O}$ (plumbonacrite). The formation of these compounds is highly influenced by pH and

dissolved inorganic carbon (DIC) (Schock et al. 1996; Marani et al. 1995; Schock 1989, 1980; Taylor & Lopata 1984). Therefore, these systems tend to be highly influenced by the pH and DIC levels present in their source water(s).

The primary factor controlling CCT effectiveness in systems that use orthophosphate-based inhibitors is the concentration of the orthophosphate ion in the treated water (Schock 1989) and the DIC level as long as the pH is in the 7.2–7.8 range. Because of the broad pH performance range, orthophosphate-based CCT may be more robust against source water quality variances than CCT on the basis of control of pH and alkalinity, provided that the orthophosphate dose used is sufficient for the highest DIC water encountered (Hayes & Hydes 2012, Schock 1989).

This article investigates the potential for CCT impacts resulting from water quality variances attributable to source water changes or blending in the distribution system. The events in Flint, Mich., that began in 2014 have sharply illustrated the potential impact that a source water change can have on a water system's corrosion control strategy (Masten et al. 2016). However, source

FIGURE 1 Average pH and alkalinity ranges reported by respondents to the 2017 Water Utility Disinfection Survey who reported either surface water-only or groundwater-only sources



water changes do not have to be as dramatic as completely switching from one source to another for source water changes to influence CCT.

Of 370 systems that responded to the 2017 Water Utility Disinfection Survey, 90 systems (24.3%) reported that they used a combination of at least two different source water types (e.g., surface water, groundwater, groundwater under direct influence of surface water, and potable reuse water; Cornwell Engineering Group 2018). Among those 280 systems reporting use of only one source water type, it is likely that at least some portion uses multiple sources (e.g., multiple water treatment plants, multiple wells). Complex systems hydraulics control how these waters from different sources mix in the distribution system (Clark & Coyle 1990). As these sources mix in the distribution system, the distribution system water quality changes as a result of the blend of different source waters. If the source waters are of similar quality, these changes will be minimal, but if there is a variance in water quality between sources, the resultant blended water quality may be substantially different from that of any one water source.

Average pH (Figure 1, part A) and alkalinity (Figure 1, part B) ranges reported at the point of disinfection by the respondents to the 2017 Water Utility Disinfection Survey indicate that, although a wide range of pH and alkalinity values can be present in both surface water and groundwater sources, surface water sources were more likely than groundwater sources to have reported pH values <7 and >8, while groundwater sources are more likely to have reported alkalinities >100 mg/L as calcium

carbonate (CaCO₃). Water quality may also vary within systems served by multiple sources of the same type. For example, while a system with multiple Lake Erie sources may experience very consistent water quality between plants, a system with plants treating a reservoir source and a river source may see variations in water quality between the two sources. Likewise, water quality between multiple groundwater wells may vary considerably depending on aquifer composition and depth.

The interaction of different source waters in the distribution system and the corresponding influence on CCT is not well understood. Past research focusing on the impact that blending different water types can have on lead release in drinking water distribution systems has focused on consistent blends at the point of entry (Liu et al. 2010, Xiao et al. 2007, Imran et al. 2006, Tang et al. 2006). Information regarding the impact of dynamic changes in water quality in the distribution system resulting from hydraulic mixing and changing source water composition is limited. Previous research has focused primarily on the dynamic modeling of the distribution of disinfection byproducts and hardness (Clark & Coyle 1990, Grayman et al. 1988) or chlorine (Cl₂) decay (Munavalli & Mohan Kumar 2005, Elton et al. 1995, Rossman et al. 1994) in drinking water distribution systems. Trussell (1998) presents algorithms for the numerical calculation of pH resulting from different source water blends, but these calculations are not linked to a dynamic hydraulic model indicating the proportionate blending of water from different sources under potential pumping and demand conditions.

TABLE 1 Comparison of treated water quality from each of utility A's sources

Parameter	Groundwater	Surface Water
Alkalinity, as CaCO ₃ —mg/L	95	9
Dissolved inorganic carbon, as C—mg/L	23	1.2
Calcium—mg/L	20	1.4
Hardness, total as CaCO ₃ —mg/L	89	5.6
Iron—mg/L	0.052	0.039
Manganese—mg/L	0.129	0.002
pH	8.0	8.0
Phosphorus, reactive—mg/L	0.121	0.003
Silica, as silicon—mg/L	19	4
Specific conductance— μ mho/cm	184	26
Chloride—mg/L	2.4	2.7
Sulfate—mg/L	4.0	0.4
Temperature—°C	13.6	13.1
Total dissolved solids—mg/L	135	8
Total organic carbon—mg/L	0.3	1.0

C—carbon, CaCO₃—calcium carbonate

Therefore, in areas of the distribution system where waters from different sources mix, or areas that are exposed to different source waters due to seasonal or operational variations in source utilization, changes in water quality that occur instantaneously or over time may not be well understood in most systems. This, in turn, can affect lead release in a manner that may not be identified for many systems that are on three-year reduced lead monitoring under the LCR. Guistino (2007) identified the influence that timing can have on the quality of water samples collected in the distribution system. If LCR monitoring occurs when water quality in the distribution is relatively stable, it may not capture the potential for elevated lead releases during periods of changing water quality associated with source water changes. Alternatively, if LCR monitoring occurs during a period of instability, it is possible that sampling may indicate higher lead levels than would be anticipated on the basis of the system's CCT.

Research was conducted on waters from two utilities to illustrate the potential impacts that source water changes can have on CCT. One case study focuses on CCT based on control of pH and alkalinity, while the other explores potential CCT considerations when blending sources that use an orthophosphate inhibitor but at different doses.

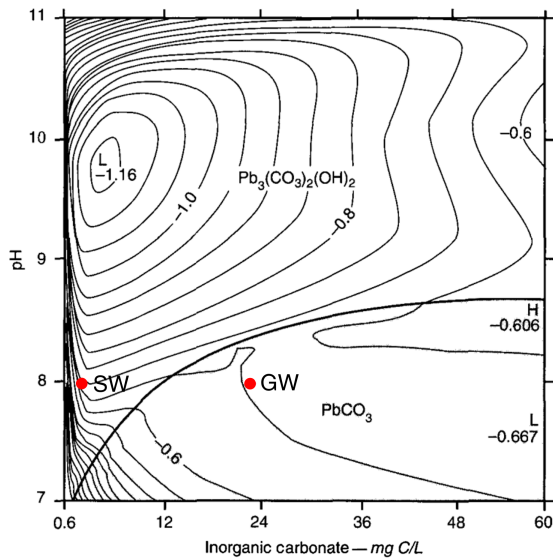
CASE STUDY A

Background. Utility A operates a water system that is primarily served by a moderate-pH, low-alkalinity surface water source. A groundwater source is also available, which utility A can use to either supplement the

surface water supply during periods of peak demand or to replace the surface water supply in the event of poor surface water quality. Lead service lines are not known to be present in utility A's system, with brass and lead solder representing the primary sources of leaded materials. Table 1 summarizes the relevant water quality parameters for utility A.

Utility A uses chloramines for secondary disinfection, so the oxidation reduction potential in the distribution system is not expected to be sufficient for maintenance of a Pb(IV) scale. Utility A also does not currently add a corrosion inhibitor, so CCT in utility A's system is based on the control of pH and alkalinity to form passivating lead oxide (PbO) or carbonate scales. Since pH values in utility A's system are moderate, plumbonacrite is not expected to be present; therefore, the predominant lead carbonate scales are expected to be hydrocerussite and/or cerussite, and lead oxide would likely be litharge or massicot. Scale analysis conducted in the system on coupons installed for 18 months in the distribution system found a predominance of hydrocerussite and litharge when the water use was primarily the surface water. Figure 2 shows the classic lead solubility contour diagram prepared by Schock et al. (1996) that indicates lead solubility as a function of pH and DIC. The upper-left-hand side of the diagram indicates the domain in which hydrocerussite is expected to control lead solubility, while the lower-right-hand side of the diagram indicates where cerussite is expected to be predominant. Note that the boundary between the two domains is approximate and is sensitive to the solubility and thermodynamic constants selected for the two solids. For

FIGURE 2 Approximate positions of utility A's surface water and groundwater quality on contour diagram of Pb(II) solubility in a pure system with varying pH and carbonate species concentrations at 25°C and $I = 0.005$ mol/L



Source: Schock et al. 1996. Reprinted with permission. © AwwaRF.

GW—groundwater, $Pb_3(CO_3)_2(OH)_2$ —hydrocerussite, $PbCO_3$ —cerussite, SW—surface water

convenience, the approximate positions of utility A's average surface water and groundwater quality are indicated in Figure 2.

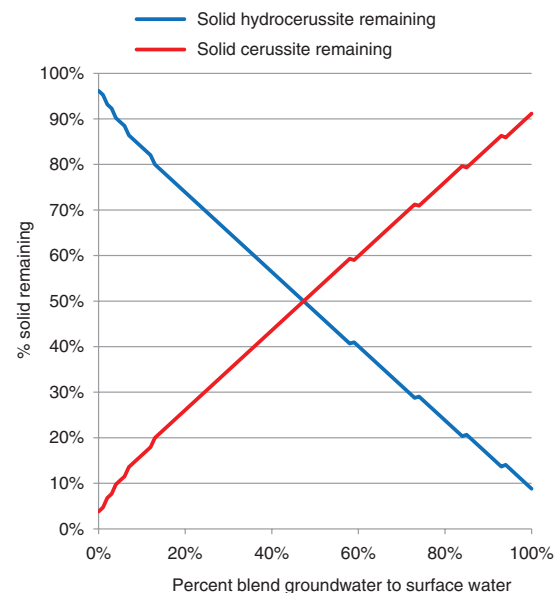
Examination of Figure 2 indicates that the theoretical lead solubilities projected for both of utility A's sources are similar based on their relative positions to the contours. However, the domain in which each source is located is different. When utility A is only feeding surface water, hydrocerussite is expected to dominate the lead carbonate scales. When the system is relying solely on groundwater, cerussite would be expected to be predominant. If both surface water and groundwater is being used, either lead carbonate might be favored depending on the extent of mixing in the distribution system.

Theoretical calculations of lead solubility, assuming the system is controlled by lead carbonate reactions, were developed for various blends of utility A's surface water and groundwater using computer software¹ (Gustafsson 2016). This software is a chemical equilibrium model that calculates aquatic chemical reactions, including metal speciation and solubility equilibria. The pH, DIC, and Ca^{2+} concentration for different blend ratios were calculated on the basis of the data presented

in Table 1; then, dissolved lead concentrations for each blend at equilibrium were calculated assuming that both hydrocerussite and cerussite solids were initially present at 3 mmol/L Pb^{2+} . Equilibrium constants for cerussite and hydrocerussite were adjusted in the model to match with the computer model (LEADSOL, a computer program developed by USEPA based on the conceptual model described in Schock [1990]) log K values presented in Schock et al. (1996). Cerussite and hydrocerussite log K values were adjusted to -13.11 and -18.00 , respectively (Schock et al. 1996). Figure 3 presents the relative modeled lead release for both hydrocerussite and cerussite for utility A's current water quality conditions. If the supply is 100% surface water, at equilibrium the scales are projected to be composed primarily of hydrocerussite. As groundwater is blended into the system, the lead carbonate scales transition to mixed scales with both hydrocerussite and cerussite. Hydrocerussite remains above 50% of the solid phase until the source water is composed of approximately 48% groundwater; as the percentage of groundwater in the source water blend increases to above 48%, cerussite becomes the dominant form of lead carbonate.

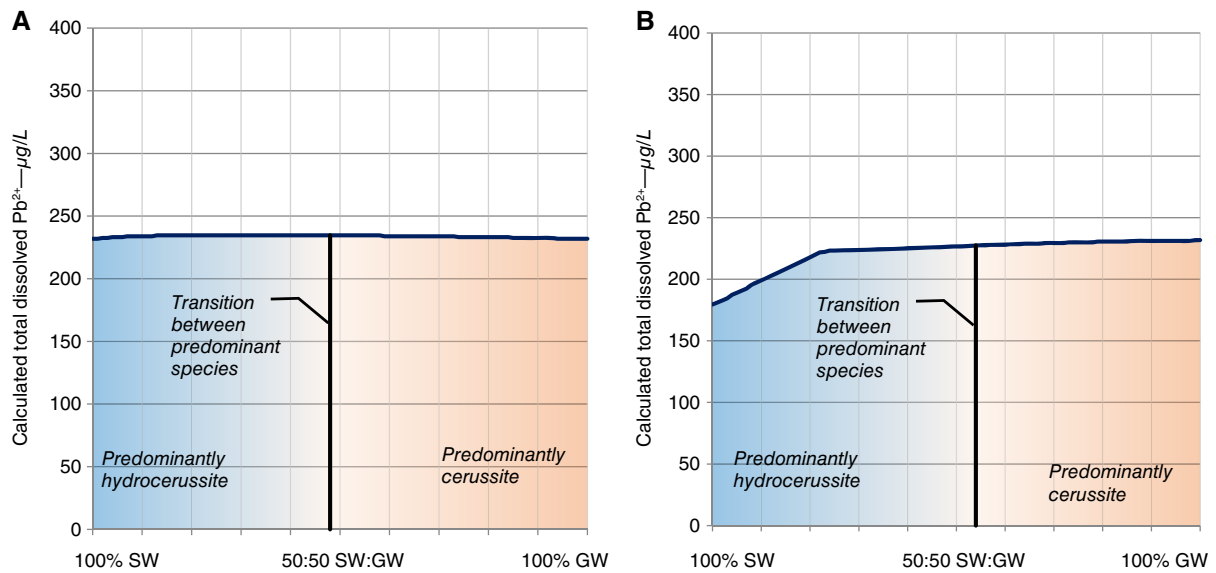
The impact that changing source water has on the theoretical lead solubility at equilibrium depends on the transition between the two source water points across the lead solubility contour lines from Figure 2. Even if

FIGURE 3 Relative presence of cerussite and hydrocerussite solids in a blend of utility A's surface water and groundwater based on calculated lead concentrations



Zero percent on the x-axis indicates a blend that is 100% surface water, while 100% on the x-axis indicates a blend that is 100% groundwater.

FIGURE 4 Calculated lead solubility at equilibrium for blends of utility A groundwater with utility A surface water at existing conditions of pH 8.0 and DIC = 2.2 mg/L as C (A) and utility A surface water adjusted to pH 8.5 and DIC = 8.3 mg/L as C (B)



C—carbon, DIC—dissolved inorganic carbon, GW—groundwater, Pb—lead, $Pb_3(CO_3)_2(OH)_2$ —hydrocerussite, $PbCO_3$ —cerussite, SW—surface water

The shaded regions indicate the dominant lead carbonate in the scale at a given blend ratio. $I = 0.005$, $T = 25^\circ C$, hydrocerussite and cerussite each 3 mmol Pb/L.

the lead solubility at equilibrium for each source water is similar, higher lead release might be expected as the blend transitions from one source to another. Figure 4, part A, shows the calculated theoretical dissolved lead concentrations of different blend ratios of utility A surface water and groundwater under existing water quality conditions. The theoretical lead solubility when the system is supplied by groundwater is identical to the theoretical lead solubility when the system is supplied by surface water (232 $\mu g/L$ Pb^{2+}). This calculation using the computer software¹ described by Gustafsson (2016) is similar to that shown by Schock in Figure 2 in that, at pH 8, the groundwater and surface water theoretically have similar lead solubility, even though the DIC is much different. Therefore, one might conclude that blending these waters would not have an impact on lead release.

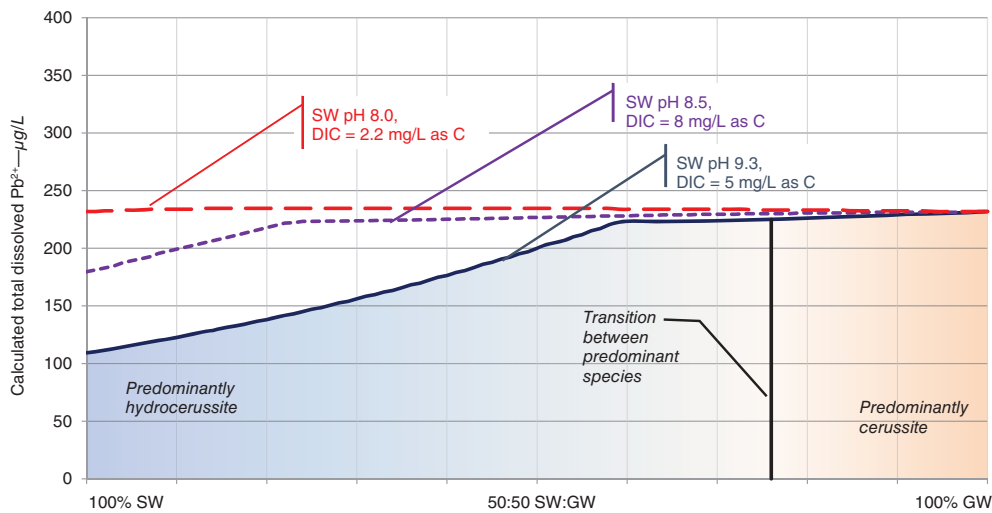
Increasing the pH for the low-alkalinity surface water used by this utility above pH 8 could lower lead levels, in accordance with Figure 2, by lowering theoretical lead solubility. For utility A, pH adjustment of the groundwater is limited by its higher alkalinity and calcium content, which increases the potential for calcite precipitation in the distribution system. However, it is feasible to increase both the pH and alkalinity of utility A's surface water source for CCT. Figure 4, part B, shows the theoretical lead solubilities for blends of utility A's groundwater with surface water that has been adjusted to a pH of 8.5 and a

DIC of approximately 8 mg/L as carbon (C). This change would decrease the theoretical lead solubility when the scale is dominated by hydrocerussite. Optimizing pH and alkalinity CCT for utility A's source water to a pH of 9.3 and DIC of 5 mg/L would further reduce overall lead solubility as shown in Figure 5.

Figures 4 and 5 also show the line at which the majority of the precipitate is hydrocerussite versus cerussite. As the pH of the surface water increases, the line shifts to the right, indicating that, at equilibrium, a higher groundwater blend could be used, and the less soluble hydrocerussite would be the predominant solid. However, both solids are still predicted to be present. The presence of both solids is indicated by the shading in Figures 4 and 5. At the far left, at 100% surface water, the hydrocerussite is indicated as dark blue. At the far right, the cerussite is orange. All the shades in between when the blue and orange are mixed represent the presence of both solid species, similar to Figure 3.

So while, for example, Figure 4, part A would lead one to believe the lead solubility is the same as the blend changes, the transformation of cerussite to hydrocerussite (or vice versa) increases the potential for lead release in utility A's system as the waters are blended through one of two mechanisms: (1) if the kinetics of formation of one mineral are not as rapid as the kinetics of dissolution of the other, the extent of scale coverage could

FIGURE 5 Comparison of the influence of surface water pH and DIC on the calculated lead solubility at equilibrium for various blends of utility A surface water and groundwater



C—carbon, DIC—dissolved inorganic carbon, GW—groundwater, Pb—lead, SW—surface water

$I = 0.005$, $T = 25^\circ\text{C}$, hydrocerussite and cerussite each 3 mmol Pb/L

decline during the transition period, and (2) changes in the physical structure of the scale associated with the mineral transformation could increase the potential for scale destabilization, leading to a source of particulate lead in the system. Bench-scale coupon testing was conducted to determine if elevated lead levels might be present during the transition from surface water to groundwater (or vice versa).

Materials and methods. The theoretical considerations for lead solubility in utility A's system that have been previously presented were researched experimentally through bench-scale coupon testing. Lead coupons were suspended in 500 mL glass jars and immersed in zero headspace conditions. Experiments were conducted in two phases to first assess the individual source water lead solubility and then to determine the potential lead solubility or scale stability impact of equilibrated coupons exposed to a blend of surface water and groundwater.

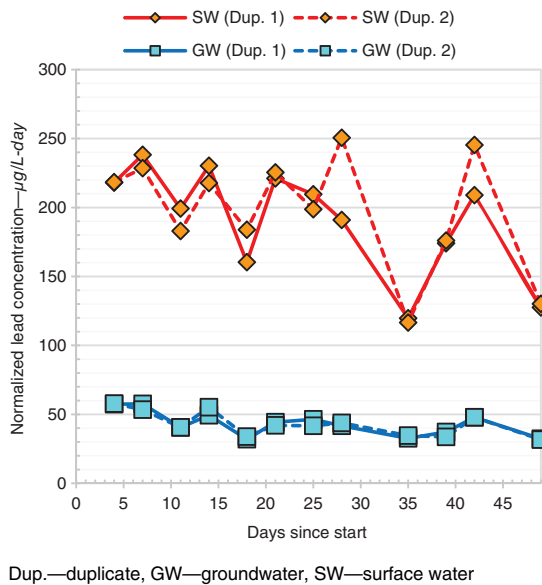
During phase 1, which was the initial scale formation phase, the coupons were immersed in 500 mL glass jars containing 400 mL of either 100% surface water or 100% groundwater. Pure lead coupons (approximate dimensions of 3 in. by $\frac{1}{2}$ in. by $\frac{1}{16}$ in.) were immersed in freshly prepared water for alternating three- and four-day stagnation periods. This procedure allows for the direct measurement of lead release from the coupons, compared with the method of determining corrosion rates on the basis of weighing coupons and calculating mass loss. It also allows for more frequent measurement of corrosion rates while minimizing the handling of—

and the associated potential for disruption of the corrosion scales on—the coupons. Each batch of water was chloraminated before testing using sodium hypochlorite (NaClO) and ammonium chloride (NH₄Cl) solutions at a 4.86 target Cl₂:H₄-N ratio to reach a target total chlorine residual of 1.7 mg/L. If necessary, the pH of each batch of water was adjusted to a pH of 8.0 before testing using a titrator.² Following water preparation, coupons were carefully transferred from the jars with stagnating water to the jars containing the aliquot of freshly prepared water. The previous aliquot of stagnating water was then acidified to a pH of less than 2 and analyzed for total lead. All coupons tested during phase 1 were tested in duplicate.

After the initial scale formation phase, which lasted for 49 days, each group of duplicates used for phase 1 testing was split for phase 2 blend testing. One of the duplicates was exposed to an 85:15% surface-water-to-groundwater blend ratio, while the other duplicate was exposed to a 15:85% surface-water-to-groundwater blend.

The influence of CCT was also evaluated, with one group of groundwater-equilibrated coupons exposed to blends with surface water adjusted to a pH of 9.3 and a DIC of 7.5 mg/L as C. During water preparation, the pH for these phase 2 surface water conditions was adjusted to 9.3 using a titrator,² and DIC adjustments were made using sodium bicarbonate solution. For both phases of this particular evaluation, coupons were immersed in 500 mL aliquots of test water under zero headspace conditions to promote pH stability throughout the test

FIGURE 6 Lead released from lead coupons at existing conditions for 100% GW or SW



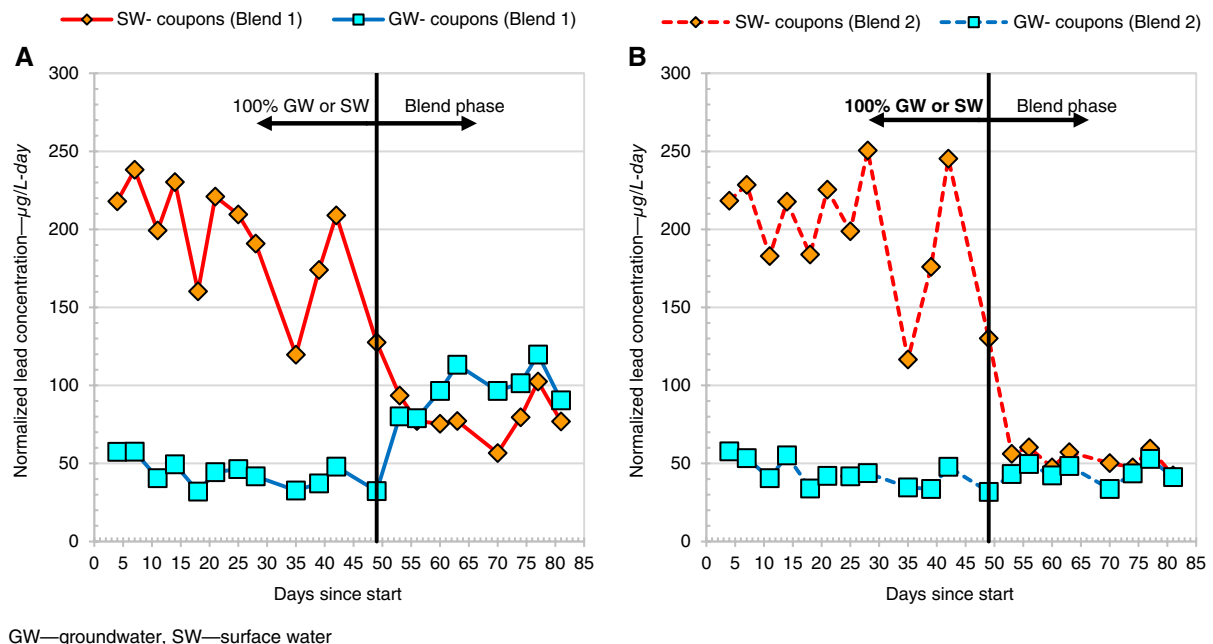
period. Other study procedures, such as stagnation period length, target total chlorine concentrations, sample acidification, and total lead measurement, were consistent through all test conditions and phases.

Results. The duration of the initial scale formation phase was 49 days, after which lead levels released from the coupons appeared to have largely stabilized, although data from day 49 of the coupons exposed to surface water suggest that a downward trend in the lead levels released from those coupons may have persisted. Figure 6 summarizes the lead concentrations released from the lead coupons, normalized by days of stagnation time. Despite similar theoretical lead solubilities based on lead carbonate chemistry, the surface water was found to have a higher plumbosolvency than the groundwater.

After the initial scale formation phase was concluded, the replicate coupons were divided, and each coupon was exposed to either blend 1, which was 85% surface water and 15% groundwater, or blend 2, consisting of 15% surface water and 85% groundwater. The lead release data after exposure to these blends are shown in Figure 7. Note that the blended water quality for both curves in Figure 7, part A, were the same after day 49 (representing blend 1). Similarly, the water quality for both curves in Figure 7, part B, were identical after day 49 (representing blend 2).

The response of the coupons that had been exposed to the surface water during the initial scale formation phase was quite different from that observed for the coupons exposed to groundwater. In both instances, when a coupon stabilized on surface water was exposed to a blend containing groundwater (either 15 or 85%), the result was a lower lead release than that observed

FIGURE 7 Lead released from GW and SW lead coupons after exposure to 85% surface water and 15% groundwater (blend 1) (A) or 15% surface water and 85% groundwater (blend 2) (B)

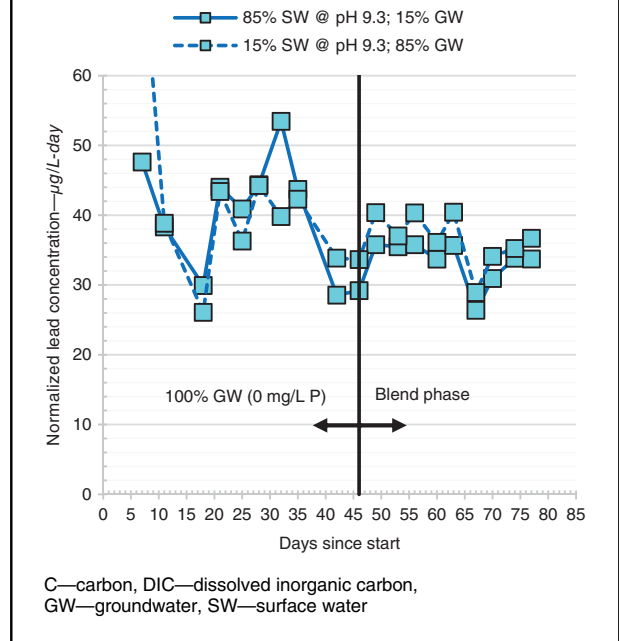


with only surface water. That is consistent with the results shown in Figure 6—that overall groundwater had lower lead levels than surface water. In this case, introduction of a blend of groundwater into the surface water had a positive impact on lead levels. However, the introduction of a blend composed of predominantly surface water (blend 1) to coupons that had been exposed initially to groundwater resulted in a rapid increase in released lead. The blend conditions for both the initially equilibrated surface water coupon and the groundwater coupon were identical in Figure 7, part A. However, the groundwater-equilibrated coupon increased lead after exposure to the blend, while the surface water-equilibrated coupon did not. After about 30 days of being exposed to the blend, the two coupons reached similar lead levels.

The data shown in Figure 7 suggest that the lead carbonate scales formed during the initial phase on the coupons exposed to groundwater, which are presumed to be predominantly cerussite, dissolved rapidly after the introduction of surface water. It can be inferred that the formation of hydrocerussite, which is favored under utility A's surface water conditions, is not as rapid as the dissolution of cerussite under those same conditions, resulting in a transitional lead release. While the kinetic dissolution and formation rate inference is speculative on the authors' part, there are some kinetic data in the literature to support this supposition. Kushnir (2014), in studying water quality parameter effects on dissolution rates of lead carbonates, found that, at a higher DIC (50 mg/L) where cerussite dominated, the dissolution rate of lead was much faster than at a lower DIC, where hydrocerussite dominated. Kushnir also cited several others that indicated that the lead carbonate dissolution reaction rate is faster than the formation rate.

In utility A's systems, optimizing CCT for the surface water can mitigate the lead released when scales that have been exposed to groundwater are subsequently exposed to surface water. Figure 8 presents data from lead coupons that were initially exposed to 100% groundwater and then exposed to a blend of surface water and groundwater when the surface water had been adjusted to a pH of 9.3 and a DIC of 7.5 mg/L as C. Unlike existing conditions, which are shown in Figure 7, there is not a large release of lead immediately following exposure to blends containing surface water. Even though there is a small increase in lead levels after the blend is introduced, a comparison of Figure 7, part A, and Figure 8 shows that increasing the pH and DIC of utility A's surface water will significantly reduce the potential for lead release following the transition from a cerussite-dominated to a hydrocerussite-dominated scale. Potentially, at a higher pH, the kinetics of hydrocerussite formation are faster than at the pH 8 conditions, reducing the kinetic effects of change in the scale form.

FIGURE 8 Lead released from lead coupons exposed to 100% GW before and after blending with different ratios of SW at a pH of 9.3, DIC = 7.5 mg/L as C



The data collected during the bench-scale testing support the lead solubility theory previously discussed. However, the bench-scale study of utility A's system did not include direct scale analysis of the lead coupons, so any discussion of cerussite dominance or hydrocerussite dominance in the lead carbonate scale is inferred from the lead-release data rather than from direct measurements. Literature presenting dynamic changes in lead scale composition based on exposure to variable source water blends is limited. However, a recent study by Friedman (2018) presents findings that support the analysis previously presented.

Friedman (2018) presents the direct observation of the lead carbonate scale transitions indicated in Figure 3 in a system similar to utility A, which is exposed to various proportions of low-DIC surface water (pH 8.1, DIC 4.8 mg/L) and higher-DIC groundwater (pH 7.5, DIC 22 mg/L). During a pipe loop study of lead goosenecks, pipe sections were harvested for scale analysis during phase 1, in which the goosenecks were exposed to low-DIC surface water, and during phase 2, in which the low-DIC surface water was replaced with a higher-DIC groundwater source. Scanning electron microscope (SEM) images of lead scale in phase 1 show that the scale was dominated by hydrocerussite, as would be expected on the basis of theoretical solubility calculations, while images of the scale from the pipe harvested in phase 2 indicate a transition to a cerussite-dominated

scale. These findings follow the scale changes predicted in utility A's system and show that exposure to variable source water blends can induce dynamic changes in the lead carbonate scale mineralogy.

Summary. Given that utility A transitions between various blends of low-DIC surface water and higher-DIC groundwater, solubility theory predicts a potential risk for increased lead release when transitioning between hydrocerussite and cerussite. Bench-scale testing observed increased lead levels when lead coupons exposed to groundwater were subsequently exposed to blends containing low-DIC surface water, which would be consistent with a shift from cerussite-dominated to hydrocerussite-dominated scales. By increasing the pH and alkalinity of the surface water to improve CCT, utility A can mitigate the risk of potential lead release when blending surface water and groundwater.

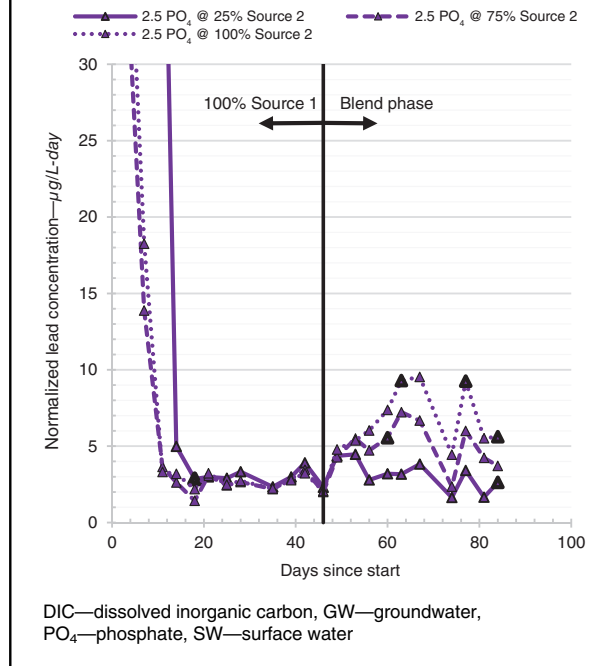
CASE STUDY B

Background. Utility B treats and distributes surface water disinfected with free chlorine, indicated in this case study as source 1. A neighboring utility intermittently shares chloraminated water with utility B during emergencies or low distribution system pressures. This secondary source, which mixes in the distribution system at various percent blends, is indicated as source 2. Both sources maintain an average pH of 8 in the location of the intertie between systems. The average DIC of source 1 in the intertie location is around 15 mg/L, while the DIC of source 2 in that location is slightly higher, ranging from 17 to 24 mg/L. Both sources use orthophosphate products to control corrosion, but at varying doses; source 1 feeds neutralized sodium orthophosphate at a dose of 2.5 mg/L as PO₄ (phosphate), while source 2 feeds a zinc orthophosphate product and maintains an orthophosphate residual around 0.5 mg/L as PO₄ in the intertie location. Bench-scale coupon immersion testing was performed on utility B-treated water to assess the potential for lead release from lead service lines in utility B's system that could result from blending sources 1 and 2 at the intertie location.

Materials and methods. Fresh lead coupons were immersed in 400 mL batches of test water prepared twice weekly for each test condition. During water preparation, disinfectant residual and pH were adjusted to simulate typical water quality parameters for each source. Source 1 was prepared with a target free chlorine residual of 1.2 mg/L, while source 2 was prepared with a target total chlorine residual of 3 mg/L and a Cl₂:NH₄-N mass ratio of 4.75. The target pH for both source waters before coupon immersion was 8.0.

Coupons were initially immersed solely in source 1 water during the first phase of testing for initial scale formation. During this preblend phase, neutralized sodium orthophosphate doses were tested in triplicate to determine relative corrosion inhibitor dose

FIGURE 9 Lead released from lead coupons exposed to 100% source 1 with 2.5 mg/L as PO₄ orthophosphate before and after blending with source 2



performance. After Pb release appeared to equilibrate in the test vessels, testing proceeded to a second phase for blend evaluation. Using the same coupons from the first phase of testing, source 1 water was blended with 25, 75, or 100% source 2 water, with the remainder composed of source 1 water. For blending, source 1 water with 2.5 mg/L as PO₄ was used for blend testing as this amount was found to be optimal from the first phase. Source 2 was dosed with zinc orthophosphate at a rate of 0.5 mg/L as PO₄ for all conditions tested as this was the dose used by this second utility.

Results. Lead release from the coupons tested during the preblend phase was determined to have reached equilibrium after 46 days of testing. Figure 9 presents the lead released from the coupons dosed with 2.5 mg/L for both the preblend phase and blend evaluation phase of testing.

As seen in Figure 9, all three blend conditions resulted in an immediate increase in released lead after blending. The blends containing 25% source 2 rapidly reequilibrated to near preblend lead levels. However, the blends containing higher proportions of source 2 water resulted in sustained increased lead levels compared with those from the preblend phase. Despite the presence of orthophosphate in both source 1 and source 2 waters, the blends containing higher proportions of source 2 water resulted in higher lead releases following blending than the blend containing the lowest

proportion (25%) of source 2 water. These data suggest that the lower orthophosphate concentration in the source 2 water diluted the orthophosphate residual of the blended water below the level required to sustain optimal CCT following blending. This may also have been exacerbated by the slightly higher DIC in the source 2 water, which would have decreased the effectiveness of orthophosphate treatment. Although a control with 100% source 1 was not maintained during the second phase of testing, there was a clear change in performance when the waters were blended, especially since the blend containing 25% source 2 did not show an increase in lead solubility postblend, unlike the blends containing higher proportions of source 2 water.

Summary. Testing indicates that the blending of source 1 and source 2 waters when the inertia between the two systems is active can result in increased lead releases in the zone exposed to the blended water. If the proportion of source 2 water is low (25% or less), the lead levels appear to revert to preblend levels within one to three weeks. At higher percentages of source 2 water, lead levels may remain sustained above preblend levels. These elevated lead levels appear to be the result of the reduced orthophosphate concentration following the introduction of the lower-dosed source 2 water. Presumably, the remaining orthophosphate residual in the blended water is below what is required to sustain the passivating lead phosphate layer. For example, at a blend of 75% source 2 water, the orthophosphate level would drop to about 1.5 mg/L. Previous testing in source 1 water has shown that this level is not optimal.

SUMMARY AND CONCLUSIONS

Effective CCT is intrinsically linked to the water quality of the source water being treated. While prior research has focused on the impact that blending source water before treatment may have on CCT, there is a knowledge gap concerning the effectiveness of CCT in areas of the distribution system exposed to variable water quality conditions due to dynamic blending from multiple sources.

Theory predicts that lead releases may occur if water quality conditions transition between domains favoring either hydrocerussite or cerussite, even if theoretical lead solubility at equilibrium in each domain is the same. The observations of lead releases in case study A were consistent with this theory, although a direct analysis of the lead scale was not performed. Blending can also impact CCT in systems using orthophosphate inhibitor, as the results from case study B indicate.

Distribution system modeling currently lacks the tools necessary to simulate the effect that dynamic blending has on water quality parameters relevant to CCT in the blended water zones. Equilibrium models can provide some insights about the potential impacts on lead levels due to blending. However, if portions of the distribution system are exposed to blends of source waters with

disparate water qualities, testing may be warranted to determine whether optimal CCT is being maintained where and when blending occurs, especially in transitional periods.

ENDNOTES

¹Visual MINTEQ, KTH, Stockholm

²Hanna HI902 Autotitrator, Hanna Instruments Inc., Woonsocket, R.I.

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