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Investigating iron release in distribution systems with blend variations of source waters and phosphate inhibitors

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ABSTRACT

The impact of phosphate-based inhibitors and pH adjustment on iron release in distribution systems was examined. Iron release was sensitive to water quality variations (alkalinity and chloride) associated with blending finished water (surface, ground, and desalinated). Finished waters with high alkalinity content (between 151 and 163 mg/L as $CaCO_3$) consistently mitigated iron release regardless of inhibitor use. Dissolved iron constituted about 10% of total iron release. An empirical model was developed that related water quality, inhibitor type, and dose to iron release. Blended orthophosphate (BOP) minimized total iron release followed closely by increasing pH (between 7.9 and 8.1), while orthophosphate (OP) dose did not affect iron release.

Keywords: Corrosion; Iron; Phosphate; Distribution systems; Source blending; Modeling

1. Introduction and background

Tampa Bay Water (TBW) manages drinking water resources for six member governments on the west coast of central Florida. In order to meet drinking water demands, TBW has developed regional surface water and desalinated supplies which will offset the reductions in groundwater (GW) use. To seek understanding of the issues involved when multiple-source waters are blended, TBW and University of Central Florida (UCF) conducted research regarding the effect of variable finished water quality on distribution system water quality. The capacities of corrosion inhibitors to control these effects, including metal release, were investigated. This paper examines the impact of blended orthopolyphosphate (BOP) inhibitor on iron release in water distribution systems, and compares it to the performance of orthophosphate (OP) and pH adjustments in a changing water quality environment. These corrosion control strategies were evaluated based on an empirical model developed to predict iron concentrations for varying inhibitor dose and water quality conditions.

Iron release is the transport of iron from the metal surface and corrosion scales to the bulk water in either particulate or soluble form due to oxidation of iron pipe surface. The release of iron in water distribution system can be the result of metal pipe corrosion (Fe ions release), dissolution of corrosion scale components (scale release), or hydraulic scouring action of flowing water (particulate release) [1]. These different sources of iron in water distribution systems have unique mechanisms, and may require different mitigation strategies. Ferrous ions (Fe(II)) produced by the corrosion of metal iron either dissolve in the water or form scales on the metal surface, which can also dissolve into the bulk water. The ferrous ions (Fe(II)) may be oxidized into ferric ions (Fe(III)) forming particles

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because of their low solubility and contribute to turbidity and color (red water), which may exceed the secondary iron standard of 0.3 mg/L [2].

The role of polyphosphate as an inhibitor was cited in numerous studies, many of which concluded that polyphosphate could prevent corrosion [3]. However, different theories were presented for the polyphosphate role. Some researchers believe that polyphosphate formed a protective film by adsorbing to the iron surface [4], while others stressed the importance of calcium to polyphosphate effectiveness in forming a protective layer [5–7]. In other studies, polyphosphate efficiency in forming a protective layer was related to flow conditions and stagnation periods [8–10].

Previous efforts show that polyphosphate is able to reduce red water when dosed at about 2–4 ppm/1 ppm of iron [10]. Effectiveness of polyphosphate in corrosion control of municipal water is progressively greater at increasing flow velocities (2–5 fps). At slow velocities (0.5 fps) or in stagnant water, the ability of polyphosphate to control iron corrosion is greatly diminished [10]. Therefore, the advantage of polyphosphate might not be fully realized because turbulent flow velocities are not continually maintained in all parts of a typical distribution system.

Lytle and Snoeyink [11] evaluated effects of OP and polyphosphate on turbidity and apparent color, as measures of iron, at various pH values and iron concentrations. OP reduced turbidity by an average of 1 NTU over a wide pH range, and apparent color values decreased with increasing OP concentrations between 1 and 3 mg/L. OP altered properties of Fe colloids by adsorbing to the particles surfaces. The authors found that polyphosphate caused dramatic reduction in turbidity more than OP [11].

Operating mechanism of polyphosphate is different from OP. Lytle and Snoeyink [11] suggested that a polyphosphate–Fe complex is formed, which limits formation of Fe nuclei and particle size. Polyphosphate reduced particle size more dramatically than OP, which may lead to better color control.

McNeill and Edwards [8] investigated phosphate inhibitors (OP and polyphosphate) in iron pipes in stagnant conditions, and at different water qualities (variable pH and alkalinity). Both OP and polyphosphate either increased or had no effect on iron concentrations, except at 300 mg/L $CaCO_3$. This observation of phosphate inhibitors influence in stagnant pipes is opposite to common experiences in flowing water conditions, in which polyphosphate addition reduced iron release in non-stagnant conditions [10,12].

In another study by Rompre et al. [9], a blend of orthopolyphosphates at 1 mg PO_4/L was tested on pilot and full-scale water distribution system. Iron release was reduced with the application of this blend under flowing water conditions. However, at reduced flow or stagnant conditions, iron release increased despite the inhibitor application. Also maintenance of dose was required to curtail iron release, because when the dose was dropped below 1.0 mg PO_4/L, iron concentrations increased in effluent measurements. McNeill and Edwards [8] attempted to correlate total iron release to the amount of phosphate consumed, but no relationship was found. For pipes that received polyphosphate, a sharp increase in iron release was observed when dosing was stopped, which may be explained by iron release from scales into the water. Inspection of the pipe showed less scale buildup than on pipes still receiving polyphosphate.

According to Boffardi and Cognetti [13], blended orthophosphate has a synergistic effect; where the polyphosphate controls calcium carbonate scale due to polyphosphate's affinity for complexing cations in the water, while OP protects against copper and lead corrosion by binding with metal oxides and forming protective films. Polyphosphate can prevent the formation of calcium carbonate scales in pipes, with as little concentration as 0.7 mg/L PO_4 [13]. Overdosing polyphosphates can cause old loose deposits, especially iron oxide deposits, to dislodge from pipe surface and disperse, increasing red water problems [14].

Sarin et al. [15] investigated iron release from corroded unlined cast-iron pipe under changing pH and alkalinity conditions, as well as OP addition. They found that raising the pH to 9.5 resulted in a noticeable decrease in iron release over a period of few months (from >1.5 to <0.3 mg/L). Variations of alkalinity at constant pH levels indicated lower alkalinities often corresponded to higher iron release and visa versa. Dosing OP at 2–3 mg/L PO_4 to iron pipe system at a pH range of 7.4–7.8 reduced iron levels below 0.2 mg/L. OP addition coupled with pH and alkalinity further reduced iron release [15].

Volk et al. [16] studied the impact of corrosion control strategies (pH adjustment or phosphate addition) on iron pipes by monitoring corrosion rates, and found them strongly dependent on seasonal variations and water temperature, even with the addition of phosphate. Slight increases in phosphate dose (from 0.9 mg PO_4/L to between 1.5 and 2.0 mg PO_4/L) were necessary to maintain low corrosion rates, especially during warm periods.

2. Materials and methods

2.1. Pilot plant design

A research facility was constructed for investigation of distribution systems water quality at the Cypress

Table 1
Characteristics of each PDS

Length	Diameter	Material
20 feet (6.1 m)	6-in. (0.15 m)	PVC
20 feet (6.1 m)	6-in. (0.15 m)	Lined cast iron
12 feet (3.7 m)	6-in. (0.15 m)	Unlined cast iron
40 feet (12.2 m)	2-in. (0.05 m)	Galvanized steel

Creek Water Treatment Facility near Tampa Bay, FL. The facility contained 14 identical pilot distribution systems (PDSs) that received the same blended water. Each PDS is a hybrid line of five pipe segments connected in series as shown in Table 1; a polyvinylchloride (PVC) pipe segment, followed by a lined cast iron pipe, then an unlined cast iron pipe, and finally a two consecutive galvanized steel pipe segments. The PDSs were constructed of aged pipes that were obtained from existing utility distribution systems to represent the pipe materials used locally. The effluent from each PDS feed a copper loop that mimicked in-house pluming system. The PDSs received blended water and inhibitors for 12-months. The inhibitor type and dose to the PDSs were constant throughout the operational period.

2.2. Inhibitors

The BOP PDSs (1, 2, and 3) received target doses of 0.5, 1.0, and 2.0 mg/L as total phosphorous (TP), respectively. The Blended orthophosphate (BOP) inhibitor was a commercial product; a blend of 60–80% OP and 20–40% polyphosphate. Similarly, The OP PDSs (4, 5, and 6) received the target doses 0.5, 1.0, and 2.0 mg/L as TP, respectively. Two PDSs (13 and 14) received only NaOH for corrosion inhibition and were used as controls. PDS 13 and 14 received blended water at pH_s and $pH_s + 0.3$, respectively. Hydrochloric acid (HCl) was used to maintain pHs in PDS 13, which resulted in higher chloride levels in the pHs PDSs than the pHs + 0.3 PDSs. The average pH value of phosphate-dosed water was 7.9, with 0.17 standard deviation (SD).

2.3. Source and blend waters

Varying blends of three different process waters were used in this study, surface water (SW), GW, and desalinated-reverse osmosis-water (RO). The blends were changed every phase to vary water quality, as shown in Table 2. Phases I and have the same blend ratio (WQ1) in order to study the seasonal effects. A water quality summary of all the blends is presented in Table 3.

Table 2
Water blend ratios

Phase	Blend	GW (%)	SW (%)	RO (%)
I (February–May 2006)	WQ1	62	27	11
II (May–August 2006)	WQ2	27	62	11
III (August–November 2006)	WQ1	62	27	11
IV (November 2006–February 2007)	WQ3	40	40	20

2.4. Sampling and analysis

Weekly samples were collected from the influent, effluent, and effluent of corrosion pipes locations and analyzed for metals and other water quality parameters in the field laboratory and UCF laboratories. Phosphate samples were collected and analyzed three times a week. Data was collected throughout the year of operation. Quality assurance and quality control of both the laboratory and field determinations of water quality parameters were established by duplicating analyses of at least 10% of the samples. Where appropriate standards were available, 10% of the samples were spiked with known concentrations of the parameter being analyzed and the recovery measured. Blind duplicates and spikes were also used to determine the accuracy of measurements. The master QA/QC plan for all data analysis and handling has followed all guidelines for chemical sampling and analysis as presented in the Standard Methods for the Examination of Water and Wastewater Analysis [17]. For example, analysis of iron samples followed the SM 3120B ICP Method.

3. Results and discussion

3.1. Iron release by PDS

Iron concentrations from each PDS influent and corrosion loop effluent were compared. Each PDS experienced a 2-day hydraulic retention time (HRT) throughout the duration of operations. Both PDS influent and corrosion loop effluent total iron measurements were averaged over the 12-month duration and presented in Fig. 1 for each PDS, with whiskers for 95% confidence interval around the mean. The annual average influent iron concentrations were slightly less than 0.03 mg/L, while the effluent concentrations varied from 0.11 to 0.22 mg/L, depending on the control strategy and the applied dose.

The significant differences in iron concentrations between influents and effluents were statistically compared using a one-tailed paired-data *t*-test. All

Table 3
Water quality summary of the blends (mg/L)

Phase	pH		Alkalinity		Chloride		Iron		Temperature (°C)	
	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
I	7.9	0.1	161	12	46	5	0.06	0.05	21.4	1.9
II	7.9	0.1	112	14	60	5	0.04	0.01	25.7	1.2
III	8.0	0.3	154	3	65	9	0.05	0.01	25.6	0.8
IV	7.8	0.1	127	7	57	6	0.04	0.01	20.3	1.6

determinations of *p*-values were below 0.05, indicating there is sufficient evidence (at 95% confidence level) that effluent concentrations from corrosion loops were greater than PDS influent iron concentrations. This statistical analysis confirmed the release of iron corrosion products from unlined cast iron or galvanized steel pipe materials at 2-day HRT, regardless of which corrosion control strategy was employed (BOP, OP, or pH adjustment). Nonetheless, medium and high doses of BOP (1.0 and 2.0 mg P/L respectively) mitigate total iron release slightly better than other inhibiting conditions, as shown in Fig. 1.

3.2. Statistical modeling of iron release

3.2.1. Initial model development

An empirical model was developed to predict total iron concentrations in the effluent of the hybrid PDSs. Monitored water quality parameters in the PDSs were evaluated using ANOVA procedures to identify statistically significant parameters at 95% confidence level. Dummy variables (0, 1) were utilized in the model to segregate data by individual corrosion control strategy. Non-linear least squares regressions (backward regression) were conducted on all data to estimate parameter exponents and coefficients. A linear correlation matrix of the entire data set revealed that some parameters were confounded, such as sodium and chloride, or dissolved oxygen and temperature. Confounded parameters are those linearly correlated (i.e. one parameter can account for the other). For example, dissolved oxygen and temperature data in this specific study had a strong correlation of 85%. Therefore, one of these correlated parameters had to be excluded in order to achieve convergence of the developed empirical model. Dissolved oxygen was excluded in favor of temperature. Also, this modeling effort utilized some relationships developed in earlier work that related iron release to water quality in the absence of inhibitors such as the anticipated relationship between chloride concentrations and iron release [18].

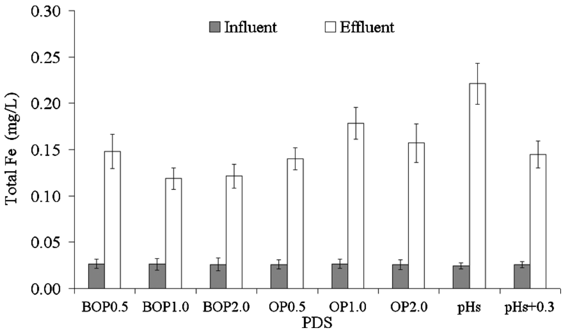

Fig. 1. Comparison of influent and effluent average iron concentration, with whiskers indicating 95% confidence interval around the mean.

The initial form of the model (Eq. (1)) did not demonstrate sensitivity to the effect of inhibitor dose on iron release, so further modifications were pursued. Variables in the model are defined under the subheading ''symbols in equations''.

$$Iron = (a * BOP + b * OP + c * pH_s) * Alk^f * Cl^g * Fe_{\mathrm{inf}}^i \tag{1}$$

3.2.2. Models development considering phosphorous speciation

The ratio of orthophosphorous (OP) to TP was added to the model to evaluate phosphorous speciation; however, the OP/TP term was statistically insignificant, and was discarded. Only the TP term was retained. Sensitivity to each phosphate-based inhibitor was still accounted for in the model through the dummy variables. The TP term refers to measurements of TP at influent of the PDSs after dosing with the inhibitors.

3.2.3. Models development considering inhibitor dose

Model sensitivity to inhibitor dose was achieved by including terms associated with the dose of each inhibitor (i.e. TP) with the dummy variable for that inhibitor. This provided each inhibitor with unique parameter estimation of exponents on the inhibitor dose. As in previous modeling attempts, statistically significant variables were identified and included in the model using ANOVA methods. Non-linear least squares regression provided parameters estimates. This final modeling modification significantly improved the empirical model's accuracy, especially with respect to inhibitor dose. Separate models for each corrosion control strategy were also developed for each inhibitor but were less robust than the combined model as the reduced data set was smaller and several singular models did not converge. Therefore, the approach to develop individual models for each control strategy was abandoned.

3.2.4. Empirical model for total iron concentration

The final form of the empirical model developed for total iron concentrations is presented in Eq. (2). The model suggests that total iron concentrations would decrease with increasing alkalinity, as evident by the negative exponent on the alkalinity term. Both chloride and influent iron have positive exponents, suggesting an increase in iron release with higher chloride or influent iron concentrations. Each inhibitor had a contributing term that was multiplied by a dummy variable in order to adjust the predicted iron concentrations as a function of the inhibitor dose. The exponents on terms in the model give an indication of the degree of influence each term has on total iron release. The addition of the phosphate-based inhibitors controlled the extent of phosphorous concentrations in the PDSs, represented by the TP term. The average influent TP before inhibitors addition was less than 0.07 mg P/L.

$$Total\ Fe = \left(0.495BOP * TP^{-0.104} + 0.593OP * TP^{0.047} + 0.661pH_s\right) * Alk^{-0.457} * Cl^{0.345} * Fe_{\text{inf}}^{0.136} \quad (2)$$

The p-values of retained independent variables were: 0.2573 for TP(BOP), 0.5332 for TP(OP), 0.0001 for Alk, 0.0002 for Cl, and 0.0011 for Fe_{inf}. TP terms were retained in the model despite their large p-values (>0.05) to include sensitivity to inhibitor dose in the model. HRT was not varied (2 days) and was not used in the model. For the conditions of this work, pH had no significant impact on iron release as stabilization with respect to $CaCO_3$ was achieved prior to discharge to the PDSs. Stabilization was achieved using CO_2 to maintain the pH within the natural water levels, especially for high alkalinity blend water.

Eq. (2) shows that the coefficient of dummy variables for BOP and OP were 0.495 and 0.593, and the TP exponents were -0.104 and 0.047, respectively. These differences indicate the different effects BOP and OP had on iron release for equivalent phosphorous doses.

Performing a comparison of predicted and actual total iron concentrations revealed that the coefficient of determination (R^2) was not robust at $R^2 = 0.25$. This value indicates the limited response of iron data to increases in inhibitor dose, which is confirmed in Fig. 1, where iron release was noticeably higher than influent concentrations across all inhibitors and doses.

Also, considerations of adverse water quality effects addressed by secondary drinking water standards, namely color (15 color units) and iron (0.3 mg/L) [19], are related to the total iron concentrations. Therefore, it's more relevant to discuss the control and prediction of total iron release than considering dissolved iron. Collected dissolved iron measurements are more appropriate for thermodynamic equilibrium calculations, such as solubility of iron species.

3.2.5. Inhibitors performance comparison

Summary for the total and dissolved iron concentrations for PDSs treated with BOP, OP, and pH adjustments are presented in Tables 5–7, respectively. Data is segregated by phase and PDS, and includes average and SD of observed iron release. Data for all treatments shows that on average, the majority of the iron was present in the particulate form (overall, particulate iron was about 90% of total iron).

3.2.6. Data summary for BOP inhibitor

Iron release data from PDS 1 to PDS 3 that received the BOP inhibitor is shown in Table 5, and suggests that controlling total iron release improved with BOP doses higher than 0.5 mg P/L. Variation in total iron release between phases was limited under the BOP treatment.

3.2.7. BOP inhibitor performance

Application of the empirical model (Eq. (2)) on data from the BOP PDSs suggests that BOP addition decreased iron release due to the negative exponent on the TP term. However, the magnitude of the exponent was the smallest in the model, indicating BOP had the least influence on total iron release. This is

Table 4
Iron release summary for the BOP PDSs

Phase	PDS	Dose (mg P/L)		Total Fe (mg/L)		Overall % dissolved Fe
		Average	SD	Average	SD	
I	1	0.57	0.16	0.14	0.07	
	2	1.08	0.30	0.10	0.02	
	3	1.82	0.61	0.12	0.05	
II	1	0.57	0.22	0.21	0.12	
	2	1.00	0.18	0.15	0.05	
	3	1.95	0.29	0.15	0.05	
III	1	0.49	0.07	0.13	0.03	
	2	0.90	0.14	0.11	0.02	
	3	1.73	0.29	0.12	0.04	
IV	1	0.68	0.13	0.12	0.05	
	2	1.31	0.19	0.13	0.05	
	3	2.66	0.44	0.09	0.04	
All	1	0.58	0.16	0.15	0.08	12
	2	1.07	0.25	0.12	0.04	12
	3	2.03	0.55	0.12	0.05	12

supported by average iron release data (Table 5), which showed little reduction of iron release with increasing dose beyond 1.0 mg P/L.

Fig. 2 shows separate bars for the average predicted and average actual concentrations of total iron release in each of the BOP PDSs for each phase. Whiskers in the figures define the 95% confidence interval for the average of both measured and predicted concentrations. Fig. 2 shows that the model does reasonably well at predicting iron release for the BOP PDSs. The medium BOP dose (1.0 mg P/L) had the best control of total iron release in Phases I and III. Both medium and high doses performed better than the low dose in Phase II, while the high dose in Phase IV resulted in the least total iron release. Fig. 2 suggests that a linear decrease total iron release was not always related to a linear increase in BOP dose.

The remaining terms in the model (alkalinity, chloride, and influent iron) are related to the water quality of the source water blend. Phases I and III were mostly

Table 5
Iron release summary for the OP PDSs

Phase	PDS	Dose (mg P/L)		Total Fe (mg/L)		Overall % dissolved Fe
		Average	SD	Average	SD	
I	4	0.49	0.14	0.12	0.04	
	5	1.04	0.49	0.14	0.03	
	6	1.84	0.29	0.11	0.06	
II	4	0.55	0.09	0.16	0.04	
	5	0.90	0.25	0.21	0.06	
	6	1.91	0.21	0.17	0.04	
III	4	0.54	0.07	0.14	0.03	
	5	0.99	0.15	0.23	0.04	
	6	1.87	0.11	0.14	0.03	
IV	4	0.47	0.08	0.13	0.06	
	5	0.82	0.25	0.13	0.06	
	6	1.69	0.10	0.20	0.13	
All	4	0.51	0.10	0.14	0.04	10
	5	0.94	0.32	0.18	0.06	8
	6	1.83	0.21	0.16	0.08	9

Table 6
Iron release summary for the pH control PDSs

Phase	PDS	pH		Total Fe (mg/L)		Overall % dissolved Fe
		Average	SD	Average	SD	
I	13	7.8	0.2	0.15	0.03	
	14	8.0	0.2	0.11	0.04	
II	13	7.9	0.2	0.28	0.06	
	14	7.9	0.1	0.19	0.07	
III	13	7.7	0.1	0.27	0.06	
	14	8.1	0.2	0.14	0.03	
IV	13	7.6	0.1	0.19	0.09	
	14	7.9	0.1	0.14	0.05	
All	13	7.7	0.2	0.22	0.08	9
	14	8.0	0.2	0.14	0.05	15

GW, which was characterized by high alkalinity (average of 163 and 150 mg/L as $CaCO_3$, respectively). Phase II utilized a blend with a greater SW composition than in other phases, resulting in a reduced alkalinity (average of 106 mg/L as $CaCO_3$). The increase in iron concentration at reduced alkalinity is consistent with the inclusion of alkalinity in the empirical model with a negative exponent on that variable. Actual total iron release (Fig. 2 and Table 5) supports this statement, where Phase II concentrations were higher than those from Phases I or III.

The model is also sensitive to chloride and influent iron. Chloride has the largest positive exponent in the model, suggesting that an increase in chloride results in increasing total iron release. Phase I had the lowest average chloride concentration among all phases (average of 44 mg/L), which would result in lower iron release for that phase. This is supported by the low levels of actual iron release in Phase I (Fig. 2 and Table 5). Influence of influent iron term is less pronounced than chloride because of its smaller exponent. Also, influent iron concentrations were consistently low, around 0.03 mg/L.

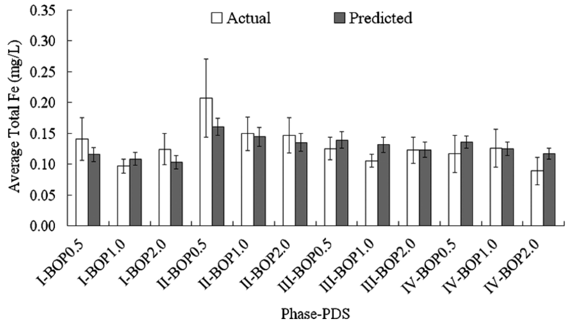

Fig. 2. Total iron release model summary for the BOP PDSs by phase, with whiskers indicating 95% confidence interval around the mean.

3.2.8. Data summary for OP inhibitor

For the PDSs treated with OP inhibitor, Table 6 shows the average dose and iron concentration for each Phase and PDS. The lowest overall iron release appeared in Phase I, which corresponded to a water blend enriched in GW resulting in the highest alkalinity concentrations. Increasing the OP inhibitor dose showed no improvement in controlling iron release.

3.2.9. OP Inhibitor performance

The differences between model forms for BOP and OP are in the model coefficient and the exponent on the TP term. The remaining water quality parameters have the same impact on iron release with both phosphorous inhibitors, because these parameters are related to the water blend, which was consistent across all PDSs in any given phase.

The model suggests that OP inhibitor application would contribute to iron release by the positive exponent on the TP term. However, the small magnitude of this exponent makes the model less sensitive to TP for the OP PDSs. The data agrees closely with this statement, as increasing the dose of OP inhibitor did not offer improved iron control (Table 6).

Fig. 3 shows the average iron release in each of the OP PDSs for each phase compared to the predicted release. The whiskers indicate the 95% confidence interval of the mean. The model does reasonably well at predicting iron concentrations for the OP PDSs. Fig. 3 clearly shows that increasing the dose did not offer improved control of iron release.

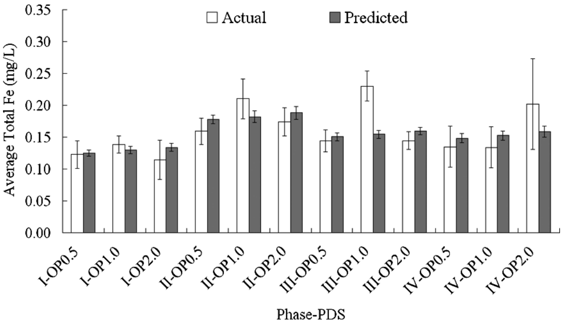

Fig. 3. Total iron release model summary for the OP PDSs by phase, with whiskers indicating 95% confidence interval around the mean.

The negative exponent on the alkalinity term suggests reduction of iron release by increasing alkalinity, which is related to the source water blend. Fig. 3 confirms the impact of alkalinity, where Phase I data had the lowest iron release and Phase II had the highest. The model is sensitive to the alkalinity of the blend due to the large magnitude of exponent and actual concentrations. The large positive exponent on the chloride term suggests a direct relation to iron release. Phase I had the lowest average chloride concentration, which is another explanation for the low levels of iron observed in Phase I in Fig. 3. Although influent iron is a significant term in the developed model, its small exponent and consistent low concentrations limited its impact on predicted iron release.

Fig. 3 shows a wide spread in the confidence interval of iron concentrations in PDS 6, during Phase IV. This is the result of a single measurement of 0.51 mg/L in the middle of the Phase, and was not related to changes in water quality.

3.2.10. Data summary for pH control

Table 7 shows that pH_s PDS (PDS 13) consistently experienced higher iron release than the $pH_s + 0.3$ PDS (PDS 14). The lowest iron release appeared in Phase I, which had the highest alkalinity. Conversely, Phase II had the highest iron release and the lowest alkalinity.

3.2.11. pH control performance

The effect of increasing the pH to $pH_s + 0.3$ is seen in the model by an increase in alkalinity. Increasing pH, and therefore alkalinity, helps in reducing iron release indicated by the negative exponent on the alkalinity term.

Fig. 4 shows the average iron release in the pH control PDSs for each phase compared to the predicted iron release, with 95% confidence interval whiskers.

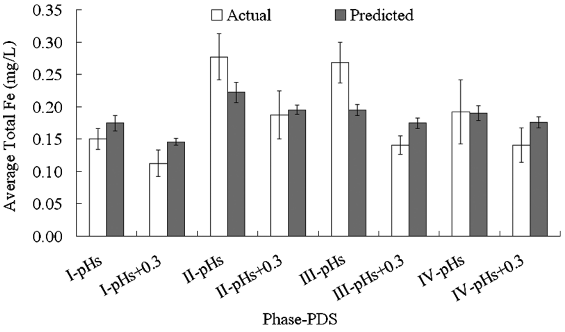

Fig. 4. Total iron release model summary for the pH control PDSs by phase, with whiskers indicating 95% confidence interval around the mean.

The wide spread between maximum and minimum values for PDS 13 confirms the difficulty of controlling iron release at pH_s (average of 7.7). The model does reasonably well at predicting iron release for the pH control PDSs. The figure shows that increasing pH consistently offered a reduction in iron release for both predicted and actual concentrations.

Alkalinity depends on pH increase in PDS 14 and on GW ratio in the blend. Phases I and III were mostly GW, which is characterized by high alkalinity. This contributed to the lowest iron release in Phase I, and the highest release in Phase II, as seen in Fig. 4 for both the observed and predicted release.

The positive exponent on the chloride term suggests an increase in chloride would increase iron release. Along with the highest alkalinity, Phase I blend had the lowest average chloride concentration, offering another suggestion for why Phase I iron release was lower than other phases (Table 7). Chloride was much higher in the pH_s PDSs than the $pH_s + 0.3$ PDSs (75 vs. 57 mg/L). The higher chloride levels would contribute to higher iron release in the pH_s PDS, as suggested by the model. Influent iron was relatively constant in the pH control PDSs in all phases. The addition of NaOH and/or HCl for pH adjustments increases the TDS in the system (i.e. high sodium levels). In a previous study [18], the increase in sodium also meant an increase in iron release.

3.2.12. Performance summary

Evaluation of inhibitors performance so far indicated that control of iron was directly affected by water quality (alkalinity content and pH level). This was evident in empirical modeling, where the exponents on alkalinity and chloride terms had the largest magnitudes, and the coefficient of the pH dummy variable was larger than those of the phosphate-based inhibitors (BOP: 0.495, OP: 0.593, and pH: 0.661). This suggests that there was no clear advantage to phosphate inhibitors dosing, especially OP, over elevated pH in PDS 14. The data confirms that PDS 13, maintained at pH_s, experienced the highest iron release among the examined control strategies.

A statistical comparison (one-tailed, paired data *t*-test for equality of means) was conducted to determine any statistical differences between the elevated pH control (PDS 14) and the phosphate inhibitors. The analysis showed that BOP at medium and high doses (1.0 and 2.0 mg P/L) reduced the composite average iron concentrations, relative to the control strategy of pH elevation (*p*-values: <0.001, 0.002). It is important to note that pH elevation may produce undesirable conditions through excessive deposition of calcium carbonate scale.

4. Conclusion

The purpose of this work was to evaluate how changes in water quality, associated with blend variations of source waters, impacted iron release; and to investigate how different inhibitors mitigated iron release under such variations. The study demonstrated the advantage of blended orthophosphate inhibitor over other controlling strategies in combating iron release under various blends.

The impact of phosphate-based corrosion inhibitors and pH adjustments on iron release from hybrid PDSs was monitored for a 12-month period. BOP and OP inhibitors were applied at three dose levels to separate PDSs in addition to a pair of PDSs maintained at two pH levels, respectively (pH_s and $pH_s + 0.3$). Source water blends were adjusted every phase to account for effects of water quality variations on iron release in the presence of inhibitors.

Iron was released from PDSs of all treatment strategies (BOP, OP, and pH control), and during all phases. The dominant form of iron in the effluent was particulate (90%). On average, medium and high doses of BOP achieved the least total iron release (around 0.12 mg/L), followed closely by elevated pH at $pH_s + 0.3$. The OP inhibitor was not able to control iron release better than elevated pH. Iron concentrations were generally highest under the pH_s treatment (0.22 mg/L), almost doubling the average release of BOP treatment.

Iron release was variable between phases for all control strategies. Water quality variations, primarily alkalinity content associated with changing water blends, played a major role in iron release. Water with higher alkalinity content and/or low chloride levels resulted in less iron concentration. Empirical modeling confirmed the pivotal role of source water quality, where alkalinity had the largest influence on model predictions of iron, followed by chloride.

This work was not conducted under controlled laboratory conditions, resulting in many variables associated with type and condition of pipe material, hydraulic and environmental conditions, and source water quality, which are site-specific. One goal was to investigate the optimum inhibitor and dose, under changing water quality environment for a given pipe system. The developed model was site-specific and should not be generalized, or extrapolated beyond the data set of this study.

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Symbols

BOP	BOP inhibitor dummy variable (0, 1)
OP	OP inhibitor dummy variable (0, 1)
pH_s	pH_s inhibitor dummy variable (0, 1)
TP	Total phosphorous, mg/L
Alk	Alkalinity, mg/L as $CaCO_3$
Cl	Chloride, mg/L
Fe_{inf}	Influent iron, mg/L
A	BOP dummy variable coefficient
B	OP dummy variable coefficient
C	pH_s dummy variable coefficient
m	TP exponent associated with BOP dummy variable
N	TP exponent associated with OP dummy variable
F	Alkalinity exponent
G	Chloride exponent
I	Influent iron exponent

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