



## MEMORANDUM

**To:** Mayor and Council Members  
**From:** Greg Meszaros, Director, Austin Water  
**Date:** September 19, 2019

**Subject:** October 2018 Flood Event Engineering Review and Recommendations

As part of Austin Water's after-action review of the October 2018 Colorado River Flooding and Boil Water Notice, the Utility commissioned an engineering study of the event. To conduct the study, Austin Water assembled a team consisting of internal engineering and operating staff, Carollo Engineers, Inc., and Professors Desmond Lawler and Lynn Katz of the University of Texas.

Austin Water has completed the study work and I have enclosed the two reports that were produced. The first, entitled "October 16, 2018 Flood Event Report and Resulting Recommendations" provides a detailed analysis of the October flooding impacts on the Utility's drinking water plants and associated recommendations for improving plant performance during future events. The second report, entitled "Bench Testing Report" provides the analytical results of testing various treatment strategies on banked raw water that was preserved from the October flooding event. The Bench Testing Report was third party reviewed by Professors Lawler and Katz and provides the analytical framework for treatment process recommendations. Key findings and recommendations include the following:

- Raw water conditions associated with the October 2018 flooding were unprecedented and the duration of raw water upset was significantly longer than past events.
- To prepare for future extreme turbidity events, Austin Water will need to enhance treatment options to improve flexibility to operate during water quality upset episodes. The recommended strategy is to add polymer-based treatment technologies at all three drinking water plants. The report estimates the capital cost for a polymer system at approximately \$9.3M. Other more capital-intensive changes, such as the addition of presedimentation basins or a conversion away



from lime softening, were considered but not warranted based on the results of the Bench Testing study.

- Improve operator instrumentation capability to precisely measure water particle charge and adjust treatment processes.
- Enhance internal extreme event operating procedures and guidelines to document lessons learned from the October flooding and provide staff improved resources to manage future water quality upset events.

Austin Water is expeditiously moving forward with these recommendations. We have begun the process of developing a scope of services to design and construct polymer feed systems at all three of our plants. We have placed orders to purchase zeta-potential meters (a device that precisely measures water particle charge) to support operations. We have updated internal procedures and guidelines and will continue to enhance these as we integrate zeta-potential meters and polymer technologies.

Should you have any questions or would like any additional information please contact me.

cc: Spencer Cronk, City Manager  
Rey Arellano, Assistant City Manager

**Attachments:** October 16, 2018 Flood Event Report and Resulting Recommendation  
Bench Testing Report



*The City of Austin is committed to compliance with the Americans with Disabilities Act.  
Reasonable modifications and equal access to communications will be provided upon request.*



City of Austin  
Process Treatment Recommendation Resulting  
from October 2018 Flood Event

## OCTOBER 16, 2018 FLOOD EVENT REPORT AND RESULTING RECOMMENDATIONS

FINAL | July 2019



TBPE No. F-882



City of Austin  
Process Treatment Recommendation Resulting from October 2018  
Flood Event

## OCTOBER 16, 2018 FLOOD EVENT REPORT AND RESULTING RECOMMENDATIONS

FINAL | July 2019



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7/15/2019



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7/15/2019



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## EXECUTIVE SUMMARY

An extreme flood event in October 2018 dramatically changed the characteristics of the raw water supply to the City of Austin's three Water Treatment Plants (WTPs). The change in raw water quality was unprecedented based on historical data from previous events. The change in quality made the water challenging to treat while meeting plant production requirements, and resulted in the City of Austin (City) issuing a mandatory Boil Water notice on October 24, 2018.

During the flood event, the City retained Carollo Engineers, Inc. (Carollo) to help provide on-site support at the Ullrich WTP. Carollo's efforts during the flood included: evaluating treatment plant operations and capabilities to understand limitations and options to operate the plant while the raw water quality remained challenging to treat; conducting bench tests to assess treatment options available to the WTP and to support recommendations for WTP operational adjustments; and, providing technical support, including mobilization of a temporary polymer feed system to improve treatment at the Ullrich WTP. This report documents observations and findings from Carollo's engagement at the Ullrich WTP during the October 2018 flood event, including:

- The impact of the flood event on raw water quality, treatability, and residuals handling,
- Limitations of the WTPs to treat the water at full plant capacity,
- Results from bench and demonstration tests conducted during the flood event and resulting recommendations for operational adjustments,
- Lessons learned from the flood event as well as from other water utilities that experience similar raw water quality challenges and operate lime softening plants,
- Conceptual level costs to implement recommended process / infrastructure modifications, and
- Conclusions and recommendations.

The October 2018 flood event resulted in drastic and sustained differences in raw water quality from what is considered typical at all three of the City's WTPs. The turbidity, a measurement of the concentrations of particles or solids in the water, increased almost 100-fold within 36 hours and remained high for several weeks. The turbidity peaked at 415 Nephelometric Turbidity Units (NTU) and needed to be reduced to 0.3 NTU to meet TCEQ requirements. This change meant that the WTPs suddenly needed to adjust operations to remove a substantial quantity of solids from the water prior to distribution to its customers. Coupled with the increase in turbidity was a decrease in the concentrations of alkalinity and hardness, two parameters that drive typical operation of the City's WTPs.

Austin's WTPs are designed to treat Lower Colorado River water as reflected by previous historical norms. The existing WTP facilities are equipped to adjust several operational set points to respond to a change in water quality. However, additional tools that are incorporated at other lime softening plants in the country that experience high turbidity loading similar in magnitude to the October 2018 flood event are not available at the City's WTPs because there is no previous precedent that would indicate those tools are needed. As an example, lime softening plants that treat the Missouri River (nicknamed the "Big Muddy" for apt reasons), incorporate horizontal collection wells, pre-sedimentation basins, and/or two-stage softening to help remove particles through the WTP. Some plants also include polymers to aid in particle removal.

In the absence of those tools, the City needed to make what operational adjustments they could to produce water to meet customer/system demands. Early in the flood event, City Plant Operations staff observed improved treatability by increasing the lime dose to achieve a softened water pH > 10.5, with additional improvement from increasing the ferric sulfate dose. The City also reduced flow through the WTPs to the extent possible to reduce the surface overflow rates through each clarifier. Bench testing confirmed that all of these steps (i.e., increasing the softening pH, increasing the ferric sulfate dose, and decreasing the flow) resulted in optimal water quality during the flood event. Bench testing also indicated improved settleability of the solids with the addition of a coagulant aid polymer, and/or a flocculant aid polymer. Based on those results, a temporary coagulant aid polymer feed system was implemented for one of the upflow solids contact clarifiers at the Ullrich WTP with positive outcomes.

The City made a decision to collect approximately 100 gallons of raw water on October 25, 2018, when the quality remained challenging with elevated turbidity and depressed alkalinity and hardness. This turned out to be very beneficial as the “banked” water was used to further assess recommended operational strategies and required WTP improvements to respond to similar extreme raw water quality events that may occur in the future. Results from those tests are documented in the Bench Testing Report (Carollo, 2019) and factored into recommended improvements presented herein.

The 2018 October flood event reset the bar in terms of the range of raw water quality that may be observed at the City's WTPs. Further, the event changed expectations in terms of the range of water quality that the WTPs need to be capable of treating. The following major steps are recommended for the City to prepare for similar future water quality events:

- Provide additional treatment options to improve flexibility to operate during extreme weather-related events. Based on observations during the October 2018 flood event and jar tests with the banked water, the following improvements are recommended:
  - Add cationic coagulant aid polymer feed capabilities at the three WTPs.
  - Add the capability to feed the same cationic polymer to the filter influent at the three WTPs.
  - Add flocculant aid polymer feed capabilities at the three WTPs.
  - Add the capability to feed the same bridging (flocculant aid) polymer to the gravity thickener influent at Ullrich and Handcox WTPs.
  - Class 5 construction cost estimates for the new polymer feed systems are approximately \$9.3 million.
- Develop a water quality event response plan, which includes Standard Operating Procedures (SOP) for stepwise and incremental adjustments in operations to optimize treatment in response to the change in water quality.

The recommended improvements represent WTP upgrades that could be made to improve resiliency to extreme events with only minor infrastructure modifications. While other options could be (and have) been considered, such as conversion from softening to coagulation or addition of a presedimentation basin, these improvements would require major changes to infrastructure that may not be needed nor warranted. The data collected during the October 2018 event as well as subsequent testing using banked water (see Bench Testing Report, Carollo 2019) highlighted the potential for improving resiliency without such drastic changes.

## Abbreviations

AWWA	American Water Works Association
Carollo	Carollo Engineers, Inc.
CCPP	calcium carbonate precipitation potential
cf	cubic feet
cfs	cubic feet per second
DBP	disinfection by-product
DOC	dissolved organic carbon
F	Fahrenheit
ft	feet
ft <sup>3</sup>	cubic feet
gpm	gallons per minute
HCW	horizontal collector well
hrs	hours
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
µg/L	micrograms per liter
MG	million gallons
µg/L	micrograms per liter
mg/L	milligrams per liter
mgd	million gallons per day
NTU	Nephelometric Turbidity Units
NOM	natural organic matter
PEA	polymer - flocculant aid
PEC	polymer - cationic
PHD	peak hour demand
PS	pump station
lbs	pounds
psi	pounds per square inch
RO	Reverse Osmosis
SCADA	supervisory control and data acquisition
SCC	solids contact clarifier
SHMP	sodium hexametaphosphate
SOP	Standard Operating Procedure
SOR	surface overflow rate
S.U.	standard units
s	second
TCEQ	Texas Commission on Environmental Quality
TOC	total organic carbon
WTP	water treatment plant



## INTRODUCTION

An extreme flood event in October 2018 dramatically changed the characteristics of the raw water supply to the City of Austin's three water treatment plants (WTPs). The change in raw water quality made the water challenging to treat, impacting the ability of the WTPs to meet the City of Austin (City) finished water quality goals at full plant capacity. Significant additional effort from City staff was required to operate the WTPs during the flood event. The City retained Carollo Engineers, Inc. (Carollo) to help provide on-site support at the Ullrich WTP. Carollo's efforts during the flood event consisted primarily of the following:

- Evaluating treatment plant operations and capabilities to understand options to operate the plant while the raw water quality remained challenging to treat.
- Setting up and conducting bench tests to assess treatment options available to the WTP and to support recommendations for WTP operational adjustments.
- Providing technical support including implementation of a temporary cationic polymer (PEC) feed system to enhance particle neutralization and removal through the Ullrich WTP.

This Technical Memorandum documents:

- The observed impacts of the flood event on raw water quality and why those differences impacted the City's ability to operate the WTPs at typical production capacity,
- Limitations of existing WTPs including residuals handling facilities constraining plant production during the flood event,
- Results from jar tests conducted during the flood event and resulting recommendations for adjustments,
- Lessons learned from the October 2018 flood event, and
- Lessons learned from other lime softening water utilities that experience similar raw water quality challenges and operate lime softening plants.

Conceptual level cost opinions to implement recommended process / infrastructure modifications are also presented, along with conclusions and recommendations.

## Section 1

# FLOOD EVENT IMPACT ON WATER QUALITY

The October 2018 flood event resulted in drastic differences in raw water quality from what is considered typical at all three of the City's WTPs. Table 1 displays historical raw water quality measured at Ullrich WTP compared to the extreme values measured during the flood event. The raw water quality trends observed at Ullrich were similar at both the Davis and Handcox WTPs. Figures 1 through 7 display the historical versus the flood event raw water quality for the following parameters:

- Turbidity.
- pH.
- Alkalinity.
- Hardness.
- Calcium.
- Magnesium.
- Total organic carbon (TOC).

While past significant rain events have resulted in short term spikes in turbidity and TOC combined with reduced hardness and alkalinity, the magnitude of the flooding, the condition of the lakes being full, and the duration of the October 2018 event was greater than past events, making it difficult for the City's WTPs to treat the water at typical flows. A detailed evaluation of historical water quality is presented in the City of Austin's After Action Report.

Table 1 Historical Raw Water Quality at the Ullrich WTP vs. Flood Event Extremes

Parameter	Flood Event Extreme	Historical Average <sup>(1)</sup>	Minimum <sup>(1)</sup>	5th Percentile <sup>(1)</sup>	95th Percentile <sup>(1)</sup>	Maximum <sup>(1)</sup>
Total Alkalinity (mg/L as CaCO <sub>3</sub> )	100	179	138	161	208	229
pH (SU)	7.92	8.21	7.70	8.10	8.40	8.50
Turbidity (NTU)	415	4.54	0.56	2.03	7.27	125.0
Total Hardness (mg/L as CaCO <sub>3</sub> )	88	216	144	190	258	280
Calcium (mg/L)	29	51	38 <sup>(2)</sup>	41	69	78
Magnesium (mg/L)	4	21	10	16	24	26 <sup>(2)</sup>
TOC (mg/L)	7.78	4.20	3.27	3.45	4.99	12.60

Notes:

(1) Data collected between January 1, 2013 and December 31, 2015.

(2) Discarded June 3, 2013 measurement as potentially erroneous outlier. Next lowest Ca and highest Mg values provided.

The discussion below lists each of the key water quality parameters and how each one impacted water treatability during the flood event.

### 1.1 Turbidity

Turbidity is a measurement of the light-scattering properties of water. Turbidity in drinking water supplies is commonly caused by the presence of suspended matter, such as clays, silts, finely divided organic and inorganic matter, plankton, and other microorganisms with the highest sensitivity being in the 0.1 to 0.5 micron particle range. High turbidity may also correlate with a high concentration of negatively charged particles which requires destabilization to facilitate removal by agglomeration followed by settling and filtration treatment processes. Therefore, turbidity is used as an indicator of drinking water quality and as an indicator of the efficiency of drinking water coagulation and filtration processes.

The typical average turbidity of the City's raw water is less than 5 NTU. Starting on October 18, the raw water turbidity at Ullrich WTP increased from 4.8 NTU to 305 NTU over the course of the first 36 hours of the flood event, as shown in Figure 1. The turbidity finally peaked at 415 NTU on October 21 and remained well above historical norms for multiple weeks after the flood event. The increase in turbidity presented several inter-related challenges for WTP operation:

1. The WTPs struggled to maintain low settled water turbidity values. A majority of the excess turbidity present in the raw water was removed during the softening process and was incorporated into the precipitated solids, resulting in solids with a lower specific gravity than typical. A lower specific gravity likely reduced the settling rate of the solids, requiring a reduction of flow through the WTPs to meet the settled water turbidity targets. Additional details of the impact of raw water and treatment approaches on solids density and settleability are provided in Section 5.
2. Higher solids loading to the filters resulted in increased backwashing frequency to meet filtered water turbidity goals. The increased filter backwashing frequency challenged the ability of the plant to meet plant production goals.
3. Capacity of the residuals handling facilities was exceeded. The mass of solids removed through the softening process increased two fold based on calculations accounting for raw water turbidity and chemical feed during the flood event. The volume of residuals conveyed to the gravity thickeners and washwater basins also increased due to changes in sedimentation basin blowdown and filter backwashing frequency as the WTPs adjusted operations to respond to the different water quality.

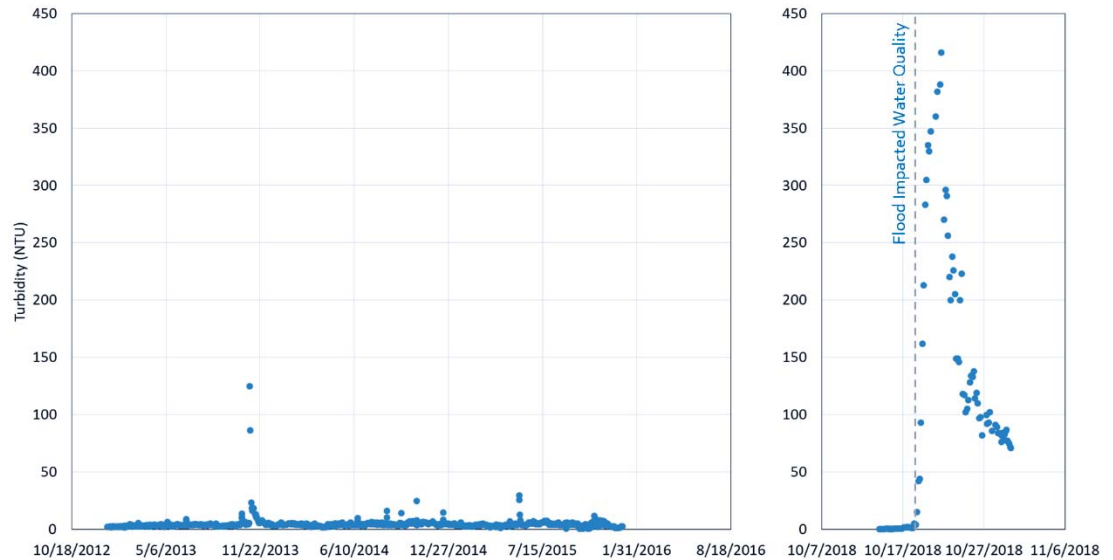


Figure 1 Raw Water Turbidity - Historical (Left) and Flood Event (Right)

## 1.2 pH and Alkalinity

pH is an expression of the negative log of the hydrogen ion concentration in water. A pH of 7.0 represents a neutral condition, a pH of greater than 7.0 represents a basic (alkaline) condition, and a pH of less than 7.0 represents an acidic condition. pH is an important parameter governing many chemical reactions in water treatment, including softening, coagulation, disinfection, and disinfection by-product (DBP) formation. The alkalinity (or buffering capacity) of a water supply moderates changes in pH. In general, the higher the alkalinity, the more resistant the water is to a change in pH.

The pH and alkalinity of the raw water typically average 8.2 and 180 mg/L as  $\text{CaCO}_3$ , respectively. During the flood event, pH values were below historical 5th percentile values (Figure 2), and the alkalinity dropped from approximately 160 mg/L as  $\text{CaCO}_3$  to a low of 100 mg/L as  $\text{CaCO}_3$ , as shown in Figure 3. The low alkalinity of the raw water resulted in insufficient carbonate ( $\text{CO}_3^{2-}$ ) to precipitate the same amount of  $\text{CaCO}_3$  that is typical of the City's WTP softening process.

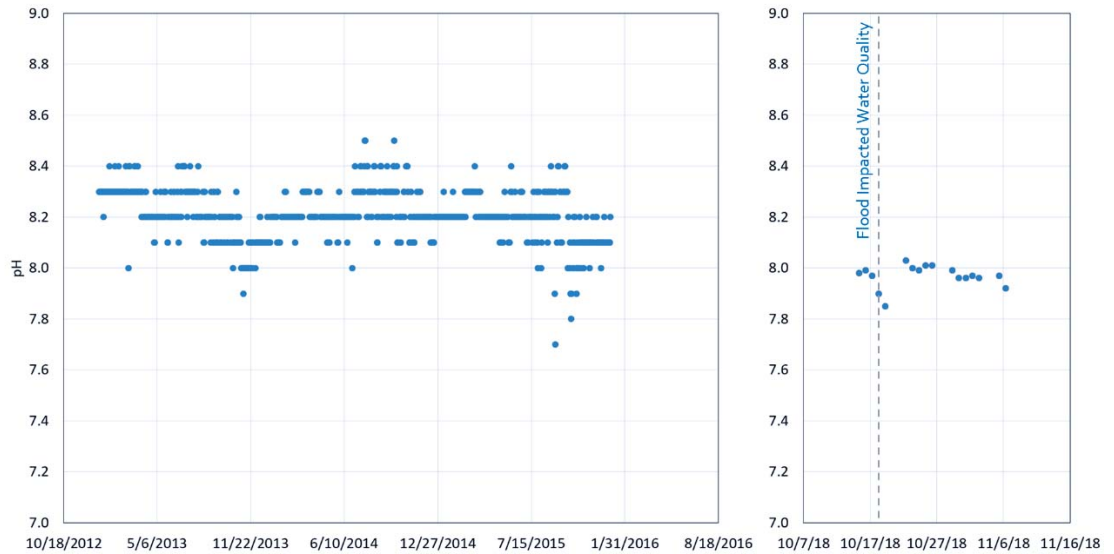


Figure 2 Raw Water pH - Historical (Left) and Flood Event (Right)

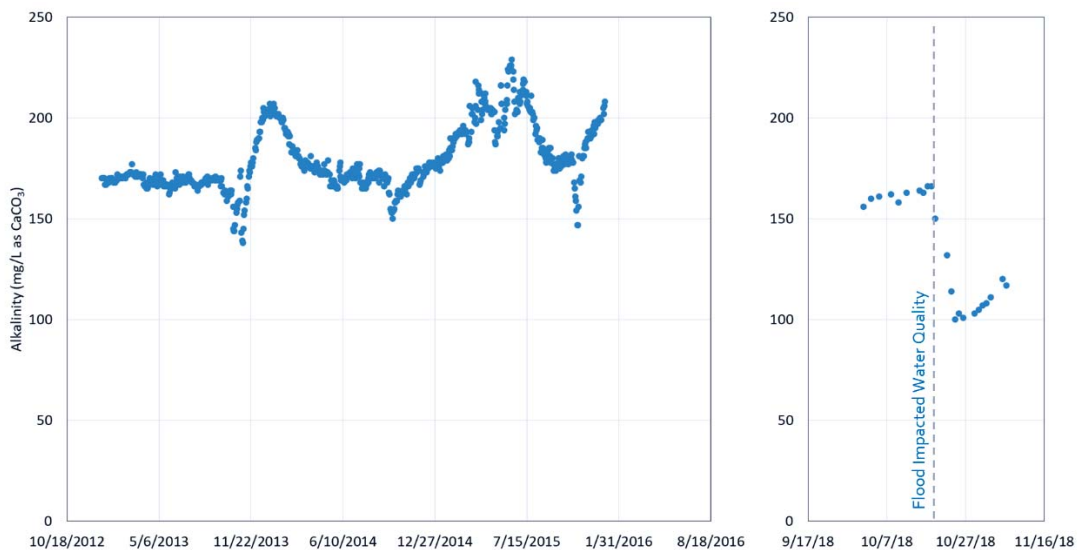


Figure 3 Raw Water Alkalinity - Historical (Left) and Flood Event (Right)

### 1.3 Hardness

Hard water may be characterized as a water that does not lather well, causes scum in the bathtub, and leaves hard, white, crusty deposits on coffee pots and water heaters. The primary components of total hardness are dissolved calcium and magnesium ions (divalent cations). Total hardness is expressed as an equivalent quantity of calcium carbonate (CaCO<sub>3</sub>). Waters having less than 75 mg/L as CaCO<sub>3</sub> are generally considered soft; levels between 75 and 150 mg/L as CaCO<sub>3</sub> are considered moderately hard, and levels greater than 150 mg/L as CaCO<sub>3</sub> are considered hard.

Figure 4 shows that during the flood event, total hardness dropped from 190 mg/L as  $\text{CaCO}_3$  to a low of 88 mg/L as  $\text{CaCO}_3$ . As expected, the decrease in total hardness was accompanied by a drastic decrease in the calcium (Figure 5) and magnesium (Figure 6) concentrations in the raw water.

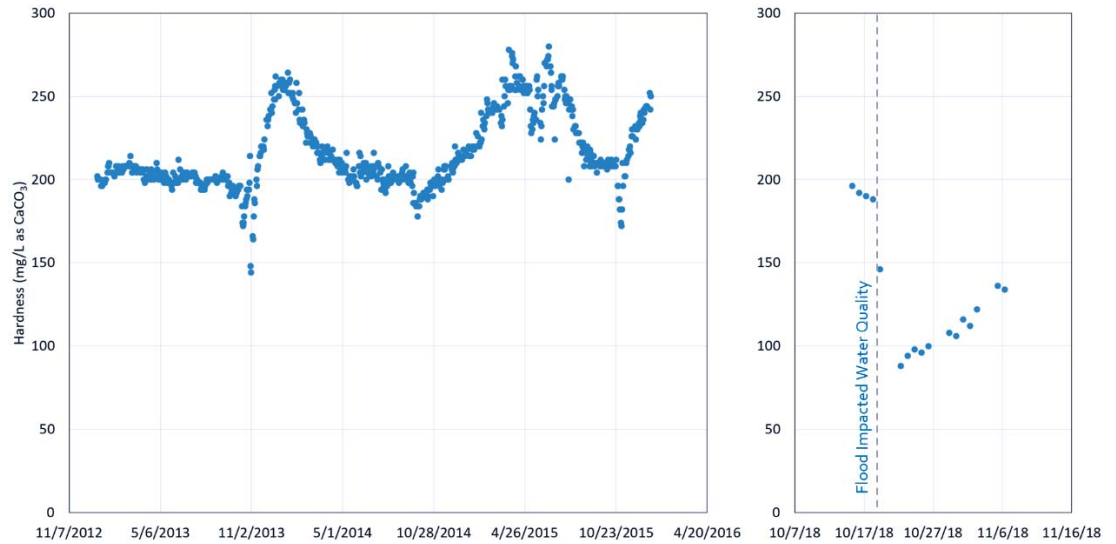


Figure 4 Raw Water Total Hardness - Historical (Left) and Flood Event (Right)

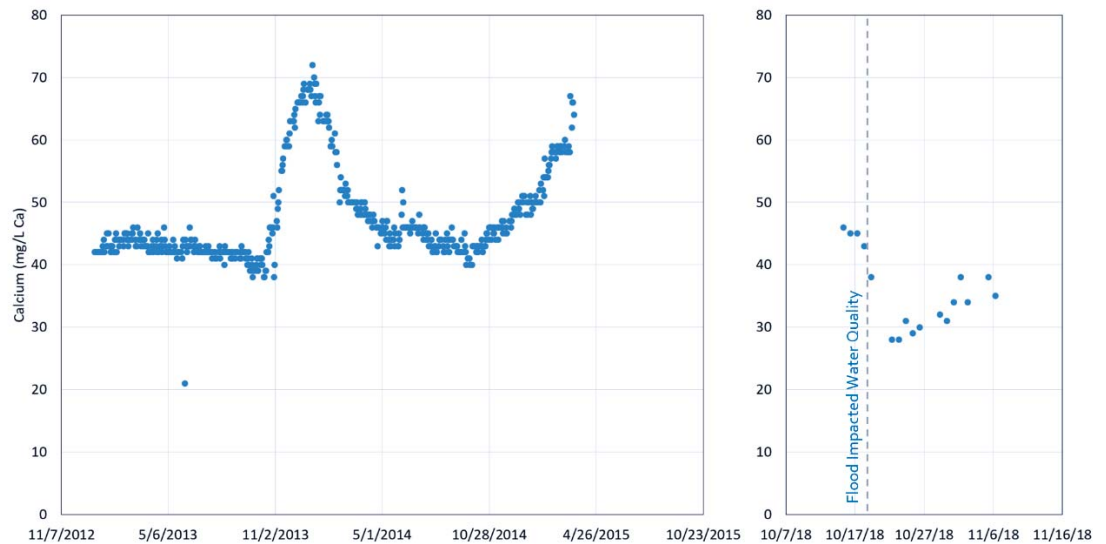


Figure 5 Raw Water Calcium - Historical (Left) and Flood Event (Right)



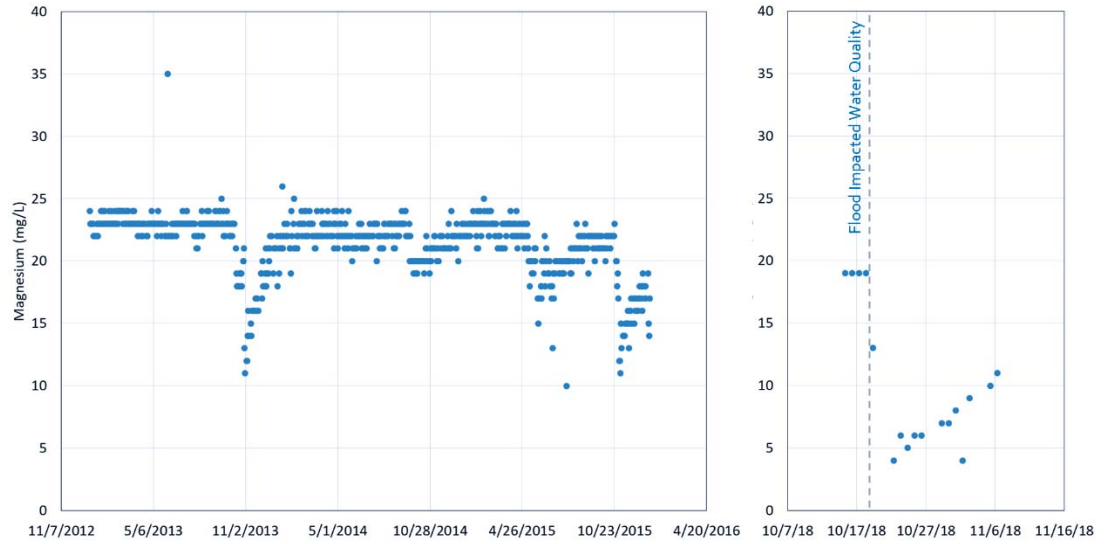


Figure 6 Raw Water Magnesium - Historical (Left) and Flood Event (Right)

#### 1.4 TOC

Total organic carbon (TOC) is a measure of the organic carbon, both particulate and dissolved, in a water. TOC is a useful parameter in gauging natural organic matter (NOM) concentrations in water. Some TOC constituents are precursors to the formation of regulated disinfection by-products (DBPs) and can also result in colored water. Increased TOC concentrations generally result in higher coagulant demand to achieve TOC removal goals.

Figure 7 shows that the TOC concentration doubled during the flood event from 3.44 to a peak of 7.78 mg/L. The TOC slowly decreased for weeks after the event.

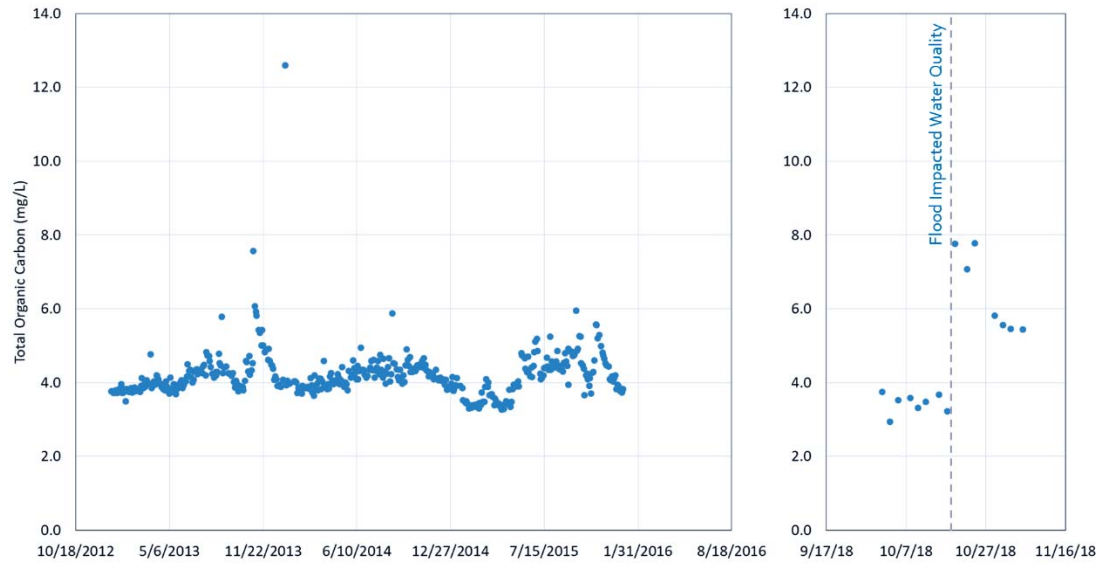


Figure 7 Raw Water Total Organic Carbon (TOC) - Historical (Left) and Flood Event (Right)

## Section 2

# LIMITATIONS OF EXISTING WTP FACILITIES

All three of the City's WTPs use lime softening coupled with filtration and chemical disinfection to treat water from the Lower Colorado River to meet all of the federal and state drinking water regulations. The City is a long-time member of the Partnership for Safe Drinking Water Program, historically producing filtered water with turbidities below 0.10 NTU.

Figure 8 and Figure 9 show the process flow diagrams for Ullrich (167 mgd), Handcox (50 mgd), and Davis (120 mgd) WTPs. The treatment processes for the WTPs are similar with the main exception being the use of conventional sedimentation basins at Davis WTP in contrast to upflow solids contact clarifiers at Ullrich and Handcox WTPs. Chlorine and ammonia are added to the raw water to form chloramines for disinfection. Ferric sulfate is added, typically at a low dose of approximately 15 mg/L as solution, to assist in organics removal and particle destabilization. This ferric sulfate solution is approximately 12 percent iron by weight, yielding a typical dose of 1.8 mg/L as Fe. Lime is added after ferric sulfate to raise the pH for precipitative softening of calcium carbonate ( $\text{CaCO}_3$ ) to meet finished water hardness goals. Lime is typically added at the WTPs to achieve a settled water pH of 10.0 to 10.2, corresponding to a minimum settled water calcium concentration and minimal magnesium precipitation. The softened water is recarbonated to a pH of approximately 9.6 prior to filtration to meet finished water stability goals. Sodium hexametaphosphate (SHMP, a sequestering agent) is also added prior to filtration to prevent excessive scale formation on filter media, underdrains, and distribution system piping. The calcium carbonate precipitation potential (CCPP) in finished water from the City's WTPs is typically 14 mg/L as  $\text{CaCO}_3$ . CCPP is an index that provides an indication of the  $\text{CaCO}_3$  scale forming tendency of water. The American Water Works Association (AWWA) recommends a CCPP range of 4-10 mg/L as  $\text{CaCO}_3$  in finished water to minimize pipe corrosion, while avoiding excessive scale formation (but this recommendation does not consider the effects of SHMP).

At Ullrich and Handcox WTP, solids settled in the solids contact clarifiers are conveyed to gravity thickeners. Supernatant from the gravity thickener is conveyed to the washwater recovery basins. The thickened solids are further concentrated through centrifuges. Cake from the centrifuges is hauled offsite.

Sedimentation basin solids at the Davis WTP are conveyed to an equalization tank. A portion of the residuals are recycled to the head of the plant, while the remainder is sent to the centrifuges for dewatering.<sup>1</sup> Overflows from the solids handling process are routed to the sewer.

Spent filter backwash water at all three WTPs is conveyed to washwater recovery basins. The decant from the recovery basins is recycled to the head of the plant at less than 10 percent recycle rate in compliance with the Filter Backwash Recycling Rule.

<sup>1</sup> Approximately 2/3 is recycled to the head of the WTP and 1/3 sent to the solids dewatering facility (Source: Davis Water Treatment Plant Solids Management Evaluation. Kennedy Jenks Consultants. August 20, 2009).

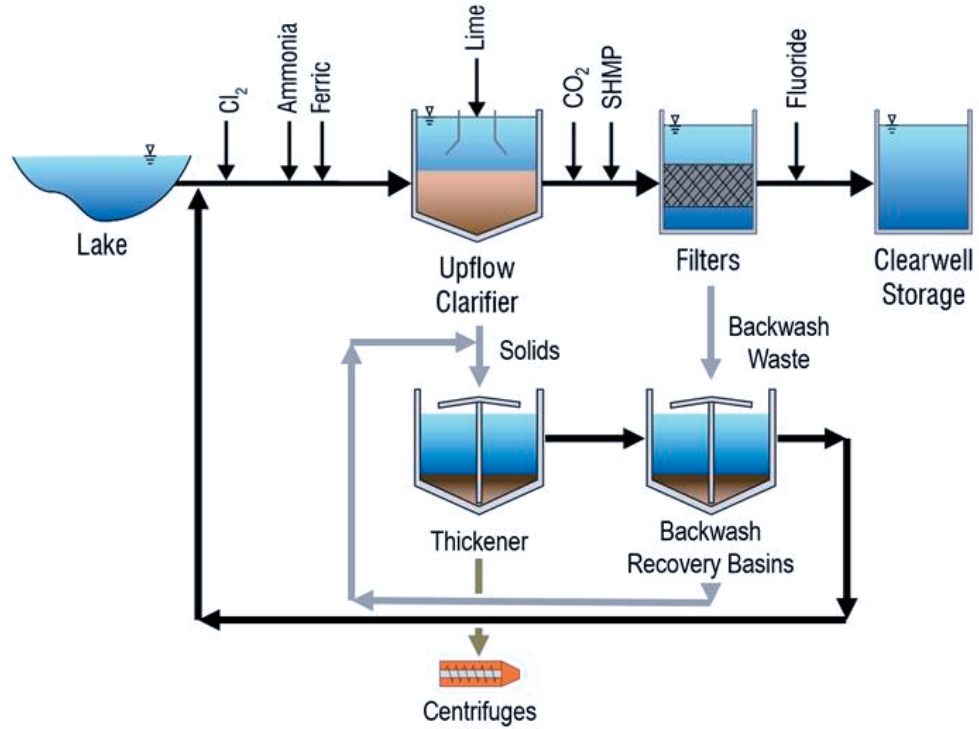


Figure 8 Process Flow Diagram for Ullrich WTP (167 mgd) and Handcox WTP (50 mgd)

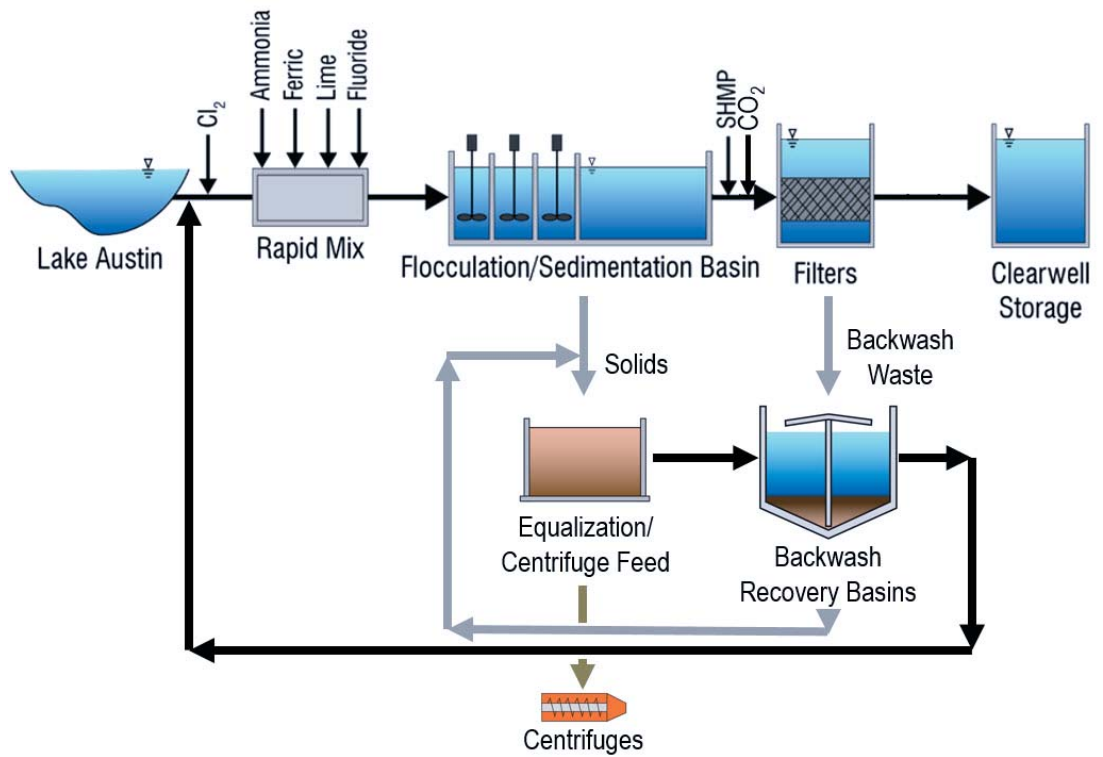


Figure 9 Process Flow Diagram for Davis WTP (120 mgd)

Table 2 and Table 3 list the design criteria for the clarifiers and filters at the Ullrich and Handcox WTPs, and the Davis WTP, respectively. Design criteria for the gravity thickeners and centrifuges are provided in Section 5 along with a discussion of the impact of the flood event on the residuals handling capacity.

The clarifiers at the Ullrich and Handcox WTPs operate at higher surface overflow rates than those at the Davis WTP, reflecting the fact that solids contact clarifiers are designed differently and are capable of higher loading rates compared to conventional sedimentation basins. All three plants typically operate with mixing speeds selected to keep the relatively dense  $\text{CaCO}_3$  solids in suspension to continue growing prior to sedimentation.

Table 2 Design Criteria for Ullrich WTP and Handcox WTP

WTP	Clarifier Loading Rate (gpm/ft <sup>2</sup> )	Center Well Mixing Energy, G (s <sup>-1</sup> )	Max Filter Loading Rate (gpm/ft <sup>2</sup> )
Ullrich	1.2 – 1.4	100 <sup>(1)</sup>	7.6
Handcox	1.6	55 <sup>(2)</sup>	7.6

Notes:

(1) Calculated from turbine speed.

(2) Handcox WTP upflow clarifier O&M manual.

Table 3 Design Criteria for Davis WTP

WTP	Sedimentation Basin Loading Rate (gpm/ft <sup>2</sup> )	Flocculation Mixing Energy, G (s <sup>-1</sup> ) <sup>(1)</sup>	Max Filter Loading Rate (gpm/ft <sup>2</sup> )
Davis	0.75	Stage 1 = 80 Stage 2 = 65 Stage 3 = 56	5.0

Notes:

(1) Davis WTP flocculator O&M manual.

The Ullrich and Handcox WTPs are designed to operate as lime softening plants with operation targeted towards reduction in hardness. Under typical operation, influent turbidities are low and hardness is moderate to high. Dense, highly settleable  $\text{CaCO}_3$  solids are formed in the clarifiers. The high mixing speed and high surface overflow rate reflect those typical operational conditions. During the flood event, the influent water quality was not directly conducive to operating under these original design assumptions. Turbidities were high and hardness was low; therefore the performance requirements shifted from hardness removal to turbidity removal. High concentrations of watershed-derived particles that translate to high influent turbidity are less dense than  $\text{CaCO}_3$  particles and negatively charged. Charge neutralization is a key mechanism for removing these negatively-charged particles in the coagulation process, requiring a different operational philosophy than typical for all three WTPs. Continued operation to achieve a settled water pH of 10.2 at a low ferric sulfate dose was not sufficient to neutralize and remove the negatively charged particles associated with the flood event. Thus, the WTPs either needed to operate at a significantly reduced flow and/or be equipped to neutralize charge without using ferric sulfate, due to its acidic nature and low density particle production.

Several aspects of the existing WTP facilities constrained the ability to make operational adjustments to respond to the change in raw water quality during the flood event. The characteristics listed below focus primarily on Ullrich WTP since that was where Carollo engineering staff focused their efforts during the flood event. Where common limitations are known for the Davis and Handcox WTPs, those similar constraints are noted as well.

- The City's WTPs currently have five variables or "knobs" to adjust for the softening and sedimentation process:
  - Lime dose.
  - Ferric sulfate dose.
  - Mixing speed.
  - Recirculation rate (solids removal rate, duration, and solids concentration in the center cone).
  - Flow (surface overflow rate).

Provision of additional tools to aid in particle destabilization and removal could provide operational flexibility needed for a more robust process during a similar extreme water quality event.

- The filtration process at the City's WTPs have two primary operational variables:
  - Flow (filter loading rate).
  - Filter run times before a backwash.
- The clarifier impellers/turbines at the Ullrich and Handcox WTPs are designed and typically operated at higher mixing speeds than targeted for a plant designed for conventional coagulation and removal of higher concentrations of watershed-derived particles (i.e., higher influent water turbidities) via metal salt (ferric sulfate) coagulation. Due to constant speed equipment, adjusting the turbine mixing speed requires physical replacement of mechanical gears, which cannot be done quickly. The inability to quickly reduce the mixing speed hindered successful operation and conversion to a conventional coagulation approach, which in theory, could be a successful way to treat water exhibiting the characteristics observed during the October 2018 flood event as long as the hydraulic loading rates of the clarifiers were also reduced.
- The capacity of the gravity thickeners were exceeded due to the increase in the volume and mass of solids that were less settleable than those of typical operation.
- Filter run times were reduced due to the challenge associated with particle removal in the clarifiers and carryover of particles. The backwash recovery basins were overwhelmed by the need to backwash the filters more frequently and the overflow could not be managed onsite. Additional capabilities to remove those residuals or reduce the filter solids loading would provide flexibility during a similar extreme water quality event.

One of the operational changes that worked during the flood event was to add sufficient lime to promote magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ) precipitation (corresponding to a settled water pH > 10.5). However, a drawback of this operational approach was the potential for  $\text{CaCO}_3$  re-precipitation in the filter influent water as illustrated in Figure 10. This operational approach resulted in a higher calcium concentration in the settled water because all of the raw water carbonate was exhausted. Because of the higher calcium concentration and settled water pH, a lower recarbonation pH was required to limit the precipitation of  $\text{CaCO}_3$  particles in the settled water prior to filtration. Recarbonation adds carbonate back to the water. During the flood event, the  $\text{CO}_2$  feed system capacity limited the ability to add sufficient  $\text{CO}_2$  to reduce the pH and prevent  $\text{CaCO}_3$  from precipitating in the filter influent water during operation at higher softened water pH. Due to kinetics of the precipitation process, even with sufficient recarbonation capacity, precipitation may still occur as the pH is reduced. Precipitating minerals on the filter media could impact processes by reducing filter runtimes and increasing headloss.



Figure 10 Precipitation in Filter Supernatant

## Section 3

# BENCH-SCALE TESTS

Testing was conducted during the flood event both at bench- and full-scale to identify optimal operational conditions to keep the plants running to meet system demands and TCEQ finished water quality requirements. Tests focused on operational conditions that could be rapidly employed during the flood event and included an assessment of the optimal lime and ferric sulfate dose, solids contact clarifier recirculation and blowdown rate, and the use of coagulant and flocculant aid polymers. Table 4 shows the raw water quality during bench scale testing. The turbidity was highest on the first day of testing and gradually decreased as the impact of the flood event on water quality lessened throughout the next 10 days. Likewise, the hardness concentration was lowest on the first day of testing and gradually increased over the next 10 days.



Table 4 Raw Water Quality during Bench Scale Testing

Parameter	10/23	10/24	10/25	10/26	10/29	10/31	11/1	11/2
pH, s.u.	8.00	7.99	8.01	8.01	7.99	7.96	7.97	7.96
Turbidity, NTU	199	118	124	98	84	54	44	---
Alkalinity, mg/L CaCO <sub>3</sub>	114	100	103	101	103	107	108	111
Total Hardness, mg/L CaCO <sub>3</sub>	94	98	96	100	108	116	112	122
Calcium, mg/L	28	31	29	30	32	34	38	34
TOC, mg/L	---	7.78	---	---	5.82	5.56	---	5.46

The 2-liter jars of a standard jar test apparatus have a sample tap located 10 cm below the top of the water to allow the sampling of small quantities of settled water for turbidity measurements. The location of the tap facilitates sample collection and analysis of settled water turbidity at times that correspond to the surface overflow rate in the WTP clarifiers, depending on plant production rates. Table 5 shows the settling time versus simulated surface loading rate.

Table 5 Simulated Surface Loading Rate for Jar Testing

Settling Time (minutes)	Simulated Surface Overflow Rate (SOR, gpm/ft <sup>2</sup> ) <sup>(1)</sup>
4	0.61
5	0.49
6	0.41
10	0.25
20	0.12

Notes:

(1) Sample port located 10 cm below the water surface.

The 2-L jars used for testing are not a perfect representation of solids contact clarifiers, since in jars, solids are only formed in a batch after chemical addition and solids do not build size over time. In solids contact clarifiers, solids are continuously formed and recirculated to achieve high solids concentrations and size. However, jar tests are still useful as a benchmark for relative comparison of settleability between different treatment options.

### 3.1 Softening at pH > 10.5

Early in the flood event, City process engineers observed improved settleability by adding lime to achieve a softened water pH > 10.5, with additional improvement from increasing the ferric sulfate dose. Jar tests were conducted to assess whether similar results were observed when compared to a range of conditions for lime and ferric sulfate addition. Figure 11 and Figure 12 show that softening in the high pH range where  $\text{Mg}(\text{OH})_2$  precipitates (i.e., pH > 10.5) resulted in lower settled water turbidity. Decreasing the surface overflow rate (SOR) from 0.56 gpm/sf to 0.40 gpm/sf improved settled water quality, reducing the settled water turbidity by approximately half. Increasing the ferric sulfate dose from 80 to 180 mg/L as solution did not have a large impact on settled water turbidity. Variations of the same test were conducted almost every day to confirm that those same operating conditions continued to result in optimal settled water turbidity.

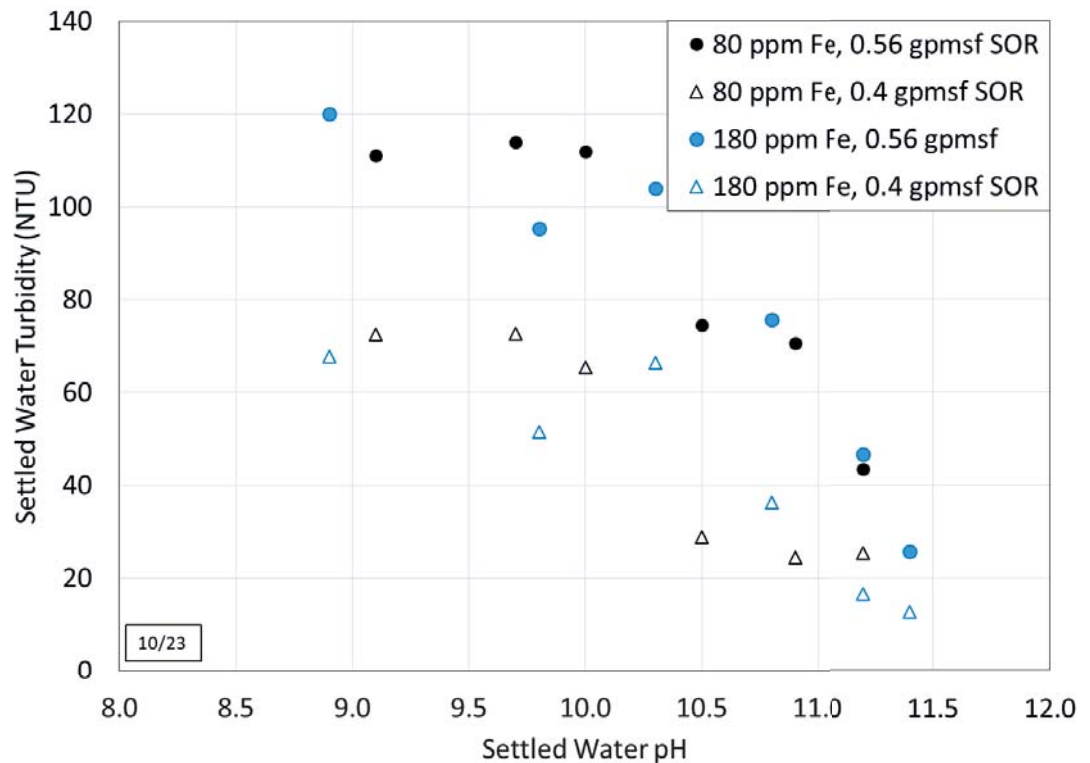


Figure 11 Impact of Ferric Dose (High Range), SOR, and pH on Settled Turbidity - 10/23/18

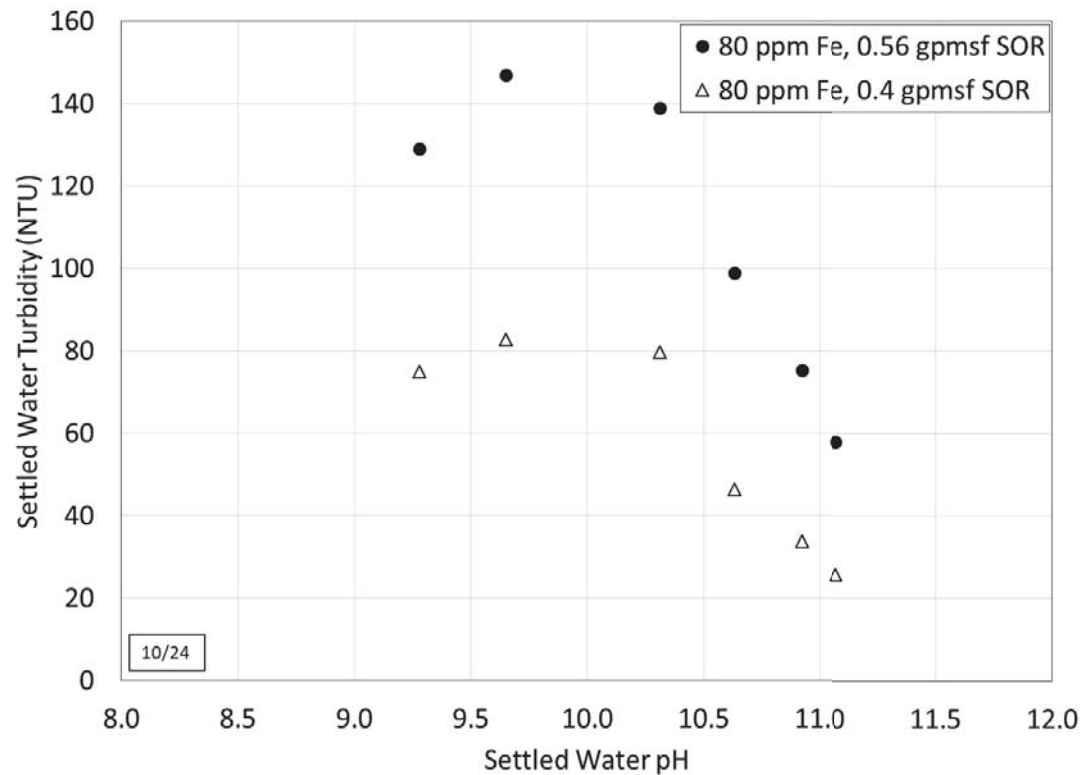


Figure 12 Impact of SOR and pH on Settled Turbidity - 10/24/18

On October 25, 2018, lower ferric sulfate doses were tested to assess whether the WTPs could reduce the dose in response to the gradually lower raw water turbidity. Figure 13 and Figure 14 show that increasing the ferric sulfate dose from 20 to 60 or 80 mg/L as solution, increasing the pH to over 10.5, and decreasing the surface overflow rate from 0.56 gpm/sf to 0.4 gpm/sf continued to improve settled water turbidity. The tests showed no clear benefit of operating at 80 versus 60 mg/L ferric sulfate as solution.

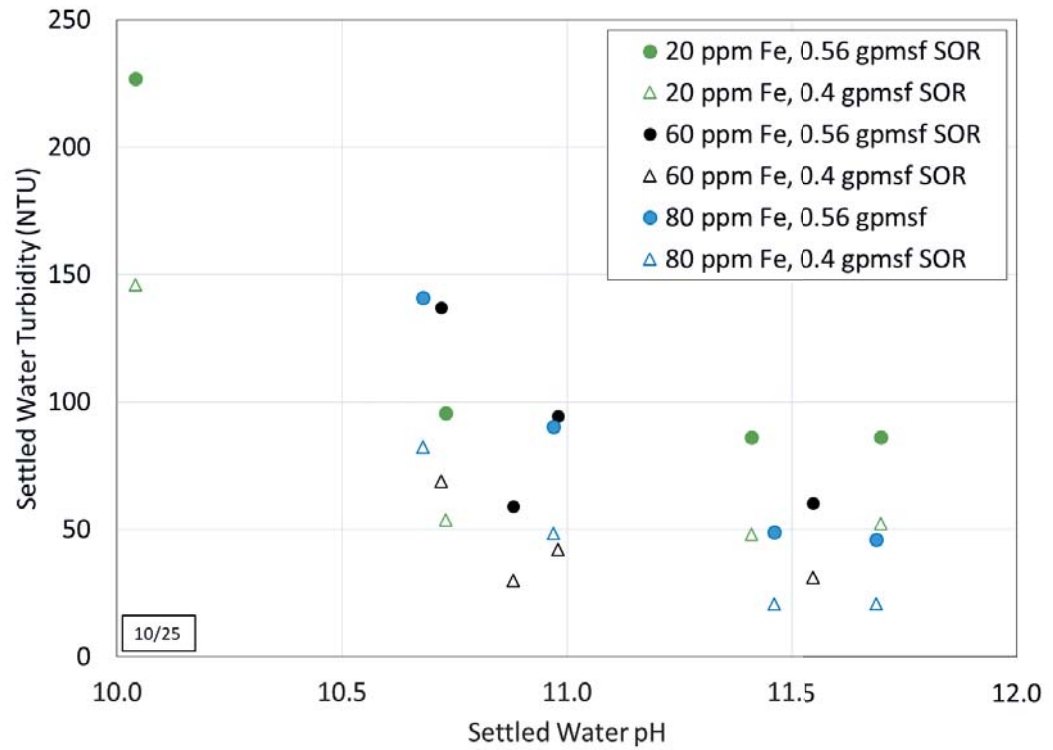


Figure 13 Impact of Ferric Dose, SOR, and pH on Settled Turbidity - 10/25/18

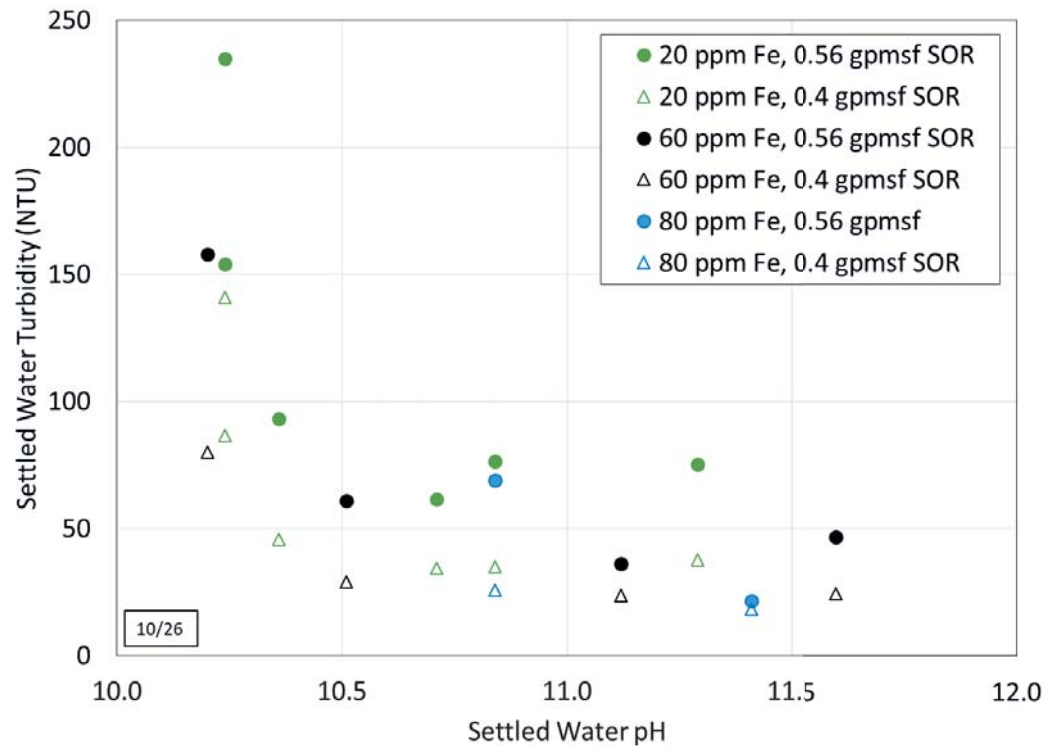


Figure 14 Impact of Ferric Dose, SOR, and pH on Settled Turbidity - 10/26/18

As the water quality slowly improved with lower turbidity and TOC in the days following the flood event, jar tests to find the optimal ferric sulfate dose to minimize settled water turbidity continued. Figure 15 shows that a ferric sulfate dose of 60 mg/L as solution achieved the best results for relative settled water turbidity for the November 1 raw water quality shown in Table 4.

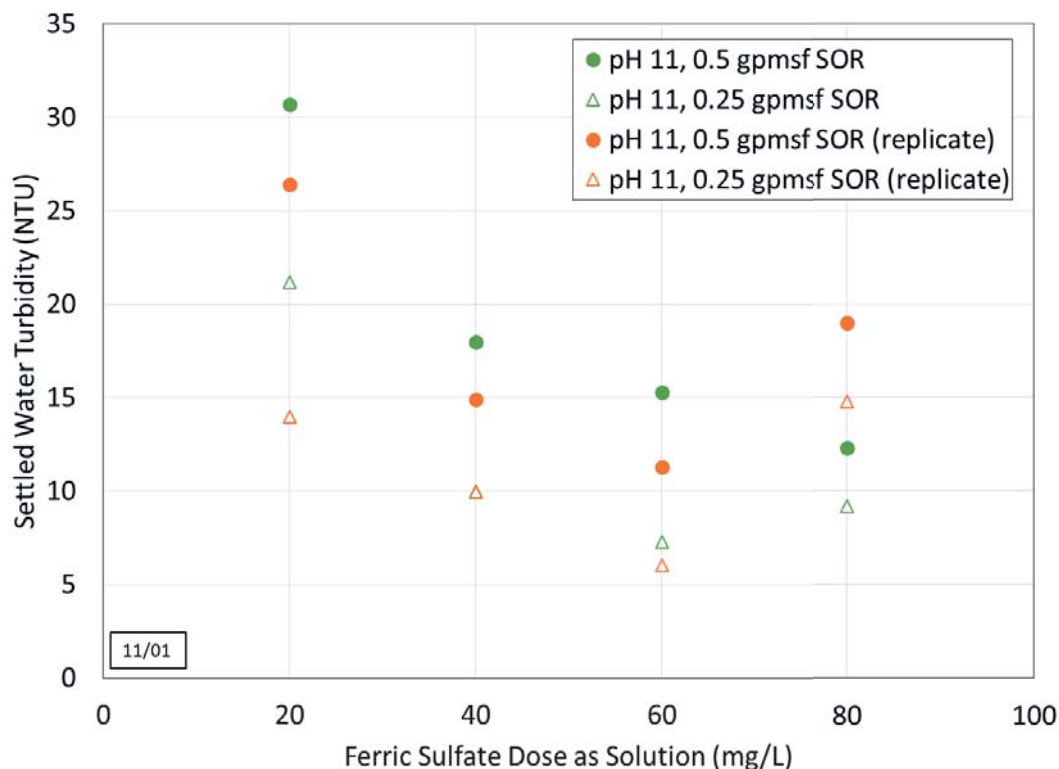


Figure 15 Impact of Ferric Dose on Settled Turbidity - 11/1/18

### 3.2 Conventional Treatment with Ferric Sulfate

Jar tests were performed to evaluate the effectiveness of conventional treatment with high ferric sulfate doses. Figure 16 and Figure 17 show that increasing the ferric dose from 15 to 200 mg/L as solution resulted in lower settled turbidity. In these jars, the pH was not adjusted and the settled water pH ranged from 7.5 to 6.2 (for ferric sulfate doses ranging from 15 and 200 mg/L, respectively). Comparing Figure 17 to Figure 18 shows that iron coagulation without pH adjustment (corresponding to settled water pH values from 6.2 to 7.5) achieved lower turbidities than coagulation with pH adjusted to 8.5-9.0, probably due to the charge neutralization capabilities of lower pH water.

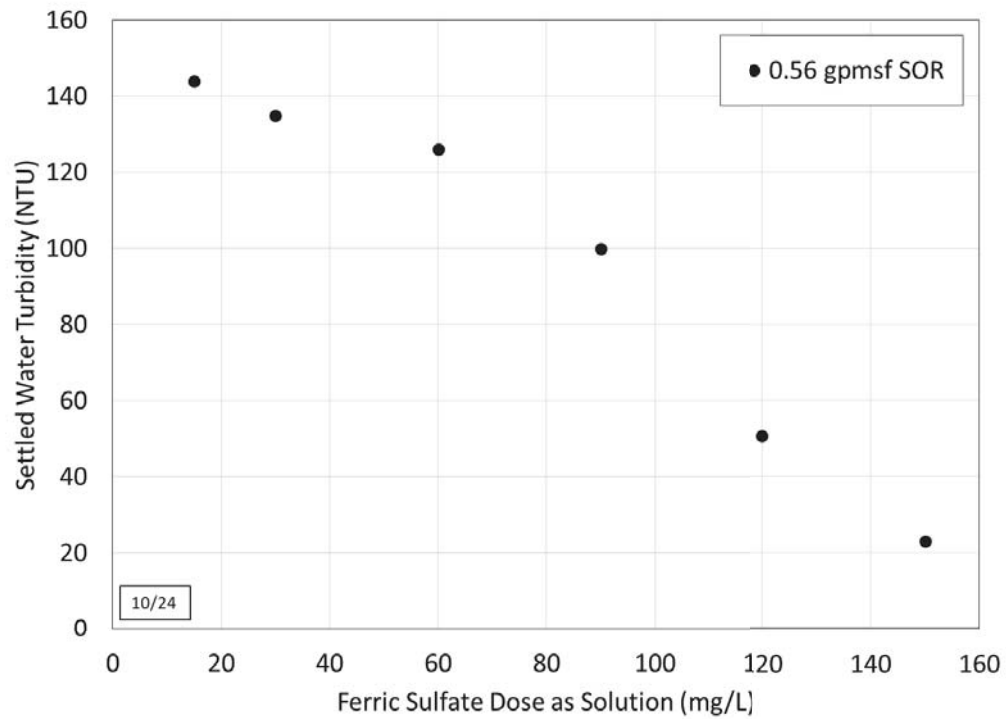


Figure 16 Impact of Ferric Dose on Settled Turbidity without pH Adjustment

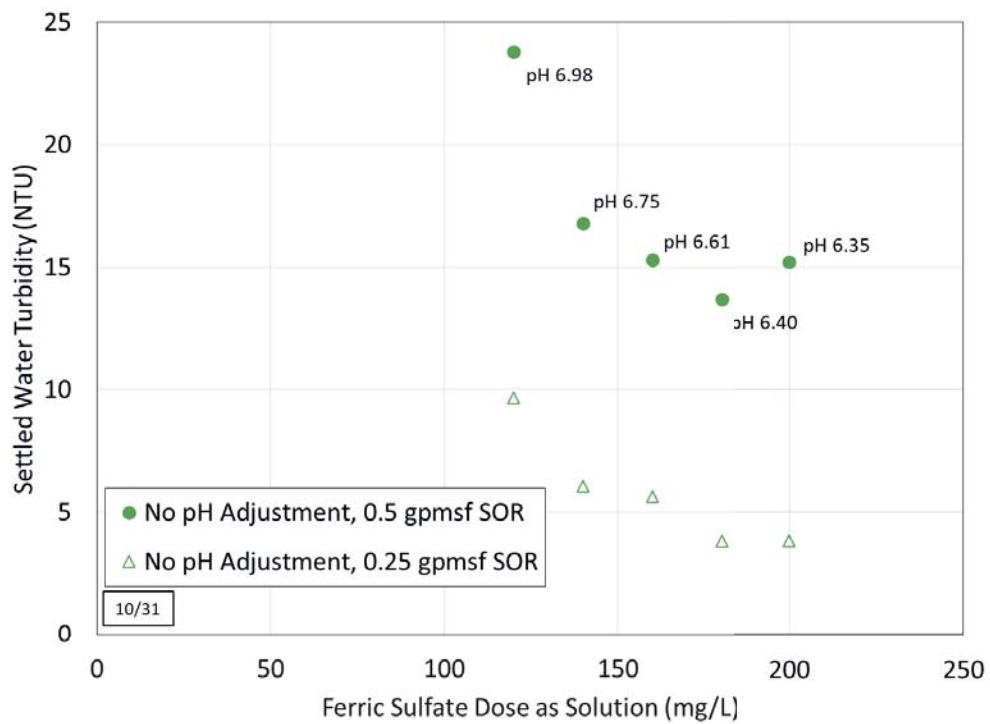


Figure 17 Impact of Ferric Dose (High Range) and SOR on Settled Turbidity without pH Adjustment



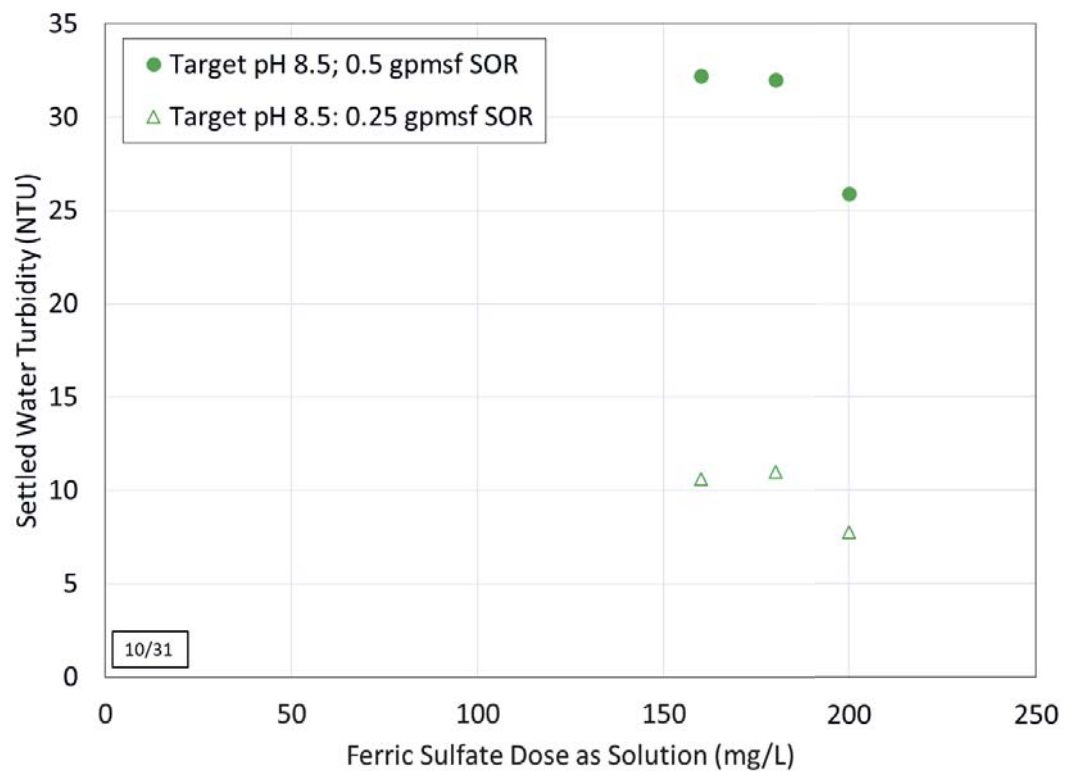


Figure 18 Impact of Ferric Dose (High Range) and SOR on Settled Turbidity at pH 8.5 - 9.0

The impact of the velocity gradient ( $G$ -value,  $\text{sec}^{-1}$ ) on treatment performance with iron coagulation was also evaluated. Normal operations at Davis WTP include three-stage tapered flocculation for 30 minutes consisting of velocity gradients of  $80 \text{ sec}^{-1}$ ,  $65 \text{ sec}^{-1}$ , and  $56 \text{ sec}^{-1}$ . The solids contact clarifiers (SCCs) at Ullrich and Handcox WTPs are designed for precipitation of dense calcium carbonate solids and normally operate at velocity gradients equal to 100 and  $55 \text{ sec}^{-1}$ , respectively. The SCCs have limited turndown capabilities due to their intent to precipitate dense calcium carbonate solids rather than flocculating the light, more fragile solids formed from coagulation with ferric sulfate. For comparison, 3-stage tapered  $G$ -values typical of conventional treatment with ferric sulfate are  $40\text{-}50 \text{ sec}^{-1}$ ,  $20\text{-}30 \text{ sec}^{-1}$ , and  $10\text{-}15 \text{ sec}^{-1}$ . Figure 19 shows the impact of velocity gradient on turbidity at the optimal ferric sulfate dose for conventional treatment at pH 9. The results demonstrated that high velocity gradients sheared the floc formed and reduced the settleability compared with operation at lower  $G$ -values more typically used for conventional coagulation.

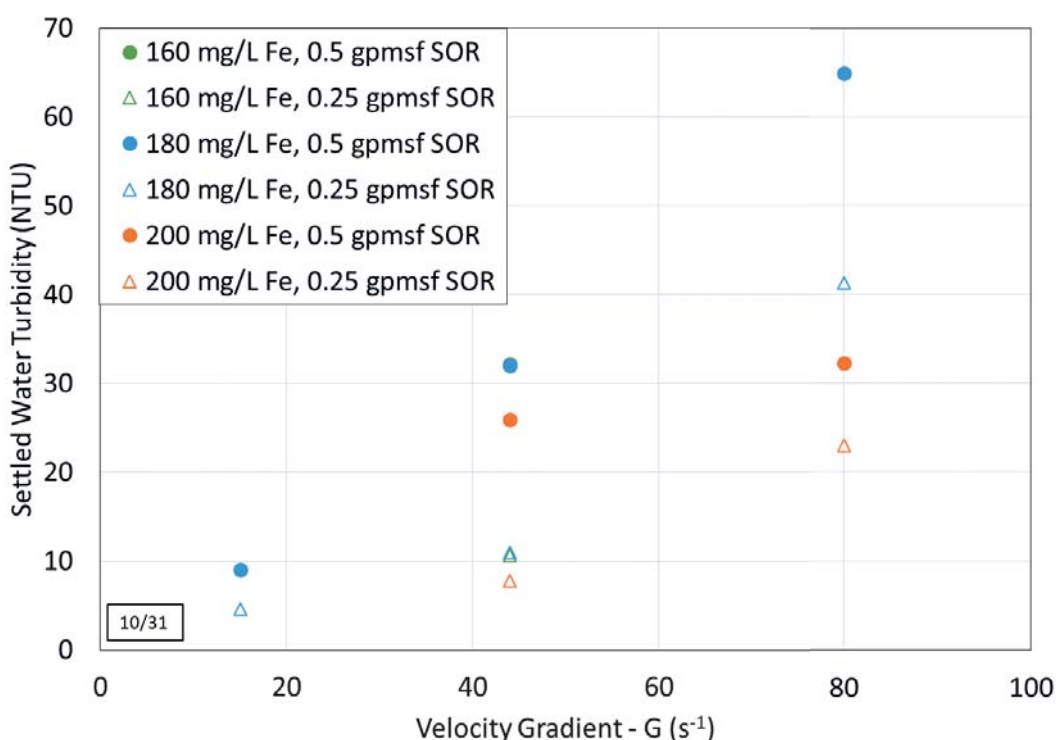


Figure 19 Impact of Ferric Sulfate Dose (Optimal Dose Range), SOR, and Velocity Gradient on Settled Turbidity at pH 9

While the jar tests conducted during the October 2018 flood event (and with banked water, Carollo 2019) illustrated that iron coagulation could in theory be a promising approach to treat flood event water, major changes to existing infrastructure would be required to make this operational scenario feasible full-scale. Switching to conventional treatment (coagulation with metal salts) will reduce pretreatment and filtration capacities, which would de-rate plant capacities because settling rates of conventionally coagulated particles are slower than lime softened particles. For example, in rectangular sedimentation basins, TCEQ requires a lower surface overflow rate for conventional treatment ( $0.6 \text{ gpm/ft}^2$ ) than softening ( $1.0 \text{ gpm/ft}^2$ ). To recover the lost capacity, plate settlers could be installed in the sedimentation basins at Davis WTP and in the clarifiers at Ullrich WTP. Plate settlers are not required at Handcox because the clarifiers are designed for 75 mgd, while the WTP is rated for 50 mgd. The conversion would also require changes to chemical storage and feed systems in response to different chemical requirements. For example, the addition of sodium hydroxide would likely be required after clarification to raise the pH higher than the settled water pH typical of iron coagulation to limit the likelihood of destabilizing pipe scale in the distribution system.

### 3.3 Polymer Addition

Polymer addition can help with managing water quality upset events. Polymers have several advantages over conventional metal salts, including forming stronger flocs that improve sludge dewatering performance (bridging polymers), reducing sludge volume due to lower dosages of metal coagulants (using low-molecular weight cationic polymers), and working effectively over a wide pH range (Kim 1995)<sup>2</sup>. Polymers can be anionic, nonionic, or cationic with regards to charge and vary in terms of molecular weight, ranging from  $10^4$  to  $10^7$  Daltons. Adding a polymer with a charge opposite that of particles in the water can aid in charge neutralization and coagulation/flocculation. Coagulant aid polymers (PEC) are typically low-molecular-weight and cationic. PEC destabilize colloidal suspensions through the same charge neutralization mechanism as metal salts like ferric sulfate, and may replace metal salts while reducing sludge volume<sup>2</sup>. Flocculant aid polymers (PEA) are typically high-molecular-weight and can be anionic, nonionic, or cationic. PEAs improve the flocculation process by bridging, forming larger flocs that settle more quickly<sup>2</sup>. Filter aid polymers are applied to the filter influent to improve particle filterability. The dose of filter aid polymers is typically low, reflecting the relatively low concentration of particles in the water applied to the filters.

Figure 20 shows the typical points at which polymer could be applied at the City's Ullrich and Handcox WTPs. Coagulant aid polymer can be applied before, simultaneously, or after the coagulant. The chemical application sequence can have a large impact on charge neutralization and corresponding settled water quality and chemical usage. Generally, waiting at least 5 seconds after dosing a coagulant to dose a coagulant aid polymer helps with charge neutralization and waiting at least 5 minutes after dosing a coagulant is necessary for optimal floc formation if using a flocculant aid, improving both the size and weight of the floc (Kawamura 1991)<sup>3</sup>. While not shown, a bridging polymer (PEA) could also be added to the influent to the gravity thickeners to augment the residuals handling capacity.

Coagulant aid and flocculant aid polymers were tested at the bench-scale for their impact on settleability during the flood event, either through charge neutralization or bridging.

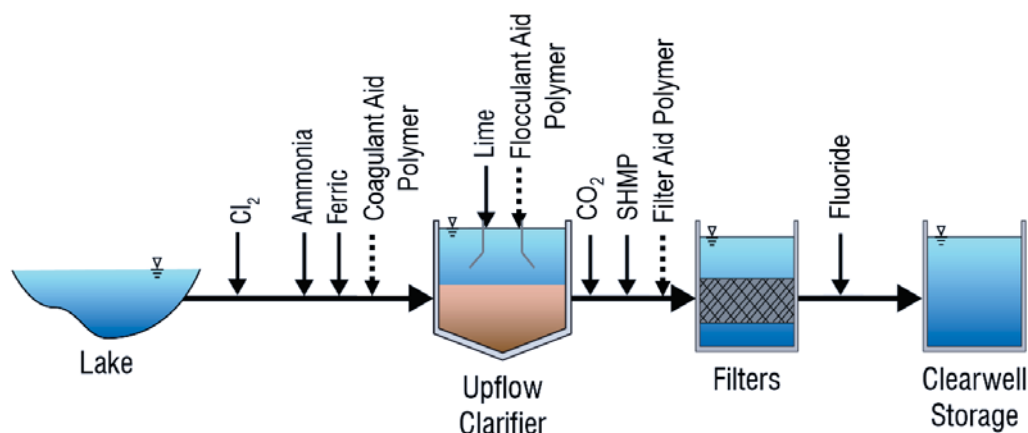


Figure 20 Typical Polymer Application Points for Ullrich and Handcox WTPs

<sup>2</sup> Kim, Yong H. (1995). *Coagulants and Flocculants: Theory and Practice*. Tall Oaks Publishing, Inc.

<sup>3</sup> Kawamura, Susumu. (1991). *Integrated Design of Water Treatment Facilities*. John Wiley and Sons, Inc.

A Zetasizer (Malvern Panalytical) was mobilized to the Ullrich WTP during the flood event to characterize the charge of particles present in the raw water and the impact of coagulant and PEC dose on charge neutralization. Figure 21 shows the results of zeta potential titrations with ferric sulfate and various PECs. Most of these PECs came from nearby utilities and local vendors. The positive charge of these cationic polymers neutralizes the negative charge of particles in the water, reducing repulsion and allowing them to flocculate when they collide and filter when passed through a dual media filter. Over 300 mg/L of ferric sulfate was required to neutralize particle charge at ambient pH (dosing 320 mg/L ferric sulfate depressed pH from 8.0 to 5.5), corresponding to a zeta potential of 0 mV. However, less than 20 mg/L of PEC was required to neutralize charge to a zeta potential near 0 mV. Table 6 shows that each one (1) mg/L dose of the various PEC tested was equivalent to approximately 15 or 30 mg/L of ferric sulfate in terms of particle charge neutralization.

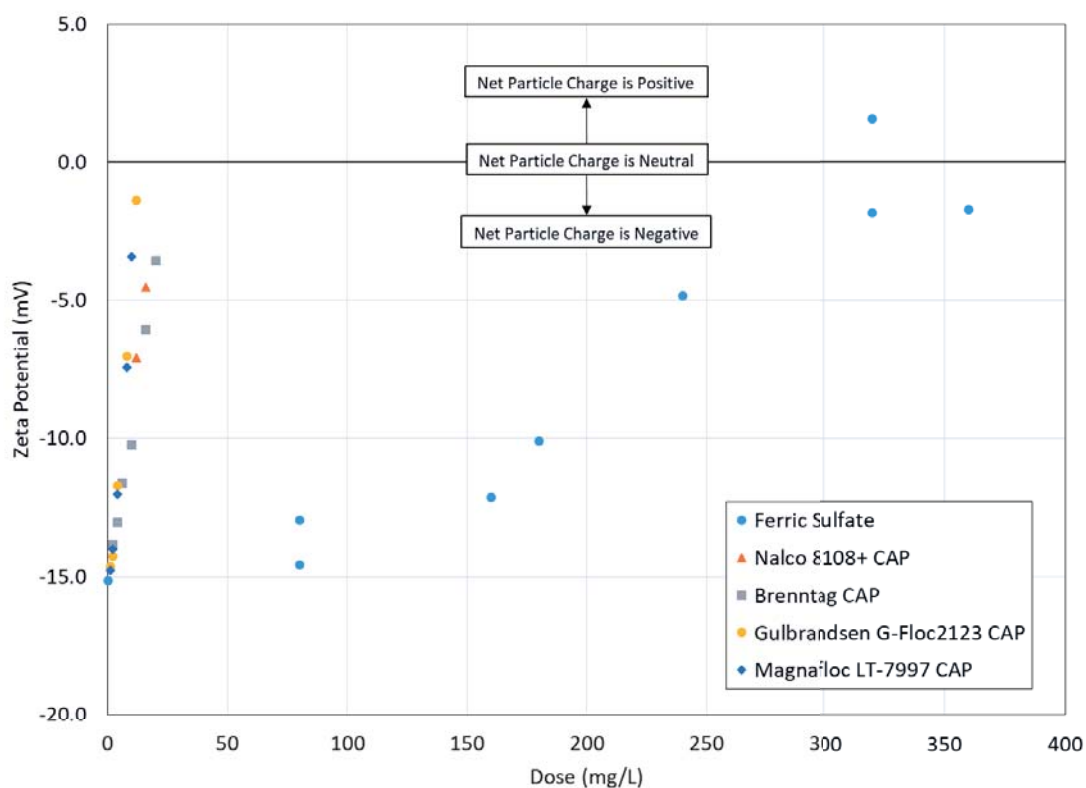


Figure 21 Zeta Potential Titration with Ferric Sulfate and Cationic Polymers

Table 6 Charge Equivalence

1 mg/L as product Cationic Polymer	Equivalent Ferric Sulfate Dose (mg/L as solution)
Nalco 8108+	15
Brenntag	15
Gulbrandsen G-Floc 2123	30
Magnafloc LT-7997	30

The coagulant aid polymers shown in Table 6 were evaluated in jar tests for their ability to neutralize highly negatively charged raw water and offset high doses of ferric sulfate. Adding a small dose of PEC can neutralize a large amount of charge and decrease the required ferric sulfate dose. Trading off ferric sulfate for polymer can result in more settleable solids with a lower total sludge volume and does not consume alkalinity (ferric sulfate is acidic and consumes alkalinity). Most of these jar tests simulated dosing polymer to the upflow clarifier raw water piping, based on available full-scale injection points. PEC was dosed during the rapid mix, followed by ferric sulfate 30 seconds later, then lime, and finally the rpm was reduced to 50 to target a velocity gradient of  $60 \text{ sec}^{-1}$ .

In the initial offset tests shown in Figure 22 and Figure 23, dosing 12 mg/L cationic polymer with only 20 mg/L ferric sulfate as solution achieved similar settled water turbidities to dosing 80 mg/L ferric sulfate.

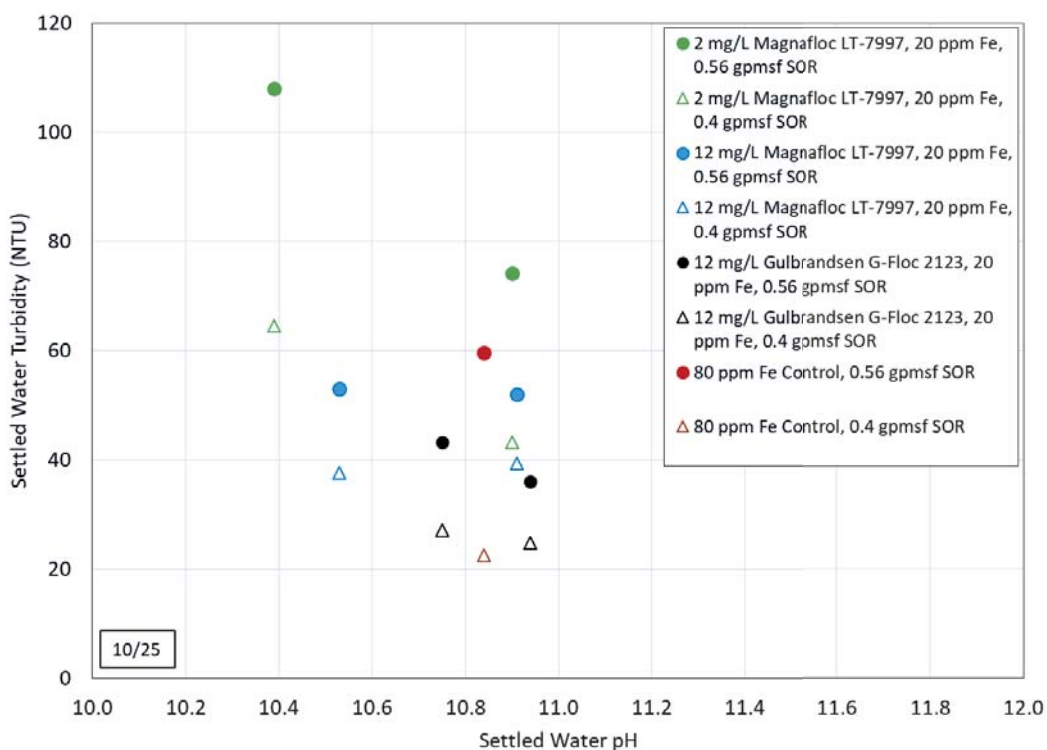


Figure 22 Impact of Offsetting Ferric Sulfate with Cationic Polymers on Settled Turbidity

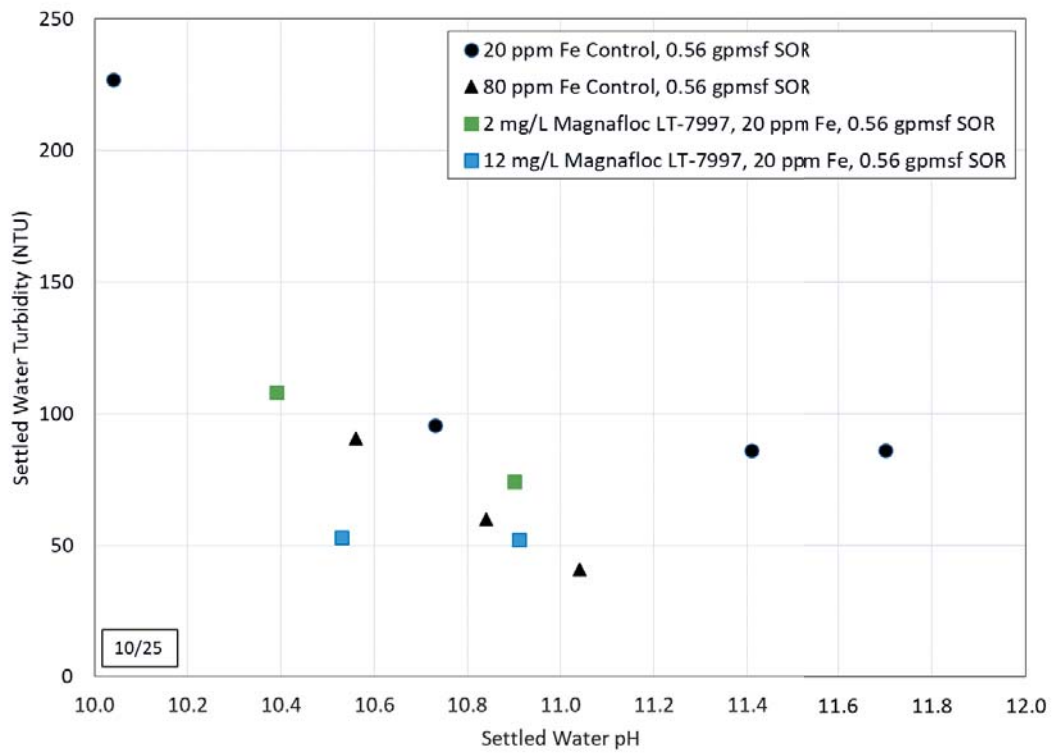


Figure 23 Impact of Offsetting Ferric Sulfate with Cationic Polymers on Settled Turbidity

Figure 24 and Figure 25 show that adding the Nalco Cat-floc 8108+ coagulant aid polymer with 20 mg/L ferric sulfate achieved a lower settled water turbidity than dosing 80 mg/L ferric sulfate or the other polymers tested above. The optimal dose of the Nalco 8108+ PEC was approximately 10 to 20 mg/L. Offsetting ferric sulfate with Nalco 8108+ PEC improved settled water turbidity at both pH 10.3 and 11 (Figure 25).

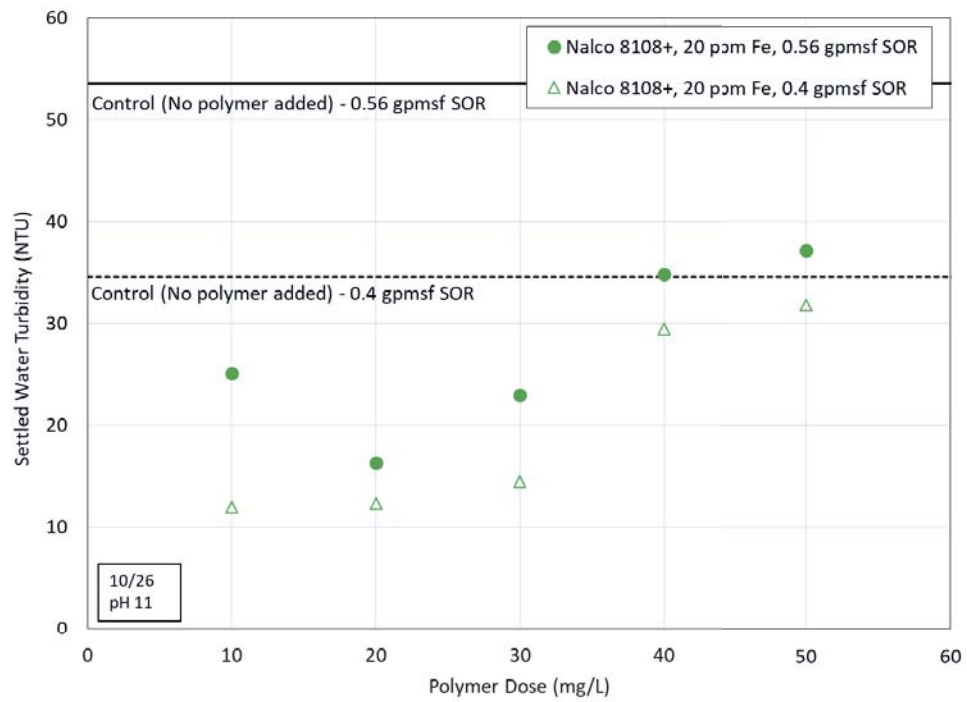


Figure 24 Impact of Offsetting Ferric Sulfate with Nalco 8108+ PEC (High Range) on Settled Turbidity

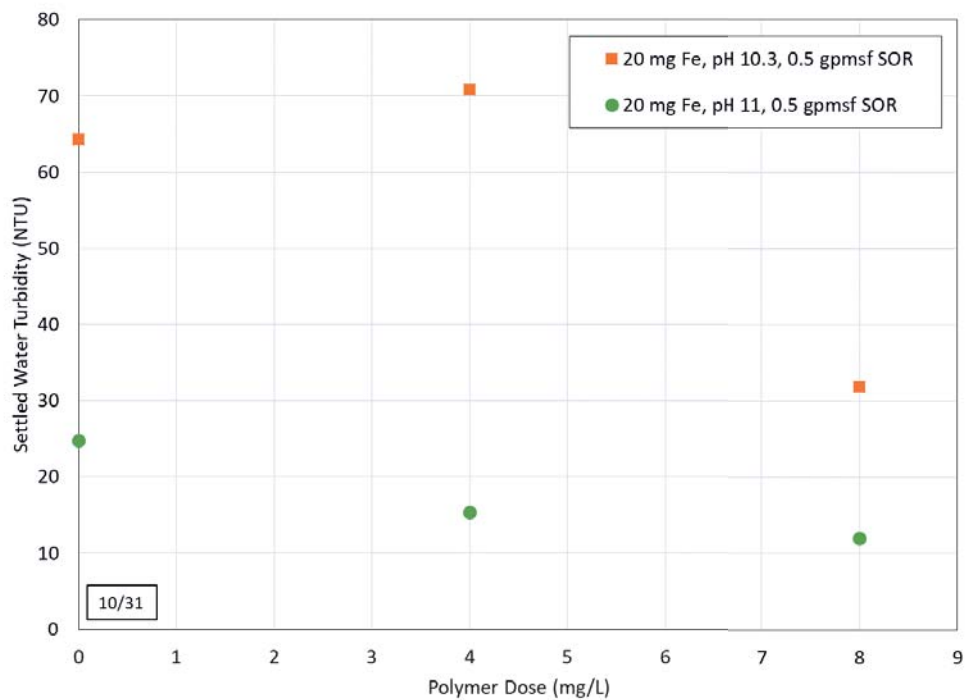


Figure 25 Impact of Offsetting Ferric Sulfate with Nalco 8108+ PEC (Low Range) on Settled Turbidity

Jars were filled with solids collected from the basin center wells to test the impact of chemical addition to center wells at the bench-scale. These jar tests simulated solids behavior in the solids contact clarifier mixing wells. Solids were collected from the top of the mixing wells of Basins 6-8. The Nalco 8108+ PEC was selected for testing with mixing well solids based on the low settled water turbidity results it achieved with raw water. Figure 26 and Figure 27 show the results for simulating polymer addition to the solids contact clarifier mixing well after ferric sulfate and lime addition. The controls shown are for settled water turbidity of mixing well solids without polymer addition. Figure 27 shows that adding Nalco 8108+ PEC to mixing well solids vastly improved solids settling at doses as low as 1 mg/L.

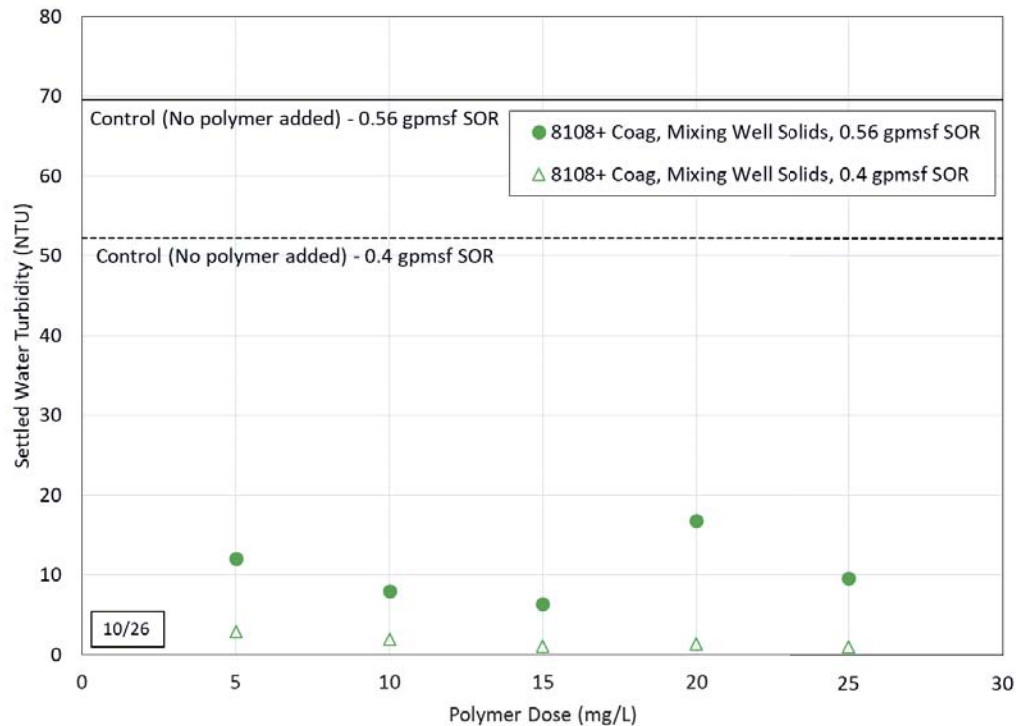


Figure 26 Impact of Offsetting Ferric Sulfate with Nalco 8108+ PEC (High Range) on Mixing Well Solids Settling



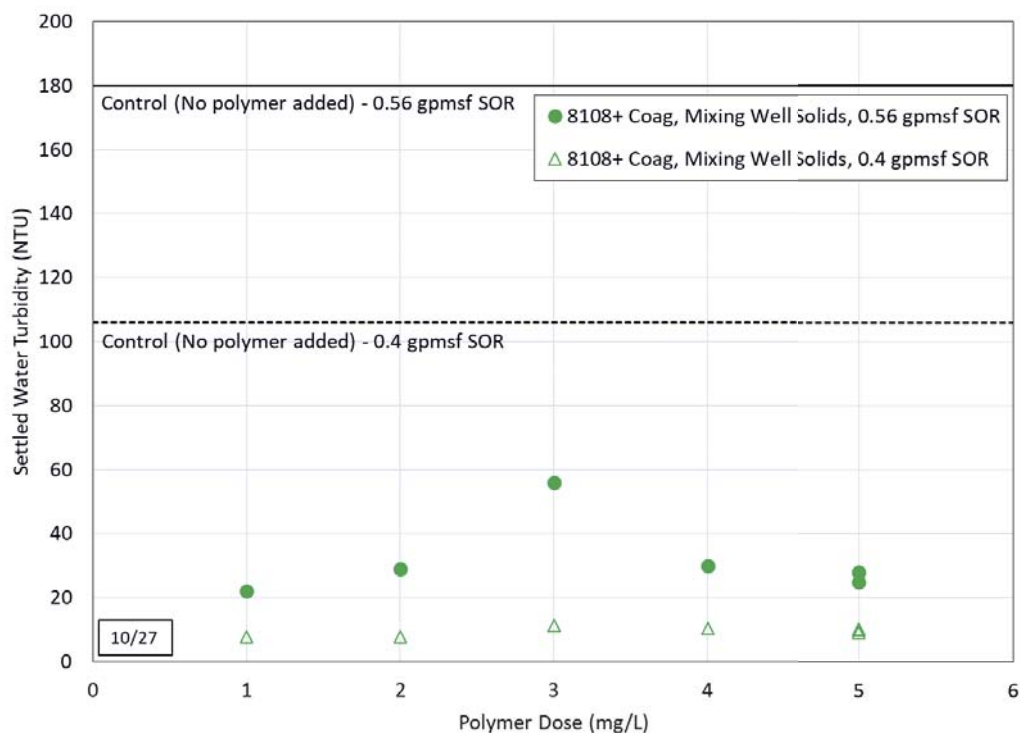


Figure 27 Impact of Offsetting Ferric Sulfate with Nalco 8108+ PEC (Low Range) on Mixing Well Solids Settling

Two non-ionic polyacrylamide flocculation aid polymers, Nalco Nalclean 8181 and Nalco Optimizer 7128, were evaluated for their impact on settled water turbidity. Low doses of flocc aid polymer were added after 80 mg/L of ferric sulfate and lime targeting pH 10.2 and 11, experiments with and without magnesium removal, respectively. Figure 28 and Figure 29 show that these flocc aid polymers had minimal impact on settled water turbidity. Due to the large proportion of small particles formed in a conventional jar test and since flocculation aid polymer dose should be proportional to the number of flocs, this test was not representative of the potential benefits of flocc aid polymer. Therefore, the next test involved adding flocc aid polymer directly to a jar of center well solids to simulate a solids contact clarifier center well.

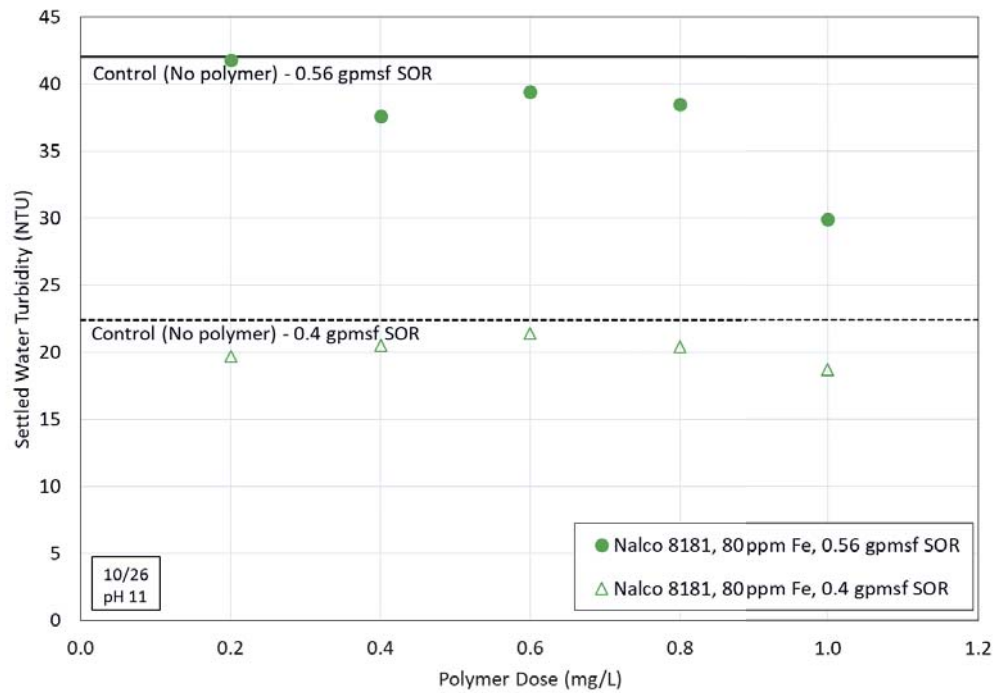


Figure 28 Impact of Nalco 8181 Flocculation Aid Polymer on Settled Turbidity

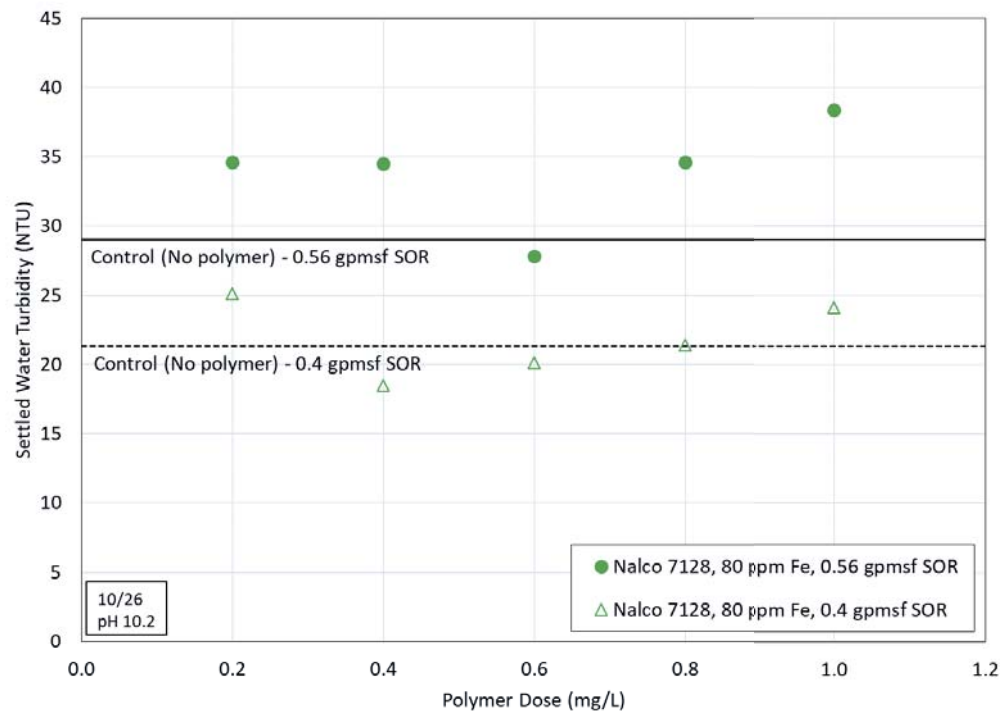


Figure 29 Impact of Nalco 7128 Flocculation Aid Polymer on Settled Turbidity

The Nalco 7128 floc aid polymer was selected for testing with solids contact clarifier mixing well solids. Figure 30 shows the results for simulating floc aid polymer addition to the mixing well after ferric sulfate and lime addition. The controls shown are for settled water turbidity of mixing well solids without polymer addition. Dosing Nalco 7128 floc aid polymer to mixing well solids vastly improved solids settling at doses as low as 0.2 mg/L, and even more at doses up to 1 mg/L. Due to the reactions in the center cone of the solids contact clarifier a low dose may react more like a higher dose in the jar test because the polymer will remain in the center well and continue to provide benefits due to solids recirculation.

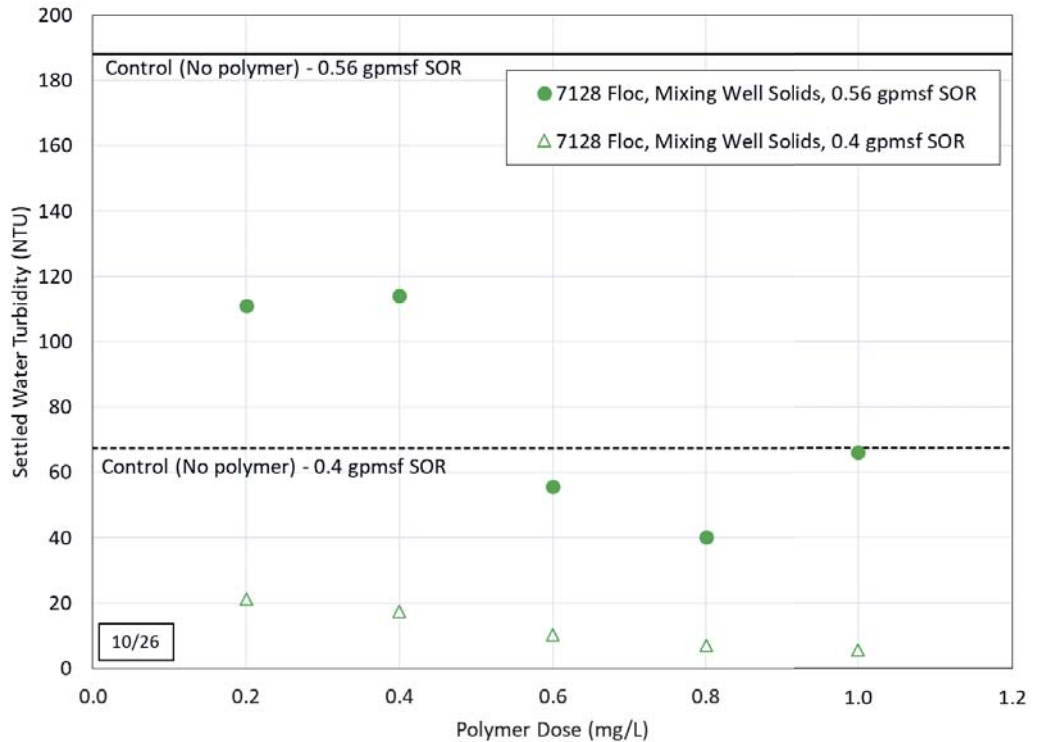


Figure 30 Impact of Nalco 8181 Flocculation Aid Polymer on Mixing Well Solids Turbidity

## Section 4

# DEMONSTRATION-SCALE POLYMER (PEC) ADDITION

Based on the promising results of coagulation aid polymer addition to center well solids at the bench-scale, a demonstration-scale polymer addition feed system was set up to feed Basin (clarifier) 8 at Ullrich WTP. Figure 31 shows the polymer injection location at the raw water inlet piping to the basin prior to ferric sulfate addition. Based on bench-scale results and availability, Nalco Cat-floc 8108 Plus, a cationic p-DADMAC polymer with a max NSF 60 dose of 50 mg/L, was selected for PEC demonstration-scale testing.



Figure 31 Demonstration-Scale Polymer Injection System

Figure 32 shows a timeline of turbidity measured after letting mixing well solids settle for 10 minutes for Basins 6-8. PEC was dosed to Basin 8 beginning the morning of October 30, while Basins 6 and 7 served as controls. When PEC dosing started, the flow rate for each of the three basins was set to approximately 10 mgd. The polymer dose was gradually increased from 2 to 5 mg/L over three days. A carrier water system was installed to improve polymer dosing the morning of October 31. On November 1, the flow rate to Basin 8 was increased to 12 mgd, while that of control Basins 6 and 7 was held at 10 mgd. The settled turbidity for the Basin 8 center well solids was generally lower than that of Basins 6 and 7 while PEC was fed. After polymer feed was stopped, the settled turbidity for the Basin 8 center well solids increased to near that for Basin 6. Table 7 shows that the basins had similar average pH values of 10.76, 10.74, and 10.77 during demonstration-scale polymer addition.

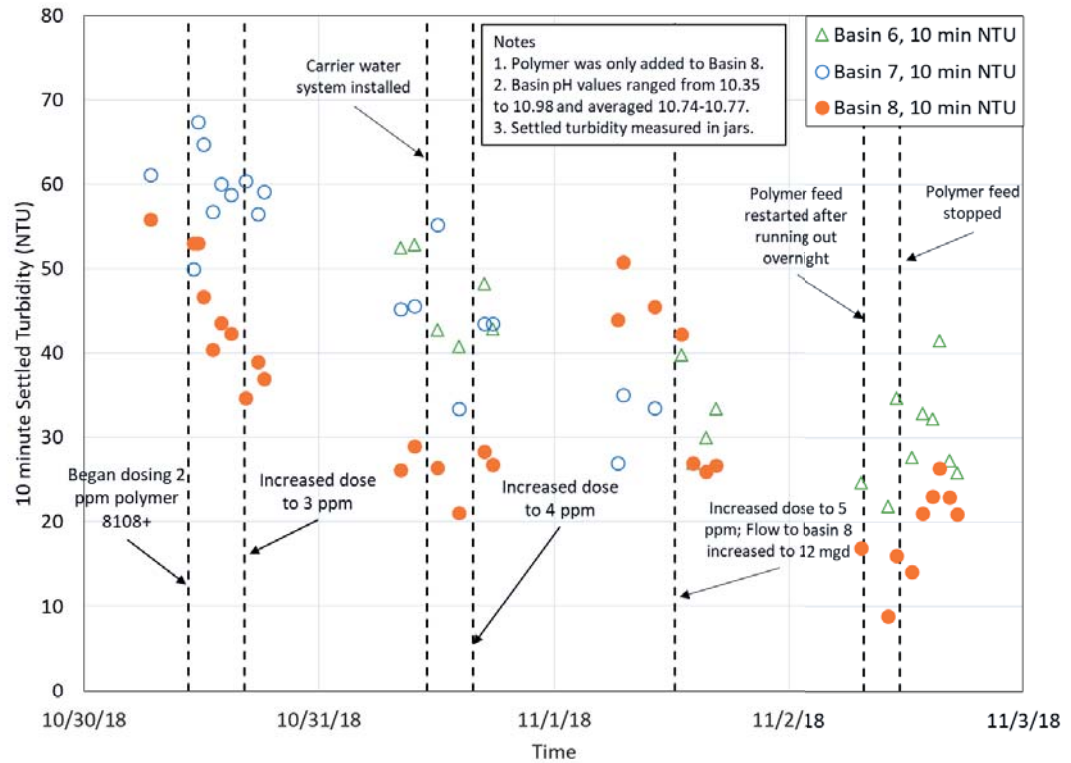


Figure 32 Demonstration-Scale Polymer Addition Timeline: Mixing Well Solids Settled Turbidity

Table 7 Basin pH During Demonstration-Scale Polymer Addition

	Basin 6	Basin 7	Basin 8
Minimum	10.60	10.35	10.62
Average	10.76	10.74	10.77
Maximum	10.91	10.94	10.98

Figure 33 shows a timeline of effluent turbidity for Basins 6-8. In the early morning of October 31, the effluent turbidity dropped in Basin 8. It is likely that polymer built up in the feed line and finally reached the raw water inlet piping at this time. The effluent turbidity of Basin 8 remained approximately half that of Basins 6 and 7 while PEC was dosed, and rose to match that of Basin 6 shortly after polymer feed was stopped.

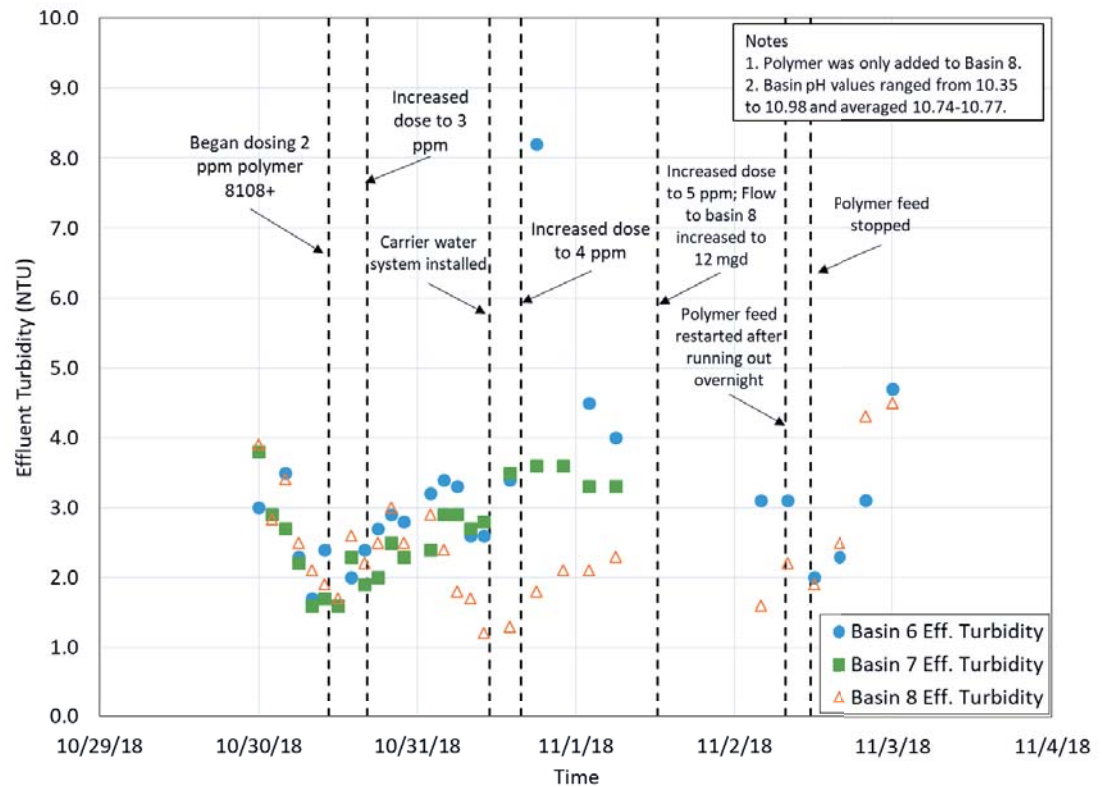


Figure 33 Demonstration-Scale Polymer Addition Timeline: Settled Water Turbidity

A near-neutral zeta potential in settled water indicates that charge neutralization occurred and that filtration would likely remove many of the remaining particles. Settled waters with zeta potentials far from neutral are likely to have high numbers of negatively charge colloidal particles that would be difficult to remove by filtration. Figure 34 shows the impact of demonstration-scale polymer addition on center well zeta potential measured the morning of October 31. Basins 6-8 had non-settled zeta potentials ranging from -10.5 to -8.5 mV. While Basins 6 and 7 had settled water zeta potentials similar to those of the non-settled samples, PEC addition to Basin 8 neutralized the zeta potential in the settled water to near zero. It is assumed that the interference of calcium carbonate, which has a negative surface charge, resulted in negative readings in non-settled samples and that the calcium carbonate particles settled out and were not measured in the settled samples. Across six mixing well settled water zeta potential samples collected on October 31, Basins 6-8 had average zeta potentials of -10.8, -9.2, and -5.7, respectively. The lower effluent turbidity for Basin 8 reinforced the improved charge neutralization attributed to addition of the cationic PEC.

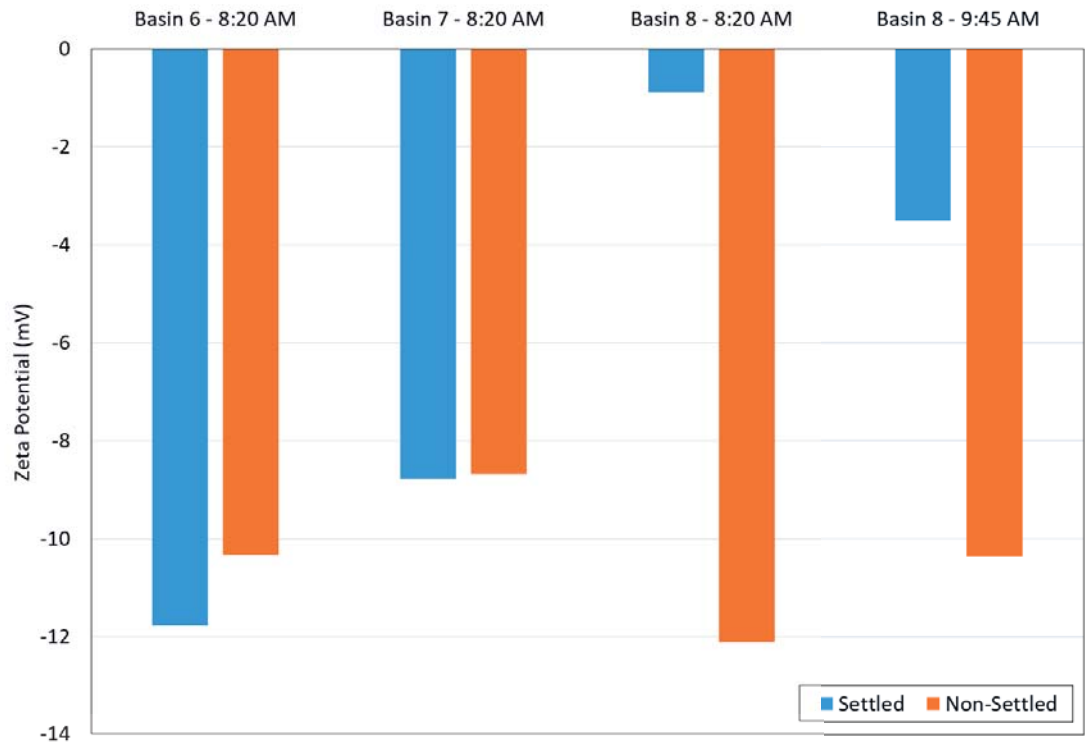


Figure 34 Impact of Demonstration-Scale Polymer Addition on Zeta Potential

## Section 5

# LESSONS LEARNED FROM AUSTIN'S OCTOBER 2018 FLOOD EVENT

There are several "lessons learned" from the October 2018 flood event that can help inform how the City may prepare for and respond to a future extreme raw water quality event.

1. The WTPs are currently constrained by only having five "knobs" to turn to optimize the first core step of treatment in response to a drastic change in raw water quality.
  - a. During the October 2018 flood event, the optimal approach to handle the increased turbidity and TOC, and decreased hardness and alkalinity was to soften at a pH > 10.5, increase the ferric sulfate dose to improve particle destabilization, and decrease the flow through the clarifiers.
  - b. Provision of additional tools to destabilize particles, and form settleable/filterable solids would help the City be able to respond to a similar future event, potentially providing flexibility to operate at higher capacity. Proposed additional tools include coagulant, flocculant, and filter aid polymer feed capabilities. Conceptual level costs to incorporate those improvements are provided in a Section 7.

2. Operation of clarifiers at reduced flow rates improved settled water quality.
3. During the event, Ullrich WTP operation was constrained by the ability to handle increased residuals due to an increase in the mass of solids produced, and increase in the clarifier blowdown and filter backwash rate. As discussed below, the ability to feed PEA to the gravity thickener influent could improve solids handling capabilities during a flood event.
4. The City already has procedures in place to respond to emergencies, including extreme weather-related events. The City's Emergency Operation Plan includes activation of the Austin-Travis County Emergency Operation Center and Department Operation Centers (DOC), steps that the City took in response to the October 2018 flood event. The City's Emergency Operations Plan should be supplemented with specific plans for the WTPs to take in response to a future extreme water quality event, drawing from the experience from the October 2018 flood. The plan should include Standard Operating Procedures (SOP) for stepwise and incremental adjustments in operations to optimize treatment in response to a significant change in raw water quality. An SOP for jar tests should be included for City staff or a consultant to evaluate changes at bench scale as a first step to identify recommended adjustments for full-scale operation at the WTP.
5. Unintended consequences of operational adjustments should be considered. For example, during the October 2018 flood event, an increase in the softened water pH resulted in post-precipitation of calcium carbonate in the recarbonated water (see Figure 10). In response, the target recarbonation pH was lowered slightly, but with careful consideration of the impact on the finished water CCPP. City staff remained cognizant of the need to maintain stable water quality in the distribution system. These types of targets and considerations should be included in a written plan for the WTPs to follow in response to an extreme raw water quality event.

### 5.1 Consideration of Charge Neutralization and Solids Density

The primary challenge associated with the change in water quality during the October 2018 flood event was how to remove a high concentration of negatively charged watershed-derived particles with relatively low specific gravity in WTPs designed to precipitate and remove high density calcium carbonate particles. The tools that worked during the flood were increasing the softening pH and adding cationic polymer, two steps that aided in charge neutralization. A review of the impact of the various operating scenarios also highlighted the importance of accounting for solids density, which impacts the settleability of the particles.



Figure 35 and Figure 36 show the estimated solids composition and calculated solids density before and after the flood event with different operating scenarios. The solids density calculations were based on literature values for density of the respective solids when wet (not dried). The characteristics of the solids formed under the varying conditions can be generalized as follows:

- $\text{CaCO}_3$  - Dense particles that are negatively charged at pH 10 to 10.2 and therefore do not provide charge neutralization benefits for NOM and turbidity removal
- $\text{Mg}(\text{OH})_2$  - Gelatinous, high surface area solids that enhance NOM and turbidity removal but are difficult to settle
- $\text{Fe}(\text{OH})_3$  - Low density flocs that enhance NOM and turbidity removal, but are more difficult to settle than  $\text{CaCO}_3$ .
- Watershed-derived particles - Comprised of negatively-charged organics and silts, with relatively low density

Figure 35 (a) shows how the particles formed during normal operation are made up of mostly calcium carbonate and have a high density, with a calculated specific gravity of 2.62.

Figure 35 (b) shows how lime softening during the flood event with an increased ferric sulfate dose resulted in less dense particles due to the lower specific gravity of particles that make up turbidity. At the high turbidity levels of 300 NTU or greater seen during the flood event, turbidity made up three-quarters of solids volume with lime softening and resulted in a low specific gravity of 1.43. While floc size also impacts settling velocity, the decrease in particle density likely translated to reduced settleability of the solids during the flood event.

Figure 36 (a) shows particle composition during flood event conditions with a turbidity of 100 NTU, seen a few days after the peak turbidity, and lime added to achieve a softening pH close to 11 and. As illustrated in Figure 36 (a), this softening condition translated to a calculated specific gravity of 2.07. Figure 36 (b) shows solids composition under the same water quality conditions, but replacing the ferric sulfate dose of 80 mg/L with 4 mg/L of a coagulant aid polymer. Replacing the ferric sulfate with polymer results in a slightly higher specific gravity due to a reduction in the low density ferric hydroxide solids component.

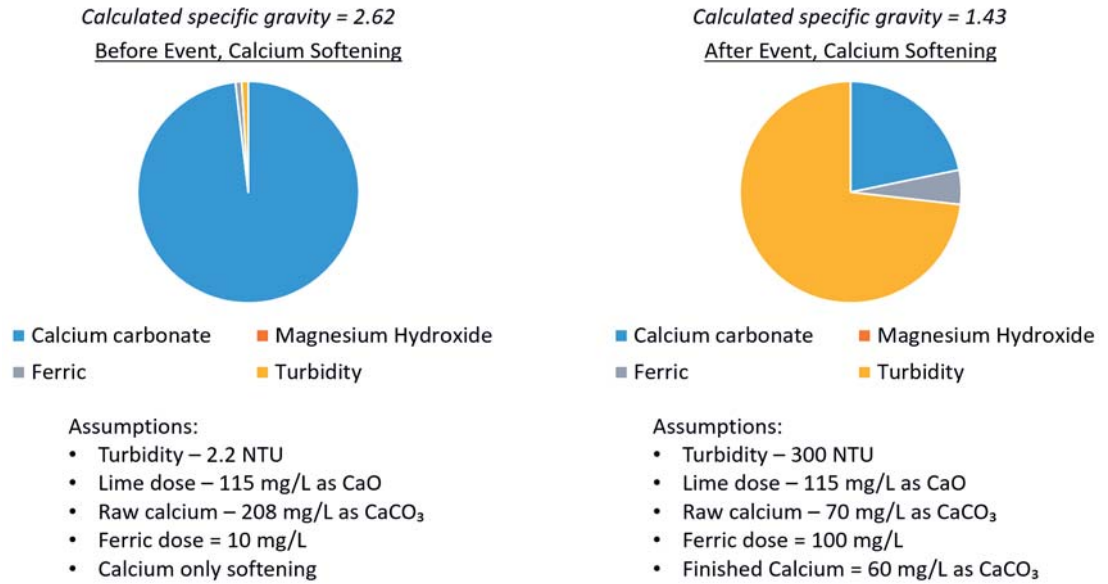


Figure 35 Solids Density (a) Before Event, Calcium Softening and (b) After Event, Calcium Softening

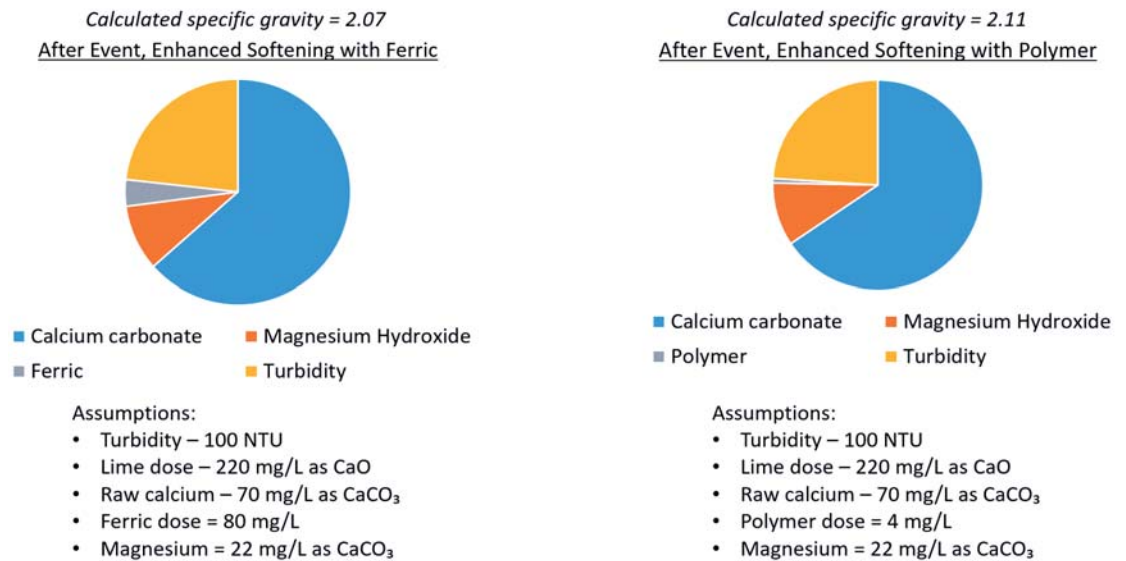


Figure 36 Solids Density (a) After Event, Enhanced Softening with Ferric Sulfate and (b) After Event, Enhanced Softening with Polymer

While primarily a paper exercise, these calculations illustrate the impact of operational changes on particle density (and settleability, factoring in floc size), which impacts the plant production capacity that can be achieved while meeting settled water turbidity goals. Based on this evaluation, one tool that was considered and tested on the banked water is to add the ability to feed carbon dioxide and potentially caustic soda to the raw water to facilitate precipitation of more calcium carbonate solids during a flood event, which in theory could improve particle settleability and the ability to operate at SORs closer to typical conditions. However, results from the tests (summarized in Section 5.2 and detailed in The Bench Testing Report) indicated only marginal improvement that does not justify the operational complexity and costs (see Appendix A) of carbon dioxide and caustic soda addition.

## 5.2 Summary of Results from Banked Water Testing

Bench testing using the banked water was conducted in February / March 2019 to evaluate additional treatment strategies that were not available to the operations staff during the flood event. Results are included in the Bench Testing Report (Carollo, 2019). The four identified strategies selected for study included:

- Addition of coagulant aid polymer (PEC).
- Addition of flocculation aid polymer (PEA).
- Addition of carbon dioxide and sodium hydroxide to allow the WTPs to develop solids that are closer to the characteristics of typical lime softening solids.
- Enhanced coagulation with ferric sulfate.

The testing demonstrated that the optimal strategy to treat challenging raw water during a flood event includes the addition of both PEC and PEA. The testing also demonstrated that enhanced coagulation, softening at  $\text{pH} > 10.5$ , and/or feeding  $\text{CO}_2$  and sodium hydroxide upstream of softening are not preferred. The tests further illustrated the benefit of maintaining solids in the center well of the SCCs.

Based on the additional testing, the following treatment approach is recommended to improve the settleability and filterability of the softening process during a flood event:

- Feeding ferric sulfate at doses typical of normal operation (i.e., 15 mg/L as solution).
- Feeding PEC 30 seconds or more after ferric sulfate to maximize charge neutralization (e.g., 12 mg/L of Magnafloc LT 7995 as solution for the banked water tested though dose will be dependent on the specific polymer used).
- Softening at pH typical of normal operation (i.e., pH 10.0- 10.2).
- Feeding PEA to the center well of the upflow clarifiers to provide particle bridging.

The recommended approach requires minimal WTP improvements (relatively low capital cost) and maintains operations (i.e., ferric sulfate dose and softening pH) near typical operation. Therefore, this approach is more easily implemented than strategies that would require a complete shift from normal operations. The recommended approach also results in finished water quality similar to that of typical operations with respect to pH, magnesium, and calcium carbonate precipitation potential (CCPP), thereby minimizing potential disruptions to water quality in the distribution system.

### 5.3 Residuals Handling Considerations

As discussed in Section 1.1, the increase in turbidity and impact to plant operations also affected the residuals handling facilities. Table 8 contrasts the mass of solids produced under typical operating conditions relative to the flood event. Based on these calculations, the solids produced during the flood event increased more than two-fold. The proposed future flood event operation strategies will produce less solids than the approach used during the flood event and improve the effectiveness of the residuals handling systems as follows:

- The addition of PEC to offset the ferric sulfate dose will decrease the mass of solids produced and reduce the amount of  $\text{Fe}(\text{OH})_3$  precipitated, which does not settle as well as calcium carbonate.
- Operation at pH 10.0-10.2 will also decrease the mass of solids produced and minimize the amount of  $\text{Mg}(\text{OH})_2$  precipitated, a gelatinous high surface area precipitate that does not settle as well as calcium carbonate.
- The improvement in settled water turbidity and charge neutralization achieved via PEC addition is expected to translate to improved filter run times compared to those experienced during the October 2018 flood event and reduce the backwashing frequency. Provisions to feed PEC as a filter aid polymer will also help improve filter performance with respect to turbidity removal.

Table 8      Estimated Solids Production Rate

Operation Scenario	Mass of dry solids produced (lb/MG)
Typical Operation (15 mg/L ferric sulfate; Softening pH = 10.2; Raw water turbidity = 5 NTU)	2,650
Flood Event Operation (80 mg/L ferric sulfate; Softening pH = 11.0; Raw water turbidity = 350 NTU)	5,700
Proposed Future Flood Event Operation (15 mg/L ferric sulfate; 10 mg/L PEC; Softening pH = 10.2; Raw water turbidity = 350 NTU)	5,000

The thickeners at Handcox and Ullrich WTPs were designed to treat up to approximately 100 dry lbs/ft<sup>2</sup>/day of solids at hydraulic loading rates of less than 300 gpd/ft<sup>2</sup>. At times during the flood event, excessive solids removal from the clarifiers at the Ullrich WTP resulted in a thickener hydraulic loading rate exceeding 2,000 gpd/ft<sup>2</sup>. The improvements to the pretreatment process described above should allow the solids removal, and therefore, the hydraulic loading rate to the thickener to be reduced. However, the solid handling capacity may still be exceeded.

Table 9 and Table 10 compare operation of the thickener and centrifuges at Ullrich and Handcox WTPs under typical conditions to residuals handling conditions that may occur during future flood events. Based on calculations shown in Table 9, both of the design parameters (i.e., solids and hydraulic loading rate) will be exceeded at Ullrich WTP during a flood event. Feeding PEA polymer to thickener influent will improve settling and will allow the thickener to operate at higher solids and hydraulic loading rates (approximately double typical rates). Therefore, it is recommended to feed PEA polymer to the thickener influent to improve thickener performance during flood events.

The increase in solids produced during flood events will also impact centrifuge operations. Based on calculations shown in Table 10, the proposed operation strategy should allow the solids to be processed if the centrifuges are operated 24 hours per day. However, the hauling requirements at each WTP approximately double.

Table 9 Gravity Thickener Operation

Parameter	Ullrich	Handcox
No.	1	1
Diameter (ft)	70	70
Normal Operation		
Solids Loading Rate (dry lbs/ft <sup>2</sup> /day)	91	94 <sup>(1)</sup>
Hydraulic Loading Rate (gpd/ft <sup>2</sup> ) <sup>(2)</sup>	267	240
Flood Event Operation (80 mg/L ferric sulfate; Softening pH = 11.0)		
Solids Loading Rate (dry lbs/ft <sup>2</sup> /day) <sup>(3)</sup>	245	74
Hydraulic Loading Rate (gpd/ft <sup>2</sup> ) <sup>(4)</sup>	584	175
Proposed Future Flood Event Operation (15 mg/L ferric sulfate; 10 mg/L PEC; Softening pH = 10.2)		
Solids Loading Rate (dry lbs/ft <sup>2</sup> /day) <sup>(3)</sup>	215	65
Hydraulic Loading Rate (gpd/ft <sup>2</sup> ) <sup>(4)</sup>	511	153

Notes:

- (1) At 150 mgd; 31 dry lbs./ft<sup>2</sup>/day @ 50 mgd.
- (2) At 5% solids and max flow rate (167 mgd for Ullrich and 150 mgd for Handcox). Loading rate for Handcox @ 50 mgd = 80 gpd/ft<sup>2</sup>.
- (3) At 167 mgd at Ullrich and 50 mgd at Handcox.
- (4) At 5% solids and max flow rate (167 mgd for Ullrich and 50 mgd for Handcox).

Table 10 Centrifuge Operation

Parameter	Ullrich	Handcox
No.	4	2
Design Flow, ea. (gpm)	2@140; 2@250	143
Operating Period (hrs/day) <sup>(1)</sup>		
Normal Operation	10	10
80 mg/L Ferric Sulfate; Softening pH 11.0	23	25
15 mg/L Ferric Sulfate; 10 mg/L Polymer; Softening pH 10.2	20	22
Truck trips (trips per day) <sup>(2)</sup>		
Flood Event Operation	16	5
80 mg/L Ferric Sulfate; Softening pH 11.0	43	13
15 mg/L Ferric Sulfate; 10 mg/L Polymer; Softening pH 10.2	38	11

Notes:

(1) Assumes 15% dry solids in thickened feed sludge; largest centrifuge out of service.

(2) Assumes 55% solids cake; 20 ton truck capacity.

Residuals from the sedimentation basins at the Davis WTP are conveyed to an equalization tank. A portion of the residuals are recycled to the head of the plant, while the remainder is sent to the centrifuges for dewatering.<sup>4</sup> Overflows from the solids handling process are routed to the sewer. During the flood event, excess residuals that could not be processed at the WTP were sent to the sewer and treated at the wastewater treatment plant. Therefore, during future food events, should the capacity of the residual system be exceeded, excess residuals may be sent to the sewer and not adversely impact the capacity of the Davis WTP.

<sup>4</sup> Approximately 2/3 is recycled to the head of the WTP and 1/3 sent to the solids dewatering facility (Source: Davis Water Treatment Plant Solids Management Evaluation. Kennedy Jenks Consultants. August 20, 2009).

## Section 6

# LESSONS LEARNED FROM OTHER UTILITIES

Table 11 presents a number of softening (and coagulation) WTPs from around the country which frequently experience periods of high turbidity. In addition to the average water quality and the characteristics of each plant, the table also outlines the operational adjustments that each plant implements to respond to extreme water quality events. The table illustrates that other lime softening plants in the country are susceptible to high turbidity events; in fact, several lime softening WTPs on the Missouri River can experience turbidity events greater than 10,000 NTU. However, they all have additional treatment processes to help respond to these types of events. In some cases, raw water is passed through presedimentation basins where turbidity is reduced with the help of cationic polymer prior to softening. In other cases, horizontal collector wells are constructed to induce aquifer recharge from the river, essentially utilizing the river bank as a prefilter. In many cases, sedimentation basins are much larger than upflow solids contact clarifiers, with surface overflow rates (SORs) at or below 0.5 gpm/sq ft. For reference, the design surface overflow rate at Handcox and Ullrich is between 1.2-1.4 gpm/sq ft. Davis was designed as a conventional flocculation/sedimentation plant and has an SOR at design capacity of 0.75 gpm/sq ft.

Of note, most of the WTPs listed in Table 4 that have horizontal collection wells, presedimentation basins, and/or two-stage softening have average turbidity values similar or higher than historical maximum values observed at the City of Austin's WTPs and a history of sustained high turbidity events, which the City has not experienced. Given historical water quality conditions and durations in Austin, there was not previously a need for additional operational features to respond to extreme water quality events. However, the October 2018 flood highlighted the potential for this type of event in Austin and the need to assess plant capabilities and potential improvements to respond to any similar future event.

Utilities that regularly experience high turbidity events on a continuous basis have tools to manage them and state agencies in states where these types of events regularly occur have codified particular treatment criteria and processes needed to deal with such events. Table 12 outlines the specific requirements for each state in addition to the Ten-States Standards requirements. While many states (including Texas) require presedimentation or pretreatment for waters that experience high turbidity, only three states (Kansas, North Carolina, and Wyoming) lay out a threshold turbidity at which pretreatment is required. The requirements for Kansas reflect the susceptibility of multiple rivers, including the Kansas River and Missouri River, in that state to high turbidity events.

Table 11 Characteristics of Other Lime Softening Plants that Experience Extreme Turbidity / Weather Events

Plant	Source Water	Average Water Quality			Plant Characteristics							Types of Extreme WQ Events Observed (qualitative)	Operational Responses to Extreme Events
		Turbidity (NTU)	Calcium (mg/L as CaCO <sub>3</sub> )	Alkalinity (mg/L CaCO <sub>3</sub> )	Horizontal collection wells (HCW)	Presedimentation Basin	Type of softening process: conventional vs. solids contact clarifiers, single vs. two-stage	Surface overflow rate (SOR)	Solids recirculation? (% solids for contact clarifier)	Coagulant dose (mg/L)	Polymer feed capabilities (type, dose, and locations fed)		
Jefferson City, MO	Missouri River – Subsurface Intake	100-200	250	200	No	1 presed	Softening- Solids contact clarifier, two stage	1 gpm/sq ft – presed 1.5 gpm/sq ft clarifier	No, but would be useful	10-15 mg/L Fe	5-15 mg/L to presed/intake	Do have a subsurface intake, but can get alkalinity drops and turbidity events that exceed 10,000 NTU	Increase polymer dose and ferric dose through testing and back off on softening pH. Add some polymer between primary and secondary to assist with turbidity increase in secondary basins.
Kansas City, MO	Missouri River	200-500	250	200	Yes, 60 mgd capacity	6 preseds, designed for surface loading rate of 1 gpm/sq ft	Softening - Conventional, two stage	0.5 gpm/sq ft	0.5% solids	10 mg/L Fe	Low MW cationic 5-10 mg/L at presed, 1-2 mg/L at influent, 0.5 mg/L following 1 <sup>st</sup> stage	Turbidity as high as 10,000-20,000 NTU	Increase flow to horizontal wells. Turn on more preseds to lower rate. Add more cationic polymer at intake. Increase solids recycle to the preseds.
Edmond, OK	Arcadia Lake	15-20	225	185	No	No	Softening- Solids contact clarifier, single stage, have pre and post ozone.	1.5 gpm/sq ft	2-5% solids	0-15 mg/L Fe	Low MW cationic 2-5 mg/L at center cone. High MW nonionic for filter aid.	Up to 300 NTU when river currents take floodwater to intake	Monitor river turbidity and lake turbidity/alkalinity. When these drop: lower plant flowrate, increase solids recycle, increase prezone, add more polymer, and turn on wells in town. Add filter aid as last resort.
Norman, OK	Lake Thunderbird "Dirty Bird"	20-30	230	170	No	No	Softening- Solids contact clarifier, single stage	1.0 gpm/sq ft	No	0-28 mg/L Fe	Low MW cationic at raw water line feed (0-10 mg/L) during spring/fall	Alkalinity drop and highly charged organics	Monitor alkalinity, reduce plant flowrate, decrease ferric, increase polymer dose. Decrease lime dose to avoid oversoftening.
Missouri American Water – North and Central WTPs	Missouri River	200-500	250	200	No	North WTP has 3 preseds, Central WTP has 4 preseds	Softening- Conventional, two stage softening process	0.25 gpm/sq ft 0.33 gpm/sq ft secondary	Yes	10-35 mg/L Fe	Low MW cationic 5-15 mg/L at intake prior to presed, 2-5 mg/L at primary basins, 1-2 mg/L at secondary basin flocculators	Up to 10,000-20,000 NTU	Increase polymer dose in primary basins and recycle more solids. Small dose of polymer to secondary basins takes care of carryover.
Colorado Springs Mesa WTP <sup>(1)</sup>	Local Sources Pike's Peak 33rd Street Intake	7 NTU	50 mg/L as CaCO <sub>3</sub>	30 mg/L as CaCO <sub>3</sub>	No	No	Conventional WTP	0.5 gpm/sq ft	No	9 mg/L alum	Cationic, 4.4 mg/L	Turbidity > 100 NTU	Add cationic polymer directly on top of filters



Table 11 Characteristics of Other Lime Softening Plants that Experience Extreme Turbidity / Weather Events (continued)

Plant	Source Water	Average Water Quality			Plant Characteristics							Types of Extreme WQ Events Observed (qualitative)	Operational Responses to Extreme Events
		Turbidity (NTU)	Calcium (mg/L Ca)	Alkalinity (mg/L CaCO <sub>3</sub> )	Horizontal collection wells (HCW)	Presedimentation Basin	Type of softening process: conventional vs. solids contact clarifiers, single vs. two-stage	Surface overflow rate (SOR)	Solids recirculation? (% solids for contact clarifier)	Coagulant dose (mg/L)	Polymer feed capabilities (type, dose, and locations fed)		
Olathe, KS	Kansas River	12 NTU	275 mg/L as CaCO <sub>3</sub>	200 mg/L as CaCO <sub>3</sub>	Yes	No	Softening- Solids contact clarifier	1.5 gpm/sq ft	10%	NA	Nonionic, 0.1 mg/L	High turbidity	HCW reduces turbidity to levels that can be accommodated at the WTP
Board of Public Utilities <sup>(1,2)</sup>	Missouri River	400 NTU	280 mg/L as CaCO <sub>3</sub>	250 mg/L as CaCO <sub>3</sub>	Yes <sup>(2)</sup>	Yes	Conventional WTP	<<0.5 gpm/sq ft	No	20 mg/L alum	8 mg/L average to presedimentation basin	High turbidity (up to 70,000 NTU)	Presedimentation basin knock turbidity down from 400 NTU to 36 NTU
Clifton Water District (Softened with RO)	Colorado River	94 NTU	50-400 mg/L as CaCO <sub>3</sub>	40-380 mg/L as CaCO <sub>3</sub>	No	Yes. 8 hours of settling time - Goal of <50 NTU.	Conventional WTP - Membrane Softening	0.3 gpm/sq ft (plate rise rate)	No	35 mg/L alum	Cationic, 3.5 mg/L average, as much as 8 mg/L, presed basin	High Turbidity (up to 54,000 NTU)	More polymer

## Notes:

HCW - horizontal collection well; WTP - water treatment plant.

(1) Not a softening plant.

(2) Quindaro WTP was decommissioned and did not have a HCW, Nearman WTP constructed as replacement and does have a HCW.

Table 12 Summary of State Specific Requirements for Addressing High Turbidity Water Sources

State <sup>(1)</sup>	Pretreatment / Presettling Basin Required?	Notes
Texas	Yes	<ul style="list-style-type: none"> <li>Reservoirs for pretreatment or selective quality control shall be provided where complete treatment facilities fail to operate satisfactorily at times of maximum turbidities or other abnormal raw water quality conditions exist.</li> </ul>
California	Yes	<ul style="list-style-type: none"> <li>Presedimentation used for <i>Cryptosporidium</i> log removal credit (LT2ESWTR)</li> </ul>
Colorado	Yes	<ul style="list-style-type: none"> <li>Up to water utility to determine intended service of presedimentation basin (e.g., intermittent, full time).</li> <li>Presedimentation basins must be designed to reduce raw water turbidity to levels which can be adequately and effectively treated using selected downstream treatment processes.</li> <li>Minimum 3 hour detention time for presedimentation basins.</li> </ul>
Idaho	Yes	<ul style="list-style-type: none"> <li>Waters exhibiting high turbidity may require pretreatment, usually sedimentation with or without the addition of coagulation chemicals.</li> </ul>
Kansas	Yes	<ul style="list-style-type: none"> <li>Source waters with turbidity in excess of 1,000 NTU should have pretreatment. Presedimentation, with or without chemicals recommended.</li> <li>Presedimentation basins must have minimum 45 min. detention time, except for the Kansas and Missouri River sources, for which 2 and 3 hours, respectively are recommended.</li> <li>Conventional sedimentation basins on the Kansas, Missouri, and Neosho Rivers must have the following detention times:               <ul style="list-style-type: none"> <li>With Presedimentation: 3 hours</li> <li>Without Presedimentation: 4 hours</li> </ul> </li> </ul>
Louisiana	Yes	<ul style="list-style-type: none"> <li>Waters containing high turbidity "may require pretreatment, usually sedimentation, with or without the addition of coagulation chemicals."</li> <li>Detention time shall consider removal requirements for the unit.</li> </ul>
Missouri	Yes	<ul style="list-style-type: none"> <li>Systems treating surface water require two stages of treatment, provided as primary rapid mix, flocculation and sedimentation followed by secondary rapid mix, flocculation and sedimentation, operated in series.</li> <li>Presedimentation recommended for systems taking water from navigable rivers.</li> <li>For solids contact clarifiers treating surface water, the detention time shall be no less than 2.5-4 hours.</li> <li>For solids contact clarifiers, the maximum upflow rate shall not exceed 1.0 gpm/sq ft.</li> </ul>
North Carolina	Yes	<ul style="list-style-type: none"> <li>Pre-settling or pre-treatment reservoir required where wide and rapid variations in turbidity, bacterial concentrations or chemical qualities occur or where the following raw water quality standards are not met: turbidity - 150 NTU, coliform bacteria - 3000/100 mL, fecal coliform bacteria - 300/100 mL, color - 75 CU.</li> </ul>
Oklahoma	Yes	<ul style="list-style-type: none"> <li>Presedimentation required for raw waters that exceed certain coliform bacteria counts.</li> <li>Surface water containing an excessive amount of suspended material requires pre-sedimentation and possibly other preliminary treatment prior to conventional treatment.</li> </ul>
Ten-State <sup>(2)</sup>	Yes	<ul style="list-style-type: none"> <li>"Waters containing high turbidity may require pretreatment, usually sedimentation, with or without the addition of coagulant chemicals."</li> <li>Three hours detention is the minimum period recommended.</li> </ul>
Tennessee	Yes	<ul style="list-style-type: none"> <li>Waters containing high turbidity or silica particles may require pretreatment, usually sedimentation with or without the addition of coagulation chemicals.</li> <li>Pre-sedimentation basins should be designed to hold maximum 3-day usage.</li> </ul>
Utah	Yes	<ul style="list-style-type: none"> <li>Waters containing heavy grit, sand, gravel, leaves, debris, or a large volume of sediments may require pretreatment, usually sedimentation with or without the addition of coagulation chemicals.</li> </ul>
Wyoming	Yes	<ul style="list-style-type: none"> <li>Raw waters which have episodes of turbidity in excess of 1,000 TU for a period of one week or longer shall be presettled.</li> <li>Basins without mechanical sludge collection shall have minimum 3 day detention time. Basins with mechanical sludge collection shall have minimum 3 hour detention time.</li> </ul>

## Notes:

(1) At the time this report was written, pretreatment / presettling basin requirements for Alabama, Alaska, Arizona, Montana, Nebraska, Nevada, South Carolina, Virginia, Washington were either not codified or were not found.

(2) The following states also adhere to the Ten-States Standard: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, New York, Ohio, Ontario, Pennsylvania, and Wisconsin.

## Section 7

# CLASS 5 COST OPINIONS

During the October 2018 flood event, the WTPs were able to operate to meet finished water goals and TCEQ requirements, but only at significantly reduced capacity. As discussed above, provision of additional tools to destabilize particles, and form dense, settleable solids would help the City be able to respond to a similar future event, potentially providing flexibility to operate at higher capacity. Based on observations and bench testing during the October 2018 flood event coupled with bench tests conducted on banked water (see Bench Testing Report, Carollo 2019), the following operating conditions are recommended to increase the resiliency of the City's WTPs to respond to future flood events:

- Feeding ferric sulfate at doses typical of normal operation (i.e., 15 mg/L as solution).
- Feeding PEC thirty (30) seconds or more after ferric sulfate to maximize charge neutralization (i.e., 12 mg/L as solution for the banked water tested).
- Softening at pH typical of normal operation (i.e., pH 10.0- 10.2).
- Feeding PEA to the center well of the upflow clarifiers to provide particle bridging.
- Including the ability to add PEC to the filter influent.
- Adding PEA to the gravity thickener influent (Ullrich WTP and Handcox WTP only).

Process modifications required to operate under those conditions include:

- **Coagulant and filter aid polymer storage and feed.** Dosing PEC neutralizes charge, allowing for a lower ferric sulfate dose and a reduction in the total sludge volume produced. This same PEC could be dosed ahead of the filters as a filter aid polymer to further neutralize the charge and improve filterability if pretreatment processes did not keep up with the dynamics of changing flood waters. Utilities such as Colorado Springs Utilities and the City of West Palm Beach utilize this method of dealing with high charge events.
- **Flocculant aid polymer storage and feed.** Dosing flocculant aid polymer to the center well of the solids contact clarifiers at Ullrich WTP and Handcox WTP, and to the second stage of flocculation at Davis WTP may result in formation of larger, stronger, more settleable particles. Testing with banked water from the flood demonstrated the benefit of PEA on particle settleability. The ability to feed PEA to the gravity thickener influent at Ullrich WTP and Handcox WTP should be included. Based on engineering experience, addition of PEA can double the hydraulic capacity of gravity thickeners.

This section provides conceptual level costs for implementing those process modifications. Costs to facilitate CO<sub>2</sub> and NaOH addition were developed (Appendix A), but those modifications are not recommended since bench testing with banked water showed minimal improvement in treatment from addition of those chemicals.

Costs were developed at an alternatives analysis / planning level of detail, consistent with an AACE Class 5 estimate suitable for study or feasibility analyses, with an expected accuracy of +50/-30 percent. Cost estimates are typically refined as projects move into preliminary and final design, with increasing levels of accuracy associated with the greater level of detail available for use in estimating. Costs are shown in 2019 dollars.

Capital costs include construction of new bulk chemical storage, feed pumps, piping, and containment areas for liquid feed systems at each plant. An allowance for electrical/instrumentation and controls costs was included as 50 percent of equipment costs. Multiplier assumptions to reach the total estimated project costs include 40 percent for unidentified items, and 15 percent for general contractor overhead, profit, and risk. Engineering, legal, and administration fees are not included. Costs for chemicals and operations and maintenance of each respective system were not calculated as part of this analysis as they would be relatively insignificant due to the small duration of these emergency events.

In consultation with the City, the following assumptions were made in developing the costs for each system:

- WTPs would be operated at 80% capacity during future flood events for determination of chemical storage requirements.
- 7 days on-site storage required for flood event chemical storage requirements.
- Chemicals will be fed to each basin (seen as most conservative for estimating piping and feed pump requirements).

### **7.1 Coagulant and Filtration Aid Polymer (PEC) Storage and Feed System Cost Estimate**

The assumptions specific to the coagulant and filter aid polymer system costs are:

- Coagulant aid polymer dose requirements: 20 mg/L as product.
- Feed points will be added to each primary treatment basin's influent piping.
- Feed points will be added to allow adding polymer just prior to filtration (basin effluent piping).

Table 13 outlines the costs associated for a coagulant aid polymer system at each WTP.

Table 13 Cost Estimate for Coagulant Aid Polymer System

Element	Davis	Handcox	Ullrich
General Conditions <sup>(1)</sup>	\$303,000	\$288,000	\$304,000
Chemical Storage Containment Area	\$81,000	\$81,000	\$81,000
Process Mechanical <sup>(2)</sup>	\$689,000	\$193,000	\$583,000
El&C Allowance <sup>(3)</sup>	\$216,000	\$61,000	\$181,000
<b>Total Direct Cost</b>	<b>\$1,289,000</b>	<b>\$624,000</b>	<b>\$1,150,000</b>
Unidentified Key Elements (40%)	\$516,000	\$250,000	\$460,000
Contractor OH&P (15%)	\$271,000	\$132,000	\$242,000
<b>Total Construction Cost</b>	<b>\$2,076,000</b>	<b>\$1,006,000</b>	<b>\$1,852,000</b>
Allowance for Change Orders (5%)	\$104,000	\$51,000	\$93,000
<b>Total Estimated Project Cost</b>	<b>\$2,180,000</b>	<b>\$1,057,000</b>	<b>\$1,945,000</b>

Notes:

- (1) General conditions assume: 9 month duration with full time project manager, superintendent, and field engineer; a half-time clerk; \$40,000 for mobilization/demobilization; a construction trailer for 9 months at \$5,000 per month; and bonding and insurance for 3.25% of the project direct cost.
- (2) Process mechanical costs assume 18 feed points for Davis (2x for 9 basins), 14 feed points for Ullrich (2x for 7 basins) and 4 feed points for Handcox (2x for 2 basins).
- (3) Electrical costs and instrumentation costs are assumed to be 35% and 15%, respectively, of the direct cost of equipment requiring electrical and instrumentation design (e.g., pumps, level monitoring for storage tanks, etc.).

Based on the above costs, the total estimated cost for a coagulant/filter aid polymer system at all three WTPs is approximately \$5.2 million.

## 7.2 Flocculant Aid Polymer Storage and Feed System Cost Estimate

The assumptions specific to the flocculant aid polymer system costs are:

- Flocculant aid polymer dose requirements: 1 mg/L as product to the solids contact clarifiers at Ullrich and Handcox WTPs and to the second stage of the flocculation process to Davis WTP.
- Feed points will be added to each basin (either the center cone or 2nd stage of flocculation).
- Feed points also added to the influent piping at the thickener at Ullrich WTP and Handcox WTP (one at each plant).
- Flocculant aid polymer systems require a blending system (for polymer activation) and aging tank.

Table 14 outlines the costs associated with implementing a flocculant aid polymer system at each WTP.

Table 14 Cost Estimate for Flocculant Aid Polymer System

Element	Davis	Handcox	Ullrich
General Conditions <sup>(1)</sup>	\$297,000	\$290,000	\$296,000
Chemical Storage Containment Area	\$81,000	\$81,000	\$81,000
Process Mechanical <sup>(2)</sup>	\$373,000	\$220,000	\$356,000
El&C Allowance <sup>(3)</sup>	\$140,000	\$80,000	\$130,000
<b>Total Direct Cost</b>	<b>\$891,000</b>	<b>\$671,000</b>	<b>\$863,000</b>
Unidentified Key Elements (50%)	\$357,000	\$269,000	\$346,000
Contractor OH&P (15%)	\$188,000	\$141,000	\$182,000
<b>Total Construction Cost</b>	<b>\$1,436,000</b>	<b>\$1,081,000</b>	<b>\$1,391,000</b>
Allowance for Change Orders (5%)	\$72,000	\$55,000	\$70,000
<b>Total Estimated Project Cost</b>	<b>\$1,508,000</b>	<b>\$1,136,000</b>	<b>\$1,461,000</b>

Notes:

- (1) General conditions assume: 9 month duration with full time project manager, superintendent, and field engineer; a half-time clerk; \$40,000 for mobilization/demobilization; a construction trailer for 9 months at \$5,000 per month; and bonding and insurance for 3.25% of the project direct cost.
- (2) Process mechanical costs assume 9 feed points for Davis (1x for 9 basins), 8 feed points for Ullrich (1x for 7 basins and 1x for the thickener), and 3 feed points for Handcox (1x for 2 basins and 1x for the thickener).
- (3) Electrical costs and instrumentation costs are assumed to be 35% and 15%, respectively, of the direct cost of equipment requiring electrical and instrumentation design (e.g., pumps, level monitoring for storage tanks, etc.).

Based on the above costs, the total estimated cost for a flocculant aid polymer system at all three WTPs is approximately \$4.1 million. As noted, the costs include pumps and piping needed to feed polymer to the solids thickener at Ullrich WTP and Handcox WTP. The cost associated with adding this portion of the system is approximately \$85,000 at each WTP.

### 7.3 Summary of Costs to Implement Recommended Improvements

Each of the process modifications outlined above should be designed and constructed in the near term to maximize operational flexibility at the WTPs in response to the likelihood of future extreme raw water quality events. In summary, those improvements include: 1) adding PEC polymer feed systems and storage for application just downstream of ferric sulfate and also to the filter influent, and 2) adding PEA polymer feed systems and storage for application to the center well at Ullrich and Handcox WTPs and the second stage of flocculation at Davis WTP, and to the gravity thickener influent at Ullrich WTP and Handcox WTP. The total estimated capital costs for these improvements are: \$3.7 million at Davis WTP, \$2.2 million at Handcox WTP, and \$3.4 million at Ullrich WTP. The cost for improvements at all three WTPs is estimated to be \$9.3 million.

If staged implementation of the recommended improvements is needed to allow the most critical improvements to be implemented more quickly, then PEC addition should be included in the first implementation stage. Results from the bench-scale testing with banked water (Carollo 2019) showed that PEC fed upstream of lime addition was critical to optimizing treatment. Testing showed that PEA addition provided additional treatment benefits, and improvements to feed PEA are also recommended. However, PEA addition is needed, but less critical, and could be implemented subsequently.

## Section 8

# CONCLUSIONS AND RECOMMENDATIONS

The October 2018 flood event resulted in an unprecedented temporary change in source water quality for the City's three WTPs. Record high concentrations of turbidity and total organic carbon along with lows of hardness and alkalinity were observed. Further, the impact of the flood on source water quality was for a longer duration than previously experienced. Water quality did not return to typical conditions for several weeks.

The change in water quality prevented treatment to the City's normal standard of quality without a significant reduction in plant production. While the City issued a recommended and subsequently, mandatory, reduction in water use, plant production required to meet demands exceeded the operational capacity of the WTPs under the water quality conditions observed throughout the flood event. Recognizing the challenges, the City quickly mobilized an increased staffing plan. This decision enabled the WTPs to operate fully staffed around the clock to regain operational control at higher rates of production.

Several factors contributed to the constraints on WTP operation:

- The unprecedented change in water quality;
- Constraints on ability to discharge solids as an emergency approach to keep the WTPs operational under the flood conditions;
- Limitation on filter backwashing due to the inability to process backwash water;
- Calcium carbonate precipitation onto the filters when operating at a higher softening pH of approximately 11.

To respond to the change in water quality, the WTPs had to change their operational philosophy from typical goals of maintaining a settled water pH of 10.2, a finished water pH of approximately 9.6, normal solids handling practices, and a finished water hardness that is 100 mg/L less than the influent value. The WTPs currently have five "knobs" they can turn to optimize the first core step of the treatment process (i.e., solids contact or coagulation, flocculation, and sedimentation) in response to a change in influent water quality:

- Lime dose.
- Ferric sulfate dose.
- Mixing speed (depending on WTP).
- Recirculation rate (blowdown).
- Flow (surface overflow rate).

Filter operation can also be adjusted by changing the filter loading rate (flow) and adjusting filter run times. Other softening plants in the country experience high turbidity events, but they tend to have additional tools to mediate those events, such as horizontal collection wells, presedimentation basins, two-stage softening, and/or coagulant aid polymer feed capabilities. Some of these plants also reduce flow to continue meeting finished water quality goals under extreme water quality events.

Jar tests were conducted at Ullrich WTP throughout the flood event to continually assess optimal settings on those "knobs" as the water quality changed during the flood event. Throughout the event, the following steps resulted in improved treatability of the flood water:

- Reducing basin flow rates (decreasing the surface overflow rate).
- Adjusting the softening process (i.e., lime dose) to target a settled water pH between 10.8 - 11.2, facilitating magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ) precipitation. It is assumed that this helped with treatability because of the cationic nature of magnesium hydroxide and not improvements in settleability.
- Increasing the ferric dose from a typical dose of 15 mg/L to 60-80 mg/L as solution.

It should be noted that while those conditions worked during the October 2018 flood event, different settings may be optimal under different extreme water quality events. Additionally, further testing (see Bench Test Report, Carollo 2019) highlighted the benefits of adding coagulant aid polymer to offset the ferric sulfate dose, enabling operation at typical ferric sulfate dose (15 mg/L as solution) and lime dose to achieve a softening pH of 10 to 10.2.

Jar tests during the October 2018 flood event indicated that a conversion to enhanced coagulation (i.e.,  $\text{pH} \leq 8.5$ , ferric dose  $> 180$  mg/L as solution) translated to improved settled water turbidity compared to softening without  $\text{Mg}(\text{OH})_2$  precipitation. However, a lower mixing speed than typically targeted for the softening process is needed to prevent shearing of the ferric hydroxide flocs and lower surface loading rates would be required (more consistent with conventional coagulation of approximately 0.5 gpm/ft<sup>2</sup>). Further, the WTPs would not be able to operate at the low pH required for coagulation with ferric sulfate to be effective without resulting in finished water quality that could destabilize pipe scale in the distribution system (unless sodium hydroxide was implemented at the end of the treatment process).

Coagulant aid polymer addition in combination with a ferric sulfate dose near the typical range currently used (e.g., 15 mg/L as solution) was identified as a beneficial approach to neutralize particle charge, translating to improved settleability (and assumed filterability) of the solids. Addition of the coagulant aid polymer to Basin (clarifier) 8 at Ullrich WTP correlated with lower settled water turbidity from that basin than other basins operated without polymer and at similar surface overflow rates. It took about 5 days to mobilize polymer addition just to one basin. Based on that experience, a more permanent system for polymer addition is recommended to facilitate rapid implementation during a flood event.

## 8.1 Recommendations

A flood event can occur at any time, and one of the best things the City can do is to prepare in advance to facilitate rapid response. The City has already taken an important step in that process by having the foresight to collect approximately 100 gallons of the water during the flood for testing, and requesting that the testing be conducted, with third party review by Professors Desmond Lawler and Lynn Katz from the University of Texas at Austin. Results from those tests are summarized in the Bench Testing Report (Carollo 2019) and factor into the recommended operating conditions and process modifications detailed below.



The following steps are recommended to prepare for future flood events:

- Add coagulant aid polymer feed capabilities at the three WTPs. Include the capability to feed the PEC polymer to the filter influent at the three WTPs to provide another tool in case charge neutralization cannot be maintained in the pretreatment process due to the dynamics of the changing source water quality.
- Add flocculant aid polymer (PEA) feed capabilities at all three WTPs.
- Include the capability to feed PEA to the gravity thickener influent at Ullrich and Handcox WTPs.
- Purchase a bench-top instrument to measure zeta potential at the three WTPs.
- Develop a water quality event response plan, which includes Standard Operating Procedures (SOP) for stepwise and incremental adjustments in operations, including for the new polymer feed systems, to optimize treatment in response to the change in water quality.

These improvements can be implemented incrementally. If a stepwise approach is taken, addition of PEC polymer feed upstream of the upflow clarifiers/sedimentation basins, procurement of benchtop instruments for zeta potential measurement, and development of a water quality event response plan should be completed first at all three WTPs. Filter aid polymer and PEA feed could be added subsequently.

During an extreme water quality event such as the October 2018 flood, the following general guiding principles should be considered when evaluating changes to the softening process:

- Adjust chemicals (primarily PEC dose) to neutralize particle charge for improved settling and filterability,
- Target higher density solids (i.e.,  $\text{CaCO}_3$  and not  $\text{Mg}(\text{OH})_2$  by not exceeding a pH of 10.2) to aid in settling at flows required to meet demands,
- Factor in the impact of any treatment change on solids production and residuals handling,
- Be mindful of the impacts of water chemistry changes on distribution system scale, and
- To the extent possible, reduce clarifier flow (SOR) rates.

## Appendix A

# COST ESTIMATE FOR CO<sub>2</sub> AND NaOH ADDITION

Adding CO<sub>2</sub> prior to the softening process would allow the plants to precipitate more of the dense, fast-settling CaCO<sub>3</sub> solids during a flood event. NaOH addition in conjunction with CO<sub>2</sub> may be needed, depending on the chemical dose and feed location to achieve pH greater than 7 for chloramine formation without forming di- and trichloramine. Adding NaOH for pH adjustment would also enable the WTPs to dial in a target finished water alkalinity. Based on bench testing with banked water (see Bench Test Report, Carollo 2019), CO<sub>2</sub> and NaOH addition is not recommended at this time. However, costs are included should a future event prompt the City to reconsider CO<sub>2</sub> and/or NaOH addition.

The assumptions specific to the carbon dioxide and sodium hydroxide system costs are:

- CO<sub>2</sub> dose requirements: 65 mg/L (based on precipitating an additional 230 mg/L of calcium carbonate in order to match or exceed "typical" calcium carbonate removal).
- NaOH dose requirements: 45 mg/L (based on achieving finished water CCPP of 14-15 mg/L as CaCO<sub>3</sub> with a finished water pH of 9.6).
- New CO<sub>2</sub> feed points can utilize existing storage to feed new points.
- Carbon dioxide storage is based on 7-day storage at maximum use. Existing storage available for new feed points assumes 15 day storage at maximum Handcox design dose (20 mg/L) and 80% plant capacity. Estimated storage requirements include:
  - Approximately 100 tons of additional storage required at Davis.
  - No additional storage required at Handcox. CO<sub>2</sub> system was designed for future expansion.
  - Approximately 250 tons of additional storage required at Ullrich.
- NaOH system will only be constructed if a new CO<sub>2</sub> system is constructed, not as a standalone system.

Table A.1 outlines the costs associated with expanding the CO<sub>2</sub> system at each WTP.

Table A.2 outlines the costs associated with implementing a NaOH system in addition to expanding the CO<sub>2</sub> system at each WTP. The total estimated cost for expansion of the CO<sub>2</sub> system at each all three WTPs is approximately \$16.5 million. The total estimated cost for expansion of the CO<sub>2</sub> system and the addition of a NaOH system at each all three WTPs is approximately \$21.2 million.

Table A.1 Cost Estimate for CO<sub>2</sub> System Improvements

Element	Davis	Handcox	Ullrich
General Conditions <sup>(1)</sup>	\$342,000	\$221,000	\$352,000
Chemical Storage Containment Area <sup>(2)</sup>	\$104,000	\$-	\$243,000
Process Mechanical <sup>(3)</sup>	\$2,556,000	\$810,000	\$2,745,000
El&C Allowance <sup>(4)</sup>	\$978,000	\$292,000	\$1,133,000
<b>Total Direct Cost</b>	<b>\$3,980,000</b>	<b>\$1,323,000</b>	<b>\$4,473,000</b>
Unidentified Key Elements (40%)	\$1,592,000	\$530,000	\$1,790,000
Contractor OH&P (15%)	\$836,000	\$278,000	\$940,000
<b>Total Construction Cost</b>	<b>\$6,408,000</b>	<b>\$2,131,000</b>	<b>\$7,203,000</b>
Allowance for Change Orders (5%)	\$321,000	\$107,000	\$361,000
<b>Total Estimated Project Cost</b>	<b>\$6,729,000</b>	<b>\$2,238,000</b>	<b>\$7,564,000</b>

## Notes:

- (1) General conditions assume: 9 month duration with full time project manager, superintendent, and field engineer; a half-time clerk; \$40,000 for mobilization/demobilization; a construction trailer for 9 months at \$5,000 per month; and bonding and insurance for 3.25% of the project direct cost.
- (2) Handcox requires no additional storage.
- (3) Process mechanical costs assume 9 feed points for Davis (1x for 9 basins), 7 feed points for Ullrich (1x for 7 basins) and 2 feed points for Handcox (1x for 2 basins).
- (4) Electrical costs and instrumentation costs are assumed to be 35% and 15%, respectively, of the direct cost of equipment requiring electrical and instrumentation design (e.g., pumps, level monitoring for storage tanks, etc.).
- (5) Handcox WTP does not require additional storage.

Table A.2 Cost Estimate for CO<sub>2</sub> and NaOH System

Element	Davis	Handcox	Ullrich
General Conditions <sup>(1)</sup>	\$377,000	\$235,000	\$389,000
Chemical Storage Containment Area <sup>(2)</sup>	\$320,000	\$108,000	\$459,000
Process Mechanical <sup>(3)</sup>	\$3,201,000	\$1,066,000	\$3,437,000
El&C Allowance <sup>(4)</sup>	\$1,200,000	\$366,000	\$1,360,000
<b>Total Direct Cost</b>	<b>\$5,098,000</b>	<b>\$1,775,000</b>	<b>\$5,645,000</b>
Unidentified Key Elements (40%)	\$2,040,000	\$710,000	\$2,258,000
Contractor OH&P (15%)	\$1,071,000	\$373,000	\$1,186,000
<b>Total Construction Cost</b>	<b>\$8,209,000</b>	<b>\$2,858,000</b>	<b>\$9,089,000</b>
Allowance for Change Orders (5%)	\$411,000	\$143,000	\$455,000
<b>Total Estimated Project Cost</b>	<b>\$8,620,000</b>	<b>\$3,001,000</b>	<b>\$9,544,000</b>

## Notes:

- (1) General conditions assume: 9 month duration with full time project manager, superintendent, and field engineer; a half-time clerk; \$40,000 for mobilization/demobilization; a construction trailer for 9 months at \$5,000 per month; and bonding and insurance for 3.25% of the project direct cost.
- (2) Handcox storage containment area requirements only include the containment area for NaOH.
- (3) Process mechanical costs assume 9 feed points for Davis (1x for 9 basins), 7 feed points for Ullrich (1x for 7 basins) and 2 feed points for Handcox (1x for 2 basins).
- (4) Electrical costs and instrumentation costs are assumed to be 35% and 15%, respectively, of the direct cost of equipment requiring electrical and instrumentation design (e.g., pumps, level monitoring for storage tanks, etc.).



City of Austin  
Process Treatment Recommendation Resulting  
from October 2018 Flood Event

## BENCH TESTING REPORT

FINAL | July 2019



TBPE No. F-882



City of Austin  
Process Treatment Recommendation Resulting from October 2018  
Flood Event

## BENCH TESTING REPORT

FINAL | July 2019



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7/15/2019



*Caroline Russell*  
7/15/19

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## EXECUTIVE SUMMARY

In October 2018, the City of Austin (City) experienced a flood event that resulted in significant and persistent changes in the raw water quality to its three Water Treatment Plants (WTPs). The flood event resulted in raw water quality characterized by higher turbidity and total organic carbon (TOC) concentrations, and lower alkalinity and hardness than historically observed at the WTPs. The change in water quality challenged the ability to operate the City's WTPs to meet demands while complying with federal and state drinking water regulations and City water quality goals.

During the flood, Carollo Engineers, Inc. (Carollo) provided onsite support to the City at the Ullrich WTP, conducting bench testing and providing input on operational adjustments that could improve the ability to treat the water. Observations and recommendations from that experience are provided in the October 16, 2018 Flood Event Report and Resulting Recommendations (Carollo, 2019). During the event, the City collected 100 gallons of raw water from the Ullrich WTP on October 25, 2018 to store for future testing. This water, referred to as "banked" water, was stored in a low temperature environment to preserve the integrity of the sample. Based on input from the City and Professors Desmond Lawler and Lynn Katz from the University of Texas at Austin (UT-Austin), Carollo conducted extensive bench testing on the collected water to further vet operational strategies that showed promise during the flood and to test additional strategies to treat the water during similar extreme raw water quality events. This report presents results from those tests and provides recommendations for treatment strategies to improve the ability of the City's WTPs to treat challenging source water during future flood events. Additional detail and conceptual level cost estimates of the recommended strategies are included in the October 16, 2018 Flood Event Report and Resulting Recommendations (Carollo, 2019).

Prior to conducting the bench testing, the water was tested to monitor changes in water quality that might have occurred during temperature controlled storage. Baseline testing was also conducted to confirm trends from tests performed during the flood event at the Ullrich WTP. Baseline testing confirmed that softening at higher pH values, consistent with conditions appropriate for  $\text{Mg}(\text{OH})_{2(s)}$  precipitation, and feeding higher doses of ferric sulfate resulted in improved turbidity and TOC removal in the Banked Water when compared to operation at historical setpoints.

Additional bench testing (beyond what was discussed in the October 16, 2018 Flood Event Report and Resulting Recommendations) was conducted to evaluate additional treatment strategies that were not available to the operations staff during the flood event. The four identified strategies selected for study included:

- Addition of coagulant aid polymer (PEC).
- Addition of flocculation aid polymer (PEA).
- Addition of carbon dioxide and sodium hydroxide to promote conditions suitable for precipitation of solids typical of those formed during normal operations.
- Enhanced coagulation with ferric sulfate.

The testing demonstrated that the optimal strategy to treat challenging raw water during a flood event includes the addition of both PEC and PEA while maintaining a typical ferric sulfate dose and softening pH value. The testing also demonstrated that enhanced coagulation, enhanced softening (i.e., softening at pH > 10.8), and/or feeding CO<sub>2</sub> and sodium hydroxide upstream of softening are not preferred.

Based on the additional testing, the following treatment approach is recommended to improve the settleability and filterability of the softening process during a flood event:

- Feeding ferric sulfate at doses typical of normal operation (i.e., 15 mg/L as solution).
- Feeding PEC 30 seconds or more after ferric sulfate to maximize charge neutralization (i.e., 12 mg/L as solution for the polymer tested in the Banked Water).
- Softening at pH values typical of normal operation (i.e., pH 10.0- 10.2).
- Feeding PEA to the center well of the upflow clarifiers to provide particle bridging.

Conceptually, this treatment strategy relies on lime addition to achieve softening and pH targets, iron addition for TOC removal, PEC for charge neutralization, and PEA for particle bridging. The strategy minimizes solids generation and formation of low density solids (e.g. ferric hydroxide and magnesium hydroxide). Further, the recommended approach requires minimal WTP improvements (relatively low capital cost) and maintains treatment (i.e., ferric sulfate dose and softening pH) near typical operation. Therefore, this approach is more easily implemented than strategies that would require a complete shift from normal operations. The recommended approach also results in finished water quality similar to that of typical operations with respect to pH, magnesium, and calcium carbonate precipitation potential (CCPP), thereby minimizing potential disruptions to water quality in the distribution system.

## Abbreviations

CaCO <sub>3</sub>	calcium carbonate
CaO	Lime (calcium oxide)
Carollo	Carollo Engineers, Inc.
CCPP	calcium carbonate precipitation potential
cf	cubic feet
cfs	cubic feet per second
CO <sub>2</sub>	carbon dioxide
DBP	disinfection by-product
EDS	energy-dispersive X-ray spectroscopy
F	Fahrenheit
ft	feet
gpcd	gallons per capita day
gpd/ac	gallons per day per acre
µg/L	micrograms per liter
L	liter
MG	million gallons
NaOH	sodium hydroxide
µg/L	micrograms per liter
mg/L	milligrams per liter
mgd	million gallons per day
PEA	flocculation aid polymer
PEC	coagulant aid polymer
psi	pounds per square inch
SEM	scanning electron micrograph
SiO <sub>2</sub>	silica (silicon dioxide)
SCADA	supervisory control and data acquisition
SHMP	sodium hexametaphosphate
SOR	surface overflow rate
TCEQ	Texas Commission on Environmental Quality
TOC	total organic carbon
WTP	water treatment plant

## Section 1

# INTRODUCTION

### 1.1 Background

An extreme flood event in October 2018 dramatically changed the characteristics of the raw water supply to the City of Austin's three water treatment plants (WTPs). The change in raw water quality resulted in treatment challenges and impacted the ability of the WTPs to meet the City of Austin (City) finished water quality goals at full plant capacity. The City retained Carollo Engineers, Inc. (Carollo) to help provide support during and after the flood event. Findings from the testing conducted on-site during the flood and resulting recommendations are documented in a separate report<sup>1</sup>.

On October 25, 2018, when the raw water remained challenging to treat, the City collected approximately 100 gallons of raw water from Lake Austin to store for future bench-scale testing. Following the flood event, Carollo developed a plan to use the water to further test strategies that worked during the flood, and to assess additional tools to facilitate a planned response to similar future extreme raw water quality events. The City and University of Texas at Austin (UT-Austin) professors Desmond Lawler and Lynn Katz provided input on the plan during a November 26, 2018 workshop and following review of a draft Bench Testing Protocol (Appendix A). This report presents results from the tests conducted on the stored water, and recommendations based on the testing.

### 1.2 Objectives

The overall goal of the bench tests was to identify treatment recommendations for the WTPs to be prepared for future flood events. That goal was met through the following specific objectives:

- Conduct jar tests to evaluate options to treat water during an extreme raw water quality event similar to the October 2018 flood.
- Identify recommended options for responding to a similar event and any needed Capital Improvement Program (CIP) projects.

### 1.3 Approach

A Bench Testing Protocol (Appendix A) was developed to use the challenging water stored to evaluate strategies to treat the water at the City's WTPs. Testing focused on the following steps:

- Conduct initial water quality analyses to confirm that the water quality did not change during storage, and to conduct initial quality assurance and control (QA/QC) on the laboratory analyses outlined in the protocol.

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<sup>1</sup> "October 16, 2018 Flood Event Report and Resulting Recommendations", Carollo Engineers, Inc., June 2019.

- Conduct initial testing to determine the operational baseline with Typical Water quality (typical) as well as with the stored water from the flood. Baseline testing with stored water was also conducted to confirm trends from previous tests conducted during the flood event, including the impact of softening pH (magnesium removal) and increased ferric sulfate addition.
- Conduct jar testing to evaluate the impact of coagulant aid polymer (PEC) addition.
- Conduct jar testing to evaluate the impact of flocculation aid polymer (PEA) addition.
- Conduct jar testing to evaluate the impact of adding carbon dioxide (CO<sub>2</sub>) and sodium hydroxide (NaOH) as a strategy to precipitate a greater mass of CaCO<sub>3</sub> solids and operate closer to typical softening conditions in terms of the composition and density of solids generated.
- Evaluate the impact of enhanced coagulation without softening.

Details of the bench testing approach are provided in Appendix A. Combinations of 200-mL and 2-L jars were used. The smaller jars were used to evaluate the effect of water chemistry, chemical selection, and doses on coagulation, while conserving the stored water. Larger 2-L Gator jars were used to assess physical parameters such as the impact of different test conditions on settleability of the solids. In the majority of the jars, the mixing speed (G value) during coagulation was set at close to 100 sec<sup>-1</sup> (correlating to 85 rpm in the 2-L Gator jars) to mimic operation at the Ullrich WTP. However, slower mixing speeds were used in some jars to assess mixing at lower G values. The test conditions are listed on the graphs so that each graph can be independently examined without the report.

The following parameters were analyzed in each of the tests:

- pH,
- alkalinity,
- settled water zeta potential,
- settled water turbidity,
- calcium,
- magnesium,
- iron,
- silica (SiO<sub>2</sub>), and
- Total organic carbon (TOC).

For some jars, the UV absorbance at 254 nanometers (nm) was also measured. In a select set of jars, scanning electron micrograph (SEM) images were taken of the solids to assess the impact of different operational conditions on particle size and morphology.

Zeta potential was also measured in settled water from all of the jar tests. Zeta potential is a measurement of the surface charge of particles using an instrument that induces a current in the water sample and measures the movement of particles towards the positive and negative poles. During the flocculation/sedimentation process, particles with a near neutral surface charge are more likely to aggregate and fall out of suspension, or be removed subsequently by filtration. Particles with a negative (or positive) surface charge will repel each other, hindering aggregation and removal. Therefore, zeta potential can be used to help determine the effectiveness of treatment chemicals or processes in neutralizing negatively charged raw water particles as a first step to facilitate removal through sedimentation and filtration.

The sections below follow the outline for testing, presenting results from the initial water quality analyses (Section 2), baseline testing (Section 3), and tests evaluating different improvement strategies (Section 4) such as PEC, PEA, and CO<sub>2</sub> and NaOH addition or conversion to enhanced coagulation. Section 5 presents information on the finished water stability depending on the operational conditions. Section 6 presents the recommended treatment approach based on the test results and findings from the October 2018 flood.<sup>2</sup>

## Section 2

# WATER QUALITY

Two types of water were used during bench testing:

- "Banked Water" - raw water that was collected from the Low Service Pump Station at the Ullrich WTP during the flood event on October 25, 2018 and stored in a refrigerated trailer until use. The Banked Water was used for the majority of the tests to assess the impact of treatment strategies to respond to similar future flood events.
- "Typical Water" - Lake Austin water collected from the Low Service Pump Station at Ullrich WTP on January 31 and February 13, 2019. At the time, this water was representative of what has historically been observed in Lake Austin.

Before using the Banked Water, samples were collected and analyzed to determine if the water quality changed while the water was held in cold storage (~ 4 degrees Celsius). Table 1 compares the original water quality recorded by Austin Water when the Banked Water was collected, and results from analyses conducted on the Banked Water after it had been stored for approximately 3 months. Also shown are the water quality extremes measured during the flood event as well as the historical Lake Austin average water quality. As can be seen in the table, the water quality of the Banked Water was not significantly changed by long term cold storage. The TOC in the banked water may have changed slightly. However, the water sample analyzed on 10/25/2018 was collected on 10/24/2018, whereas the banked water was collected on 10/25/2018. Therefore, TOC may have decreased in storage, and/or may have been lower upon sample collection. Regardless, TOC concentrations in the banked water remained above historical average TOC concentrations and the experiments with banked water can be considered as being conducted on the 'same' water the WTPs were treating during the flood event.

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<sup>2</sup> Ibid.

Table 1 Historical and Flood Event Raw Water Quality

Parameter	Historical Lake Austin Average <sup>(1)</sup>	Flood Event Extreme	Flood Event <sup>(2)</sup> Analyzed 10/25/2018	Flood Event <sup>(2)</sup> Analyzed Jan. - Feb. 2019
Total Alkalinity (mg/L as CaCO <sub>3</sub> )	179	100	103	102
pH (SU)	8.21	7.92	8.01	8.04
Turbidity (NTU)	4.77	415	124	117
Total Hardness (mg/L as CaCO <sub>3</sub> )	215	88	81	95
Calcium (mg/L)	51	29	29	30
Magnesium (mg/L)	21	4	8 <sup>(3)</sup>	5
TOC (mg/L)	4.14	7.78	7.78 <sup>(4)</sup>	5.75
Iron, total (mg/L)	0.15 <sup>(5)</sup>	NA	NA	4.13
Iron, dissolved (mg/L)	NA	NA	NA	0.011
Silica, total (mg/L as SiO <sub>2</sub> )	10 <sup>(6)</sup>	NA	NA	12.5

## Notes:

(1) Data collected between 1/1/2013 and 12/31/2015.

(2) Sample collected 10/25/2018.

(3) Result for sample collected 10/29/2018.

(4) Result for sample collected 10/24/2018.

(5) City of Austin quarterly grab sample data from 2014-16.

(6) Source: Morabbi, M. and Clark, S. (1999). "Methods for Assessing the Effects of pH Reduction on Lime Softening Distribution Systems." City of Austin – Water and Wastewater Utility.

(7) NA = Not analyzed.

In addition to conducting water quality analyses to confirm that the Banked Water remained relatively unchanged following storage, results from jar tests conducted in February 2019 using the Banked Water were compared to results from similar tests conducted during the October 2018 flood event. Figure 1 compares the 5-min settled water turbidity for jars conducted October 24 and 25, 2018 to jar tests conducted February 18, 2019 with the Banked Water. The turbidity results for the Banked Water mirror the trends observed during the October 2018 jar tests, further indicating that any changes that could have occurred during storage (e.g., slight degradation of organic matter) had negligible impact on the observed treatability.



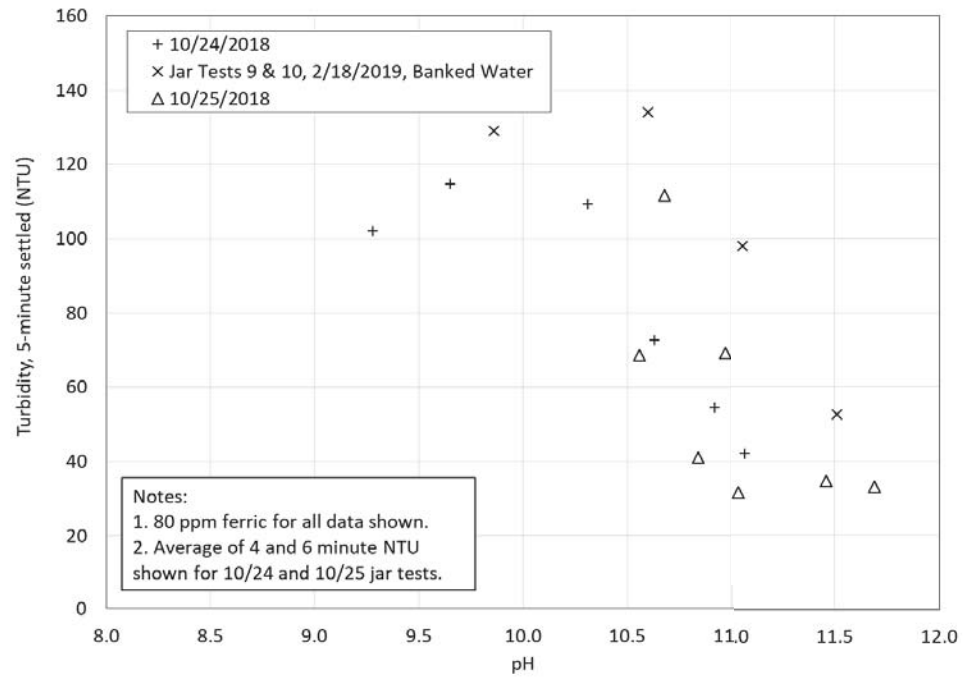


Figure 1 Settleability of Flood Event Raw Water in October 2018 and re-tested in February 2019

The Lake Austin water collected January 31 and February 13, 2019 was used to establish baseline treatment with Typical Water quality during normal operations. It was also used to test the impact of incorporating flood event response strategies (e.g., coagulant aid polymer addition) as part of day-to-day operations at the City's WTPs if deemed beneficial both for ongoing treatment and mobilization for flood event response. Table 2 compares the characteristics of the water collected on January 31 and February 13, 2019 with the historical Lake Austin average water quality. As can be seen in the table, the water collected is similar to the historical averages and it is reasonable to consider it as representing 'typical' raw water quality.

Table 2 Comparison of Historical, January 2019 and February 2019 Raw Water Quality

Parameter	Historical Lake Austin Average <sup>(1)</sup>	Lake Austin Jan. 31, 2019 <sup>(2)</sup>	Lake Austin Feb. 13, 2019 <sup>(3)</sup>
Total Alkalinity (mg/L as CaCO <sub>3</sub> )	179	157	NA
pH (SU)	8.21	8.17	8.03
Turbidity (NTU)	4.77	3.65	3.56
Total Hardness (mg/L as CaCO <sub>3</sub> )	215	182	189
Calcium (mg/L)	51	46	46
Magnesium (mg/L)	21	16	18
TOC (mg/L)	4.14	3.58	3.60
Iron, total (mg/L)	0.15 <sup>(4)</sup>	0.104	0.064
Iron, dissolved (mg/L)	ND	<0.005	<0.005
Silica, total (mg/L as SiO <sub>2</sub> )	10 <sup>(5)</sup>	8.99	NA

## Notes:

(1) Data collected between 1/1/2013 and 12/31/2015.

(2) Measured by AWU lab.

(3) Measured at UT Austin lab.

(4) City of Austin quarterly grab sample data from 2014-16.

(5) Source: Morabbi, M. and Clark, S. (1999). "Methods for Assessing the Effects of pH Reduction on Lime Softening Distribution Systems." City of Austin – Water and Wastewater Utility.

(6) NA = Not analyzed.

Prior to starting the bench testing, Austin Water staff collected and analyzed samples of the Banked Water and the Typical Water at the City's laboratory to serve as a check on the analytical equipment at the University of Texas. The Austin Water results concurred with the measurements recorded at the University of Texas. For example, the TOC concentration measured in the Banked Water by Austin Water was 5.75 mg/L in comparison to the measured value at the University of Texas of 5.66 mg/L. These results can be found in Appendix B.

## Section 3

# BASELINE TESTING

Baseline testing was conducted with Typical Water (collected February 13, 2019) as well as with the Banked Water to characterize softening chemistry under typical and flood event conditions. These tests focused on providing the following information:

- The lime dose and softening pH corresponding to the minimum calcium concentration using both Typical and Banked Water.
- The softening pH at which magnesium hydroxide (Mg(OH)<sub>2</sub>(s)) begins to precipitate based on a measured decrease in settled water magnesium concentrations under typical as well as flood event conditions.

- Settled water turbidity under typical as well as flood event conditions at the typical operating set point for the Ullrich WTP, specifically, settled water pH of 10.2 and 15 mg/L ferric sulfate addition (as solution).
- Impact of ferric sulfate addition during typical as well as flood event conditions.

Results from the tests were also used to confirm that similar trends were observed using the Banked Water after it had been stored for approximately 3 months relative to jars run under the same conditions in October 2018 (see Figure 1)<sup>3</sup>.

Appendix C provides graphs summarizing the impact of lime dose on settled water pH, alkalinity, calcium, and magnesium concentrations in the Typical and Banked Water with and without ferric sulfate addition. The results confirm that adding lime to achieve a pH of 10.0 - 10.4 corresponds to softening conditions where calcium concentrations are minimized from calcium carbonate precipitation, but magnesium hydroxide precipitation is minimal. Higher lime doses (i.e., corresponding to settled water pH values > 10.6) resulted in magnesium hydroxide precipitation, as expected based on calculated values for  $\text{Mg}(\text{OH})_2$  saturation (Q) exceeding the solubility constant ( $K_{sp}=10^{-11.16}$ ).

### 3.1 Impact of Iron Addition in Typical and Banked Water

Figure 2 shows the settled water turbidity in Typical and Banked Water without (Part A) and with (Part B) ferric sulfate addition. Several trends are apparent from the graphs:

- Turbidity is higher in the Banked Water reflecting the challenging raw water quality conditions during the October 2018 flood.
- Without iron addition, softening at higher pH values correlating to  $\text{Mg}(\text{OH})_2(\text{s})$  precipitation is required to achieve a substantial reduction in the settled water turbidity in the Banked Water (Part A).
- Addition of 15 mg/L ferric sulfate (as solution) dramatically reduces the settled water turbidity in both the Typical and Banked Water across the range of softening conditions evaluated (Part B).

<sup>3</sup> Several sets of conditions (e.g., varying lime and ferric sulfate doses) were tested with the Banked Water as were evaluated during the flood event; in all cases, the trends are consistent.

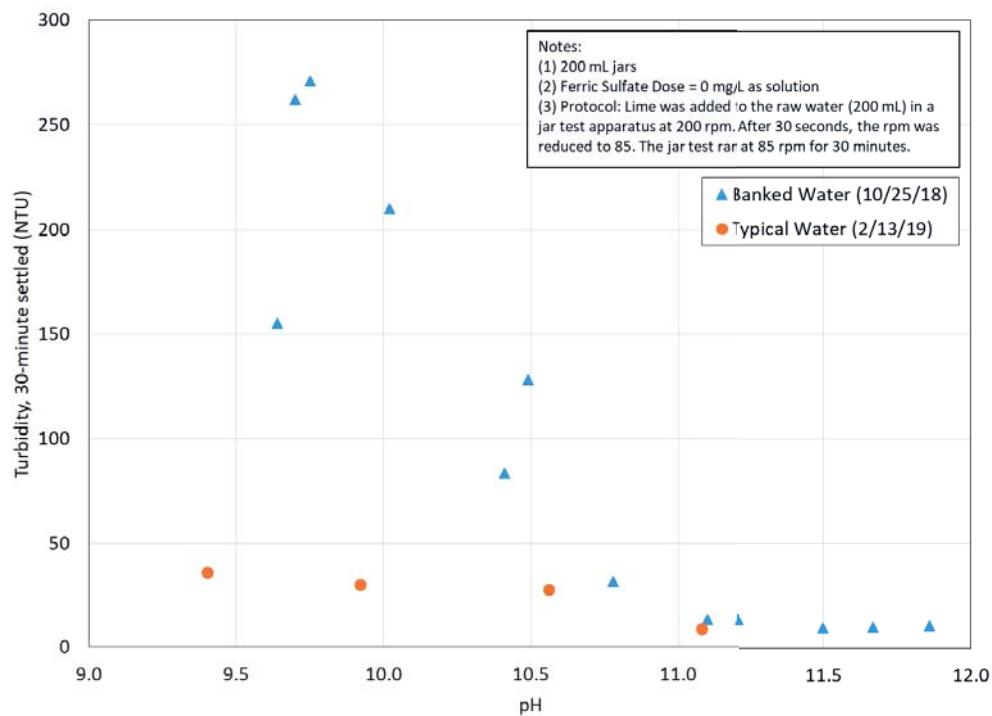
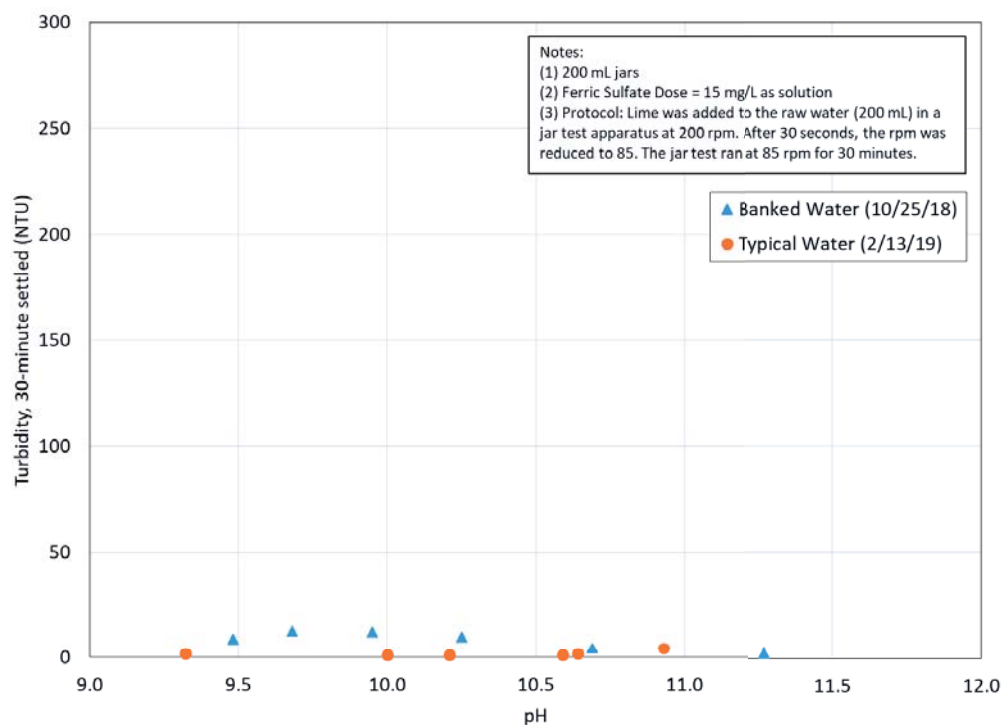
**PART A****PART B**

Figure 2 Settled Water Turbidity in Typical and Banked Water without (Part A) and with (Part B) Ferric Sulfate Addition

A set of tests were conducted to evaluate the impact of higher ferric sulfate doses applied during the October 2018 flood for pH values ranging from 9 to 12 in the Banked Water. The results of the test (see Figure 3) further highlight that higher pH (> 10.5) is required for substantial reduction in turbidity without iron (presumably due to the positive charge contributed by the precipitated magnesium hydroxide). At pH values closer to 10.0 - 10.2 where Ullrich WTP typically operates, addition of 80 mg/L ferric sulfate (as solution) or higher translated to lower settled water turbidities than addition of 15 mg/L (or 0 mg/L) ferric sulfate.

Figure 4 illustrates the impact of ferric sulfate addition on the zeta potential measured in settled water from the same set of tests conducted with the Banked Water. As shown in the figure, ferric sulfate aids in charge neutralization, improving floc formation, settling, and resulting settled water turbidity (Figure 3). Iron addition also reduced the total organic carbon (TOC) concentration in Banked Water (Figure 5) and in Typical Water (see Appendix C). These tests demonstrate that the particles in the raw water during this event were highly negatively charged and required the addition of a corresponding amount of positive charge to result in proper treatment.

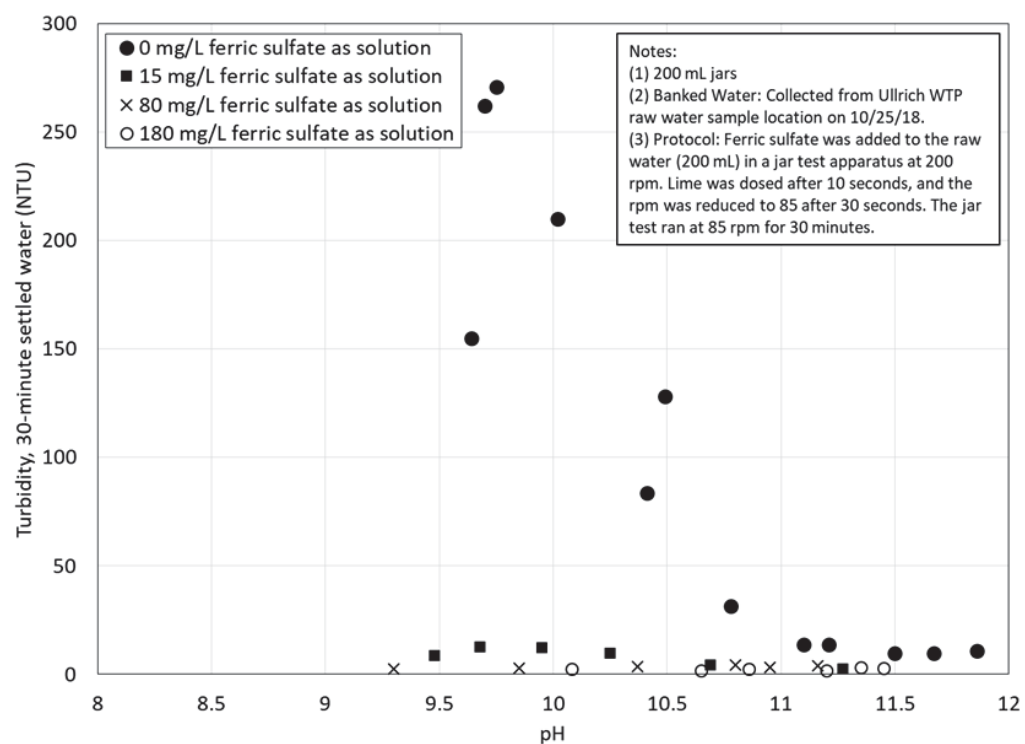


Figure 3 Impact of Higher Ferric Sulfate Doses and pH on Settled Water Turbidity in Banked Water

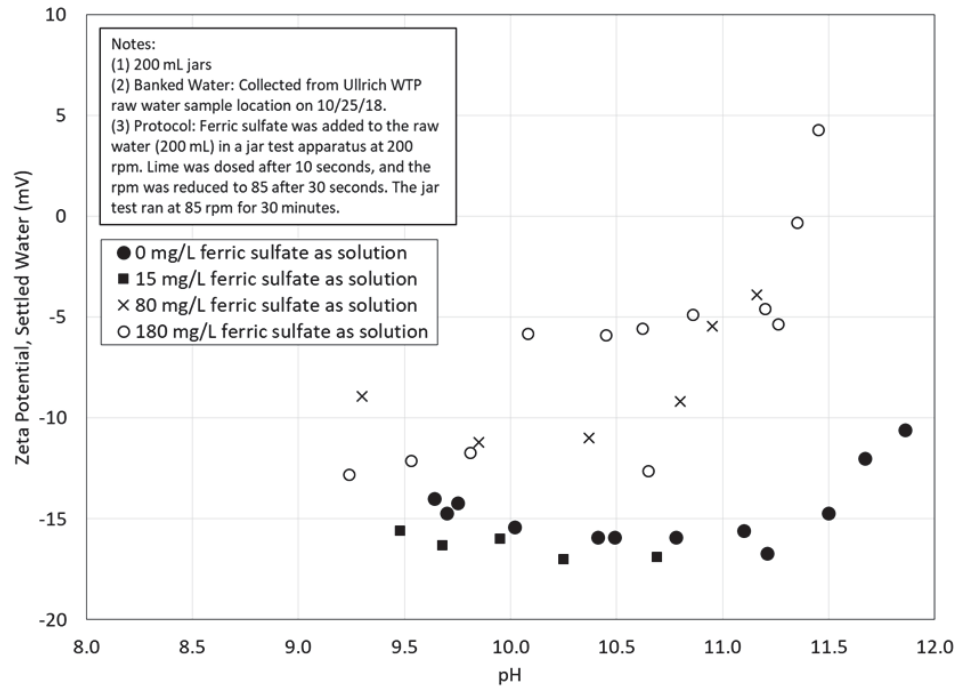


Figure 4 Impact of Ferric Sulfate Dose and pH on Zeta Potential in Banked Water

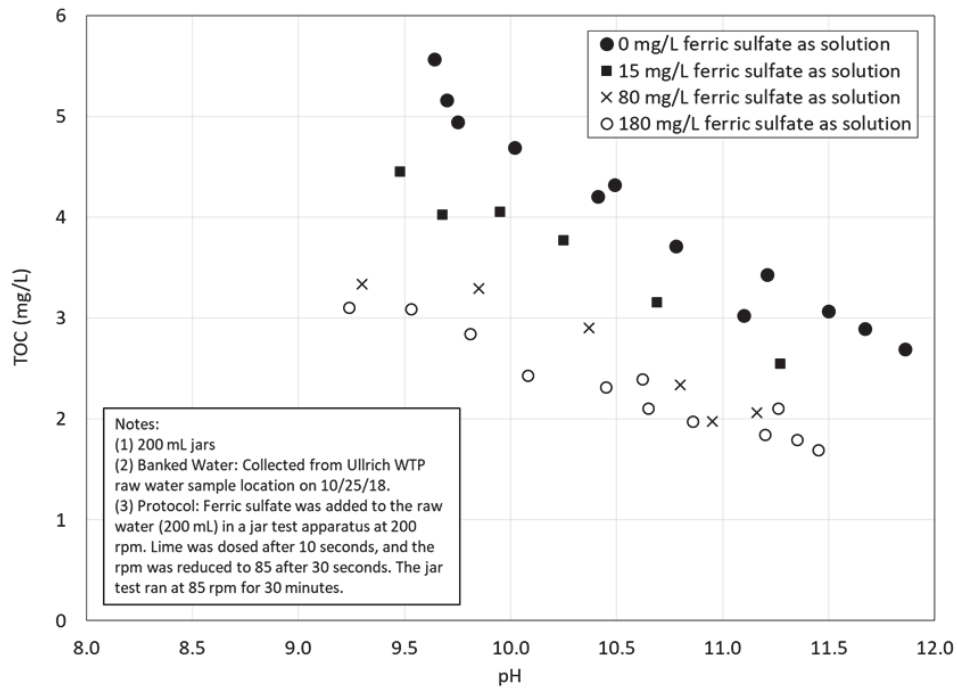


Figure 5 Impact of Ferric Sulfate Addition and pH on TOC Removal in Banked Water

All of the baseline tests presented above (and in Appendix C) were conducted in 200 mL jars to conserve water while evaluating the impact of a broader range of conditions on softening chemistry (i.e., pH, alkalinity, calcium and magnesium concentrations, zeta potential and TOC). In the 200 mL jars, settled water turbidity was measured at 30 minutes. A subsequent set of tests were conducted using 2-L gator jars to assess settled water turbidities corresponding to the operating conditions at Ullrich WTP (i.e., surface overflow rates (SOR) of 0.25 gpm/sf to 0.5 gpm/sf). Figure 6 shows the settled water turbidity measured in the 2-L gator jars after 5 and 10 minutes of settling, corresponding to an SOR of 0.5 gpm/sf and 0.25 gpm/sf, respectively (this does not consider bulk rotation that continues for a period of time after mixing stops). The data confirm the benefit of adding a higher iron dose (e.g., 80 mg/L ferric sulfate as solution) during the flood conditions than typically used (i.e., 15 mg/L ferric sulfate as solution) to achieve a lower settled water turbidity particularly at pH values in the range where Ullrich WTP typically operates. Settled water turbidity was also reduced at higher pH values corresponding to  $\text{Mg}(\text{OH})_2$  precipitation for all iron doses evaluated. These trends were consistent with findings from bench tests conducted at Ullrich WTP during the flood event (October 16, 2018 Flood Event Report and Resulting Recommendations).

### 3.2 Summary from Baseline Testing

The baseline tests confirmed consistent trends as were identified during the October 2018 flood, namely:

- The particles in the raw water during the flood event were highly negatively charged and required the addition of a corresponding amount of positive charge to result in proper treatment.
- Operating at higher pH values associated with  $\text{Mg}(\text{OH})_2$  precipitation and/or with higher ferric sulfate doses improved settled water turbidity in the Banked Water due to the positive charge contributions of both constituents.
- Ferric sulfate addition has a clear benefit for both typical and extreme raw water quality. Improved settled water turbidities and lower TOC concentrations were observed when adding ferric sulfate in both Typical and Banked Water compared to jars run at the same pH without ferric sulfate. It should be noted that solids were not added to these jar tests so these results are not directly relatable to a solids contact clarifier.
- Ferric sulfate and magnesium hydroxide aid in charge neutralization, which can improve floc formation, settling, and corresponding settled and filtered water turbidities.

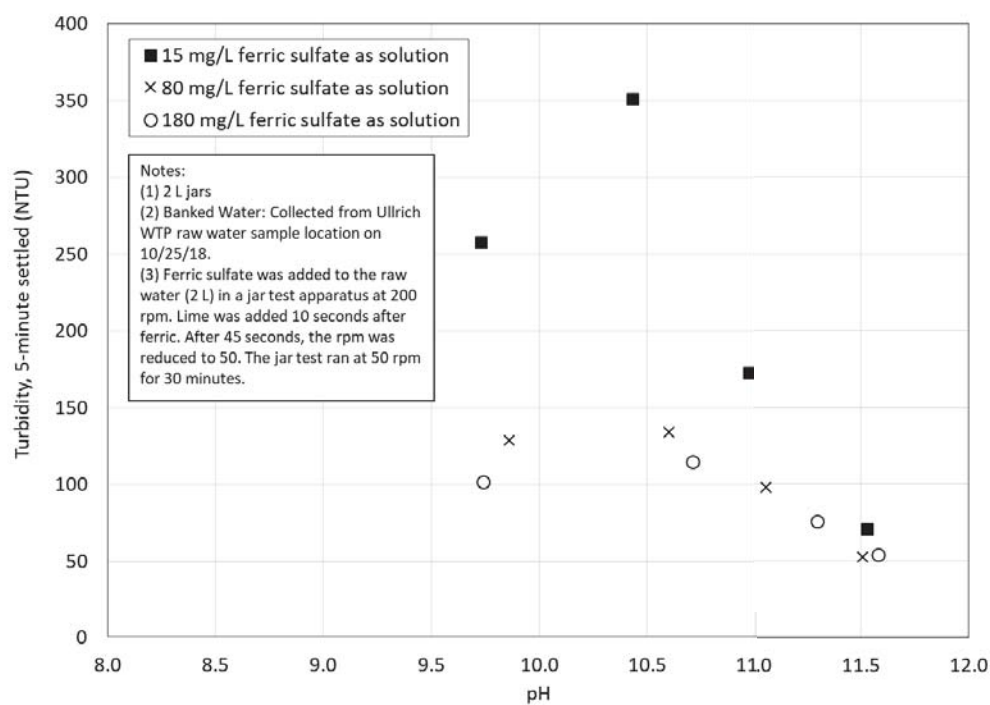
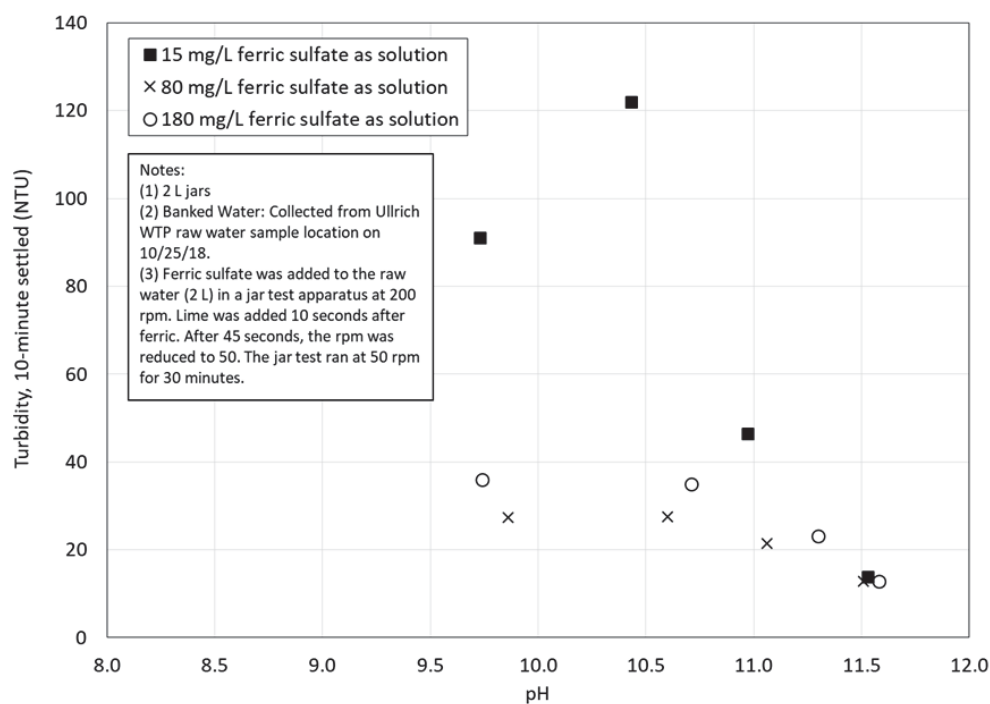
**PART A****PART B**

Figure 6 Impact of Ferric Sulfate Dose and pH on Turbidity in Banked Water



## Section 4

# BENCH TESTING TO EVALUATE TREATMENT IMPROVEMENT STRATEGIES

Bench testing was conducted to investigate the effectiveness of four potential treatment improvement strategies. The strategies identified by the project team for further evaluation included:

- Addition of coagulation aid polymer (PEC).
- Addition of flocculation aid polymer (PEA).
- Addition of carbon dioxide and sodium hydroxide to the softening process.
- Enhanced coagulation without softening.

### 4.1 Coagulant Aid Polymer (PEC)

Coagulant aid polymers (PEC) can range from low to high -molecular-weight and are typically cationic. The charge of cationic PEC polymer is opposite that of the particles in Lake Travis/Austin water (which are negative). Therefore, adding PEC polymer can displace the requirements for ferric sulfate addition or magnesium hydroxide precipitation and aid in charge neutralization and coagulation/flocculation, and improve settling. During the flood event, operation with relatively high ferric sulfate doses (60-80 mg/L) and softening at a high pH (pH > 10.8) was required to neutralize charge and improve settling and filterability. Bench testing using the Banked Water was conducted to determine if PEC could be used to reduce the ferric sulfate dose to a more typical value (e.g., 15 mg/L) while maintaining softening operations at pH 10.2. In essence, this operational strategy focused on use of lime to achieve softening and pH goals, iron for organics removal, and PEC for charge neutralization. This operational strategy is expected to result in more settleable solids, reduce the total sludge volume, and not consume as much alkalinity (ferric sulfate is acidic and consumes alkalinity) compared to the operation approach used during the flood event. This approach also does not remove magnesium, which may help maintain the integrity of the scale in the distribution system<sup>4</sup>.

Figure 7 shows the results of zeta potential titrations with ferric sulfate and various PECs tested with the Banked Water. Approximately 300 mg/L of ferric sulfate (with no pH adjustment) was required to neutralize charge (zeta potential of 0 mV). Significantly lower doses of PEC, ranging between 15 to 22 mg/L as solution, were required (Figure 8). Therefore, adding a small dose of PEC can neutralize a large amount of charge and decrease the required ferric sulfate dose or amount of magnesium precipitation required. Similar results were observed during testing in October during the flood event (October 16, 2018 Flood Event Report and Resulting Recommendations). To neutralize the same charge, ferric sulfate generates more than 10 times the solids when compared to cationic polymer.

<sup>4</sup> Distribution system scale is predominately composed of magnesium silicate material (Morabbi, M. and Clark, S. 1999. Methods for Assessing the Effects of pH Reduction on Lime Softening Distribution Systems." City of Austin Water and Wastewater Utility. Austin, Texas)

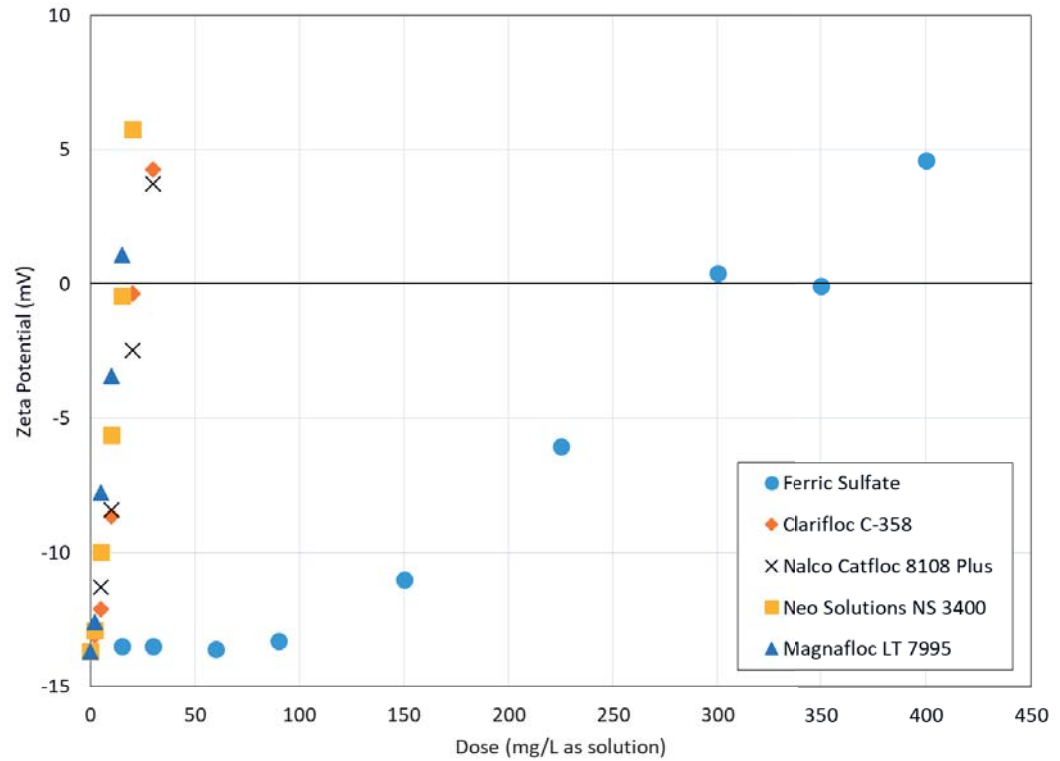


Figure 7 Zeta Potential Titration with Ferric Sulfate and Cationic Polymers (PEC)

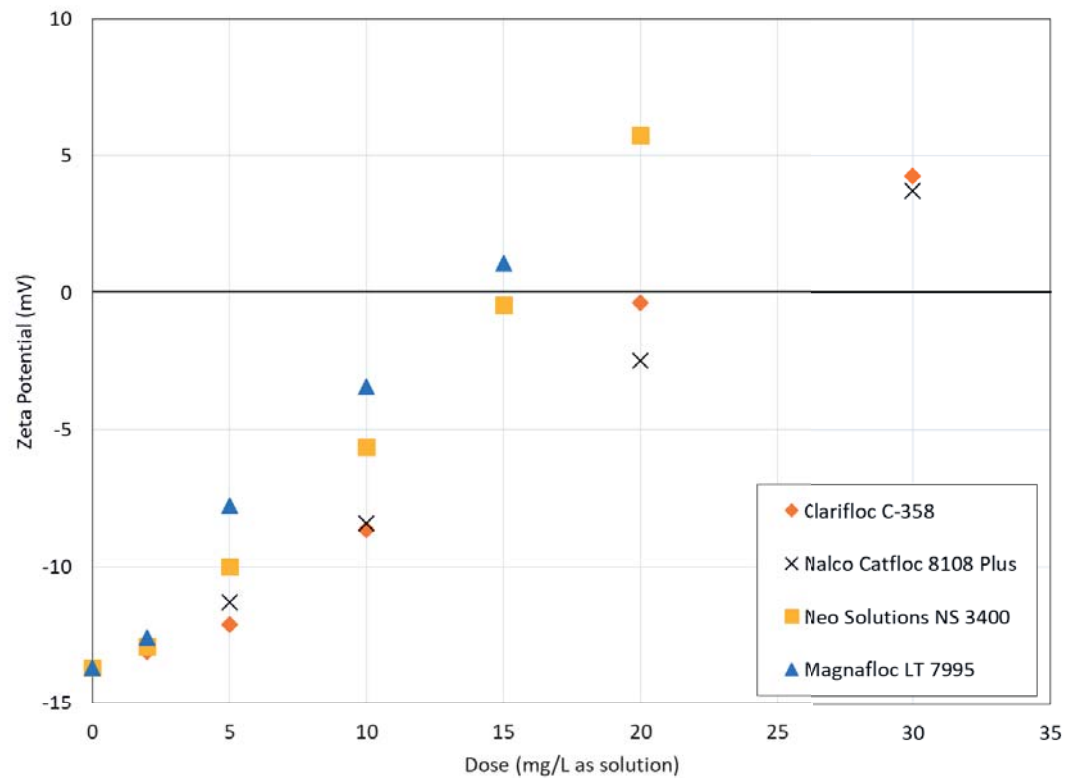


Figure 8 Impact of PEC Dose on Charge Neutralization

A summary of the charge neutralization capacity of each of the polymers tested is provided in Table 3. Each of the polymers tested were either 20- or 40-percent active product (which is also reflected in the maximum allowable dose from NSF). Accounting for the percent of active polymer in each different solution normalized the charge neutralization capacity of each polymer tested (Figure 9). PEC doses ranging between 4 and 6 mg/L as active polymer were required to neutralize the charge to near zero. Since available PEC solutions vary in the amount of charge neutralization they provide as well as the percent active polymer contained in each solution, the use of zeta potential may be a useful innovative approach to compare the effectiveness of polymers and evaluate bids during procurement. This approach would allow the City to bid polymers on the basis of their charge neutralizing capacity instead of their weight.

The impact of polymer dose on charge neutralization was also measured in Lake Austin water collected February 13, 2019 to determine dose requirements to neutralize charge under typical conditions. Results are shown in Appendix F. As expected, lower doses, ranging from 4-8 mg/L as solution were required.

Table 3      **Maximum Allowable Dose, Percent Active Product, and Charge Equivalence for 1 mg/L of Cationic Polymer (PEC)**

Cationic PEC	Maximum NSF 60 Dose (mg/L)	Percent Active %	Equivalent Ferric Sulfate Dose (mg/L) <sup>(1)</sup>
Nalco Cat-floc 8108 Plus	50	20	15
Magnafloc LT-7995	25	40	25
Neo Solutions NS 3400P	25	40	23
Clarifloc C-358	50	20	18

Notes:

(1) 1 mg/L PEC neutralizes as much charge as the listed ferric sulfate dose (PEC dose as mg/L as solution and ferric sulfate dose as solution).

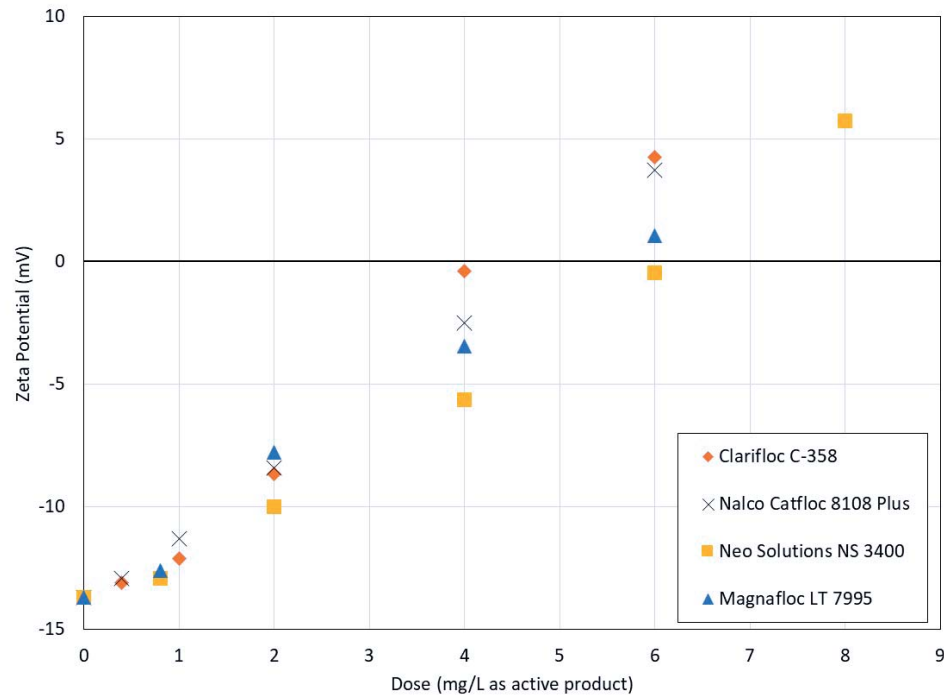


Figure 9 Impact of PEC Dose on Zeta Potential (Normalized for Percent Active Polymer)

Experiments were conducted to investigate the impact of feeding PEC in conjunction with ferric sulfate prior to the softening process. Three doses of ferric sulfate were investigated:

- 15 mg/L to represent typical operation,
- 80 mg/L to represent the dose fed full-scale during the October flood event, and
- 180 mg/L.

The resulting settled water turbidity and zeta potential are shown in Figure 10 and Figure 11, respectively. These results indicate that PEC aids in charge neutralization and reduces the settled water turbidity. The lowest settled water turbidities were observed with low ferric sulfate doses (15 mg/L) and PEC doses of 10-15 mg/L as solution. Higher doses of ferric sulfate resulted in higher settled water turbidity, even when the charge neutralization achieved was similar to that observed at the lower ferric sulfate dose with PEC. This trend reflects the lower specific gravity of a ferric hydroxide dominated floc as compared to a polymer floc which is denser. Additionally, ferric sulfate generates more than 10 times the mass of solids, which will result in more turbidity after settling (assuming the same particle removal efficiency). These data also show the potential adverse effects of overfeeding PEC, resulting in a positive settled water zeta potential. For example, feeding 10 mg/L of PEC in conjunction with 180 mg/L of ferric sulfate resulted in settled water zeta potential of +8.5 and offered minimal improvement to the settled water turbidity when compared to feeding 180 mg/L of ferric sulfate alone.

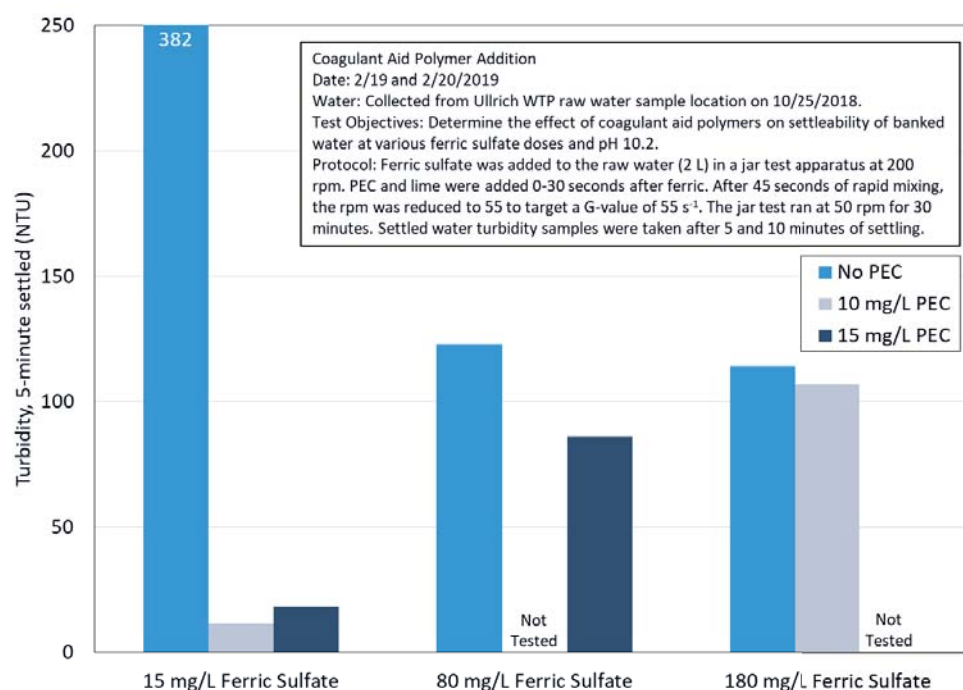


Figure 10 Impact of Offsetting Ferric Sulfate Demand with PEC on Settled Turbidity

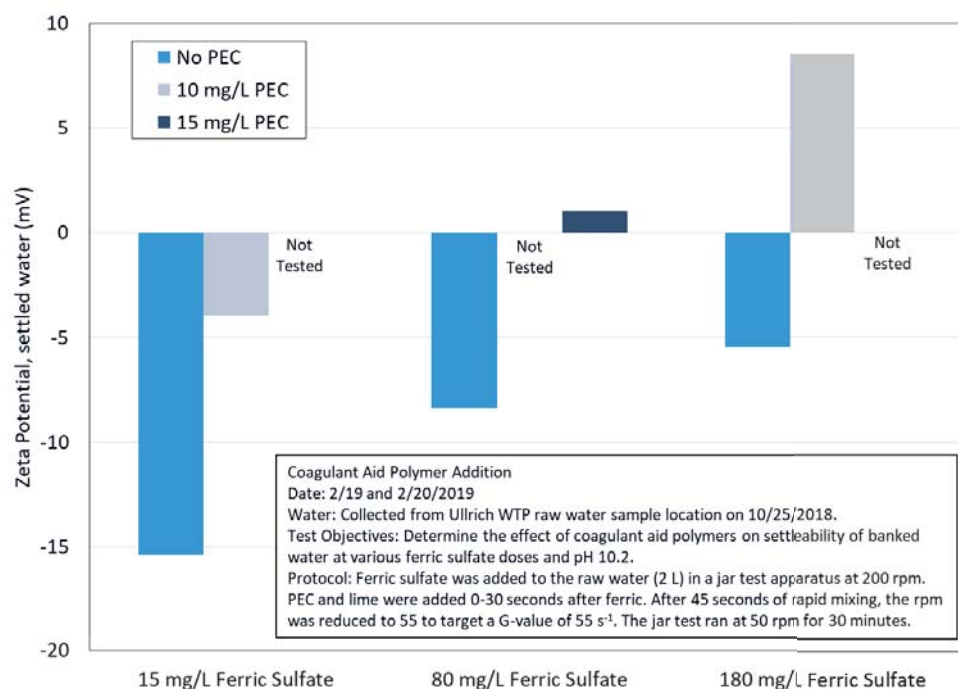


Figure 11 Impact of Offsetting Ferric Sulfate Demand with PEC on Settled Zeta Potential

The impact of PEC addition was also investigated at high softening pH since softening at high pH precipitated magnesium hydroxide, provided more charge neutralization, and improved settled water turbidity full-scale during the October 2018 flood event. The settled water turbidity and zeta potential resulting from different PEC doses at pH 10.2 and 11.0 are compared in Figure 12 and Figure 13. These results indicate that:

- Softening at pH 11.0 in the absence of PEC addition reduces the settled water turbidity. This impact can likely be attributed to the precipitation of magnesium hydroxide, which also serves to neutralize charge.
- Feeding PEC resulted in significantly lower settled water turbidity at both pH 10.2 and 11.0.
- The lowest settled water turbidity was achieved by feeding PEC and softening at pH 10.2. This is likely because magnesium hydroxide (unlike calcium carbonate) is a gelatinous high surface area precipitate that does not settle well.

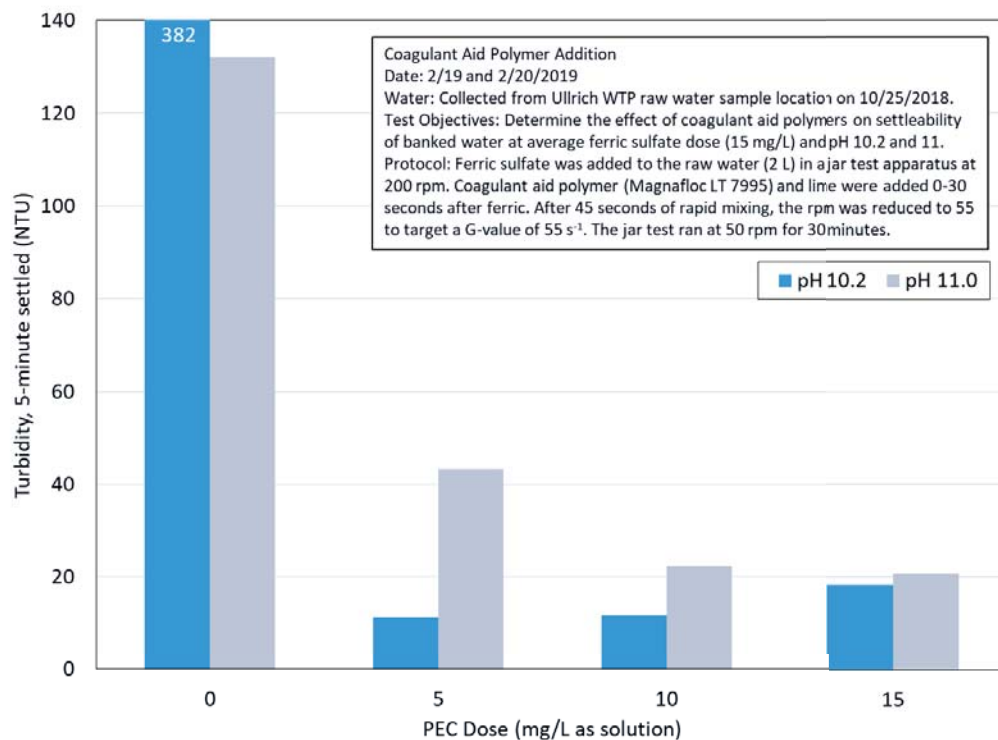


Figure 12 Impact of PEC Dose on Settled Turbidity

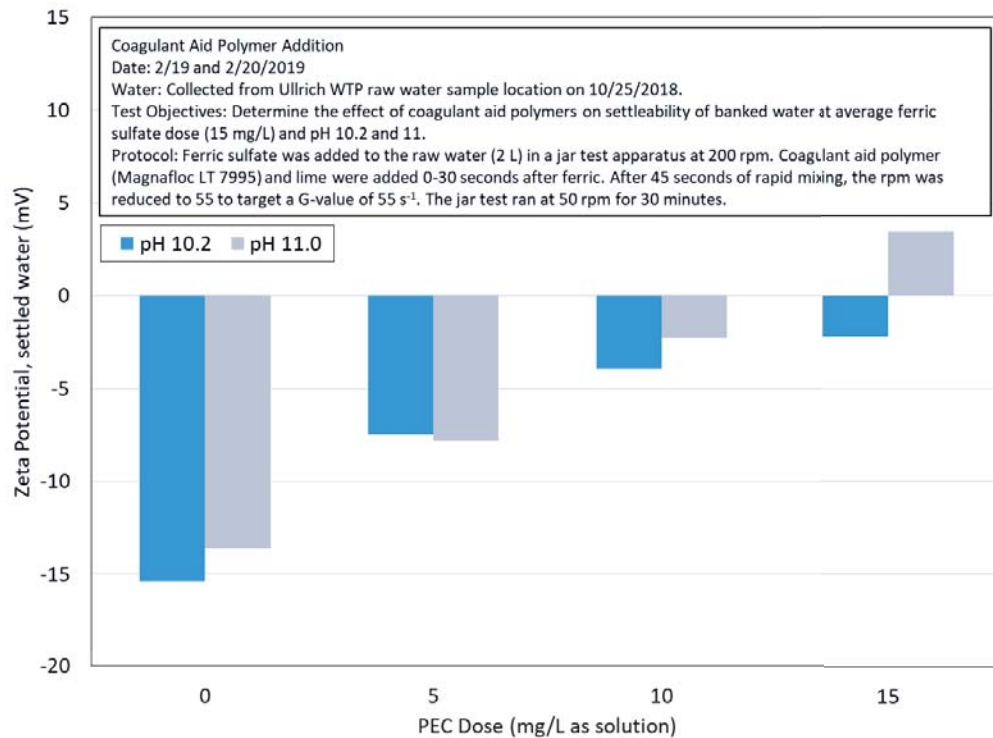


Figure 13 Impact of PEC Dose on Settled Zeta Potential

The impact of feeding PEC to Typical Water was also investigated to determine if PEC provided value during normal operation. Results of these experiments are shown in Figure 14 and Figure 15. Based on these results, feeding low doses of PEC (i.e., 1 mg/L) in conjunction with ferric sulfate resulted in improved settled water turbidity compared to feeding ferric sulfate alone. These results also show that feeding ferric sulfate alone resulted in improved settled water turbidity compared to feeding PEC alone. For example, feeding 3 mg/L of PEC and 0 mg/L ferric sulfate resulted in a higher settled water turbidity than feeding 15 mg/L of ferric sulfate alone even though similar levels of charge neutralization were achieved with each approach. Therefore, the addition of ferric sulfate is important and cannot be completely replaced by feeding PEC.

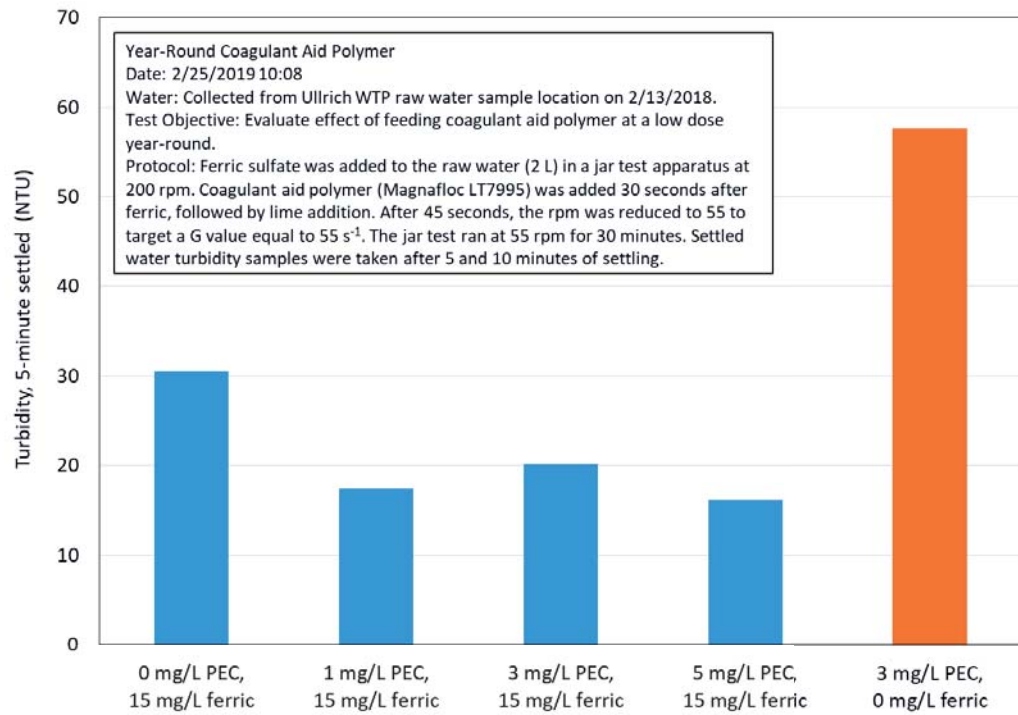


Figure 14 Impact of PEC on Turbidity with Typical Raw Water

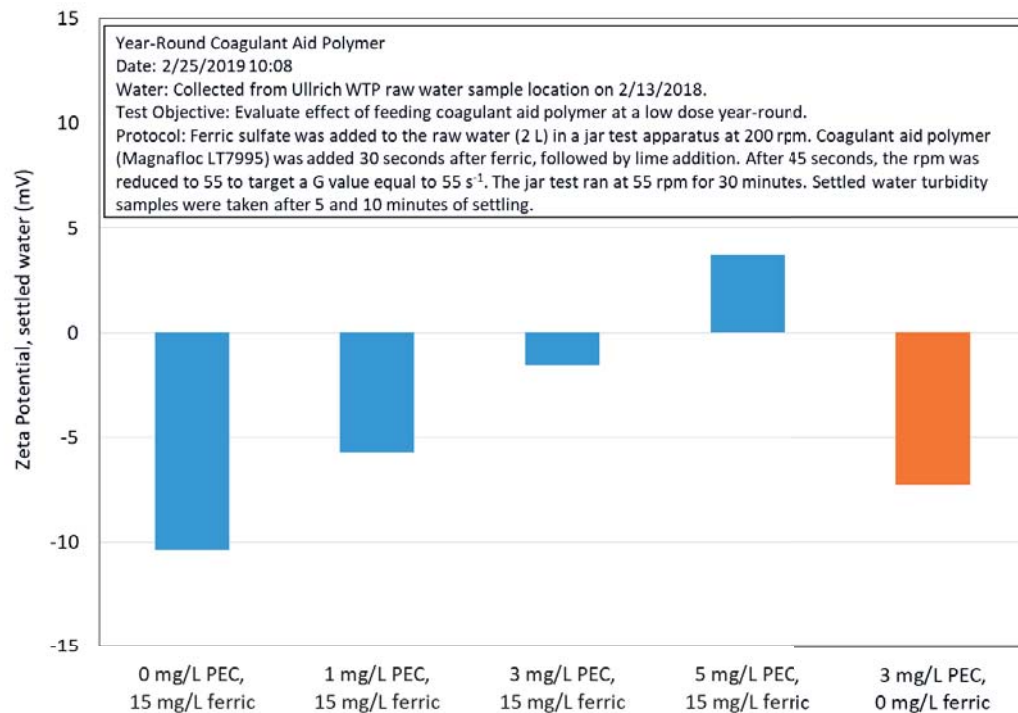


Figure 15 Impact of PEC on Zeta Potential with Typical Raw Water



The order of chemical addition is also important when feeding PEC. Figure 16 compares the zeta potential observed from feeding: 1) 15 mg/L of ferric sulfate, 2) 10 mg/L of PEC, 3) 10 mg/L PEC 30 seconds upstream of 15 mg/L ferric sulfate, and 4) 15 mg/L ferric sulfate 30 seconds upstream of PEC. These results indicate that the optimal location of PEC feed is downstream of ferric sulfate addition. Figure 17 compares the resulting zeta potential from feeding ferric sulfate/PEC simultaneously to feeding ferric sulfate 30 seconds and 90 seconds prior to PEC. A benefit to charge neutralization was observed when separating the ferric sulfate and PEC addition from zero to 30 seconds. This observation may be a result of the cationic polymer adsorbing to the iron floc particles, which are likely negatively charged at the pH values tested. However, no additional benefit to charge neutralization was observed from increasing the separation between ferric sulfate and PEC to 90 seconds. During an event, adopting this sequence of timing of chemical addition would reduce the polymer dose by approximately 5 mg/L of polymer (based on the zeta potential presented in Figure 8 and comparing a Zeta Potential of -5 mV versus a Zeta Potential of -2.5 mV).

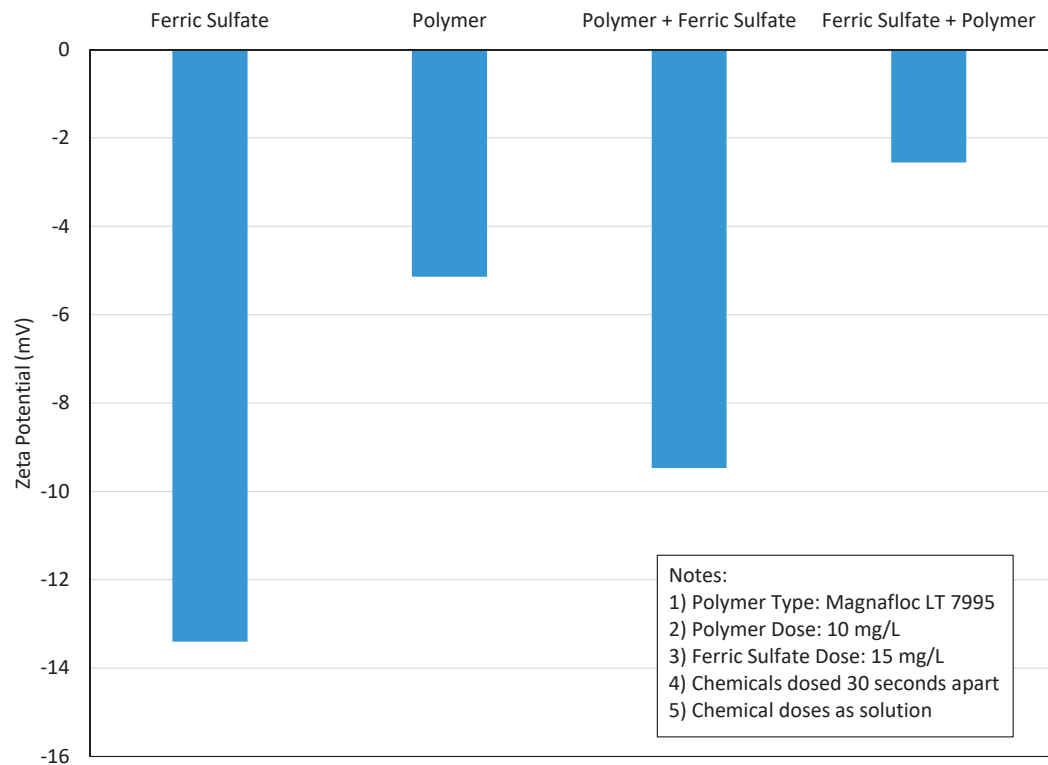


Figure 16 Impact of Order of PEC Addition on Zeta Potential

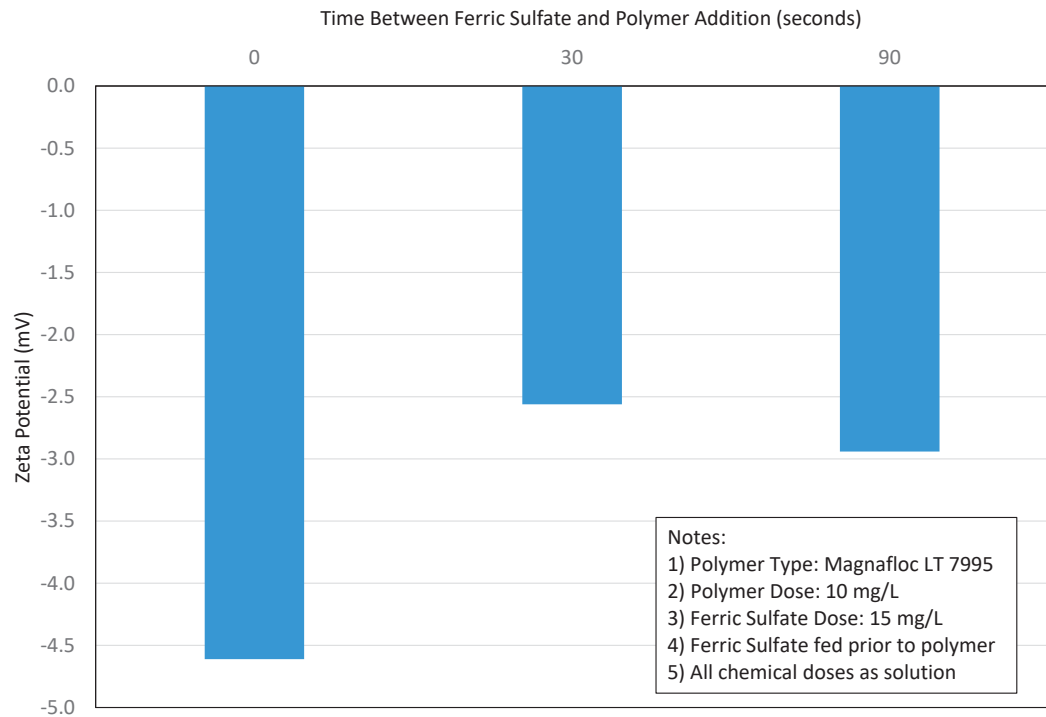


Figure 17 Impact of Time Delay between Ferric Sulfate and PEC addition on Zeta Potential

The impact of the order of chemical addition on settled water turbidity is shown in Figure 18. The scenarios shown in the figure represent potential options for implementing polymer feed at the Ullrich WTP, and can be applied to both the Davis and Handcox WTPs as well. Feeding ferric sulfate and PEC simultaneously (simulating feeding polymer near the typical ferric sulfate feed points at the Ullrich WTP) resulted in the highest settled water turbidity. Feeding PEC and lime simultaneously (simulating feeding PEC in the clarifier centerwell) resulted in lower settled water turbidity than feeding PEC simultaneously with ferric sulfate. However, feeding PEC 30 seconds after ferric sulfate addition and prior to lime addition (simulating feeding ferric sulfate and PEC in the raw water pipeline prior to the clarifiers) resulted in the lowest settled water turbidity.

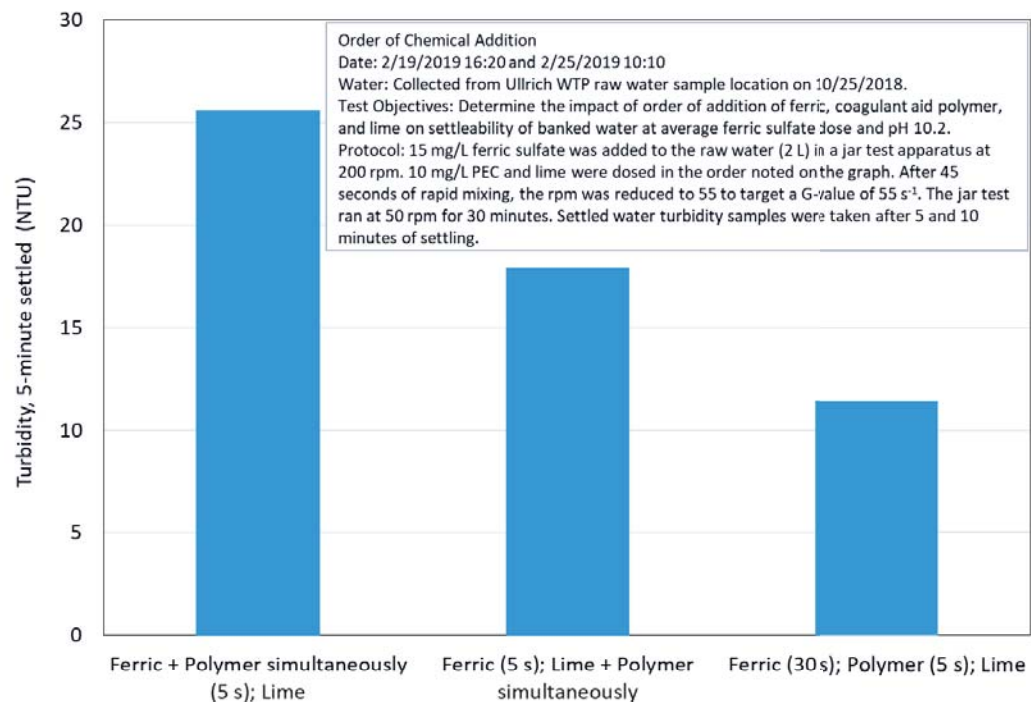


Figure 18 Impact of Order of Chemical Addition on Settled Water Turbidity

Additional experiments were performed to further investigate the optimal polymer dose while feeding PEC under optimal conditions. In these experiments, PEC was added 30 seconds after ferric sulfate, followed by lime addition 5 seconds later. Results are shown in Figure 19 and Figure 20. These results indicate that the optimal dose of the tested PEC may range from 10-12 mg/L for the Banked Water.

In general, PEC addition in combination with a low ferric sulfate dose significantly improved settled water turbidity by neutralizing particle charge. This result may not only translate to improved settleability full-scale, but also potentially improve the filterability of the solids that carry over onto the filters from the sedimentation basins or solids contact clarifiers.

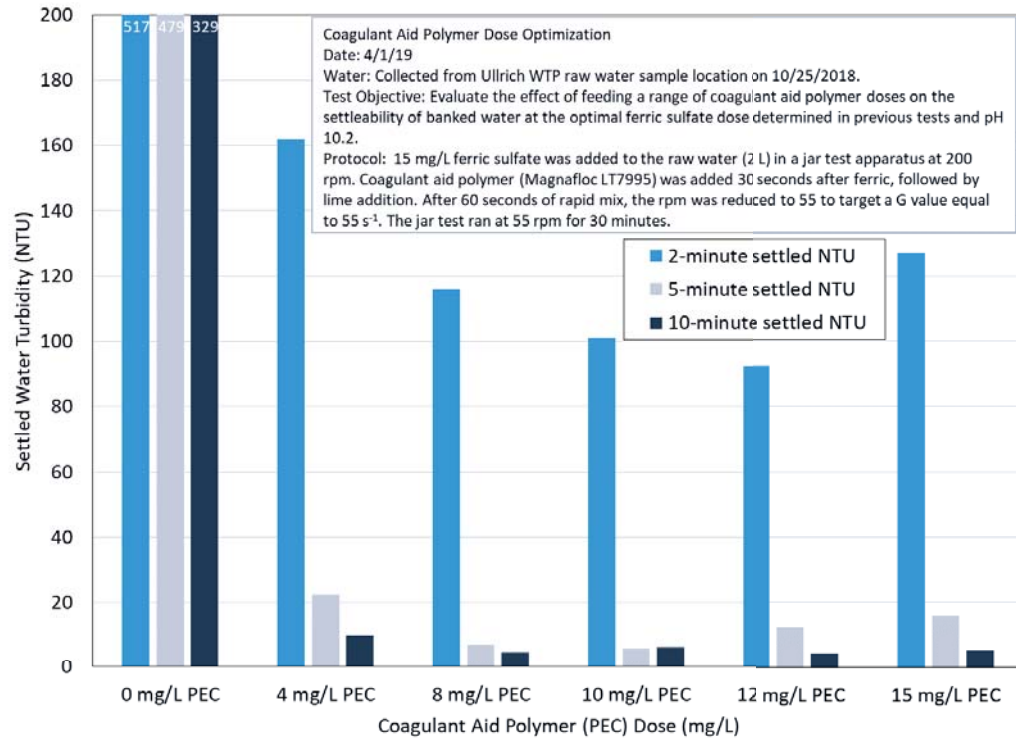


Figure 19 Impact of PEC Dose on Settled Turbidity

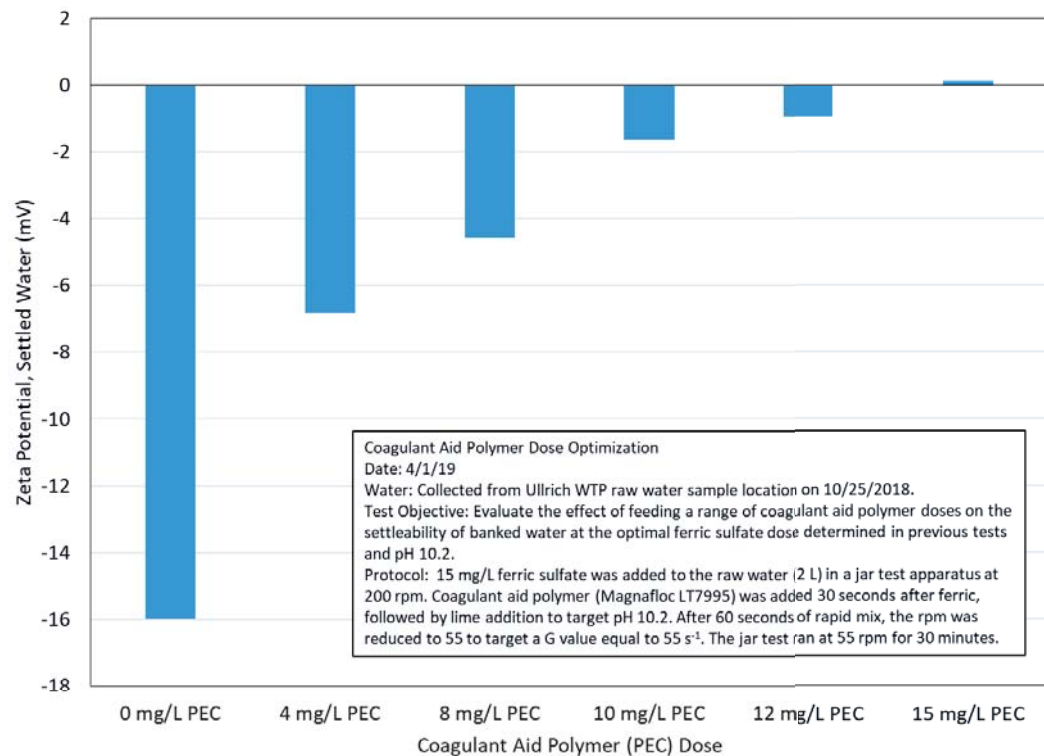


Figure 20 Impact of PEC Dose on Zeta Potential

## 4.2 Flocculant Aid Polymer (PEA)

Flocculant aid polymers (PEA) are typically high-molecular-weight long-chain molecules that can be anionic, nonionic, or cationic. PEAs improve the flocculation process by bridging, forming larger particles that settle more quickly. Experiments were conducted to determine if PEA addition would further improve settling rates from those observed by feeding 15 mg/L of ferric sulfate and 10-15 mg/L of PEC prior to softening at pH 10.2. All of the polymers tested were polyacrylamides. Table 4 summarizes the PEA polymers tested.

Table 4 Flocculant Aid Polymers (PEA) Tested

PEA	Company	Charge Type	Maximum NSF 60 Dose (mg/L)	Molecular Weight
Nalclear 7766 Plus	Nalco	Nonionic	1	---
Clarifloc A-6330	Polydyne	Anionic	1	Very High
Clarifloc C-6220	Polydyne	Cationic	3	High

Experiments were first conducted by feeding PEA in conjunction with lime, or 10 minutes after lime addition (Figure 21). In these experiments 15 mg/L of ferric sulfate was added 30 seconds prior to 10 mg/L PEC. Lime and PEA were added 5 seconds after PEC. The addition of PEA did not improve settled water turbidity in this scenario. Since floc aid polymer dose should be proportional to the number of particles, the lack of improvement observed may be due to the large proportion of small particles formed in a conventional jar test. Therefore, this test may not be representative of the potential benefits of floc aid polymer.

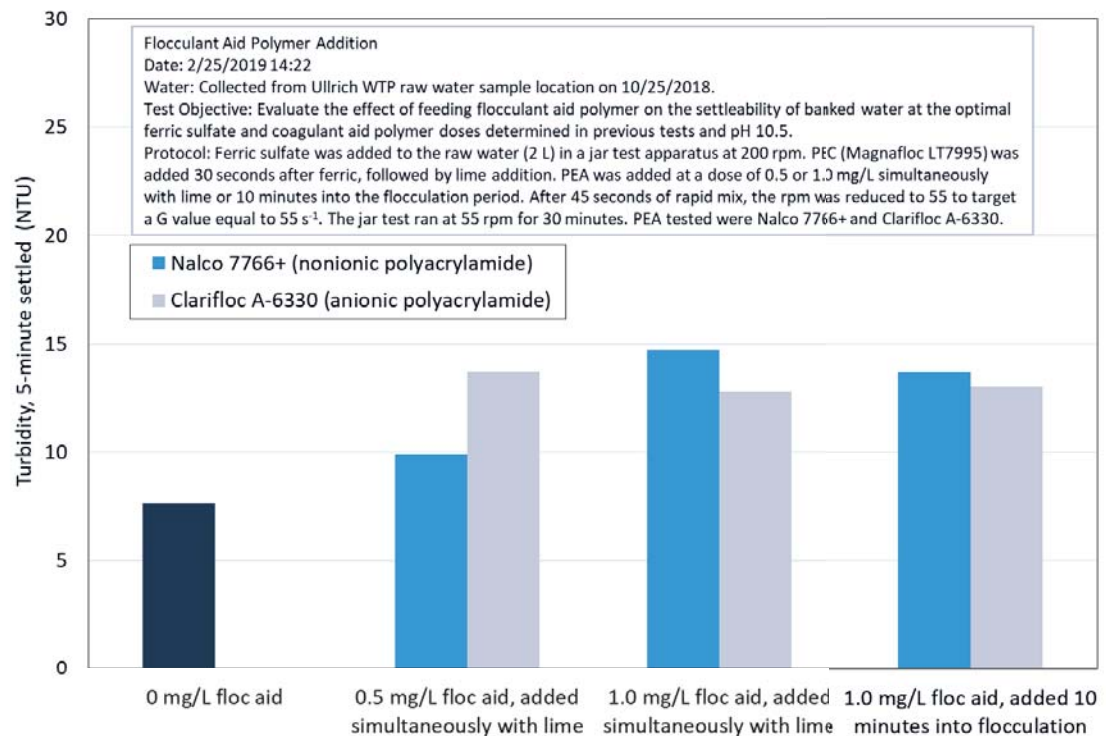


Figure 21 Impact of PEA on Banked Water Settled Turbidity

Additional testing was performed with solids collected from the Handcox WTP to test whether PEA would offer benefits if fed to solids more representative of those typical of a solids contact clarifier (SCC) like those at Ullrich and Handcox WTPs. All three types of PEA (nonionic, cationic, and anionic) were tested. Results are summarized in Figure 22. These experiments indicate that PEA addition did improve settleability when solids from the full-scale WTP were present. The anionic PEA performed better than the other polymers tested, potentially a result of its higher molecular weight. Therefore, the anionic PEA was selected for further study.

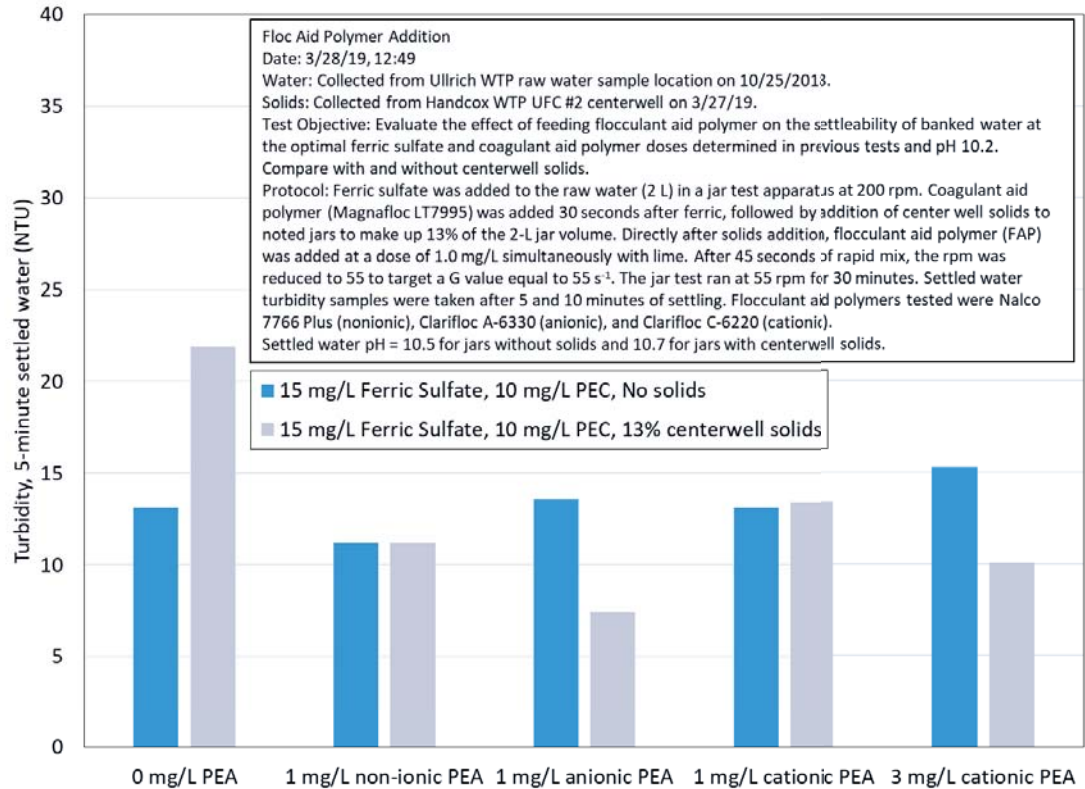


Figure 22 Impact of PEA on Banked Water Settled Turbidity - Seeded with SCC Solids

#### 4.2.1 Iterative Generation of Solids

To better simulate an upflow solids contact clarifier, an iterative approach to solids generation was used during the jar testing. In these experiments, the chemical feed to the first iteration included 15 mg/L of ferric sulfate dosed 30 seconds before 12 mg/L of PEC addition. Lime and PEA were dosed 5 seconds after PEC addition. After settling, the settled water was decanted and the solids were collected. It should be noted that a 2 minute settling time is equivalent to a SCC rise rate of 1.23 gpm/ft<sup>2</sup>. In all subsequent iterations, 15 mg/L of ferric sulfate was dosed 30 seconds before 12 mg/L of PEC addition. Lime, PEA, and solids from the previous iteration were then dosed 5 seconds after PEC addition. Results of the settled water turbidity during this iterative approach without PEA addition, and with 1 mg/L and 0.1 mg/L PEA addition are shown in Figure 23, Figure 24, and Figure 25, respectively. The resulting settled water turbidity upon achieving 3-percent solids (approximately 5 iterations) to match typical concentrations maintained in the full-scale SCCs (which range from 3 to 5-percent), is summarized in Figure 26. These results indicate that:

- Settled water turbidity improved as the solids concentration increased, even in the absence of PEA. The improved settling rates are likely a function of increased particle size.
- Even at low doses (e.g., 0.1 mg/L) PEA addition improved settled water turbidity.
- PEA reduced the variability of settled water turbidity.
- These were the only tests that matched normal operating settled water turbidities (i.e., 3 NTU or less), indicating that this approach to bench testing is more representative of SCCs than traditional jar testing procedures.
- The use of a PEA might also be of value if the solids concentration in the center well of a SCC is low.

Based on these results, the optimal treatment approach to reducing the settled water turbidity includes:

- Feeding PEC 20 - 30 seconds after ferric sulfate addition prior to softening at pH 10.2 to neutralize charge, and
- Feeding low doses of PEA to the clarifier center well to further aid in settling the particles formed in the treatment process.



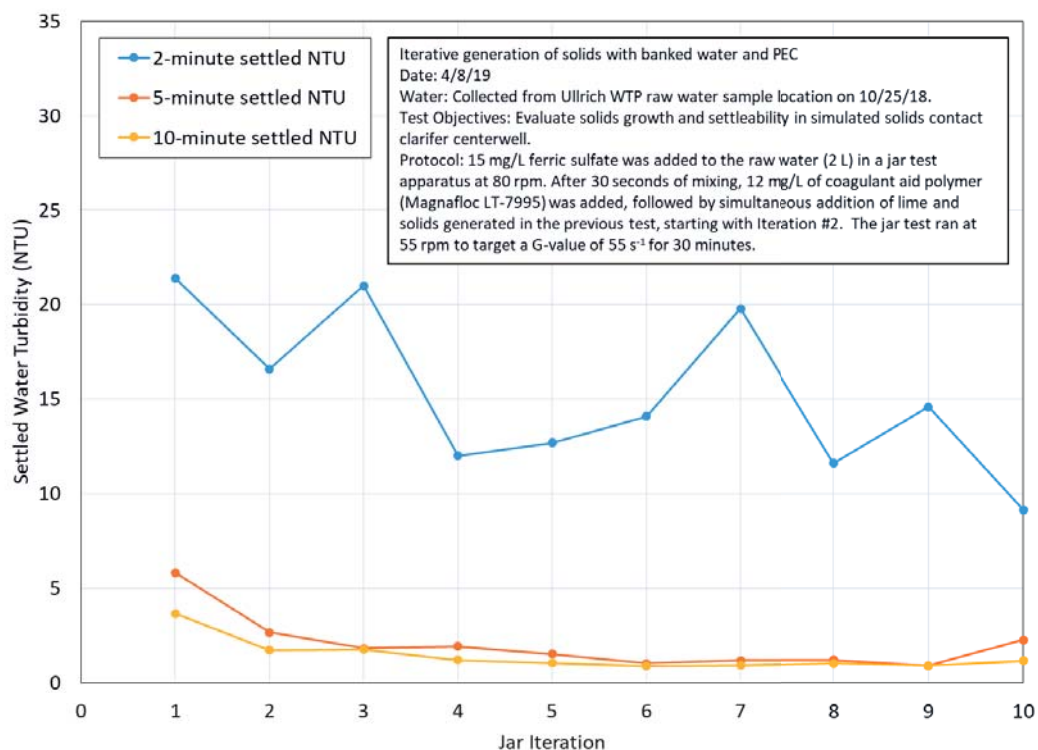


Figure 23 Iterative Generation of Solids with 0 mg/L PEA

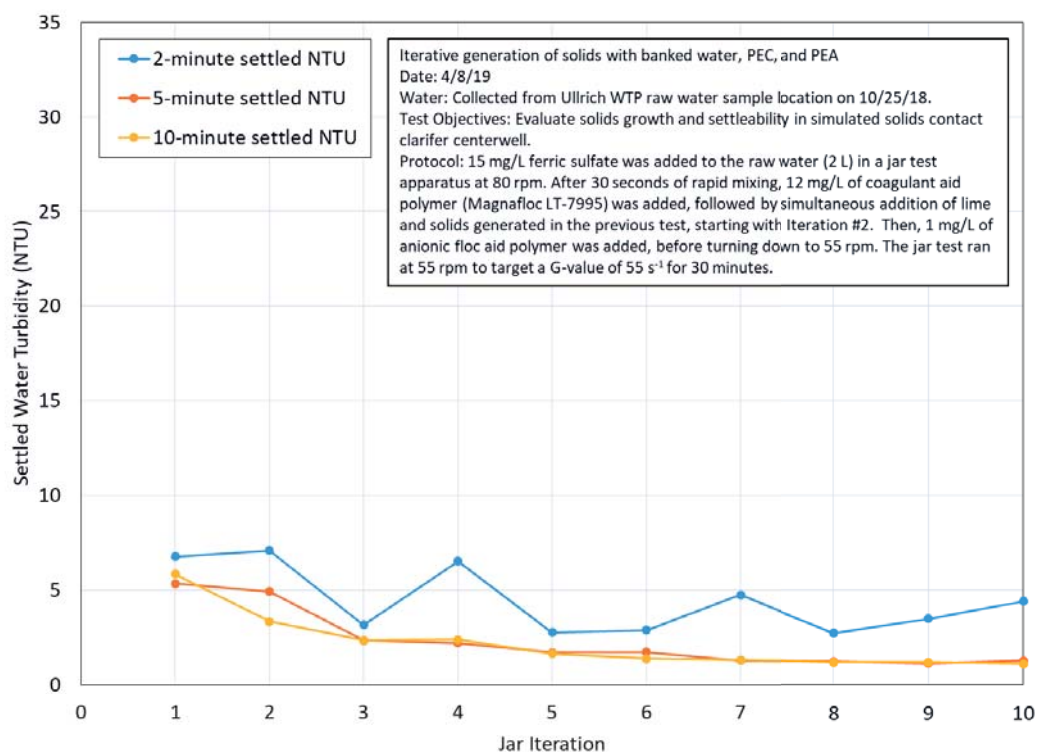


Figure 24 Iterative Generation of Solids with 1 mg/L PEA



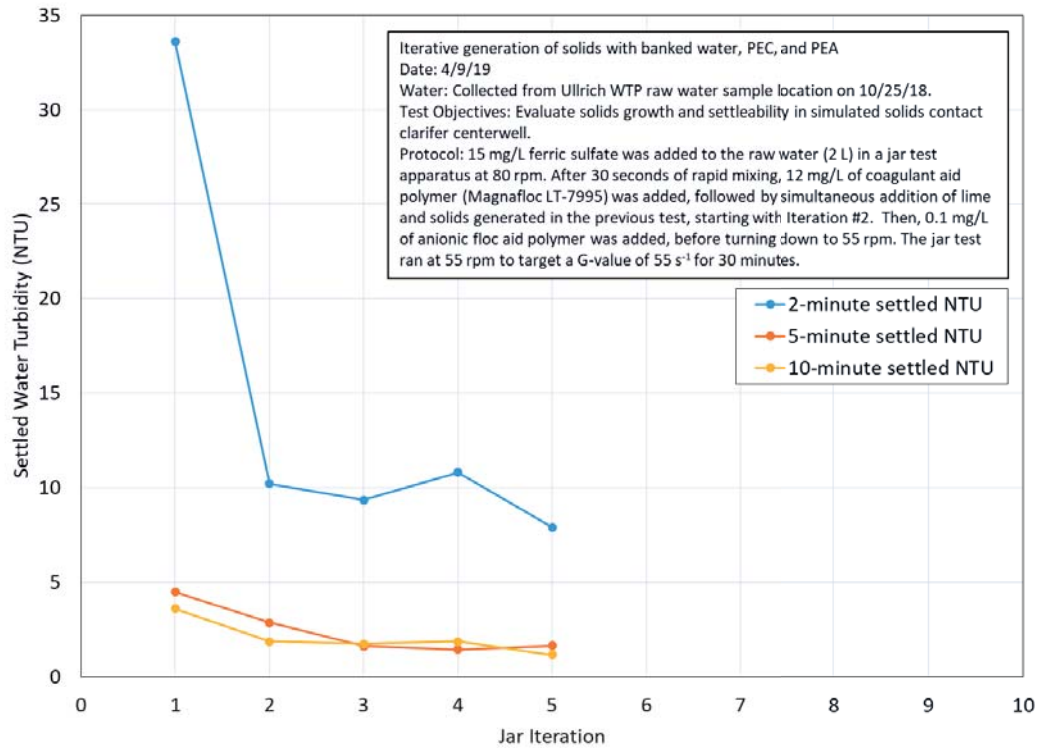


Figure 25 Iterative Generation of Solids with 0.1 mg/L PEA

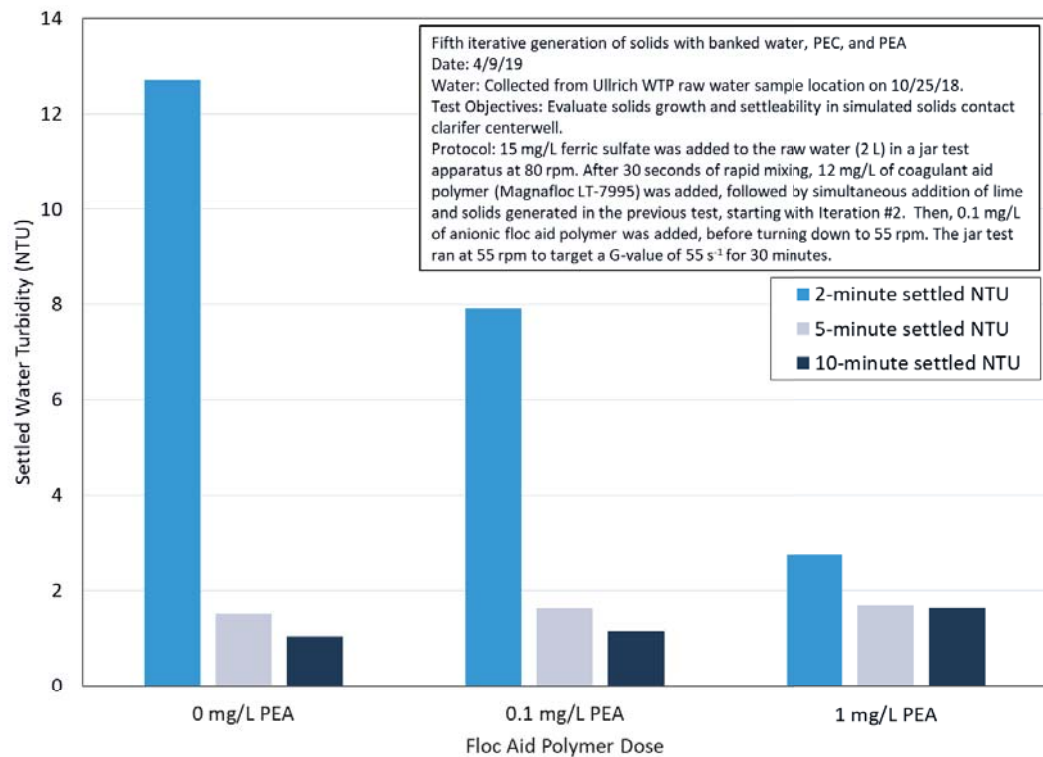


Figure 26 Impact of PEA Dose on Settled Turbidity for 3% Solids Generated from Banked Water

### 4.3 Carbon Dioxide and Caustic Soda Addition

During the October 2018 flood, the raw water alkalinity and hardness concentrations dropped well below historical norms, resulting in little carbonate or calcium available for precipitation of  $\text{CaCO}_3$  solids. The ability to add carbon dioxide ( $\text{CO}_2$ ) and potentially caustic soda ( $\text{NaOH}$ ) prior to softening was identified as a potential approach to allow the WTPs to operate closer to typical conditions during a similar extreme raw water quality event while simultaneously maintaining finished water alkalinity goals. This operational scenario would result in precipitation of more calcium carbonate solids which would increase the specific gravity and settleability of the solids during a flood event (assuming the same size particles).  $\text{NaOH}$  addition would allow the operators to dial in the settled water alkalinity if needed to meet finished water stability goals, and could provide flexibility in terms of where  $\text{CO}_2$  is added.

Figure 27 shows potential locations where  $\text{CO}_2$  and  $\text{NaOH}$  could be added at the Ullrich WTP. Part A shows  $\text{CO}_2$  addition after ammonia, but prior to ferric sulfate addition. In the absence of  $\text{NaOH}$  addition,  $\text{CO}_2$  would need to be added after ammonia to avoid formation of dichloramine at low pH conditions. Part B shows  $\text{CO}_2$  and  $\text{NaOH}$  addition after chlorine but before ammonia. Other alternatives are possible for  $\text{CO}_2$  and  $\text{NaOH}$  addition. Under either scenario (with or without  $\text{NaOH}$ ), polymers (PEC and PEA) would also be added.

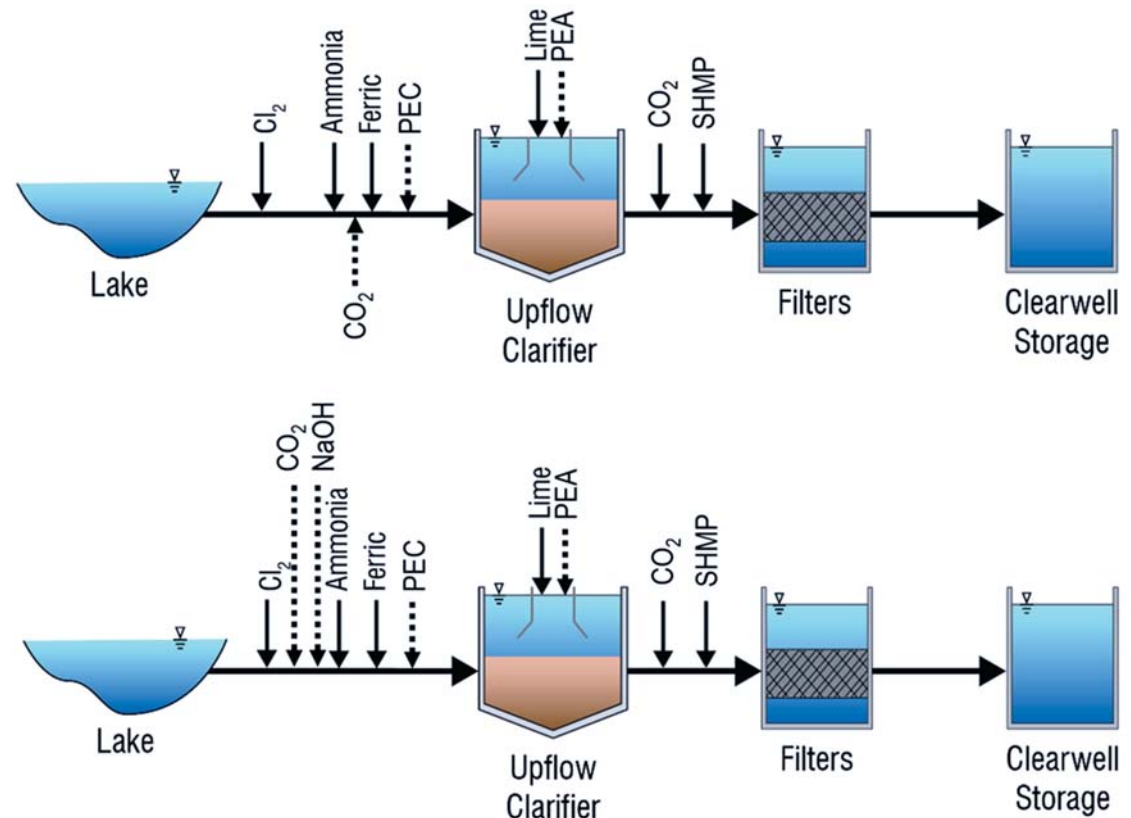


Figure 27 Potential Locations for  $\text{CO}_2$  and  $\text{NaOH}$  Addition at Ullrich WTP

Bench tests were conducted to evaluate the impact of adding CO<sub>2</sub> with and without NaOH on particle settleability, and resulting settled water quality. PEC was also added in some of the tests, and some tests were conducted with center well solids collected from either the Ullrich or Handcox WTPs to simulate the impact of CO<sub>2</sub> under solids contact conditions. Table 5 summarizes the different test conditions that were evaluated with CO<sub>2</sub> and NaOH addition. Results from the tests are summarized in the paragraphs below; the full set of results can be found in Appendix E.

Table 5 Summary of Jar Tests Conducted to Assess Impact of CO<sub>2</sub> and NaOH Addition

Jar Test ID	Jar Size	CO <sub>2</sub> Dose (mg/L)	Settled pH	NaOH Dose (mg/L)	PEC Dose (mg/L)	Center Well Solids (%)
JT18 and JT19	200 mL	0 - 65	10.0-10.7	0	0	0
JT22	200 mL	44	9.8-10.3	30	0	0
JT23	2 L	44-65	10.1-10.5	30-45	0 & 10	0
JT2.2 and JT2.3	2 L	0-88	9.7-10.5	0	0 & 10	0 & 13

A 44 mg/L CO<sub>2</sub> dose was used as a baseline for assessing the impact of CO<sub>2</sub> addition. That dose corresponds to the molar equivalent of the deficit in total carbonate concentrations during the October 2018 flood event relative to typical conditions (0.001 M). CO<sub>2</sub> addition was simulated by adding sodium bicarbonate (NaHCO<sub>3</sub>) to the Banked Water, followed by an equivalent amount of hydrochloric acid (HCl) prior to initiating rapid mix. After initiating rapid mix, ferric sulfate, PEC, center well solids, and/or lime were added depending on the target test condition. When NaOH was added, the dose was determined based on the target settled water alkalinity to achieve a finished water CCPP of 15 mg/L as CaCO<sub>3</sub> at pH 9.6 (typical operational value). Additional details on the jar testing procedures are provided in the Bench Testing Protocol (Appendix A).

Figure 28, Figure 29, Figure 30, and Figure 31 show results from the first set of jar tests using 200-mL jars to evaluate the impact of adding 22, 44, and 65 mg/L CO<sub>2</sub>. Addition of CO<sub>2</sub> translated to an increased mass of CaCO<sub>3</sub> solids precipitated, as expected (Figure 28). Between 44 - 65 mg/L CO<sub>2</sub> addition resulted in close to the same amount of CaCO<sub>3</sub> precipitated as with Typical Water at the same softening pH although the increased raw water solids in the Banked Water likely result in water with a different final solids specific gravity. Addition of CO<sub>2</sub> also increased the degree of saturation at the initiation of softening (Figure 29).

The greater mass of CaCO<sub>3</sub> precipitated translated to a higher calculated solids density for the jars to which CO<sub>2</sub> was added (Figure 30). While the 30 minute settled water turbidity was not impacted (results in Appendix E), a difference was observed in the settling rate (Figure 31).

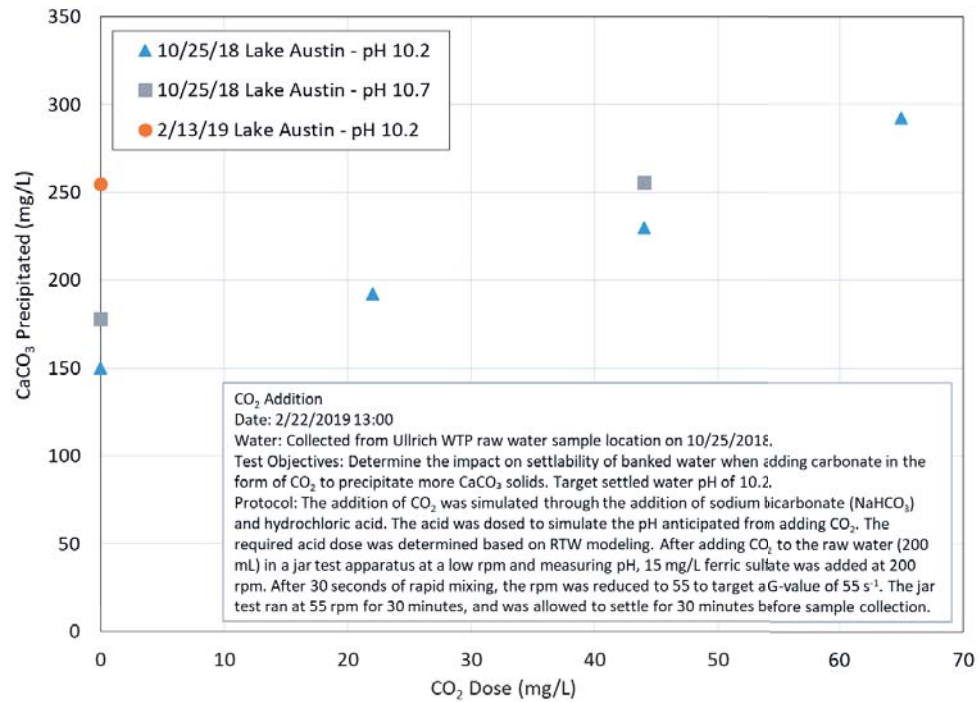
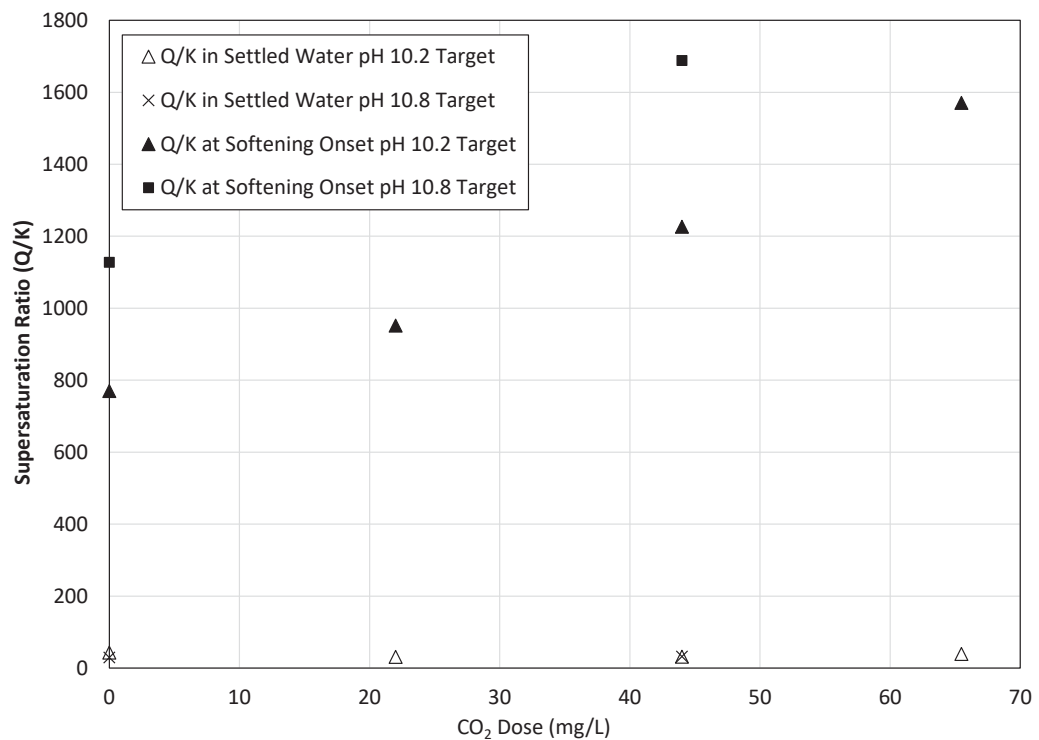


Figure 28 Impact of Carbon Dioxide Addition on Calcium Carbonate Precipitation

Figure 29 Impact of Carbon Dioxide Addition on CaCO<sub>3</sub> Saturation

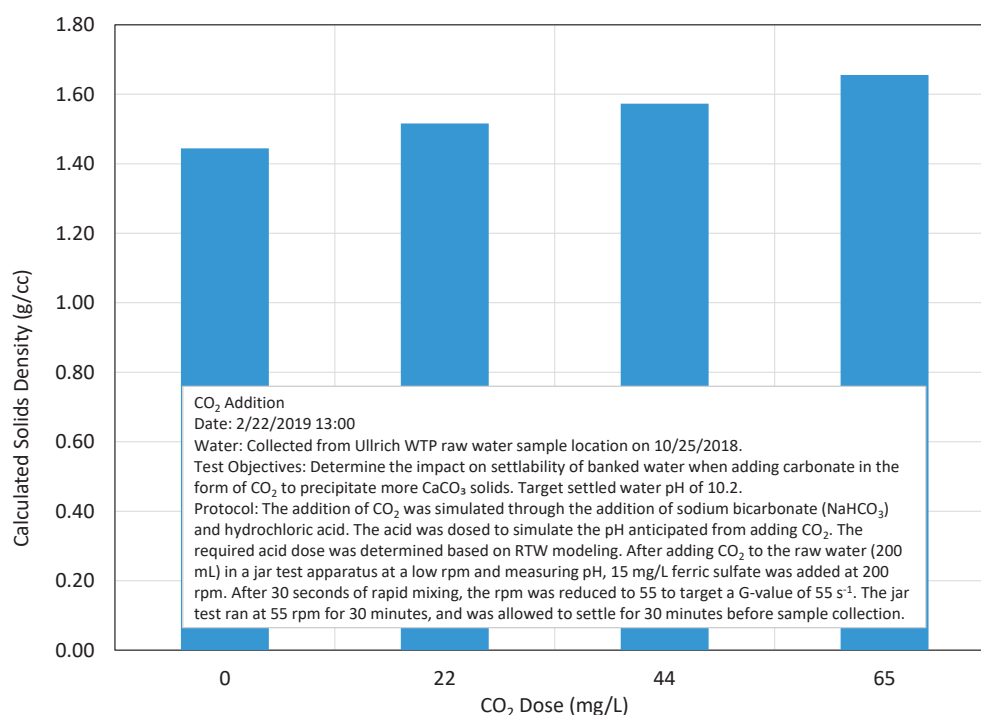


Figure 30 Impact of Carbon Dioxide Addition on Calculated Solids Density<sup>5</sup>

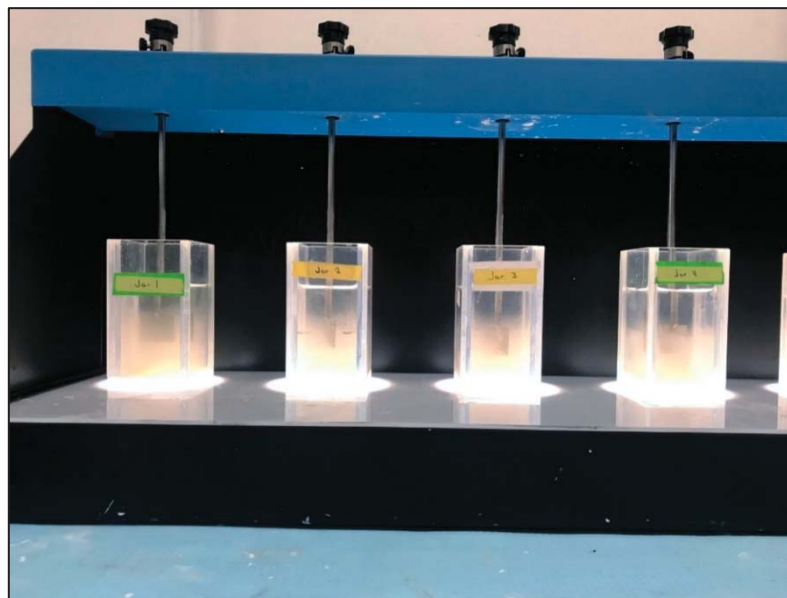


Figure 31 Image of Solids Settling in 200-mL Jars with CO<sub>2</sub> Doses Increasing (left to right) from 0 to 65 mg/L

<sup>5</sup> The solids density calculations were based on solids composition (estimated based on mass balance calculations from the jar test results) and literature values for density of the respective solids when wet (not dried).

To further assess the impact on settleability, similar conditions were tested in 2-L jars. As illustrated in Figure 32, a slight difference in the 5-minute settled water turbidity was observed between the jar in which no CO<sub>2</sub> was added (275 NTU) compared to the jar to which 65 mg/L CO<sub>2</sub> was added (230 NTU). In contrast, the addition of 10 mg/L PEC resulted in turbidity 1/10 than that achieved without PEC regardless of CO<sub>2</sub> dose. Given the cost and complexity of CO<sub>2</sub> addition prior to rapid mix, this operational strategy is not recommended as an improvement to help the City respond to similar future extreme raw water quality events.

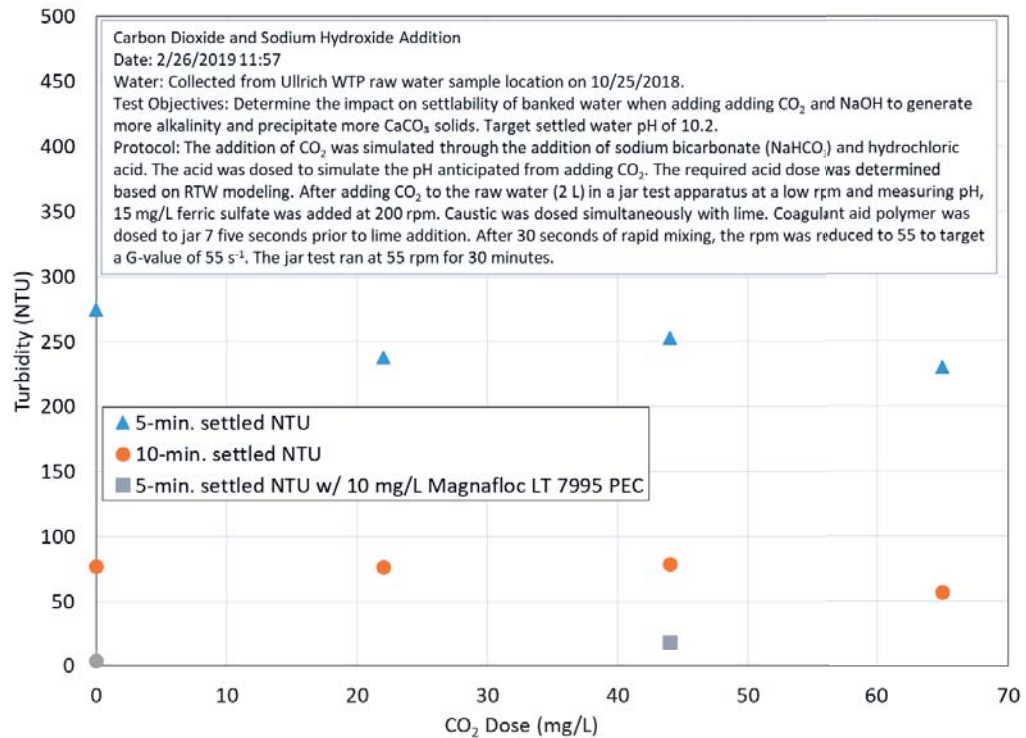


Figure 32 Impact of Carbon Dioxide Addition on Settled Turbidity

As illustrated in Figure 33, if CO<sub>2</sub> addition were reconsidered in the future, NaOH addition may not be needed to achieve target finished water CCP values. However, NaOH addition could provide benefits in terms of achieving a higher finished water alkalinity, and feeding NaOH would provide flexibility for the CO<sub>2</sub> feed point relative to the location of ammonia addition by allowing the pH to be maintained in the optimal range for chloramine formation.



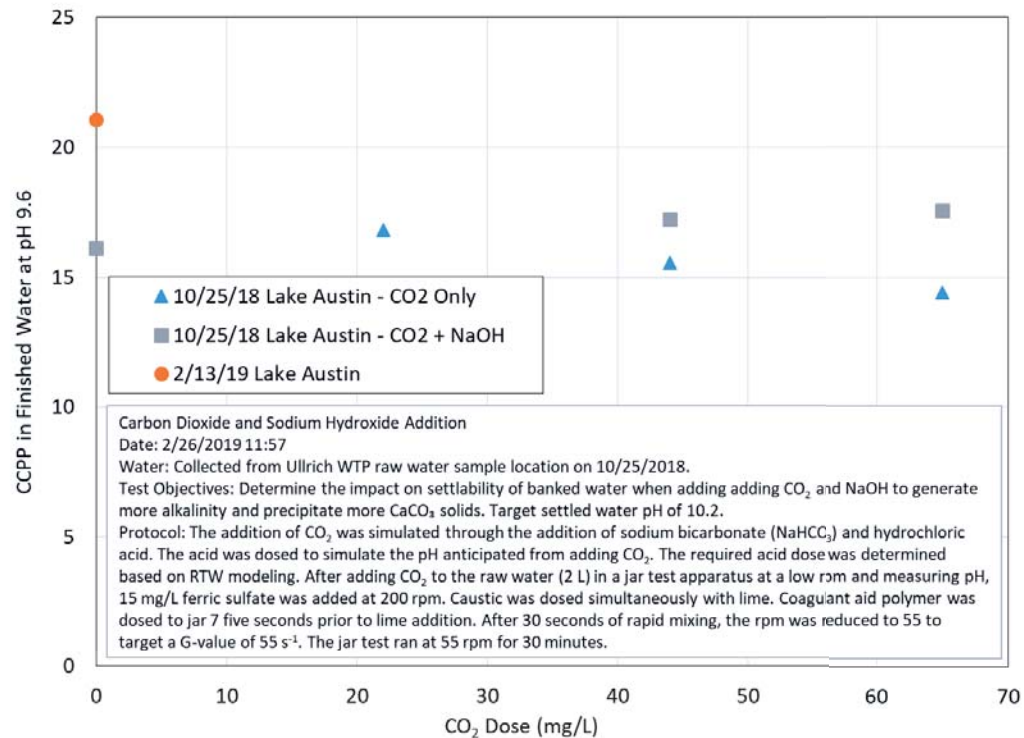


Figure 33 Impact of NaOH Addition on Finished Water CCPP Values

#### 4.4 Enhanced Coagulation

Enhanced coagulation relies on coagulation with a metal salt (i.e., ferric sulfate) under conditions that target organics removal. Jar tests were performed to evaluate the effectiveness of enhanced coagulation with higher ferric sulfate doses while maintaining a coagulation pH between 6 and 7 (the raw water pH of 8.0 was depressed by ferric sulfate addition and adjusted to pH 6 - 7 as needed by adding lime). Since the coagulation pH was maintained between 6 and 7, softening (e.g., hardness removal via calcium carbonate precipitation) did not occur.

Figure 34 shows that increasing the ferric sulfate dose from 80 to 280 mg/L had minimal impact on the 5-minute settled water turbidity. Figure 34 also shows a data point from softening at optimal conditions, where lime softening at a pH of 10.2 with 15 mg/L of ferric sulfate and 10 mg/L of coagulant aid polymer resulted in a settled water turbidity 1/5 that achieved by enhanced coagulation. According to zeta potential titrations, a ferric sulfate dose of approximately 300 mg/L was required to neutralize charge at ambient pH (Figure 7). Figure 35 shows that increasing the ferric sulfate dose generally resulted in a more neutral settled water zeta potential. Figure 36 shows that increasing the ferric sulfate dose from 80 to 280 mg/L improved settled water TOC from 3.4 to 1.4 mg/L, respectively. Increasing the ferric sulfate dose also improved settled water specific UV-absorbance (SUVA).

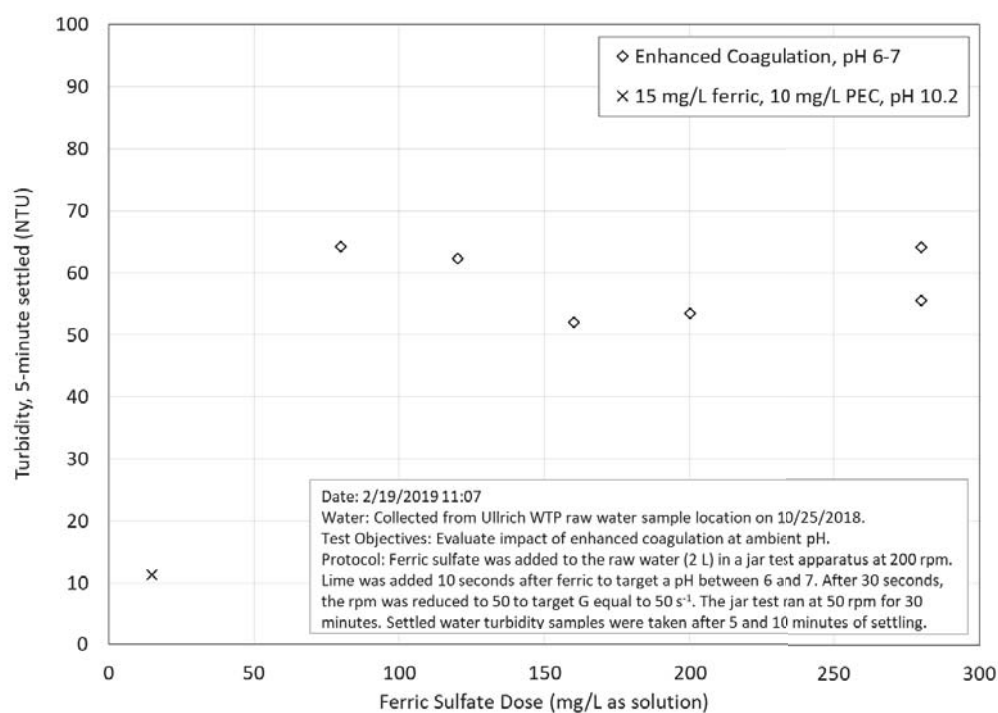


Figure 34 Impact of Ferric Sulfate Dose on Settled Turbidity at a Coagulation pH of 6-7

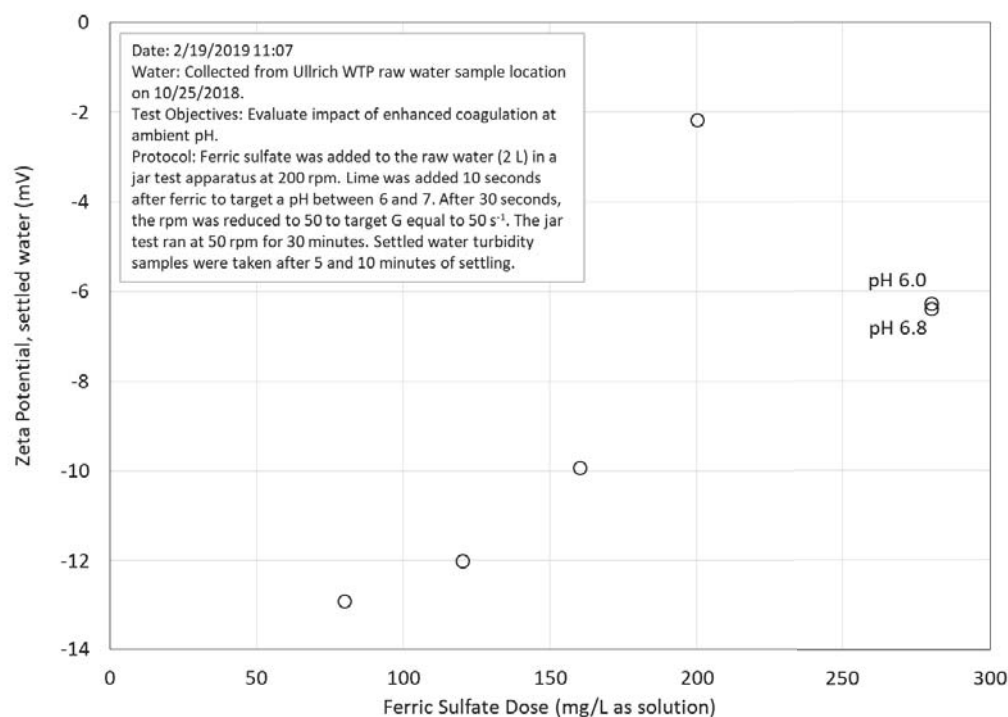


Figure 35 Impact of Ferric Sulfate Dose on Settled Zeta Potential at a Coagulation pH of 6-7



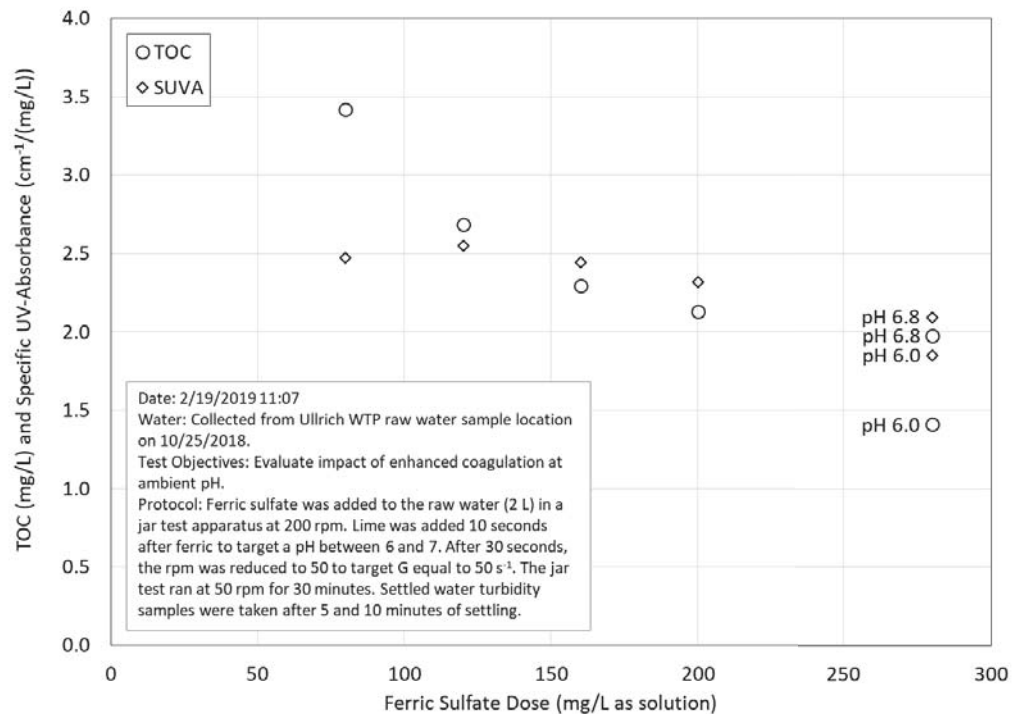


Figure 36 Impact of Ferric Sulfate Dose on TOC and SUVA at a Coagulation pH of 6-7

Operating with enhanced coagulation conditions would not be feasible at full-scale due to the required settling time of low specific gravity ferric hydroxide solids and high G-value imparted by the solids contact clarifiers at Ullrich and Handcox WTPs that demonstrate shearing of the ferric hydroxide solids. A lower mixing speed than typically targeted for the softening process would be needed to prevent shearing of the ferric hydroxide flocs. Lower surface loading rates of approximately 0.5 gpm/ft<sup>2</sup>, which are more consistent with conventional coagulation operation, would be required, necessitating a significant reduction in flow and plant production capacity at the Ullrich and Handcox WTPs. Further, the WTPs would not be able to operate at the low pH required for effective enhanced coagulation with ferric sulfate without resulting in finished water quality that could destabilize pipe scales in the distribution system, unless sodium hydroxide was implemented at the end of the treatment process to raise the pH.

#### 4.5 Summary

Bench testing was conducted to investigate the effectiveness of four potential treatment improvement strategies in treating raw water during a flood event:

- Addition of coagulation aid polymer (PEC).
- Addition of flocculation aid polymer (PEA).
- Addition of carbon dioxide and sodium hydroxide.
- Enhanced coagulation without softening.

These strategies, excluding PEA addition, are compared to both typical operation (15 mg/L ferric sulfate; softening at pH 10.2) and the most effective strategy used full-scale during the flood event (80 mg/L ferric sulfate; softening at pH 11.0) in Figure 37. These jar tests results show the optimal strategy to treat challenging raw water during a flood event includes the addition of PEC (15 mg/L ferric sulfate; 10 mg/L PEC; softening at pH 10.2). Subsequent testing with PEA showed additional settleability benefits. Therefore, the following treatment approach is recommended to improve the settleability of the softening process during a flood event:

- Feeding ferric sulfate at doses typical of normal operation (i.e., 15 mg/L as solution).
- Feeding PEC 30 seconds or more after ferric sulfate to neutralize charge (i.e., 12 mg/L as solution for the polymer tested and the Banked Water).
- Softening at pH typical of normal operation (i.e., pH 10.0- 10.2).
- Feeding low doses of PEA to the centerwell of the solids contact clarifiers at Ullrich and Handcox WTPs (or to the flocculation basins at the Davis WTP) (i.e., bench testing showed improved settling at doses as low as 0.1 mg/L as solution).

Conceptually, this treatment strategy relies on lime addition to achieve softening and pH targets, iron addition for TOC removal, PEC for charge neutralization, and PEA for particle bridging. Testing also showed that PEC and PEA could be fed during normal operations and adjusted as required during a flood event. Additional discussion pertaining to operations during both normal and storm conditions are discussed in Section 6 of this report.

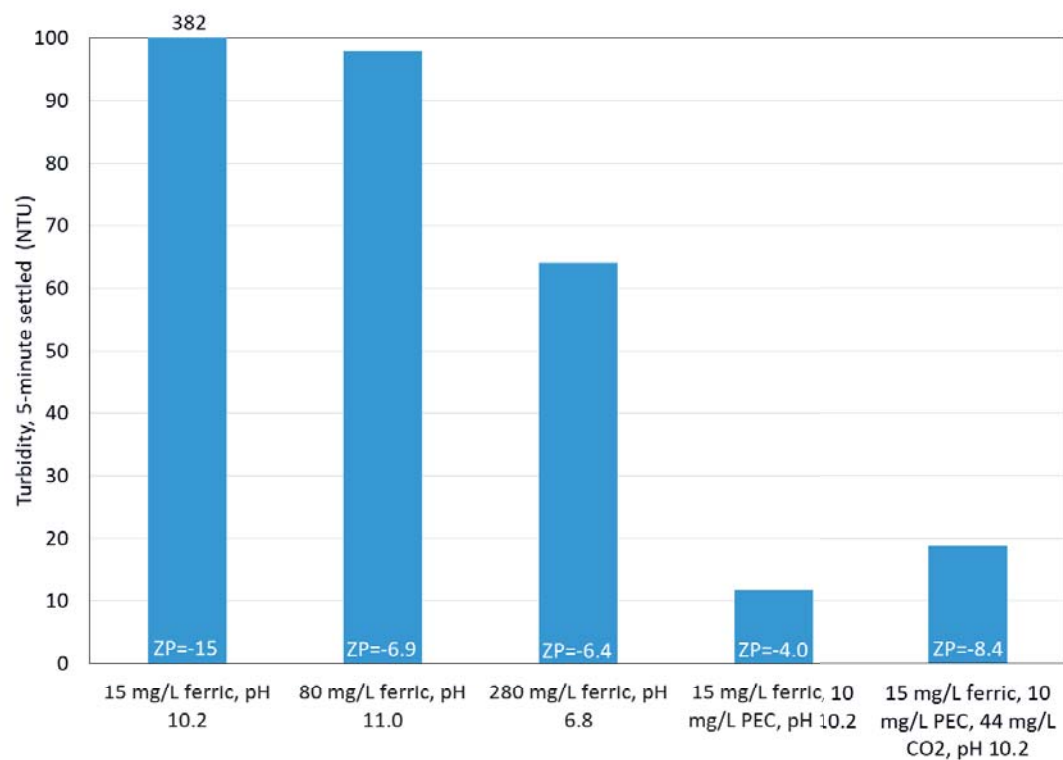


Figure 37 Summary of Settleability of Different Treatment Approaches

## Section 5

# IMPACT ON FINISHED WATER STABILITY

The City targets a finished water pH of approximately 9.6 or higher to minimize re-dissolution of pipe scales in the distribution system. Operation at this pH under typical finished water quality conditions (i.e., calcium and alkalinity concentrations) translates to an average calcium carbonate precipitation potential of 16 mg/L as  $\text{CaCO}_3$ <sup>6</sup>. The City adds sodium hexametaphosphate (SHMP) at the WTPs to sequester calcium and inhibit formation of calcium carbonate scale in the distribution system. Previous studies have indicated that the pipe scales are primarily composed of a magnesium silicate mineral identified as either chrysotile or lizardite<sup>7,8</sup>. Based on these characteristics, best practices to reduce the potential for a disruption in pipe scales are to:

- Avoid fluctuations in the finished water pH of more than 0.2 log units,
- Maintain a finished water CCPP close to 16 mg/L (by maintaining an elevated pH).
- Avoid disruptions in the solubility of the magnesium silicate scale, by avoiding significant pH changes (see first bullet) and changes in the finished water magnesium and silicate concentrations.

Table 6 lists the estimated finished water quality characteristics corresponding to the various operating scenarios that were implemented at full-scale during the October 2018 flood event and/or were tested in the laboratory on Banked Water as a potential option to respond to similar future extreme raw water quality events. All of the scenarios result in estimated finished water CCPP values in range of typical values at a finished water pH of 9.6.

Softening at a pH  $\geq 10.8$  results in lower finished water alkalinity relative to the scenarios where a softening pH closer to typical conditions (i.e., softening at pH 10 - 10.2) is targeted. Higher finished water alkalinity can be preferable since it provides buffering capacity and reduces potential impacts of chemical or microbial reactions (like nitrification) at the pipe surface.

Softening at higher pH also results in lower finished water magnesium (since magnesium is removed through  $\text{Mg}(\text{OH})_2$  precipitation) and slightly lower silicate concentrations (via co-precipitation with magnesium hydroxide). Combined, these finished water conditions could impact the solubility of the magnesium silicate scale in the distribution system. While modeling using MINEQL+ (or similar equilibrium chemistry software) may help elucidate the impact of the different operational scenarios on the solubility of the magnesium silicate scale, the comparative analysis illustrates the benefit of softening at pH 10 - 10.2 on finished water stability.

<sup>6</sup> Alternative Process Evaluation for Austin's Water Treatment Plants, Final report submitted to the City of Austin, June 2017.

<sup>7</sup> Morabbi, M. and Clark, S. 1999. Methods for Assessing the Effects of pH Reduction on Lime Softening Distribution Systems." City of Austin Water and Wastewater Utility. Austin, Texas.

<sup>8</sup> Snoeyink, V.L. and Price, M. 1996. Assessment of pH, Corrosion and Scaling," Technical Memorandum prepared for the City of Austin - Water and Wastewater Utility, February 28, 1996.

Table 6 Impact of Flood Event Operations on Finished Water Quality

Parameter	Enhanced Softening (pH $\geq$ 10.8)	Softening at pH 10 - 10.2 with PEC	Softening at pH 10 - 10.2 with CO <sub>2</sub>	Softening at pH 10 - 10.2 with CO <sub>2</sub> and NaOH	Historical Finished Water Average (2013-2015)
Plant Operation (Jar Test)	JT10-1	JT14-3	JT23-3	JT22-5	Lime Softening
Ferric sulfate dose, mg/L	80	15	15	15	15 <sup>(2)</sup>
Initial CO <sub>2</sub> dose, mg/L	0	0	44	44	0
Settled pH	11.1	10.2	10.2	10.2	10.1 <sup>(3)</sup>
Recarbonation CO <sub>2</sub> dose <sup>(1)</sup> , mg/L	27	11	11	13	<sup>(4)</sup>
Post-recarbonation pH	9.6	9.6	9.6	9.6	9.6
Alkalinity, total, mg/L as CaCO <sub>3</sub>	50	60	60	75	63
Calcium, total, mg/L	31	21	16	13	13
Magnesium, total, mg/L	2	7	6	6	16
SiO <sub>2</sub> , total, mg/L	6	8	10	11	10 <sup>(3)</sup>
LSI	1.4	1.3	1.1	1.1	1.1
CCPP, mg/L as CaCO <sub>3</sub>	16	17	15	17	16

Note:

- (1) Calculated using Rothberg, Tamburini and Winsor (RTW) Model for Corrosion Control and Process Chemistry.  
 (2) Approximate average operation.  
 (3) Source: Morabbi, M. and Clark, S. (1999). "Methods for Assessing the Effects of pH Reduction on Lime Softening Distribution Systems." City of Austin – Water and Wastewater Utility.  
 (4) Dosed to target post-recarbonation pH equal to 9.6.

## Section 6

# RECOMMENDED TREATMENT APPROACH

Additional tools to destabilize particles while minimizing solids, and forming dense, settleable solids would help the City be able to respond to a similar future event, potentially providing flexibility to operate closer to the rated capacity. The following WTP improvements are recommended:

- Provide the ability to add PEC upstream of softening at pH 10.2 (and to the filter influent to act as a filter aid polymer).

- PEC should be added after ferric sulfate, with the chemical addition points ideally separated by 30 seconds or greater.
- Measure zeta potential of settled water to confirm the PEC dose required to neutralize charge. Over time the correct zeta value will be determined but an initial target would be between - 4 and +4 mV.
- Provide the ability to add PEA to the center well of the upflow clarifier at doses ranging from 0.1 to 1 mg/L. This type of polymer requires activation.

Several additional operational scenarios were confirmed:

- Ferric sulfate addition at doses close to the typical operational condition is beneficial and should be maintained.
- Continue to soften at pH 10 - 10.2.
- Maintain solids in the center well since improved settling rates were observed in the iterative jar tests with Banked Water. PEA can provide additional settleability especially when solids in the center well cannot be maintained.

The tests with Banked Water also confirmed that the following scenarios are not preferred:

- Enhanced coagulation at lower pH (6-7).
- Enhanced softening (i.e., softening at pH > 10.8).
- Feeding CO<sub>2</sub> and caustic upstream of softening.

The recommended approach requires minimal WTP improvements and maintains operations (i.e., ferric sulfate and softening pH) near typical operation. Therefore, this approach is more easily implemented than strategies that would require a complete shift from normal operations. The recommended approach also results in finished water similar to that of typical operations with respect to pH and CCPP, thereby minimizing potential re-dissolution of existing scale in the distribution system.

The impact of an extreme rain event / flood can vary depending on the intensity, duration, and portion of the watershed that is affected. Thus, a critical step for the City's response to an event will be to test the raw water quality and use zeta potential to determine the optimal PEC dose since either underfeeding or overfeeding may result in poor performance. Those tests could be supplemented by jar testing with raw water and center well solids and/or close analysis of settled water turbidity and zeta potential, and filtered water turbidity, with incremental changes in PEC and PEA dose. These tests are recommended to inform plant operations since raw water quality likely deteriorates rapidly during a flood event and then improves slowly (i.e., weeks) after a storm passes through.

## Appendix A

# BENCH TESTING PROTOCOL



City of Austin  
Process Treatment Recommendation  
Resulting From October 2018 Flood Event

## BENCH TESTING PROTOCOL

DRAFT FINAL | February 2019



City of Austin  
Process Treatment Recommendation  
Resulting from October 2018 Flood Event

## BENCH TESTING PROTOCOL

DRAFT FINAL | February 2019

This document is released for the purpose of information exchange review and planning only under the authority of Phillip G. Pope, 02/06/2019, State of Texas PE# 104762.



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## Section 1

# PURPOSE AND OBJECTIVES

An extreme flood event in October 2018 dramatically changed the characteristics of the raw water supply to the City of Austin's three water treatment plants (WTPs). The change in water quality impacted the ability to treat the water to meet the finished water quality goals depending on the target plant production rate. Testing was conducted during the flood event both at bench- and full-scale to identify optimal operational conditions to keep the plants running to meet demands and TCEQ requirements. Tests focused on operational conditions that could be rapidly employed during the flood event and included an assessment of the optimal lime and ferric dose, sedimentation basin recirculation and blowdown rate, and the use of coagulant and flocculant aid polymers.

The City collected and stored 100 gallons of raw water on October 24, 2018 characterized by high turbidity and TOC, and low alkalinity and hardness. The City requested that Carollo Engineers, Inc. conduct testing on the banked water to meet the following objectives:

- 1) Further evaluate the optimal treatment approach during similar future challenge events, and
- 2) Identify potential facility improvements that would enhance the City's ability to respond to such events.

Testing will be completed in two phases. Phase 1 will consist of initial screening tests of various treatment strategies identified as potential approaches to respond to extreme raw water quality changes similar to the October 2018 event. Phase 2 will consist of additional testing to further vet promising alternatives identified in Phase 1 as well as additional strategies proposed based on the initial test results.

This document outlines the experimental matrix and approach for conducting the Phase 1 tests.

## Section 2

# EQUIPMENT

The following equipment will be provided by the University of Texas and will be used by Carollo Engineers, Inc. for the testing:

1. One (1) standard jar testing apparatus.
2. Twelve (12) 200 mL rectangular jars with specially constructed mixing paddles.
3. pH and temperature meter with electrode (buffers for 3-point calibration = 4.0, 7.0, 10.0).
4. Titration apparatus for alkalinity including prepared acid solution.
5. Spectrophotometer (Hach DR/4000 or equivalent) with cell for UV254 measurement.

6. ICP-OES for Ca, Mg, and Fe analysis and associated standard solutions for instrument calibration.
7. TOC analyzer and standard solutions for instrument calibration.
8. One (1) stir plate and various sized stir bars.
9. Cold storage space for up to 100 gallons of water in 20 L containers.
10. Trace metal grade nitric acid for preservation of samples for metals analysis.
11. Analytical grade phosphoric acid for preservation of TOC samples.
12. Analytical grade sodium hydroxide.
13. Analytical grade sodium bicarbonate.
14. Analytical grade hydrochloric acid.
15. Miscellaneous glassware.
16. Deionized water for miscellaneous lab use (up to 10 L).

The following equipment will be provided by Austin Water (AW) and will be used by Carollo Engineers, Inc. for the testing:

1. "Banked" raw water from during the water quality event.
2. Five (5) gallons of raw water sample to be used as representative of "typical" water quality.
3. Two (2) standard jar testing apparatuses.
4. Twelve (12) 2-L gator jars for use with the jar testing apparatuses.
5. Ferric sulfate.

The following equipment will be provided by Carollo Engineers, Inc. for the testing:

1. Turbidimeter (visible light) and sample cell.
2. Zetasizer and sample cell.
3. One (1) 10 mL autopipette with tips.
4. One (1) 1000  $\mu$ L autopipette with tips.
5. Five hundred (500) 15 mL falcon tubes to be used as sample containers for use with ICP-OES.
6. One hundred forty four (144) 40 mL glass sample containers with PP caps and PTFE septa for use with TOC analyzer.
7. Analytical grade calcium hydroxide.
8. Six funnels (plastic).
9. Six 1000-mL plastic beakers.
10. Six 250-mL Erlenmeyer flask (plastic).
11. One hundred (100) 1-mL syringes.
12. One hundred (100) 3-mL syringes.
13. One hundred (100) 5-mL syringes.
14. One hundred (100) 10-mL syringes.
15. One hundred (100) 25-mm PES syringe filters (0.45  $\mu$ m pore size).
16. Two timers.
17. One measuring spoon.
18. Paper towels.

## Section 3

# PROCEDURES

### 3.1 Jar Testing

Two types of tests will be conducted: water chemistry and charge tests, and settleability tests. Water chemistry tests will be conducted in specially constructed 200-mL jars with matching paddles. Water chemistry tests will be conducted to determine the effect of varying softening and coagulation conditions (i.e., lime and ferric dose) on precipitate characteristics (e.g., zeta potential and calculated composition and solids density) and settled water quality (i.e., pH, calcium, magnesium, alkalinity, and TOC concentrations, and UV254 absorbance).

Settleability tests will be conducted with a standard jar test apparatus with six rectangular 2-liter "gator" jars. This equipment uses previously developed relationships that correlate mixing energy with stirrer speed and water temperature (that is, velocity gradient (G)) at the bench-scale level (Figure 3.1). The specially designed gator jars have a sample tap located at a precise distance (10 cm) from the top of the water to allow the sampling of small quantities of settled water for turbidity measurements.

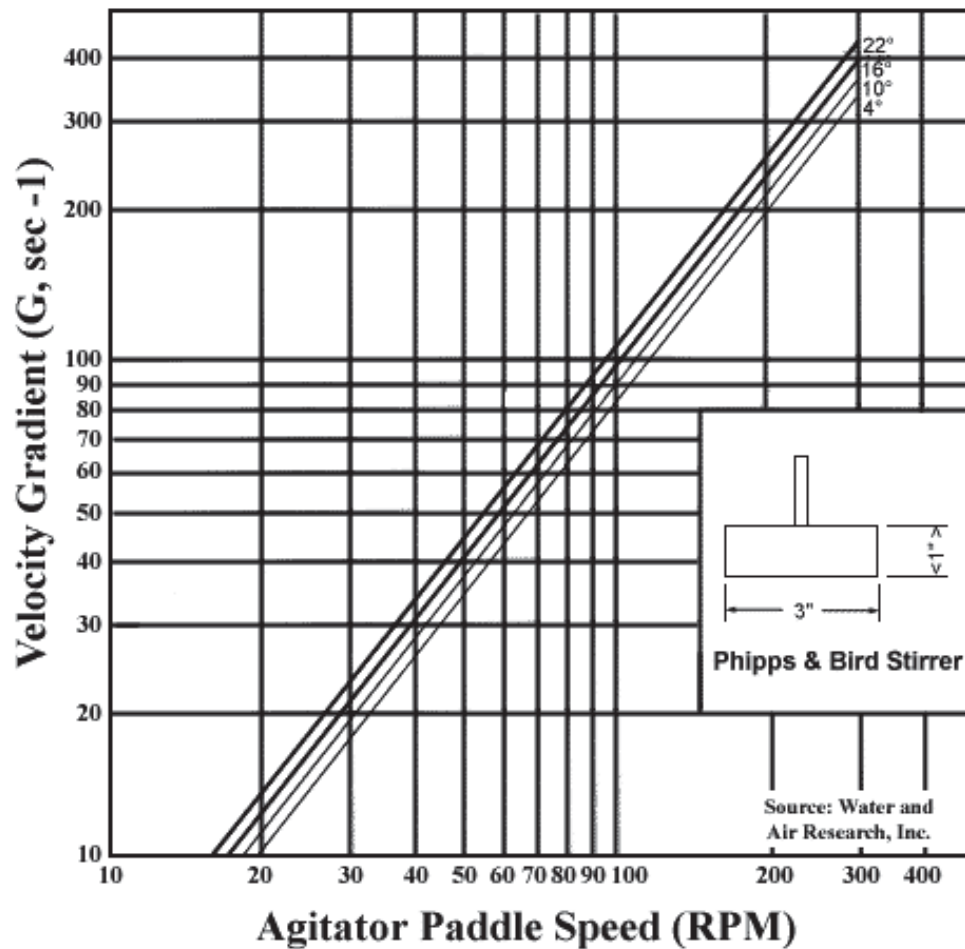


Figure 3.1 Velocity Gradient vs. RPM for 2 Liter Square Jars

The general methodology of the jar test procedure is outlined below:

- Stock solutions of primary treatment chemicals will be prepared as follows:
  - Lime slurry will be prepared by adding a specified mass of dry calcium hydroxide to 1 mL deionized water for the water chemistry tests (200 mL jars) and 10 mL deionized water for the settleability tests (2 L jars). Methods outlined in Roalson et al (2003) will be followed.
  - Ferric sulfate solution will be prepared from recent stocks obtained from the WTP.
  - Polymer solutions will be prepared from chemicals obtained from chemical vendors.
  - Caustic and sodium bicarbonate solutions will be prepared from reagent grade chemicals at UT Austin.
- 200 mL of raw water will be added to each jar for the water chemistry tests; two liters of raw water will be added to each jar for the settleability tests.
  - The jars will be flash mixed using a G value of 300 seconds<sup>-1</sup> for 30 seconds during which the chemicals will be dosed to each jar. The order of chemical addition will generally follow the sequencing illustrated in process flow diagrams from the November 26, 2018 meeting with the City and UT Austin. Additional details on timing of chemical addition are provided below for each set of tests.
- The mixing speed will then be reduced to simulate flocculation.
  - For most tests, flocculation conditions will be as follows:
    - $G = X \text{ sec}^{-1}$  simulating the typical recirculation speed in the solids contact clarifiers at Ullrich WTP.
    - Three stage tapered flocculation to simulate conditions at the Davis WTP. The flocculation conditions at the Davis WTP will be simulated for a majority of the testing since the jars cannot directly simulate the age, growth, and resulting composition of solids that form in the solids contact clarifiers used at Ullrich and WTP4. The flocculation conditions at Davis include:
      - ◀ Stage 1: 80 sec<sup>-1</sup>
      - ◀ Stage 2: 65 sec<sup>-1</sup>
      - ◀ Stage 3: 56 sec<sup>-1</sup>
    - 30 minutes, consistent with the floc basin detention time at Davis WTP at design flow. The flocculation time for Davis WTP is used since the jars cannot directly simulate the age, growth, and resulting composition of solids that form in the solids contact clarifiers used at Ullrich and WTP4.
  - For tests evaluating the impact of flocculation conditions, the mixing speed and duration will be varied as described in Section 3.6.
- The mixing will then be stopped and the water will be gravity settled for 30 minutes in the 200 mL jars and for 5 to 10 minutes in the 2 L jars.
- Following settling, water will be collected through the sampling port and analyzed for turbidity and other water quality parameters. For the 2 L jars, turbidity samples will be taken at 5 and 10 minutes following cessation of fluid rotation and start of settling. The jars used for the testing have a sample tap located 10 cm from the top of the water to allow the sampling of small quantities of settled water for turbidity measurements. The location of the sample tap allows the theoretical surface loading rate of the sedimentation to be estimated. Table 3.1 shows the settling time versus simulated surface loading rate.

Table 3.1 Simulated Surface Loading Rate for Jar Testing - 2 L jars

Settling Time (minutes)	Simulated Surface Loading Rate (gpm/ft <sup>2</sup> )
5	0.49
10	0.25

Notes:

(1) Sample point located 10 cm below the water surface.

Table 3.2 lists the parameters that will be analyzed in settled water from the jar tests. The experimental matrix for each set of jar tests is provided in the following sections.

Table 3.2 General Settled Water Quality for Jar Testing

Parameter	Laboratory Requirements	Sample Volume Requirement
pH <sup>(1)</sup>	UT	100 mL
UV254 <sup>(2)</sup>	UT	30 mL
TOC <sup>(3)</sup>	UT	50 mL
Metals via ICP-OES (Ca, Mg, and Fe)	UT	10 mL
Alkalinity	UT	100 mL
Zeta Potential	UT	5 mL
Turbidity	UT	50 mL
SUVA <sup>(3)</sup>	Calculation	N/A
Solids Density/Mass	Calculation	N/A
Finished Water Stabilization Requirements	Calculation	N/A
Total sample volume required <sup>(4)</sup>	-	245 mL

Notes:

(1) Measured in the same volume of sample used for alkalinity analysis.

(2) UV254 will be measured on samples that have been filtered through 0.45 µm syringe filters that have been pre-rinsed with deionized water.

(3) Not included for 200 mL jars due to sample volume constraints; TOC will be used for calculation.

(4) Total volume is for 2 L jars. Volume assumes pH and alkalinity measured from same sample volume. Sample volume requirements for 200 mL jars approximately 195 mL if TOC is not measured.

### 3.2 Baseline Testing

Testing will be conducted to:

- Determine operational baseline with typical water quality treated with an average ferric sulfate dose while varying pH (Test 1).
- Assess softening chemistry during flood event, identifying lime doses corresponding to the minimum calcium concentration and point of magnesium hydroxide precipitation (Test 2).
- Evaluate the impact of ferric addition at lime doses bracketing the softening conditions targeted during the October 2018 flood event (pH ~10.2 and 11) (Test 3 and 4).
- Evaluate the impact of softening at optimal ferric doses on settleability using 2 L jars (Test 5).
- Evaluate impact of enhanced coagulation at ambient pH (Test 6).

The analytical results will be reviewed for:

- Settled water quality, specifically, pH, alkalinity, calcium, and magnesium concentration, UV254, and turbidity.
- Precipitate charge, composition (based on a mass balance of raw and settled water quality), and density (calculated).
- Potential need for post-stabilization under the varying conditions based on calculated values for CCPP and LSI.

Tests 3 - 6 are similar to the tests conducted during the October 2018 flood event (presented during the November 8, 2018 meeting at Ullrich WTP with the City and UT Austin) and focus on confirming previous findings and carefully evaluating the softening chemistry corresponding to the varying operational conditions. While the primary focus of the Phase 1 and 2 bench tests is to identify alternate approaches to flood event response for the City's water treatment plants than those employed during the October 2018 event (which were already demonstrated), Tests 3 - 6 are included as a starting point to fully assess the softening chemistry and precipitate characteristics under the range of ferric and lime doses that could be employed. The results are expected to provide a baseline of the particle density, charge, and settleability that could be achieved with the current "knobs" that the City can turn, and then use that data to compare alternate approaches to be evaluated in subsequent tests.

Details for each test are provided in Table 3.3 to Table 3.7. In all of the tests, ferric will be added approximately 5 seconds before lime.

Table 3.3 Test 1 - Operational Baseline at Typical Water Quality (200 mL jars)

Jar	Lime Dose (mg/L) <sup>(1)</sup>	Ferric Sulfate Dose <sup>(2)</sup> (mg/L)	Target pH	Settling Test
1	0	AVG	Ambient	-
2	30	AVG		-
3	60	AVG	-	-
4	100	AVG	-	-
5	130	AVG	-	-
6	160	AVG	-	-
7	185	AVG	-	-
8	210	AVG	-	-
9	235	AVG	-	-
10	260	AVG	-	-
11	285	AVG	11.5	-
12 (dupl)	160	AVG	-	-

Notes:

- (1) Lime doses target increased resolution around anticipated points of minimum calcium and magnesium hydroxide precipitation. Dose range will be selected based on a target pH range and corresponding lime dose estimated from a softening chemistry model. The doses shown are based on data from Roalson et al. (2003) and Kalscheur et al. (2006) and will be updated based on the raw water characterization of the typical water quality.
- (2) Dosed as solution. Based on current operating conditions.



Table 3.4 Test 2 - Impact of pH on Banked Water (200 mL jars)

Jar	Lime Dose <sup>(1)</sup> (mg/L)	Ferric Sulfate Dose <sup>(2)</sup> (mg/L)	Target pH	Settling Test
1	0	0	Ambient	-
2	30	0		-
3	60	0		-
4	100	0		-
5	130	0		-
6	160	0		-
7	185	0		-
8	210	0		-
9	235	0		-
10	260	0		-
11	285	0	11.5	-
12 (dupl)	160	0		-

Notes:

- (1) Lime doses target increased resolution around anticipated points of minimum calcium and magnesium hydroxide precipitation. Dose range will be selected based on a target pH range and corresponding lime dose estimated from a softening chemistry model. The doses shown are based on data from Roalson et al. (2003) and Kalscheur et al. (2006) and will be updated based on the raw water characterization of the banked water quality.
- (2) Dosed as solution.

Table 3.5 Test 3 - Impact of Ferric Dose Bracketing Softening Conditions Around pH 10.2 and 11: Lower Fe doses (200 mL jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Settling Test
1	TBD	30	9.6	-
2	TBD	30	10	-
3	TBD	30	10.2	-
4	TBD	30	10.4	-
5	TBD	30	10.8	-
6	TBD	30	11.2	-
7	TBD	60	9.6	-
8	TBD	60	10	-
9	TBD	60	10.2	-
10	TBD	60	10.4	-
11	TBD	60	10.8	-
12	TBD	60	11.2	-

Notes:

- (1) Dosed as solution.

Table 3.6 Test 4 - Impact of Ferric Dose Bracketing Softening Conditions Around pH 10.2 and 11: Higher Fe doses (200 mL jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Settling Test
1	TBD	90	9.6	-
2	TBD	90	10	-
3	TBD	90	10.2	-
4	TBD	90	10.4	-
5	TBD	90	10.8	-
6	TBD	90	11.2	-
7	TBD	180	9.6	-
8	TBD	180	10	-
9	TBD	180	10.2	-
10	TBD	180	10.4	-
11	TBD	180	10.8	-
12	TBD	180	11.2	-

Notes:

(1) Dosed as solution.

Table 3.7 Test 5 - Settleability Test at Optimal Softening Range and Ferric Dose (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Settling Test
1	TBD	Low (TBD)	9.7	X
2	TBD	Low (TBD)	10.0	X
3	TBD	Low (TBD)	10.3	X
4	TBD	Low (TBD)	10.6	X
5	TBD	Low (TBD)	10.9	X
6	TBD	Low (TBD)	11.2	X
7	TBD	High (TBD)	9.7	X
8	TBD	High (TBD)	10.0	X
9	TBD	High (TBD)	10.3	X
10	TBD	High (TBD)	10.6	X
11	TBD	High (TBD)	10.9	X
12	TBD	High (TBD)	11.2	X

Notes:

(1) Dosed as solution. Based on current operating conditions.

Table 3.8 Test 6 - Impact of Enhanced Coagulation at Baseline Mixing Speed (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Settling Test
1	0	120	Ambient	X
2	0	160	Ambient	X
3	0	200	Ambient	X
4	0	240	Ambient	X
5	0	280	Ambient	X
6	TBD	120	8 - 8.5	X
7	TBD	160	8 - 8.5	X
8	TBD	200	8 - 8.5	X
9	TBD	280	8 - 8.5	X

Notes:

(1) Dosed as solution. Target dose range will be confirmed based on a charge titration. During the October 2018 flood event, approximately 300 mg/L ferric as solution was required to neutralize the charge of particles in solution.

### 3.3 Coagulant Aid Polymer Testing

Coagulant aid polymer will be tested in banked water at two pH values, 10.2 to represent optimum softening conditions, and 11.2 to represent enhanced softening conditions. Tests utilizing coagulant aid polymer will be conducted to evaluate the following:

- Determine the coagulant aid polymers which best neutralize charge.
- Determine the effect of coagulant aid polymers on settleability of banked water at average ferric sulfate dose and pH 10.2 and 11.0.
- Determine the effect of coagulant aid polymers on settleability of banked water at varying ferric sulfate dose and pH 10.2.

Test number 1 will consist of titrations of banked water with coagulant aid polymer and ferric sulfate to determine the concentration of each chemical required to neutralize the charge of the particles in the banked water. The two polymers which neutralize the most charge per unit mass will be utilized in jar tests to determine their overall effect on settleability. Titrations of banked water with ferric sulfate, and the order of chemical addition will also be evaluated. Titration testing includes:

- Polymer A.
- Polymer B.
- Polymer C.
- Ferric Sulfate.
- Optimum polymer dose added 30 seconds before ferric sulfate.
- Optimum polymer dosed 1.5 minutes after ferric sulfate.
- Simultaneous addition of optimum polymer and ferric sulfate.
- Ferric sulfate dosed 30 seconds before polymer.

Tests 2 through 6 will be jar tests to determine the effect of coagulant aid polymer on the settleability of banked water. For Tests 2- 5, coagulant aid polymer will be added first at initiation of rapid mix. Ferric will be added approximately 5 seconds after polymer and lime will be added approximately 5 seconds after ferric. Test 6 will investigate alternate orders and timing of chemical addition.

The following parameters will be measured after settling in each jar:

- pH.
- UV-254.
- TOC.
- Metals by ICP-OES (Ca, Mg, and Fe).
- Alkalinity.
- Turbidity.
- Zeta potential.

Details for each test are provided in Table 3.9 to Table 3.13 Settling tests described above will also be conducted.

Table 3.9 Test 2 - Coagulant Aid Polymer A at Typical Ferric Sulfate Dose and pH 10.2 (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Polymer Type <sup>(2)</sup>	Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	Avg (TBD)	10.2	A	0	X
2	TBD	Avg (TBD)	10.2	A	TBD	X
3	TBD	Avg (TBD)	10.2	A	TBD	X
4	TBD	Avg (TBD)	10.2	A	TBD	X
5	TBD	Avg (TBD)	10.2	A	TBD	X
6	TBD	Avg (TBD)	10.2	A	TBD	X

Notes:

(1) Dosed as solution. Based on current operating conditions.

(2) Polymer type may be changed based on titration tests.

(3) Dosed as solution.

Table 3.10 Test 3 - Coagulant Aid Polymer B at Typical Ferric Sulfate Dose and pH 10.2 (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Polymer Type <sup>(2)</sup>	Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	Avg (TBD)	10.2	B	TBD	X
2	TBD	Avg (TBD)	10.2	B	TBD	X
3	TBD	Avg (TBD)	10.2	B	TBD	X
4	TBD	Avg (TBD)	10.2	B	TBD	X
5	TBD	Avg (TBD)	10.2	B	TBD	X
6	TBD	Avg (TBD)	10.2	B	TBD	X

Notes:

(1) Dosed as solution. Based on current operating conditions.

(2) Polymer type may be changed based on titration tests.

(3) Dosed as solution.

Table 3.11 Test 4 - Coagulant Aid Polymer A at Typical Ferric Sulfate Dose and pH 11.0 (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Polymer Type	Polymer Dose <sup>(2)</sup> (mg/L)	Settling Test
1	TBD	Avg (TBD)	11.0	--	0	X
2	TBD	Avg (TBD)	11.0	OPT(TBD)	TBD	X
3	TBD	Avg (TBD)	11.0	OPT(TBD)	TBD	X
4	TBD	Avg (TBD)	11.0	OPT(TBD)	TBD	X
5	TBD	Avg (TBD)	11.0	OPT(TBD)	TBD	X
6	TBD	Avg (TBD)	11.0	OPT(TBD)	TBD	X

Notes:

(1) Dosed as solution. Based on current operating conditions.

(2) Dosed as solution.

Table 3.12 Test 5 - Coagulant Aid Polymer Offset at Varying Ferric Sulfate Doses and pH 10.2 (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Polymer Type <sup>(4)</sup>	Polymer Dose <sup>(5)</sup> (mg/L)	Settling Test
1	TBD	0	10.2	A	TBD	X
2	TBD	Mid (TBD) <sup>(2)</sup>	10.2	A	TBD	X
3	TBD	High (TBD) <sup>(3)</sup>	10.2	A	TBD	X
4	TBD	0	10.2	B	TBD	X
5	TBD	Mid (TBD) <sup>(2)</sup>	10.2	B	TBD	X
6	TBD	High (TBD) <sup>(3)</sup>	10.2	B	TBD	X

Notes:

(1) Dosed as solution. Based on current operating conditions.

(2) Approximately 2x the average plant dose.

(3) Approximately 5-10x the average plant dose. TBD based on results from Baseline Testing.

(4) Polymer type may be changed based on titration tests.

(5) Dosed as solution.

Table 3.13 Test 6 - Coagulant Aid Polymer with and without Ferric Sulfate Varying Addition Sequence and Duration Between Chemical Addition (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	Polymer Type	Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	0	Opt <sup>(2)</sup>	A <sup>(8)</sup>	TBD	X
2	TBD	0	Opt <sup>(2)</sup>	B <sup>(8)</sup>	TBD	X
3 <sup>(4)</sup>	TBD	0	Opt <sup>(2)</sup>	A <sup>(8)</sup>	TBD	X
4 <sup>(5)</sup>	TBD	Opt	Opt <sup>(2)</sup>	A <sup>(8)</sup>	TBD	X
5 <sup>(6)</sup>	TBD	Opt	Opt <sup>(2)</sup>	A <sup>(8)</sup>	TBD	X
6 <sup>(7)</sup>	TBD	0	Opt <sup>(2)</sup>	A <sup>(8)</sup>	TBD	X

Notes:

(1) Dosed as solution. Optimal dose determined during previous testing.

(2) Optimal pH determined during previous testing.

(3) Optimal dose determined during previous testing.

(4) Polymer to be added 30-60 seconds before lime addition.

(5) Polymer to be added 90 seconds after ferric sulfate addition. Lime to be added 30 seconds after polymer.

(6) Polymer to be added after ferric sulfate and at the same time as lime.

(7) Polymer to be added at the same time as lime.

(8) Polymer type may be changed based on results from previous testing.

### 3.4 CO<sub>2</sub> and NaOH Addition Testing

One issue during the flood event was the alkalinity and hardness of the raw water dropped well below historical norms and the turbidity increased significantly, resulting in little carbonate available for precipitation as CaCO<sub>3</sub> solids and a significant increase in source water solids. A possible remedy for such water quality is addition of carbonate to the raw water prior to flocculation and sedimentation. One method of adding carbonate at all three Austin water treatment plants is to add a CO<sub>2</sub> feed point upstream of the flocculation process. CO<sub>2</sub> is already used in the recarbonation step of the treatment process. CO<sub>2</sub> could be added alone or in conjunction with sodium hydroxide (NaOH), which would also add alkalinity. Soda ash was also considered for testing but was not included because it can inhibit organics removal and result in an increased number of negatively charged particles, which is the opposite of the goal of this testing.

This set of tests will be initiated by modeling target conditions for CO<sub>2</sub> addition with and without NaOH addition, factoring in impact on solids concentration and density. Jar tests will then be conducted to simulate:

- The impact on settlability of banked water when adding carbonate in the form of CO<sub>2</sub> to precipitate more CaCO<sub>3</sub> solids.
- The impact on settleability of banked water when adding CO<sub>2</sub> and NaOH to generate more alkalinity and precipitate more CaCO<sub>3</sub> solids.

The addition of CO<sub>2</sub> will be simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and acid (hydrochloric or sulfuric). The acid will be dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose will be determined based on Rothberg, Tamburini, and Winsor (RTW) modeling. The following parameters will be measured after settling in each jar:

- pH.
- UV-254.
- TOC.
- Metals by ICP-OES (Ca, Mg, and Fe).
- Alkalinity.
- Turbidity.
- Zeta potential.

Details for each jar test are outlined in Table 3.14 to Table 3.18. Settling tests will also be conducted as described above.

Prior to conducting the jar tests with CO<sub>2</sub> and NaOH, preliminary tests will be conducted to evaluate the affect of the order of CO<sub>2</sub>, NaOH, ferric, and lime addition on the zeta potential of settled water. The order of chemical addition to be evaluated takes into account what is feasible at the WTPs based on current process configurations. The specific conditions for the jar test are outlined in Table 3.14, and the order of chemical addition is outlined below.

- Jar 1: CO<sub>2</sub> → Ferric → Caustic → Lime
- Jar 2: CO<sub>2</sub> → Ferric → Caustic & Lime
- Jar 3: CO<sub>2</sub> → Caustic → Ferric → Lime

Results will be discussed with the Project Team to determine preferred order of chemical addition for Tests 2 through 5 below.

Jar tests 2 and 3 will be conducted using the 200 mL jars to confirm water chemistry. Tests 4 and 5 will then be conducted with the 2 L jars to test settleability based on target conditions from the previous two tests.

Note: Since CO<sub>2</sub> will depress the pH, it should be added after chloramines have formed to avoid dichloramine formation and degradation of the disinfectant residual.

Table 3.14 Test 1 - Assessment the Order of Chemical Addition on Settled Water with CO<sub>2</sub> and NaOH (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	CO <sub>2</sub> Addition <sup>(2)</sup>	NaOH (mg/L)	Settling Test
1	TBD	Avg	TBD	X	TBD	X
2	TBD	Avg	TBD	X	TBD	X
3	TBD	Avg	TBD	X	TBD	X
4 <sup>(3)</sup>	TBD	TBD	TBD	TBD	TBD	-
5 <sup>(3)</sup>	TBD	TBD	TBD	TBD	TBD	-
6 <sup>(3)</sup>	TBD	TBD	TBD	TBD	TBD	-

Notes:

- (1) Dosed as solution.
- (2) Sodium bicarbonate will be added in eq/L to precipitate excess calcium. X is the difference in calcium carbonate precipitated under typical conditions relative to the amount precipitated during the flood event without the addition of excess carbonate to facilitate precipitation of additional solids
- (3) No tests currently planned for jars 4 through 6. Discussions with the project team may determine additional jars are needed.

Table 3.15 Test 2 - Initial Assessment of Water Chemistry with CO<sub>2</sub> (200 mL jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	CO <sub>2</sub> Addition <sup>(2)</sup>	NaOH (mg/L)	Settling Test
1	TBD	Avg (or zero)	10.2	0	0	-
2	TBD	Avg (or zero)	10.2	0.3X	0	-
3	TBD	Avg (or zero)	10.2	0.6X	0	-
4	TBD	Avg (or zero)	10.2	1.0X	0	-
5	TBD	Avg (or zero)	TBD <sup>(3)</sup>	0	0	-
6	TBD	Avg (or zero)	TBD	0.3X	0	-
7	TBD	Avg (or zero)	TBD	0.6X	0	-
8	TBD	Avg (or zero)	TBD	1.0 X	0	-
9	TBD	TBD	TBD	TBD	0	-
10	TBD	TBD	TBD	TBD	0	-
11	TBD	TBD	TBD	TBD	0	-
12	TBD	TBD	TBD	TBD	0	-

Notes:

- (1) Dosed as solution.
- (2) Sodium bicarbonate will be added in eq/L to precipitate excess calcium. X is the difference in calcium carbonate precipitated under typical conditions relative to the amount precipitated during the flood event without the addition of excess carbonate to facilitate precipitation of additional solids
- (3) A slightly higher pH corresponding to minimal calcium concentrations but below the point of magnesium hydroxide addition will be targeted.

Table 3.16 Test 3 - Initial Assessment of Water Chemistry with NaOH and CO<sub>2</sub> (200 mL jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH	CO <sub>2</sub> Addition <sup>(2)</sup>	NaOH (mg/L)	Settling Test
1	TBD	Avg (or zero)	10.2	0	0	-
2	TBD	Avg (or zero)	10.2	0.3X	TBD	-
3	TBD	Avg (or zero)	10.2	0.6X	TBD	-
4	TBD	Avg (or zero)	10.2	1.0X	TBD	-
5	TBD	Avg (or zero)	TBD <sup>(3)</sup>	0	0	-
6	TBD	Avg (or zero)	TBD	0.3X	TBD	-
7	TBD	Avg (or zero)	TBD	0.6X	TBD	-
8	TBD	Avg (or zero)	TBD	1.0 X	TBD	-
9	TBD	TBD	TBD	TBD	TBD	-
10	TBD	TBD	TBD	TBD	TBD	-
11	TBD	TBD	TBD	TBD	TBD	-
12	TBD	TBD	TBD	TBD	TBD	-

Notes:

- (1) Dosed as solution.
- (2) Sodium bicarbonate will be added in eq/L to precipitate excess calcium. X is the difference in calcium carbonate precipitated under typical conditions relative to the amount precipitated during the flood event without the addition of excess carbonate to facilitate precipitation of additional solids
- (3) A slightly higher pH corresponding to minimal calcium concentrations but below the point of magnesium hydroxide addition will be targeted.

Table 3.17 Test 4 - Evaluate the Impact of Adding CO<sub>2</sub> to precipitate more CaCO<sub>3</sub> solids (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate / Polymer Dose <sup>(1)</sup> (mg/L)	Target pH	CO <sub>2</sub> Addition <sup>(2)</sup>	NaOH (mg/L)	Settling Test
1	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X
2	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X
3	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X
4	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X
5	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X
6	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	0	X

Notes:

- (1) Dosed as solution.
- (2) Sodium bicarbonate will be added in eq/L to precipitate excess calcium.



Table 3.18 Test 5 - Evaluate the Impact of Adding NaOH and CO<sub>2</sub> (2 L jars)

Jar	Lime Dose (mg/L)	Ferric Sulfate / Polymer Dose <sup>(1)</sup> (mg/L)	Target pH	CO <sub>2</sub> Addition <sup>(2)</sup>	NaOH (mg/L)	Settling Test
1	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X
2	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X
3	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X
4	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X
5	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X
6	TBD	Opt (TBD)	Opt (TBD)	Ca Precip	TBD	X

Notes:

(1) Dosed as solution.

(2) Sodium bicarbonate will be added in eq/L to precipitate excess calcium.

### 3.5 Flocculant Aid Polymer Testing

Tests on banked water utilizing flocculant aid polymer will be conducted to evaluate its effect on the settleability of banked water utilizing the optimal ferric sulfate and coagulant aid polymer doses determined in previous tests. Flocculant aid polymer will be activated in distilled water up to 12 hours prior to use. Fresh polymer dosing solutions will be prepared each day. Flocculant aid polymer will be added toward the middle of the flocculation period in order to allow for the formation of larger particles prior to polymer addition. Results from each test will be used to inform the experimental parameters of subsequent tests. The tests will be conducted at the following conditions:

- Enhanced softening conditions - pH 11.0.
- Optimal softening conditions - pH 10.2.
- Enhanced coagulation conditions - pH 8.0-8.5.

The following parameters will be measured after settling in each jar:

- pH.
- UV-254.
- TOC.
- Ca.
- Mg.
- Alkalinity.
- Turbidity.
- Zeta potential.

Details for each test are outlined in Table 3.19 to Table 3.22. Settling tests described above will also be conducted.

Table 3.19 Test 1 - Flocculent Aid Polymer Evaluation

Jar	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH <sup>(2)</sup>	Coag Polymer Type <sup>(1)</sup>	Coag Polymer Dose <sup>(1)</sup> (mg/L)	Floc Polymer Type	Floc Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	11.0	--	--	--	0	X
2	TBD	11.0	--	--	A	TBD	X
3	TBD	11.0	--	--	B	TBD	X
4	TBD	10.2	--	--	--	TBD	X
5	TBD	10.2	--	--	A	TBD	X
6	TBD	10.2	--	--	B	TBD	X

Notes:

(1) Optimized from previous testing.

(2) Lime dose optimized from previous testing to achieve target pH

(3) Dosed as solution; Maximum NSF dose for each polymer will be used.

Table 3.20 Test 2 - Flocculent Aid Polymer Evaluation

Jar	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH <sup>(2)</sup>	Coag Polymer Type <sup>(1)</sup>	Coag Polymer Dose <sup>(1)</sup> (mg/L)	Floc Polymer Type	Floc Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	10.2	A or B	TBD	A	0	X
2	TBD	10.2	A or B	TBD	B	TBD	X
3	TBD	11.0	A or B	TBD	A	TBD	X
4	TBD	11.0	A or B	TBD	B	TBD	X
5							
6							

Notes:

(1) Optimized from previous testing.

(2) Lime dose optimized from previous testing to achieve target pH

(3) Dosed as solution.

Table 3.21 Test 3 - Flocculent Aid Polymer Evaluation at Enhanced Coagulation Conditions

Jar	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH <sup>(2)</sup>	Coag Polymer Type <sup>(1)</sup>	Coag Polymer Dose <sup>(1)</sup> (mg/L)	Floc Polymer Type	Floc Polymer Dose <sup>(3)</sup> (mg/L)	Settling Test
1	TBD	8.0-8.5	--	--	A	0	X
2	TBD	8.0-8.5	--	--	A	TBD	X
3	TBD	8.0-8.5	--	--	A	TBD	X
4	TBD	8.0-8.5	--	--	B	TBD	X
5	TBD	8.0-8.5	--	--	B	TBD	X
6	TBD	8.0-8.5	A or B	TBD	B	TBD	X

Notes:

(1) Optimized from previous testing.

(2) Lime dose optimized from previous testing to achieve target pH

(3) Dosed as solution.

Table 3.22 Test 4 - Flocculent Aid Polymer Evaluation with Optimized CO<sub>2</sub> NaOH Doses

Jar	Ferric Sulfate Dose <sup>(1)</sup> (mg/L)	Target pH <sup>(1)</sup>	Coag Polymer Dose <sup>(1)</sup> (mg/L)	Floc Polymer Type	Floc Polymer Dose (mg/L)	CO <sub>2</sub> Addition <sup>(1)</sup>	NaOH <sup>(1)</sup> (mg/L)	Settling Test
1	TBD	TBD	TBD	A	0	TBD	TBD	X
2	TBD	TBD	TBD	A	TBD	TBD	TBD	X
3	TBD	TBD	TBD	A	TBD	TBD	TBD	X
4	TBD	TBD	TBD	B	TBD	TBD	TBD	X
5	TBD	TBD	TBD	B	TBD	TBD	TBD	X
6	TBD	TBD	0	B	TBD	TBD	TBD	X

Notes:

(1) Optimized from previous testing.

### 3.6 Mixing Rate Testing

The final set of tests for Phase 1 testing will explore the effect of mixing rate, or the velocity gradient (G), on the settleability of coagulated solids. The tests will evaluate the effect of mixing rate on the settleability of solids formed under the following conditions:

- Ferric sulfate coagulation at optimal coagulation conditions (e.g., pH~8) with no polymer addition.
- Enhanced softening at pH~11, potentially with and without polymer addition pending findings from previous tests.

Water chemistry analyses will not be conducted as the purpose of the tests are to evaluate settleability only. Velocity gradients at the existing WTPs will be verified and used as the baseline for conducting the tests. Additional test will be run at optimal mixing speeds to determine impacts on settling, focusing primarily on lower mixing speeds to avoid floc shear when targeting ferric hydroxide and magnesium hydroxide floc formation.

## Section 4

# SOURCE WATER QUALITY

The parameters listed in Table 4.1 will be measured to characterize the source water quality. In addition to the samples analyzed at AWU, samples will also be analyzed at UT for the following parameters to serve as a quality management check on the equipment and methods:

- pH.
- UV254.
- TOC.
- Calcium.
- Magnesium.
- Iron.
- Alkalinity.

Table 4.1 Source Water Quality

Parameter	Laboratory Requirements
Temperature	On-site
pH	On-site
Alkalinity	AW
Hardness	AW
Calcium	AW
Magnesium	AW
Turbidity	On-site
TOC	AW
DOC	AW
UV254	On-site
Fe, total	AW
Fe, dissolved	AW
Mn, total	AW
Mn, dissolved	AW
Ammonia	AW
Chloride	AW
Fluoride	AW
Sulfate	AW
TDS	AW
Color	AW
Bromide	AW
Silica	AW
Zeta Potential	On-site

## Appendix B

# SPLIT SAMPLING ANALYTICAL RESULTS

Table B.1 Flood Event and January 2019 Water Quality - Split Sampling

Parameter	Jan. 2019 AWU Lab Results	Jan. 2019 UT Lab Results	Banked Water AWU Lab Results	Banked Water UT Lab Results
Sample Date	1/31/19	1/31/19	10/25/18	10/25/18
pH	8.17	8.09	8.04	8.04
Turbidity, NTU	3.65	3.56	117	148
Alkalinity, mg/L as CaCO <sub>3</sub>	157	160	102	105
Calcium, mg/L	46	45	30	36
Magnesium, mg/L	16	17	5	8
Iron, total, mg/L	0.104	NA	4.13	3.71
Iron, dissolved, mg/L	< 0.005	NA	0.011	0.02
Silica, mg/L	8.99	NA	8.1	7.6
TOC, mg/L	3.58	3.74	5.75	5.66
DOC, mg/L	3.46	NA	3.40	NA

Notes:

(1) NA = Not analyzed.

## Appendix C

# BASELINE TESTING

Figure C.1 shows the settled water pH for the range of lime doses evaluated using both the Typical Water (collected 2/13/19) and the Banked Water (collected 10/25/18). As expected, the pH increased with increasing lime dose.<sup>9</sup> A slightly lower lime dose was required to achieve the same settled water pH in Banked Water compared to Typical Water, reflecting the lower alkalinity in the Banked Water. For example, a lime dose of less than 60 mg/L as CaO resulted in a settled water pH above 10.2 in the Banked Water whereas close to 120 mg/L of CaO was required to achieve a similar settled water pH in the Typical Water.

Figure C.2 shows the calcium concentrations with increasing settled water pH for both Typical and Banked Water, with (Part A) and without (Part B) ferric sulfate addition at the dose typically applied at Ullrich WTP (i.e., 15 mg/L as product). As expected, a lower softening pH is required to precipitate calcium carbonate and achieve minimum settled water calcium concentrations in the typical compared to the Banked Water. Based on the data, calcium concentrations are at a minimum at a settled water pH < 10 in the Typical Water, whereas a pH of 10 or higher is required to achieve minimum calcium concentrations in the Banked Water. Since the influent hardness concentration during the flood event was equivalent to typical targets for the *finished* water, it shows that the only calcium hardness removed during the event was the calcium added by lime addition. Iron addition slightly inhibited calcium carbonate precipitation, as expected based on literature (Katz et al., 1993<sup>10</sup>). Additionally, tests conducted with ferric required higher lime doses because the ferric sulfate is acidic.

At settled water pH values above 10.5, settled water magnesium concentrations started to decrease reflecting precipitation of magnesium hydroxide, consistent with a degree of saturation (Q/K) exceeding 1.0. At pH values above 11.5, most of the magnesium was removed (Figure C.3). The addition of ferric sulfate resulted in lower magnesium levels at the same settled water pH. This is most likely due to the coagulation and removal of some of the magnesium hydroxide particles.

Figure C.4 shows the impact of ferric sulfate dose and magnesium removal on TOC and SUVA in Typical Water.

The series of figures included at the end of this appendix summarizes the impact of lime dose on settled water pH, alkalinity, calcium, and magnesium concentrations in the Typical and Banked Water with and without ferric sulfate addition.

<sup>9</sup> The pH at 170 mg/L CaO in current water was slightly lower than the pH at 150 mg/L CaO. These results reflect challenges associated with maintaining a thoroughly mixed lime slurry and applying small doses. Generally, the settled water pH is considered a more accurate representation of softening conditions than the applied lime dose.

<sup>10</sup> Katz, J.L., Reick, M.R., Herzog, R.E., Parsiegla, K.L. 1993. Calcite Growth Inhibition by Iron, *Langmuir*, 9:1423-1430.



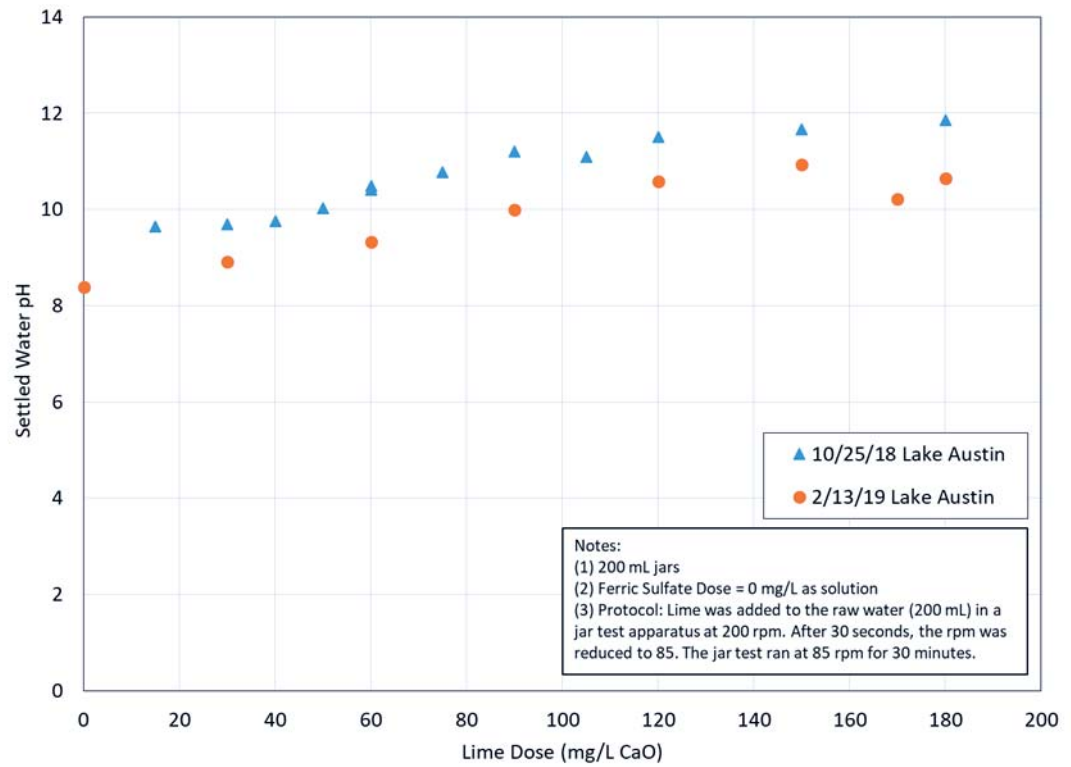


Figure C.1 Impact of Lime Dose on Settled Water pH for Typical and Banked Water

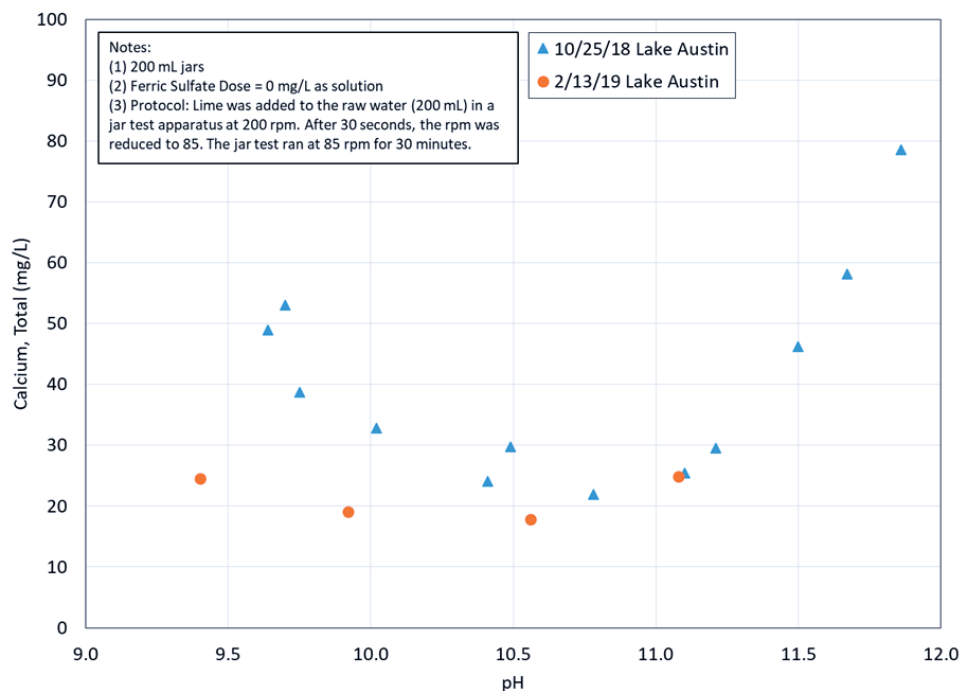
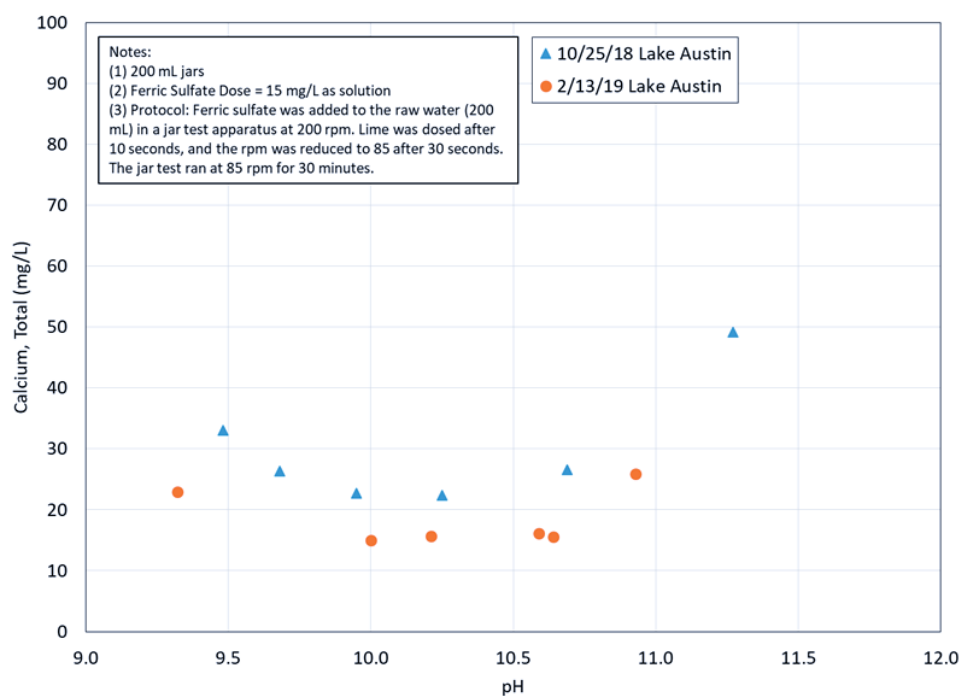
**PART A****PART B**

Figure C.2 Calcium Concentrations with Increasing pH in Typical and Banked Water without (Part A) and with (Part B) Ferric Sulfate Addition

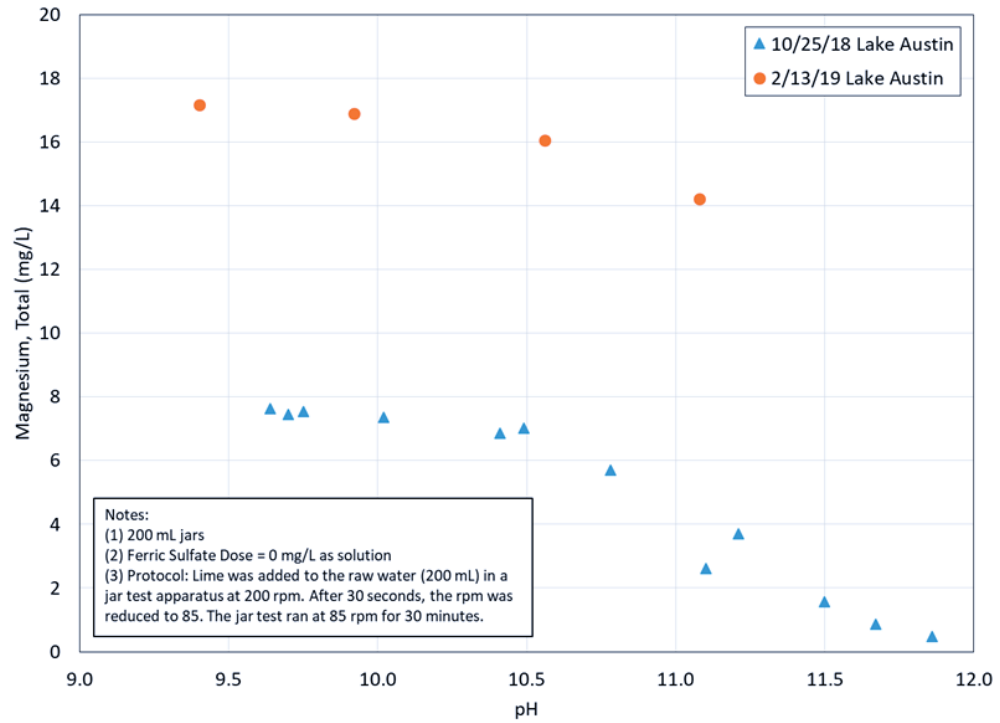
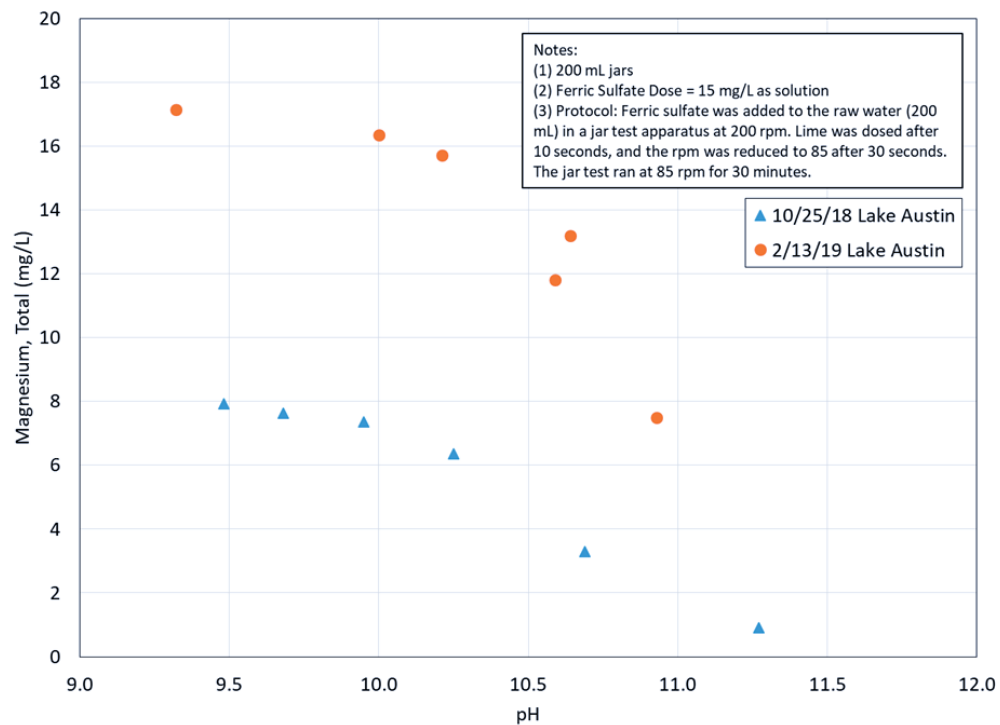
**PART A****PART B**

Figure C.3 Magnesium Concentrations with Increasing pH in Typical and Banked Water without (Part A) and with (Part B) Ferric Sulfate Addition

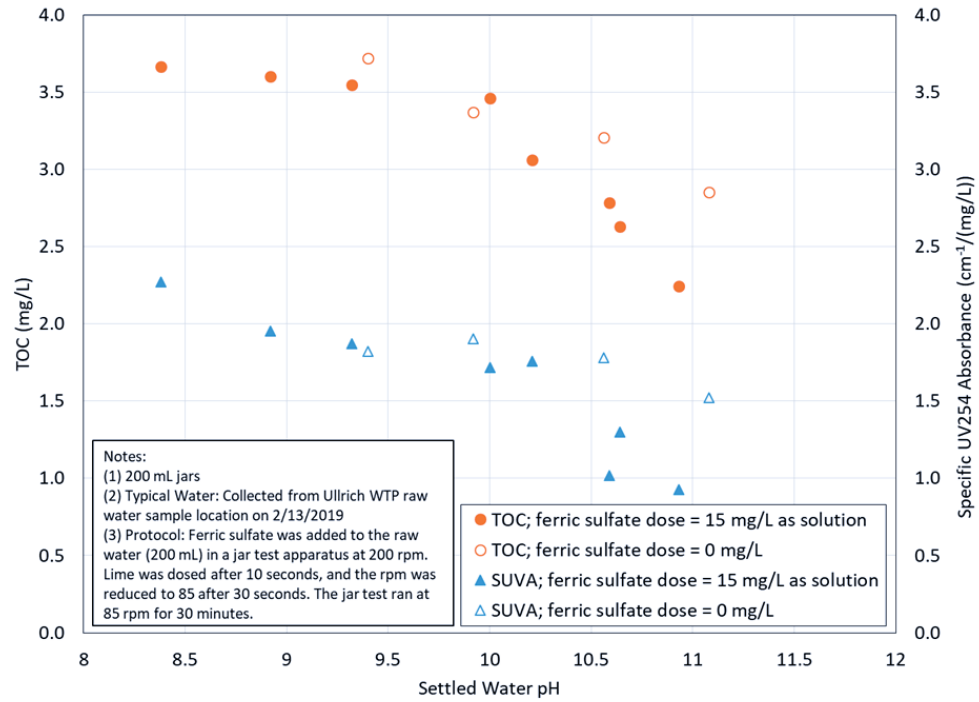
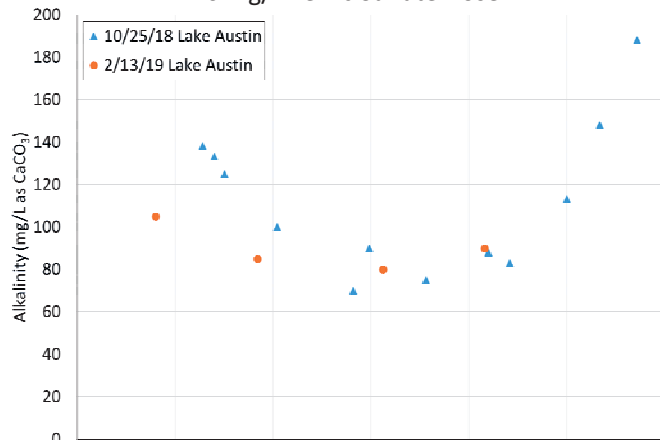


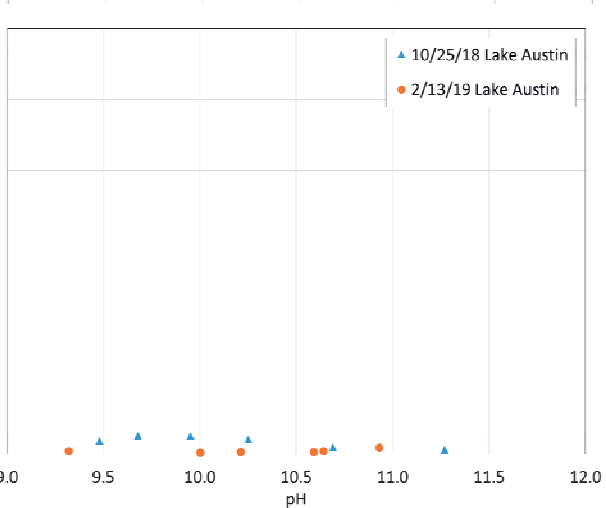
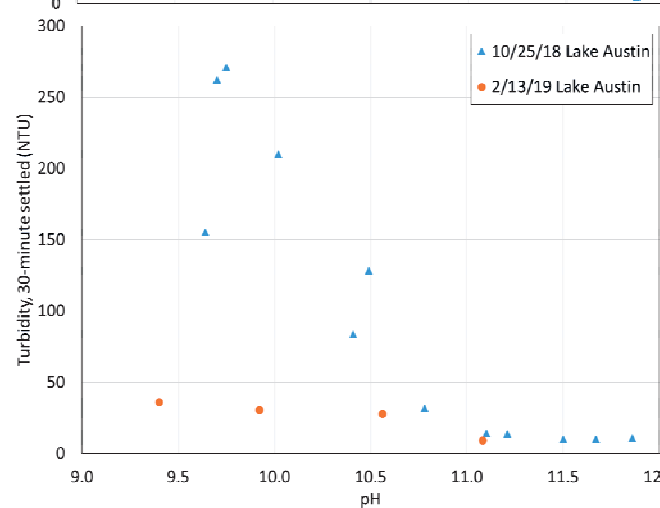
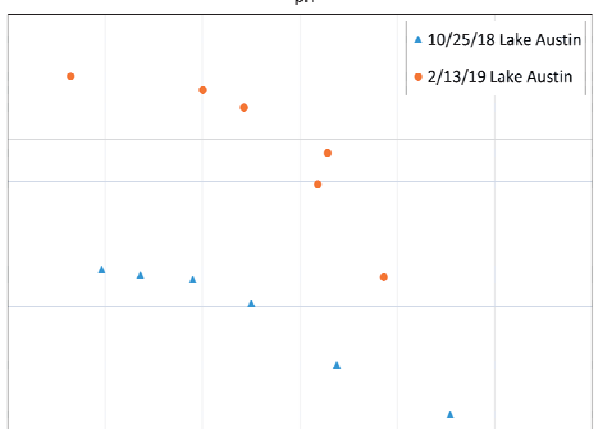
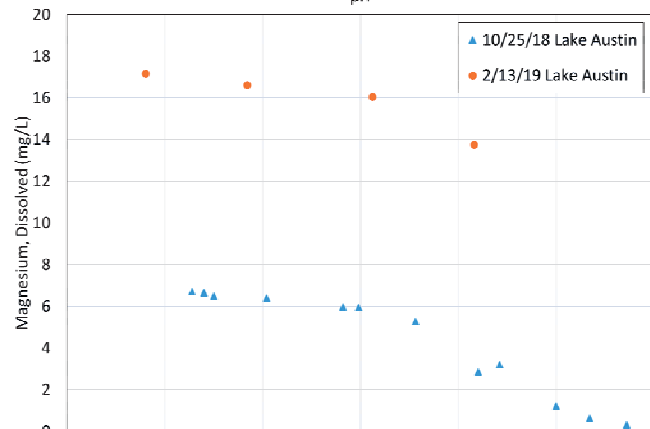
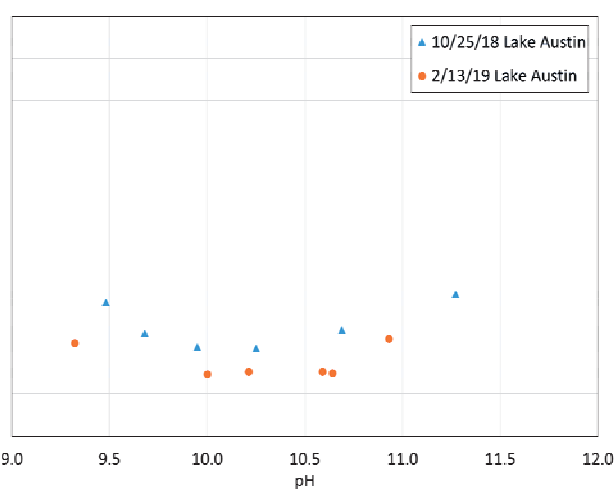
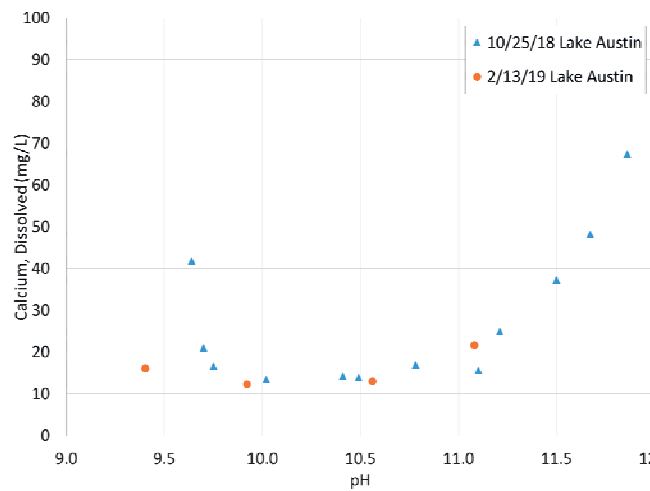
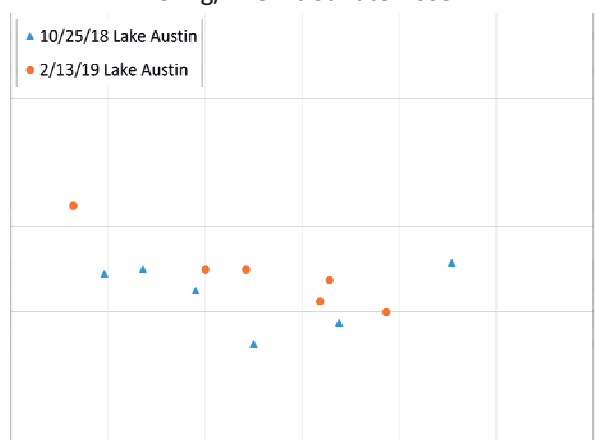
Figure C.4 Impact of Ferric Sulfate Dose and Magnesium Removal on TOC and SUVA in Typical Water

## Baseline Testing Summary

0 mg/L Ferric Sulfate Dose



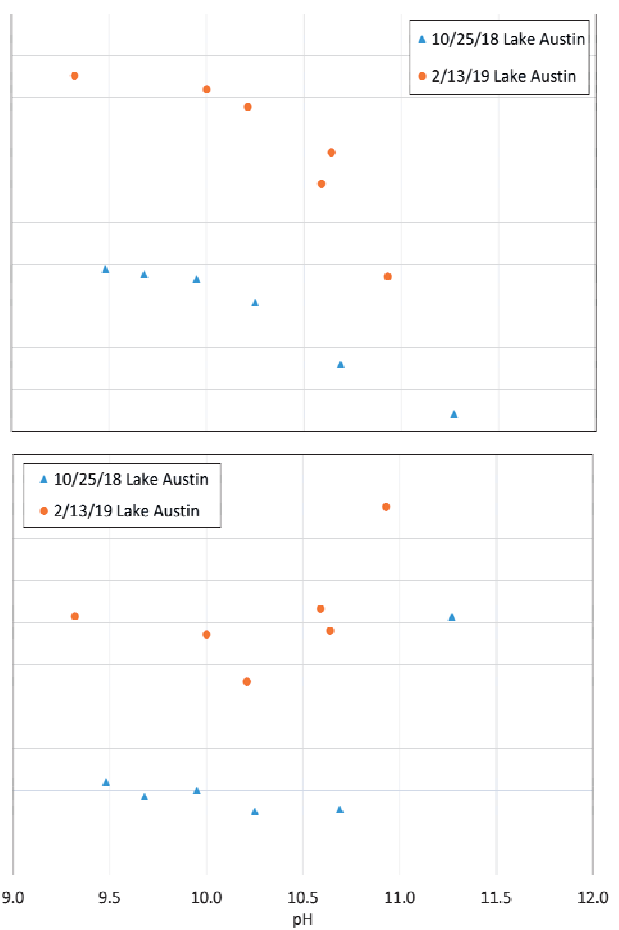
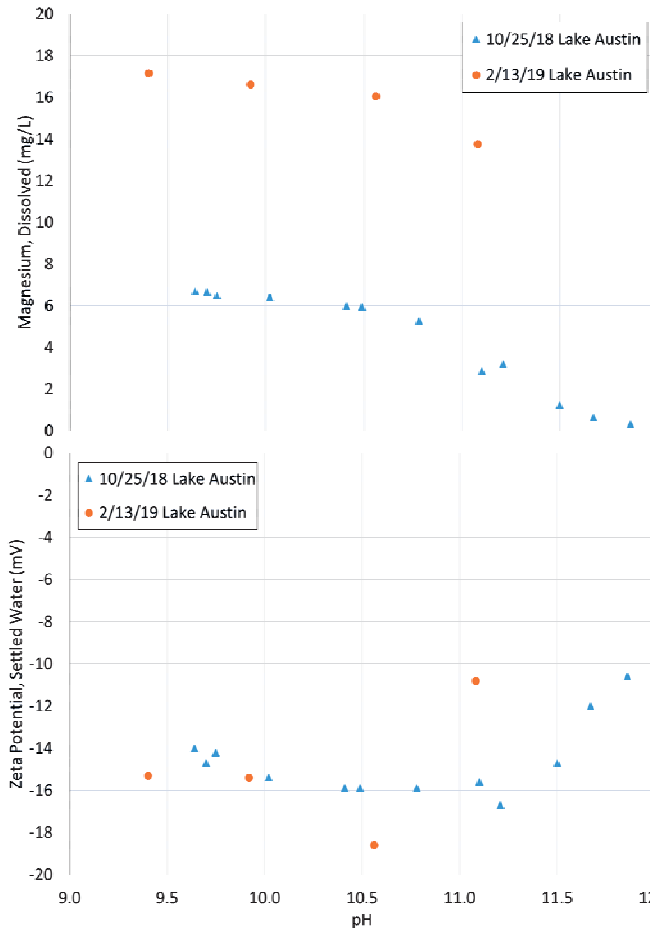
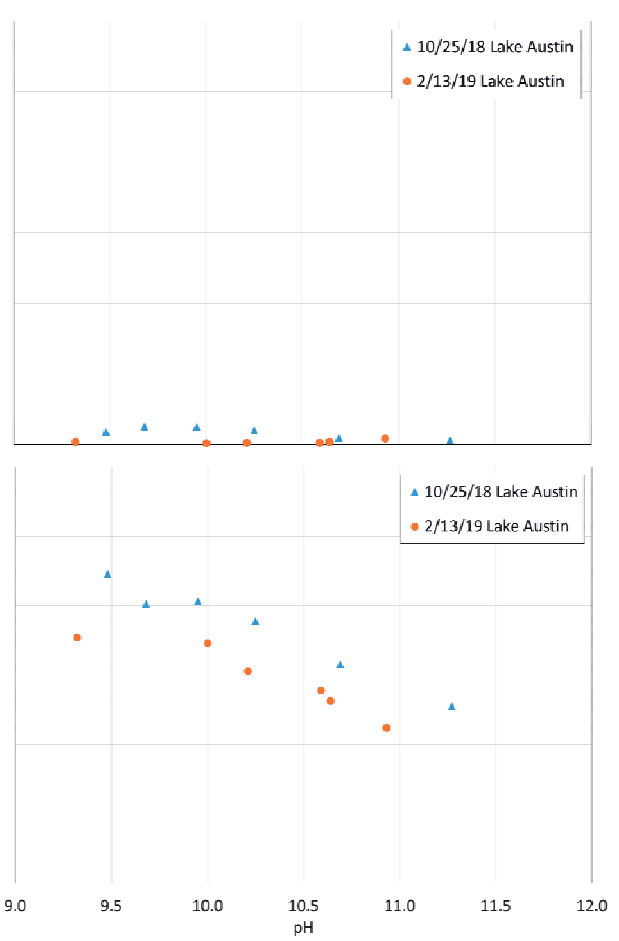
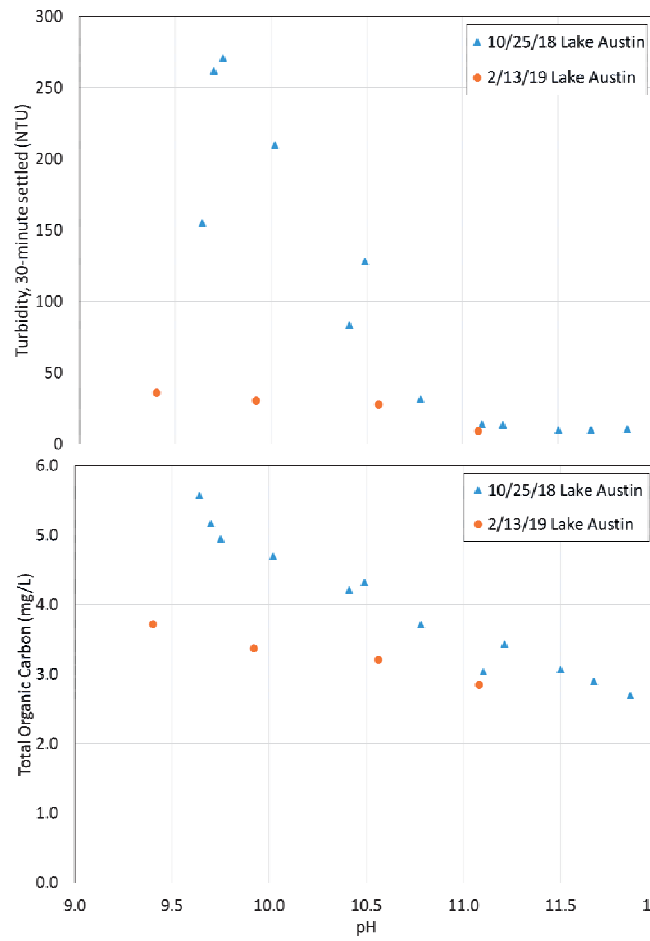
15 mg/L Ferric Sulfate Dose



## Baseline Testing Summary

0 mg/L Ferric Sulfate Dose

15 mg/L Ferric Sulfate Dose



## Appendix D

# SEM/EDS ANALYSIS OF SOLIDS PRODUCED DURING JAR TESTS AND ITERATIVE SOLIDS GENERATION EXPERIMENTS

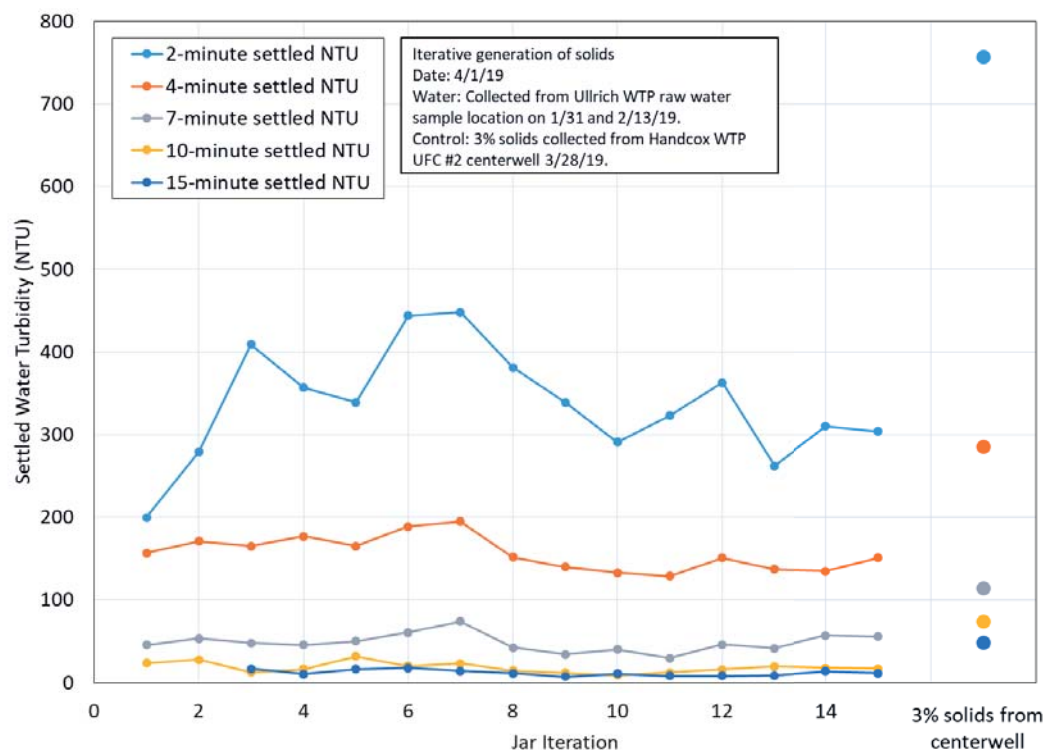


Figure D.1 Iterative Generation of Solids Versus Control (15 mg/L Ferric Sulfate at pH 10.2)

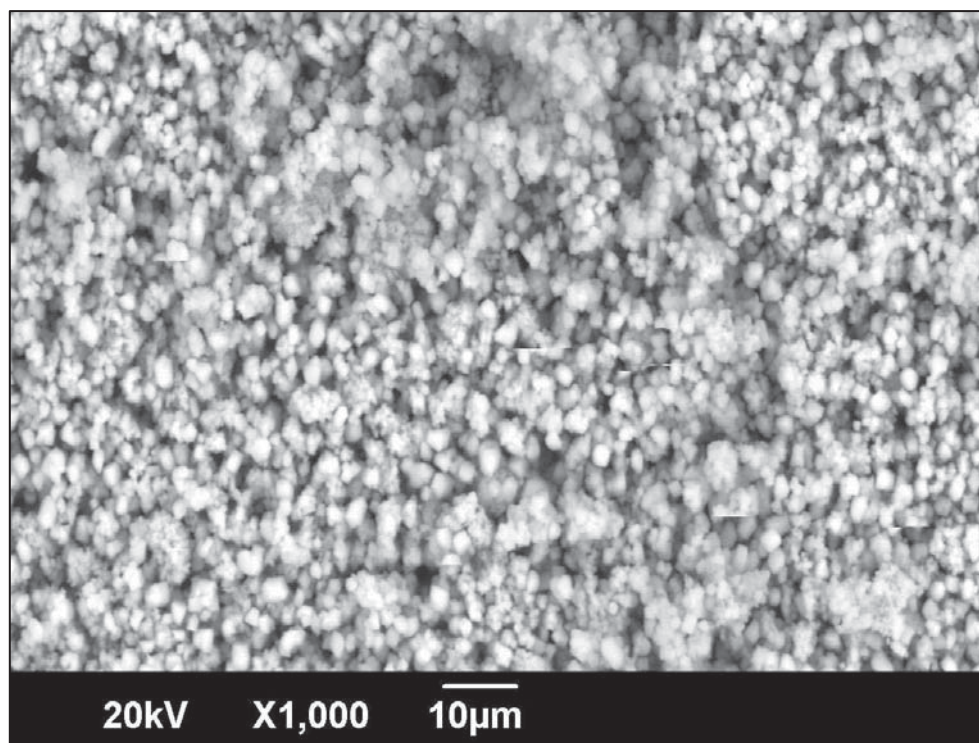


Figure D.2 SEM Image of Solids Produced with Raw Water Collected in January and February, 2019 Softened at pH 10.2 with 15 mg/L Ferric Sulfate (Solids Generation Iteration #1)



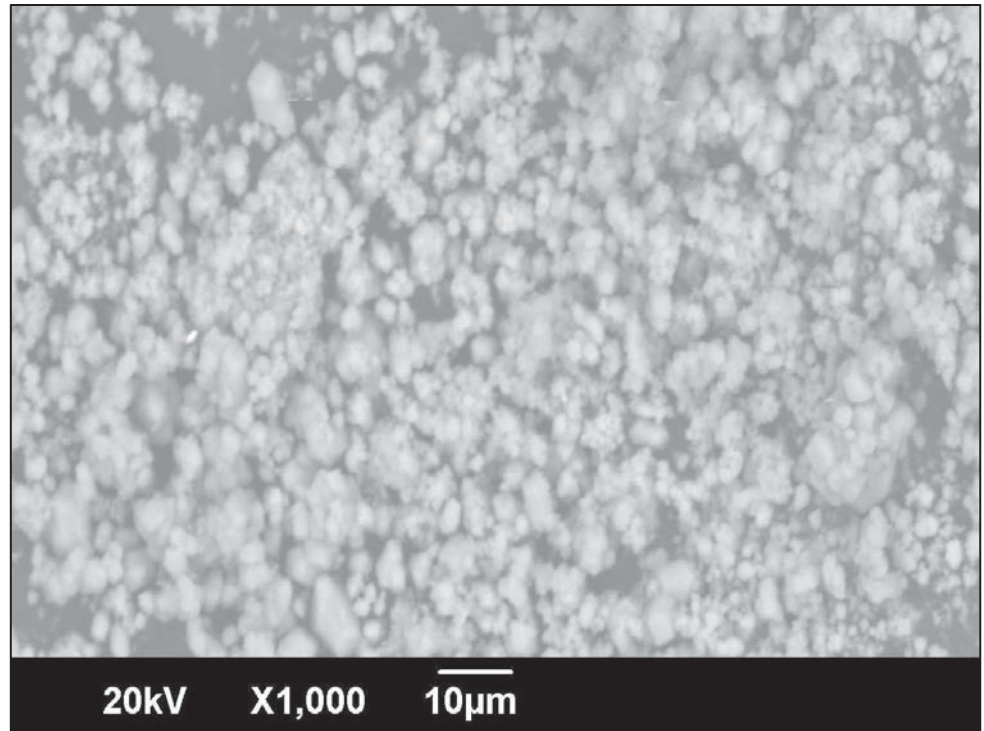


Figure D.3 SEM Image of Solids Produced with Raw Water Collected in January and February, 2019 Softened at pH 10.2 with 15 mg/L Ferric Sulfate (Solids Generation Iteration #15)

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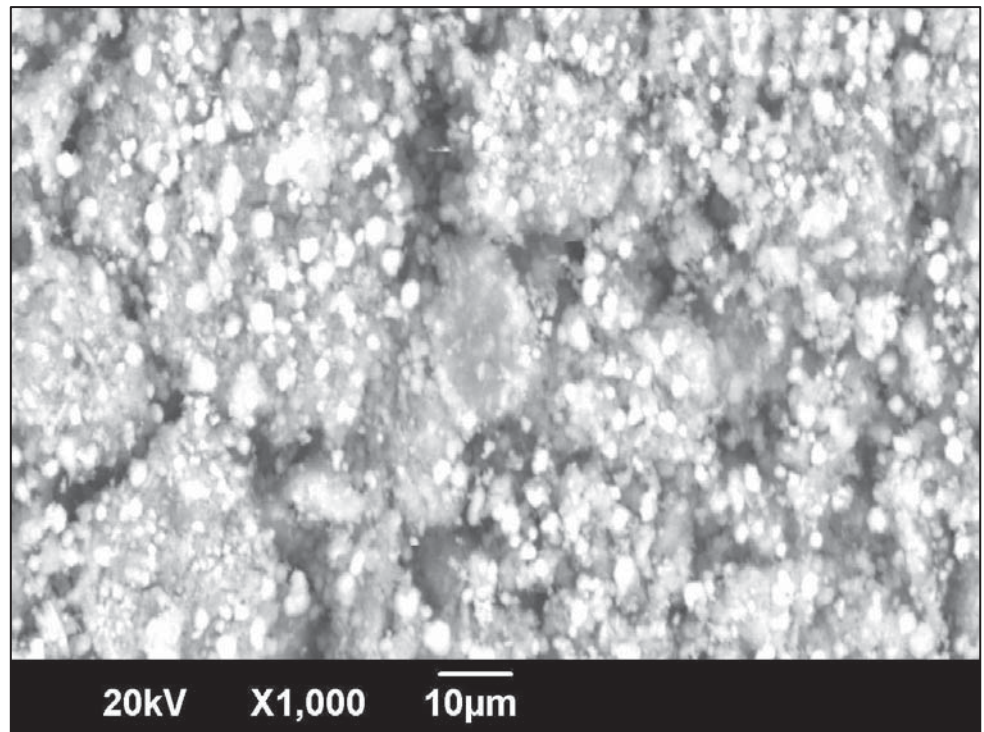


Figure D.4 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate and 12 mg/L PEC (Solids Generation Iteration #1)

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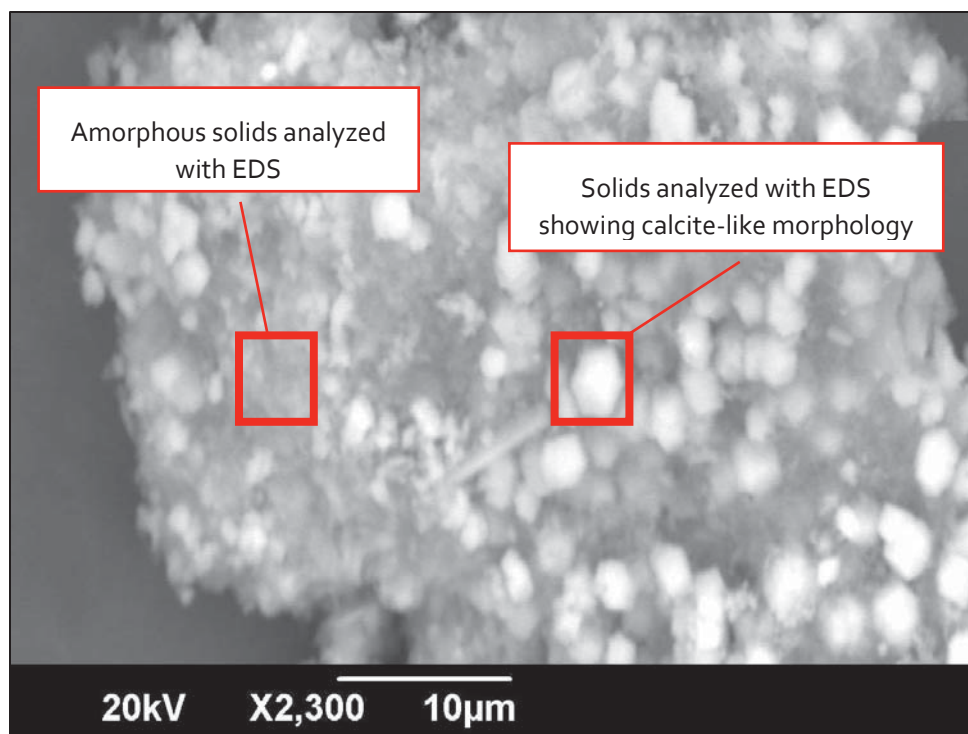


Figure D.5 SEM Image Showing Locations of EDS Analyses of Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate and 12 mg/L PEC (Solids Generation Iteration #1)

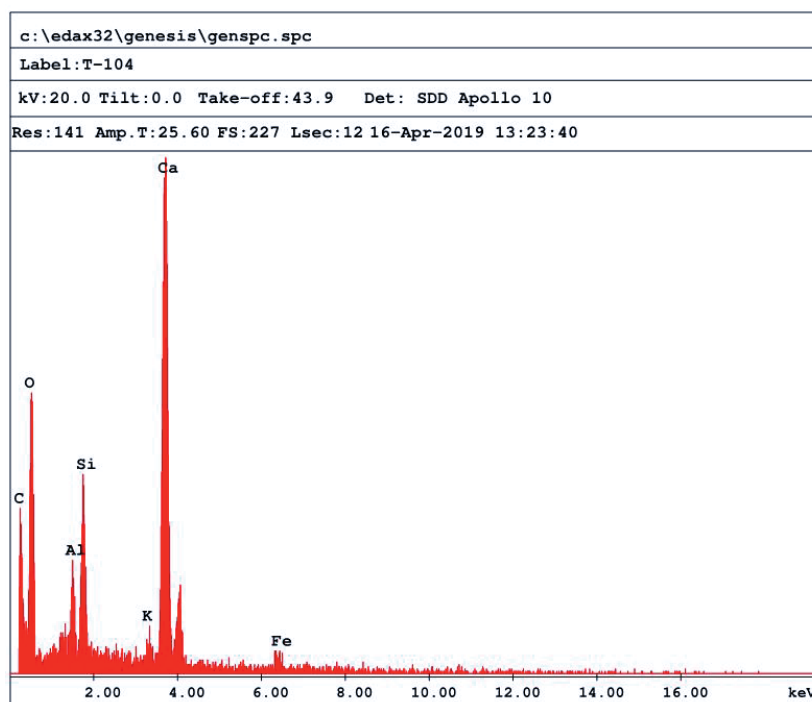


Figure D.6 EDS Spectrum of Solids Showing Calcite-like Morphology Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate and 12 mg/L PEC (Solids Generation Iteration #1)

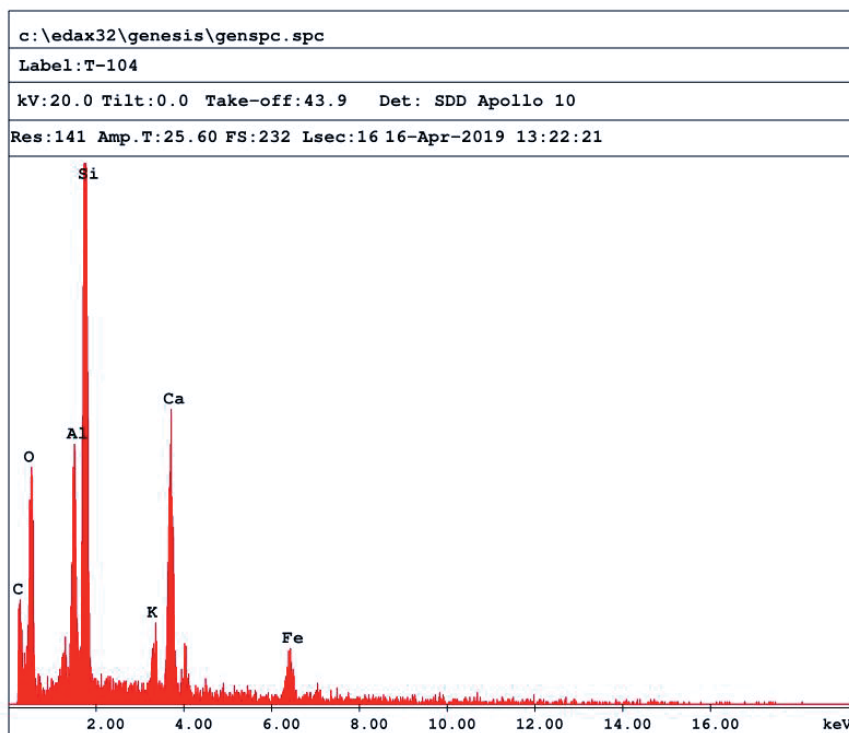


Figure D.7 EDS Spectrum of Amorphous Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate and 12 mg/L PEC (Solids Generation Iteration #1)

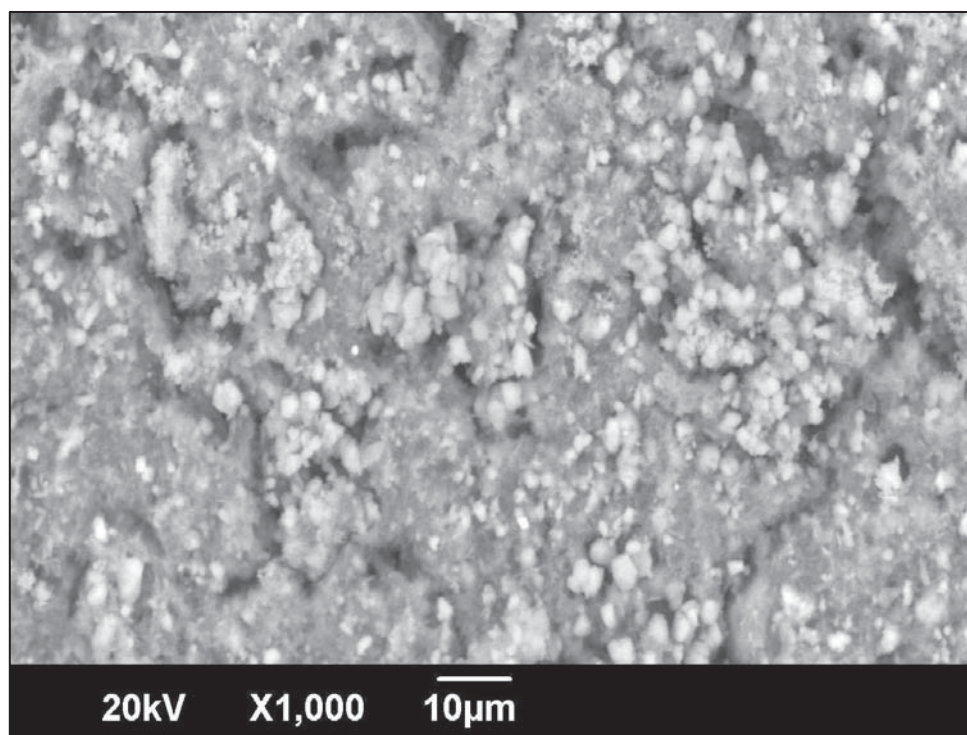


Figure D.8 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate and 12 mg/L PEC (Solids Generation Iteration #10)



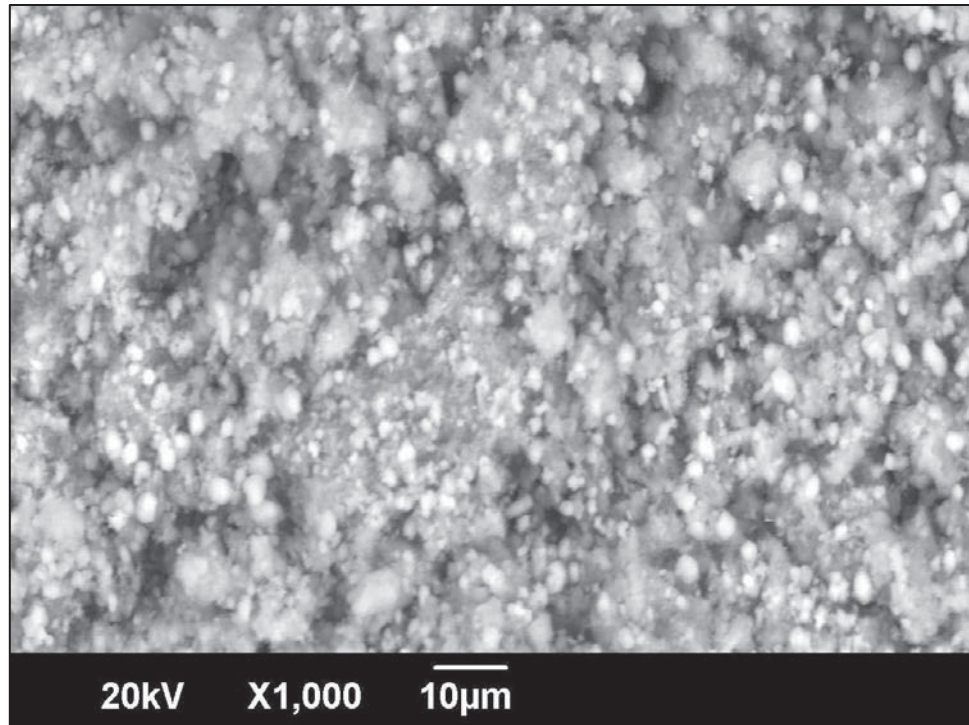


Figure D.9 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate, 12 mg/L PEC, and 1 mg/L PEA (Solids Generation Iteration #1)

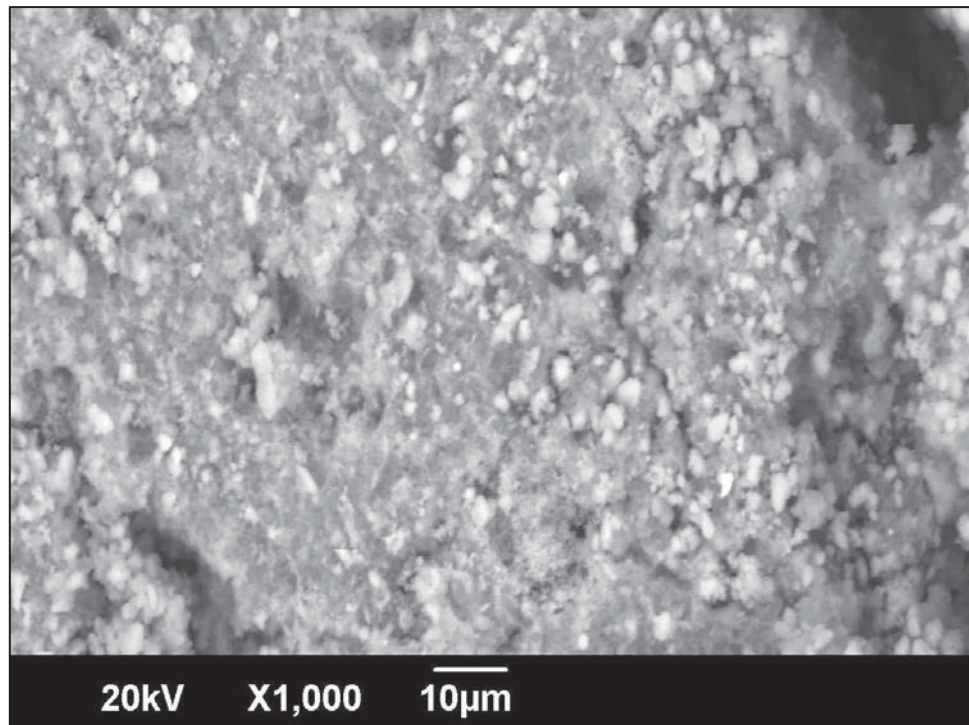


Figure D.10 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 15 mg/L Ferric Sulfate, 12 mg/L PEC, and 1 mg/L PEA (Solids Generation Iteration #10)

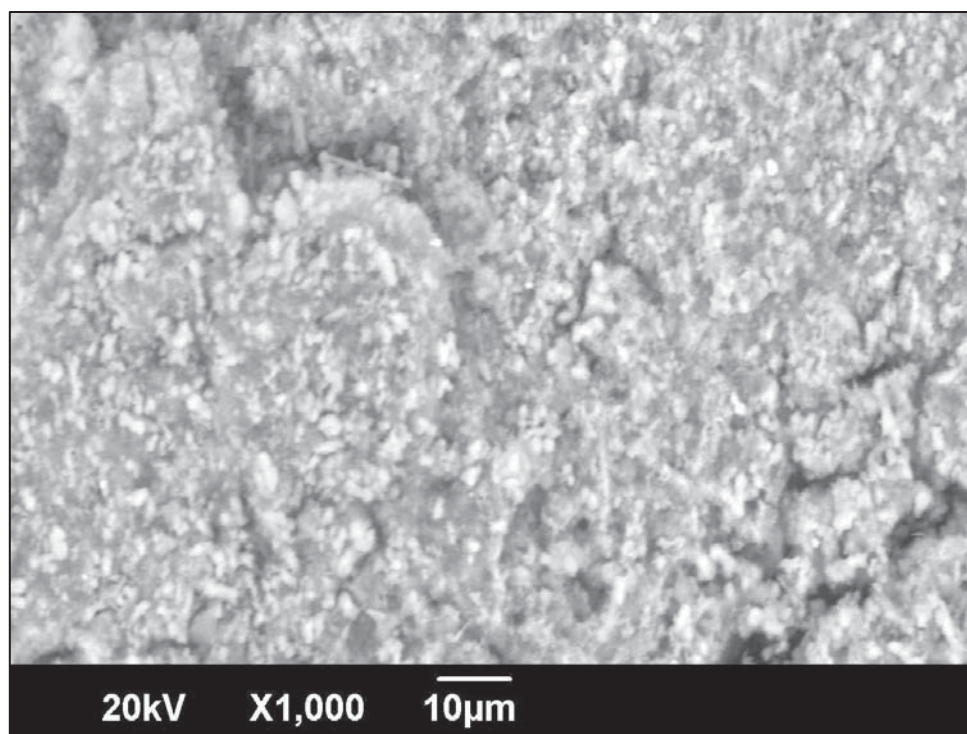


Figure D.11 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 10 mg/L PEC, and no Ferric Sulfate

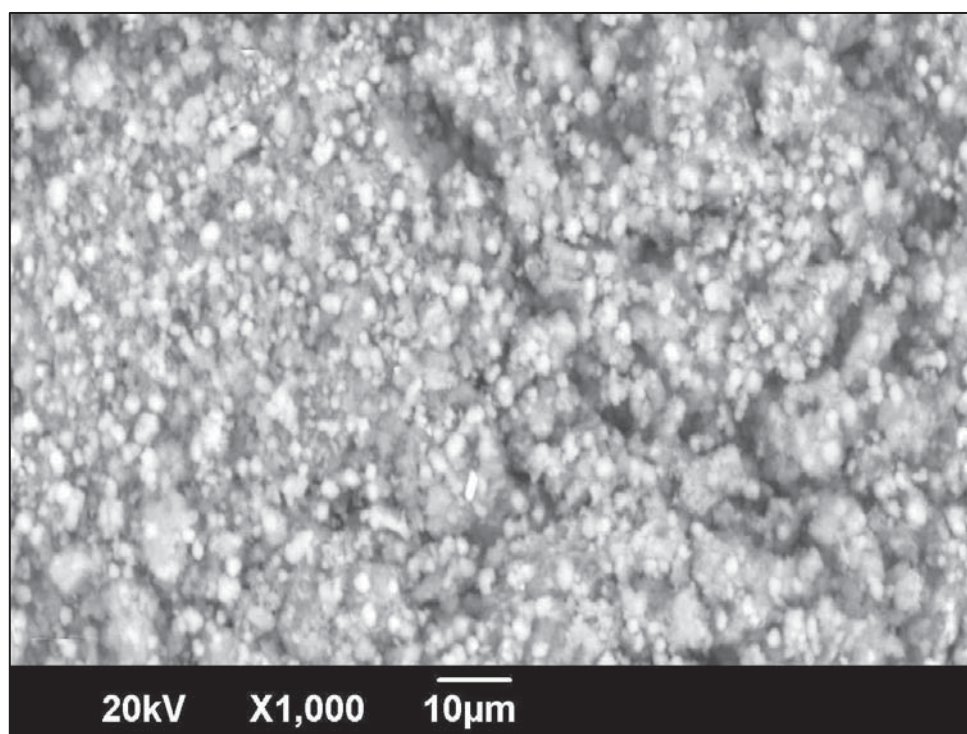


Figure D.12 SEM Image of Solids Produced with Banked Water Softened at pH 10.2 with 80 mg/L Ferric Sulfate and 10 mg/L PEC

## Appendix E

# JAR TEST DATA

Phase 1 Jar Testing

Jar Test #	Water Supply	Jar Type	General Description	Ferric?	Center Well Solids?	Coag Aid Polymer?	Floc Aid Polymer?	CO2?	NaOH?
1 & 2	Current water	200 mL	Baseline Current Water	Yes	No	No	No	No	No
3 & 4	Banked water	200 mL	Baseline - Lime Only	No	No	No	No	No	No
5, 6, 7, & 8	Banked water	200 mL	Baseline - Varying Ferric	Yes	No	No	No	No	No
9 & 10	Banked water	2 L	Baseline - Settleability	Yes	No	No	No	No	No
11	Banked water	2 L	Enhanced Coagulation	Yes	No	No	No	No	No
12	Current water	2 L	Center well solids	Yes	Yes	No	No	No	No
13, 14, 15, & 16	Banked water	2 L	Effect of coagulant aid polymer	Yes	No	Yes	No	No	No
17	Banked water	2 L	Center well solids	Yes	Yes	Yes	No	No	No
18 & 19	Banked water	200 mL	Impact of CO2 addition	Yes	No	No	No	Yes	No
20	Current water	2 L	Impact of coagulant aid polymer year round	Yes	No	Yes	No	No	No
21	Banked water	2 L	Impact of flocculant aid polymer	Yes	No	Yes	Yes	No	No
22	Banked water	200 mL	Impact of CO2 and NaOH - Chemistry	Yes	No	No	No	Yes	Yes
23	Banked water	2 L	Impact of CO2 and NaOH - Settleability	Yes	No	Yes <sup>(1)</sup>	No	Yes	Yes

<sup>(1)</sup> One condition only

Jar Test # 1  
 Date 2/13/2019  
 Start Time 12:00

Jar Size 200 mL

Date: 2/13/2019 12:00  
 Water: Collected from Ullrich WTP raw water sample location on 2/13/2019 at 8:00 am.  
 Test Objective: Determine the settled turbidity and pH after different doses of lime.  
 Determine operational baseline with typical water quality treated with an average ferric sulfate dose and without ferric while varying pH.  
 Protocol: Ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds. The jar test ran at 85 rpm for 30 minutes. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality											
	Lime	Ferric Dose	Ferric	Lime	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg
Units	mg/L CaO	mg/L as solution			SU	NTU	mV	1/cm	mg/L		mg/L	mg/L	mg/L	ug/L	ug/L	mg/L
1	0	15	0sec	5sec	8.38	0.89	-8.74	8.32E-02	3.67	2.27	145	45.6	45.7	341.1	3.3	17.6
2	30	15	0sec	5sec	8.92	2.35	-9.76	7.03E-02	3.60	1.95	140	40.7	36.8	90.6	7.6	17.4
3	60	15	0sec	5sec	9.32	1.91	-7.68	6.64E-02	3.55	1.87	110	22.9	22.1	80.4	3.7	17.2
4	90	15	0sec	5sec	10.00	1.15	-8.56	5.94E-02	3.46	1.72	80	15.0	14.8	65.6	3.8	16.4
5	120	15	0sec	5sec	10.59	1.21	-7.32	2.83E-02	2.78	1.02	65	16.1	15.4	14.7	2.5	11.8
6	150	15	0sec	5sec	10.93	4.35	-2.47	2.08E-02	2.24	0.93	60	25.9	23.1	13.4	2.0	7.5



Jar Test # 2  
Date 2/13/2019  
Start Time 16:00

Jar Size 200 mL

Date: 2/13/2019 16:00  
Water: Collected from Ullrich WTP raw water sample location on 2/13/2019 at 8:00 am.  
Test Objective: Determine the settled turbidity and pH after different doses of lime.  
Determine operational baseline with typical water quality treated with an average ferric sulfate dose and without ferric while varying pH.  
Protocol: Ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds.  
The jar test ran at 85 rpm for 30 minutes. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality												
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)
1	170	15	0sec	5sec	10.21	1.21	-10.8	5.38E-02	3.06	1.76	80	15.6	15.3	64.8	2.2	15.7	15.6
2	180	15	0sec	5sec	10.64	1.92	-8.36	3.42E-02	2.63	1.30	75	15.5	15.0	24.4	2.9	13.2	13.4
3	60	0	0sec	5sec	9.40	36.1	-15.3	6.77E-02	3.72	1.82	105	24.6	16.1	30.5	2.2	17.2	17.2
4	80	0	0sec	5sec	9.92	30.5	-15.4	6.42E-02	3.37	1.90	85	19.1	12.4	25.9	2.3	16.9	16.6
5	100	0	0sec	5sec	10.56	28.1	-18.6	5.71E-02	3.21	1.78	80	17.8	13.1	19.8	2.5	16.0	16.1
6	130	0	0sec	5sec	11.08	9.33	-10.8	4.34E-02	2.85	1.52	90	24.8	21.7	10.0	3.1	14.2	13.8

Jar Test # 3  
Date 2/14/2019  
Start Time 10:00

Jar Size 200 mL

Date: 2/14/2019 10:00  
Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
Test Objective: Assess softening chemistry during flood event, identifying lime doses corresponding to the minimum calcium concentration and point of magnesium hydroxide precipitation  
Protocol: Lime was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. After 30 seconds, the rpm was reduced to 85. The jar test ran at 85 rpm for 30 minutes to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Target pH		Settled Water Quality											
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	RTW	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)
1	30	0	0sec	5sec	8.5	9.7	262	-14.7	1.52E-01	5.17	2.93	133	53.0	21.0	1560.6	31.2	7.5	6.7
2	60	0	0sec	5sec	9.7	10.49	128	-15.9	1.27E-01	4.32	2.94	90	29.8	13.8	1708.8	25.3	7.0	6.0
3	90	0	0sec	5sec	10.8	11.21	13.7	-16.7	8.90E-02	3.44	2.59	83	29.6	24.9	198.5	6.4	3.7	3.2
4	120	0	0sec	5sec	11.3	11.5	9.75	-14.7	6.98E-02	3.07	2.27	113	46.2	37.2	92.2	4.5	1.6	1.2
5	150	0	0sec	5sec	11.6	11.67	9.82	-12	6.17E-02	2.90	2.13	148	58.1	48.2	54.4	3.4	0.9	0.6
6	180	0	0sec	5sec	11.7	11.86	10.7	-10.6	5.35E-02	2.69	1.99	188	78.5	67.3	33.4	3.4	0.5	0.3

**Jar Test #** 4  
**Date** 2/14/2019  
**Start Time** 12:30  
 Vary pH

**Jar Size** 200 mL

Date: 2/14/2019 12:30  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objective: Assess softening chemistry during flood event, identifying lime doses corresponding to the minimum calcium concentration and point of magnesium hydroxide precipitation  
 Protocol: Lime was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. After 30 seconds, the rpm was reduced to 85. The jar test ran at 85 rpm for 30 minutes to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

	Chemical Dose		Chemical Dosing Time		Settled Water Quality													Filtered Zeta
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	Alkalinity	TOC	SUVA	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	
1	15	0	0sec	5sec	9.64	155	-14	1.69E-01	138	5.57	3.04	49.0	41.8	2213.2	14.0	7.6	6.7	
2	40	0	0sec	5sec	9.75	271	-14.2	1.45E-01	125	4.95	2.93	38.7	16.6	2258.5	10.3	7.5	6.5	
3	50	0	0sec	5sec	10.02	210	-15.4	1.37E-01	100	4.69	2.92	32.8	13.4	2396.7	7.2	7.4	6.4	-12.1
4	60	0	0sec	5sec	10.41	83.5	-15.9	1.26E-01	70	4.21	2.98	24.1	14.3	1742.1	7.9	6.9	6.0	
5	75	0	0sec	5sec	10.78	31.6	-15.9	1.10E-01	75	3.71	2.96	22.0	16.9	524.2	4.1	5.7	5.3	
6	105	0	0sec	5sec	11.1	13.8	-15.6	8.72E-02	88	3.03	2.88	25.4	15.6	119.3	3.5	2.6	2.9	-8.01

**Jar Test #** 5  
**Date** 2/15/2019  
**Start Time** 9:00  
 Low ferric dose, vary pH  
**Jar Size** 200 mL

Date: 2/15/2019 9:00  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objective: Evaluate the impact of 15 mg/L ferric addition at lime doses bracketing the softening conditions targeted during the October 2018 flood event (pH ~10.2 and 11).  
 Protocol: Ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test ran at 85 rpm for 30 minutes. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality												
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	Alkalinity	TOC	SUVA	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)
1	30	15	0sec	5sec	9.48	8.82	-15.6	1.40E-01	78	4.46	3.14	33.1	31.7	360.8	19.1	7.9	7.8
2	40	15	0sec	5sec	9.68	12.7	-16.3	1.36E-01	80	4.02	3.38	26.3	24.4	530.3	38.6	7.6	7.5
3	50	15	0sec	5sec	9.95	12.3	-16	1.29E-01	70	4.06	3.18	22.7	21.1	511.7	39.6	7.4	7.3
4	60	15	0sec	5sec	10.25	9.83	-17	1.13E-01	45	3.77	2.99	22.4	20.8	412.8	21.2	6.4	6.2
5	80	15	0sec	5sec	10.69	4.48	-16.9	7.89E-02	55	3.16	2.50	26.5	25.2	109.8	2.8	3.3	3.2
6	120	15	0sec	5sec	11.27	2.6	-7.73	5.34E-02	83	2.55	2.10	49.1	33.7	25.3	0.0	0.9	0.8

**Jar Test #** 6  
**Date** 2/15/2019  
**Start Time** 13:00  
 Medium ferric doses, vary pH

**Jar Size** 200 mL

Date: 2/15/2019 13:00  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objective: Evaluate the impact of 80 mg/L ferric addition at lime doses bracketing the softening conditions targeted during the October 2018 flood event (pH ~10.2 and 11).  
 Protocol: Ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds. The jar test ran at 85 rpm for 30 minutes to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality												
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)
1	50	80	0sec	5sec	9.30	2.68	-8.92	1.03E-01	3.34	3.09	55	30.8	30.0	116.0	1.8	7.4	7.4
2	70	80	0sec	5sec	9.85	3.04	-11.20	9.31E-02	3.30	2.83	43	24.9	24.4	90.5	2.7	6.6	6.6
3	90	80	0sec	5sec	10.37	3.64	-11.00	6.49E-02	2.90	2.23	45	31.0	30.0	104.0	0.0	2.9	2.8
4	110	80	0sec	5sec	10.80	4.23	-9.19	4.90E-02	2.34	2.09	55	42.0	40.1	70.4	1.5	0.7	0.7
5	130	80	0sec	5sec	10.95	3.33	-5.46	4.32E-02	1.98	2.18	75	53.5	51.0	69.6	0.0	0.4	0.3
6	150	80	0sec	5sec	11.16	3.80	-3.89	4.05E-02	2.07	1.96	103	65.0	60.8	74.0	2.2	0.2	0.2

**Jar Test #** 7  
**Date** 2/15/2019  
**Start Time** 15:00  
 High ferric dose, vary pH  
**Jar Size** 200

Date: 2/15/2019 15:00  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objective: Evaluate the impact of 180 mg/L ferric addition at lime doses bracketing the softening conditions targeted during the October 2018 flood event (pH ~10.2 and 11).  
 Protocol: Ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test ran at 85 rpm for 30 minutes. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality												
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)
1	100	180	0sec	5sec	10.08	2.39	-5.81	6.06E-02	2.43	2.49	30	37.0	37.2	116.2	0.0	4.3	4.3
2	120	180	0sec	5sec	10.65	1.95	-12.6	4.53E-02	2.11	2.15	40	48.0	47.7	131.7	0.3	1.3	1.3
3	140	180	0sec	5sec	10.86	2.44	-4.87	4.14E-02	1.98	2.09	68	57.4	56.5	104.1	0.0	0.6	0.6
4	160	180	0sec	5sec	11.20	1.78	-4.57	3.75E-02	1.85	2.03	105	70.5	68.9	100.3	0.0	0.3	0.2
5	180	180	0sec	5sec	11.35	3.33	-0.284	3.53E-02	1.80	1.96	138	82.0	80.1	155.7	2.7	0.2	0.1
6	200	180	0sec	5sec	11.45	3.03	4.31	3.37E-02	1.70	1.99	155	89.3	82.2	175.6	3.5	0.2	0.1

**Jar Test #** 8  
**Date** 2/18/2019  
**Start Time** 9:45  
 High ferric dose, vary pH, order of chem addition  
**Jar Size** 200

Date: 2/18/2019 9:45  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objective: Evaluate the impact of 180 mg/L ferric addition at lime doses bracketing the softening conditions targeted during the October 2018 flood event (pH ~10.2 and 11). Evaluate the impact of the order of chemical addition.  
 Protocol: In four jars, ferric sulfate was added to the raw water (200 mL) in a jar test apparatus at 200 rpm. Lime was dosed after 10 seconds, and the rpm was reduced to 85 after 30 seconds. In two jars, the dosing order was switched. The jar test ran at 85 rpm for 30 minutes to target a velocity gradient equal to 100 sec<sup>-1</sup>. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Jar	Chemical Dose		Chemical Dosing Time		Settled Water Quality														
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	pH	Turbidity	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)
1	70	180	0sec	5sec	9.24	1.89	-12.8	7.79E-02	3.11	2.51	50	33.1	33.6	144.1	2.9	7.0	7.1	3.4	3.4
2	80	180	0sec	5sec	9.53	1.19	-12.1	7.48E-02	3.09	2.42	40	28.7	28.9	112.0	1.8	6.8	6.9	3.2	3.2
3	90	180	0sec	5sec	9.81	1.44	-11.7	6.49E-02	2.85	2.28	30	27.7	28.0	111.7	1.8	6.4	6.6	3.2	3.2
4	110	180	0sec	5sec	10.62	2.33	-5.55	3.78E-02	2.40	1.58	38	37.7	36.2	52.7	0.7	2.1	2.1	5.8	3.7
5	110	180	5sec	0sec	10.45	0.83	-5.87	4.17E-02	2.32	1.80	60	35.4	36.0	52.4	0.9	2.4	2.4	3.4	3.5
6	140	180	5sec	0sec	11.26	1.68	-5.33	3.00E-02	2.11	1.42	70	56.4	41.9	143.6	0.8	0.5	0.5	3.8	3.9

Jar Test # 9 and 10

Date 2/18/2019

Start Time 14:25

Settleability Test

Jar Size 2000 mL

Date: 2/18/2019 14:25

Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.

Test Objectives:

Evaluate the impact of softening at optimal ferric doses on settleability using 2 L jars.

Correlate results from 200 mL jars to results from tests run in October.

See if similar settleability is observed at 5 and 10 minutes (e.g., correlating to full-scale SOR) under same/similar conditions now as in October.

Confirm the optimal iron dose under October 2018 water quality conditions.

Assess whether settled water turbidity goals could be met with iron and lime at pH 10.2 (i.e., is high pH needed at representative SORs?)

Confirm through wet chemistry what iron is doing under these conditions as first step to see if iron impact can be achieved with polymer instead.

Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Lime was added 10 seconds after ferric. After 45 seconds, the rpm was reduced to 50. The jar test ran at 50 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

	Chemical Dose		Chemical Dosing Time		Target pH		Settled Water Quality														Turbidity (NTU)	
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime	RTW	pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min	
1	35	15	0sec	5sec		9.6	9.73	-14.5	1.30E-01	4.19	3.10	85	31.4	27.3	501.1	29.6	7.5	7.4	8.8	7.3	258	91
2	60	15	0sec	5sec		10.2	10.43	-17.7	1.15E-01	4.17	2.75	58	21.3	17.3	613.3	42.7	7.1	6.9	8.8	7.4	351	122
3	80	15	0sec	5sec		10.7	10.97	-16.2	7.51E-02	3.20	2.35	58	23.2	20.6	159.6	6.8	3.9	3.5	8.0	7.6	173	46
4	110	15	0sec	5sec		11.2	11.53	-13.8	5.40E-02	2.63	2.05	88	38.8	36.1	54.7	2.4	1.5	1.3	7.4	7.4	71	14
5	60	80	0sec	5sec		9.6	9.86	-11.8	7.05E-02	3.58	1.97	48	24.6	22.9	274.4	2.5	7.1	4.1	5.7	5.8	129	27
6	85	80	0sec	5sec		10.2	10.60	-9.2	1.00E-01	3.15	3.18	43	40.1	22.5	284.2	4.2	4.7	7.1	6.1	5.5	134	28
1	105	80	0sec	5sec		10.7	11.06	-6.94	5.84E-02	2.87	2.03	50	30.9	30.6	120.7	3.2	1.6	1.6	6.0	6.0	98	21
2	150	80	0sec	5sec		11.2	11.51	-5.16	4.38E-02	2.31	1.89	118	63.5	59.0	373.5	3.8	0.5	0.3	5.9	5.8	53	13
3	80	180	0sec	5sec		9.6	9.74	-7.87	8.86E-02	3.13	2.83	40	36.5	29.0	1839.6	2.4	7.0	6.7	3.9	3.2	102	36
4	105	180	0sec	5sec		10.2	10.71	-6.49	6.72E-02	2.76	2.44	40	38.6	31.8	1399.0	2.0	4.3	3.9	4.2	3.6	115	35
5	125	180	0sec	5sec		10.7	11.30	-3.59	5.49E-02	2.43	2.26	58	48.2	42.4	956.4	2.5	1.4	1.1	4.1	3.8	76	23
6	160	180	0sec	5sec		11.2	11.58	-4.76	5.10E-02	2.24	2.28	105	69.4	61.5	488.8	3.9	0.5	0.3	4.1	4.1	54	13



Jar Test # 11  
Date 2/19/2019  
Start Time 11:07  
Enhanced Coagulation  
Jar Size 2000

Date: 2/19/2019 11:07  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objectives: Evaluate impact of enhanced coagulation at ambient pH.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Lime was added 10 seconds after ferric to target a pH between 6 and 7. After 30 seconds, the rpm was reduced to 50 to target G equal to 50 s<sup>-1</sup>. The jar test ran at 50 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

Jar	Chemical Dose		Chemical Dosing Time		Target pH	Settled Water Quality														Turbidity (NTU)	
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Ferric	Lime		pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	5.3	80	0sec	5sec	8	7.20	-12.90	8.45E-02	3.42	2.47	90	40.7	39.4	1051.2	46.7	7.7	7.6	8.3	7.0	64.2	19.1
2	9.1	120	0sec	5sec	8	7.11	-12.00	6.85E-02	2.69	2.55		43.9	43.8	752.0	13.5	7.7	7.7	7.0	6.8	62.3	21.2
3	15.1	160	0sec	5sec	8	7.00	-9.92	5.60E-02	2.29	2.44	85	47.2	46.6	795.9	5.7	7.6	7.6	6.6	6.4	52.1	14.9
4	20.4	200	0sec	5sec	8	5.83	-2.17	4.94E-02	2.13	2.32		52.2	51.5	801.5	2.8	7.8	7.7	6.2	6.1	53.5	21.9
5	30.3	280	0sec	5sec	8	6.77	-6.39	4.14E-02	1.98	2.09	85	59.6	58.7	1412.8	1.3	7.8	7.7	6.1	5.9	64.1	25.6
6	0	280	0sec	5sec		6.02	-6.27	2.61E-02	1.41	1.85	50	41.6	41.8	1404.7	329.1	7.9	8.0	6.9	7.0	55.5	24.7

**Jar Test # 12 and 13**

**Date** 2/19/2019

**Start Time** 10:00

Impact of Center Well Solids

**Jar Size** 2000 mL

Date: 2/19/2019 10:00 and 14:30

Water: Collected from Ullrich WTP raw water sample location on 2/13/2019 at 8:00 am.

Solids: Collected from Ullrich WTP UFC center well on 2/19/2019 at 7:30 am, included PAC.

Test Objective: Mimic some of the conditions tested so far (with and without iron, using current water as well as banked water) to see if the presence of solids makes a notable difference in chemistry and settleability. Assess whether ferrihydrite solids are providing a seed for  $\text{CaCO}_3$  precipitation or complexing organics that would otherwise inhibit  $\text{CaCO}_3$  crystal growth.

Protocol: Concentrated center well solids were added to noted jars to make up 13% of the 2-L jar volume. Solids were either added before rapid mix or 10 seconds after ferric addition. At the start of rapid mix, ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. After 30 seconds, lime was dosed and the rpm was reduced to 85 in Jar Test 12 and 55 in Jar Test 13. The jar test ran for 30 minutes. The jar test was allowed to settle for 30 minutes before settled water turbidity samples were taken.

Chemical Dose				Chemical Dosing Time			Target pH	Settled Water Quality			Turbidity (NTU)	
Jar	Lime (mg/L CaO)	Center well solids	Ferric Dose (mg/L)	Ferric	Lime	Solids		pH	Turbidity	Zeta	5-min	10-min
1	0.0	100%	0	0sec		pre-mix	Ambient	9.505		-12.9	422	80.1
2	105.0	0%	15	0sec			10.3	10.408	8.77	-12.4	207	14.6
3	105.0	13%	15	0sec		pre-mix	10.3	10.494		-4.76	69.8	6.62
4	90.0	13%	0	0sec		pre-mix	10.3	10.205		-16.4	230	51.5
1	105	13%	15	0sec	30sec	5sec	10.4	10.5		-11.00	15.1	6.01
2	90			0sec	30sec		10.2	10.07		-17.90	329	181
3	140	13%	15	0sec	30sec	5sec	10.8	10.96		-6.25	27	8.52
4	140	13%	15	0sec	30sec	pre-mix	10.8	10.98		-3.33	26.1	6.85
5	140		15	0sec	30sec		10.8	10.91		-5.00	66	17.4
6	125			0sec	30sec		10.8	10.93		-15.50	460	144

Jar Test # 14  
Date 2/19/2019  
Start Time 16:20

Polymer  
Jar Size 2000 mL

Date: 2/19/2019 16:20  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objectives: Determine the effect of coagulant aid polymers on settleability of banked water at average ferric sulfate dose and pH 10.2.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. In jars 2-4, lime was added 30 seconds after ferric, followed by polymer addition. In jar 5, ferric and polymer were added simultaneously, followed by lime addition. In jar 6, ferric was added, followed by simultaneous addition of polymer and lime. After 45 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 50 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

Jar	Chemical Dose					Chemical Dosing Time		
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Label	Polymer Type	Polymer Dose	Ferric	Polymer	Lime
1	57	15	Ferric (30 s); Lime	Magnafloc LT7995	0	0sec	0	30sec
2	57	15	Ferric (30 s); Lime (5 s); Polymer	Magnafloc LT7995	5	0sec	35sec	30sec
3	57	15	Ferric (30 s); Lime (5 s); Polymer	Magnafloc LT7995	10	0sec	35sec	30sec
4	57	15	Ferric (30 s); Lime (5 s); Polymer	Magnafloc LT7995	15	0sec	35sec	30sec
5	57	15	Ferric + Polymer simultaneously (5 s); Lime	Magnafloc LT7995	10	30sec	30sec	35sec
6	57	15	Ferric (5 s); Lime + Polymer simultaneously	Magnafloc LT7995	10	30sec	35sec	35sec

Jar	Target pH		Settled Water Quality														Turbidity (NTU)	
	pH		Zeta		UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	10.2	-15.4		1.21E-01	3.65	3.31	65	19.6	16.9	451.7	28.7	6.8	6.6	8.8	7.3	382.0	130.0
2	10.2	10.23	-7.49		9.80E-02	3.26	3.00	65	20.3	19.7	64.4	4.0	6.6	6.7	7.4	7.4	11.3	5.3
3	10.2	10.23	-3.95		8.67E-02	3.16	2.74	60	20.5	19.7	86.6	2.9	6.7	6.7	7.5	7.3	11.7	4.2
4	10.2	10.23	-2.2		7.34E-02	3.13	2.35	60	20.7	18.8	157.5	2.1	6.8	6.8	7.7	7.3	18.2	7.3
5	10.2	10.3	-3.53		8.63E-02	3.12	2.76	55	18.4	17.6	47.8	1.6	6.6	6.5	7.4	7.3	25.6	10.8
6	10.2	10.26	-2.87		8.95E-02	3.91	2.29	60	21.8	20.4	115.1	3.0	6.6	6.7	7.6	7.3	17.9	8.6

Jar Test # 15  
 Date 2/20/2019  
 Start Time 9:32

Polymer  
 Jar Size 2000 mL

Date: 2/20/2019 9:32  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
 Test Objectives: Determine the effect of coagulant aid polymers on settleability of banked water at average ferric sulfate dose and pH 10.8-11.  
 Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. In jars 2-4, polymer was added 30 seconds after ferric, followed by lime addition. In jar 5, ferric and polymer were added simultaneously, followed by lime addition. In jar 6, ferric was added, followed by simultaneous addition of polymer and lime. After 45 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 50 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

Jar	Chemical Dose				Chemical Dosing Time		
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Ferric	Polymer	Lime
1	90	15	Magnafloc LT7995	0	0sec	0	30sec
2	90	15	Magnafloc LT7995	5	0sec	30sec	35sec
3	90	15	Magnafloc LT7995	10	0sec	30sec	35sec
4	90	15	Magnafloc LT7995	15	0sec	30sec	35sec
5	90	15	Magnafloc LT7995	10	30sec	30sec	35sec
6	90	15	Magnafloc LT7995	10	30sec	35sec	35sec

	Target pH	Settled Water Quality														Turbidity (NTU)	
Jar		pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	11	10.83	-13.6	7.01E-02	2.75	2.55	65	26.7	24.8	98.2	8.6	2.8	2.6	7.6	7.4	132.0	23.8
2	11	10.84	-7.81	6.38E-02	2.57	2.48	65	26.5	25.4	30.2	4.3	3.2	3.1	7.4	7.3	43.2	5.6
3	11	10.83	-2.25	5.80E-02	2.50	2.32	65	26.8	25.6	48.0	5.7	3.3	3.2	7.4	7.3	22.4	4.9
4	11	10.87	3.46	5.03E-02	2.51	2.01	70	26.6	25.7	61.9	6.4	3.3	3.3	7.4	7.2	20.6	5.7
5	11	10.8	-0.295	5.68E-02	2.48	2.29	70	25.5	25.1	42.1	61.9	3.4	3.3	7.3	7.2	14.3	4.6
6	11	10.76	-0.717	5.97E-02	2.48	2.41	60	24.6	24.0	59.5	34.5	3.6	3.7	7.4	7.4	12.5	4.1

Jar Test # 16  
 Date 2/20/2019  
 Start Time 1:35

Polymer  
 Jar Size 2000 mL

Date: 2/20/2019 13:35  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
 Test Objectives: Determine the effect of coagulant aid polymers on settleability of banked water at various ferric sulfate doses and pH 10.2.  
 Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Polymer was added 30 seconds after ferric, followed by lime addition. After 45 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 50 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling. Polymer types included Magnafloc LT7995 and Clarifloc C-358.

Jar	Chemical Dose				Chemical Dosing Time		
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Ferric	Polymer	Lime
1	83	80	Magnafloc LT7995	0	0sec	30sec	35sec
2	83	80	Magnafloc LT7995	15	0sec	30sec	35sec
3	100	180	Magnafloc LT7995	0	0sec	30sec	35sec
4	100	180	Magnafloc LT7995	10	0sec	30sec	35sec
5	57	15	C-358	10	0sec	30sec	35sec
6	57	15	C-358	15	0sec	30sec	35sec
7	57	15	C-358	20	0sec	30sec	35sec

	Target pH	Settled Water Quality													Turbidity (NTU)		
Jar		pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	10.28	-8.36	7.59E-02	2.74	2.77	40	22.5	21.7	138.6	10.6	4.4	4.4	5.6	5.7	123.0	24.2
2	10.2	10.34	1.03	5.11E-02	2.43	2.10		21.2	20.9	119.7	17.2	4.7	4.6	5.5	5.5	86.1	6.3
3	10.2	10.17	-5.46	6.48E-02	2.45	2.65	35	31.3	30.7	301.3	10.3	5.2	5.3	3.1	3.1	114.0	35.4
4	10.2	10.12	8.52	4.76E-02	2.29	2.08		30.2	28.9	441.9	13.8	5.5	5.5	3.1	3.0	107.0	35.1
5	10.2	10.05	-9.19	9.04E-02	3.21	2.81	65	19.1	18.6	79.0	9.7	6.7	6.5	7.3	7.2	7.5	3.0
6	10.2	10.06	-5.79	8.55E-02	3.22	2.65		18.2	17.8	69.4	21.4	6.5	6.5	7.4	7.3	9.1	3.8
7	10.2	10.10	-1.89	7.90E-02	3.22	2.45		18.5	17.6	85.3	25.8	6.6	6.5	7.6	7.4	14.5	3.4

Jar Test # 17  
Date 2/21/2019  
Start Time 11:53

Impact of Center Well Solids  
Jar Size 2000 mL

Date: 2/21/2019 11:53  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Solids: Collected from Handcox WTP UFC center well on 2/21/2019 at 7:30 am.  
Test Objective: Mimic some of the conditions tested so far (15 and 30 mg/L ferric, using banked water) to see if the presence of solids makes a notable difference in chemistry and settleability. Assess whether ferrihydrite solids are providing a seed for CaCO<sub>3</sub> precipitation or complexing organics that would otherwise inhibit CaCO<sub>3</sub> crystal growth.  
Protocol: At the start of rapid mix, ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. After 30 seconds, coagulant aid polymer was dosed to jars 4 and 5, lime was dosed to all jars, solids were added to jars 2, 3, and 6, and the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. Concentrated center well solids were added to noted jars to make up 13% of the 2-L jar volume simultaneously with lime. The jar test ran for 30 minutes. Settled water turbidity samples were collected after 5 and 10 minutes of settling.

Chemical Dose							Chemical Dosing Time			
Jar	Lime (mg/L CaO)	Center well solids	Ferric Dose (mg/L)	Description	Polymer Type	Polymer Dose	Ferric	Polymer	Lime	Solids
1	85	0%	80	80 mg/L ferric, no solids	None	0	0sec		30sec	
2	85	13%	80	80 mg/L ferric, solids added 2nd	None	0	0sec		30sec	30sec
3	60	13%	15	15 mg/L ferric, 15 mg/L CAP, solids added last	Magnafloc	15	0sec	30sec	35sec	35sec
4	60	0%	15	15 mg/L ferric, 15 mg/L CAP, no solids	Magnafloc	15	0sec	30sec	35sec	
5	130	0%	80		None	0	0sec		30sec	
6	130	13%	80		None	0	0sec		30sec	30sec

Target pH		Settled Water Quality														Turbidity (NTU)	
Jar		pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	10.46	-8.41	7.28E-02	3.009	2.42	45	22.0	21.2	122.8	4.1	4.2	4.1	5.7	5.7	177.0	43.8
2	10.2	10.71	-12.1	5.62E-02	2.677	2.10	45	24.4	23.4	65.1	2.9	3.5	3.4	6.0	5.9	40.4	9.1
3	10.2	10.52	0.69	5.76E-02	2.862	2.01		15.8	15.9	38.7	1.3	6.5	6.4	7.5	7.3	10.1	1.7
4	10.2	10.29	-0.354	7.06E-02	3.207	2.20	60	15.9	16.0	59.9	1.4	6.6	6.5	7.4	7.3	8.6	4.2
5	11	11.3		4.25E-02	2.269	1.87	90	45.4	44.1	56.8	3.0	0.3	0.3	6.4	6.4	69.5	19.7
6	11	11.26	-4.88	3.77E-02	2.185	1.72		47.5	46.6	34.3	3.3	0.3	0.3	6.6	6.7	21.7	6.3

Jar Test # 18  
Date 2/21/2019  
Start Time 16:30

CO2 addition

Jar Size 200 mL

pH undershot target  
Date: 2/21/2019 16:30  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objectives: Determine the impact on settlability of banked water when adding carbonate in the form of CO<sub>2</sub> to precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2.  
Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (200 mL) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. After 30 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes, and was allowed to settle for 30 minutes before sample collection.

	Chemical Dose					Initial pH	Settled Water Quality													
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Simulated CO2 Dose (mg/L)	NaHCO3 as soln (mg/L)	HCl (eq/L)		pH	Turbidity	Zeta	UV 254	TOC	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)
1	60	15	0	0	0.0000	8.05	10.03	7.43	-16.5	1.18E-01	3.975	55	16.8	16.3	290.1	21.8	6.4	6.4	8.4	7.3
2	80	15	22	42	0.0005	7	9.77	8.61	-17	1.20E-01	4.017	55	16.5	15.5	521.6	29.6	6.8	6.7	9.4	7.2
3	100	15	44	84	0.0010	6.68	9.2	7.54	-16.9	1.18E-01	3.91	65	17.6	17.0	449.2	21.7	6.8	6.7	9.1	7.1
4	135	15	65	125	0.0015	6.48	9.38	7.46	-18.9	1.10E-01	3.73	55	16.9	14.7	419.9	18.2	6.6	6.5	8.8	7.1
5	76	15	0	0	0.0000	8.02	9.98	4.19	-17.2	9.01E-03	3.408	55	19.5	17.9	150.4	7.8	4.3	4.1	8.0	7.5
6	115	15	44	84	0.0010	6.72	9.69	7.09	-17.5	1.07E-01	3.68	50	15.4	14.7	390.0	14.3	6.2	6.1	8.8	7.2

**Jar Test #** 19  
**Date** 2/22/2019  
**Start Time** 13:00  
**Jar Size** 200 mL  
 CO2 addition, JT18 redo

JT 18 redo for pH  
 Date: 2/22/2019 13:00  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
 Test Objectives: Determine the impact on settlability of banked water when adding carbonate in the form of CO<sub>2</sub> to precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2.  
 Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (200 mL) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. After 30 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes, and was allowed to settle for 30 minutes before sample collection.

	Chemical Dose					Chemical Dosing Time (sec)			
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Simulated CO2 Dose (mg/L)	NaHCO3 as soln (mg/L)	HCl (eq/L)	HCl Stock (mL)	Ferric	Polymer	Lime
1	57	15	0	0	0.0000	0	0		5
2	80	15	22	42	0.0005	1	0		5
3	100	15	44	84	0.0010	2	0		5
4	135	15	65	124	0.0015	3	0		5
5	76	15	0	0	0.0000	0	0		5
6	115	15	44	84	0.0010	2	0		5

	Initial pH	Settled Water Quality													
Jar		pH	Turbidity	Zeta	UV 254	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)
1		10.36	8.94	-18	1.13E-01	3.87	60	16.7	16.5	318.8	21.1	5.9	6.1	7.9	7.2
2	6.99	10.15	12.4	-16.8	1.15E-01	3.83	50	16.3	15.4	387.7	26.4	6.3	6.3	7.7	7.1
3	6.71	10.09	10	-17.1	1.12E-01	3.71	55	15.5	14.9	341.1	22.4	6.4	6.3	7.7	7.0
4	6.54	10	8.57	-17	1.08E-01	3.69	50	15.5	14.5	325.7	16.3	6.3	6.3	7.6	7.0
5		10.71	6.41	-18.6	8.23E-02	3.20	50	19.1	18.7	86.8	6.1	3.4	3.4	7.5	7.2
6	6.76	10.31	7.52	-17.4	9.94E-02	3.71	50	15.9	14.9	225.1	7.9	5.6	5.4	7.8	7.1



Jar Test # 20  
Date 2/25/2019  
Start Time 10:08  
Polymer  
Jar Size 2000 mL

Jar Test 20, Jars 1-5  
Date: 2/25/2019 10:08  
Water: Collected from Ullrich WTP raw water sample location on 2/13/2018.  
Test Objective: Evaluate effect of feeding coagulant aid polymer at small dose year-round.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. After 45 seconds, the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

Jar Test 20, Jars 6-8  
Date: 2/25/2019 10:08  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objective:  
Compare polymer addition before and after lime addition as follow-up to JT14.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. In Jar 8, the order of lime and polymer addition was reversed. After 45 seconds, the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

	Chemical Dose					Chemical Dosing Time		
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Description	Polymer Type	Polymer Dose (mg/L)	Ferric	Polymer	Lime
1	105	15	0 mg/L PEC, 15 mg/L ferric	Magnafloc LT7995	0	0sec	30sec	35sec
2	105	15	1 mg/L PEC, 15 mg/L ferric	Magnafloc LT7995	1	0sec	30sec	35sec
3	105	15	3 mg/L PEC, 15 mg/L ferric	Magnafloc LT7995	3	0sec	30sec	35sec
4	105	15	5 mg/L PEC, 15 mg/L ferric	Magnafloc LT7995	5	0sec	30sec	35sec
5	90	0	3 mg/L PEC, 0 mg/L ferric	Magnafloc LT7995	3	0sec	30sec	35sec
6	57	15	Ferric (30 s); Polymer (5 s); Lime		0	0sec	30sec	35sec
7	57	15	Ferric (30 s); Polymer (5 s); Lime	Magnafloc LT7995	10	0sec	30sec	35sec
8	57	15	Ferric (30 s); Lime (5 s); Polymer	Magnafloc LT7995	10	0sec	35sec	30sec

	Target pH	Settled Water Quality														Turbidity (NTU)	
Jar		pH	Zeta	UV 254	TOC	SUVA	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	10.71	-10.4	6.37E-02	3.025	2.10	80	19.3	18.2	89.2	1.1	16.8	16.7	7.9	7.9	30.5	14.0
2	10.2	10.66	-5.71	5.93E-02	2.939	2.02		19.6	18.2	59.6	0.8	16.9	16.7	7.9	7.9	17.4	10.5
3	10.2	10.67	-1.57	5.41E-02	2.916	1.86		18.8	17.1	47.1	0.1	16.4	16.6	7.7	7.9	20.1	9.8
4	10.2	10.65	3.74	4.98E-02	2.948	1.69	85	18.1	16.8	56.7	0.1	16.4	16.7	7.8	7.9	16.2	9.7
5	10.2	10.41	-7.28	5.87E-02	3.308	1.78	55	22.8	15.9	9.8	-0.3	17.3	17.3	8.4	8.4	57.6	40.1
6	10.2	10.23	-16.5	1.20E-01	3.921	3.07	65	22.0	17.2	472.9	20.3	6.9	6.8	8.6	7.1	460.0	196.0
7	10.2	10.17	-7.53	8.06E-02	3.371	2.39	75	23.4	21.7	71.7	1.9	6.8	6.7	7.3	7.0	11.4	5.6
8	10.2	10.35	-6.78	8.20E-02	3.574	2.30		24.0	22.3	82.0	1.3	6.8	6.8	7.3	7.2	10.7	6.7

Jar Test # 21  
Date 2/25/2019  
Start Time 14:22

Floc Aid Polymer  
Jar Size 2000 mL

Jar Test 21  
Date: 2/25/2019 14:22  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objective: Evaluate the effect of feeding flocculant aid polymer on the settleability of banked water at the optimal ferric sulfate and coagulant aid polymer doses determined in previous tests and pH 10.5.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. Flocculant aid polymer was added at a dose of 0.5 or 1.0 mg/L simultaneously with lime or 10 minutes into the flocculation period. After 45 seconds of rapid mix, the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling. Flocculant aid polymers tested were Nalco 7766+ and Clarifloc A-6330.

Chemical Dose			Coag Aid		Floc Aid		Chemical Dosing Time (sec)				Target pH	Settled Water Quality		Turbidity (NTU)	
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Description	Polymer Type	Polymer Dose (mg/L)	Polymer Type	Polymer Dose (mg/L)	Ferric	Coag Aid	Floc Aid	Lime	pH	Zeta	5-min	10-min
1	57	15	0 mg/L floc aid	Magnafloc LT7995	10			0	30		35	10.2	10.53	-5.6	7.64
2	57	15	0.5 mg/L floc aid, added simultaneously with lime	Magnafloc LT7995	10	Nalco 7766+	0.5	0	30	35	35	10.2	10.63	-5.26	9.9
3	57	15	1.0 mg/L floc aid, added simultaneously with lime	Magnafloc LT7995	10	Nalco 7766+	1	0	30	35	35	10.2	10.59	-6.6	14.7
4	57	15	1.0 mg/L floc aid, added 10 minutes into flocculation	Magnafloc LT7995	10	Nalco 7766+	1	0	30	600	35	10.2	10.58	-11.7	13.7
5	57	15	0.5 mg/L floc aid, added simultaneously with lime	Magnafloc LT7995	10	Clarifloc A-6330	0.5	0	30	35	35	10.2	10.61	-6.15	13.7
6	57	15	1.0 mg/L floc aid, added simultaneously with lime	Magnafloc LT7995	10	Clarifloc A-6330	1	0	30	35	35	10.2	10.6	-12.2	12.8
7	57	15	1.0 mg/L floc aid, added 10 minutes into flocculation	Magnafloc LT7995	10	Clarifloc A-6330	1	0	30	600	35	10.2	10.58	-12.1	13

**Jar Test #** 22  
**Date** 2/26/2019  
**Start Time** 11:57  
 CO2 & caustic  
**Jar Size** 200 mL

Date: 2/26/2019 11:57

Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.

Test Objectives: Determine the impact on settlability of banked water when adding adding CO<sub>2</sub> and NaOH to generate more alkalinity and precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2.

Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (200 mL) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. Caustic was dosed simultaneously with or 5 seconds prior to lime, as noted. After 30 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes, and was allowed to settle for 30 minutes before sample collection.

Jars 4-6 hit target settled water pH of 10.2.

Jar	Chemical Dose							Chemical Dosing Time (sec)		
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Simulated CO2 Dose (mg/L)	NaHCO3 as soln (mg/L)	HCl (eq/L)	NaOH (mg/L)	NaOH (eq/L)	Ferric	Caustic	Lime
1	65	15	44	84	0.001	30	0.00075	0	30	35
2	65	15	44	84	0.001	30	0.00075	0	30	30
3	65	15	44	84	0.001	30	0.00075	15	0	20
4	84	15	44	84	0.001	30	0.00075	0	30	35
5	84	15	44	84	0.001	30	0.00075	0	30	30
6	84	15	44	84	0.001	30	0.00075	15	0	20

Jar	Initial pH	Settled Water Quality											
	pH	NTU	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)
1	6.79	9.90	13.8	-17.9	7.56	90	14.9	13.5	1008.6	66.1	6.3	6.2	9.9
2		10.03	9.95	-17.1	5.14	85	14.9	13.3	761.8	54.0	6.3	6.1	8.6
3		9.79	12.8	-19.2	4.29	90	15.9	14.8	789.8	35.2	6.3	6.3	10.2
4		10.24	19.6	-20.3	4.06	75	12.3	10.6	1031.4	43.2	6.0	5.7	11.3
5		10.23	20.2	-20.5	4.20	75	12.7	10.6	1052.1	41.7	5.9	5.7	11.3
6		10.28	15.8	-21.4	4.18	75	12.7	10.0	741.2	31.8	5.9	5.6	9.6

Jar Test # 23  
Date 2/27/2019  
Start Time 10:34

CO2 & caustic

Jar Size 2000 mL

Date: 2/26/2019 11:57

Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.

Test Objectives: Determine the impact on settlability of banked water when adding adding CO<sub>2</sub> and NaOH to generate more alkalinity and precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2

Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (2 L) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. Caustic was dosed simultaneously with lime. Coagulant aid polymer was dosed to jar 7 five seconds prior to lime addition. After 30 seconds of rapid mixing, the rpm was reduced to 55 to target a G-value of 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

	Chemical Dose						Coag Aid		Chemical Dosing Time (sec)			
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	NaHCO <sub>3</sub> as soln (mg/L)	HCl (eq/L)	NaOH (mg/L)	NaOH (eq/L)	Polymer Type	Polymer Dose	Ferric	Caustic	CAP	Lime
1) 0 mg/L CO <sub>2</sub>	55	15	0	0.0000	0	0		0	0			30
2) 22 mg/L CO <sub>2</sub>	80	15	42	0.0005	0	0		0	0			30
3) 44 mg/L CO <sub>2</sub>	105	15	84	0.0010	0	0		0	0			30
4) 65 mg/L CO <sub>2</sub>	140	15	125	0.0015	0	0		0	0			30
5) 44 mg/L CO <sub>2</sub>	84	15	84	0.0010	30	0.00075		0	0	30		30
6) 65 mg/L CO <sub>2</sub>	94	15	125	0.0015	45	0.001125		0	0	30		30
7) 44 mg/L CO <sub>2</sub>	105	15	84	0.0010	0	0	Magnafloc LT7995	10	0		30	35

	pH	pH HQ400				Settled Water Quality												Turbidity (NTU)	
Jar	Target	Initial pH	Start of Flocculation	End of Flocculation	Settled	pH Orion	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO <sub>2</sub>	SiO <sub>2</sub> (Filt)	5-min	10-min
1) 0 mg/L CO <sub>2</sub>	10.2	8.3	10.58	10.46	10.39	10.28	-16.5	4.33	60	16.6	15.4	842.4	60.1	6.4	6.3	10.4	7.1	275.0	77.3
2) 22 mg/L CO <sub>2</sub>	10.2	7.23	10.59	10.46	10.43	10.25	-17.1	4.03	60	16.1	15.0	668.4	47.7	6.3	6.2	9.5	7.1	238.0	76.9
3) 44 mg/L CO <sub>2</sub>	10.2	6.95	10.46	10.32	10.29	10.09	-17.1	3.94	60	15.5	14.3	691.6	38.7	6.2	6.2	9.7	7.0	253.0	79.3
4) 65 mg/L CO <sub>2</sub>	10.2	6.72	10.86	10.75	10.69	10.52	-16.9	3.78	55	14.7	13.9	308.8	14.2	5.4	5.2	7.9	7.0	230.0	57.1
5) 44 mg/L CO <sub>2</sub>	10.2	6.93	10.65	10.56	10.52	10.29	-20.6	4.08	80	10.9	9.5	1023.0	56.7	5.9	5.7	11.2	7.0	263.0	80.7
6) 65 mg/L CO <sub>2</sub>	10.2	6.73	10.5	10.41	10.39	10.17	-21.2	4.15	95	9.8	8.5	851.5	58.8	6.0	5.8	10.1	6.8	239.0	62.7
7) 44 mg/L CO <sub>2</sub>	10.2	6.89	10.65	10.51	10.41	10.24	-8.39	3.49	55	15.3	15.0	66.8	3.5	5.9	6.0	6.9	6.9	18.8	3.6

Phase 2 Jar Testing

Jar Test #	Water Supply	Jar Type	General Description	Ferric?	Center Well Solids?	Coag Aid Polymer?	Floc Aid Polymer?	CO2?	NaOH?	pH
1	Banked water	2 L	Impact of flocculant aid polymer	Yes	Handcox	Yes	Yes	No	No	10.5
2 & 3	Banked water	2 L	Impact of CO2 with solids and PEC	Yes	Handcox	Yes	No	Yes	No	9.7-10.5
4	Banked water	2 L	Coagulant aid polymer dose optimization	Yes	No	Yes	No	No	No	10.3
5 & 6	Banked water	2 L	Impact of pH	Yes	No	Yes	No	No	No	9.6-10.5
7	Current water	2 L	Impact of velocity gradient (G)	Yes	Handcox	No	No	No	No	10.1-10.3
S1	Current water	2 L	Iterative generation of solids with current water	Yes	Generated	No	No	No	No	10.1-10.3
S2	Banked water	2 L	Iterative generation of solids with PEC	Yes	Generated	Yes	No	No	No	9.9-10.2
S3	Banked water	2 L	Iterative generation of solids with PEC & 1 mg/L PEA	Yes	Generated	Yes	Yes	No	No	9.9-10.2
S4	Banked water	2 L	Iterative generation of solids with PEC & 0.1 mg/L PEA	Yes	Generated	Yes	Yes	No	No	9.9-10.1
S5	Banked water	2 L	Iterative generation of solids with PEC & 0.3 mg/L PEA	Yes	Generated	Yes	Yes	No	No	9.8

Jar Test # 1 Phase 2  
Date 3/28/2019  
Start Time 12:49  
Floc Aid Polymer  
Jar Size 2000 mL

Floc Aid Polymer Pretests  
Date: 3/28/19, 12:49  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Solids: Collected from Handcox WTP UFC #2 centerwell on 3/27/19.  
Test Objective: Evaluate the effect of feeding flocculant aid polymer on the settleability of banked water at the optimal ferric sulfate and coagulant aid polymer doses determined in previous tests and pH 10.2. Compare with and without centerwell solids.  
Protocol: Ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by addition of center well solids to noted jars to make up 13% of the 2-L jar volume. Directly after solids addition, flocculant aid polymer (FAP) was added at a dose of 1.0 mg/L simultaneously with lime. After 45 seconds of rapid mix, the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling. Flocculant aid polymers tested were Nalco 7766 Plus (nonionic), Clarifloc A-6330 (anionic), and Clarifloc C-6220 (cationic).  
Settled water pH = 10.5 for jars without solids and 10.7 for jars with centerwell solids.

	Chemical Dose			Coag Aid		Floc Aid				Chemical Dosing Time (sec)				
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Label	Polymer Type	Polymer Dose	Polymer Type	Charge	Polymer Dose	CW Solids	CW Solids	Ferric	Coag Aid	Floc Aid	Lime
1	55	15	0 mg/L PEA	Magnafloc LT7995	10			0	0%		0	30		60
2	55	15	1 mg/L non-ionic PEA	Magnafloc LT7995	10	Nalco 7766+	Non-ionic	1	0%		0	30	60	60
3	55	15	1 mg/L anionic PEA	Magnafloc LT7995	10	Clarifloc A-6330	Anionic	1	0%		0	30	60	60
4	55	15	1 mg/L cationic PEA	Magnafloc LT7995	10	Clarifloc C-6220	Cationic	1	0%		0	30	60	60
5	55	15	3 mg/L cationic PEA	Magnafloc LT7995	10	Clarifloc C-6220	Cationic	3	0%		0	30	60	60
6	55	15	0 mg/L PEA	Magnafloc LT7995	10			0	13%	35-60	0	30		60
7	55	15	1 mg/L non-ionic PEA	Magnafloc LT7995	10	Nalco 7766+	Non-ionic	1	13%	35-60	0	30	60	60
8	55	15	1 mg/L anionic PEA	Magnafloc LT7995	10	Clarifloc A-6330	Anionic	1	13%	35-60	0	30	60	60
9	55	15	1 mg/L cationic PEA	Magnafloc LT7995	10	Clarifloc C-6220	Cationic	1	13%	35-60	0	30	60	60
10	55	15	3 mg/L cationic PEA	Magnafloc LT7995	10	Clarifloc C-6220	Cationic	3	13%	35-60	0	30	60	60

	Target pH	Settled Water Quality												Turbidity (NTU)	
Jar		pH-HQ40D	pH-OrionStarA214	Zeta	TOC	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	10.53	10.52	-12.3	4.17	20.3	18.1	69.5	0.6	6.9	6.3	7.2	6.9	13.1	5.2
2	10.2	10.54		-10.1	3.45	25.5	22.2	94.2	0.3	7.0	6.8	7.3	7.1	11.2	6.3
3	10.2	10.56	10.50	-8.69	3.24	27.8	23.1	98.5	-0.2	6.9	6.8	7.3	7.2	13.6	7.5
4	10.2	10.53		-3.29	3.49	23.8	21.8	88.6	0.4	6.7	6.9	7.3	7.2	13.1	8.6
5	10.2	10.49	10.48	-5.52	3.51	28.4	22.7	123.5	0.8	6.8	6.7	7.2	7.2	15.3	9.2
6	10.2	10.76	10.73	-3.12	3.36	17.6	16.7	40.5	0.0	7.1	6.9	7.1	7.1	21.9	3.8
7	10.2	10.78	10.74	-4.06	3.13	18.9	17.5	65.5	1.9	7.1	6.8	7.1	7.1	11.2	3.0
8	10.2	10.74	10.75	-5.71	3.39	19.3	18.5	68.4	1.0	7.1	7.0	7.2	7.1	7.4	4.5
9	10.2	10.81	10.77	-6.83	3.22	18.7	17.8	73.6	0.9	6.9	6.9	7.2	7.0	13.4	4.0
10	10.2	10.73	10.70	-10.8	3.59	21.5	19.8	116.6	1.8	7.0	7.1	7.1	7.1	10.1	6.5

Jar Test # 2 Phase 2  
Date 3/29/2019  
Start Time 9:58  
CO2

Jar Size 2000 mL

CO2 Addition Pretests  
Date: 3/29/19  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Solids: Collected from Handcox WTP UFC #2 centerwell on 3/27/19.  
Test Objectives: Determine the impact on settlability of banked water when adding adding a high CO<sub>2</sub> dose to precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2.  
Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (2 L) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. Coagulant aid polymer was dosed to jars 4-6 five seconds prior to lime addition. After 30 seconds of rapid mixing, the rpm was reduced to 85 to target a G-value of 100 s<sup>-1</sup>. The jar test ran at 85 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

	Chemical Dose					Coag Aid		Chemical Dosing Time (sec)			
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Simulated CO <sub>2</sub> (mg/L)	NaHCO <sub>3</sub> as soln (mg/L)	HCl (eq/L)	Polymer Type	Polymer Dose	Center well solids	Ferric	CAP	Lime
1	53	15	0	0	0.0000	Magnafloc LT7995	0		0		60
2	105	15	44	84	0.0010	Magnafloc LT7995	0		0		60
3	150	15	88	168	0.0020	Magnafloc LT7995	0		0		60
4	53	15	0	0	0.0000	Magnafloc LT7995	10		0	30	60
5	105	15	44	84	0.0010	Magnafloc LT7995	10		0	30	60
6	150	15	88	168	0.0020	Magnafloc LT7995	10		0	30	60
7	48	15	0	0	0.0000	Magnafloc LT7995	0	35-60	0		60
8	103	15	44	84	0.0010	Magnafloc LT7995	0	35-60	0		60
9	148	15	88	168	0.0020	Magnafloc LT7995	0	35-60	0		60

	pH	pH HQ40D	Settled Water Quality												Turbidity (NTU)	
Jar	Target	Initial pH	pH Orion	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO <sub>2</sub>	SiO <sub>2</sub> (Filt)	5-min	10-min
1	10.2	8.01	10.31	-15.7	3.94	85	19.1	16.0	415.2	39.7	6.8	6.6	7.6	7.1	499	252
2	10.2	7.11	10.07	-16.6	4.01	70	18.8	15.8	435.4	32.5	6.8	6.7	7.5	7.1	589	245
3	10.2	6.62	9.66	-18.8	3.73	65	20.7	18.2	360.6	19.9	6.7	6.7	7.5	7.0	579	216
4	10.2		10.37	-9.05	3.43	65	17.9	17.4	35.2	1.2	6.7	6.5	7.1	7.1	14.8	5.5
5	10.2	7.07	10.09	-6.00	3.34	65	16.7	16.8	28.5	0.1	6.5	6.6	7.0	7.1	16.7	3.0
6	10.2	6.65	9.72	-8.17	3.42	65	18.6	18.2	22.3	0.0	6.7	6.6	6.9	7.0	18.4	4.2
7	10.2		10.36	-17.7	3.46	65	23.7	15.7	358.8	4.5	7.6	7.3	7.5	6.9	153	54
8	10.2	6.99	10.51	-15.7	3.43	60	33.5	14.0	485.1	0.9	7.4	6.3	7.7	7.8	170	62
9	10.2	6.62	10.51	-13.1	3.39	65	17.5	14.0	160.3	1.3	6.5	6.4	7.2	6.8	215	61

**Jar Test #** 3 Phase 2  
**Date** 4/1/2019  
**Start Time** 10:47  
 CO2 with solids and PEC  
**Jar Size** 2000 mL

CO2 Addition Pretests  
 Date: 4/1/19  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
 Solids: Collected from Handcox WTP UFC #2 centerwell on 3/27/19.  
 Test Objectives: Determine the impact on settlability of banked water when adding adding a high CO<sub>2</sub> dose to precipitate more CaCO<sub>3</sub> solids. Target settled water pH of 10.2.  
 Protocol: The addition of CO<sub>2</sub> was simulated through the addition of sodium bicarbonate (NaHCO<sub>3</sub>) and hydrochloric acid. The acid was dosed to simulate the pH anticipated from adding CO<sub>2</sub>. The required acid dose was determined based on RTW modeling. After adding CO<sub>2</sub> to the raw water (2 L) in a jar test apparatus at a low rpm and measuring pH, 15 mg/L ferric sulfate was added at 200 rpm. Coagulant aid polymer was dosed 30 seconds after ferric addition, followed by solids addition and lime addition. After at least 60 seconds of rapid mixing, the rpm was reduced to 85 to target a G-value of 100 s<sup>-1</sup>. The jar test ran at 85 rpm for 30 minutes. Settled water turbidity samples were taken after 5 and 10 minutes of settling.

	Chemical Dose					Coag Aid		Chemical Dosing Time (sec)			
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Simulated CO2 (mg/L)	NaHCO3 as soln (mg/L)	HCl (eq/L)	Polymer Type	Polymer Dose	Center well solids	Ferric	CAP	Lime
1	46	15	0	0	0.0000	Magnafloc L17995	10	35-60	0	30	60
2	99	15	44	84	0.0010	Magnafloc L17995	10	35-60	0	30	60
3	144	15	88	168	0.0020	Magnafloc L17995	10	35-60	0	30	60

	pH	pH HQ40D	Settled Water Quality												Turbidity (NTU)	
Jar	Target	Initial pH	pH HQ40D	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	5-min	10-min
1	10.2	8.1	10.47	-5.66	2.97	60	17.5	17.0	35.6	0.0	7.5	7.4	6.8	6.8	9.7	3.6
2	10.2	7.4	10.46	-8.79	3.11	60	15.7	15.5	27.1	0.0	7.2	7.1	6.8	6.8	14.9	4.0
3	10.2	7.1	10.25	-4.68	3.10	55	16.8	15.5	37.8	0.0	7.2	7.2	6.7	6.7	31.4	3.9



**Jar Test #** 4 Phase 2  
**Date** 4/1/2019  
**Start Time** 14:40  
**Coag Aid Polymer**

**Jar Size** 2000 mL

Coagulant Aid Polymer Dose Optimization

Date: 4/1/19

Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.

Test Objective: Evaluate the effect of feeding a range of coagulant aid polymer doses on the settleability of banked water at the optimal ferric sulfate dose determined in previous tests and pH 10.2.

Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. After 60 seconds of rapid mix, the rpm was reduced to 55 to target a G value equal to  $55 \text{ s}^{-1}$ . The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 2, 5 and 10 minutes of settling.

Jar	Chemical Dose		Coag Aid			Chemical Dosing Time (sec)			Target pH	Settled Water Quality		Turbidity (NTU)		
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Description	Polymer Type	Polymer Dose	Ferric	Coag Aid	Lime		pH	Zeta	2-min	5-min	10-min
1	52	15	0 mg/L PEC	Magnafloc LT7995	0	0	30	35	10.2	10.35	-16	517	479	329
2	52	15	4 mg/L PEC	Magnafloc LT7995	4	0	30	35	10.2	10.33	-6.83	162	22.5	10
3	52	15	8 mg/L PEC	Magnafloc LT7995	8	0	30	35	10.2	10.35	-4.57	116	7.02	4.7
4	52	15	10 mg/L PEC	Magnafloc LT7995	10	0	30	35	10.2	10.33	-1.62	101	5.9	6.4
5	52	15	12 mg/L PEC	Magnafloc LT7995	12	0	30	35	10.2	10.33	-0.94	92.4	12.1	4.3
6	52	15	15 mg/L PEC	Magnafloc LT7995	15	0	30	35	10.2	10.36	0.113	127	15.8	5.1

Jar Test # 5 Phase 2  
Date 4/2/2019  
Start Time 11:48

pH Optimization

Jar Size 2000 mL

Effect of pH (Jars 1-4)  
Date: 4/2/19  
Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.  
Test Objective: Evaluate the effect of pH (9.8-10.2) on the settleability of banked water at the optimal coagulant aid polymer and ferric sulfate doses determined in previous tests.  
Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. After 60 seconds of rapid mix, the rpm was reduced to 55 to target a G value equal to 55 s<sup>-1</sup>. The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 2, 5 and 10 minutes of settling.

	Chemical Dose		Coag Aid		Chemical Dosing Time (sec)		
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Ferric	Coag Aid	Lime
1	37	15	Magnafloc LT7995	10	0	30	35
2	40	15	Magnafloc LT7995	10	0	30	35
3	43	15	Magnafloc LT7995	10	0	120	35
4	46	15	Magnafloc LT7995	10	0	30	35
5	43	0	Magnafloc LT7995	0	0	30	35
6	60	80	Magnafloc LT7995	0	0	30	35

	Target pH	Settled Water Quality												Turbidity (NTU)		
Jar		pH	Zeta	TOC	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	2-min	5-min	10-min
1	9.9	10.13	-3.67	3.26	95	31.9	28.1	72.4	0.0	6.8	6.8	7.1	6.9	57	4.92	3.64
2	10.0	10.20	-3.59	3.43	95	28.7	25.8	75.4	0.0	6.7	6.6	7.1	6.9	57.1	5	3.13
3	10.1	10.25	-4.86	3.42	85	28.7	25.5	73.5	0.0	6.7	6.8	7.1	6.9	24	4.12	3.38
4	10.2	10.44	-2.74	3.36	80	26.9	23.3	74.4	0.0	6.7	6.7	7.1	6.9	24.4	5.14	3.37
5	10.2	10.40	-15.4	4.50		77.7	16.9	705.2	16.1	7.6	6.8	9.9	7.4			388
6	10.2	10.24	-14.4	3.59		23.1	22.1	186.6	0.2	6.4	6.5	5.2	5.0			54.3

Jar Test # 6 Phase 2

Date 4/2/2019

Start Time 15:15

pH Optimization - low

Jar Size 2000 mL

Effect of pH

Date: 4/2/19

Water: Collected from Ullrich WTP raw water sample location on 10/25/2018.

Test Objective: Evaluate the effect of pH (9.8-10.2) on the settleability of banked water at the optimal coagulant aid polymer and ferric sulfate doses determined in previous tests.

Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Coagulant aid polymer (Magnafloc LT7995) was added 30 seconds after ferric, followed by lime addition. After 60 seconds of rapid mix, the rpm was reduced to 55 to target a G value equal to  $55 \text{ s}^{-1}$ . The jar test ran at 55 rpm for 30 minutes. Settled water turbidity samples were taken after 2, 5 and 10 minutes of settling.

	Chemical Dose		Coag Aid		Chemical Dosing Time (sec)		
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Ferric	Coag Aid	Lime
1	23	15	Magnafloc LT7995	10	0	30	35
2	27	15	Magnafloc LT7995	10	0	30	35
3	31	15	Magnafloc LT7995	10	0	120	35
4	35	15	Magnafloc LT7995	10	0	30	35

	Target pH	Settled Water Quality												Turbidity (NTU)		
Jar		pH	Zeta	TOC	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	2-min	5-min	10-min
1	9.9	9.61	-2	3.812	115	32.9	33.7	67.6	0.0	6.9	7.1	7.2	7.1	27.8	2.79	1.75
2	10.0	9.69												25.0	2.68	1.87
3	10.1	9.77	-3.62	3.525	90	28.0	28.1	69.0	0.0	7.0	6.9	7.2	7.0	28.9	3.26	1.94
4	10.2	9.86	-3.06	3.473	90	26.1	25.5	68.4	0.0	7.0	6.8	7.2	7.1	24.5	2.63	2.17

Jar Test # 7 Phase 2

Date 4/8/2019

Start Time 9:00

Impact of G-value

Jar Size 2000 mL

Impact of G-value

Date: 4/8/19

Water: Collected from Handcox WTP raw water sample location on 4/5/2019.

Solids: Collected from Handcox WTP UFC centerwell on 4/5/2019.

Test Objective: Evaluate the effect of G-value on the settleability of current water at the average ferric sulfate dose.

Protocol: Concentrated solids were added to make up 2% of jar volume as noted either before ferric sulfate or simultaneously with lime. 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. Lime was added 30 seconds after ferric. After 60 seconds of rapid mix, the rpm was reduced to 85 or 45 to target G-values equal to 100 s<sup>-1</sup> and 40 s<sup>-1</sup>. The jar test ran for 30 minutes.

Jar	Chemical Dose	Ferric Dose (mg/L)	Label	CW Solids	Chemical Dosing Time (sec)			rpm	Settled Water	Turbidity (NTU)		
	Lime (mg/L CaO)				CW Solids	Ferric	Lime		Quality	2-min	5-min	10-min
1	82	15	G=100 1/sec, no solids, ferric 1st, lime 2nd	0%		0	35	85	10.35	218	70.7	13.8
2	82	15	G=100 1/sec, solids 1st, ferric 2nd, lime 3rd	3%	pre	0	35	85	10.15	402	166	85.2
3	82	15	G=40 1/sec, no solids, ferric 1st, lime 2nd	0%		0	35	45	10.25	28.3	5.7	5.7
4	82	15	G=40 1/sec, solids 1st, ferric 2nd, lime 3rd	3%	pre	0	35	45	10.22	288	66.5	20.2
5	82	15	G=40 1/sec, ferric 1st, then solids and lime simultaneously	3%	35	0	35	45	10.10	316	54.2	9.63

Jar Test # S1

Date 4/1/2019

Jar Size 2000 mL

Iterative generation of solids  
 Date: 4/1/19  
 Water: Collected from Ullrich WTP raw water sample location on 2/13/19.  
 Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 200 rpm. After 30 seconds of rapid mixing, lime and solids generated in the previous test were added, starting with iteration #2. The jar test ran at 85 rpm to target a G-value of 100 s<sup>-1</sup> for 30 minutes.

Chemical Dose		pH		pH HQ40D												Turbidity (NTU)					
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Target	Initial pH	Settled pH	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	2-min	4-min	7-min	10-min	15-min
1	85	15	10.2	10.65	10.32	-7.64	3.351	105	22.5	19.3	84.4	0.0	17.2	17.1	7.8	7.7	200.0	157.0	45.7	23.7	
2	83	15			10.34	-5.94		100									279.0	171.0	53.4	27.8	
3	83	15			10.15	-7.5											409.0	165.0	47.8	12.5	17.0
4	83	15			10.15	-7.62											357.0	177.0	45.7	16.1	10.5
5	83	15			10.15	-5.84	3.379	85	14.7	13.6	65.9	0.0	17.1	16.7	7.7	7.6	339.0	165.0	50.1	32.1	16.5
6	83	15			10.1	-6.26											444.0	189.0	60.7	19.8	17.5
7	83	15			10.19	-9.84											448.0	195.0	74.2	23.1	14.2
8	83	15			10.21	-7.66											381.0	152.0	42.2	14.3	11.1
9	83	15			10.22	-4.09	3.247		14.5	11.7	85.1	0.0	17.1	16.7	7.6	7.6	339.0	140.0	34.2	11.7	7.3
10	83	15			10.13	-3.72											291.0	133.0	40.0	9.0	11.0
11	83	15			10.3	-5.88											323.0	129.0	29.7	12.0	7.9
12	83	15			10.29	-6.22											363.0	151.0	46.2	15.7	8.0
13	83	15			10.18	-4.52											262.0	137.0	41.6	19.4	8.5
14	83	15			10.29	-7.42											310.0	135.0	57.1	17.5	13.4
15	83	15			10.16	-11.5	3.702		13.0	10.5	73.9	0.0	16.9	16.7	7.6	7.5	304.0	151.0	55.6	16.6	11.5
3% solids					10.26	-8.13											757.0	285.0	114.0	73.8	48.4
S1-1.2							3.13		25.2	20.6	139.4	0.0	17.4	17.3	7.8	7.9					

Jar Test # 52  
Date 4/8/2019  
Start Time 10:00

Jar Size 2000 mL

Iterative generation of solids with banked water and PEC  
Date: 4/8/19  
Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
Test Objectives: Evaluate solids growth and settleability in simulated solids contact clarifier centerwell.  
Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 80 rpm. After 30 seconds of rapid mixing, 12 mg/L of coagulant aid polymer (Magnafloc LT-7995) was added, followed by simultaneous addition of lime and solids generated in the previous test, starting with Iteration #2. The jar test ran at 55 rpm to target a G-value of 55 s<sup>-1</sup> for 30 minutes.

	Chemical Dose		Coag Aid		Chemical Dosing Time (sec)			
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Center well solids	Ferric	PEC	Lime
1	43	15	Magnafloc LT-7995	12	40	0	30	40
2	43	15	Magnafloc LT-7995	12	40	0	30	40
3	43	15	Magnafloc LT-7995	12	40	0	30	40
4	45	15	Magnafloc LT-7995	12	40	0	30	40
5	45	15	Magnafloc LT-7995	12	40	0	30	40
6	49	15	Magnafloc LT-7995	12	40	0	30	40
7	49	15	Magnafloc LT-7995	12	40	0	30	40
8	54	15	Magnafloc LT-7995	12	40	0	30	40
9	43	15	Magnafloc LT-7995	12	40	0	30	40
10	43	15	Magnafloc LT-7995	12	40	0	30	40

	pH	pH												Turbidity (NTU)			Solids (inches)	
Jar	Target	Settled	Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	2-min	5-min	10-min		% solids
1	10.1	10.18	-0.83	3.41		25.6	23.2	105.5	0.0	6.7	6.7	7.2	7.1	21.4	5.82	3.65		
2	10.1	10.02	-1.75		75									16.6	2.66	1.71		
3	10.1	9.94	-4.27											21	1.81	1.75	0.15	2.5%
4	10.1	10.01	-1.76											12	1.91	1.2		
5	10.1	9.98	-1.04											12.7	1.52	1.03		
6	10.1	9.93	-4.21	3.44	60	16.2	16.2	33.3	0.0	6.7	6.5	7.1	7.0	14.1	1.02	0.87	0.21	3.5%
7	10.1	9.86	-5.33											19.8	1.18	0.92		
8	10.1	9.96	-3.94											11.6	1.19	1.01		
9	10.1	9.86	-4.66											14.6	0.89	0.9		
10	10.1	9.64	-5.24	3.44	65	16.7	16.8	25.1	0.0	6.9	6.9	7.0	7.0	9.14	2.26	1.15	0.29	4.9%

Jar Test # 53

Date 4/8/2019  
Start Time 10:00

Jar Size 2000 mL

Iterative generation of solids with banked water, PEC, and PEA

Date: 4/8/19

Water: Collected from Ullrich WTP raw water sample location on 10/25/18.

Test Objectives: Evaluate solids growth and settleability in simulated solids contact clarifier centerwell.

Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 80 rpm. After 30 seconds of rapid mixing, 12 mg/L of coagulant aid polymer (Magnafloc LT-7995) was added, followed by simultaneous addition of lime and solids generated in the previous test, starting with Iteration #2. Then, 1 mg/L of anionic floc aid polymer was added, before turning down to 55 rpm. The jar test ran at 55 rpm to target a G-value of  $55\text{ s}^{-1}$  for 30 minutes.

Jar	Chemical Dose		Coag Aid		Floc Aid			Chemical Dosing Time (sec)			
	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Polymer Type	Charge	Polymer Dose	Center well solids	Ferric	PEC	Lime
1	43	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
2	43	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
3	43	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
4	45	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
5	45	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
6	49	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
7	49	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
8	54	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
9	50	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40
10	43	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	1	40	0	30	40

Jar	pH		Zeta	TOC (mg/L)	Alkalinity	Calcium	Ca (Filt)	Iron	Fe (Filt)	Mg	Mg (Filt)	SiO2	SiO2 (Filt)	Turbidity (NTU)			Solids (inches)	% solids
	Target	Settled												2-min	5-min	10-min		
1	10.2	10.17	-4.74	3.33		30.9	25.5	122.0	0.0	6.8	6.7	7.3	7.1	6.8	5.4	5.9		
2	10.2	10.12	-3.6		75									7.1	4.9	3.3		
3	10.2	9.93	-4.93											3.2	2.3	2.3	0.14	2.4%
4	10.2	10.06	-4.28											6.5	2.2	2.4		
5	10.2	9.94	-5.83											2.8	1.7	1.6		
6	10.2	10.06	-2.92	3.58	60	18.4	18.6	58.8	0.0	6.7	6.7	7.2	7.0	2.9	1.7	1.4	0.20	3.4%
7	10.2	9.92	-4.19											4.7	1.3	1.3		
8	10.2	10.03	-4.09											2.7	1.2	1.2		
9	10.2	9.92	-6.66											3.5	1.1	1.2		
10	10.2	9.71	-7.51	3.39	65	17.5	17.5	45.3	0.0	6.9	6.9	7.1	7.0	4.4	1.3	1.1	0.29	4.9%

Jar Test # S4  
Date 4/9/2019  
Start Time 10:00

Jar Size 2000 mL

Iterative generation of solids with banked water, PEC, and PEA  
Date: 4/9/19  
Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
Test Objectives: Evaluate solids growth and settleability in simulated solids contact clarifier centerwell.  
Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 80 rpm. After 30 seconds of rapid mixing, 12 mg/L of coagulant aid polymer (Magnafloc LT-7995) was added, followed by simultaneous addition of lime and solids generated in the previous test, starting with Iteration #2. Then, 0.1 mg/L of anionic floc aid polymer was added, before turning down to 55 rpm. The jar test ran at 55 rpm to target a G-value of 55 s<sup>-1</sup> for 30 minutes.

	Chemical Dose							Coag Aid				Floc Aid				Chemical Dosing Time (sec)				pH		Turbidity (NTU)					
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Polymer Type	Charge	Polymer Dose	Center well solids	Ferric	PEC	Lime	Target	Settled	Zeta	2-min	5-min	10-min	Solids (inches)	% solids								
1	48	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.1	40	0	30	40	10.2	9.96	-0.855	33.6	4.47	3.6		0.00								
2	54	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.1	40	0	30	40	10.2	10.09	-4.64	10.2	2.85	1.86										
3	50	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.1	40	0	30	40	10.2	10.01	-1.25	9.35	1.61	1.73										
4	50	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.1	40	0	30	40	10.2	9.73	-6.84	10.8	1.44	1.86	0.15	2.5%								
5	60	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.1	40	0	30	40	10.2	10.04	-2.83	7.91	1.64	1.15										



Jar Test # S5  
 Date 4/9/2019  
 Start Time 14:00

Jar Size 2000 mL

Iterative generation of solids with banked water, PEC, and PEA  
 Date: 4/8/19  
 Water: Collected from Ullrich WTP raw water sample location on 10/25/18.  
 Test Objectives: Evaluate solids growth and settleability in simulated solids contact clarifier centerwell.  
 Protocol: 15 mg/L ferric sulfate was added to the raw water (2 L) in a jar test apparatus at 80 rpm. After 30 seconds of rapid mixing, 12 mg/L of coagulant aid polymer (Magnafloc LT-7995) was added, followed by simultaneous addition of lime and solids generated in the previous test, starting with Iteration #2. Then, 0.3 mg/L of anionic flocc aid polymer was added, before turning down to 55 rpm. The jar test ran at 55 rpm to target a G-value of 55 s<sup>-1</sup> for 30 minutes.

	Chemical Dose		Coag Aid		Floc Aid			Chemical Dosing Time (sec)				pH	pH		Turbidity (NTU)		
Jar	Lime (mg/L CaO)	Ferric Dose (mg/L)	Polymer Type	Polymer Dose	Polymer Type	Charge	Polymer Dose	Center well solids	Ferric	CAP	Lime	Target	Settled	Zeta	2-min	5-min	10-min
1	48	15	Magnafloc LT-7995	12	Clarifloc A-6330	anionic	0.3	40	0	30	40	10.2	9.78	-3.27	13.8	2.67	2.43

## Appendix F

# PEC TESTING IN TYPICAL LAKE AUSTIN WATER

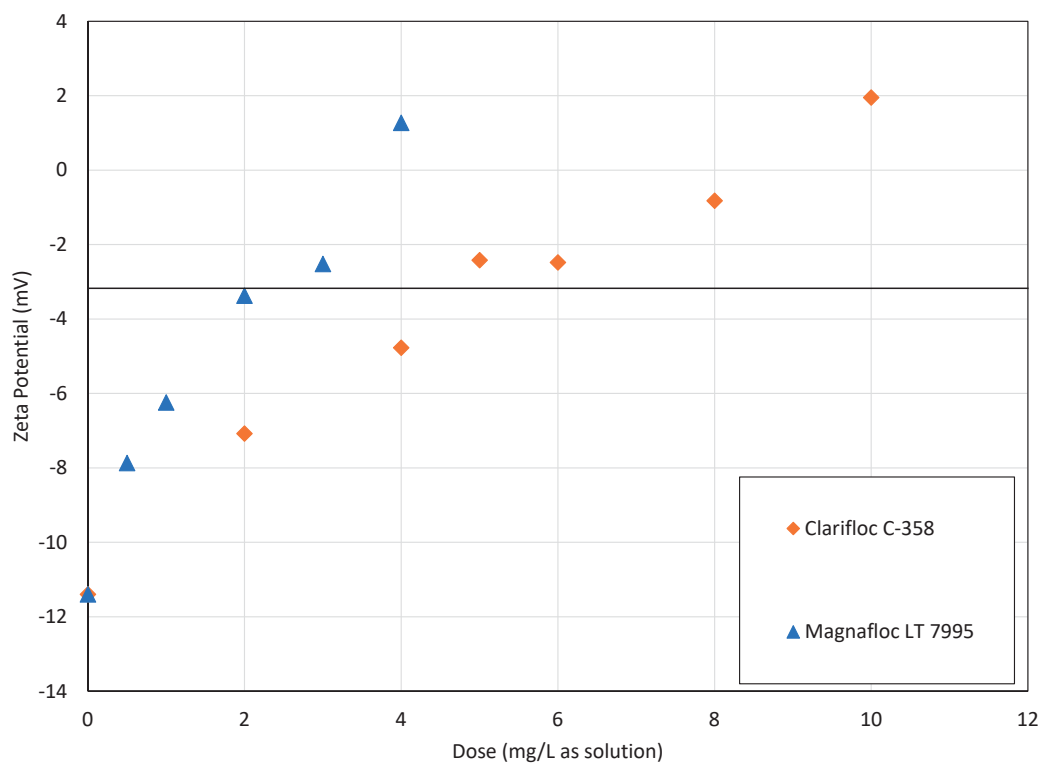


Figure F.1 Impact of PEC Dose on Zeta Potential in Typical Water

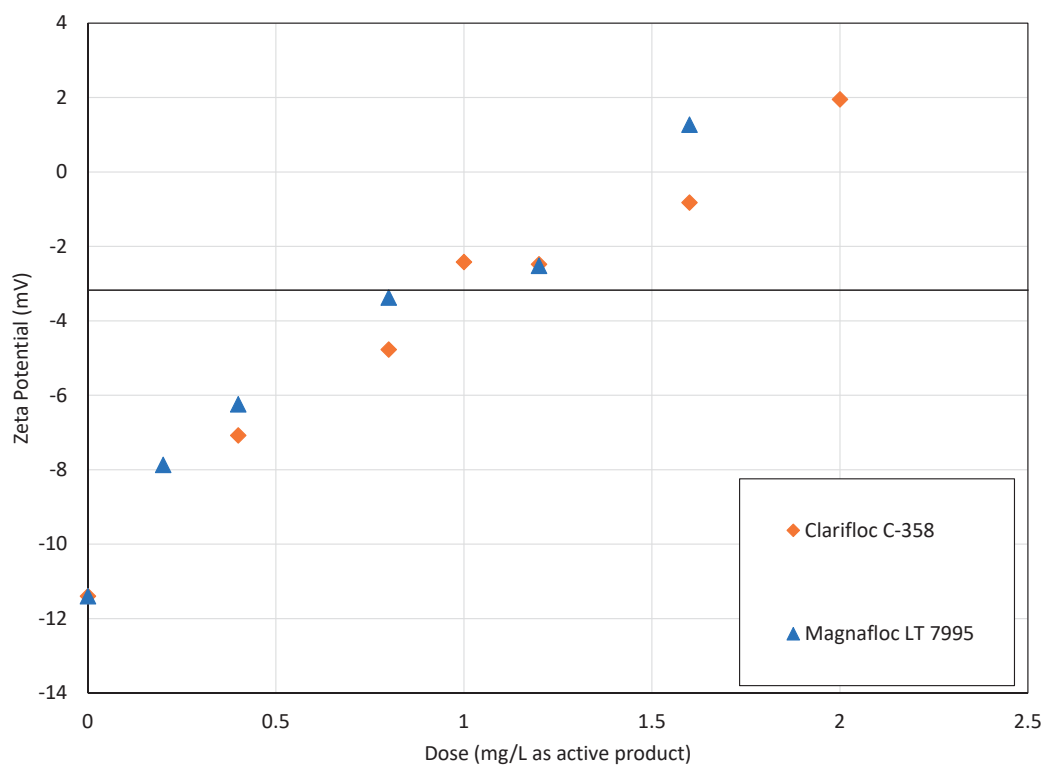


Figure F.2 Impact of PEC Dose on Zeta Potential in Typical Water