Conducting distribution system corrosivity evaluations using an innovative jar test procedure

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ABSTRACT

There have been several attempts in enhancing corrosion jar testing methods to better mimic real-world conditions found in drinking water distribution systems. A key feature that is generally omitted in such studies is zero headspace and the lack of interaction with the atmosphere within the jars as well as the flow interactions which affect total metal release. This work proposes a modified method to typical corrosion jar testing protocols to better simulate distribution system conditions. Modified separatory funnels with the addition of a rubber stopper and coupon holder were set-up to allow an in-flow and out-flow for water replacement every three to 4 d. The results demonstrated the effectiveness and reproducibility of the modified method, specifically with the analysis of variance conducted. A synthetic water test using both the modified and original methods showed a statistical difference between the two, and decreased variability in the metal release with the new procedure. Enhanced dissolved oxygen depletion was also observed with the modified method. The results of another study conducted, using actual waters, was used to create an empirical model with the water quality parameters measured, and the total metal release. This model was a good fit, with a 0.81 R-squared value and a 0.71 linear slope between the predicted and measured copper concentrations. In addition, first-order rate law models were created for fitting the metal release observed. The resultant equations were not good fits the batch testing conducted, however, the first-rate models created for the direct-connection study resulted in up to a 0.98 R-squared value with slopes close to unity when plotting the calculated vs. measured metal release.

Keywords: Jar test; Immersion; Corrosion; Drinking water; Copper; Flow-through; Metal release

1. Introduction

Physical and chemical processes can result in the internal corrosion of water distribution systems. There are several methods commonly used in industry to determine a public water system's (PWS) corrosion potential and possible treatment options, but these are highly variable in scope and cost. On one end, there are pipe loop studies, using new or harvested pipe, that can be expensive and time- and labor-intensive; however, it can be the best method for simulating real-world conditions [1]. On the other hand, there are inexpensive, jar testing methods for immersion studies that provide less reliable data because of the lack of hydraulic conditions found in distribution systems. However, jar testing can be completed in a quick and efficient manner to compare alternative treatment options. Other possibilities include electrochemical methods that provide instantaneous corrosion rate analysis but lack concentration data, a critical component for compliance of the United States' Environmental Protection Agency's (USEPA) Lead and Copper Rule (LCR).

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The LCR, first promulgated in 1991, regulates lead and copper through action levels at 0.015 and 1.3 mg/L, respectively. Recently, the rule has undergone major changes, collectively titled the Lead and Copper Rule Revisions (LCRR). These changes became effective in 2021 and require PWSs to comply by October 2024. The LCRR includes updates to the approved corrosion testing protocols and suggests bench-scale evaluations be eliminated for screening corrosion control treatment (CCT) options, unless the absence of lead service lines (LSLs) is confirmed [2]. For systems that do not contain LSLs, bench-scale jar testing methods continue to be a cost effective and useful option for screening different treatment alternatives.

Schock et al. [3], conducted several corrosion evaluations that incorporate pipe loops and also bench-scale testing to evaluate metal release. The bench-scale studies incorporated 30 mL Teflon cells (containing the metal coupons) with aliquot replacements every few days, from a tank that was refilled on a weekly basis. Cornwell and Wagner [4] developed a bench-scale test procedure where metal coupons were suspended in 500 mL jars that held a 400 mL sample aliquot for three to 4 d. Similar methods proposed by Korshin et al. [5] used 900 mL glass jars, that held an 850 mL stagnant aliquot, for bench-scale corrosion studies evaluating the supernatant metal content after a 7-d exposure period. Edwards and Ferguson [6] evaluated metal release using the typical jar test where a 500 mL jar was filled with a 400 mL sample aliquot and analyzed after either a one- or 3-d exposure period. The study conducted by Edwards and Ferguson [6] also evaluated corrosion rates at the bench-scale by performing electrochemical tests with a Reiber cell [7].

While these methods have been used commonly in industry and academia, it appears they did not consider flow effects nor include dissolved oxygen monitoring that have been shown by others as factors that impact metal release [8–10]. Drinking water pipelines are theoretically under pressure and sealed conditions, assuming there are no major faults in the line or oxygen introduction throughout the system. The goal of this research was to build upon existing bench-scale jar testing methods to provide a sealed, zero-headspace environment with an enhanced aliquot-replacement technique.

2. Materials and methods

The method described herein includes the use of modified separatory funnels, that allow for an inflow and outflow, unlike the stagnant jars used in common bench-scale corrosion evaluations. The modified 500 mL separatory funnels were designed and made through Chemglass Inc. (New Jersey, USA). Bulk water was prepared in at least 3.5 L batches prior to introduction, using a peristaltic pump, for a period of 15 min, after sample collection of the previous aliquot. After the 15 min period, the funnel is sealed and allowed to sit in stagnant, dark conditions. This procedure was repeated on a daily or semi-weekly basis. Before each water changeout, the full volume was sampled for dissolved and suspended metal content, and immediately refilled with the new batch of water. Fig. 1 presents the simplified design drawing for one funnel.

Suspended within each funnel is a 3-inch by 1/2-inch by 1/16-inch metal coupon, suspended by a coupon holder that seals the funnel using a rubber stopper. Within the rubber stopper there is an air release that allows for the environment to be sealed using laboratory film, Parafilm®. The Parafilm® is to be removed prior to sampling in order to drain the funnel. Ball valves are placed at the inflow and outflow of the separatory funnel and are connected to the funnel using Tygon® E-food tubing.

The batch water samples are introduced using a peristaltic pump, with water flow through the funnel for a period of 15 min prior to the stagnation period. The work presented herein conducts the periods of flow at a rate of 200 mL/min, however this may be adjusted accordingly, depending on water volume availability, so long as the time is kept consistent throughout the length of the study and with the understanding that increased flowrate will be more representative of pipeline conditions.

Because of the flow-through aliquot replacement design, and the tubing connections, this method can analyze existing corrosivity, with a direct connection to a tap at a facility or within the distribution system itself. With the use of a flow meter and necessary fittings, the metal release over time of an existing system can be monitored without the need to prepare bulk water. This also provides PWSs the freedom to investigate corrosivity at sites throughout their distribution system and study the long-term effects of water quality on metal release in the selected locations. So long as there is a tap connection, or faucet, this procedure for jar testing can be implemented. The direct connection method would be preferable if the finished water is not already aerated during treatment, to prevent exposure to the atmosphere throughout the corrosion testing process.
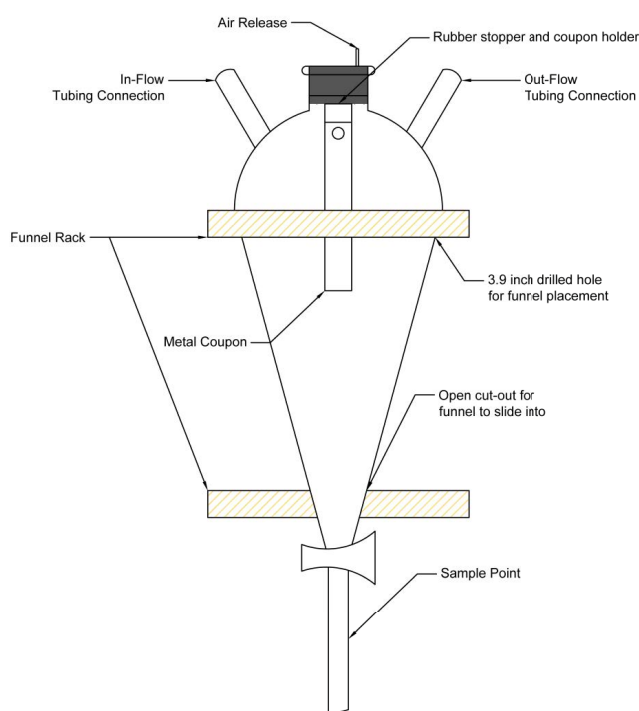

Fig. 1. Modified funnel design and description.

The following is a list of materials needed, some of which may or may not apply depending on whether the study is to be conducted using bulk water and a peristaltic pump or through a direct connection to an existing tap.

- Modified separatory funnel (at least one per condition to be tested);
- Tygon® E-Food Tubing size L/S 18 with an inner diameter of 0.311-inch;
- Tubing for air release (1 mm outer diameter);
- Ball valve with 1/4-inch hose barb (two per funnel);
- Metal coupon, alloy of choice (3-in by ½ in by 1/16-in);
- Coupon holder (nylon, 2-in long);
- Rubber stopper (stopper size 6, 25 mm neck size);
- Parafilm® (to seal air release after each water changeout);
- Funnel rack or holder;
- Large HDPE carboys for holding bulk water when necessary;
- Peristaltic pump;
- Flowmeter.

Presented in Table 1 is a summary of the studies conducted to a) validate the use of the method compared to existing methods and b) to evaluate a city's current and projected water quality in terms of copper release using this new UCF-designed protocol. The first test compared the use of the modified method and a typical jar test procedure for a low and high total dissolved solids (TDS) synthetic water condition. This first test had water changeouts every 24 h for a total of 15 changeouts during the testing period. After the ninth water changeout, an orthophosphate corrosion inhibitor (Carus 4200) was added to the bulk water solutions. Water quality parameters were monitored, in the feed bulk water and collected samples, daily and are provided as part of the supplemental materials.

Test 2 evaluated the copper release associated with different process waters from a local utility, and how they contribute to the overall corrosivity of the final blend. A projected condition was also evaluated using an analogous system's process water, representing the utility's impending enhanced treatment infrastructure updates to their surficial groundwater supply. Water changeouts were conducted two times per week, over a period of five weeks, for a total of ten water changeouts. The blends created were dosed with varying degrees of sodium hydroxide (NaOH) for pH adjustment, an orthophosphate corrosion inhibitor (Carus 4200), and sodium hypochlorite (NaOCl) for disinfection

requirements. For the blends with pH adjustment, the goal pH was 8.0 +/– 0.1, and a 2.0 +/– 0.1 mg/L free chlorine residual goal.

The final test implemented the UCF-modified method for use in a direct connection evaluation at the utility's facilities. The same procedure was conducted as in test 2 but instead of batch testing with a peristaltic pump, the funnels were directly connected to a tap with flow-control using a flowmeter, during the 15 min flow period.

3. Results and discussion

3.1. Method comparison test

Two groundwater quality scenarios were examined during the method comparison test. The first is a low TDS, low sulfate water, and the second is a high TDS, high sulfate condition. Figs. 2 and 3 provide the results of the 2-week study for method comparison between the UCF-modified method and the typical jar testing method, for the two water quality scenarios. Note, dissolved oxygen levels in the feed solutions are also presented in Figs. 2 and 3 to demonstrate its effect on metal release, especially without the inhibitor addition. In a sealed environment the atmospheric oxygen transfer should not be a concern and the oxygen in solution should deplete over time. If the environment is not fully sealed, the oxygen transfer can continue to occur, with a decrease in the observable oxygen depletion over time. The oxygen depletion observed for each method and water quality scenario is presented in Figs. 4 and 5.

Dissolved oxygen content was monitored in the feed solutions and in the samples collected for metals analysis,

Fig. 2. Results of two-week study evaluating copper release using both the original methods outlined by Cornwell and Wagner [4] and the UCF-modified procedure suggested herein, for the high total dissolved solids synthetic water condition.

Table 1
Overview of tests conducted and presented herein

Test ID	Test description
Method comparison	Two-week study for the purpose of demonstrating difference between typical jar tests, using beakers, and the UCF modified method with funnels.
Blended waters study	Five-week study evaluating corrosivity of existing (high total dissolved solids) and projected (low total dissolved solids) conditions for copper with process water collected from city's water treatment plant and an analogous system. Corrosivity of each contributing process was also evaluated.
Direct-connection study	11-week study evaluating the city's existing water through a direct connection using a tap in the city's laboratories as proof of concept for this direct connection method.

after the 24 h stagnant period. Dissolved oxygen content monitoring provides insight as to its depletion during the exposure period. The box-and-whisker plots presented in Figs. 4 and 5 illustrate the oxygen depletion for the two jar testing procedures evaluated. There was consistently lower oxygen depletion with the original jar testing method as compared to the UCF-modified procedure, as expected, due to the unsealed vs. sealed environments, respectively.

An analysis of variance (ANOVA) was calculated to determine the statistical difference in copper release between the two methods and is summarized in Table 2. The modified method showed statistically lower copper concentrations and less variability throughout the two-week period for the high TDS water. This is especially the case when inhibitor addition began on water changeout number ten. Even though both methods showed a decrease in copper release with the inhibitor addition, the modified method had a 23 µg/L average copper release and a 0.53 µg/L standard deviation. This is compared

to the original method with a 37 µg/L average copper release and a 6.6 µg/L standard deviation after inhibitor addition. For the low TDS condition, there is statistical difference between the two methods prior to inhibitor addition, where the F-statistic is larger than the $F_{critical}$ value in the single factor ANOVA test presented in Table 2. After inhibitor addition, both methods produced similar copper release results for the low TDS condition, illustrated in Fig. 3, and supported by the single factor ANOVA that produced an F-statistic below the $F_{critical}$ value. A summary of the copper release is illustrated in Fig. 6, including the average and standard deviation for each condition, where it is observed that before inhibitor addition the modified method had less variability for both water conditions as compared to the typical jar test. After inhibitor addition, this trend continues for the high TDS water but not for the low TDS condition, where the standard deviation for the modified method is 1.9 µg/L and for the typical jar test it is 1.2 µg/L.
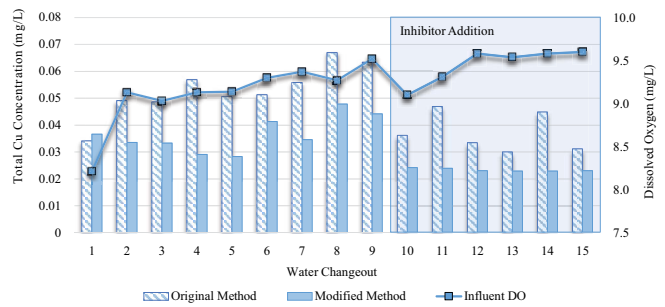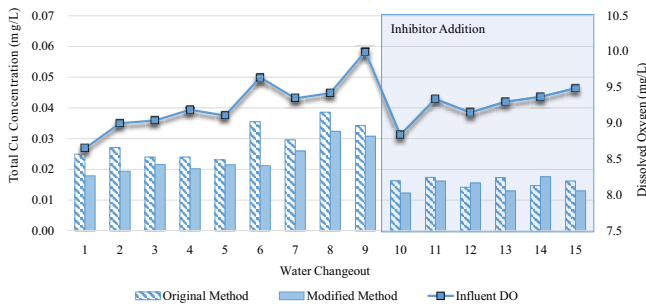

Fig. 3. Results of two-week study evaluating copper release using both the original methods outlined by Cornwell and Wagner [4] and the UCF-modified procedure, for the low total dissolved solids synthetic water condition.
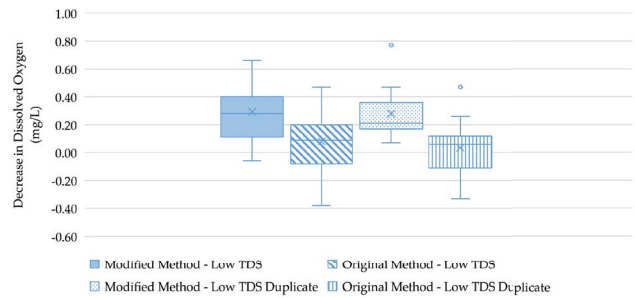
Fig. 5. Decrease in dissolved oxygen levels after exposure period for the low total dissolved solids condition using the modified and original jar test methods. Note, negative value signifies an increase in dissolved oxygen.
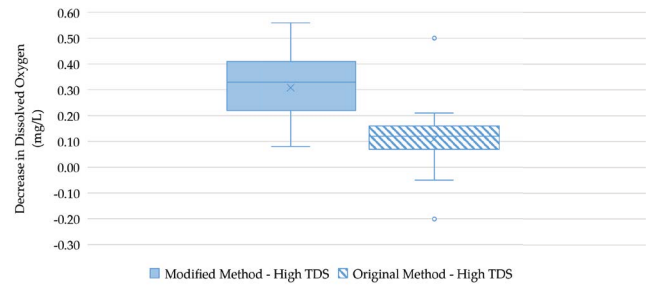

Fig. 4. Decrease in dissolved oxygen levels after exposure period for the high total dissolved solids condition using the modified and original jar test methods. Note, negative value signifies an increase in dissolved oxygen.
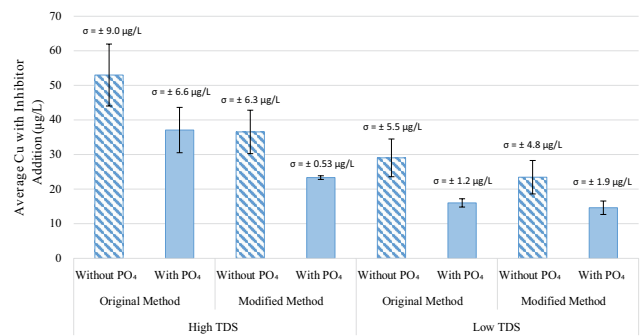
Fig. 6. Summary of average copper release, error bars denote the standard deviation (σ) during this period.

Table 2
Summary of analysis of variance results between the high and low total dissolved solids conditions

Water condition	ANOVA before inhibitor			ANOVA after inhibitor		
	F	P-value	F_{crit}	F	P-value	F_{crit}
High total dissolved solids	18	0.00061	4.5	22	0.00087	5.0
Low total dissolved solids	4.7	0.45	4.5	1.9	0.20	5.0

The results obtained from the modified method showed statistically less variable results than the typical jar method. The most significant difference in the datasets are the results and variability of the metal release with the modified method, especially for the high TDS synthetic water, where little to know variation is observed after inhibitor addition. These results showed promise for data reproducibility using the modified method.

3.2. Blended waters study

The encouraging method comparison test results led to a second phase of lab experiments where actual waters were collected from a local utility's water treatment plant (WTP) and evaluated for corrosivity. Currently the utility treats a brackish water supply using reverse osmosis (RO) and a surficial water supply with partial treatment using cation exchange (CIX) for hardness removal. The surficial water supply also contributes to the final blend with a partial raw bypass. The final blend is pH adjusted with NaOH and disinfected with NaOCl. The three water streams were blended, at the appropriate ratios, to create the "existing" condition for the purposes of this study. In addition, a "projected" condition was made with nanofiltration (NF) permeate from an analogous system and blended with the utility's RO permeate to evaluate and consider the changes to corrosivity if enhanced treatment of the surficial water supply were to be included. The expected enhanced treated surficial groundwater quality is similar to the analogous system's NF permeate. Table 3 summarizes the blends and individual processes examined for this part of the study. For the conditions that include orthophosphate addition, the inhibitor was not introduced until after the sixth water changeout to allow for a period of stabilization.

The results of the blend study for the existing condition and its associated process waters are presented in Fig. 7. The major component contributing to the overall water corrosivity is the raw bypass and to a lesser extent the CIX process water as evidenced by the bars in Fig. 7. The RO permeate did not contribute, to the extent that the raw bypass and CIX waters did, to the overall corrosivity of the blended water and may be, in part, due to the lower sulfate concentration in the permeate than in the surficial

groundwater [11]. During the initial no-inhibitor phase, there is a correlation between the copper release associated with the separate components and the blend. Once the orthophosphate inhibitor is introduced this correlation is not observed, with a drop in the copper release even when, for example, the raw bypass and CIX components increased.

The results for the projected condition, where the RO permeate is blended only with NF permeate, are presented in Fig. 8. The RO permeate rapidly stabilizes and only contributes to the overall corrosivity at a small margin compared to the NF permeate. The addition of the
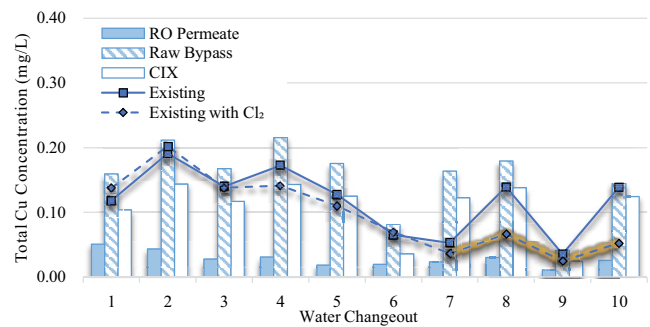
Fig. 7. Results of blend study for existing condition and its corresponding components. Note, the data highlighted in yellow included the addition of the orthophosphate inhibitor.
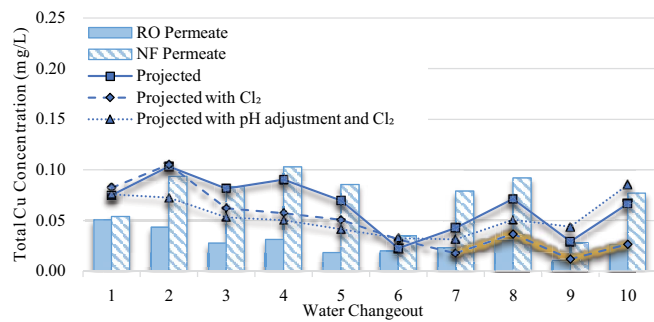
Fig. 8. Results of blend study for projected condition and its corresponding components. Note, the data highlighted in yellow included the addition of the orthophosphate inhibitor.

Table 3
Waters and blend scenarios tested as part of five-week study

Test condition	Chemical dosing	Blend ratio
Raw bypass	None	Not applicable
Cation exchange process water	None	Not applicable
RO permeate	None	Not applicable
NF permeate*	None	Not applicable
Existing blend	None	58% RO permeate
	NaOCl and orthophosphate	21% cation exchange
		21% raw bypass
Projected blend	None	58% RO permeate
	NaOCl and NaOH	42% NF permeate*
	NaOCl and orthophosphate	

*Analogous system NF permeate.

orthophosphate inhibitor with the projected condition helps control the copper release, even at the lower levels observed, as compared to the pH adjustment CCT.

When comparing the different blends and the associated chemical additions, the projected condition has lower copper release than the existing by just over 50%, on average, before and after the inhibitor introduction. As shown in Fig. 8, and further illustrated in Fig. 9, the orthophosphate inhibitor addition controls the copper release even when the blend component concentrations increase. While there is an observed increase in copper release for the components themselves, there is no associated increase from exposure to the blend, with the inhibitor addition. The use of the modified method with the funnels showed consistent and reliable data for the water sources and blends evaluated in this study. A duplicate experiment was conducted for the CIX water, that resulted in a 0.1 relative % difference (RPD), on average, between the ten water changeouts. The RPD values between the sample and duplicate experiment confirms the reliability of this method in reproducing metal release results.

Using the water quality and copper release data obtained during this portion of the study, a linear empirical model was created to fit against the measured metal concentration based on pH, dissolved oxygen (DO), free chlorine (Cl_2), reactive phosphorus (PO_4), alkalinity (ALK), and the chloride-to-sulfate mass ratio (CSMR). The linear empirical model is presented in Eq. (1). 90% of the data was used to create the empirical equation and the resulting 10%, presented in Fig. 10, was used to test the model. The trend between the predicted copper and measured copper release is linearly related with a 0.81 R-squared value and a 0.71 slope.

$$C_{Cu} = 0.233 - 0.0116pH - 0.0107DO + 0.00735Cl_2 \\ - 0.0298PO_4 + 0.000523ALK - 0.00144CSMR \quad (1)$$

Copper release for the second test was also examined and fit using first-order kinetics, like in Eq. (2), for the nine conditions. Presented in Figs. 11 and 12 are the results for the most relevant conditions, the existing (high TDS) and projected (low TDS) conditions with and without chemical addition. The full datasets, including the modeled results for the individual processes are provided in the supplemental material. The blends that include disinfectant and

corrosion inhibitor addition show a better fit than those without. In general, the kinetic models over predict lower copper levels and under predict the higher concentrations, with slopes closer to zero than one in most circumstances.

$$[Cu]_t = [Cu]_0 e^{-kt} \quad (2)$$

The blended water study conducted demonstrates the modified method's applicability in evaluating varying water quality and source conditions effects on copper release. The linear water quality empirical model resulted in a high correlation between the calculated and measured values with a slope of 0.7 for the test data. The various first-order kinetic models did not have great fit characteristics except for the existing with chlorine and the projected with pH
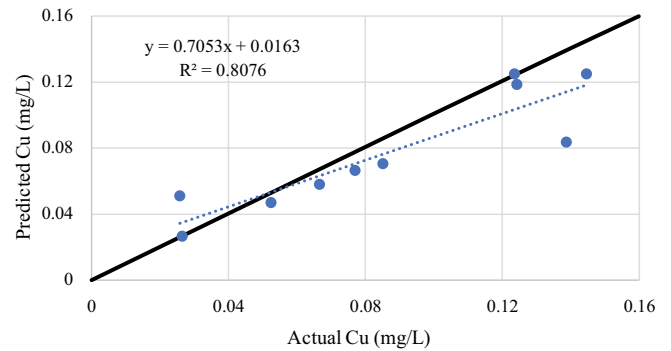
Fig. 10. Predicted vs. actual copper concentrations calculated using Eq. (1) and water quality data from laboratory blend study.
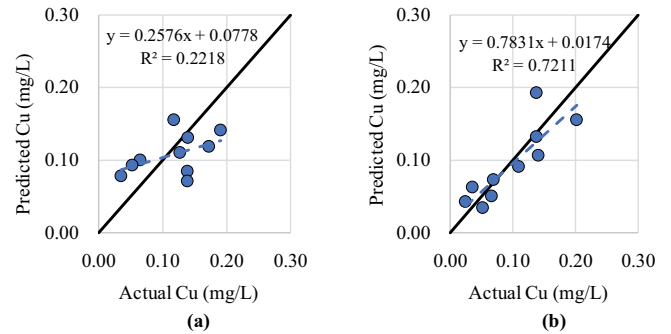
Fig. 11. Predicted Cu release based on first-rate law for (a) existing and (b) existing with chlorine.
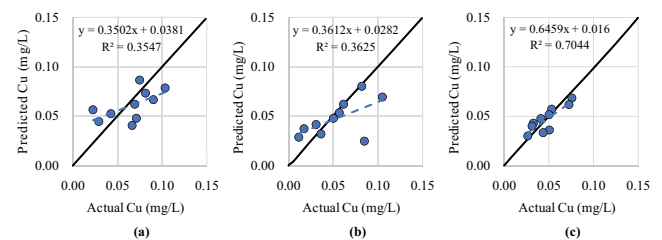
Fig. 12. Predicted Cu release based on first-rate law for (a) projected, (b) projected with chlorine, and (c) projected with pH adjustment and chlorine.

Fig. 9. Results of blend study directly comparing the existing and projected condition. Note, the data highlighted in yellow included the addition of the orthophosphate inhibitor.
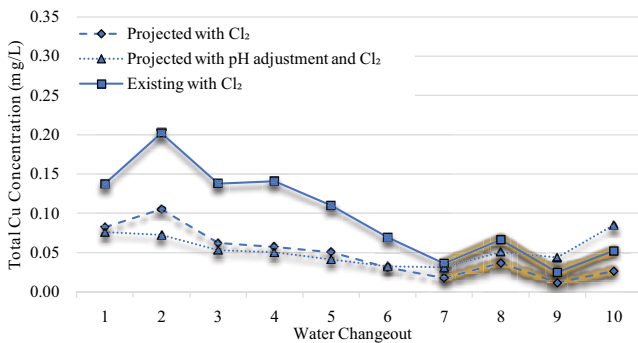
adjustment and chlorine conditions. A second successful corrosion evaluation using this set-up and procedure leads to the following question; how can the UCF-modified method be used for other applications?

3.3. Direct connection study

The first two studies presented herein confirm the modified method's ability to evaluate corrosivity and metal release with exposure to different water quality conditions. This last study was conducted to confirm the method's applicability for corrosion monitoring with direct connections to an existing tap, whether that be at a utility's WTP or elsewhere within the distribution system. Two funnels, for duplicate analysis, were set-up at the utility's WTP, directly connected to a laboratory tap, to monitor copper release over an 11-week period with semi-weekly water changeouts. Between the water changeouts were stagnation periods. The set-up for the direct-connection test is presented in Fig. 13.

Illustrated in Fig. 14 are the average total copper concentrations measured during the direct connection study. Note, the average copper release considers both the sample and its duplicate. The linear model created during the blended waters study, Eq. (1), was fit to the direct-connection results. The empirical model was adjusted to account for a time-dependent variable during the stabilization period, and resulted in significantly better results. The time factor for the beginning stabilization period was found to provide better correlation between the calculated vs. measured concentrations for the first month, with a 0.80 R^2 value and a 0.62 slope, as shown in Fig. 15. Once the field samples reach equilibrium, the copper concentration is no longer significantly time-dependent, for this reason, the initial empirical water quality model was used. However, it over-predicts copper release by a factor of 2.7, on average, which was incorporated into the empirical model and presented in Eq. (4). Fig. 16 illustrates the post-stabilization fit results, with a 0.10 R^2 value. In trying to fit the water quality empirical model to other conditions, poor correlations are observed and confirm the water quality effects are circumstantial and cannot be compared.

$$C_{Cu, \text{stabilization}} = e^{-0.045(t_i - t_0)} \begin{pmatrix} 0.233 - 0.0116\text{pH} - 0.0107\text{DO} \\ +0.00735\text{Cl}_2 - 0.0298\text{PO}_4 \\ +0.000523\text{ALK} - 0.00144\text{CSMR} \end{pmatrix} \quad (3)$$

$$\begin{aligned} C_{Cu, \text{post-stabilization}} = {} & 0.0853 - 0.00425\text{pH} - 0.00391\text{DO} \\ & + 0.00269\text{Cl}_2 - 0.0109\text{PO}_4 \\ & + 0.000192\text{ALK} - 0.000527\text{CSMR} \quad (4) \end{aligned}$$

The first order rate law [Eq. (3)] was also used to depict the time dependency on metal release, where the copper concentration at time, t, is determined by the initial metal content and the exponential of the time and rate law constant, k, product. Two first order rate equations were created, one for the stabilization period and one for the post-stabilization

Fig. 13. Image of set-up during direct-connection test.
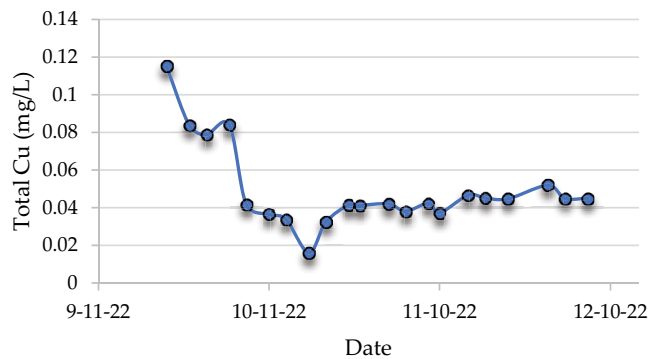
Fig. 14. Total copper release during direct-connection field study, error bars showing duplicate.
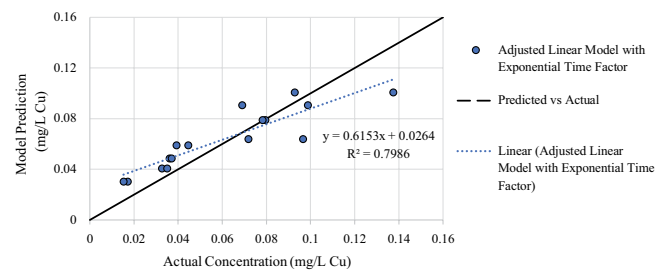
Fig. 15. Modified copper release model predictions vs. actual copper concentrations for stabilization period using Eq. (3).
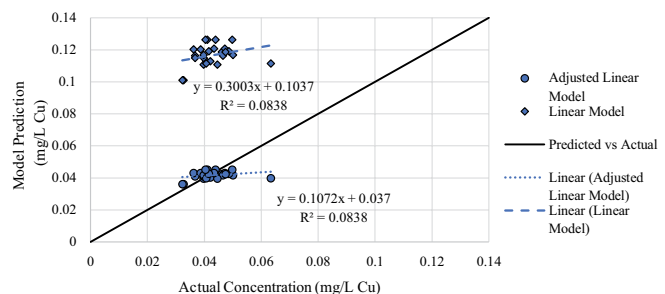
Fig. 16. Modified copper release fit model predictions vs. actual copper concentrations for post-stabilization period using Eq. (4).

period, the linear form for each is presented in Eqs. (5) and (6), respectively. The results for these models are illustrated in Fig. 17.
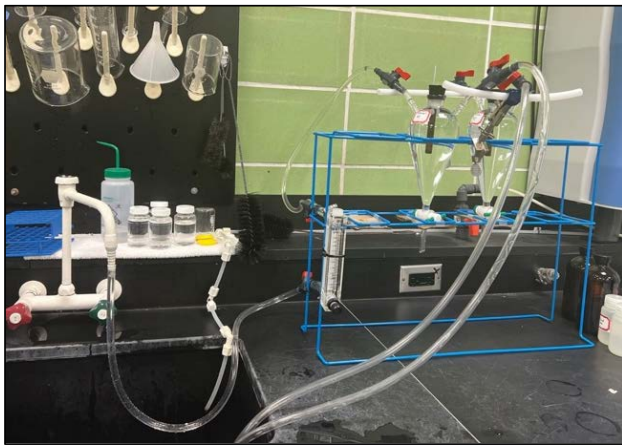
$$\ln\left[Cu\right]_t = -0.0779t - 1.6532 \tag{5}$$

$$\ln\left[Cu\right]_t = 0.0102t - 3.6932 \tag{6}$$
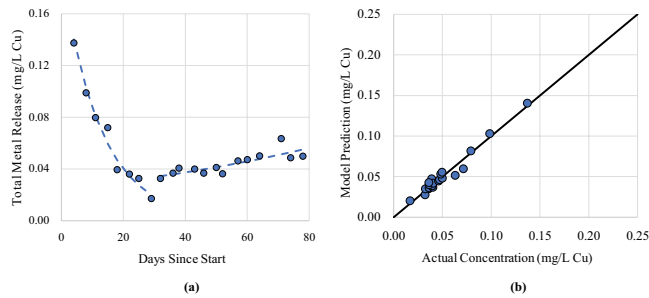
Fig. 17. Total copper release sampled in field test (a) vs. time and (b) model fit predictions vs. actual copper release.

The first-order models were effective in fitting the copper concentrations when using the modified testing method with a direct connection and the specified time period. By setting Eq. (5) equal to Eq. (6), the theoretical equilibrium point can be solved for. The point at which the metal release reaches equilibrium, in this case, is just over 23 d after exposure. Provided in Table 4 is a summary of the predicted vs. measured copper release for the direct-connection study, both for the linear empirical water quality and first-order rate models during stabilization and after. The best performing models when considering the R^2 values and linear fit slopes, between the predicted and measured concentrations, were the first-order equations.

3.4. Test method costs

A test where five conditions are to be evaluated and each is to be conducted in duplicate, 10 funnels are needed. Testing for both lead and copper, Table 5 provides an estimated operating cost and Table 6 an estimated capital cost, for a 12-week evaluation period per metal. The metal analysis in Table 5 considers the total concentration, additional sample costs would need to be included if interested in

Table 4
Summary of fit model results for copper release

Fit model type	Stabilization phase	Equation no.	Predicted: measured R^2	Calculated: measured linear slope
Linear water quality	Stabilization	3	0.80	0.61
	Post-stabilization	4	0.10	0.11
First-order rate law	Stabilization	5	0.98	1.01
	Post-stabilization	6	0.67	0.67

Table 5
Estimated operating cost for assumed testing regime

Item	Quantity	Unit of measure	Unit cost	Subtotal
Tygon® E-food tubing	1	50-foot roll	$243.49	$243.49
Metal coupon (alloy: L55030)	10	10 coupons	$63.50	$635.00
Metal coupon (alloy: CDA260)	10	10 coupons	$8.30	$83.00
Metal analysis	480	1 metal	$15.00	$7,200.00
Estimated total operating cost				$8,161.49

Table 6
Estimated total capital cost for flow-through jar test method

Item	Quantity	Unit of measure	Unit cost	Subtotal
Modified funnel	10	1 funnel	$157.50	$1,575.00
Ball valve	20	1 valve	$26.01	$520.20
Rubber stopper	10	pack of 18	$14.34	$143.40
Coupon holder	10	1 holder	$22.20	$222.00
Funnel rack	3	4-spot rack	$162.00	$486.00
Parafilm	1	1,250 ft roll	$103.00	$103.00
HDPE 4-L container	10	1 container	$84.00	$840.00
Estimated total capital cost				$3,889.60

the dissolved measurement. Note, the chemical addition costs, if any, are not included in these estimates. The estimated total cost for such a screening study is approximately $12,000.

4. Summary of findings and conclusions

Bench-scale coupon studies have their limitations for accurately predicting the conditions in distribution system plumbing. However, jar tests serve as a useful method for identifying possible CCT options and understanding water quality effects on corrosivity in a quick and inexpensive manner. This work's goal was to build upon existing jar test methods to better mimic distribution system conditions, by creating a sealed and zero-headspace environment with an enhanced water replacement strategy. Below are the main conclusions from the work presented herein.

- The UCF-modified method provides statistically less variable copper release, compared to traditional jar tests commonly performed for CCT evaluations. This conclusion is supported by the first study conducted, summarized in Section 3.1 – Method comparison test, that showed generally lower standard deviations in the copper release compared to the typical jar test method. The funnel set-up also resulted in lower copper levels, possibly due to the 15 min flow period.
- The method comparison test, in Section 3.1 – Method comparison test, also presented the difference in dissolved oxygen depletion between the UCF-modified procedure and typical jar tests. As expected, the funnel set-up, that is sealed and with zero-headspace, resulted in increased oxygen depletion, as compared to the jars.
- The blended waters study, presented in Section 3.2 – Blended waters study, showed consistent results between the individual components and the blended waters. The water quality empirical model created was a good fit for the data and could be used to predict results under the same testing and sample conditions.
- The first-order rate models resulted in good fits for the metal release observed during the direct-connection study, reviewed in Section 3.3 – Direct connection study. The empirical water quality model initially created using the blend study results (Section 3.2 – Blended waters study) did not provide a good fit to the data obtained from the direct-connection test. The water quality empirical model is circumstantial and cannot predict metal release in different conditions.
- The proposed method provides utilities with an economical approach for CCT studies, compared to pilot-scale alternatives [1]. The capital and operating estimated cost to evaluate the suggested testing regime is approximately $12,000.

During the direct-connection study, the observed metal release, once stable, was similar to concentrations measured within the utility's distribution system in 2019, which was on average 0.05 mg/L. The direct-connection study results confirm the method's beneficial use as a means for monitoring a utility's finished water corrosivity. This experiment could be conducted at several locations within a distribution system, so long as the feed water is first allowed to flush and is tested for background metals concentrations prior to introduction into the funnel.

It is recommended that a test be conducted for at least 24 water changeouts based on the results presented in Section 3.3 – Direct connection study. Longer evaluation periods can be beneficial to allow for corrosion rate stabilization before introducing changes to the test conditions.

The result of this work provides promising data for the use of this UCF-designed method to evaluate CCT options in a cost-effective manner. There is room for further enhancements of the method, for example, with the addition of an electrode-based analysis for real-time corrosion rates, similar to the set-ups used by Edwards et al. [12]. While the methods described herein do not provide the exact settings observed in distribution systems, it is a step towards mimicking these conditions to a higher extent at the bench-scale. The UCF-modified method is portable, provides a sealed, zero-headspace environment, and is cost-effective as compared to large-scale pipe loop studies that require a higher level of technical expertise, time, and funds.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Supporting information

Table S1
Blend study copper concentrations and results of first-order rate law for each process and blend also includes field test

Sample name	Date	Time from start (d)	Copper (Cu) concentration (mg/L)	Natural Log of Cu concentration	Slope (m)	Intercept (b)	ln(Cu) = mt + b	exp(ln(Cu))
	11/17/22	3.0	0.051	−3.0			−3.2	0.040
	11/21/22	7.0	0.043	−3.1			−3.3	0.036
	11/24/22	10	0.028	−3.6			−3.4	0.033
	11/28/22	14	0.031	−3.5			−3.5	0.030
RO permeate	12/1/22	17	0.018	−4.0	−0.028	−3.1	−3.6	0.027
	12/5/22	21	0.020	−3.9			−3.7	0.024
	12/8/22	24	0.023	−3.8			−3.8	0.022
	12/12/22	28	0.030	−3.5			−3.9	0.020
	12/15/22	31	0.011	−4.5			−4.0	0.019
	12/19/22	35	0.026	−3.7			−4.1	0.017
	11/17/22	3.0	0.054	−2.9			−2.5	0.080
	11/21/22	7.0	0.093	−2.4			−2.6	0.077
	11/24/22	10	0.084	−2.5			−2.6	0.075
	11/28/22	14	0.10	−2.3			−2.6	0.071
NF permeate	12/1/22	17	0.085	−2.5	−0.011	−2.5	−2.7	0.069
	12/5/22	21	0.035	−3.4			−2.7	0.066
	12/8/22	24	0.079	−2.5			−2.7	0.064
	12/12/22	28	0.092	−2.4			−2.8	0.061
	12/15/22	31	0.028	−3.6			−2.8	0.059
	12/19/22	35	0.077	−2.6			−2.9	0.057
	11/17/22	3.0	0.16	−1.8			−1.6	0.203
	11/21/22	7.0	0.21	−1.6			−1.7	0.185
	11/24/22	10	0.17	−1.8			−1.8	0.173
	11/28/22	14	0.22	−1.5			−1.8	0.158
	12/1/22	17	0.18	−1.7			−1.9	0.147
Verna	12/5/22	21	0.081	−2.5	−0.023	−1.5	−2.0	0.134
	12/8/22	24	0.16	−1.8			−2.1	0.126
	12/12/22	28	0.18	−1.7			−2.2	0.115
	12/15/22	31	0.042	−3.2			−2.2	0.107
	12/19/22	35	0.14	−1.9			−2.3	0.098

Table 1 (Continued)

Table S1

Sample name	Date	Time from start (d)	Copper (Cu) concentration (mg/L)	Natural Log of Cu concentration	Slope (m)	Intercept (b)	ln(Cu) = $mt + b$	exp(ln(Cu))
CIX	11/17/22	3.0	0.10	–2.3			–2.0	0.130
	11/21/22	7.0	0.14	–1.9			–2.1	0.120
	11/24/22	10	0.12	–2.1			–2.2	0.113
	11/28/22	14	0.14	–1.9			–2.3	0.104
	12/1/22	17	0.13	–2.1	–0.020	–2.0	–2.3	0.098
	12/5/22	21	0.036	–3.3			–2.4	0.091
	12/8/22	24	0.12	–2.1			–2.5	0.086
	12/12/22	28	0.14	–2.0			–2.5	0.079
	12/15/22	31	0.024	–3.7			–2.6	0.074
	12/19/22	35	0.12	–2.1			–2.7	0.069
CIX-D	11/17/22	3.0	0.093	–2.4			–2.2	0.110
	11/21/22	7.0	0.13	–2.0			–2.3	0.104
	11/24/22	10	0.096	–2.3			–2.3	0.100
	11/28/22	14	0.12	–2.1			–2.4	0.094
	12/1/22	17	0.11	–2.2	–0.014	–2.2	–2.4	0.090
	12/5/22	21	0.035	–3.4			–2.5	0.085
	12/8/22	24	0.12	–2.2			–2.5	0.082
	12/12/22	28	0.14	–2.0			–2.6	0.077
	12/15/22	31	0.026	–3.7			–2.6	0.074
	12/19/22	35	0.12	–2.1			–2.7	0.070
Future	11/17/22	3.0	0.075	–2.6			–2.4	0.087
	11/21/22	7.0	0.10	–2.3			–2.5	0.079
	11/24/22	10	0.082	–2.5			–2.6	0.073
	11/28/22	14	0.090	–2.4			–2.7	0.067
	12/1/22	17	0.069	–2.7	–0.02	–2.4	–2.8	0.062
	12/5/22	21	0.023	–3.8			–2.9	0.056
	12/8/22	24	0.043	–3.2			–2.9	0.053
	12/12/22	28	0.071	–2.6			–3.0	0.048
	12/15/22	31	0.029	–3.5			–3.1	0.044
	12/19/22	35	0.067	–2.7			–3.2	0.040
Future with Cl$_2$	11/17/22	3.0	0.082	–2.5			–2.5	0.080
	11/21/22	7.0	0.105	–2.3			–2.7	0.069
	11/24/22	10	0.062	–2.8			–2.8	0.062
	11/28/22	14	0.057	–2.9			–2.9	0.054
	12/1/22	17	0.051	–3.0	–0.037	–2.4	–3.0	0.048
	12/5/22	21	0.031	–3.5			–3.2	0.041
	12/8/22	24	0.018	–4.0			–3.3	0.037
	12/12/22	28	0.037	–3.3			–3.4	0.032
	12/15/22	31	0.012	–4.4			–3.5	0.029
	12/19/22	35	0.085	–2.5			–3.7	0.025
Future with pH adjustment and Cl$_2$	11/17/22	3.0	0.076	–2.6			–2.7	0.068
	11/21/22	7.0	0.072	–2.6			–2.8	0.062
	11/24/22	10	0.053	–2.9			–2.9	0.057
	11/28/22	14	0.050	–3.0			–3.0	0.051
	12/1/22	17	0.041	–3.2	–0.026	–2.6	–3.0	0.048
	12/5/22	21	0.033	–3.4			–3.1	0.043
	12/8/22	24	0.031	–3.5			–3.2	0.040
	12/12/22	28	0.050	–3.0			–3.3	0.036
	12/15/22	31	0.044	–3.1			–3.4	0.033
	12/19/22	35	0.026	–3.6			–3.5	0.030

Table 1 (Continued)

Table S1

Sample name	Date	Time from start (d)	Copper (Cu) concentration (mg/L)	Natural Log of Cu concentration	Slope (m)	Intercept (b)	$\ln(Cu) = mt + b$	$\exp(\ln(Cu))$
Existing	11/17/22	3.0	0.12	–2.1			–1.9	0.155
	11/21/22	7.0	0.19	–1.7			–2.0	0.141
	11/24/22	10	0.14	–2.0			–2.0	0.131
	11/28/22	14	0.17	–1.8			–2.1	0.119
	12/1/22	17	0.13	–2.1			–2.2	0.110
	12/5/22	21	0.065	–2.7	–0.025	–1.8	–2.3	0.100
	12/8/22	24	0.053	–2.9			–2.4	0.093
	12/12/22	28	0.14	–2.0			–2.5	0.084
	12/15/22	31	0.035	–3.3			–2.5	0.078
	12/19/22	35	0.14	–2.0			–2.6	0.071
Existing with Cl_2	11/17/22	3.0	0.14	–2.0			–1.6	0.193
	11/21/22	7.0	0.20	–1.6			–1.9	0.155
	11/24/22	10	0.14	–2.0			–2.0	0.132
	11/28/22	14	0.14	–2.0			–2.2	0.107
	12/1/22	17	0.11	–2.2	–0.054	–1.5	–2.4	0.091
	12/5/22	21	0.069	–2.7			–2.6	0.073
	12/8/22	24	0.036	–3.3			–2.8	0.062
	12/12/22	28	0.066	–2.7			–3.0	0.050
	12/15/22	31	0.025	–3.7			–3.2	0.043
	12/19/22	35	0.052	–2.9			–3.4	0.034
Field test	9/23/22	4.0	0.14	–2.0			–2.0	0.140
	9/27/22	8.0	0.099	–2.3			–2.3	0.103
	9/30/22	11	0.080	–2.5			–2.5	0.081
	10/4/22	15	0.072	–2.6	–0.078	–1.7	–2.8	0.060
	10/7/22	18	0.039	–3.2			–3.1	0.047
	10/11/22	22	0.036	–3.3			–3.4	0.034
	10/14/22	25	0.033	–3.4			–3.6	0.027
	10/18/22	29	0.017	–4.1			–3.9	0.020
	10/21/22	32	0.033	–3.4			–3.4	0.034
	10/25/22	36	0.037	–3.3			–3.3	0.036
	10/27/22	38	0.041	–3.2			–3.3	0.037
	11/1/22	43	0.040	–3.2			–3.3	0.039
	11/4/22	46	0.037	–3.3			–3.2	0.040
	11/8/22	50	0.041	–3.2			–3.2	0.041
	11/10/22	52	0.036	–3.3	0.010	–3.7	–3.2	0.042
	11/15/22	57	0.046	–3.1			–3.1	0.045
	11/18/22	60	0.047	–3.1			–3.1	0.046
	11/22/22	64	0.050	–3.0			–3.0	0.048
	11/29/22	71	0.063	–2.8			–3.0	0.051
	12/2/22	74	0.049	–3.0			–2.9	0.053
	12/6/22	78	0.050	–3.0			–2.9	0.055

Table S2
Feed water quality measured during method comparison test

Sample name	Date	Time from start (d)	pH (s.u.)	Tem-perature (°C)	DO (mg/L)	Cl_2 (mg/L)	PO_4 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Dissolved metal (mg/L)	Suspended metal (mg/L)	Total metal (mg/L)
	8/16/22	1.0	8.05	22.2	8.21	1.90	N/A	68.8	0.243	0.032	0.002	0.034
	8/17/22	2.0	7.92	19.2	9.13	2.03	N/A	71.3	0.219	0.045	0.004	0.049
	8/18/22	3.0	7.89	20.8	9.03	2.14	N/A	71.3	0.221	0.044	0.005	0.049
	8/19/22	4.0	7.98	21.2	9.13	2.07	N/A	73.8	0.220	0.053	0.003	0.057
	8/20/22	5.0	7.97	20.1	9.14	1.86	N/A	71.3	0.215	0.046	0.005	0.051
	8/21/22	6.0	8.03	22.5	9.30	2.17	N/A	71.3	0.220	0.047	0.005	0.051
Existing original method	8/22/22	7.0	8.01	22.7	9.37	2.10	N/A	72.5	0.220	0.051	0.005	0.056
	8/23/22	8.0	8.06	24.1	9.27	2.09	N/A	68.8	0.220	0.059	0.008	0.067
	8/24/22	9.0	8.05	20.3	9.52	2.13	N/A	71.3	0.219	0.058	0.005	0.063
	8/25/22	10	8.00	21.3	9.10	2.08	1.37	66.3	0.219	0.033	0.003	0.036
	8/26/22	11	8.05	21.9	9.31	1.93	1.66	71.3	0.219	0.032	0.015	0.047
	8/27/22	12	8.03	20.6	9.58	1.98	1.60	71.3	0.219	0.030	0.003	0.033
	8/28/22	13	8.04	21.4	9.54	1.97	1.66	73.8	0.219	0.027	0.003	0.030
	8/29/22	14	8.00	20.7	9.58	2.02	1.58	70.0	0.219	0.042	0.003	0.045
	8/30/22	15	7.98	20.8	9.60	2.04	1.57	72.5	0.219	0.029	0.003	0.031
	8/16/22	1.0	7.84	23.0	8.65	2.01	N/A	27.5	6.51	0.023	0.002	0.025
	8/17/22	2.0	7.57	19.0	9.00	2.09	N/A	27.5	5.44	0.025	0.002	0.027
	8/18/22	3.0	7.93	20.3	9.04	2.09	N/A	27.5	5.15	0.021	0.003	0.024
	8/19/22	4.0	7.98	20.7	9.19	2.12	N/A	28.8	5.78	0.020	0.004	0.024
	8/20/22	5.0	7.99	18.7	9.11	1.89	N/A	28.8	5.69	0.020	0.003	0.023
	8/21/22	6.0	8.08	21.3	9.64	1.98	N/A	28.8	5.79	0.023	0.012	0.036
Future original method	8/22/22	7.0	7.95	21.5	9.35	1.81	N/A	30.0	5.72	0.027	0.002	0.030
	8/23/22	8.0	8.03	21.3	9.42	2.03	N/A	28.8	6.04	0.035	0.003	0.039
	8/24/22	9.0	8.06	20.3	10.00	2.14	N/A	28.8	5.87	0.032	0.003	0.034
	8/25/22	10	8.07	20.8	8.84	2.00	1.35	28.8	5.77	0.014	0.002	0.016
	8/26/22	11	8.12	21.3	9.34	2.10	1.64	28.8	5.82	0.015	0.002	0.017
	8/27/22	12	8.12	20.6	9.15	1.98	1.61	30.0	5.86	0.012	0.002	0.014
	8/28/22	13	8.12	21.3	9.30	2.02	1.64	28.8	5.87	0.012	0.005	0.017
	8/29/22	14	8.05	20.5	9.37	1.96	1.60	27.5	5.92	0.013	0.002	0.015
	8/30/22	15	8.00	20.3	9.49	2.05	1.66	30.0	5.91	0.014	0.002	0.016
	8/16/22	1.0	7.88	22.5	8.58	1.96	N/A	28.8	5.83	0.030	0.003	0.033
	8/17/22	2.0	7.96	19.1	8.75	1.90	N/A	27.5	5.72	0.018	0.002	0.019
	8/18/22	3.0	8.03	21.1	8.95	2.12	N/A	28.8	5.82	0.018	0.003	0.020
	8/19/22	4.0	8.02	20.7	9.21	2.12	N/A	28.8	5.79	0.014	0.003	0.018
	8/20/22	5.0	8.06	19.4	9.46	2.07	N/A	28.8	5.84	0.021	0.004	0.024
	8/21/22	6.0	8.09	20.5	9.66	2.05	N/A	28.8	5.86	0.022	0.002	0.025
Future duplicate original method	8/22/22	7.0	8.05	22.1	9.35	2.09	N/A	30.0	5.95	0.027	0.002	0.029
	8/23/22	8.0	7.95	20.8	9.23	1.87	N/A	28.8	6.41	0.034	0.003	0.037
	8/24/22	9.0	8.05	21.0	9.89	2.13	N/A	28.8	5.90	0.035	0.004	0.039
	8/25/22	10	8.07	20.8	8.93	2.08	1.36	30.0	5.85	0.014	0.002	0.016
	8/26/22	11	8.13	21.4	9.25	2.00	1.58	27.5	5.89	0.015	0.003	0.018
	8/27/22	12	8.12	20.7	9.24	2.08	1.60	27.5	5.90	0.014	0.001	0.015
	8/28/22	13	8.13	21.6	9.36	2.04	1.58	30.0	5.90	0.012	0.004	0.016
	8/29/22	14	8.04	20.2	9.47	2.01	1.57	28.8	5.82	0.012	0.002	0.014
	8/30/22	15	8.04	20.1	9.74	2.03	1.59	28.8	5.84	0.015	0.003	0.019

Table 2 (Continued)

Table S2

Sample name	Date	Time from start (d)	pH (s.u.)	Temperature (°C)	DO (mg/L)	Cl_2 (mg/L)	PO_4 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Dissolved metal (mg/L)	Suspended metal (mg/L)	Total metal (mg/L)
	8/16/22	1.0	8.05	22.2	8.21	1.90	N/A	68.8	0.243	0.033	0.004	0.037
	8/17/22	2.0	7.92	19.2	9.13	2.03	N/A	71.3	0.219	0.031	0.002	0.034
	8/18/22	3.0	7.89	20.8	9.03	2.14	N/A	71.3	0.221	0.030	0.003	0.033
	8/19/22	4.0	7.98	21.2	9.13	2.07	N/A	73.8	0.220	0.026	0.003	0.029
	8/20/22	5.0	7.97	20.1	9.14	1.86	N/A	71.3	0.215	0.025	0.003	0.028
	8/21/22	6.0	8.03	22.5	9.30	2.17	N/A	71.3	0.220	0.038	0.003	0.041
Existing	8/22/22	7.0	8.01	22.7	9.37	2.10	N/A	72.5	0.220	0.032	0.003	0.035
modified	8/23/22	8.0	8.06	24.1	9.27	2.09	N/A	68.8	0.220	0.045	0.003	0.048
method	8/24/22	9.0	8.05	20.3	9.52	2.13	N/A	71.3	0.219	0.040	0.004	0.044
	8/25/22	10	8.00	21.3	9.10	2.08	1.37	66.3	0.219	0.022	0.002	0.024
	8/26/22	11	8.05	21.9	9.31	1.93	1.66	71.3	0.219	0.022	0.002	0.024
	8/27/22	12	8.03	20.6	9.58	1.98	1.60	71.3	0.219	0.021	0.002	0.023
	8/28/22	13	8.04	21.4	9.54	1.97	1.66	73.8	0.219	0.020	0.003	0.023
	8/29/22	14	8.00	20.7	9.58	2.02	1.58	70.0	0.219	0.021	0.002	0.023
	8/30/22	15	7.98	20.8	9.60	2.04	1.57	72.5	0.219	0.021	0.002	0.023
	8/16/22	1.0	7.84	23.0	8.65	2.01	N/A	27.5	6.51	0.017	0.001	0.018
	8/17/22	2.0	7.57	19.0	9.00	2.09	N/A	27.5	5.44	0.018	0.002	0.019
	8/18/22	3.0	7.93	20.3	9.04	2.09	N/A	27.5	5.15	0.017	0.005	0.022
	8/19/22	4.0	7.98	20.7	9.19	2.12	N/A	28.8	5.78	0.017	0.003	0.020
	8/20/22	5.0	7.99	18.7	9.11	1.89	N/A	28.8	5.69	0.017	0.005	0.022
	8/21/22	6.0	8.08	21.3	9.64	1.98	N/A	28.8	5.79	0.019	0.002	0.021
Future	8/22/22	7.0	7.95	21.5	9.35	1.81	N/A	30.0	5.72	0.023	0.003	0.026
modified	8/23/22	8.0	8.03	21.3	9.42	2.03	N/A	28.8	6.04	0.030	0.002	0.032
method	8/24/22	9.0	8.06	20.3	10.00	2.14	N/A	28.8	5.87	0.028	0.003	0.031
	8/25/22	10	8.07	20.8	8.84	2.00	1.35	28.8	5.77	0.011	0.001	0.012
	8/26/22	11	8.12	21.3	9.34	2.10	1.64	28.8	5.82	0.014	0.002	0.016
	8/27/22	12	8.12	20.6	9.15	1.98	1.61	30.0	5.86	0.014	0.002	0.016
	8/28/22	13	8.12	21.3	9.30	2.02	1.64	28.8	5.87	0.011	0.002	0.013
	8/29/22	14	8.05	20.5	9.37	1.96	1.60	27.5	5.92	0.008	0.009	0.018
	8/30/22	15	8.00	20.3	9.49	2.05	1.66	30.0	5.91	0.012	0.001	0.013
	8/16/22	1.0	7.88	22.5	8.58	1.96	N/A	28.8	5.83	0.020	0.005	0.024
	8/17/22	2.0	7.96	19.1	8.75	1.90	N/A	27.5	5.72	0.018	0.002	0.019
	8/18/22	3.0	8.03	21.1	8.95	2.12	N/A	28.8	5.82	0.017	0.002	0.019
	8/19/22	4.0	8.02	20.7	9.21	2.12	N/A	28.8	5.79	0.017	0.002	0.018
	8/20/22	5.0	8.06	19.4	9.46	2.07	N/A	28.8	5.84	0.018	0.003	0.021
	8/21/22	6.0	8.09	20.5	9.66	2.05	N/A	28.8	5.86	0.020	0.003	0.023
Future	8/22/22	7.0	8.05	22.1	9.35	2.09	N/A	30.0	5.95	0.022	0.002	0.024
duplicate	8/23/22	8.0	7.95	20.8	9.23	1.87	N/A	28.8	6.41	0.028	0.002	0.030
modified	8/24/22	9.0	8.05	21.0	9.89	2.13	N/A	28.8	5.90	0.026	0.003	0.029
method	8/25/22	10	8.07	20.8	8.93	2.08	1.36	30.0	5.85	0.010	0.002	0.012
	8/26/22	11	8.13	21.4	9.25	2.00	1.58	27.5	5.89	0.010	0.007	0.017
	8/27/22	12	8.12	20.7	9.24	2.08	1.60	27.5	5.90	0.009	0.001	0.010
	8/28/22	13	8.13	21.6	9.36	2.04	1.58	30.0	5.90	0.009	0.001	0.010
	8/29/22	14	8.04	20.2	9.47	2.01	1.57	28.8	5.82	0.011	0.002	0.012
	8/30/22	15	8.04	20.1	9.74	2.03	1.59	28.8	5.84	0.008	0.001	0.010

Table S3
Feed water quality for field test

Sample name	Date	Time from start (d)	pH (s.u.)	Temperature (°C)	DO (mg/L)	Cl_2 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Total metal (mg/L)	Total metal duplicate (mg/L)
	9/23/22	4.0	7.88	25.4	7.41	2.08	80.0		0.190	0.137	0.093
	9/27/22	8.0	8.04	27.7	6.4	1.98	73.8		0.271	0.099	0.069
	9/30/22	11	8.06	27.3	6.51	1.98	73.8		0.206	0.080	0.078
	10/4/22	15	8.04	26.6	6.97	1.93	73.8		0.178	0.072	0.097
	10/7/22	18	8.06	26.8	6.39	1.9	73.8		0.209	0.039	0.045
	10/11/22	22	8.05	27.3	6.64	1.91	73.8		0.234	0.036	0.037
	10/14/22	25	8.03	27.3	7.3	1.93	73.8		0.243	0.033	0.035
	10/18/22	29	8.04	27.0	8.53	1.89	73.8		0.281	0.017	0.015
	10/21/22	32	7.96	26.0	8.79	1.72	71.3		0.219	0.033	0.032
	10/25/22	36	8.06	24.5	7.35	1.87	73.8		0.207	0.037	0.046
Field	10/27/22	38	8.04	25.9	7.69	1.84	73.8		0.175	0.041	0.042
	11/1/22	43	8.03	27.1	8.02	2.03	73.8		0.164	0.040	0.045
	11/4/22	46	7.93	26.1	7.55	1.75	71.3		0.189	0.037	0.040
	11/8/22	50	8.05	26.7	6.4	1.84	73.8		0.201	0.041	0.044
	11/10/22	52	8.04	26.8	6.97	1.82	73.8		0.185	0.036	0.039
	11/15/22	57	8.06	25.8	7.17	1.91	73.8		0.211	0.046	0.047
	11/18/22	60	8.07	26.5	6.92	1.85	73.8		0.201	0.047	0.043
	11/22/22	64	8.09	24.6	–	1.82	72.5		0.240	0.050	0.040
	11/29/22	71	7.96	24.2	7.85	1.76	73.8		0.192	0.063	0.041
	12/2/22	74	8.07	26.4	7.2	2.05	73.8		0.236	0.049	0.042
	12/6/22	78	7.99	26.1	6.53	1.91	73.8		0.208	0.050	0.040

Table S4
Feed water quality measured during blend water tests

Sample name	Date	Time from start (d)	pH (s.u.)	Temperature (°C)	DO (mg/L)	Cl_2 (mg/L)	PO_4 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Dissolved metal (mg/L)	Suspended metal (mg/L)	Total metal (mg/L)
	11/17/22	3.0	7.01	19.9	9.52	N/A	N/A	10.0	5.27	0.049	0.002	0.051
	11/21/22	7.0	6.88	18.7	9.80	N/A	N/A	9.38	4.44	0.042	0.001	0.043
	11/24/22	10	6.77	21.1	8.84	N/A	N/A	9.38	4.44	0.026	0.001	0.028
	11/28/22	14	7.19	20.6	8.94	N/A	N/A	8.75	4.44	0.029	0.002	0.031
RO permeate	12/1/22	17	7.07	21.8	8.85	N/A	N/A	9.38	4.21	0.017	0.002	0.018
	12/5/22	21	6.80	21.5	9.42	N/A	N/A	9.38	4.44	0.018	0.002	0.020
	12/8/22	24	6.70	21.6	9.37	N/A	N/A	9.38	3.57	0.021	0.002	0.023
	12/12/22	28	6.92	21.7	8.75	N/A	N/A	9.38	5.00	0.029	0.001	0.030
	12/15/22	31	6.90	21.5	9.06	N/A	N/A	9.38	4.45	0.009	0.002	0.011
	12/19/22	35	6.82	21.7	9.54	N/A	N/A	9.38	4.16	0.024	0.002	0.026
	11/17/22	3.0	8.09	20.2	8.77	N/A	N/A	71.3	15.9	0.041	0.012	0.054
	11/21/22	7.0	7.88	18.5	9.50	N/A	N/A	74.4	13.6	0.080	0.013	0.093
	11/24/22	10	7.92	20.9	9.19	N/A	N/A	74.4	13.6	0.070	0.014	0.084
	11/28/22	14	7.99	20.6	9.66	N/A	N/A	77.5	13.6	0.089	0.014	0.103
NF permeate	12/1/22	17	8.00	21.8	9.76	N/A	N/A	74.4	16.1	0.073	0.013	0.085
	12/5/22	21	7.76	21.8	9.27	N/A	N/A	74.4	13.6	0.022	0.013	0.035
	12/8/22	24	8.06	21.7	8.76	N/A	N/A	74.4	17.2	0.068	0.011	0.079
	12/12/22	28	8.03	21.7	9.30	N/A	N/A	74.4	15.9	0.081	0.011	0.092
	12/15/22	31	8.00	21.7	9.52	N/A	N/A	74.4	8.13	0.018	0.009	0.028
	12/19/22	35	8.00	21.8	9.45	N/A	N/A	74.4	8.12	0.069	0.008	0.077

Table 4 (Continued)

Table S4

Sample name	Date	Time from start (d)	pH (s.u.)	Temperature (°C)	DO (mg/L)	Cl_2 (mg/L)	PO_4 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Dissolved metal (mg/L)	Suspended metal (mg/L)	Total metal (mg/L)
	11/17/22	3.0	7.07	20.5	7.38	N/A	N/A	156	0.0375	0.157	0.002	0.159
	11/21/22	7.0	7.67	19.1	9.04	N/A	N/A	156	0.0552	0.208	0.003	0.212
	11/24/22	10	7.82	21.0	9.30	N/A	N/A	156	0.0552	0.164	0.003	0.168
	11/28/22	14	7.93	21.0	7.33	N/A	N/A	156	0.0552	0.212	0.003	0.215
Verna	12/1/22	17	7.82	21.6	8.70	N/A	N/A	156	0.0563	0.173	0.002	0.175
raw	12/5/22	21	7.82	21.7	9.40	N/A	N/A	156	0.0552	0.077	0.004	0.081
	12/8/22	24	7.88	21.5	9.58	N/A	N/A	156	0.0625	0.161	0.003	0.164
	12/12/22	28	7.98	21.5	10.31	N/A	N/A	156	0.0521	0.177	0.002	0.179
	12/15/22	31	7.89	21.7	8.98	N/A	N/A	156	0.0606	0.040	0.001	0.042
	12/19/22	35	7.83	21.9	9.25	N/A	N/A	156	0.0622	0.142	0.003	0.145
	11/17/22	3.0	7.93	19.7	8.57	N/A	N/A	156	0.0426	0.103	0.001	0.104
	11/21/22	7.0	7.87	19.0	9.18	N/A	N/A	158	0.0463	0.142	0.001	0.144
	11/24/22	10	8.01	21.1	9.35	N/A	N/A	158	0.0463	0.116	0.002	0.117
	11/28/22	14	8.05	20.7	8.12	N/A	N/A	161	0.0463	0.140	0.002	0.143
CIX	12/1/22	17	8.13	21.9	8.83	N/A	N/A	158	0.0440	0.124	0.001	0.125
	12/5/22	21	8.11	21.6	9.29	N/A	N/A	158	0.0463	0.034	0.002	0.036
	12/8/22	24	8.16	21.7	9.25	N/A	N/A	158	0.0432	0.121	0.001	0.123
	12/12/22	28	8.21	21.7	9.45	N/A	N/A	158	0.0445	0.136	0.002	0.138
	12/15/22	31	8.24	21.7	9.46	N/A	N/A	158	0.0515	0.023	0.001	0.024
	12/19/22	35	8.27	21.8	9.48	N/A	N/A	158	0.0521	0.123	0.002	0.124
	11/17/22	3.0	7.91	20.3	8.35	N/A	N/A	156	0.0428	0.092	0.001	0.093
	11/21/22	7.0	7.89	19.8	9.04	N/A	N/A	158	0.0470	0.131	0.002	0.134
	11/24/22	10	8.02	22.4	8.87	N/A	N/A	158	0.0470	0.095	0.002	0.096
	11/28/22	14	8.10	20.5	8.35	N/A	N/A	161	0.0470	0.118	0.003	0.120
CIX	12/1/22	17	8.13	21.6	8.81	N/A	N/A	158	0.0439	0.107	0.002	0.109
duplicate	12/5/22	21	8.12	21.5	8.99	N/A	N/A	158	0.0470	0.032	0.003	0.035
	12/8/22	24	8.17	21.6	9.20	N/A	N/A	158	0.0488	0.114	0.002	0.116
	12/12/22	28	8.23	21.7	9.25	N/A	N/A	158	0.0430	0.137	0.002	0.139
	12/15/22	31	8.27	21.7	9.16	N/A	N/A	158	0.0511	0.024	0.002	0.026
	12/19/22	35	8.27	22.0	8.88	N/A	N/A	158	0.0523	0.121	0.002	0.124
	11/17/22	3.0	7.68	20.7	8.82	N/A	N/A	75.0	0.127	0.116	0.002	0.118
	11/21/22	7.0	7.65	19.0	9.24	N/A	N/A	75.0	0.141	0.189	0.002	0.191
	11/24/22	10	7.75	21.9	9.00	N/A	N/A	75.0	0.141	0.138	0.002	0.140
	11/28/22	14	7.81	20.6	8.55	N/A	N/A	75.0	0.141	0.169	0.003	0.173
Existing	12/1/22	17	7.87	21.6	8.75	N/A	N/A	75.0	0.140	0.124	0.003	0.127
blend	12/5/22	21	7.83	21.7	9.24	N/A	N/A	75.0	0.141	0.061	0.004	0.065
	12/8/22	24	7.86	21.6	9.42	N/A	N/A	75.0	0.137	0.050	0.003	0.053
	12/12/22	28	7.97	21.9	9.50	N/A	N/A	75.0	0.144	0.136	0.003	0.139
	12/15/22	31	7.88	21.7	9.08	N/A	N/A	75.0	0.149	0.033	0.002	0.035
	12/19/22	35	7.84	21.8	9.13	N/A	N/A	75.0	0.151	0.136	0.003	0.139
	11/17/22	3.0	7.76	20.7	8.96	1.52	N/A	73.8	0.158	0.135	0.002	0.138
	11/21/22	7.0	7.79	19.8	9.41	2.44	N/A	75.0	0.174	0.200	0.002	0.202
	11/24/22	10	7.86	21.4	8.70	2.15	N/A	75.0	0.174	0.136	0.002	0.138
Existing	11/28/22	14	7.92	20.4	8.28	2.16	N/A	76.3	0.174	0.139	0.002	0.141
blend	12/1/22	17	8.05	21.8	8.71	2.46	N/A	75.0	0.174	0.104	0.006	0.110
with	12/5/22	21	7.96	21.7	9.17	2.19	N/A	75.0	0.174	0.063	0.006	0.069
chlorine	12/8/22	24	7.97	21.6	9.61	2.03	1.55	75.0	0.183	0.034	0.002	0.036
	12/12/22	28	8.05	21.8	9.41	1.64	1.60	75.0	0.169	0.065	0.002	0.066
	12/15/22	31	7.99	21.6	8.98	1.89	1.59	75.0	0.183	0.017	0.007	0.025
	12/19/22	35	8.05	21.6	9.06	2.16	1.70	75.0	0.179	0.051	0.001	0.052

Table 4 (Continued)

Table S4

Sample name	Date	Time from start (d)	pH (s.u.)	Temperature (°C)	DO (mg/L)	Cl_2 (mg/L)	PO_4 (mg/L)	Alkalinity (mg/L $CaCO_3$)	CSMR	Dissolved metal (mg/L)	Suspended metal (mg/L)	Total metal (mg/L)
	11/17/22	3.0	7.69	20.6	9.18	N/A	N/A	37.5	7.13	0.065	0.010	0.075
	11/21/22	7.0	7.54	20.1	9.35	N/A	N/A	37.5	5.77	0.093	0.010	0.103
	11/24/22	10	7.54	21.7	8.99	N/A	N/A	37.5	5.77	0.072	0.009	0.082
	11/28/22	14	7.74	20.6	9.35	N/A	N/A	37.5	5.77	0.080	0.010	0.090
Future	12/1/22	17	7.74	21.8	9.12	N/A	N/A	37.5	5.62	0.060	0.010	0.069
blend	12/5/22	21	7.60	22.0	9.16	N/A	N/A	37.5	5.77	0.013	0.010	0.023
	12/8/22	24	7.66	21.8	9.54	N/A	N/A	37.5	4.53	0.034	0.009	0.043
	12/12/22	28	7.75	21.8	8.90	N/A	N/A	37.5	6.60	0.064	0.007	0.071
	12/15/22	31	7.71	21.7	9.08	N/A	N/A	37.5	5.44	0.023	0.006	0.029
	12/19/22	35	7.67	21.8	9.18	N/A	N/A	37.5	5.28	0.061	0.006	0.067
	11/17/22	3.0	7.85	21.0	8.80	1.06	N/A	37.5	7.57	0.071	0.011	0.082
	11/21/22	7.0	7.82	20.5	8.88	3.44	N/A	36.9	7.79	0.088	0.018	0.105
	11/24/22	10	7.84	19.5	8.79	2.11	N/A	36.9	7.79	0.051	0.011	0.062
Future	11/28/22	14	7.98	19.7	8.95	1.89	N/A	36.2	7.79	0.050	0.007	0.057
blend	12/1/22	17	7.92	21.9	8.91	2.34	N/A	36.9	7.66	0.041	0.009	0.051
with	12/5/22	21	7.87	21.9	8.77	2.00	N/A	36.9	7.79	0.022	0.009	0.031
chlorine	12/8/22	24	7.89	21.6	9.22	1.86	1.57	36.9	8.83	0.010	0.008	0.018
	12/12/22	28	7.98	21.8	8.88	1.42	1.54	36.9	8.17	0.031	0.006	0.037
	12/15/22	31	8.01	21.7	8.83	1.94	1.60	36.9	7.82	0.007	0.005	0.012
	12/19/22	35	8.05	21.6	8.55	2.06	1.56	36.9	6.71	0.022	0.005	0.026
	11/17/22	3.0	7.98	21.1	8.82	1.10	N/A	38.8	7.99	0.064	0.012	0.076
	11/21/22	7.0	7.99	19.8	9.21	3.34	N/A	39.4	7.35	0.062	0.011	0.072
Future	11/24/22	10	8.06	19.6	9.17	2.19	N/A	39.4	7.35	0.044	0.009	0.053
blend	11/28/22	14	8.10	20.3	9.27	1.83	N/A	40.0	7.35	0.043	0.007	0.050
with pH	12/1/22	17	8.09	21.9	9.08	2.40	N/A	39.4	7.78	0.032	0.009	0.041
adjust-	12/5/22	21	8.09	21.9	8.58	2.00	N/A	39.4	7.35	0.023	0.009	0.033
ment and	12/8/22	24	8.10	21.7	9.30	1.87	N/A	39.4	6.19	0.022	0.010	0.031
chlorine	12/12/22	28	8.08	21.6	8.94	1.51	N/A	39.4	8.12	0.043	0.007	0.050
	12/15/22	31	8.16	21.7	9.10	1.89	N/A	39.4	7.23	0.036	0.008	0.044
	12/19/22	35	8.00	21.7	9.16	2.36	N/A	39.4	6.77	0.078	0.007	0.085