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To: Town of Culpeper

From: Hazen and Sawyer

Town of Culpeper Water Quality Analysis

DRAFT

As described in the Water System Evaluation, the Town has maintained compliance with applicable primary drinking water regulations. A Water Quality Data Analysis was performed to evaluate reported aesthetic-related water quality reports summarized in the Water System Evaluation, focusing on water discoloration, unpleasant taste and odor, and hardness. The Water Quality Analysis consisted of the following.

- An analysis of historical source water, finished water, and distribution system water quality data related to the reported aesthetic issues;
- An evaluation of the water treatment plant (WTP) process based on historical operating data and on-site treatment testing; and,
- A distribution system evaluation using the Town's distribution system hydraulic model to characterize source water blending and water age in the distribution system.

Results from the Water Quality Data Analysis were used to identify water quality characteristics that likely influence water aesthetics in the Town. Key findings of the data analysis were used to develop and prioritize recommendations for system optimization to further minimize aesthetic water quality issues.

Table of Contents

Town of Culpeper Water Quality Analysis.....	1
1. Introduction	4
1.1 Approach.....	5
1.2 Report Organization.....	5
2. Background.....	7
2.1 Background on Water Discoloration	7
2.1.1 Source Water and Treatment	7
2.1.2 Distribution System Iron Corrosion	8
2.1.3 Distribution System Legacy Deposits	9
2.1.4 Strategies for Managing Corrosion and Legacy Deposits	10
2.2 Background on Taste and Odor.....	11
2.2.1 Taste and Odor Compounds Derived from Surface Water.....	12
2.2.2 Taste and Odor Associated with Chlorination	13
2.2.3 Taste and Odor Compounds Derived from the Distribution System	13
3. Water Quality Analysis.....	14
3.1 Iron Data Analysis.....	14
3.1.1 WTP Raw Water Iron Levels	14
3.1.2 WTP Finished Water Iron Levels	15
3.1.3 Groundwater Iron Levels	15
3.1.4 Distribution System Iron Levels	16
3.1.5 Summary of Iron Data Analysis	17
3.2 Manganese Data Analysis	18
3.2.1 Raw Water Manganese Concentrations	18
3.2.2 WTP Finished Water Manganese Levels	18
3.2.3 Groundwater Manganese Levels.....	21
3.2.4 Distribution System Manganese Levels	23
3.2.5 Summary of Manganese Data Analysis.....	26
3.3 Taste and Odor	27
3.3.1 Powdered Activated Carbon	27
3.3.2 Chlorine Data Analysis	28

3.3.3	Source Water Ammonia and Organic Compounds	29
3.3.4	Taste and Odor Summary	29
3.4	Hardness.....	30
4.	Treatment Process Data Analysis.....	33
4.1.1	Oxidation of Iron and Manganese.....	33
4.1.2	Filter Performance	34
4.1.3	WTP Process Data Analysis Summary	35
4.2	Corrosion Control Treatment	35
4.2.1	Finished Water pH, Alkalinity, and Dissolved Inorganic Carbon (DIC).....	35
4.2.2	Distribution System pH, Alkalinity, and Dissolved Inorganic Carbon (DIC)	38
4.2.3	Orthophosphate	39
4.2.4	Chloride and Sulfate	43
4.2.5	Silica and Aluminum	45
4.2.6	Summary of Corrosion Control Treatment Data Analysis	46
5.	Distribution System Blending and Water Age Analysis	47
5.1	Distribution System Blending Analysis	47
5.2	Distribution System Water Age	51
6.	Water Treatment Plant On-site Testing.....	54
6.1	Permanganate Dose	54
6.2	Clarifier Testing.....	55
6.2.1	Plant Profile Sampling	56
6.2.2	Bench-Scale Coagulation Testing	56
6.2.3	Settled Water Monitoring	57
6.2.4	Clarifier Design Implications	58
6.3	Filter Testing	58
6.3.1	Chlorine Residual Monitoring.....	59
6.3.2	Backwash Testing.....	59
7.	Conclusion	61

1. Introduction

The Town of Culpeper (Town) retained Hazen and Sawyer (Hazen) to perform an independent Water System Assessment. A Water System Study evaluating source water, treatment, and distribution was performed as part of the Assessment, and the results are summarized in three technical memoranda: (1) Water System Evaluation; (2) Water Quality Analysis; and (3) Water Quality Recommendations. The objectives of each memorandum are detailed in **Figure 1-1**.

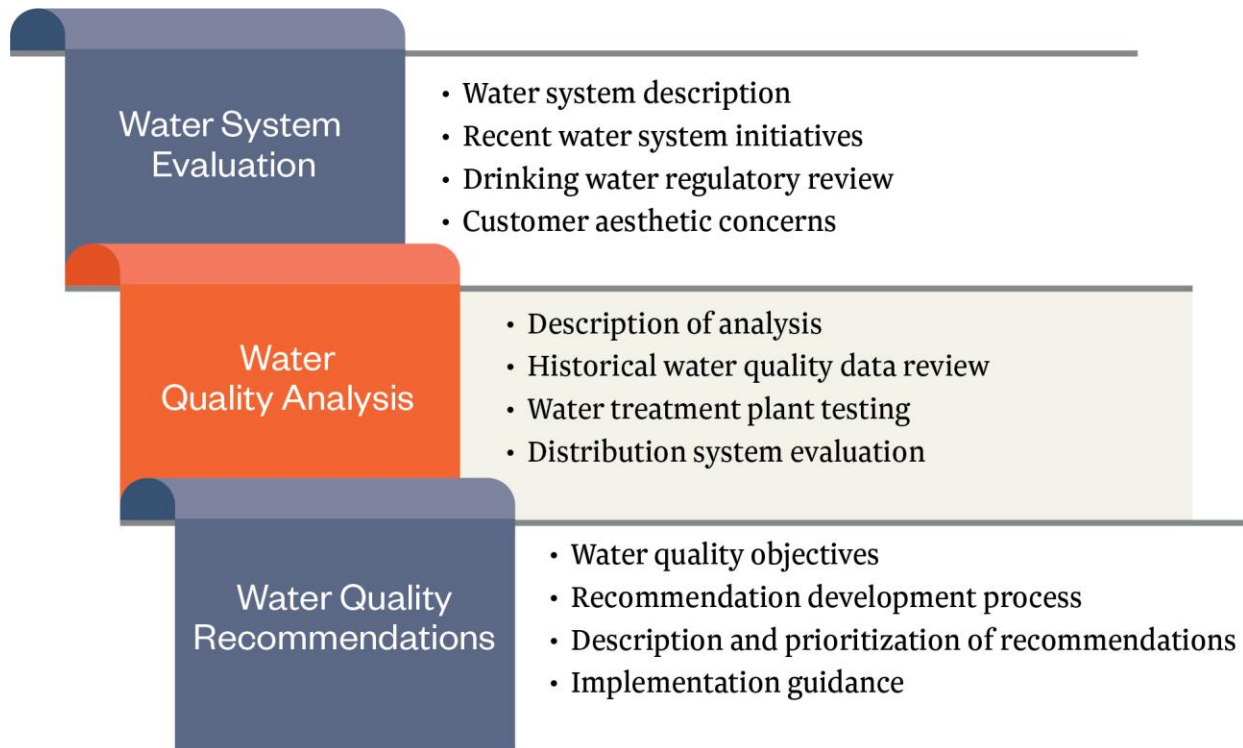


Figure 1-1. Summary of Water System Study Tasks and Objectives

As described in the Water System Evaluation, the Town has maintained compliance with applicable drinking water regulations and primary standards. However, the Town has experienced occasional iron and manganese levels in the distribution system above the respective Secondary Maximum Contaminant Levels (SMCLs), which are unenforceable standards related to water aesthetics, consistent with isolated customer complaints of episodic water discoloration. Other consumer reports also suggested episodic events of taste and odor or elevated water hardness in tap water. This memo summarizes the results of the Water Quality Analysis performed as part of the Water System Study to investigate these aesthetic aspects of water quality delivered to customers, including water discoloration, unpleasant taste and odor, and water hardness.

The analysis was performed to address the following objectives.

- To evaluate water quality parameters related to water discoloration and characterize iron and manganese levels in the system

- To assess the water treatment plant (WTP) process for control of water discoloration and iron corrosion
- To evaluate potential factors affecting water taste and odor
- To analyze water quality data related to hardness in the Town's source water

Results from the Water Quality Analysis were used to develop and prioritize recommendations for system optimization to further improve water quality aesthetics, which are presented in the Water Quality Recommendations technical memorandum.

1.1 Approach

A broad analysis of the Town's historical water quality data was conducted. The water quality data analysis was performed to focus on the episodic aesthetic issues identified in the Water System Evaluation. Data analysis results are generally presented since 2015, when groundwater was introduced into the distribution system, consistent with current system operations. Data prior to 2015 represents conditions in the system prior to introduction of groundwater, when the Lake Pelham WTP was the sole water source supplying the Town. A summary of water quality and treatment process data evaluated for the assessment is presented in **Table A-1** and **Table A-2** in **Appendix A**. Figures displaying the data are included in **Appendix B** through **Appendix F**.

In addition, testing was conducted at the WTP by Hazen and Sawyer in July 2019 to investigate WTP performance; those testing results are also presented in this technical memorandum.

1.2 Report Organization

This technical memorandum consists of the following sections:

- **Section 1** – Introduction: This section describes the purpose and approach taken for the Water Quality Analysis.
- **Section 2** – Background: This section presents an overview of potential causes of water discoloration and taste and odor.
- **Section 3** – Water Quality Analysis: This section presents an evaluation of water quality data related to discoloration, taste and odor, and hardness.
- **Section 4** – Treatment Process Data Analysis: This section presents results of an analysis of treatment performed at the WTP and groundwater wells, related to potential drivers for discoloration, taste and odor, and hardness.
- **Section 5** – Distribution System Blending and Water Age Analysis: This section utilizes the updated hydraulic model to investigate water quality, including source tracing and water age.
- **Section 6** – Water Treatment Plant On-site Testing: This section presents additional on-site testing that was conducted at the WTP to investigate key aspects of plant performance identified from the historical water quality data analysis.
- **Section 7** – Conclusion: This section summarizes the findings from the Water Quality Analysis and presents the focus for the Recommendations.

The following appendices referenced in the memorandum provide additional detail to support the Water Quality Data Analysis.

- Appendix A: Water Quality Data Sources
- Appendix B: Distribution System Maps and Data
- Appendix C: WTP Data
- Appendix D: Chandler Street Well Data
- Appendix E: Nalles Mill Well Data
- Appendix F: Rockwater Park Well Data

2. Background

To provide context for the water quality data analysis, this section provides additional background information on water discoloration and taste and odor, which were the two primary episodic water aesthetic issues reported in the Town.

2.1 Background on Water Discoloration

Water discoloration is commonly caused by iron or manganese. Iron typically causes a red, brown, or rusty color and can cause red or orange staining of fixtures. Manganese can cause a black or brown water color or black staining of fixtures. The USEPA SMCLs intended to minimize noticeable discoloration for iron and manganese are 0.3 mg/L and 0.05 mg/L, respectively. Recently (after issuance of SMCLs), a more aggressive finished water goal for manganese of 0.02 mg/L has been typically recommended in the industry due to the potential for water discoloration at levels above this threshold (Sly et al, 1990; Tobiasson et al, 2016). Manganese is included on the Fourth Unregulated Contaminant Monitoring Rule, with nationwide testing currently underway, partly to evaluate potential justification for lowering the SMCL.

Factors associated with source water, treatment, and distribution can influence iron and manganese levels and the potential for water discoloration; these factors are detailed in the following subsections.

2.1.1 Source Water and Treatment

Iron and manganese are naturally occurring elements present in many source waters including Lake Pelham and the Town's groundwater. Iron and manganese can enter reservoir sources through release from sediments. Dissolved iron and manganese can enter source water in reservoirs when anoxic conditions occur at the sediment-water interface at the bottom of the reservoir. Thermal stratification of a reservoir is one such event that can lead to oxygen depletion in the deeper levels of the reservoir.

Iron and manganese can be present in raw water in the dissolved, colloidal, and particulate forms, which can necessitate different treatment strategies. Particulate iron and colloidal/particulate manganese present in source water can often be removed effectively through coagulation without addition of an oxidant. Dissolved iron and manganese typically require oxidation and precipitation for effective removal through coagulation and filtration processes. Although free chlorine can be an effective oxidant for dissolved iron, free chlorine reaction rates with dissolved manganese are low, and a strong oxidant, such as permanganate or chlorine dioxide, is typically needed to effectively oxidize and precipitate dissolved manganese during coagulation. Dissolved manganese can also be removed through sorption to manganese-oxide coated filter media in the presence of free chlorine (i.e. the "induced greensand effect"). Any dissolved iron and manganese not removed at a treatment facility can be oxidized by free chlorine added for disinfection to form particles that contribute to water discoloration.

Permanganate is an effective strong oxidant for dissolved iron and manganese. Permanganate is known to produce manganese oxide solids in the colloidal size range, especially in waters with low calcium and magnesium hardness, which can be difficult to remove through coagulation and filtration. The net

negative surface charge of manganese oxide particles produced by permanganate oxidation can influence the coagulation process (Brandhuber et al, 2013). The presence of a permanganate residual in the filter influent can increase the risk of manganese oxide colloids in the filter effluent (Tobiason et al, 2016).

A sequestering agent, such as polyphosphate used in the Town of Culpeper, can be added to bind with dissolved iron and manganese present in finished water and inhibit or delay subsequent oxidation by free chlorine in the distribution system and formation of discolored water. However, reversion of polyphosphate to orthophosphate in the distribution system or premise plumbing can release sequestered iron and manganese and allow oxidation in the bulk water.

2.1.2 Distribution System Iron Corrosion

Corrosion in the distribution system has implications for water quality as well as the physical condition of critical infrastructure that must be considered to maximize the life cycle of existing water distribution infrastructure. Iron pipe corrosion is influenced by a variety of water quality, hydraulic, and physical factors, as well as source water and treatment changes. Iron materials including cast iron and galvanized iron are present in the Town's distribution system and in privately-owned premise plumbing systems.

Iron pipe corrosion can result in several potential secondary impacts (McNeill et al, 2001), including the following:

- Pipe degradation (i.e. as measured by weight loss) can increase the potential for leaks and water main breaks.
- Scale formation and tuberculation of cast iron water mains can restrict the hydraulic capacity of the pipe and increase pumping costs.
- Corrosion by-product release from cast iron mains can cause aesthetic concerns due to "red water".
- Iron corrosion and tuberculation can create an environment that harbors biological growth, protected from disinfection by the chlorine demand exerted by iron scale surfaces, which can cause aesthetic concerns related to tastes and odors.
- In some cases, iron can affect lead release from premise plumbing. Particulate iron is known to scavenge and sorb lead, potentially increasing lead levels at measured taps.

Iron corrosion and release are affected by physical and water quality factors including pH, alkalinity/DIC, hardness, phosphate, chloride, and sulfate concentrations. Higher levels of alkalinity/DIC decrease iron pipe degradation, corrosion by-product release, and potential for red water. Higher alkalinity levels also increase the buffer intensity, which provides further benefits for controlling iron corrosion. Surface water from Lake Pelham contains relatively low levels of alkalinity and DIC, increasing the potential for iron corrosion. Groundwater in the Town of Culpeper has intermittent low pH levels, which can also influence iron corrosion.

Dissolved oxygen and disinfectant residual can also impact iron corrosion and release. At equilibrium, measurable levels of dissolved oxygen and disinfectant residual provide the driving force to minimize

iron dissolution (Benjamin et al., 1996). Stagnant conditions in pipelines can yield red water due to depletion of dissolved oxygen at the pipe surface followed by reduction of iron scale, release of ferrous, iron, Fe(II) and oxidation of the ferrous to red ferric, Fe(III), iron in the bulk water. Conditions in Lake Pelham and blending of surface water and groundwater may influence dissolved oxygen levels in the distribution system.

Chloride increases iron release and is believed to diffuse through iron scale layers to the porous interior (Lytle et al, 2005). Chloride concentrations increased in finished water at the Culpeper WTP following the change from alum to PACl for coagulation, whereas chloride levels in the Town's groundwater sources are relatively low.

Silicates present in source water can lead to the formation of a protective iron scale and reduce the corrosion rate (AWWA and DVGW, 1996; Tang et al, 2018). Relatively high levels of naturally occurring silica are present in the Town's groundwater sources, which may provide benefits for iron corrosion in areas supplied with groundwater. Orthophosphate can significantly reduce iron release into drinking water (Lytle et al, 2005) and polyphosphate can sequester dissolved iron to reduce the potential for discolored water (USEPA, 2016). Sequestration treatment with polyphosphate, which is added at each treatment facility in Culpeper, may mask the appearance of discolored water but may not decrease the iron corrosion rate (McNeill et al, 2001). However, excess polyphosphate can increase levels of soluble levels of lead and copper in some cases (Cantor, 2000).

2.1.3 Distribution System Legacy Deposits

Iron and manganese entering the distribution system from water treatment facilities, even at low levels, can contribute to the formation of deposits. As these deposits form gradually over a period of years or decades, they are commonly termed "legacy deposits". Brandhuber (2013) described that "a utility with legacy manganese in their distribution system cannot predict upcoming releases, and, as a result, is typically in response mode... the utility might not know there is a problem until receiving customer complaints."

Legacy deposits can be formed by either chemical or biological processes in the distribution system. Oxidation of dissolved manganese by free chlorine in the bulk water causes formation of manganese particles, which can settle in the distribution system to create deposits of loose particles. Distribution system mains containing significant iron corrosion scale or tuberculation enhance the potential for deposition of particles. Chemical oxidation can also create formation of manganese coatings on distribution system surfaces (Tobiason et al, 2016). Chemical oxidation and deposition can occur when the free chlorine concentration is above approximately 0.2 mg/L (Brandhuber, 2013). Biological accumulation of iron and manganese by biofilm can also occur, especially with chlorine residuals less than approximately 0.2 mg/L, which can occur at pipe walls within tuberculated pipe sections.

Water quality, especially pH and oxidation reduction potential, influences the oxidation state and formation of legacy deposits. Water quality changes can cause shifts between insoluble iron and manganese species (Brandhuber, 2013). Changes in the pH and oxidation reduction potential can occur at the pipe surface or with scale or deposit layers, creating conditions at the pipe-water interface that can destabilize manganese legacy deposits and result in release of soluble manganese.

Hydraulic disturbances in the distribution system can also cause release of loose deposits in the distribution system due to sudden velocity changes, flow reversals, large demands (e.g. fire flow), main breaks, or distribution system maintenance activities.

Legacy deposits in the distribution system can be removed by unidirectional flushing, water main cleaning (e.g. pigging or swabbing), and pipe replacement (Friedman et al, 2010; Brandhuber, 2013).

2.1.4 Strategies for Managing Corrosion and Legacy Deposits

Stabilizing water quality and hydraulic conditions can be an effective strategy for managing the release of distribution system deposits. **Table 2-1** summarizes factors impacting iron corrosion and the stability and release of legacy deposits and describes stabilization strategies to control release. Consistent corrosion control treatment can reduce the potential for discoloration and release of legacy deposits. Blending of surface water and groundwater in the distribution system provides unique challenges than can impact release of deposits due to changes in water quality and system hydraulics (Friedman et al, 2010).

Optimization of system operation to address these strategies provides an opportunity for the Town to reduce the risk of legacy deposit release in the distribution system.

Table 2-1. Stabilization Strategies to Manage Corrosion and Legacy Deposits

Water Quality Characteristic	Impacts on Corrosion or Mobilization of Legacy Deposits	Town of Culpeper Conditions
Provide a stable pH within the distribution system (± 0.2 units)	Formation of pipe scale and stability of deposits are highly sensitive to pH. Low pH, and particularly variable pH can increase likelihood for iron corrosion and release of legacy deposits.	pH in the distribution system is variable. WTP finished water pH has shown significant variability, and groundwater well pH is generally lower than desired.
Provide a stable oxidation-reduction potential (ORP) within the distribution system ($\pm 20\%$)	Stability of formed scales is dependent on ORP, which is a function of pH and oxidant (i.e. chlorine and dissolved oxygen) concentrations. Once formed, scales are susceptible to release with high variability in ORP.	Stable free chlorine residuals were observed in the distribution system. Potential ORP differences between groundwater and surface water and variability in the distribution system
Provide a stable orthophosphate concentration within the distribution system ($\pm 20\%$)	Orthophosphate can react with common inorganic elements to produce precipitates that may serve as accumulation sinks or low-solubility passivation layers. In either case, it is important to maintain a near-constant concentration to promote stability of these solids.	Orthophosphate doses provided at the surface WTP are different than doses at the groundwater facilities. Variable orthophosphate levels observed at the WTP.
Provide adequate corrosion control	Optimized and consistent corrosion control chemical feed can reduce the formation of iron corrosion scale and tubercles, leading to reduced occurrence of red water episodes.	Evidence of iron corrosion byproduct release from tuberculated iron mains, which can cause water discoloration.
Avoid uncontrolled blending of surface water and groundwater	Groundwater and surface water supplies typically have very different water quality profiles, including mineral/ionic distribution, NOM concentrations, and ORP. The uncontrolled blending, or periodic switching back-and-forth, of these different source types can prevent formation of stable corrosion scales and contribute to the release of existing scales and associated contaminants.	Culpeper's Groundwater and Surface Water sources regularly blend throughout the distribution system. Blending patterns vary depending on demands and system operations.

Adapted from Friedman et al. 2010

2.2 Background on Taste and Odor

A wide variety of compounds can cause unpleasant tastes and odors in drinking water. Drinking water tastes and odors have been classified into a common industry lexicon presented in the taste and odor wheel (**Figure 2-1**) which summarizes the wide variety of potential taste and odor issues in drinking water and typical flavor descriptors.

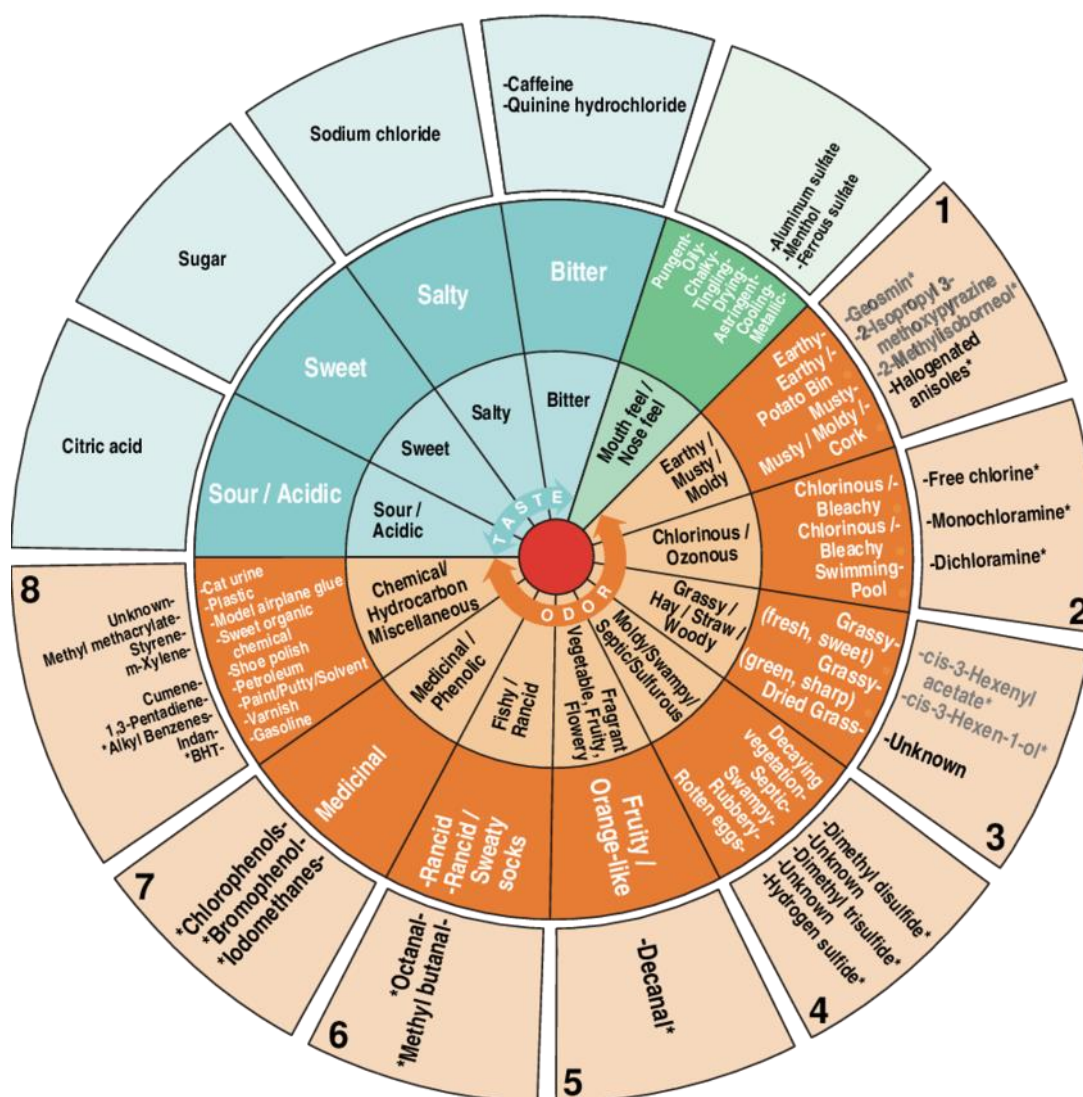


Table 2-2. Typical Taste and Odor Compounds Associated with Biological Growth in Surface Water

Compound	Source Water Organisms	Odor
Geosmin	Actinomycetes and Cyanobacteria	Earthy
MIB	Actinomycetes and Cyanobacteria	Musty
Isopropyl meth-oxypyrazine	Actinomycetes	Potato-bin musty
Cadinene-ol	Actinomycetes	Woody/earthy
trans, cis-2,6-nonadienal	Algae	Cucumber
B-Cyclocitral	Cyanobacteria	Tobacco-like
n-Hexanal and n-heptanal	Flagellated algae diatoms	Fishy
trans, cis-2,4-decadienal	Flagellated algae	Cod liver oil
2-trans,4-cis,7-cis-decatrienal	Algae	Fishy/cod liver oil

2.2.2 Taste and Odor Associated with Chlorination

While the presence of free chlorine in drinking water at typical levels creates a noticeable taste and odor, compounds with a strong chlorinous odor can be formed during free chlorine disinfection. Compounds causing chlorinous odors include free chlorine, dichloramine, and trichloramine, which can be formed during free chlorine application in the presence of background ammonia. Dichloramine and trichloramine can create a strong “swimming pool” odor.

Additional compounds affecting taste and odor can occur as a byproduct of reactions between free chlorine and organic compounds, including the formation of chlorophenols. Chlorophenols have been described as having a “medicinal” or “antiseptic” taste and odor (Roche et al, 2007), as noted in the taste and odor wheel. Chlorophenols can convert to chlorinated anisols in the distribution system, which can also cause “earthy or moldy” taste and odor issues (Roche et al, 2007).

2.2.3 Taste and Odor Compounds Derived from the Distribution System

Release of metals in the distribution system, such as iron, to drinking water can cause a noticeable metallic taste. Additional taste and odor issues can occur as a result of biological growth in the distribution system. Despite the presence of a disinfectant residual in treated water, distribution systems contain biofilm on the pipe wall, and certain microorganisms, such as iron reducing bacteria and sulfate reducing bacteria, can cause taste and odor problems (AWWA, 2004). Tuberculation, rough pipe corrosion scales, sediment deposits, and low flow areas in distribution systems create an environment to harbor biofilms providing protection for biological growth from disinfectants in the bulk water. In addition, reactions between disinfectant residuals and biofilm in the distribution system can result in taste and odor issues (Geldreich and LeChevallier, 1999).

3. Water Quality Analysis

Historical water quality and treatment data provided by the Town was compiled and evaluated to investigate possible water quality drivers of discoloration, taste and odor, and hardness aesthetic concerns in the Culpeper system.

The following sections present an evaluation of water quality data associated with source water, treatment, and distribution focused on water discoloration, which is commonly caused by iron and manganese.

3.1 Iron Data Analysis

Since iron can contribute to water discoloration, an analysis of the Town's iron data associated with raw water, finished water, and distribution system was performed. Consumer reports of brown and red water in the Town are consistent with water discoloration associated with iron.

3.1.1 WTP Raw Water Iron Levels

Iron levels in raw water are monitored routinely in the raw water sample point at the WTP. **Figure 3-1** presents historical raw water iron concentrations entering the WTP from Lake Pelham. The average raw water iron concentration is approximately 0.6 mg/L. Generally, iron levels in Lake Pelham are not elevated, although periods of elevated raw water iron levels have occurred, in summer 2018.

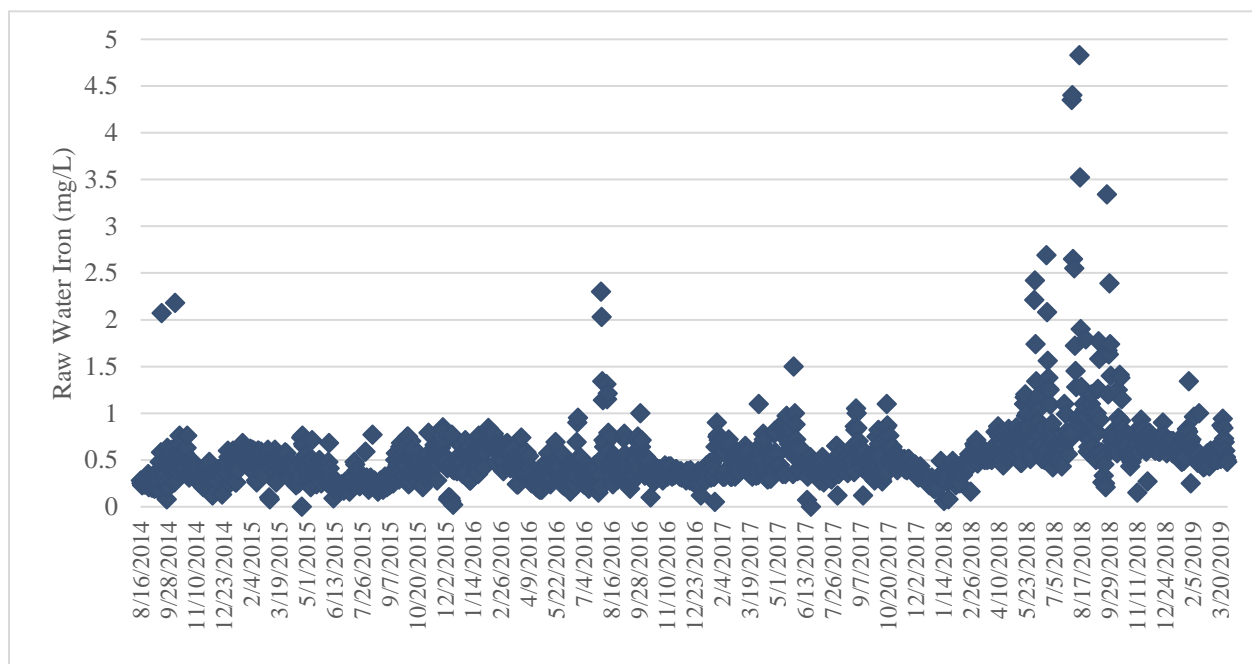


Figure 3-1. Raw Water Iron Concentrations at the WTP

3.1.2 WTP Finished Water Iron Levels

Finished water iron concentrations at the WTP are presented in **Figure 3-2**. Iron has been effectively removed at the WTP, including the period in summer 2018 when raw water iron levels were elevated, and finished water iron levels have been below 0.1 mg/L since 2017. Short-term intermittent levels of iron in WTP finished water occurred between 2014 and 2016, and may have contributed legacy deposits to the system. The levels of iron in finished water at the WTP since 2017 have been greatly reduced, and are not likely to contribute to water discoloration in the distribution system.

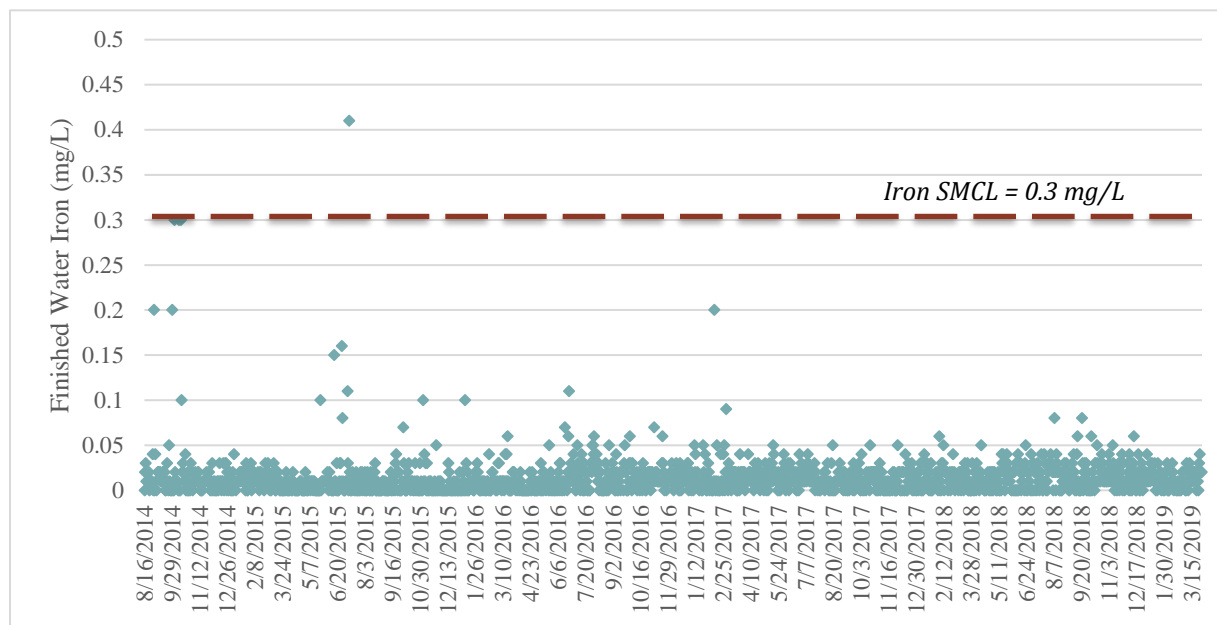


Figure 3-2. Finished Water Iron Concentrations at the WTP

3.1.3 Groundwater Iron Levels

Table 3-1 presents raw water iron levels at each groundwater facility, indicating that iron concentrations are generally low in the groundwater and have remained below the SMCL of 0.3 mg/L. Additional trends on groundwater iron concentrations are presented in **Appendix D**, **Appendix E**, and **Appendix F**.

Table 3-1. Summary of Raw Groundwater Iron Levels

Facility	Iron Concentration (mg/L, Average and Range)
Chandler Street	0.03 (0 – 0.29)
Nalles Mill	0.02 (0 – 0.14)
Rockwater Park	0.04 (0 – 0.23)

As iron removal treatment is not necessary at the groundwater treatment facilities, finished water iron concentrations are consistent with and directly impacted by raw groundwater levels. The low levels of

iron present in finished water at the Town's groundwater treatment facilities do not significantly contribute to water discoloration in the system.

3.1.4 Distribution System Iron Levels

Since iron levels in finished water at the WTP and groundwater sources have been consistently below the SMCL, iron discoloration at the tap could occur through release of legacy deposits, corrosion of iron mains, or corrosion of iron premise plumbing materials.

As part of the monthly distribution system sampling for chlorine residuals, the Town also proactively collects water quality data on pH, alkalinity, hardness, turbidity, iron, and manganese. Iron levels observed in the Town's routine monthly distribution system monitoring have been below the SMCL in 99.5% of samples.

For routine distribution system monitoring from September 2016 to March 2019, out of 575 samples taken, only three samples, listed in **Table 3-2**, had iron concentrations over the secondary MCL of 0.3 mg/L.

Table 3-2. Summary of Iron Levels in Monthly Distribution System Monitoring

Distribution System Site	Date	Iron Concentration (mg/L)
110	2/22/2017	0.46
120	6/27/2018	0.34
170	3/28/2017	0.62

The Town has also collected distribution system water samples in response to customer complaints. Samples are typically collected at the meter to characterize the water in the distribution system. The iron concentrations in this dataset are generally higher than those collected during routine monthly distribution system monitoring. **Figure 3-3** presents the number of samples by the Town in response to complaints with iron concentrations over the SMCL by month. The increased number of samples collected during 2018 coincided with the timing of ice pigging in Oaklawn and conversion to polyaluminum chloride at the WTP, although the quantity of samples may not directly correlate to discolored water episodes due to differences in customer reporting patterns and Town staff responses.

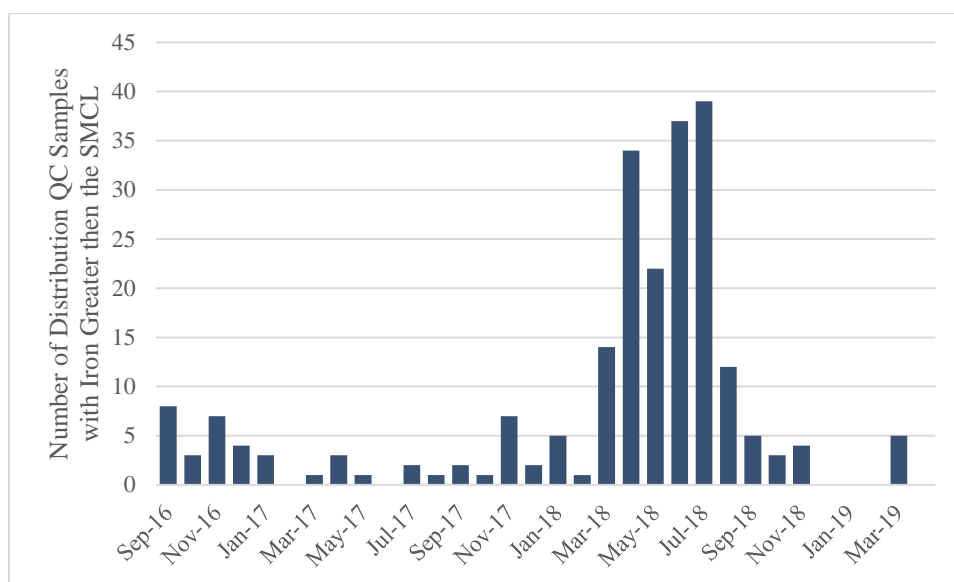


Figure 3-3. Distribution System Samples in Response to Customer Complaints with Iron Concentrations Greater than the SMCL

Table 3-3 presents statistics for the distribution system samples collected in response to customer complaints. Approximately 40% of samples collected in response to customer complaints had iron levels over the SMCL, versus only 0.5% of samples in routine monitoring. The observed levels of iron above the SMCL may cause water discoloration. While iron is not typically present in routine distribution system monitoring, episodic release of iron corrosion byproducts may contribute to customer complaints.

Table 3-3. Observed Distribution System Iron Levels in Response to Customer Complaints

Statistic	Iron Concentration (mg/L)
5 th Percentile	0.01
Median	0.2
95 th Percentile	2.1

3.1.5 Summary of Iron Data Analysis

Iron is a naturally occurring element present in the Town's surface water. The Culpeper WTP effectively removes iron, and finished water iron levels have been consistently below the SMCL. Iron levels in groundwater sources are consistently low. Elevated iron levels in the distribution system have been intermittently observed and may contribute to water discoloration. The cause of elevated iron in distribution system samples is likely release from distribution system legacy deposits, corrosion of iron mains or disturbance of existing scale, and corrosion of iron in premise plumbing systems may also affect water discoloration.

3.2 Manganese Data Analysis

Since manganese can contribute to water discoloration, the Town's manganese data associated with source water, treatment, and distribution was also analyzed, and the results are presented in this section. This section also presents an evaluation of treatment processes for manganese removal.

3.2.1 Raw Water Manganese Concentrations

Figure 3-4 presents historical raw water manganese levels at the WTP, which are measured at the WTP using Hach Method 8149. As permanganate contains manganese and is added prior to the raw water sample point, chemical addition influences the observed raw water manganese concentration. Observed raw water manganese levels vary seasonally due to source water changes and permanganate dose changes, and can be very elevated.

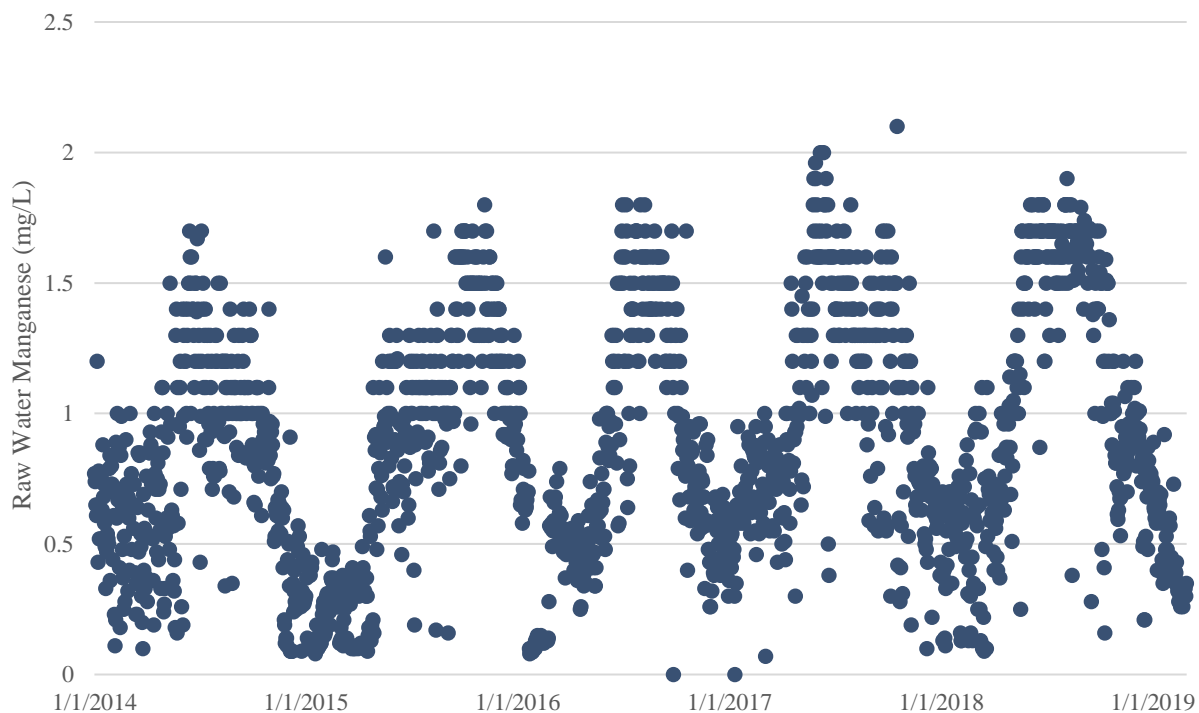


Figure 3-4. Raw Water Manganese Concentrations at the WTP

3.2.2 WTP Finished Water Manganese Levels

Figure 3-5 presents historical daily average finished water manganese levels recorded at the WTP according to Hach Method 8149. Manganese concentrations have only exceeded the SMCL of 0.05 mg/L on approximately 3% of days since 2008. Observed manganese concentrations in finished water have exceeded the manganese treatment goal of 0.02 mg/L on approximately 37% of days. Manganese levels in 2018 were slightly higher compared to recent years. Based on prior research and industry guidance on

manganese removal, the observed finished water manganese levels could allow episodic water discoloration issues and gradual accumulation of manganese legacy deposits in the distribution system.

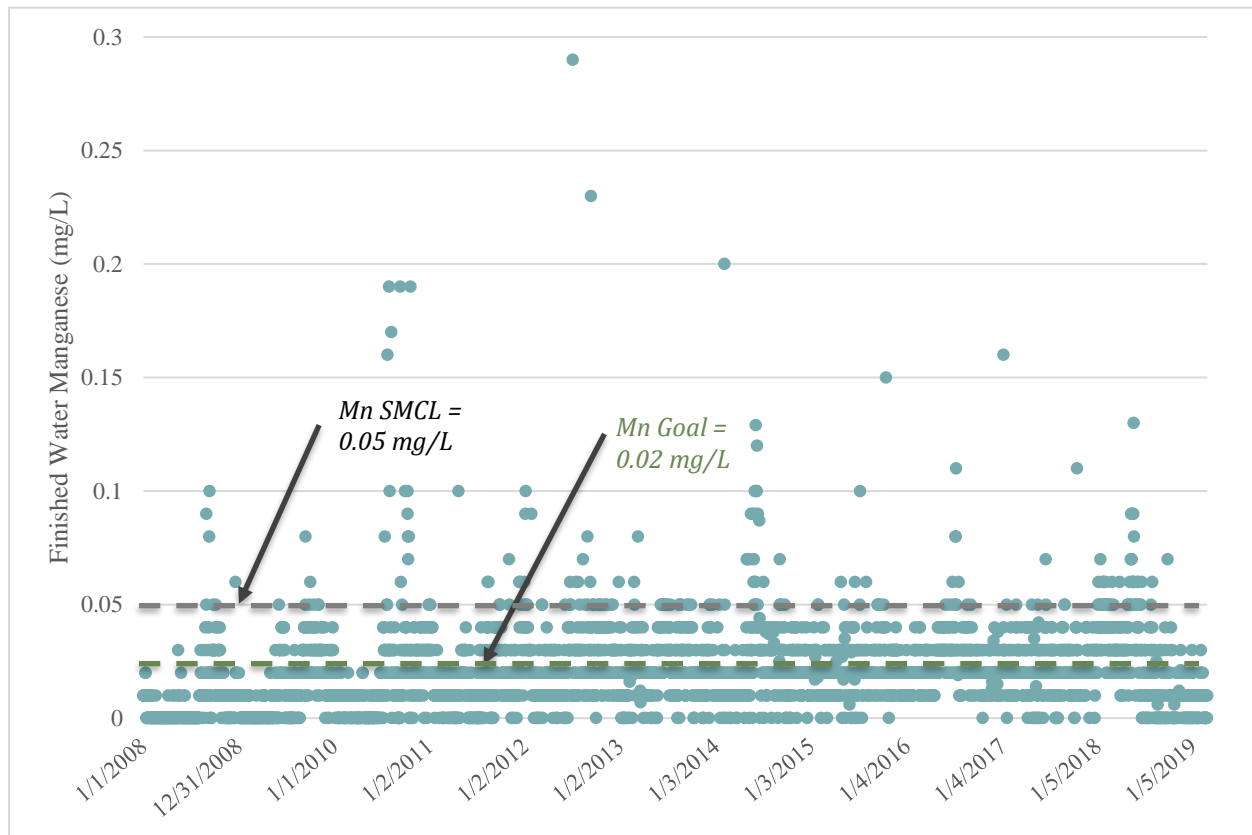


Figure 3-5. WTP Finished Water Manganese Levels

The Town has tested manganese levels according to the Hach Method 8149 using a Hach laboratory spectrophotometer, which is a common industry method for process monitoring of manganese. To verify the accuracy of this method for quantifying manganese concentration, the Town conducted comparative sampling for manganese in October 2019. Manganese concentrations obtained using the Hach method in the Town's water treatment laboratory were compared to third-party laboratory results using EPA Method 200.7 and EPA Method 200.8, which are accepted methods for analyzing manganese concentrations according to the Code of Federal Regulations §143.4. In samples with manganese levels less than approximately 0.05 mg/L, manganese results obtained using EPA Method 200.8 were lower than the Hach method by approximately 13% to 38%, with an average difference of 0.008 mg/L. These initial results suggest that the Hach method historically used by the Town may overestimate actual manganese concentrations in finished water at the WTP. The Hach method offers a rapid and low cost testing procedure, and its continued use will be necessary for process control. Additional periodic manganese testing using the EPA 200.8 method is recommended to verify manganese concentrations.

To further examine the potential impacts of this difference between manganese test methods, historical finished water manganese concentrations at the WTP obtained by Hach Method 8149 were adjusted by 0.008 mg/L, which was the average difference with EPA Method 200.8. **Figure 3-6** presents a

comparison of historical finished water manganese data obtained by Hach Method 8149 and adjusted manganese levels, representative of EPA Method 200.8. The adjusted manganese concentrations exceeded the SMCL of 0.05 mg/L on approximately 2.5% of days and the manganese treatment goal of 0.02 mg/L on approximately 32% of days since 2008. Additional comparative sampling between methods over a longer period of time (e.g. monthly testing for at least 12 months) would be necessary to confirm the magnitude of difference between methods.

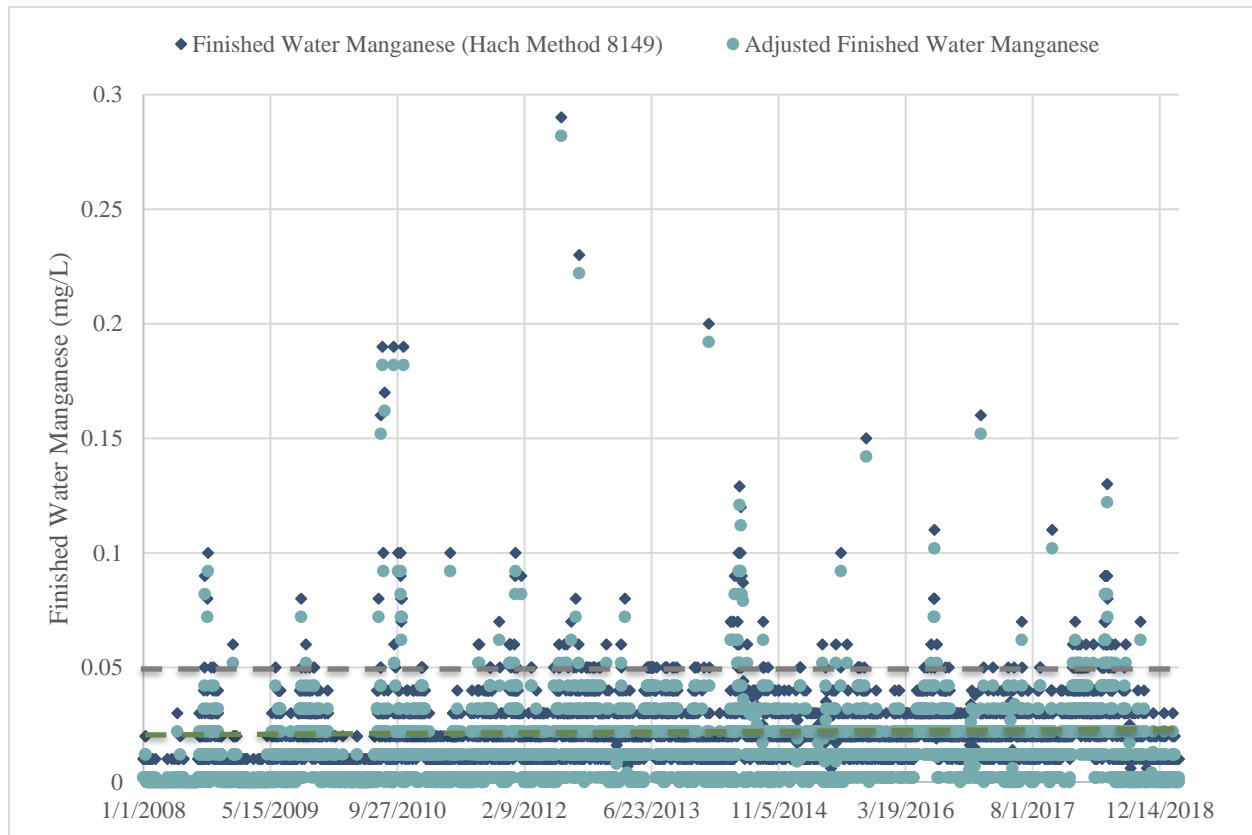


Figure 3-6: Comparison of WTP Historical and Adjusted Finished Water Manganese Levels

3.2.3 Groundwater Manganese Levels

Table 3-4 summarizes observed manganese levels in the groundwater treatment facilities based on the Town’s daily manganese monitoring data, obtained with Hach Method 8149, since startup of each facility. For the Chandler Street and Nalles Mill groundwater facilities, which contain multiple wells, these values represent the average manganese concentration in the combined well flow. Manganese levels vary among individual wells, and well operation rates can affect observed combined manganese levels.

Table 3-4. Raw Groundwater Manganese Levels

Statistic	Manganese Concentration (mg/L)			
	Chandler Street (Jan 2015 – July 2018) ¹	Chandler Street (Aug 2018 – April 2019) ²	Nalles Mill	Rockwater Park
25 th Percentile	0.04	0.02	0.01	0.01
Median	0.05	0.03	0.01	0.02
75 th Percentile	0.06	0.03	0.02	0.02
95 th Percentile	0.07	0.05	0.04	0.03
99 th Percentile	0.10	0.08	0.08	0.04
Maximum	0.36	0.08	0.12	0.06

Notes:

1. Manganese testing from January 2015 to July 2018 was conducted by Hach Method 8149 without the use of Rochelle salt to correct for hardness interference.
2. Manganese testing after August 2018 was conducted with the use of Rochelle salt to correct for hardness interference as recommended in Hach Method 8149.

The highest apparent manganese levels were observed at the Chandler Street well facility, and analysis of individual well data indicated that well C-1 typically has the highest manganese levels at this facility.

Figure 3-7 presents observed historical manganese concentrations at Chandler Street. Manganese was tested in the Chandler Street groundwater in 2012 during well development, and observed manganese levels were less than 0.008 mg/L.

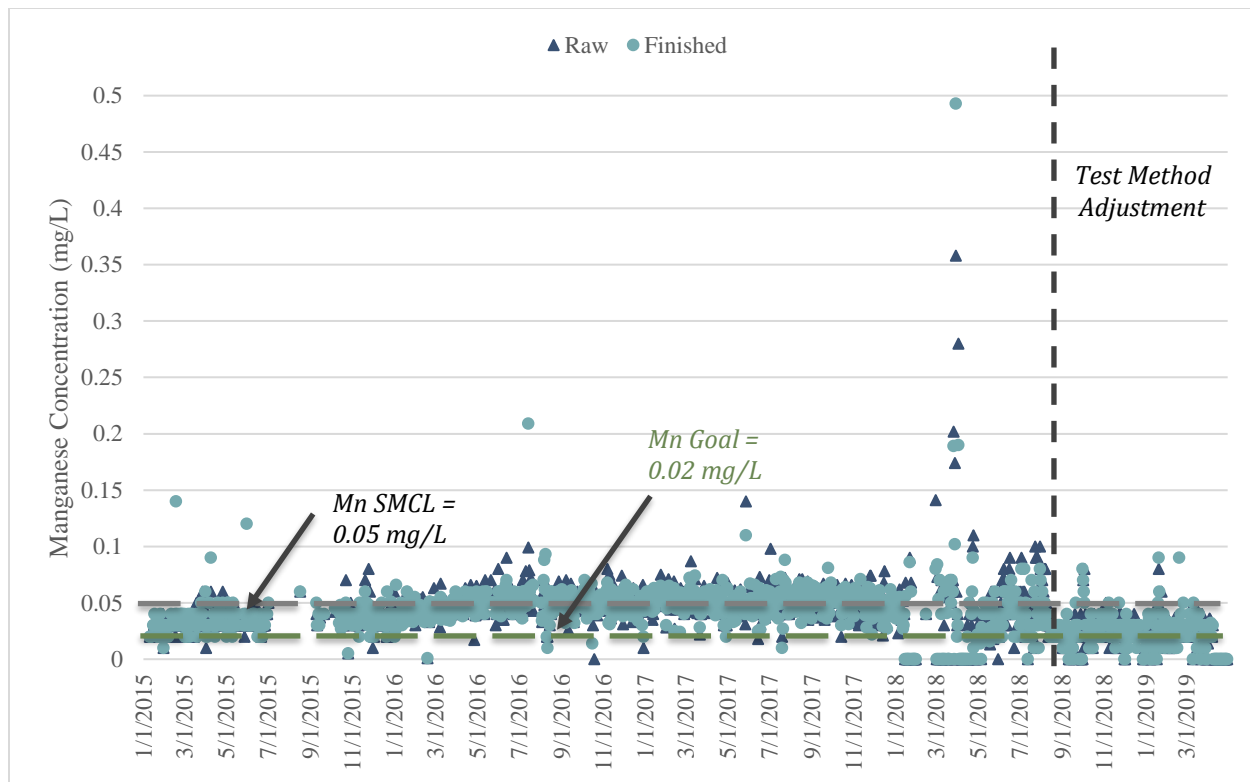


Figure 3-7. Manganese Concentrations at the Chandler Street Groundwater Facility

The Hach Method 8149 indicates that the following interferences by several substances present in groundwater may affect observed manganese levels, including: calcium above 1,000 mg/L as CaCO_3 , magnesium above 300 mg/L as CaCO_3 , and hardness above 300 mg/L as CaCO_3 . Individual calcium and magnesium levels in groundwater at Chandler Street are below the respective interference levels, but the total hardness typically exceeds 300 mg/L as CaCO_3 at Chandler Street.

Due to the hardness interference, the Hach Method 8149 indicates to add four drops of “Rochelle Salt Solution” to samples with hardness above 300 mg/L as CaCO_3 as part of the test procedure. In accordance with the Hach procedure, the Town began adding Rochelle salt solution to manganese samples at Chandler Street with total hardness greater than 300 mg/L as CaCO_3 , which decreased observed manganese concentrations. **Figure 3-7** indicates the approximate date when the test procedure was adjusted to include Rochelle Salt, which corresponded to a decrease in observed manganese concentrations. As a result, it is expected that observed manganese concentrations prior to 2018 may have been higher than actual values due to the absence of Rochelle salt in the test procedure.

Due to the reported interference affecting observed manganese concentrations at Chandler Street, additional analysis was performed to investigate test methods. Hach was contacted to request additional technical details and clarifications on reported interferences for Method 8149, but additional clarifying information was not provided. Samples were collected from Chandler Street (individual wells C-1, C-3, and C-6) and Nalles Mill combined flow for comparison of manganese levels between different test methods. Manganese test results using Method 8149 with and without Rochelle salt were compared with

laboratory tests at two certified laboratories according to EPA Methods 200.7 and 200.8 (**Table 3-5**). Hardness levels at Nalles Mill were lower than the interference level reported by Hach, above which application of Rochelle salt is recommended by Hach. Tests were conducted at Nalles Mill with and without Rochelle Salt to further investigate the impacts of this solution on test results with moderate hardness. Observed manganese levels in groundwater were lower in laboratory tests conducted by inductively coupled plasma methods compared to Hach Method 8149.

Table 3-5. Comparison of Manganese Test Methods

Source	Manganese Hach Method 8149		Manganese (mg/L)		Calcium (mg/L as CaCO ₃)	
	No Rochelle Salt	4 Drops Rochelle Salt Solution	Lab A	Lab B	Lab A	Lab B
Well C-1	0.328	0.228	0.0074	0.048	653	625
Well C-3	0.012	0.029	0.0345	<0.005	328	350
Well C-6	0.199	0.064	0.0126	<0.005	258	275
Nalles Mill Combined	0.258	0.066	0.0009	<0.005	137	140

Notes:

1. Analysis at Lab A per EPA Method 200.8
2. Analysis at Lab B per EPA Method 200.7

It is recommended that the Town collect samples of groundwater from each Chandler Street well, Nalles Mill, and Rockwater Park on a monthly basis to be analyzed for manganese at a certified lab according to the inductively coupled plasma method. Results should be tracked over time and correlated with recorded daily values from Hach Method 8149. Collection of baseline manganese data according to standard EPA methods will provide improved data quality to track manganese levels at Chandler Street.

3.2.4 Distribution System Manganese Levels

Manganese concentrations reported in the Town's distribution system monitoring data have occurred at levels that are representative of potential episodic water discoloration. Manganese concentrations in the distribution system were intermittently higher than typical finished water concentrations, providing evidence of potential cyclic manganese accumulation and release from distribution system legacy deposits.

A total of 575 distribution system samples were collected from September 2016 to April 2019 over 20 sites and analyzed for manganese using the Hach 8149 method. Twenty-five distribution system samples (4%) experienced manganese concentrations greater than the SMCL. **Figure 3-8** presents the number of manganese concentrations greater than the SMCL at each distribution system sampling location. **Figure B-1** in **Appendix B** presents a map of manganese SMCL exceedances at these locations, indicating that SMCL exceedances were distributed throughout the system. Fifty percent of the observed manganese concentrations in the Town's monthly distribution system monitoring were greater than the goal of 0.02 mg/L.

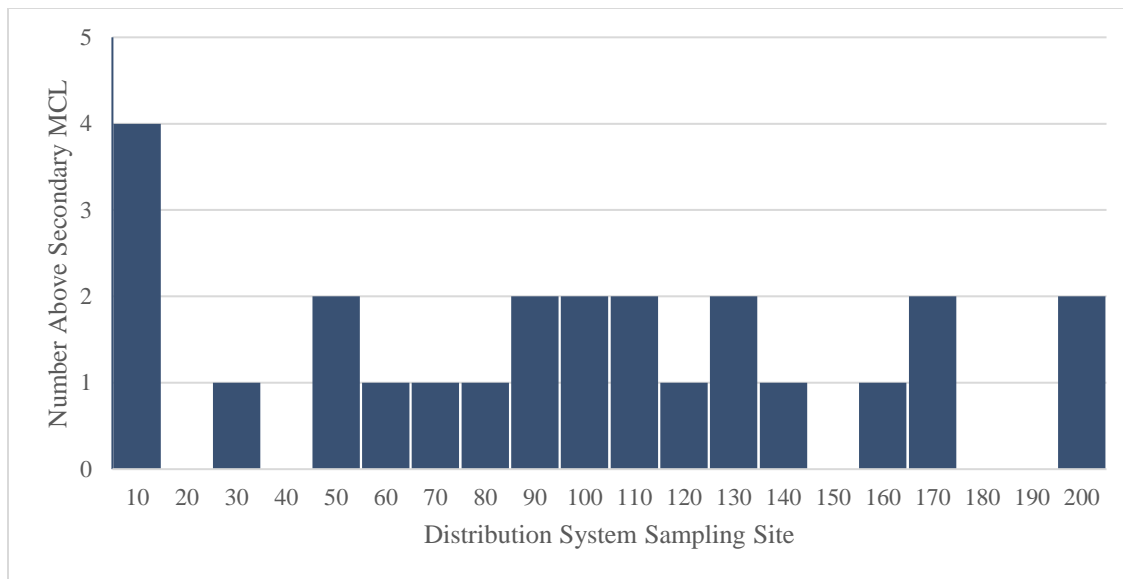


Figure 3-8. Number of Distribution System Samples with Manganese Concentrations Greater than SMCL

Distribution system sampling site 10 is located near the WTP (**Figure B-1**) and experienced the highest quantity of manganese levels above the SMCL in the Town's routine distribution system monitoring according to Hach Method 8149. **Figure 3-9** presents observed manganese concentrations at Site 10 in comparison to finished water manganese levels at the WTP. Elevated concentrations of manganese above finished water levels were occasionally observed, providing evidence of cyclic manganese accumulation and release in the distribution system. Observed manganese levels at this site have decreased since 2018. Similar trends with infrequent spikes in the manganese concentration were observed at other distribution system sites, and additional data on distribution system manganese levels is presented in **Appendix B**.

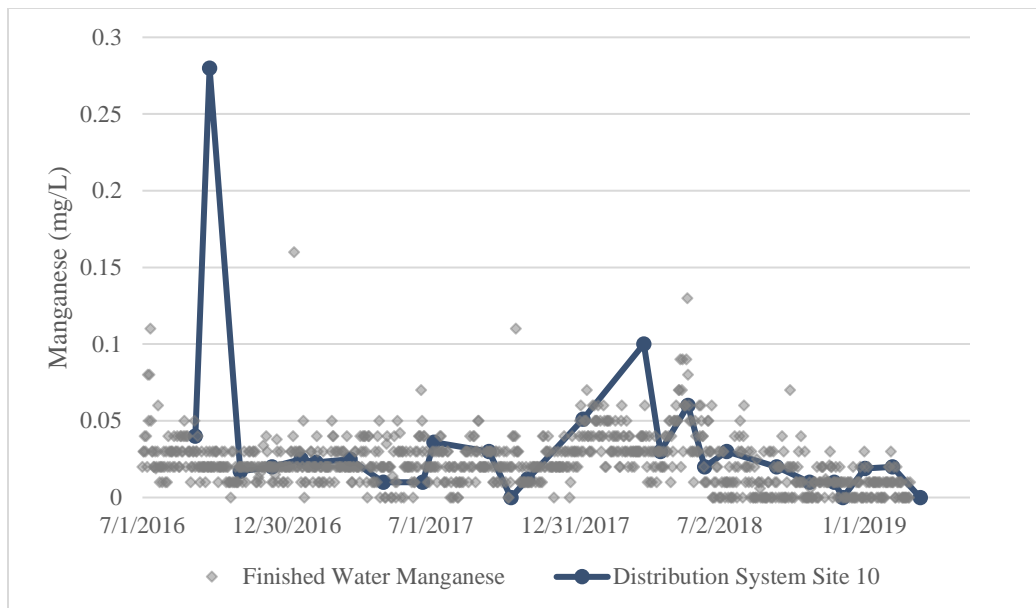


Figure 3-9. Manganese Concentrations at Distribution System Site 10

From September 2016 to April 2019, the Town collected 604 samples in response to consumer complaints, and samples were typically collected at the meter. **Figure 3-10** presents the number of samples greater than the SMCL for manganese per month. Approximately 27% of samples collected in response to customer complaints had manganese concentrations greater than the SMCL of 0.05 mg/L, and approximately 70% had manganese concentrations greater than the goal of 0.02 mg/L, as measured by Hach Method 8149.

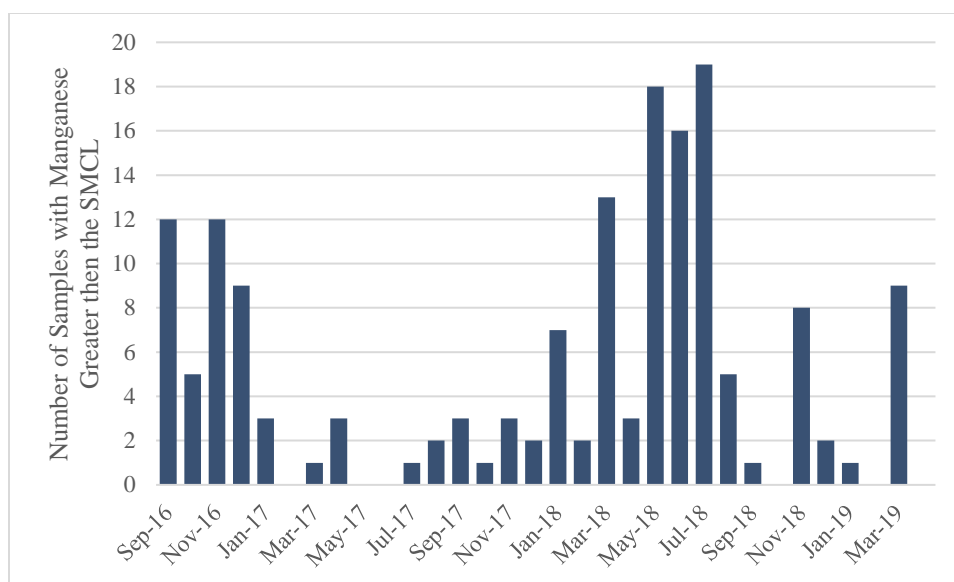


Figure 3-10. Distribution System Samples in Response to Customer Complaints with Manganese Concentrations Greater than the SMCL

Table 3-6 summarizes the manganese levels for samples collected by the Town in response to customer complaints. Manganese levels were above the goal of 0.02 mg/L in approximately 75% of samples tested for manganese, indicating the manganese is a key factor influencing customer reports of water discoloration.

Table 3-6. Distribution System Samples in Response to Customer Complaints – Manganese Statistics

Statistic	Manganese Concentration (mg/L)
5 th Percentile	0.01
25 th Percentile	0.02
Median	0.03
75 th Percentile	0.06
95 th Percentile	0.23

3.2.5 Summary of Manganese Data Analysis

Manganese is a naturally occurring element present in the Town’s surface water. Levels in Lake Pelham elevate episodically and can be at times very high. The Culpeper WTP regularly meets treatment goals for manganese removal, but historical observations have indicated occasional higher levels of manganese in finished water, potentially leading to legacy deposits in the system. Manganese levels in groundwater sources are relatively low based on independent laboratory testing coordinated by Hazen and Sawyer; however, the Town should consider routine laboratory testing of manganese in groundwater using the inductively coupled plasma method, as high hardness levels can interfere with the accuracy of the Hach 8149 method. A review of manganese levels in the distribution system describe intermittent levels above the treatment goal and SMCL, suggesting the potential for water discoloration due to cyclic accumulation and release of manganese legacy deposits.

3.3 Taste and Odor

The most common categories of taste and odor complaints reported by customers in the Town of Culpeper include “earthy/musty/moldy” (wheel category 1) and “chlorinous” or “swimming pool” (wheel category 2). Utilities are typically not able to monitor for each taste and odor compound until the likely source of the issue has been identified through analysis of customer reports or Flavor Profile Analysis. As a result, limited data was available from the Town to directly quantify tastes and odors. The Town has reported seasonal algae growth in Lake Pelham, but data characterizing the speciation and quantity of algae was not available for review. This section presents a qualitative evaluation of factors that may contribute to tastes and odors reported by customers in the Town and analysis of available treatment process data related to control of potential taste and odor compounds.

3.3.1 Powdered Activated Carbon

Powdered activated carbon is added at the WTP which can adsorb certain compounds causing unpleasant tastes and odors in addition to other organic compounds. Powdered activated carbon is removed in the clarification and filtration processes to remove sorbed compounds from finished water. The WTP was designed with a carbon feed location prior to the rapid mix, providing limited contact time for carbon adsorption prior to coagulation, which can reduce powdered activated carbon adsorption efficiency due to enmeshment in floc. The concentration of natural organic matter may influence the necessary PAC dose for removal of taste and odor compounds.

Historical powdered activated carbon doses at the WTP are presented in **Figure 3-11**. Powdered activated carbon has only been added to raw water prior to the rapid mix. Addition of powdered activated carbon may provide benefits for removal of taste and odor compounds from surface water, such as MIB and geosmin. However, additional data would be necessary to analyze the optimal carbon dose and feed location necessary to remove taste and odor compounds from surface water.

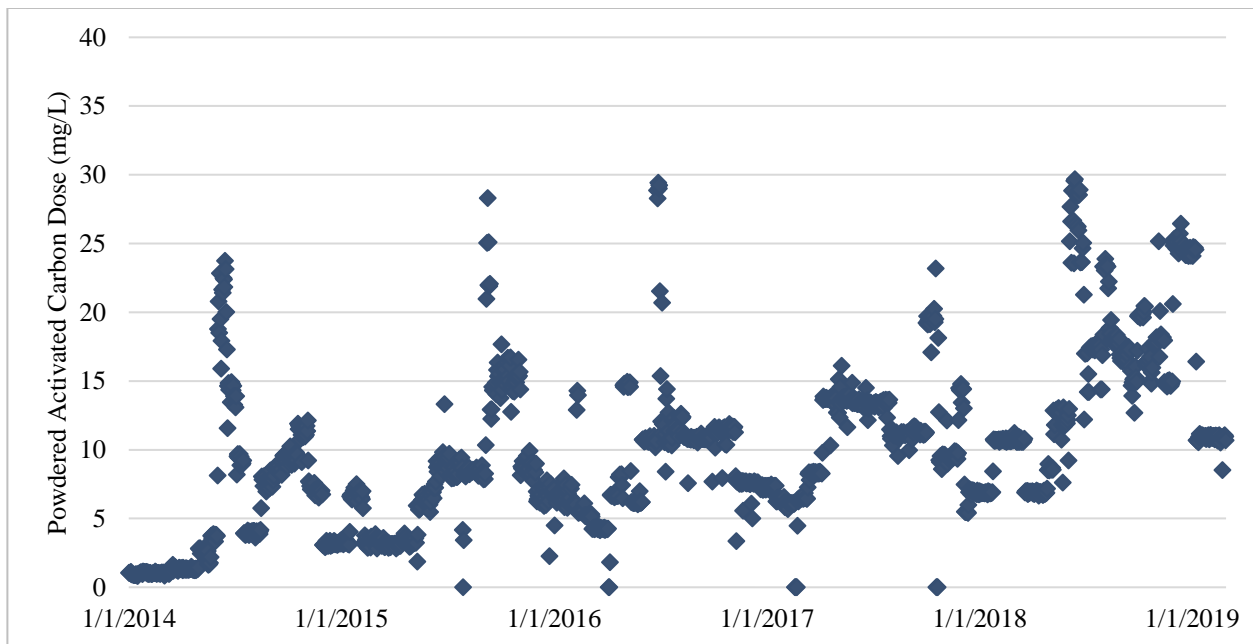


Figure 3-11. WTP Powdered Activated Carbon Dose to Raw Water

3.3.2 Chlorine Data Analysis

Reported taste and odor complaints have described a strong chlorine taste and odor, and consumers have expressed concerned about perceived high levels of chlorine. The USEPA has established a maximum chlorine concentration in drinking water of 4 mg/L.

Chlorine is added for disinfection at each of the Town's treatment facilities. **Table 3-7** summarizes free chlorine levels at the point-of-entry to the distribution system for each facility. Chlorine residuals in the distribution system were consistent with these levels and decrease in portions of this system with high water age.

Table 3-7. Daily Average Point-of-Entry Free Chlorine Residuals

Facility	Average Chlorine Residual (mg/L, Average and Range)
WTP	1.9 (1.1 – 3.0)
Chandler Street	1.65 (0.62– 7.57 ¹)
Nalles Mill	1.58 (1.00 – 2.18)
Rockwater Park	1.52 (0.90 – 2.20)

1. Three daily finished water chlorine residuals greater than 4 mg/L were reported. Corresponding reported chlorine doses were below 4 mg/L.

The observed levels of free chlorine in the Town are within acceptable levels for drinking water and are appropriate for maintaining a residual throughout the system to protect public health. A noticeable taste and odor may be present at these levels of free chlorine, as noted on the taste and odor wheel (category 2).

3.3.3 Source Water Ammonia and Organic Compounds

Raw water from Lake Pelham contained 0.11 mg/L as N of ammonia and 1.1 mg/L as N of total organic nitrogen based on a grab sample collected in July 2019 (**Table 3-8**). Depending on the chlorine and ammonia doses, ammonia present in source water may cause formation of di- or trichloramine. The observed organic nitrogen compounds may contribute to formation of organochloramines that could affect water taste and odor. In WTP testing conducted during July 2019, approximately 0.3 to 0.4 mg/L of combined chlorine was present in addition to free chlorine in the filter influent and the filter effluent. While free chlorine was mostly consumed in the filters, combined chlorine persisted in the filter effluent. Combined chlorine may consist of dichloramine, trichloramine, and organochloramines, which could cause noticeable chlorinous taste and odor at the measured concentrations.

Table 3-8. WTP Raw Water Nitrogen Levels (July 31, 2019)

Parameter	WTP Raw Water
Ammonia (mg/L as N)	0.11
Total Organic Nitrogen (mg/L as N)	1.1

Additionally, raw water from Lake Pelham contains 3 to 7 mg/L of total organic carbon, and reactions between free chlorine and organic compounds could form odorous byproducts of chlorination such as chlorophenol, as noted on the taste and odor wheel. Although chlorophenols are typically characterized by a “medicinal” taste or odor, there are a variety of chlorophenol compounds that could affect chlorinous water complaints in the Town. The presence of chlorophenols in the Town of Culpeper has not been tested. The Town should consider analyzing raw water samples for phenol and finished water samples for chlorophenol species with gas chromatography (EPA Method 604) to quantify these compounds, especially in response to chlorinous taste and odor reports.

3.3.4 Taste and Odor Summary

As is common for situations involving unpleasant water tastes or odor, limited data is available to characterize precise causes of taste and odor complaints. The analysis suggests that algae growth in Lake Pelham and naturally occurring nitrogen compounds may influence taste and odor issues. Such odors can potentially be addressed through PAC addition, which the Town has historically added at the WTP, algae management, which the Town currently performs with a peroxide-based algaecide, in-situ reservoir treatment, or advanced treatment processes. Additional PAC studies and optimization may provide an opportunity to augment the Town’s current efforts for taste and odor control. Additional taste and odor issues may arise in the distribution system or in private premise plumbing systems, and these issues can often be addressed through routine flushing.

3.4 Hardness

Hardness does not have a SMCL based on USEPA standards but can affect aesthetic qualities of the water. Water hardness quantifies the combined concentration of calcium, magnesium, and certain other cations. According to the World Health Organization, hardness measures “the capacity of water to react with soap, hard water requiring considerably more soap to produce a lather.” High levels of hardness can cause scaling or deposits on fixtures.

Table 3-9 presents generally accepted hardness ranges according to the World Health Organization. Total hardness (e.g. combined calcium and magnesium) is typically presented in terms of milligrams per liter of calcium carbonate (CaCO_3).

Table 3-9. Typical Water Hardness Ranges

Category	Concentration (mg/L as CaCO_3)
Soft	<60
Moderately Hard	60-120
Hard	120-180
Very Hard	>180

The hardness levels vary among water sources in the Town of Culpeper. **Table 3-10** presents typical observed hardness levels at each water source. The WTP produces soft water due to the characteristics of surface water in Lake Pelham. The groundwater wells produce hard water, and the highest hardness levels occur in the Chandler Street wells. Hardness is a result of natural groundwater characteristics, and hardness levels in the Town could be reduced by decreasing groundwater usage (especially at Chandler Street) or by constructing water softening treatment facilities.

Table 3-10. Town of Culpeper Water Hardness Levels

Water Source	Average Total Hardness (mg/L as CaCO_3)	Hardness Category
WTP	49	Soft
Chandler Street	374	Very Hard
Nalles Mill	171	Hard
Rockwater Park	155	Hard

Based on over 2,000 groundwater samples across the country, the median total hardness was 162 mg/L as CaCO_3 , and the 90th percentile total hardness was 370 mg/L as CaCO_3 (Cotruvo et al, 2017). Groundwater hardness in the Town of Culpeper is generally above the national median. The observed hardness levels in the Town of Culpeper are consistent with consumer reports about aesthetic impacts of hardness.

Customers located near the Chandler Street wells are likely to experience the highest hardness levels, although hard water may sometimes enter other portions of the distribution system depending on system operations. **Figure 3-12** presents historical hardness levels in groundwater at Chandler Street. Hardness was tested in Chandler Street groundwater during well development in 2012, and observed hardness levels in the three wells ranged from 110 to 220 mg/L as CaCO_3 . Groundwater hardness levels have increased during operation of the Chandler Street facility.

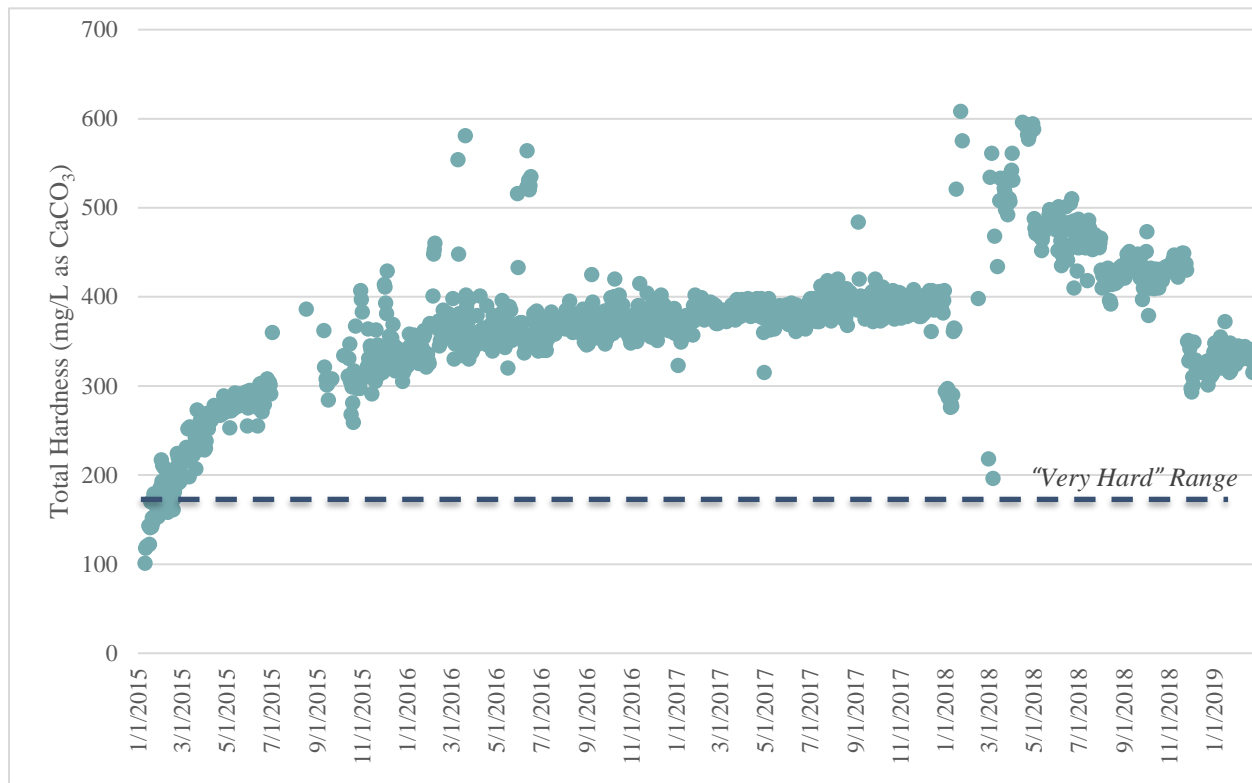


Figure 3-12. Total Hardness Levels in Groundwater at Chandler Street

In some cases, hardness can contribute to the potential for scaling in the distribution system. Calcium reacts with carbonate species in the water to form insoluble calcium carbonate scale. Low levels of calcium carbonate supersaturation, as defined by a calcium carbonate precipitation potential of approximately 4-10 mg/L as CaCO_3 is often recommended for distribution system stability and iron main corrosion control (AWWA, 2017). However, higher CCPP values can cause excessive levels of scaling and contribute to loss of hydraulic capacity and valve operational problems.

The calcium carbonate precipitation potential (CCPP) was calculated based on average water quality conditions to characterize the potential for calcium carbonate scaling. **Table 3-11** presents typical estimated CCPP values for each source. The resulting CCPP values indicate that the water is not expected to form calcium carbonate scales in the distribution system. Despite the high calcium concentrations in groundwater, especially at the Chandler Street wells, precipitation of calcium carbonate is limited by the low carbonate concentrations in the system at the typical pH. Precipitation of calcium carbonate could occur at higher pH levels.

Table 3-11. Town of Culpeper Average CCPP Values

Water Source	Average CCPP (mg/L as CaCO ₃)
WTP	-8.8
Chandler Street	-4.2
Nalles Mill	-12.3
Rockwater Park	-24.9

Hardness levels in the distribution system were analyzed as an indicator of blending between surface water, with low hardness, and groundwater, with high hardness. **Figure B-3 in Appendix B** presents average hardness levels at each monitoring location. Lower average hardness levels were generally observed in the western portion of the distribution system near the WTP, and higher hardness levels occur in the eastern portion of the distribution system near the Chandler Street and Nalles Mill facilities. Based on the geospatial analysis of hardness levels, the apparent midpoint of the blending zone between groundwater and surface water occurs in the vicinity of sample sites 80, 100, 110, and 120, located in the downtown area, which show variable hardness levels in monthly sampling. For example, **Figure 3-13** presents observed hardness levels at Site 100 (located near 100 West Davis Street), illustrating fluctuations between low and high hardness levels from different water sources.

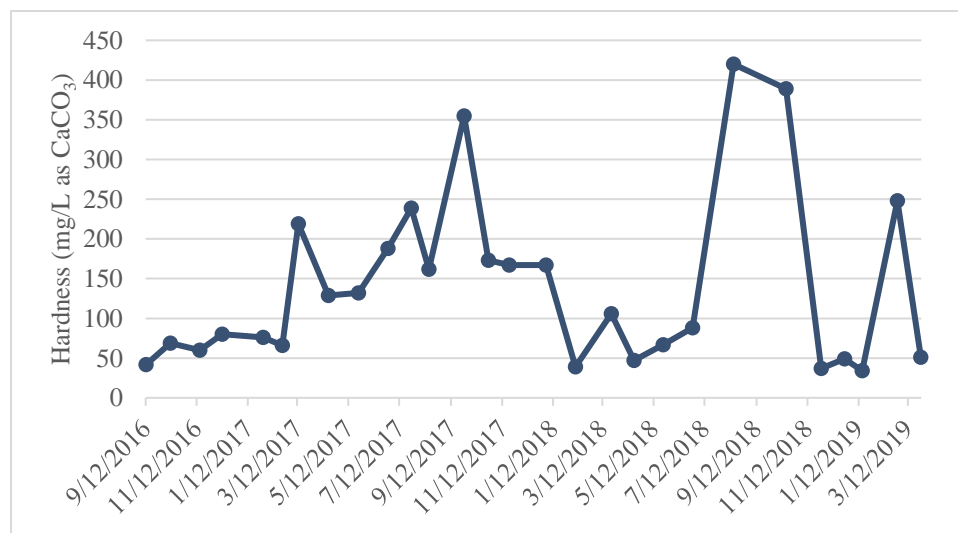


Figure 3-13. Total Hardness Levels at Distribution System Sampling Site 100

In summary, high hardness levels are present in the Town's groundwater sources, especially at the Chandler Street facility. Despite the high calcium hardness levels, calcium scale formation in the distribution system is not anticipated at the typical historical pH and alkalinity levels. Blending of sources waters in the distribution system results in variable hardness levels throughout the system. High hardness in certain portions of the distribution system may affect water aesthetics (e.g. the feel of water with soap).

4. Treatment Process Data Analysis

Recognizing episodic elevated levels of iron and particularly manganese in Lake Pelham, a review of available WTP process data was performed to characterize removal of iron and manganese, which can contribute legacy deposits to the system. Additionally, corrosion control practices at each of the Town's treatment facilities can potentially contribute to reducing iron corrosion in the distribution system. Therefore, a review of Town's corrosion control practices at each facility was also performed.

4.1.1 Oxidation of Iron and Manganese

The WTP adds potassium permanganate to the raw water to support iron and manganese removal at the WTP. The WTP has the facilities to add permanganate to the raw water near the Lake Pelham dam and just prior to the rapid mix basin at the WTP. Addition of permanganate to the raw water pipeline at the chemical facility near the dam provides approximately 16 minutes of contact time at a flow rate of 4 MGD before raw water reaches the rapid mix, which provides a suitable opportunity for oxidation of dissolved iron and manganese prior to coagulation. Oxidized particulate iron and manganese are removed in the clarifiers.

Figure 4-1 presents historical permanganate doses, and these values represent the combined dose added to raw water at both feed locations. Permanganate doses have varied seasonally and exceeded 20 mg/L during the summer of 2018.

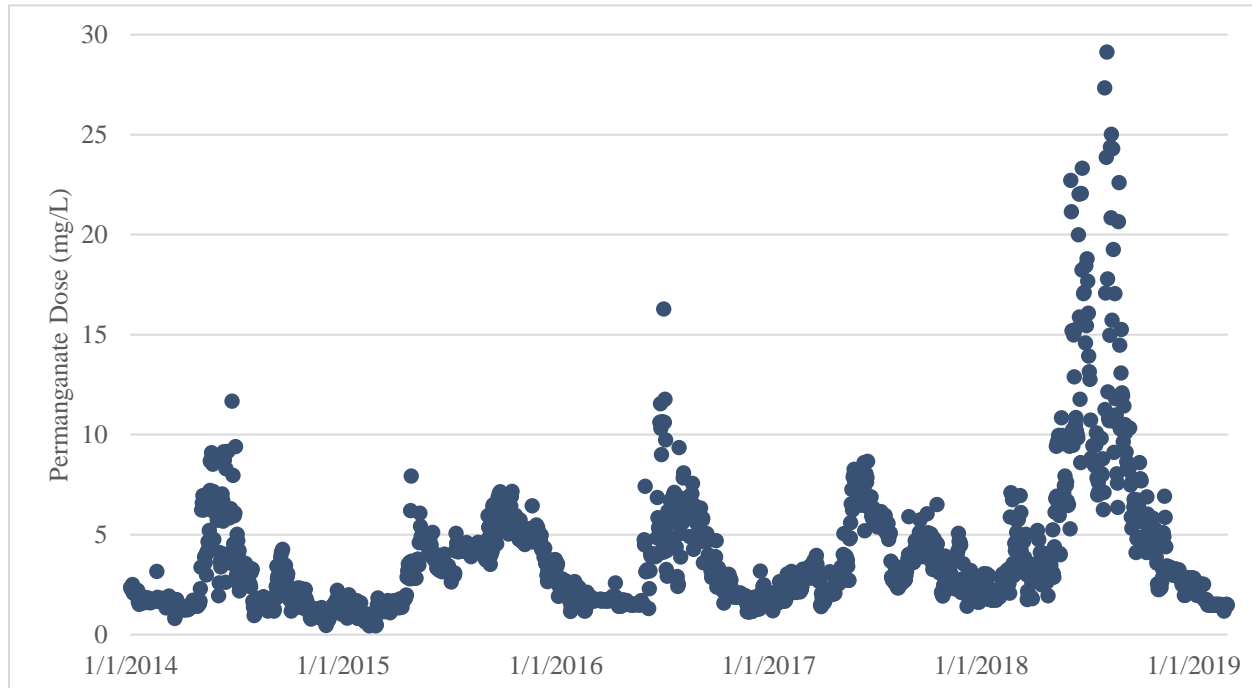


Figure 4-1. Historical WTP Permanganate Doses

4.1.2 Filter Performance

The filters provide an additional barrier for iron and manganese removal, including any particulate manganese released from the sludge blanket clarifiers. Free chlorine is an effective oxidant for dissolved iron, and addition of free chlorine to the filter influent will also help to maintain effective iron removal at the WTP. Dissolved manganese can also be removed through sorption to manganese-oxide coated filter media in the presence of free chlorine (i.e. the “induced greensand effect”). Filter operational and performance data were analyzed due to the importance of filtration for discolored water control.

A filter effluent chlorine residual of approximately 0.5 mg/L is often needed to promote catalytic sorption of dissolved manganese to oxide-coated filter media. The WTP adds free chlorine to the combined filter influent channel and monitors the chlorine residual in the filter influent shortly after chlorine injection. The WTP adds additional chlorine for disinfection in the filter effluent weir chamber and measures the chlorine residual shortly after chlorine injection as well as in finished water. However, the WTP design does not include provisions for monitoring of filter effluent chlorine residuals (i.e., the chlorine residual remaining from chlorine addition to the filter influent) prior to the addition of chlorine for disinfection. As a result, the WTP has not been equipped to monitor and control filter effluent chlorine residuals to promote dissolved manganese removal in the filters.

Figure 4-2 presents the chlorine dose and measured residuals for the filter influent. Prior to 2017, the WTP typically added a chlorine dose of 0.1 to 0.5 mg/L to filter influent. These minimal chlorine doses were likely not sufficient to continuously promote sorption of manganese to filter media. Filter influent chlorine doses were increased starting in 2017 and were particularly high the summer of 2018. Despite this increase in chlorine doses during 2018, measured chlorine residuals near the injection point remained consistent.

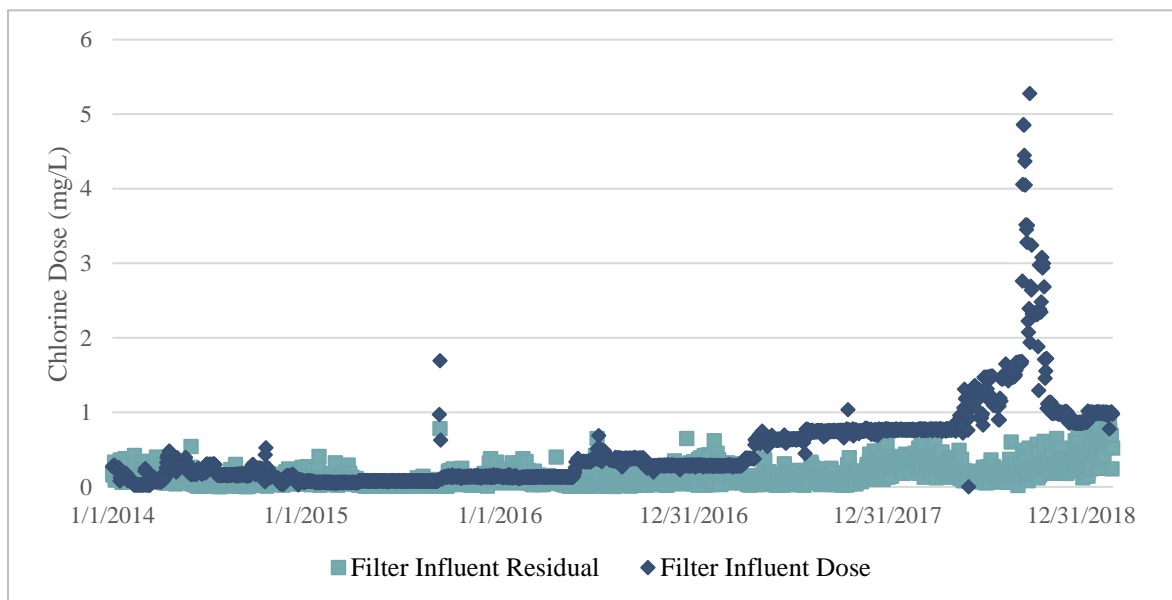


Figure 4-2. WTP Historical Filter Influent Chlorine Dose and Residual

4.1.3 WTP Process Data Analysis Summary

The WTP process data analysis approach was focused on aspects of the treatment process related to iron and manganese removal, including pre-oxidation of dissolved iron and manganese with permanganate, and filtration. Permanganate is an effective oxidant for iron and manganese, but addition of permanganate may contribute to accumulation of manganese in the sludge blanket, which could be episodically released under reducing water quality conditions, and contribute to periodic manganese breakthrough. Chlorine doses applied to the filters have historically often been below levels typically needed to support sorption of dissolved manganese in the filters, possibly contributing to historical (pre-2017) manganese breakthrough and system legacy deposits. Increasing pre-filter chlorine doses, subject to confirmation of DBP impacts, could provide an opportunity to further enhance iron and manganese removal.

4.2 Corrosion Control Treatment

Water quality and corrosion control treatment influence corrosion of aging distribution system mains, service lines, and plumbing materials. While corrosion of iron distribution materials can result in discolored water, corrosion of plumbing materials containing lead and copper can release these metals into drinking water causing serious health concerns for consumers. In addition to analyzing iron corrosion throughout the Culpeper water system, optimizing lead and copper corrosion control was also evaluated.

The 90th percentile lead and copper levels in the Town have historically been below the Action Levels. Recommendations for optimizing corrosion control must balance treatment objectives for iron corrosion control while minimizing lead and copper release. Key water quality parameters affecting corrosion control in the distribution system were analyzed and include pH, alkalinity, dissolved inorganic carbon (DIC), orthophosphate, chloride, sulfate, silica and aluminum.

4.2.1 Finished Water pH, Alkalinity, and Dissolved Inorganic Carbon (DIC)

Adjusting the pH and/or alkalinity is a common corrosion control strategy that can be used to decrease lead, copper, and iron release. The pH, alkalinity, and dissolved inorganic carbon (DIC) affect the formation and solubility of internal corrosion scales that influence corrosion of distribution system and premise plumbing materials. In systems with an orthophosphate corrosion inhibitor, the optimum pH range for orthophosphate effectiveness for lead and copper corrosion control is typically 7.2 to 7.8 (USEPA, 2016). Low levels of alkalinity/DIC (e.g. DIC below about 5 mg/L as C) can increase lead release (Edwards et al, 1999; USEPA, 2016), and very high DIC levels can interfere with the effectiveness of orthophosphate for lead corrosion control. Higher levels of pH and alkalinity/DIC decrease iron corrosion by-product release and the potential for red water. In situations with iron corrosion concerns, corrosion control treatment strategies must be carefully balanced to simultaneously address lead, copper, and iron corrosion.

Table 4-1 summarizes the pH, alkalinity, and DIC levels for finished water at each source in the Town of Culpeper. The DIC is typically not directly measured and was calculated based on observed pH and alkalinity levels. The pH levels are generally similar between sources, and the average pH is consistent

with USEPA guidelines for systems using orthophosphate for corrosion control. Alkalinity and DIC levels are generally higher in groundwater than surface water. The wide variation in alkalinity and DIC may influence corrosion processes and destabilize corrosion scales in the system.

Table 4-1. Summary of Finished Water pH, Alkalinity, and DIC Levels

Parameter	WTP	Chandler Street	Nalles Mill	Rockwater Park
pH	7.4 (6.8 – 7.9)	7.4 (7.2 – 7.7)	7.3 (6.8 – 7.8)	7.1 (6.4 – 7.7)
Alkalinity (mg/L as CaCO ₃)	24.7 (11 – 55)	64.4 (37 – 100)	93.9 (64 – 249)	100 (47 – 197)
Dissolved Inorganic Carbon (mg/L as C)	6	17	22	28

Figure 4-3 presents reported daily average pH values in finished water at the WTP. USEPA corrosion control treatment guidance includes a goal for finished water pH variability of ± 0.2 pH units. Daily average finished water pH values are often within this range, although lower pH values have been frequently observed and may affect corrosion in the distribution system.

The finished water pH is adjusted at the Town's WTP using lime, and historical lime doses are presented in **Appendix C**. The Culpeper WTP previously used soda ash for pH adjustment, which also increased the DIC of the water. The use of soda ash was replaced with lime in November 2011. Application of lime does not increase DIC and adds a low dose of calcium to the water, which promotes consistency with higher hardness levels in the Town's groundwater sources.

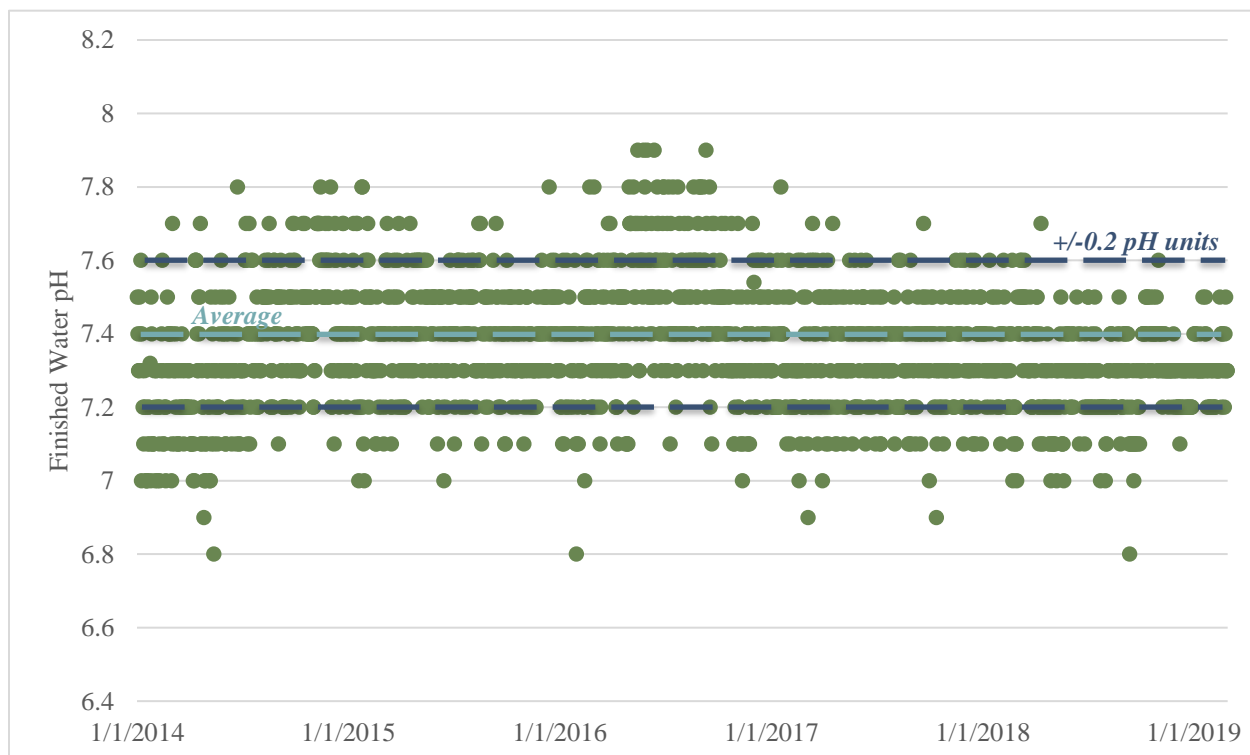


Figure 4-3. Historical WTP Daily Average Finished Water pH

The finished water pH is typically not adjusted at the groundwater treatment facilities, and the pH entering the distribution system is based on natural groundwater characteristics. **Figure 4-4** presents the historical daily average pH values at the Chandler Street groundwater treatment facility, which has the greatest production of groundwater in the system. Similar graphs for Nalles Mill and Rockwater Park facilities are presented in **Appendix E** and **Appendix F**, respectively. The pH at Chandler Street has decreased gradually since initial introduction of groundwater in 2015, and lower pH values in 2018 and 2019 may affect corrosion in the distribution system. The pH values at Nalles Mill and Rockwater Park have often been below 7.2. Although the Rockwater Park facility has been operated less than other groundwater sources, it may have contributed to lower pH levels in the Culpeper system with low finished water pH values (e.g. 6.5 to 7.0) occurring during the summer of 2018 when the facility was operated more consistently (**Figure F-1**). Analysis of groundwater quality using the Rothberg, Tamburini, and Windsor model indicated that the groundwater pH can be increased to at least 7.6 using sodium hydroxide without causing excessive calcium carbonate scaling in the distribution system.

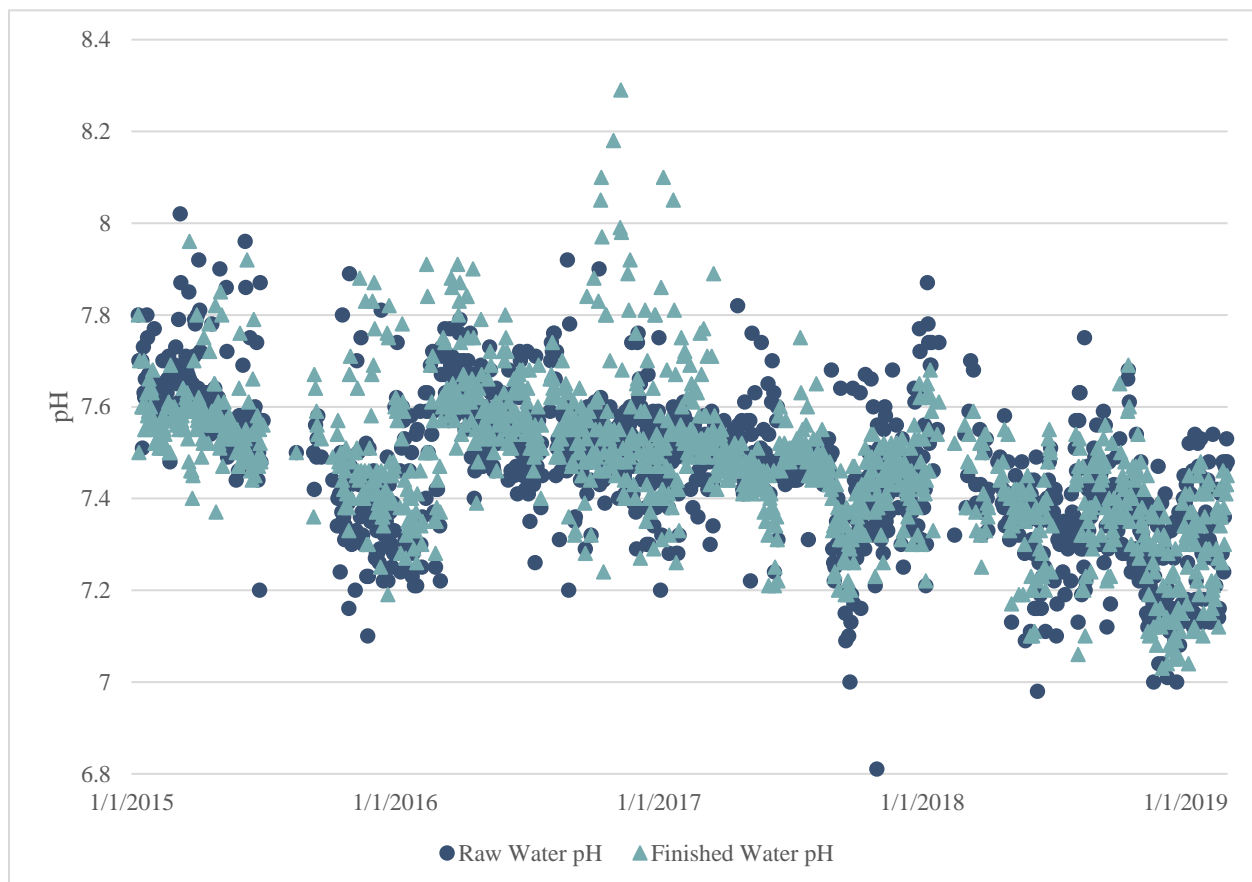


Figure 4-4. Historical Daily Average pH at the Chandler Street Facility

Alkalinity and DIC levels in the system are influenced by raw water quality characteristics from surface water and groundwater. Moderate seasonal variations in raw water alkalinity have occurred in Lake Pelham, with raw water levels generally ranging between 10 to 40 mg/L as CaCO_3 . Raw water alkalinity levels in the groundwater system has ranged between 20 and 215 mg/L as CaCO_3 . Graphs presenting historical trends for alkalinity levels in raw water and finished water at the WTP, Chandler Street, Nalles

Mill, and Rockwater Park facilities are presented in Appendix B, Appendix C, Appendix D, and Appendix E, respectively. Finished water alkalinity levels ranged between 11 and 55 mg/L as CaCO₃ for the surface water treatment system and between 37 and 249 mg/L as CaCO₃ for the groundwater system. The pH and alkalinity conditions correspond to an average finished water DIC level of 6 mg/L as C for the surface water treatment facility and between 17 and 28 for the groundwater system. The significant differences in DIC levels between sources may promote different mechanisms of corrosion control and scale formation and present challenges for the application of a unified systemwide corrosion control strategy.

4.2.2 Distribution System pH, Alkalinity, and Dissolved Inorganic Carbon (DIC)

The Town routinely monitors pH in the distribution system at 20 sites on a monthly basis in conjunction with bacteriological testing. **Figure B-2** in **Appendix B** presents average pH values observed at each site in the distribution system. The pH levels in the distribution system are variable and increase slightly in certain areas with higher water age. The lowest observed average pH values typically occur at Site 10, which is supplied primarily by the WTP. Historical pH trends for Site 10 are presented in **Figure 4-5**, indicating that low pH values (e.g. <7.2) have been intermittently observed at this location, and a wide range of pH values from 6.82 to 8.16 was observed.

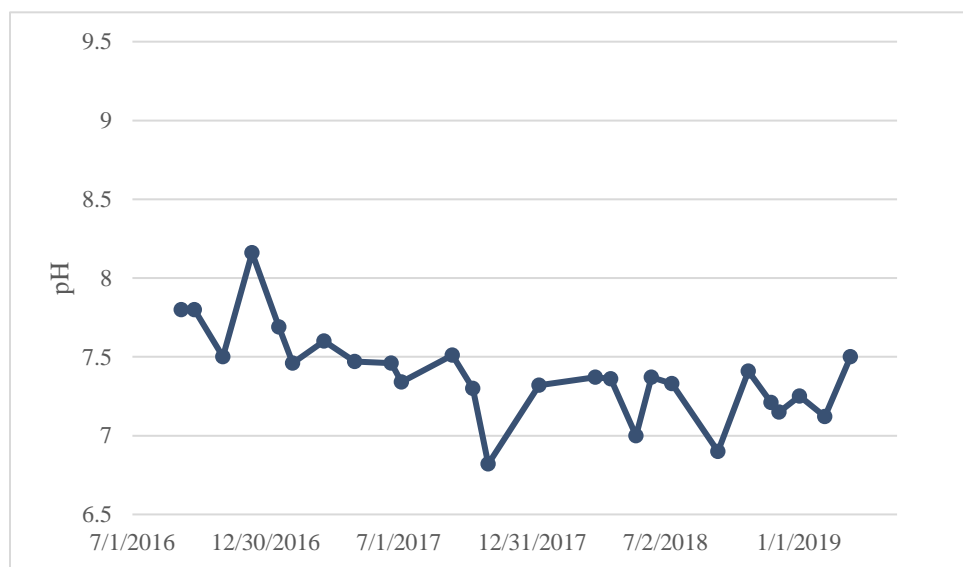


Figure 4-5. Distribution System pH at Sample Site 10

Higher pH values have been observed in areas of the distribution system with high water age. Distribution system sample site 30 is located in the southern portion of the distribution system and experiences consistently higher pH levels. **Figure 4-6** presents measured pH values at sample site 30 in the Town's monthly distribution system monitoring. Higher pH values greater than 8 may reduce the effectiveness of orthophosphate for lead corrosion control. A wide range of pH values (7.56 to 9.13) was also observed at site 30. Higher pH levels in this range (e.g. pH >8.5) may reduce iron corrosion byproduct release but may alter the effects of orthophosphate for lead corrosion control.

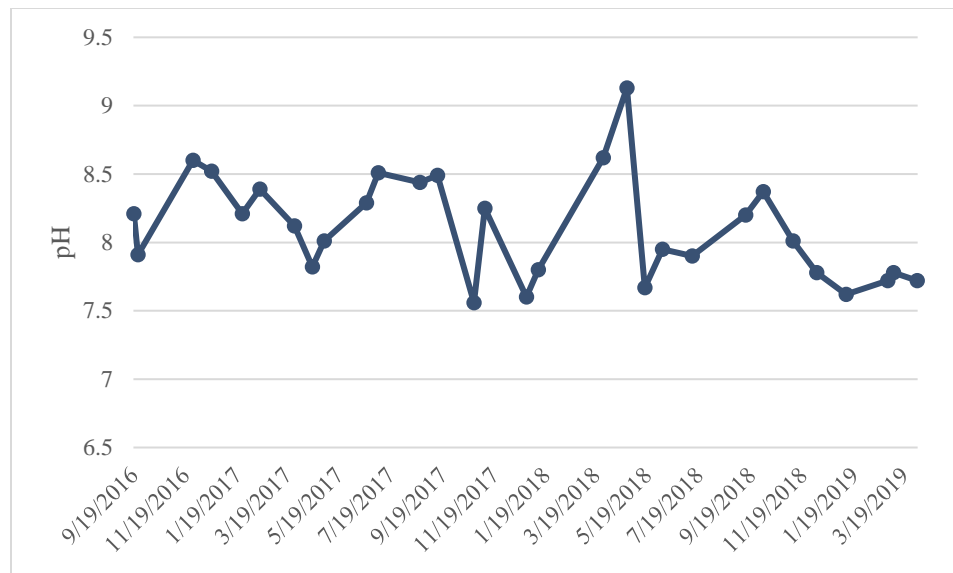


Figure 4-6. Distribution System pH at Sample Site 30

4.2.3 Orthophosphate

Orthophosphate-based corrosion inhibitors are known to be effective in controlling lead and copper release and can form a low-solubility scale on the surface of premise plumbing materials. The 2016 EPA corrosion control guidance includes a typical range of orthophosphate concentrations of 1.0 – 3.0 mg/L as PO₄ in the pH range of 7.2 to 7.8. Orthophosphate can also be effective for controlling iron release from cast iron and galvanized mains (Lytle et al, 2005; Tang et al, 2018).

The effectiveness of orthophosphate depends on many factors including the concentration, pH, DIC, and other constituents such as aluminum, iron, and manganese. Optimizing the pH is beneficial to maximize inhibitor effectiveness (Dodrill et al, 1995; Cantor et al, 2000; McNeill et al, 2002). A stable orthophosphate concentration should be maintained throughout the distribution system to ensure the effectiveness of this corrosion control treatment strategy.

Blended phosphate corrosion inhibitors contain a combination of both orthophosphate and polyphosphate and may provide a reduction in metal release (orthophosphate) as well as sequestration of metals (polyphosphate). It is important to limit the amount of polyphosphate in the blend to the concentration necessary for sequestration (i.e. iron, manganese, or calcium), as excess polyphosphate may increase soluble metal levels in drinking water.

The Town has historically used a blended phosphate corrosion inhibitor containing 50% orthophosphate and 50% polyphosphate for corrosion control at each treatment facility. The product has changed periodically due to market factors associated with annual chemical bids, and the Town has procured products from Shannon Chemical, Univar, and Coyne Chemical (**Table 4-2**). Each of these products contains 50% orthophosphate but is proprietary and may present differences in chemical characteristics and polyphosphate types.

Table 4-2. Town of Culpeper Corrosion Inhibitor Products

Year	Vendor	Product
2010	Coyne	Calgon C-4
2011	Coyne	Calgon C-4
2012	Univar	LP 1001
2013	Univar	LP 1003
2014	Univar	LP 1003
2015	Univar	Carus 8500
2016	Shannon	SLI-5250
2017	Univar	Carus 8500
2018	Shannon	SLI-5250
2019	Shannon	SLI-5250

Figure 4-7 presents historical corrosion inhibitor doses at the WTP. Corrosion inhibitor doses have been adjusted multiple times since 2014 and were particularly high in 2018. Prior to 2014, corrosion inhibitor doses added at the WTP were typically minimal (e.g. less than 0.2 mg/L as product).

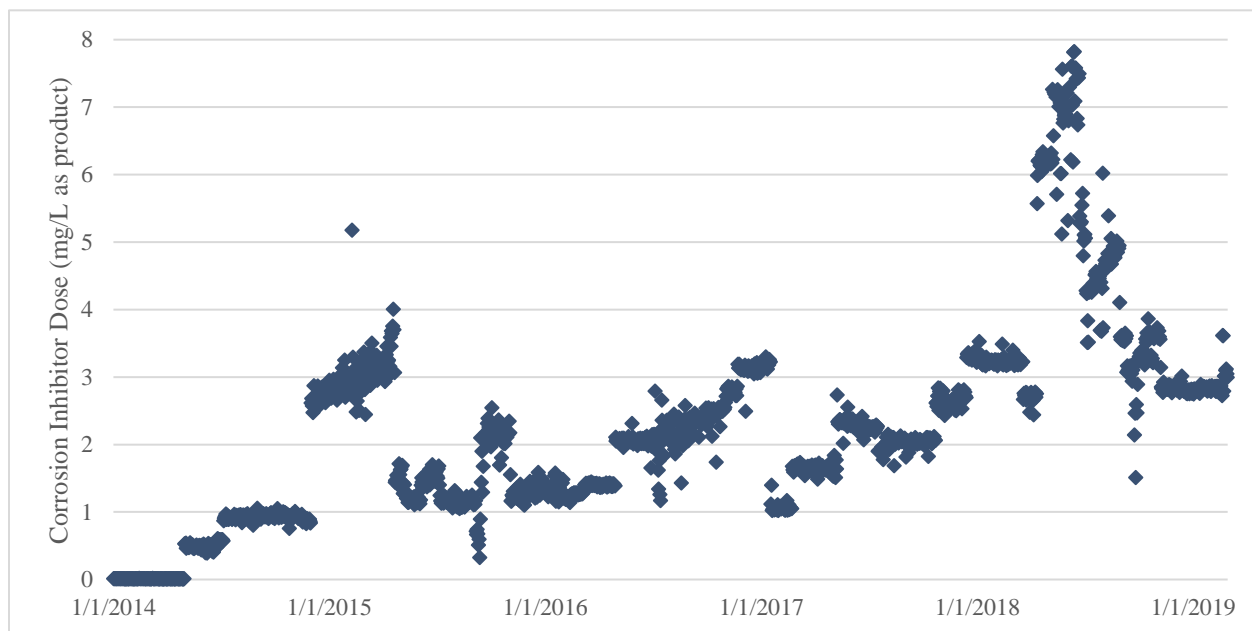


Figure 4-7. Historical Corrosion Inhibitor Doses at the WTP

Orthophosphate levels at the WTP have not been consistently measured over the last 5 years. To estimate orthophosphate levels in finished water, the orthophosphate dose added at the WTP was calculated based on the chemical strength and the reported corrosion inhibitor dose (as product). **Figure 4-8** presents a comparison of calculated orthophosphate doses to observed orthophosphate concentrations in finished water at the WTP. Reported doses of orthophosphate have often been below the range of 1 to 3 mg/L as PO_4 recommended in USEPA guidance (USEPA, 2016). However, higher levels of orthophosphate have been observed in finished water at the WTP. Elevated orthophosphate levels in finished water indicate that that equivalent polyphosphate concentrations were present in the system, which may increase soluble metals release.

During 2017 and 2018, trends in observed finished water orthophosphate concentrations were not consistent with chemical doses. This finding suggests that limitations in the chemical feed system or orthophosphate monitoring may be present. The Town should review chemical feed and orthophosphate sample tap locations and determine an optimal orthophosphate testing location to ensure consistent and accurate orthophosphate dosing at the WTP.

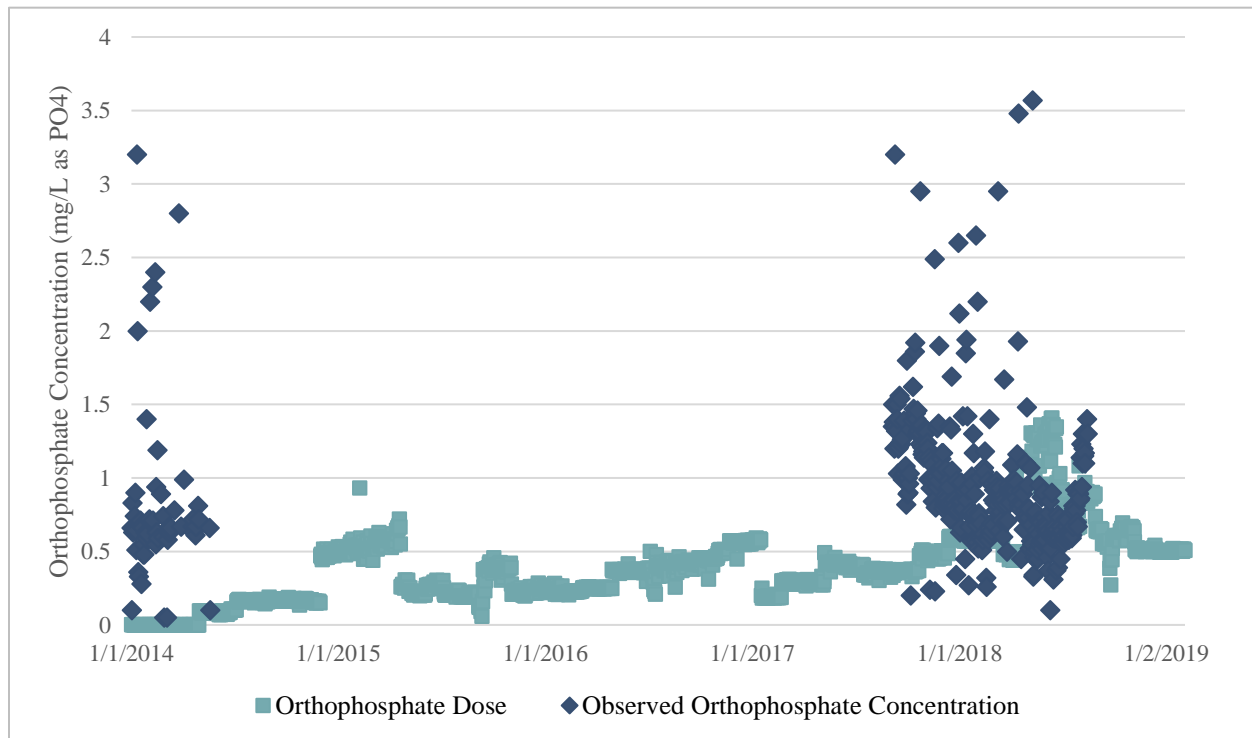


Figure 4-8. Comparison of Corrosion Inhibitor Doses to Observed Orthophosphate Concentrations at the WTP

Consistent orthophosphate concentrations in the distribution system can be promoted by ensuring equivalent corrosion inhibitor dosing at each treatment facility. **Figure 4-9** presents a comparison of reported corrosion inhibitor doses at the Town’s four treatment facilities since the startup of the Nalles Mill and Rockwater Park facilities. While corrosion inhibitor doses at the groundwater treatment facilities have been generally consistent, the corrosion inhibitor doses have been considerably higher at the WTP, leading to potential orthophosphate variability in the distribution system.

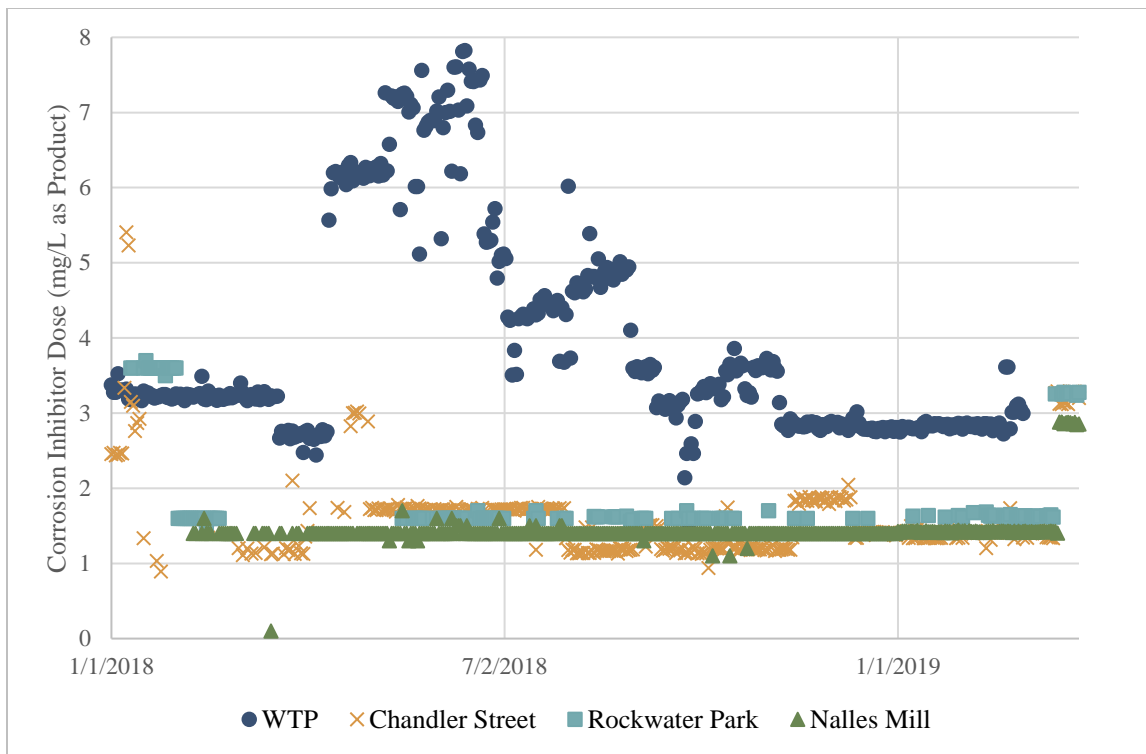


Figure 4-9. Comparison of Treatment Facility Corrosion Inhibitor Doses

Maintaining a stable orthophosphate concentration throughout the system is important for corrosion control. Variable orthophosphate concentrations derived from dose adjustments, inconsistencies between treatment facilities, and potential limitations in the chemical feed system may interfere with corrosion control treatment effectiveness. The Culpeper WTP does not have capabilities for automated flow pacing of chemicals, and variations in the filter effluent flow rate during the backwash cycle may affect chemical dosing accuracy and consistency.

In intermittent sampling performed by the Town in response to customer complaints, orthophosphate was measured starting in May 2018. The Town of Culpeper began performing routine monthly monitoring of orthophosphate concentrations in the distribution system in March 2019. **Figure 4-10** presents historical orthophosphate levels observed in the distribution system when sampling in response to consumer complaints, indicating that orthophosphate concentrations were highly variable. Variable orthophosphate concentrations could interfere with the formation of stable protective phosphate-based scales for lead and iron corrosion control.

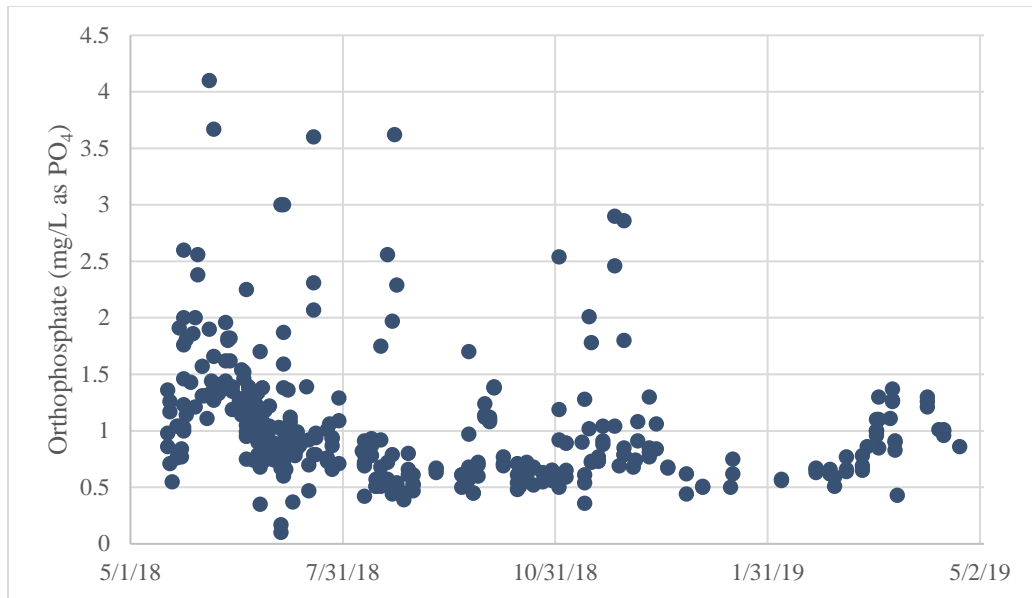


Figure 4-10. Distribution System Orthophosphate Data in Samples Collected in Response to Consumer Complaints

4.2.4 Chloride and Sulfate

The chloride-to-sulfate mass ratio (CSMR) can be used to evaluate the potential for lead contamination from galvanic corrosion (e.g. lead solder, brass fixtures, or partially replaced lead service lines). Chloride may increase lead leaching due to the formation of soluble complexes such as $PbCl^+$. In contrast, sulfate can reduce lead release by forming insoluble $PbSO_4$ scale. Systems with CSMR values greater than 0.5 are more likely to have increased risk of galvanic corrosion of lead. Changes to the CSMR can occur as a result of coagulant changes (Nguyen et. al, 2010). **Figure 4-11** shows a flow diagram that can be used to predict the potential for galvanic corrosion and lead release depending on CSMR.

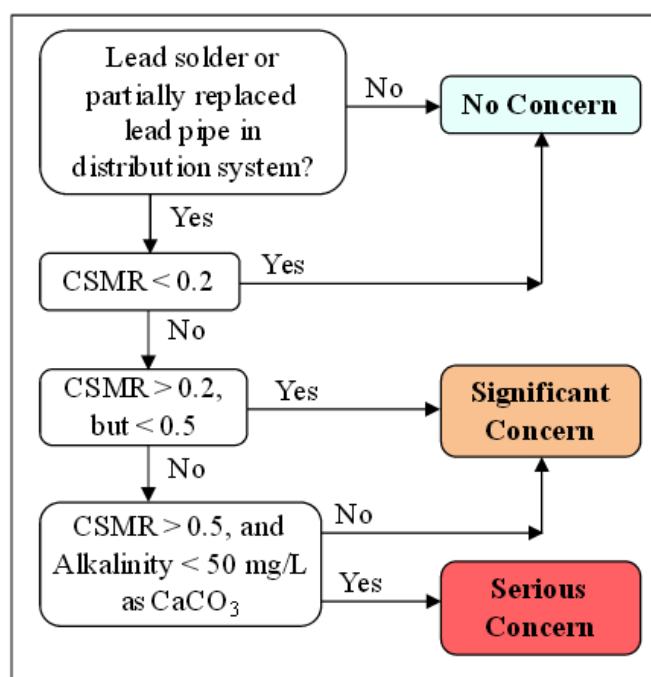


Figure 4-11. Lead Galvanic Corrosion Concern Relative to CSMR (Nguyen et al, 2010)

Table 4-3 presents a summary of chloride and sulfate concentrations for each source based on grab samples collected in July 2019.

The observed CSMR in finished water at the WTP was approximately 13.4 in July 2019 (**Table 4-3**). Prior to the change to PACl coagulant at the WTP in 2018, addition of alum increased the sulfate concentration in finished water, and it is estimated that the CSMR was approximately 0.5 prior to the coagulant change. In 2018, the WTP changed coagulants from alum to polyaluminum chloride, which decreased the sulfate dose and increased the chloride dose, increasing the CSMR. Thus, the coagulant change resulted in a significant increase in the CSMR value above the threshold of concern for systems with alkalinity less than 50 mg/L as CaCO₃. The high CSMR value and low alkalinity levels in finished water from the surface WTP suggest an increased risk of galvanic corrosion of lead solder in portions of the distribution system supplied primarily by the WTP. Higher chloride levels may also increase the potential for release of iron corrosion byproducts from cast iron mains (Lytle et al, 2005).

In response to this long-term treatment change from alum to PACl, the Town collected tap samples for lead and copper at 60 sites in October and November 2018 in accordance with LCR and VDH requirements. Follow-up sampling indicated that the lead levels were below the Action Level after the change to PACl, and all observed lead concentrations were below 2 ppb. Due to the blending of surface water and groundwater in the system, it is not clear which source supplied each LCR sampling site on each date of sample collection. Due to the potential risks associated with elevated CSMR in low alkalinity water, the Town should continue to monitor lead release at sites supplied by the WTP containing lead solder and copper pipe carefully evaluate and monitor corrosion control treatment.

As shown in **Table 4-3**, sulfate levels in the Chandler Street and Nalles Mill wells are particularly high. Rockwater Park wells were not in operation during July 2019 and could not be tested. Blending between surface water and groundwater in the distribution system results in highly variable CSMR values.

Table 4-3. Observed Chloride and Sulfate Values in July 2019

Parameter	WTP	Chandler Street	Nalles Mill	Rockwater Park
Chloride	26.7	9.3	17.5	N/A
Sulfate	2	282	93.9	N/A
CSMR	13.4	0.03	0.19	N/A

4.2.5 Silica and Aluminum

Silica is naturally present in some source waters, and sodium silicate corrosion inhibitors are sometimes added for corrosion control (USEPA, 2016). Silicates may form a metal-silicate diffusion barrier on the pipe surface to reduce metals release. A wide range of silicate corrosion inhibitor doses from approximately 8-50 mg/L as SiO₂ have been reported in the literature (AWWA & DVGW, 1996; Thompson et al, 1997; Rushing et al, 2003; Schock et al, 2005; Lintereur, 2008; Woszczynski, 2015). Silicate corrosion inhibitors can provide benefits for control of red water associated with iron corrosion (Rushing et al, 2003; Lintereur, 2008). Silicate can provide sequestration of iron and manganese by inhibiting crystallization of iron particles and maintaining stable iron colloidal suspensions.

Although the Town of Culpeper does not add a silicate corrosion inhibitor, sampling conducted during July 2019 indicated that groundwater supplies in the Town of Culpeper contain naturally occurring silica (**Table 4-4**). Higher levels of silica in groundwater have the potential to provide benefits for iron corrosion control and control of red water. However, silica levels in the distribution system are likely highly variable due to blending between groundwater and surface water, the latter of which contains lower levels of silica, limiting potential benefits of silica for corrosion control.

Aluminum can also influence lead corrosion scale formation and can react with orthophosphate added for corrosion control. Aluminum can be present in finished water due to carryover of aluminum from coagulation in WTPs using alum or polyaluminum chloride. Naturally occurring aluminum is sometimes present in groundwater. Sampling during July 2019 indicated that aluminum levels were below the detection limit at each water source in the Town. Given these low levels, aluminum is likely not inhibiting the effectiveness of orthophosphate in forming a protective scale on distribution materials.

Table 4-4. Observed Finished Water Silica and Aluminum Values in July 2019

Source	Silica Concentration (mg/L)	Aluminum Concentration (mg/L)
WTP	7.87	<0.01
Chandler Street	35.1	<0.01
Nalles Mill	31.4	<0.01
Rockwater Park	N/A	N/A

4.2.6 Summary of Corrosion Control Treatment Data Analysis

Corrosion control data analysis evaluated parameters related to iron, lead and copper corrosion. The pH levels in the Town's water system have been variable, which may limit corrosion control effectiveness. Low pH values have been observed in the Town's groundwater supplies, which blend into the distribution system. Adjusting pH values at all sources to a consistent value may provide improvements for corrosion control.

The Town's corrosion inhibitor consists of 50% orthophosphate and 50% polyphosphate. Corrosion inhibitor doses have been adjusted and resulted in variable levels of orthophosphate and polyphosphate in the system. Orthophosphate concentrations have often been lower than 2016 USEPA corrosion control guidelines. Increasing the fraction of orthophosphate in the corrosion inhibitor and increasing the orthophosphate dose may provide benefits for iron, lead, and copper corrosion control, subject to confirmation by corrosion testing performed in accordance with LCR requirements.

Blending of source waters with unique water quality characteristics, including pH, DIC, hardness, CSMR, and silica leads to variable water quality conditions in the distribution system and present challenges for implementation of a unified systemwide corrosion control treatment strategy. As a result, changes to blending operations, either by operation of treatment facilities 24 hours per day or controlled source water blending, could provide significant benefits for corrosion control in the system. The impacts of source water blending should be carefully considered in any future corrosion testing performed by the Town.

5. Distribution System Blending and Water Age Analysis

Distribution system operations can significantly affect water quality delivered to the tap. Release of distribution system legacy deposits and/or corrosion of iron mains can cause water discoloration. Blending of different source waters and water age are other key factors affecting distribution system water quality in the Town of Culpeper. Thus, the Town's distribution system hydraulic model was updated and calibrated to simulate current system operations to support the water quality evaluation. The process included expanding the current extent of distribution system mains in the model, updating customer demand allocation in the model, and calibrating the model based on recent hydrant test results.

The updated hydraulic model was used to perform a source trace simulation to analyze the zone of influence of each water source in the distribution system and to evaluate blending patterns between the surface water and groundwater supplies. The source trace analysis was performed based on the following assumptions:

- Average day demands were based on the 2018 demand of 2.13 MGD, consisting of 1.3 MGD surface water and 0.83 MGD groundwater
- 12 hour per day operation of the water treatment plant
- 12 hour per day operation of all three groundwater well facilities, opposite of the hours of WTP operation

5.1 Distribution System Blending Analysis

Blending of surface water and groundwater in the distribution system influences water quality and hydraulic patterns in the distribution system (Dewis et al, 2010; Taylor et al, 2005). Variable water quality conditions can affect stability of distribution system legacy deposits and corrosion control for iron, lead, and copper. Hydraulic patterns, including low flow conditions, sudden velocity changes, and flow reversals can affect accumulation and release of distribution system legacy deposits.

Figure A-16 in Appendix A presents the results of the distribution system source trace analysis, indicating the average percent of surface water throughout the distribution system. For purposes of this analysis, the blending patterns between surface water and combined groundwater supply from three treatment facilities were evaluated. The portion of the distribution system located adjacent to the WTP receives primarily surface water. The midpoint of the blending zone between surface water and groundwater (i.e. 50% surface water and 50% groundwater) is predicted to occur in the downtown area of Culpeper. The influence of groundwater generally increases in the eastern portion of the system near the Chandler Street and Nalles Mill groundwater facilities.

Source trace analysis results from the distribution system hydraulic model were analyzed to characterize blending patterns at several representative locations in the distribution system, as indicated on **Figure B-4** in **Appendix B**. Model predictions of source water blending patterns in the distribution system were consistent with the results of distribution system hardness data analysis (refer to Section 5). Distribution system blending patterns at these locations are described as follows; blending pattern graphs for these locations are presented in Appendix A.

- **Downtown Culpeper near 415 S. Main Street (J-1414)** – This location is near the midpoint of the blending zone and receives a combination of groundwater and surface water. Since this location represents a critical point in the blending zone, **Figure 5-1** presents the modeled blending pattern in the distribution system near 415 S. Main Street over a 48 hour period from the source trace analysis. The results indicate that the water source at this location alternates on a daily basis between 100% surface water and 100% groundwater.
- **West of Lake Pelham WTP near 671 Hunters Road (J-2085)** – The primary water source at this location is surface water from the WTP. The percent of surface water at this location varies on a daily basis from approximately 75% to 100%, indicating a moderate influence of groundwater during portions of the day.
- **Near 1087 Oaklawn Drive (J-2268)** – The primary water source supplying Oaklawn is surface water from the WTP. The blending analysis indicates that Oaklawn Drive receives 100% surface water while the WTP is in operation and receives up to approximately 95% groundwater during a short portion of each day. The influence of groundwater in Oaklawn varies depending on the operation of the nearby Rockwater Park facility. The model source trace analysis reflects minimal use of the Rockwater Park facility (i.e. ~1% of total water supply in 2018), and increased use of this well could increase the overall percentage of groundwater supplied to Oaklawn.
- **Northeast Culpeper near 15150 Montanus Drive (J-1506)** – The northeast portion of the distribution system is supplied primarily by groundwater from the Nalles Mill and Chandler Street facilities. This location receives groundwater during the majority of the day and receives a blend of up to 80% surface water during a portion of each day, as water from the Route 29 Elevated Storage tank supplies this location when groundwater facilities are not in operation, and the tank is filled primarily by the WTP during each day of operation.
- **South Culpeper near 2201 Orange Road (J-423)** – The high pressure zone is located in the southern portion of the distribution system. Water is pumped into the high pressure zone from the Route 15 Standpipe. The Route 15 Standpipe provides a location for blending of surface water and groundwater prior to introduction into the high pressure zone. As a result, this location receives a more consistent blend ratio containing an average of 44% surface water.

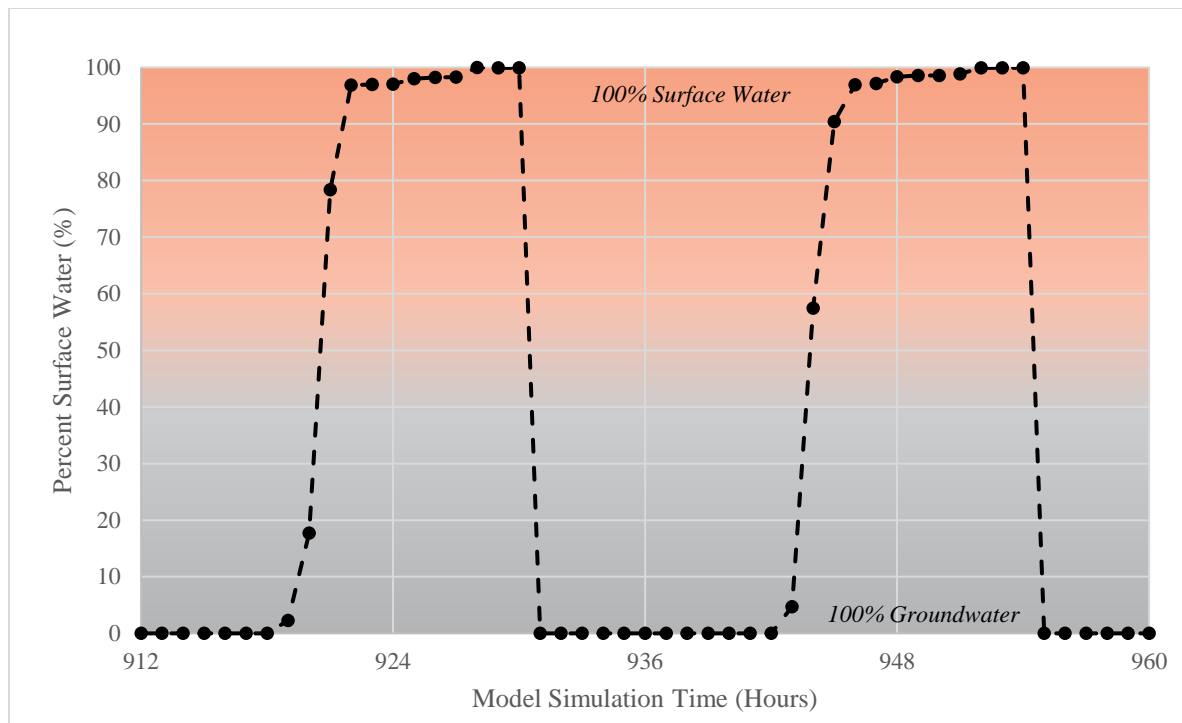


Figure 5-1. Modeled Distribution System Blending Pattern near 415 S. Main Street

Based on a review of system operations, treatment facility operations change frequently based on operational and water quality factors in the Town. The daily duration of WTP operation and each groundwater facility varies frequently. The modeled source trace output represents one typical scenario of treatment facility operation. However, blending patterns and water sources throughout the system are expected to vary significantly depending on system operations. It is expected that any location in the system could be supplied by all surface water or predominantly groundwater as system operations are adjusted.

Maintaining consistent water quality conditions throughout the distribution system is necessary to develop formation of a stable and protective corrosion scale on distribution system and premise plumbing materials. Based on the water quality data analysis results, distribution system blending of surface water and groundwater significantly affects the pH, alkalinity, DIC, hardness, chloride, sulfate, silica, and potentially dissolved oxygen levels, which can all influence scale formation and corrosion byproduct release.

Distribution system hydraulic patterns can also affect accumulation and release of legacy deposits in the distribution system. Hydraulic model results indicated that flow reversals (i.e. an abrupt change in the direction of pipe flow) occur throughout the majority of the distribution system due to blending. **Figure 5-2** presents an example of modeled flow reversals in downtown Culpeper that occur on a daily basis due to distribution system blending.

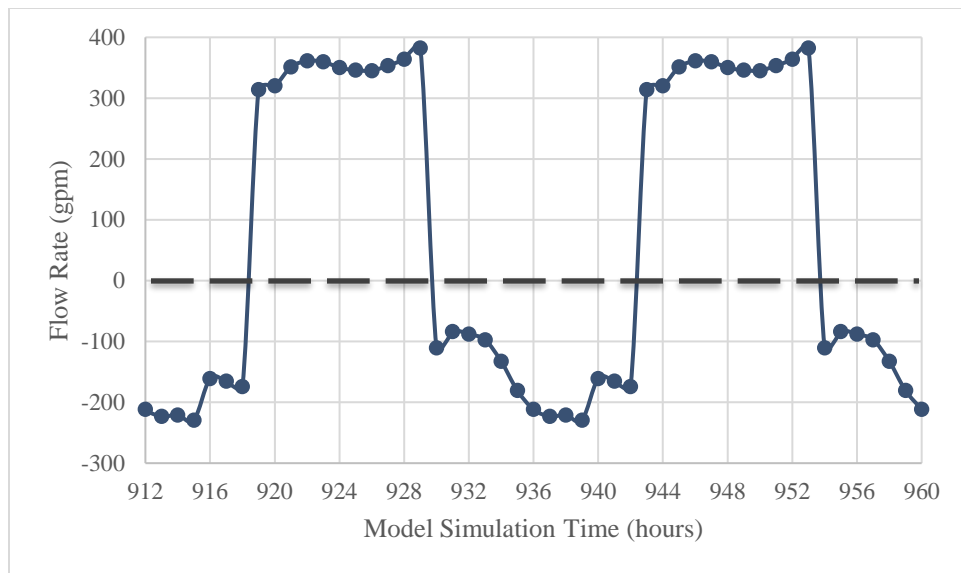


Figure 5-2. Modeled Flow Rate in 12-inch Pipe on Scanlon Street (226 W Scanlon St)

In contrast to pipes with consistent flow velocity, extended low-flow conditions in the distribution system may promote deposition and accumulation of deposits. Daily on/off operation of the WTP contributes to stagnant conditions in portions of the distribution system, followed by sudden velocity changes. **Figure 5-3** presents an example of modeled hydraulic conditions in the 12-inch diameter distribution main on Route 522, which exhibits stagnant conditions followed by sudden flow reversals on a daily basis.

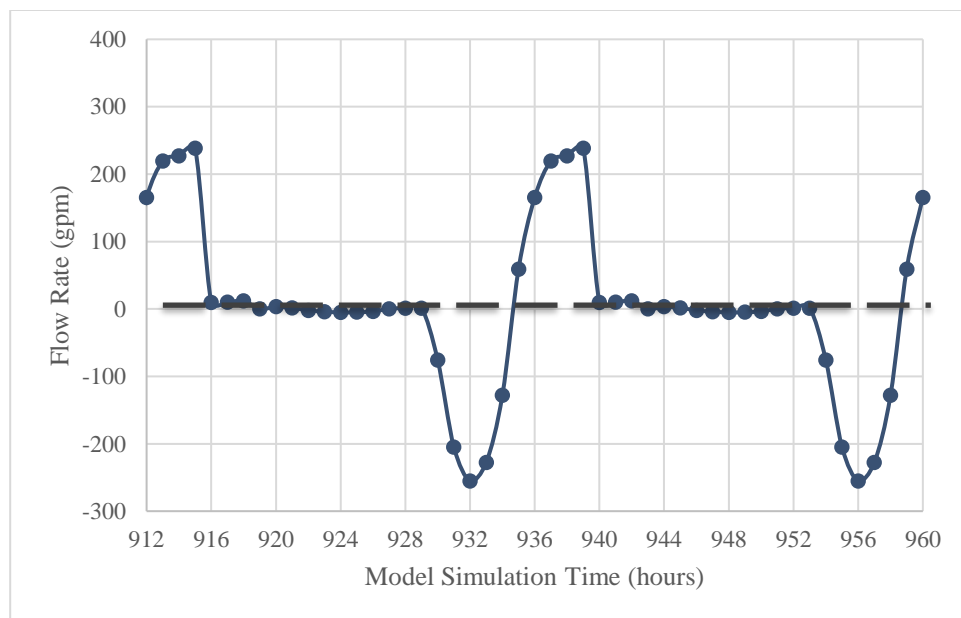


Figure 5-3. Modeled Flow Rate in 12-inch Pipe on Route 522 (1200 Sperryville Pike)

Continuous operation of water treatment facilities 24 hours per day has the potential to stabilize distribution system blending patterns. Under current system operations, treatment facility operation schedules create frequent water quality variations and abrupt hydraulic changes and flow reversals in the distribution system on a daily basis. Operating treatment facilities on a continuous basis at consistent flow rates may stabilize blending patterns in the distribution system, thereby reducing the potential for release of legacy deposits due to hydraulic disturbances and promoting the formation of stable iron corrosion scales to reduce iron release in drinking water.

5.2 Distribution System Water Age

The updated distribution system hydraulic model was used to perform water age simulations of the distribution system. Water age represents the duration of time water stays in the distribution system after water treatment and prior to use by customers. Higher water age is typically correlated with the potential for lower chlorine residuals and elevated DBPs in the distribution system. However, source water characteristics also influence the potential for DBP formation, and DBP formation is typically lower in groundwater. Source trace should also be considered in evaluating DBPs to distinguish source waters in areas with high water age.

Figure A-7 in Appendix A presents the modeled water age based on the stated hydraulic model assumptions. The water age in the central portion of the distribution system and downtown area is generally less than 24 hours. Higher water age occurs at the extremities of the distribution system, and approximately 5% of the pipe length in the distribution system has an estimated water age greater than 6 days. West of the WTP, the water age increases due to limited customer demands and high hydraulic residence time in the Route 522 Standpipe. Higher water age values occur in dead-end mains in the north and east portions of the distribution system as well as in the high pressure zone, as water stored in the Route 15 Standpipe is pumped into the high pressure zone, increasing overall residence time in the system.

Additional hydraulic modeling was performed to understand if increased turnover in the Route 522 Standpipe (Tank T-3) would reduce the age of the water in the tank. The following analyses were performed to understand the impact of increased turnover in Tank T-3:

- Current (12-hr) WTP operation without pumping (Option A-1)
- 24-hr WTP operation without pumping (Option A-2)
- 12-hr WTP operation with pumping. Two sub-options were evaluated:
 - Option A-1B (am) assumed that the tank would fill at night and would be pumped out during the day
 - Option A-1B (pm) assumed that the tank would fill during the day and would be pumped out at night
- 24-hr WTP operation with pumping during the day

All analyses were performed under average day demand conditions over a 480-hr extended period simulation and assuming that the contents of the tank are completely mixed. Pumping operations were based on a pumping rate of 700 gpm @ 40 ft TDH for 12 hours (with timing as noted above) and assuming a control valve is added to the tank influent to control filling operations (e.g., [pressure sustaining valve with timer and level control](#)).

The results of the analysis suggest that pumping, when coupled with plant operating time adjustments, could provide widespread benefits relative to water age in the vicinity of Tank T-3. When moving from 12 hour WTP operation to 24 hour WTP operation, without pumping, the average age of the water in the tank increases from approximately 270 hrs to 440 hours, largely due to the fact that the constant pressure from the WTP over 24 hours limits the turnover in the tank. When pumping operations are added in, the average age of the water in the tank is reduced by approximately 50% for 12 hr WTP operation and by about 85% for 24 hr WTP operation, as compared to the respective no-pumping operation. Refer to **Figure 5-4** below.

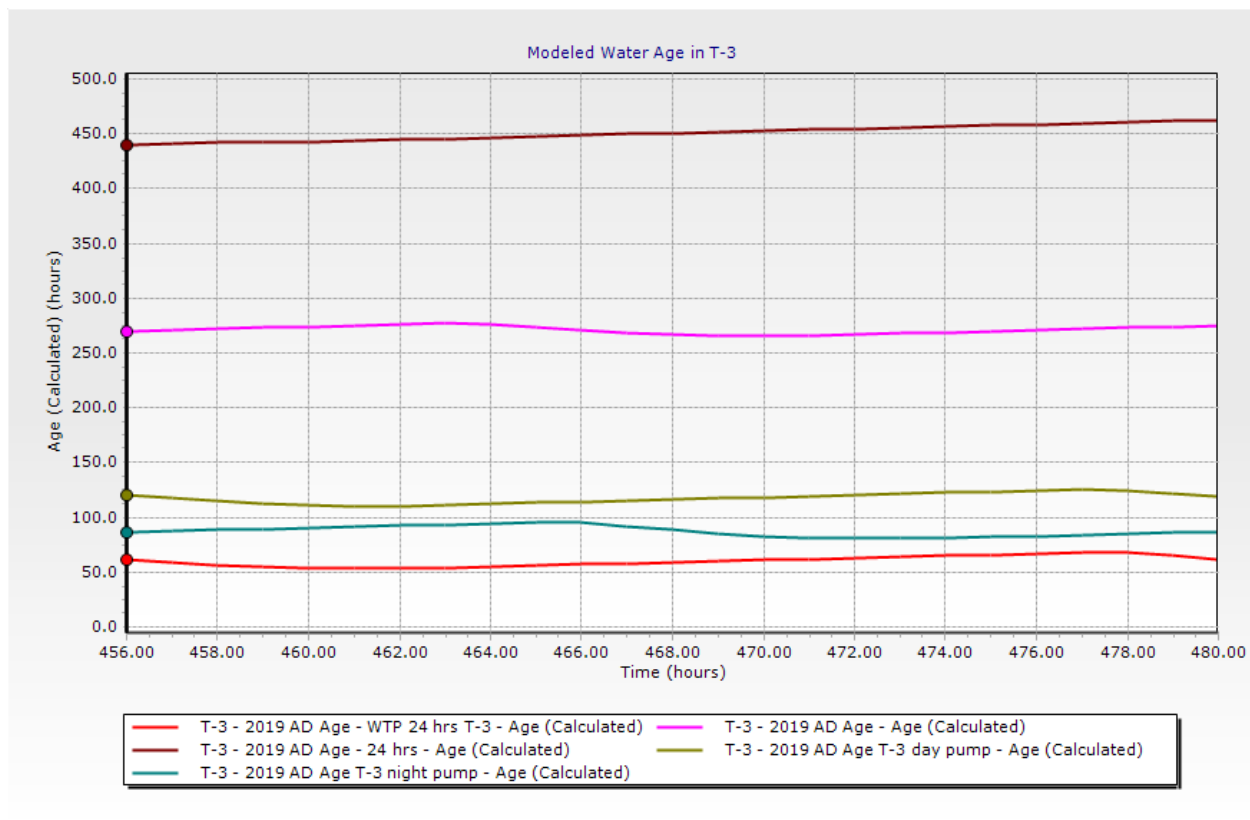


Figure 5-4: Modeled Water Age in Tank T-3 for Operating Alternatives

However, if the focus of the water age reduction is to reduce disinfection byproducts (particularly TTHMs) in the tank, then tank aeration may provide a more reliable and economic alternative. TTHMs in Tank T-3 could be reduced by as much as 30 to 40% based on the operating data and proposed aeration system provided by the Town. DBP sampling at the compliance point will inform the magnitude of potential benefits of tank aeration at the compliance point based on tank fill and draw cycles. To fully

evaluate the pumping operational benefits relative to DBP formation reduction, more information needs to be gathered relative to DBP formation kinetics (i.e., the timing of formation) and the extent of tank reach within the distribution system (with and without pumping).

6. Water Treatment Plant On-site Testing

Additional on-site testing was conducted at the WTP to investigate key aspects of plant performance identified from the historical data analysis. Plant testing focused on treatment processes related to iron and manganese removal, which can contribute to water discoloration and accumulation of legacy deposits in the distribution system. Plant testing included analysis of oxidation by permanganate, monitoring and bench-scale testing of settling performance in the clarifiers, and filter operations.

6.1 Permanganate Dose

Permanganate dose screening was performed during July 2019 to evaluate the effectiveness of permanganate for oxidation of dissolved manganese in raw water from Lake Pelham. Raw water samples were collected from the reservoir intake structure. As illustrated in **Figure 6-1**, raw water samples were dosed with potassium permanganate ranging from 0 to 6 mg/L, and the full-scale WTP permanganate dose on the date of testing was 6 mg/L. A reaction time of approximately 16 minutes with gentle mixing was provided after addition of permanganate to simulate conditions in the raw water pipeline. Samples from each jar were filtered to quantify particulate and total manganese and determine the concentration of raw water dissolved manganese oxidized by permanganate.

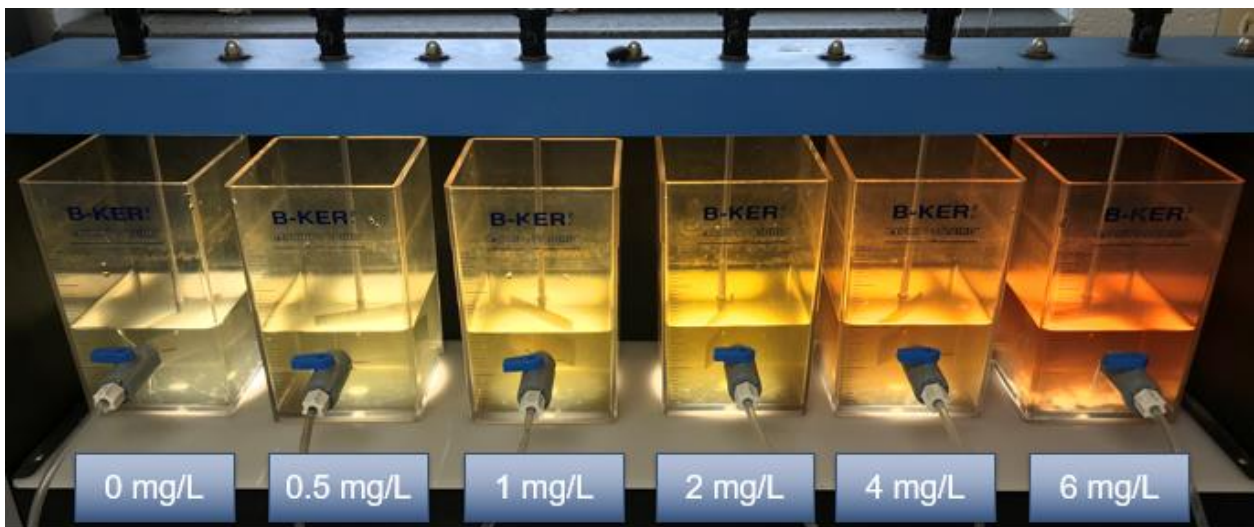


Figure 6-1. Permanganate Screening Testing

Bench-scale testing conducted at the WTP demonstrated that permanganate is an effective pre-oxidant for dissolved manganese in Lake Pelham. The results of the permanganate screening are presented in **Figure 6-2**. Approximately 0.57 mg/L of manganese was present in filtered raw samples, quantifying the concentration of dissolved and colloidal manganese. Addition of permanganate decreased the concentration of dissolved and colloidal manganese in filtered samples up to a dose of 2 mg/L. In jars with permanganate doses higher than 2 mg/L, filtered manganese concentrations were higher than in the raw water. Filtered samples with 4 mg/L and 6 mg/L of permanganate had a noticeable pink color, indicative of a permanganate residual, suggesting that these samples contained dissolved manganese in

the Mn(VII) oxidation state. The permanganate demand and optimal dose is expected to vary depending on raw water quality and may be impacted by the concentrations of iron, manganese, and natural organic matter in the raw water. Jar testing did not measure the impacts of retention in the sludge blanket clarifiers on the permanganate dose, and permanganate demand may differ when measured in settled water; jar test results provide a guideline for the minimum effective permanganate dose of oxidation, and overall iron and manganese removal at the WTP plant should be considered to determine the optimal full-scale dose.

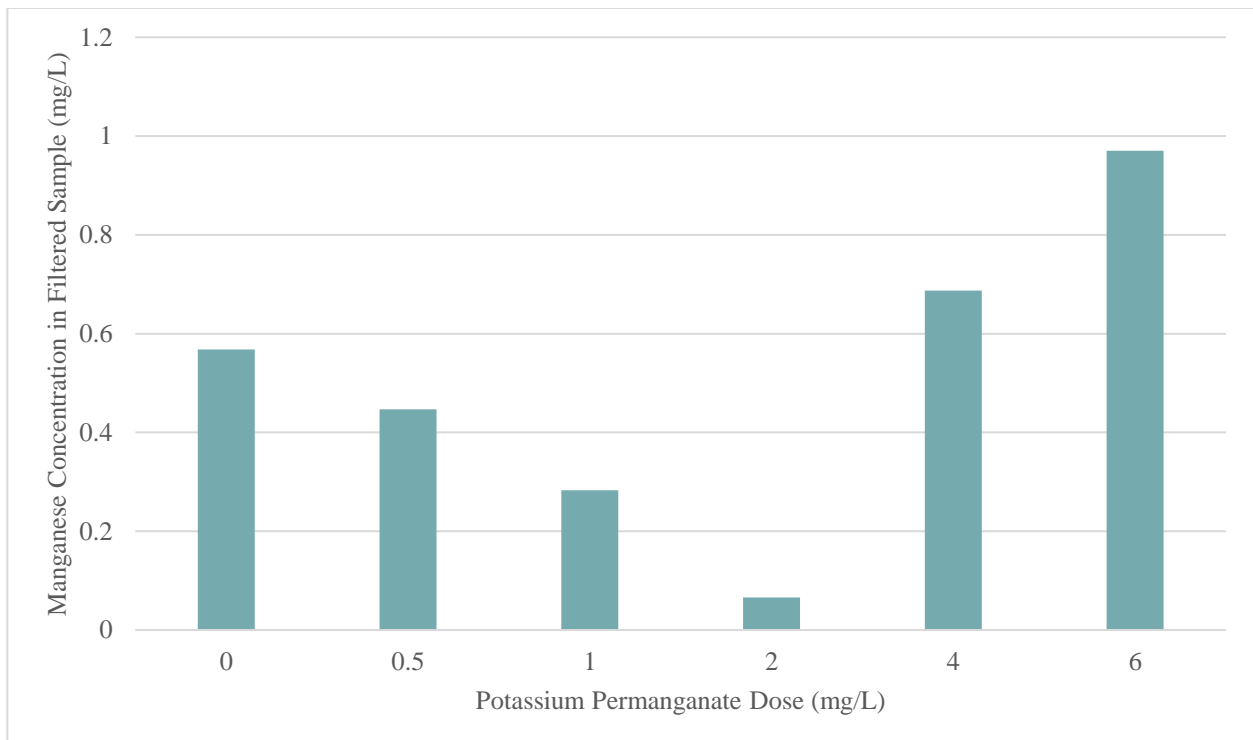


Figure 6-2. Permanganate Screening Test Results (July 11, 2019)

Optimizing permanganate dosing presents an opportunity to reduce the overall manganese loading to the sludge blanket clarifiers. As permanganate contains manganese, addition of permanganate increases the total manganese loading to the sludge blanket clarifiers. Due to the retention of solids in the sludge blanket clarifier and daily on-off operation of the WTP, manganese release from the clarifiers should be carefully monitored.

6.2 Clarifier Testing

Oxidized particulate iron and manganese is removed in the sludge blanket clarifiers. Performance of the coagulation and clarification processes was evaluated due to their importance for removal of iron and manganese, especially with application of permanganate as a raw water oxidant.

6.2.1 Plant Profile Sampling

Profile sampling conducted at the WTP in July 2019 demonstrates the criticality of coagulation and clarification for iron and manganese removal. **Figure 6-3** presents a profile of manganese levels (in the particulate form and dissolved/colloidal form in filtered samples) at the WTP. The majority of manganese present in raw water was removed through oxidation, coagulation, and clarification.

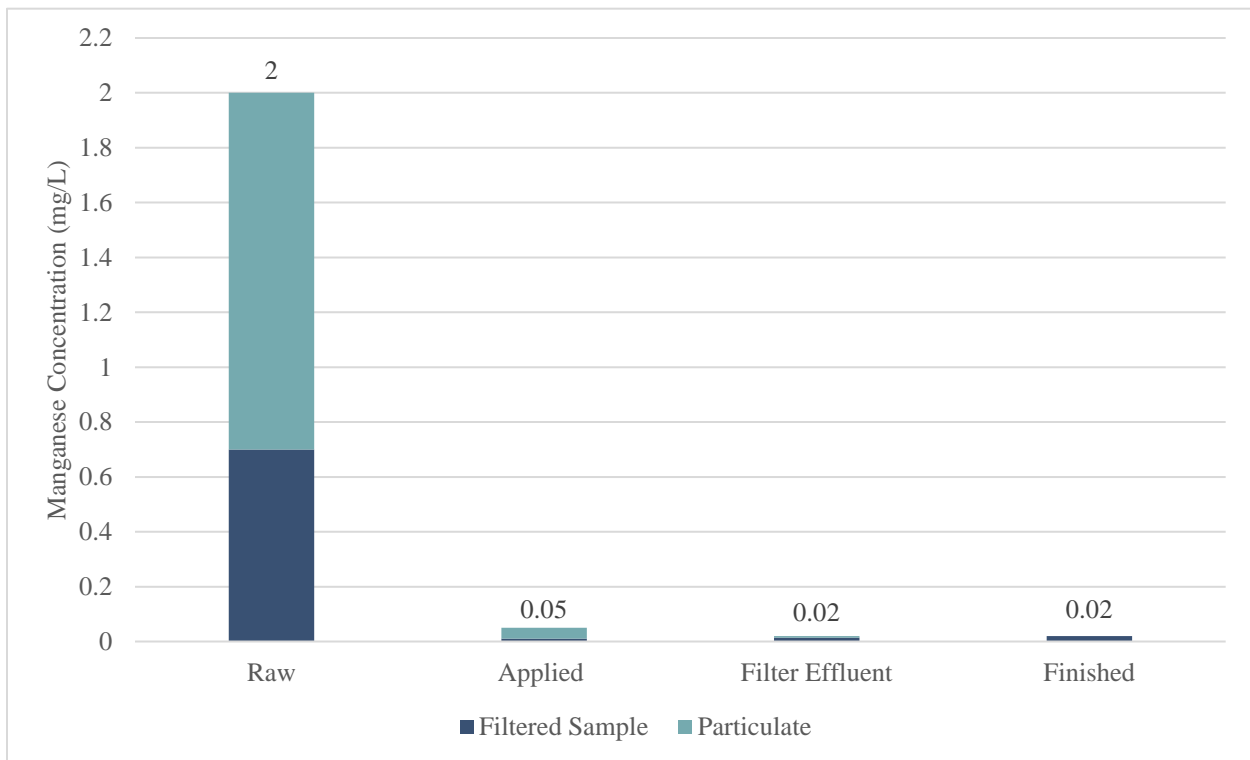


Figure 6-3. WTP Manganese Removal Profile (July 9, 2019)

6.2.2 Bench-Scale Coagulation Testing

Bench-scale testing was performed to evaluate removal of iron and manganese by coagulation and clarification. **Figure 6-4** presents the results of coagulation testing performed to examine overall manganese removal through the oxidation and coagulation process. Permanganate was added to the jars at doses of 1 mg/L and 2 mg/L based on the results of the permanganate screening prior to the addition of the polyaluminum chloride coagulant. The polyaluminum chloride dose on the date of testing was approximately 51 mg/L, and higher and lower coagulant doses were also tested in the jars. In the absence of permanganate addition to raw water, particulate manganese present in raw water was effectively removed through coagulation, and approximately 0.47 mg/L of dissolved manganese remained in settled water. With a dose of 1 or 2 mg/L of permanganate, total manganese levels of approximately 0.06 mg/L or less were achieved in the jars. Lower and higher doses of coagulant slightly increased total manganese concentrations in the jars, suggesting the that the full-scale coagulant dose on the date of testing was effective for manganese removal.

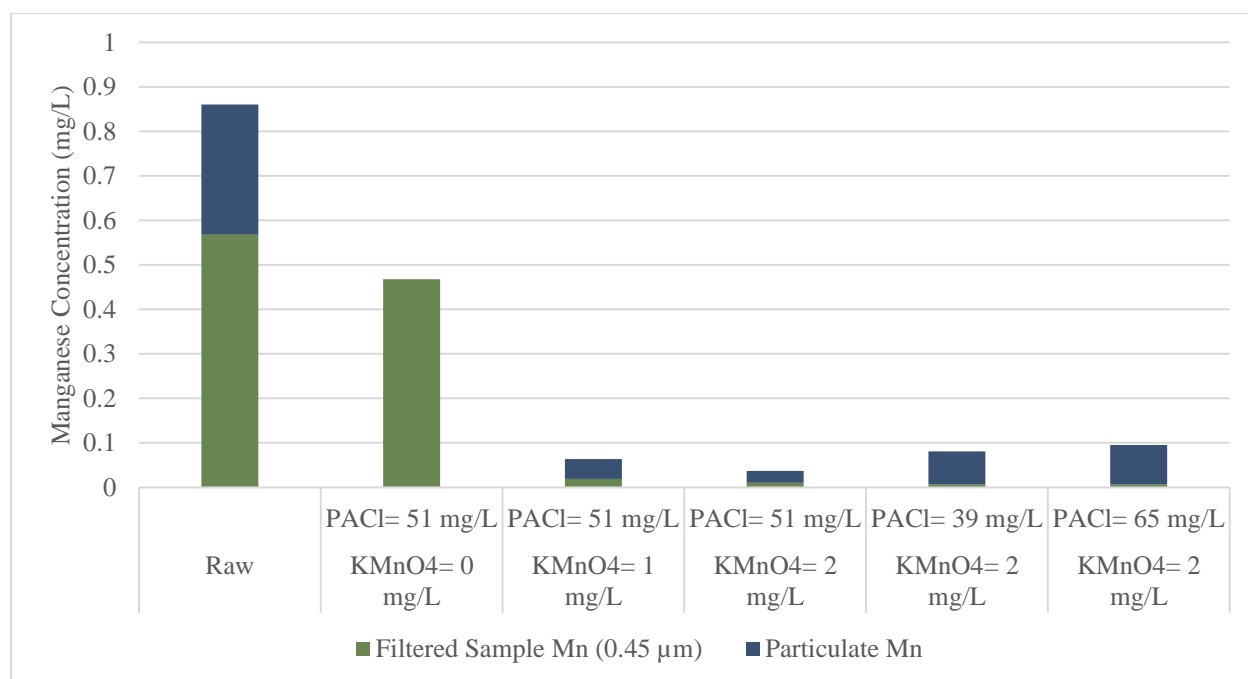


Figure 6-4. WTP Coagulation Testing for Manganese Removal (July 11, 2019)

6.2.3 Settled Water Monitoring

Grab sampling conducted as part of WTP testing suggests that intermittent loss of solids from the sludge blanket clarifiers may occur during operation and lead to higher levels of turbidity and manganese entering the filters. **Table 6-1** presents the turbidity results in grab samples collected concurrently from each filter influent channel in the center column, which distributes water to each individual filter, on July 11, 2019. The filter influent sample collected for Filter 2 on July 11 had a manganese concentration in excess of 20 mg/L, likely explaining the elevated turbidity value (**Table 6-1**). Visual observations of black particles in the sample (prior to acidification and analysis) suggest that the manganese was in the particulate form.

Table 6-1. Individual Filter Influent Turbidity in Simultaneous Grab Samples (July 11, 2019)

Filter	Turbidity (NTU)
Filter 1	0.77
Filter 2	7.55
Filter 3	0.97
Filter 4	1.05

Additional grab samples were collected from each filter influent channel and analyzed for manganese on July 31, 2019. As shown in **Table 6-2**, manganese concentrations varied significantly between filters, and elevated manganese levels were observed in the filter influent for Filters 3 and 4. These manganese levels are considerably higher than typical settled water manganese levels observed in profile testing on July 9,

2019. These observations from on-site testing suggest that periodic loss of manganese solids from the sludge blanket clarifiers can occur.

Table 6-2. Individual Filter Influent Manganese Concentrations in Grab Samples (July 31, 2019)

Filter	Mn Concentration (mg/L)
Filter 1	0.07
Filter 2	0.07
Filter 3	0.23
Filter 4	0.31

6.2.4 Clarifier Design Implications

Industry guidance indicates that high-rate sludge blanket clarifiers can be an effective treatment technology for some systems with stable raw water quality and consistent flow rates but may present disadvantages for systems with variable raw water quality or production flow rates (Baruth, 2005). According to AWWA Manual M37, sludge blanket clarifiers should be operated on a continuous basis, 24 hours per day, with a constant rate of flow. Manual M37 notes that “*daily increases and decreases in flow in a blanket clarifier and, worse, on-and-off operation of such process equipment can cause serious problems, especially when floc in the blanket is only slightly more dense than water.*” Additionally, the manufacturer, SUEZ, recommends that the Superpulsator® system be operated on a continuous basis, and if it is necessary to remove the basin from service, the flow rate should be gradually increased at startup to avoid disturbing the sludge blanket. It is recommended that the Town minimize abrupt hydraulic flow rate changes in the clarifiers.

Sludge blanket clarifiers may present additional operational disadvantages in situations with elevated iron or manganese in raw water. Oxidized iron and manganese particles accumulate in the sludge blanket layer and may be released due to disturbances to the blanket, anoxic conditions, or absence of an oxidant. AWWA Manual M37 describes that “*if biological activity is present in the sludge and anoxia occurs, oxidized metals such as iron or manganese can be released and pass onto the filters... these now reduced [dissolved] metals will pass through the filters*”. The WTP has historically been operated for a portion of each day, and settling of the sludge blanket, loss of permanganate residual in the sludge blanket, and loss of chlorine residual in the filters during the night may increase soluble manganese levels upon startup in the morning. Operating the WTP continuously for 24 hours per day at a lower flow rate could provide an opportunity to improve WTP performance by reducing hydraulic loading rates to treatment processes and minimizing abrupt changes to flow rate that may adversely affect sludge blanket clarifier performance.

6.3 Filter Testing

As part of the filter testing approach, filter free chlorine residuals and the backwash process were monitored at the WTP.

6.3.1 Chlorine Residual Monitoring

Free chlorine levels across the filters influence iron and manganese removal in the filters. Grab samples were collected at the WTP during July 2019 to evaluate chlorine dosage variation between filters and examine filter effluent chlorine residuals, which are not routinely monitored at the WTP. Filter 1 and Filter 4, located on the opposite side of the center column from the filter influent channel, consistently received a higher chlorine dose than Filter 2 and Filter 3 (**Table 6-3**). The difference in filter influent chlorine dispersion led to lower filter effluent chlorine residuals for Filter 2 and Filter 3, with barely detectable residuals on July 31, 2019. These results suggest that lower filter influent chlorine doses prior to 2017 could have limited the potential for further iron oxidation and may have allowed desorption of manganese in the filters or passage of dissolved manganese through the filters.

Table 6-3. Filter Influent and Effluent Chlorine Residuals in Grab Samples (July 31, 2019)

Filter	July 11, 2019		July 31, 2019	
	Filter Influent	Filter Effluent	Filter Influent	Filter Effluent
Filter 1	1.79	0.86	1.1	0.21
Filter 2	0.98	0.2	0.48	0.03
Filter 3	0.78	0.19	0.35	0.01
Filter 4	1.48	0.66	1.06	0.1

Historical chlorine doses added to the filter influent have not been sufficient to promote sorption of manganese to the filter media, and increasing filter chlorine doses presents an opportunity to further enhance iron and manganese removal. However, increasing chlorine doses could increase DBP formation, and DBP impacts should be evaluated through a full-scale trial prior to implementing long-term increases to the chlorine dose. Additional detail on filter optimization strategies and full-scale demonstration testing to evaluate DBP impacts are presented in the Water Quality Recommendations memorandum.

6.3.2 Backwash Testing

Limited filter testing was conducted during July 2019 to evaluate filter backwash performance of the proprietary filter design that backwashes by gravity, rather than by a pumped backwash flow. Key findings from the filter testing include:

- **Media Expansion** – The total bed depth of anthracite and sand layers is 40 inches. A bed expansion of approximately 8 inches was measured in Filter 1 during water backwash, which is equivalent to approximately 20% expansion, which is consistent with common goals for filter media expansion. However, the testing was conducted during warm summer conditions, and lower bed expansion may occur during the winter due to the filter system design. Additional monitoring of filter bed expansion during cold weather conditions could be performed to examine seasonal impacts.
- **Backwash Turbidity Profile** – The turbidity of the waste backwash water was measured throughout the backwash cycle to evaluate filter cleanliness at the end of the backwash cycle.

Industry guidelines suggest that a backwash water turbidity at the end of the backwash cycle of 10 NTU provides optimal filter cleaning and ripening. In backwash profiling conducted in July 2019, filter backwash turbidity was less than 1 ntu after 4 minutes of backwash (**Figure 6-5**), versus the WTP's typical backwash water duration of 8 minutes.

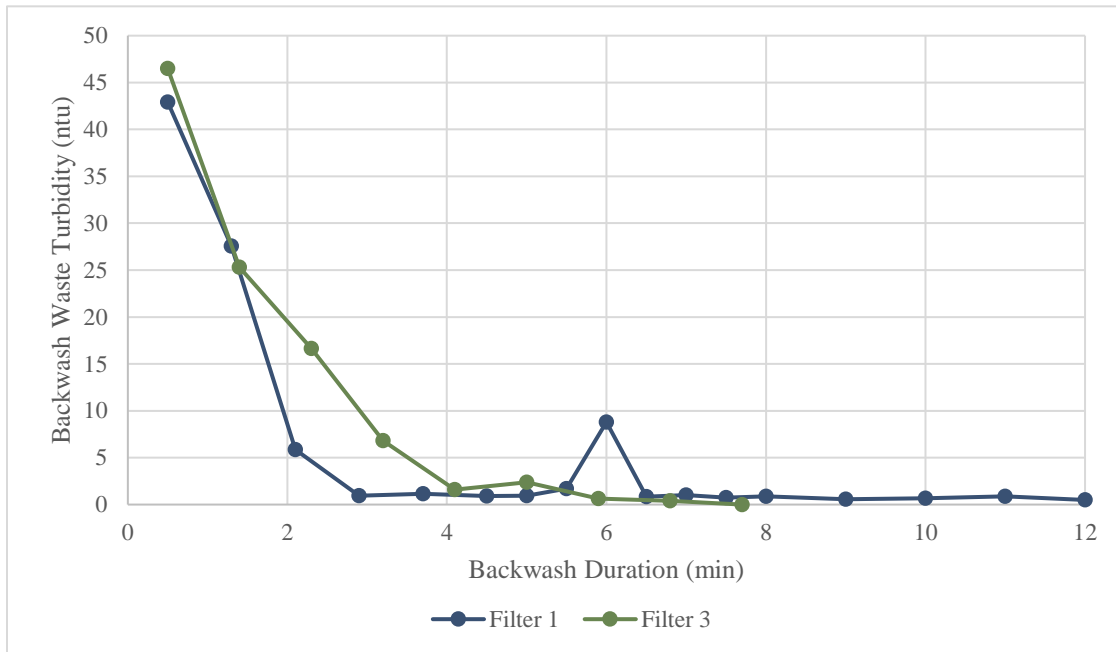


Figure 6-5. WTP Filter Backwash Turbidity Testing (July 31, 2019)

7. Conclusion

The Water Quality Data Analysis characterizes aesthetic aspects of water quality identified in the Water System Evaluation that have affected customer perception of water quality. The USEPA has established secondary standards as non-mandatory guidelines for water quality parameters that may cause aesthetic effects but do not present a risk to human health. The data analysis focused on water quality parameters and treatment processes related to iron, manganese, taste and odor, and hardness. **Table 7-1** summarizes key findings of the Water Quality Data Analysis.

Table 7-1. Summary of Water Quality Data Analysis

Water Quality Parameter	Key Findings
Iron	<ul style="list-style-type: none"> Iron may contribute to water discoloration and may be released from distribution system legacy deposits, corrosion of iron mains, or corrosion of iron in premise plumbing Iron present in raw water from Lake Pelham is readily removed at the WTP, and finished water levels are below the SMCL Iron levels are low in groundwater sources Iron levels above the SMCL were occasionally observed in the distribution system
Manganese	<ul style="list-style-type: none"> Manganese may contribute to water discoloration and may arise from finished water at the WTP or release of distribution system legacy deposits. Manganese levels from Lake Pelham can episodically be elevated, increasing risk of dissolved manganese breakthrough and contribution to legacy deposits Manganese is generally removed at the WTP below the SMCL and a more aggressive target treatment goal of 0.02 mg/L for control of water discoloration. Elevated manganese levels were occasionally observed in distribution system sampling, suggesting presence of legacy deposits in the system.
Taste and Odor	<ul style="list-style-type: none"> Lake Pelham has experienced seasonal algae growth, and customer complaints of musty/earthy taste and odor are consistent with presence of MIB and geosmin. Naturally occurring nitrogen compounds in Lake Pelham may contribute to taste and odor complaints.
Hardness	<ul style="list-style-type: none"> High hardness from groundwater sources may affect the feel of water with soap and cause calcium deposits Water from the WTP has low hardness and is considered soft Water from the groundwater wells is considered hard due to high calcium levels

An evaluation of treatment facilities operations suggested improvements could be implemented in the near-term to improve control of distribution system discoloration by increasing robustness of iron and manganese treatment and also tightening control of finished water chemical dosing. These improvements will serve to reduce the risk of periodic iron and manganese breakthrough and contribution to legacy deposits in the system and also reduce potential for distribution system iron corrosion and release of legacy deposits. When combined with an aggressive distribution system unidirectional flushing protocol designed to eliminate legacy deposits, these improvements can reduce localized water discoloration issues.

Appendix A: Water Quality Data Sources

Table A-1. Summary of Analysis of Water Quality Data provided by the Town

Parameter	WTP	Chandler Street	Nalles Mill	Rockwater Park
Raw Water pH	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Raw Water Alkalinity	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Raw Water Hardness	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Raw Water Manganese	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Raw Water Iron	N/A	Jan 2015 – Feb 2019; Daily Average; Combined Well Data	Feb 2018 – Feb 2019; Daily Average; Combined Well Data	Jan 2018 – Feb 2019; Daily Average; Combined Well Data
Raw Water Total Dissolved Solids	N/A	Jan 2015 – Feb 2019; Daily Average; Combined Well Data	Feb 2018 – Feb 2019; Daily Average; Combined Well Data	Jan 2018 – Feb 2019; Daily Average; Combined Well Data
Applied Chlorine Residual	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Applied Turbidity	Jan 2008 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Finished Turbidity	Jan 2008 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Applied pH	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Finished pH	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Finished Alkalinity	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Finished Hardness	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR

Finished Chlorine Residual	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Finished Water Manganese	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Finished Water Iron	N/A	Jan 2015 – Feb 2019; Daily Average; Combined Well Data	Feb 2018 – Feb 2019; Daily Average; Combined Well Data	Jan 2018 – Feb 2019; Daily Average; Combined Well Data
Finished Water Total Dissolved Solids	N/A	Jan 2015 – Feb 2019; Daily Average; Combined Well Data	Feb 2018 – Feb 2019; Daily Average; Combined Well Data	Jan 2018 – Feb 2019; Daily Average; Combined Well Data
Permanganate Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
PAC Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Applied Chlorine Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Lime Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Coagulant Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Fluoride Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Corrosion Inhibitor Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR
Polymer Dose	Jan 2014 – Feb 2019; Daily Average; WTP MOR	N/A	N/A	N/A
Flow Rate	Jan 2014 – Feb 2019; Daily Average; WTP MOR	Jan 2015 – April 2019; Daily Average; MOR	Feb 2018 – April 2019; Daily Average; MOR	Jan 2018 – April 2019; Daily Average; MOR

Table A-2. Summary of Analysis of Distribution System Water Quality Data provided by the Town

Parameter	Data Source	Parameter	Data Source
pH	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	Orthophosphate	March 2019 – April 2019; Monthly; Distribution Data Points Spreadsheet
Turbidity	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	TDS	March 2019 – April 2019; Monthly; Distribution Data Points Spreadsheet
Chlorine Residual	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	Lead	2002 – 2018; Compliance Data
Manganese	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	Copper	2002 – 2018; Compliance Data
Iron	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	TTHM	1 st Quarter 2013 – 4 th Quarter 2018; Quarterly Average; PDF
Alkalinity	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet	HAA5	1 st Quarter 2013 – 4 th Quarter 2018; Quarterly Average; PDF
Hardness	Sept 2016 – April 2019; Monthly; Distribution Data Points Spreadsheet		

Appendix B: Distribution System Maps and Data

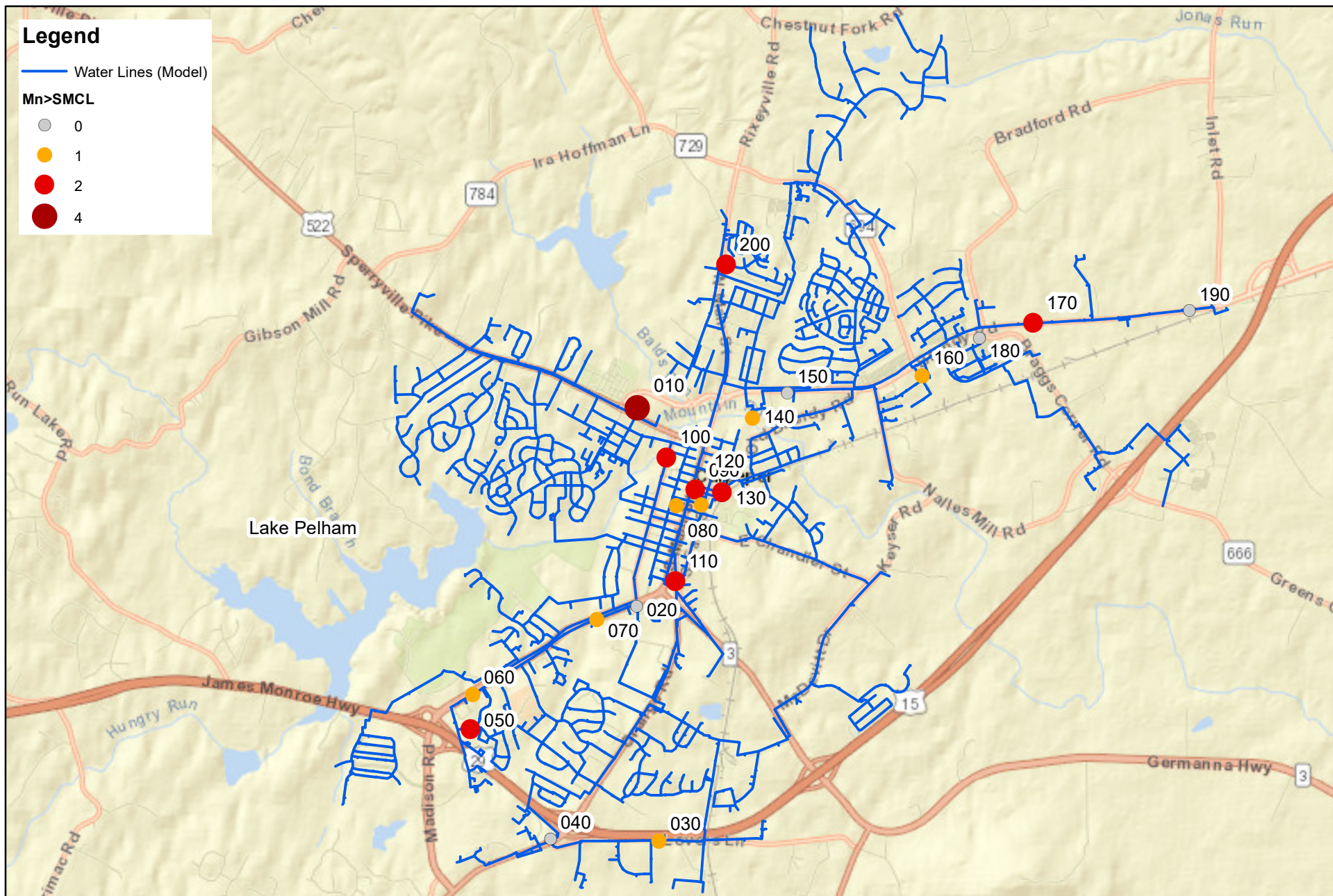


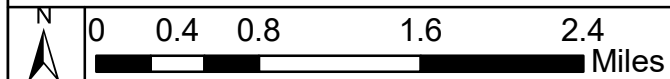
Figure B-1: Number of Manganese Values > Secondary MCL (Sept 2016 - March 2019)

Client: Town of Culpeper

Project: Town of Culpeper Water System Assessment

Location: Culpeper, Virginia

Date: January 2020



Hazen

4035 Ridge Top Road
Fairfax, VA 22030

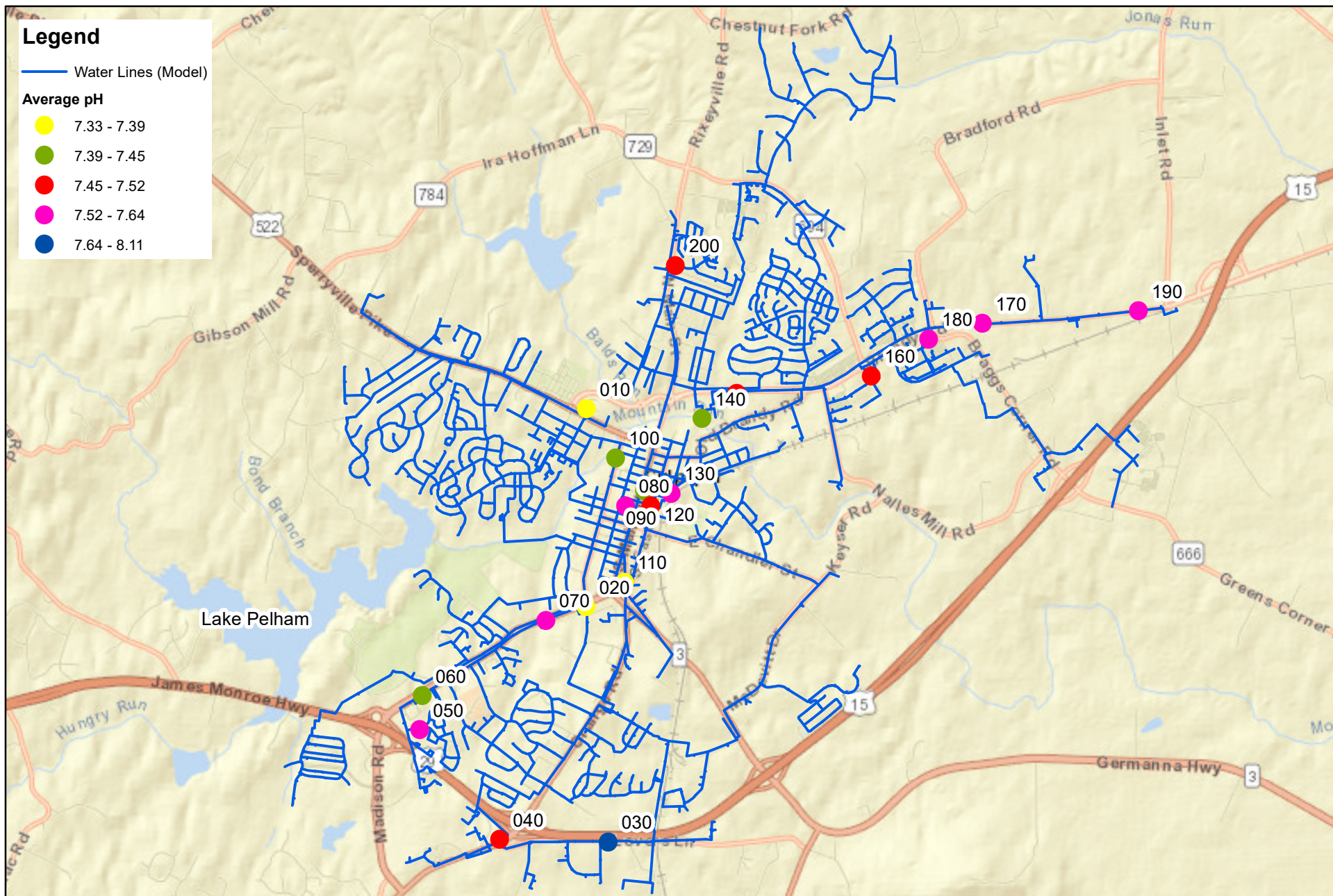


Figure B-2: Distribution Average pH

Client: Town of Culpeper

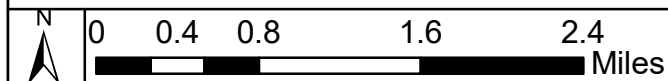
Project: Town of Culpeper Water System Assessment

Location: Culpeper, Virginia

Date: January 2020

Hazen

4035 Ridge Top Road
Fairfax, VA 22030



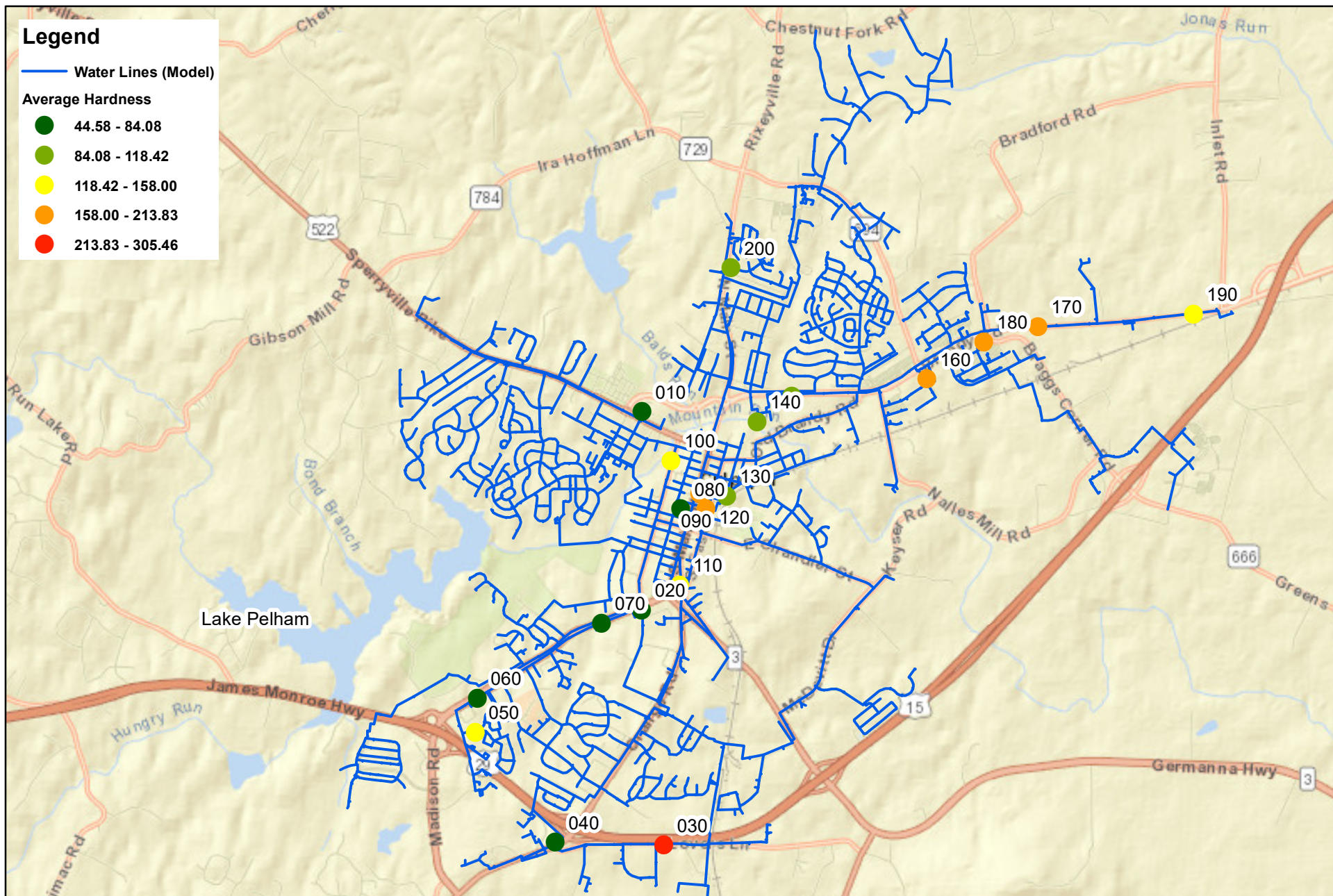


Figure B-3: Distribution System Hardness

Client: Town of Culpeper

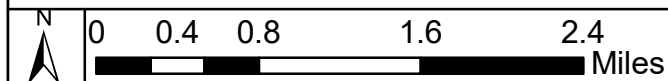
Project: Town of Culpeper Water System Assessment

Location: Culpeper, Virginia

Date: January 2020

Hazen

4035 Ridge Top Road
Fairfax, VA 22030



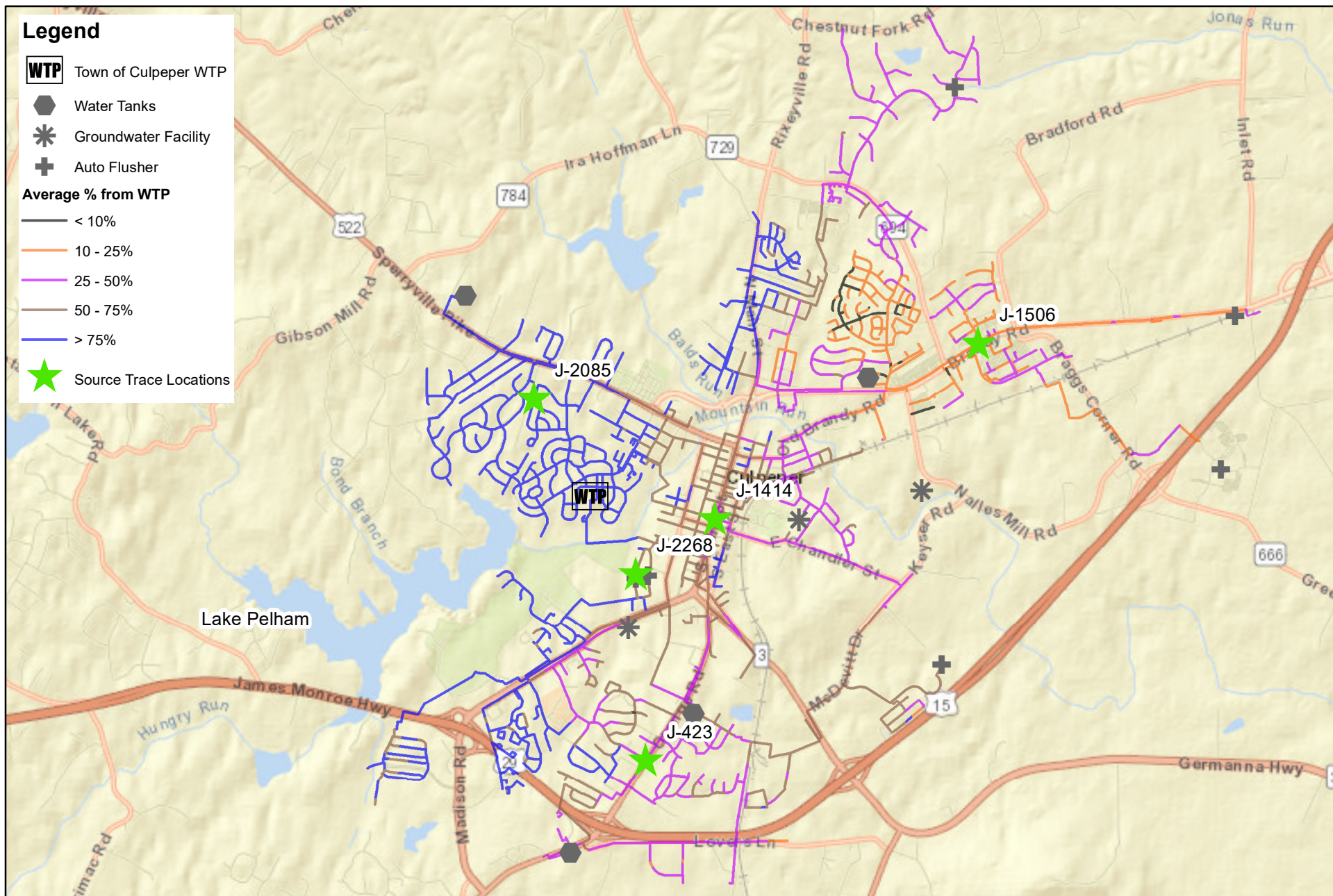


Figure B-4: WTP Source Tracing Graphs

Client: Town of Culpeper

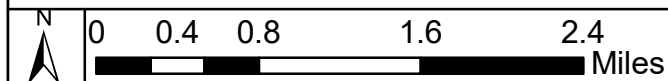
Project: Town of Culpeper Water System Assessment

Location: Culpeper, Virginia

Date: January 2020

Hazen

4035 Ridge Top Road
Fairfax, VA 22030



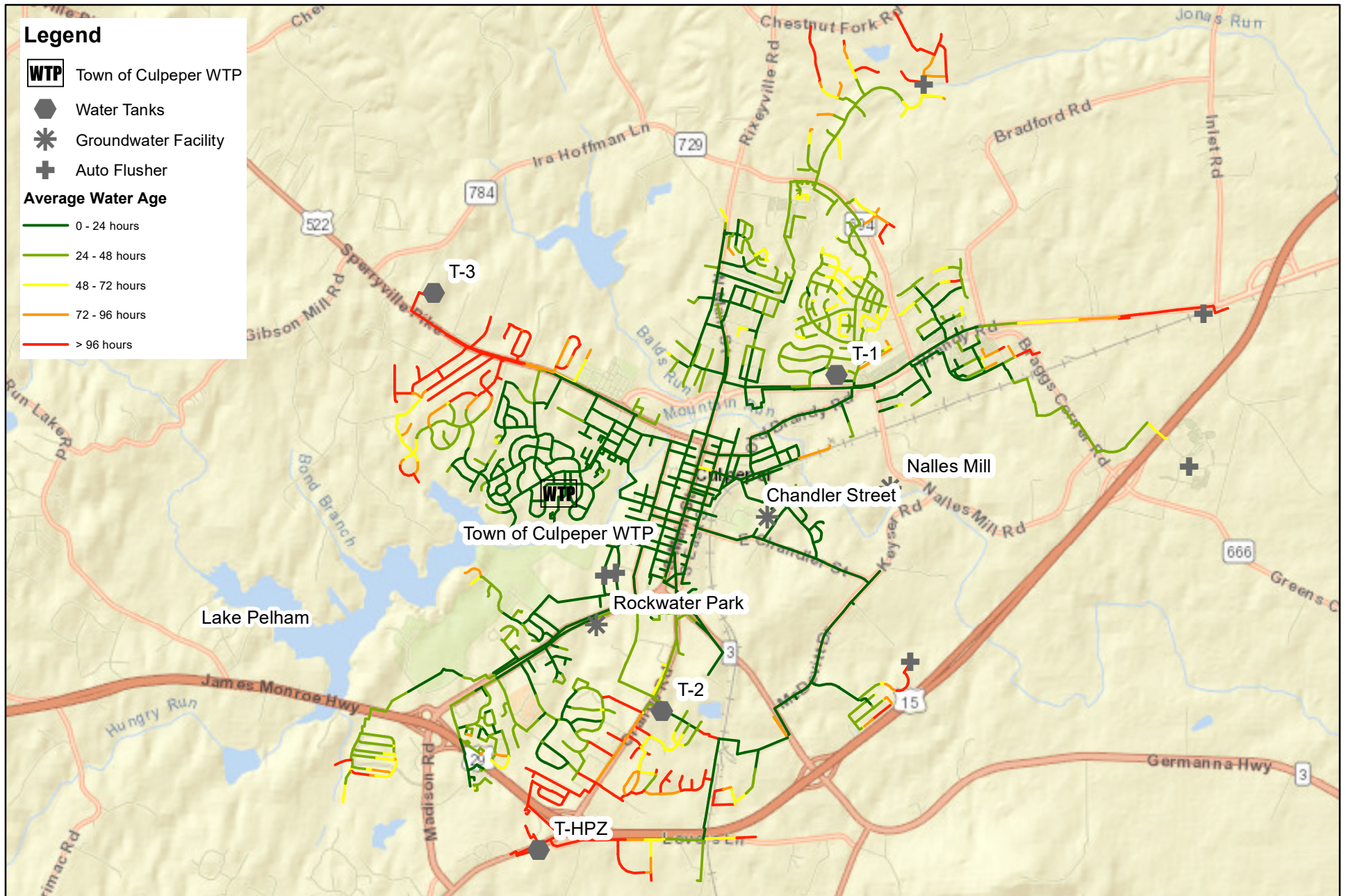


Figure B-5: Average Water Age

Client: Town of Culpeper

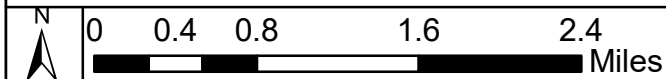
Project: Town of Culpeper Water System Assessment

Location: Culpeper, Virginia

Date: January 2020

Hazen

4035 Ridge Top Road
Fairfax, VA 22030



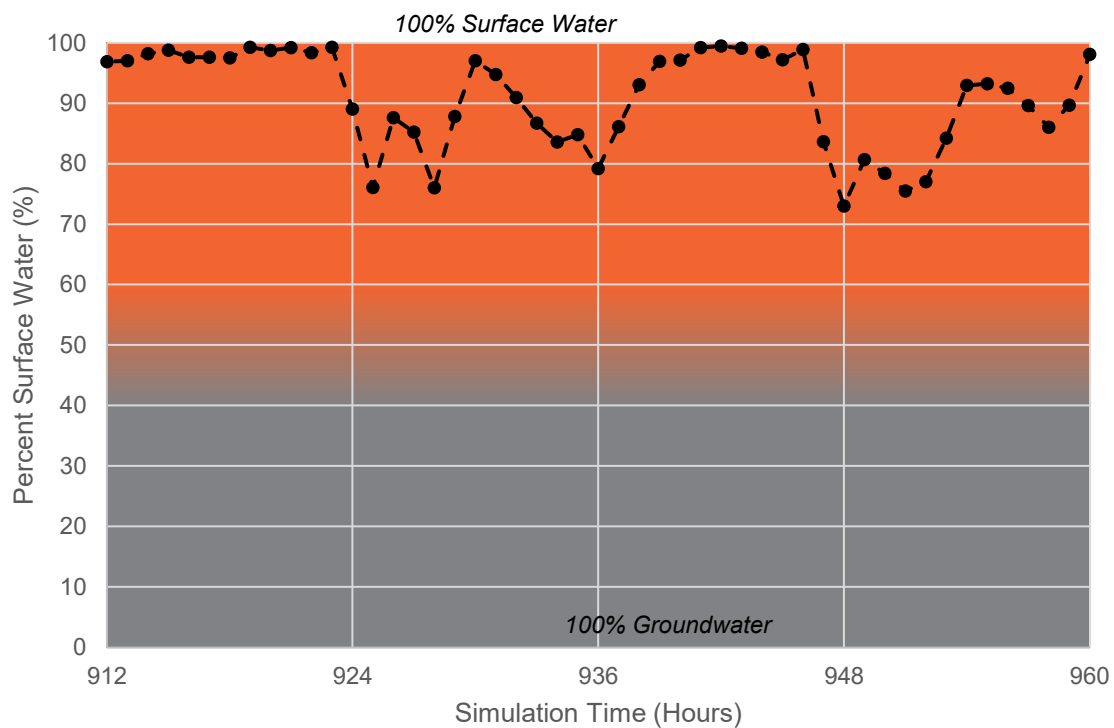


Figure B-6: Modeled Distribution System Blending Pattern near 671 Hunters Road (J-2085)

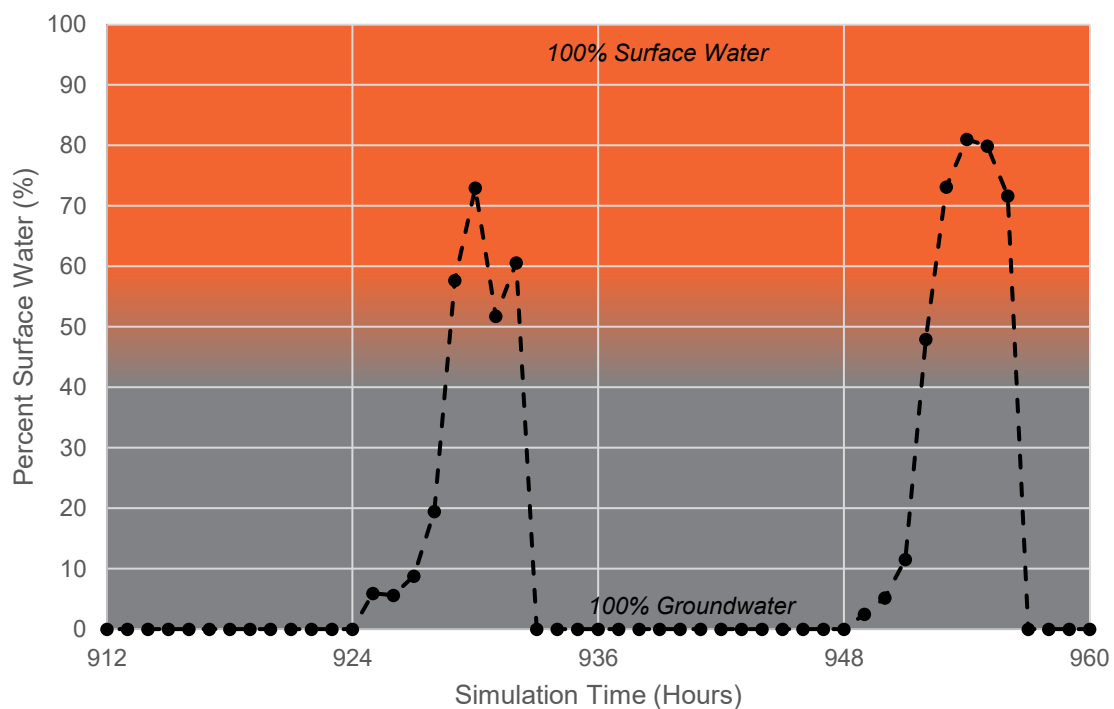


Figure B-7: Modeled Distribution System Blending Pattern near 15150 Montanus Drive (J-1506)

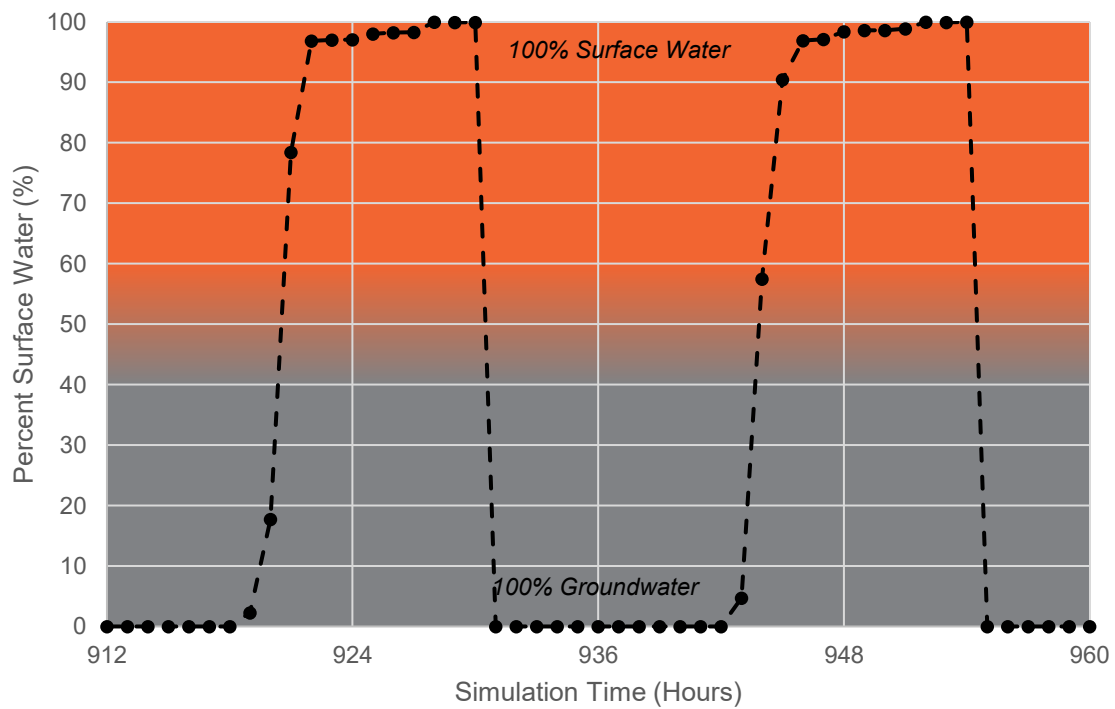


Figure B-8: Modeled Distribution System Blending Pattern near 415 S. Main Street (J-1414)

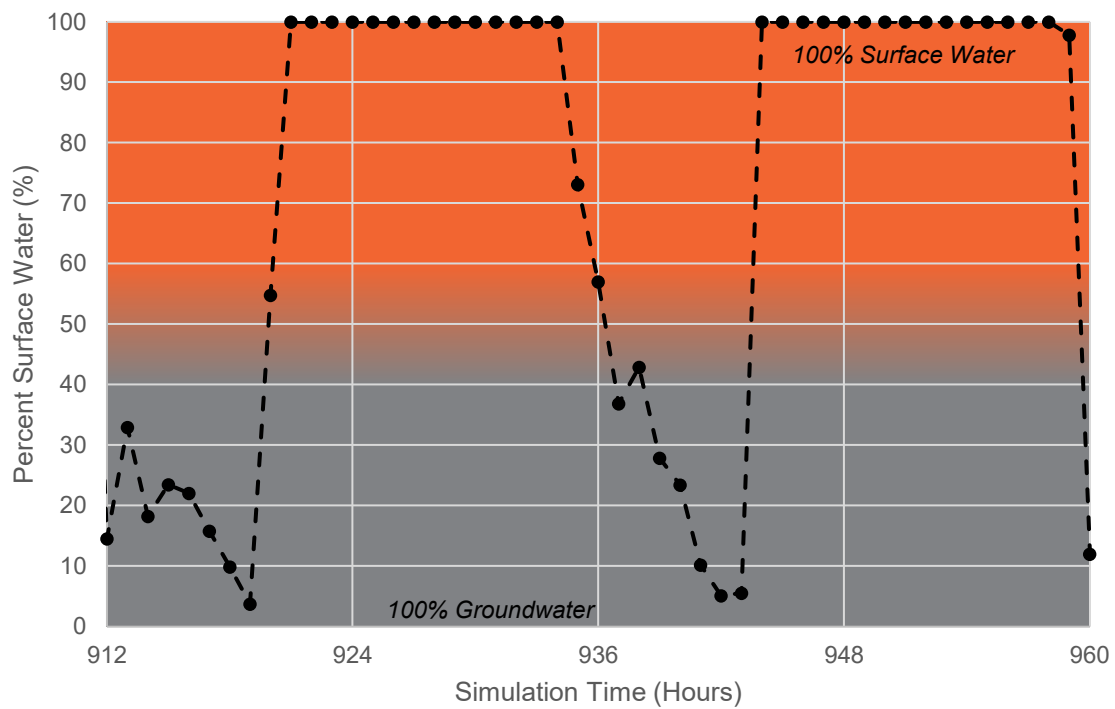


Figure B-9: Modeled Distribution System Blending Pattern near 1087 Oaklawn Drive (J-2268)

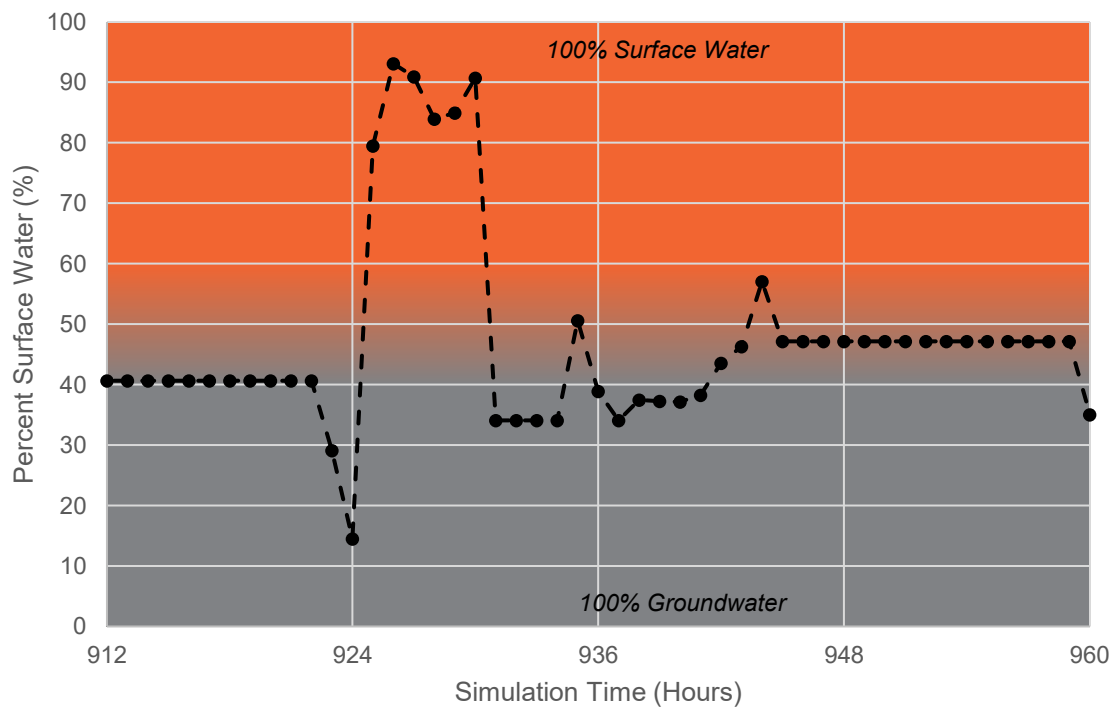


Figure B-10: Modeled Distribution System Blending Pattern near 2201 Orange Road (J-423)



Figure B-11: Bacti Site 10 pH



Figure B-12: Bacti Site 10 Temperature



Figure B-13: Bacti Site 10 Turbidity



Figure B-14: Bacti Site 10 Chlorine Residual

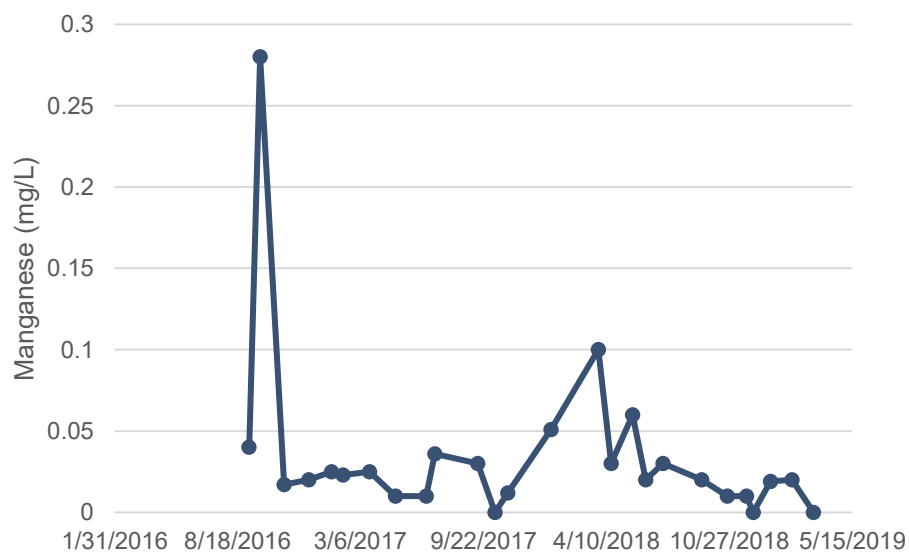


Figure B-15: Bacti Site 10 Manganese

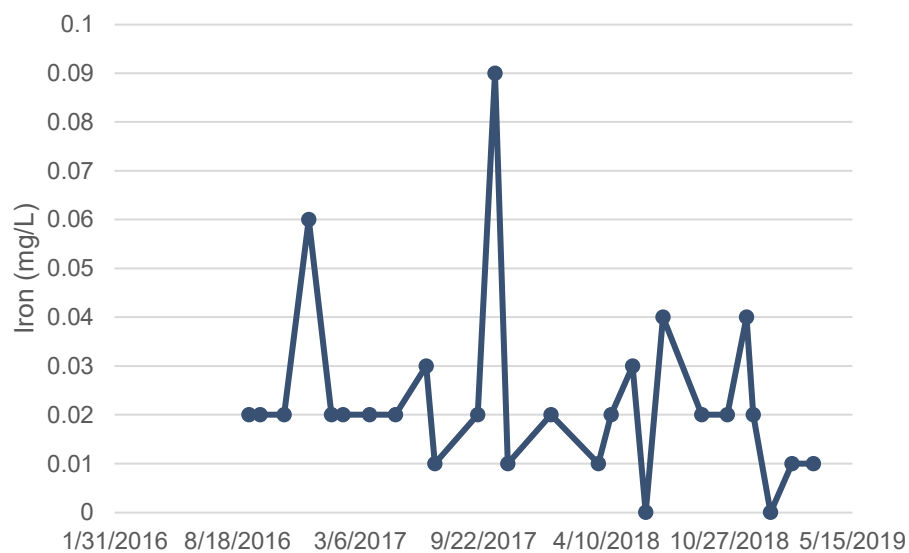


Figure B-16: Bacti Site 10 Iron

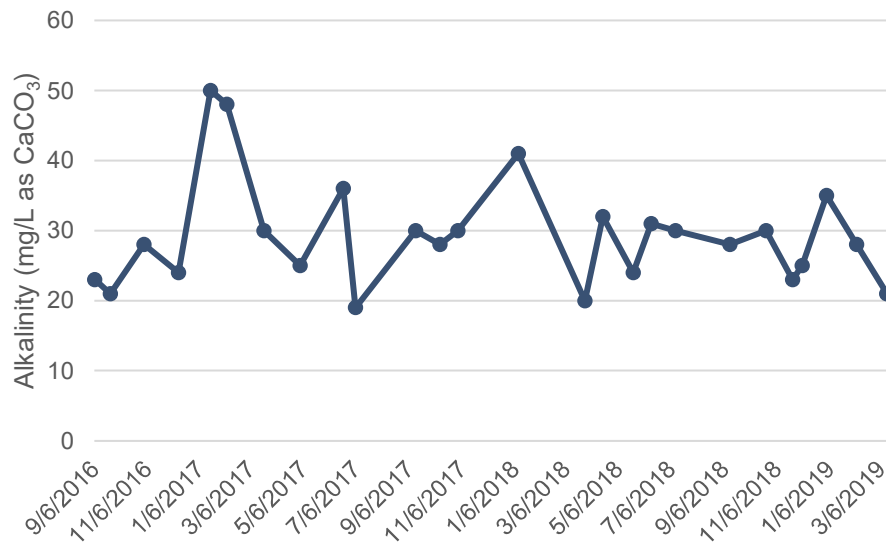


Figure B-17: Bacti Site 10 Alkalinity

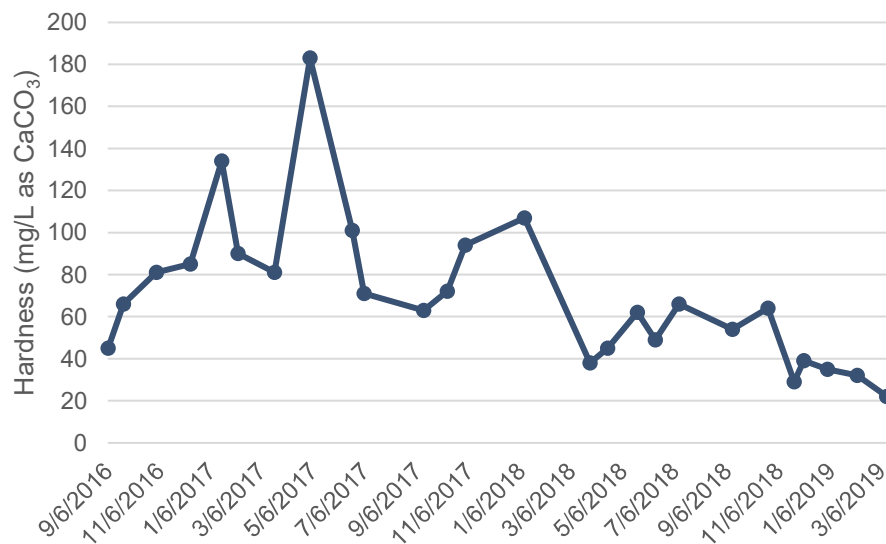


Figure B-18: Bacti Site 10 Hardness

Table A-1: Bacti Site 10 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/13/2019	0.7	57.7

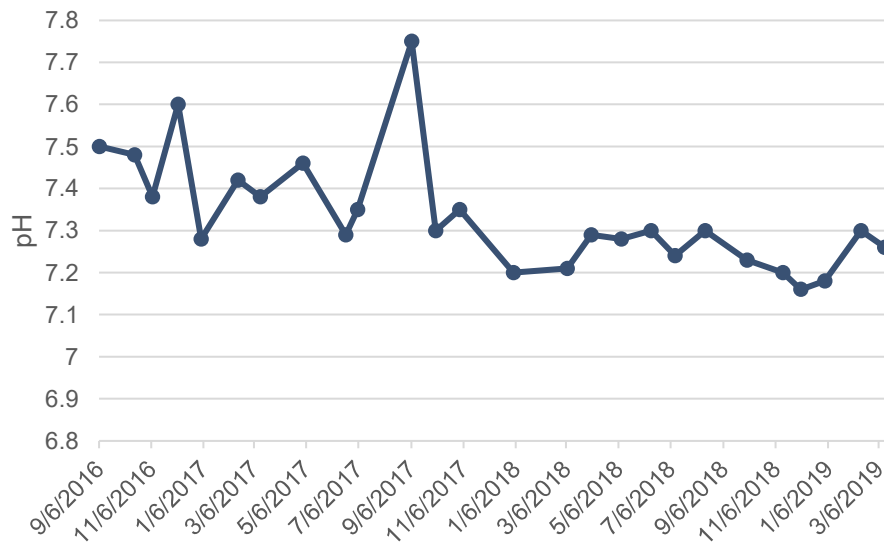


Figure B-19: Bacti Site 20 pH

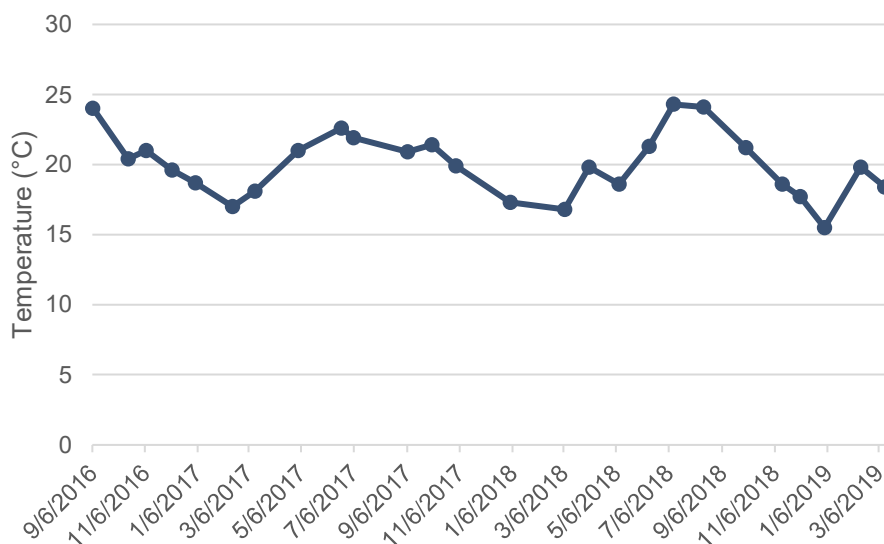


Figure B-20: Bacti Site 20 Temperature

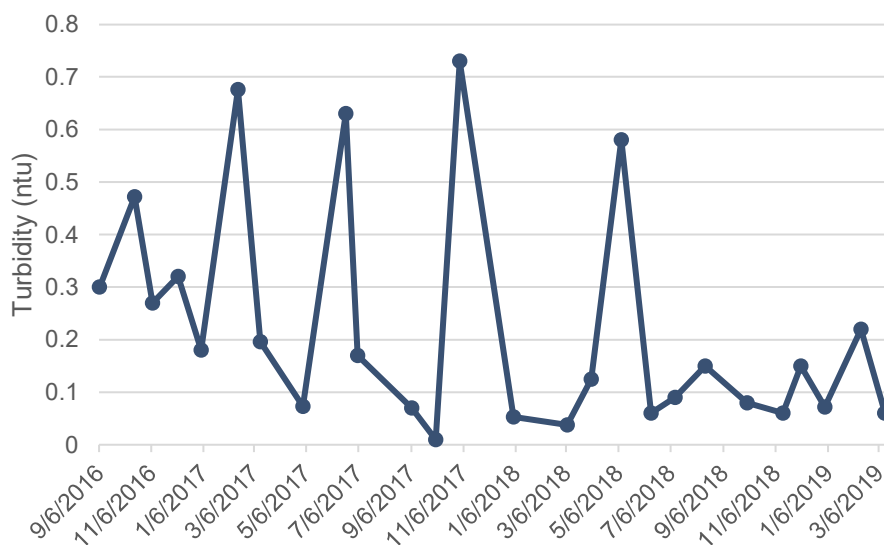


Figure B-21: Bacti Site 20 Turbidity

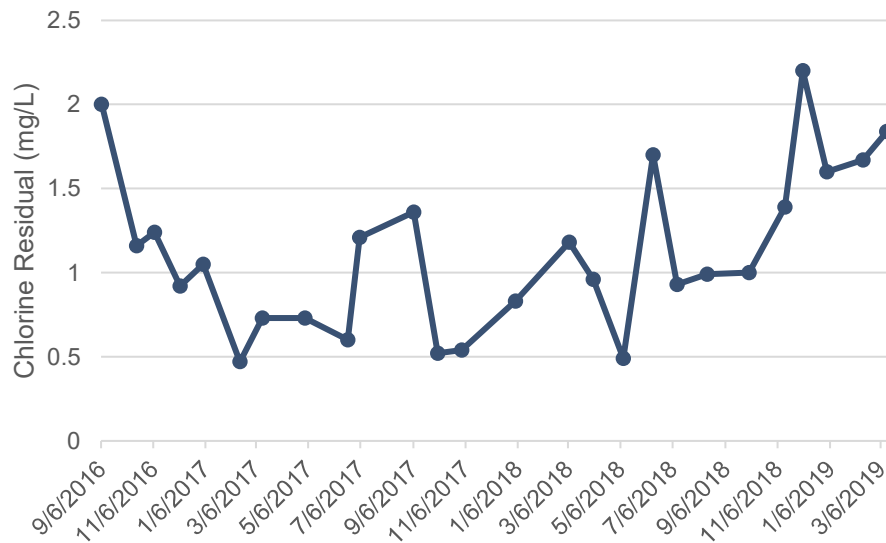


Figure B-22: Bacti Site 20 Chlorine Residual

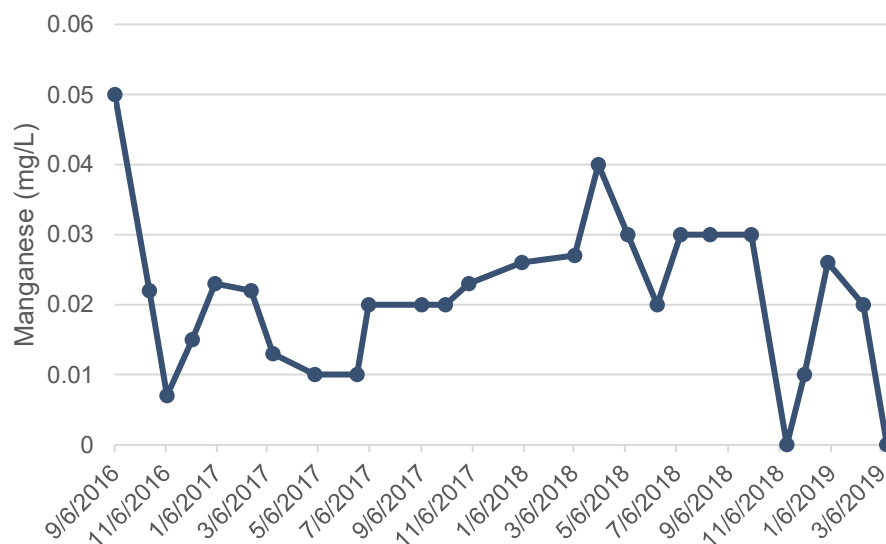


Figure B-23: Bacti Site 20 Manganese

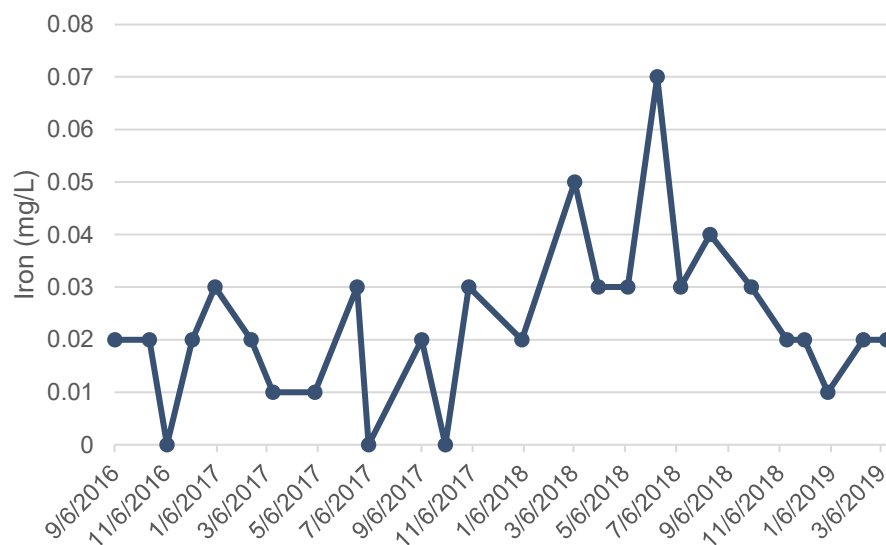


Figure B-24: Bacti Site 20 Iron

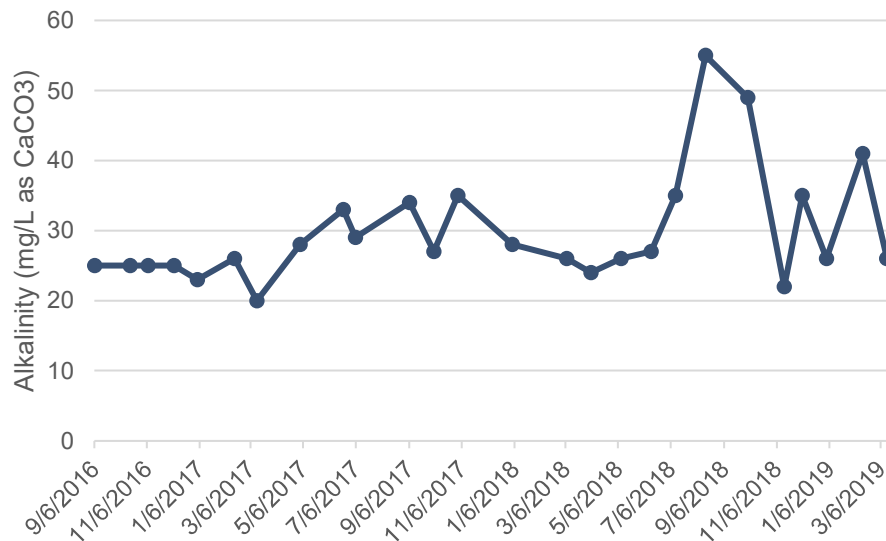


Figure B-25: Bacti Site 20 Alkalinity

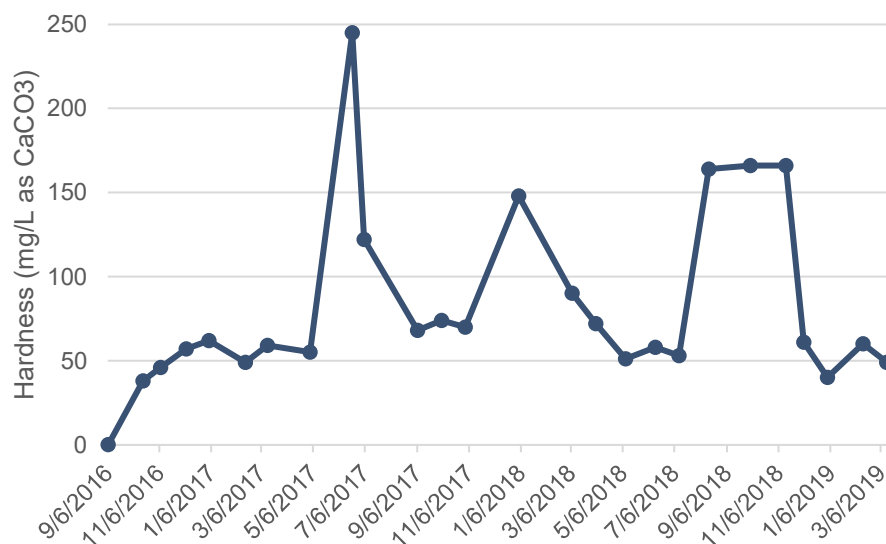


Figure B-26: Bacti Site 20 Hardness

Table A-2: Bacti Site 20 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/13/2019	0.76	63.1

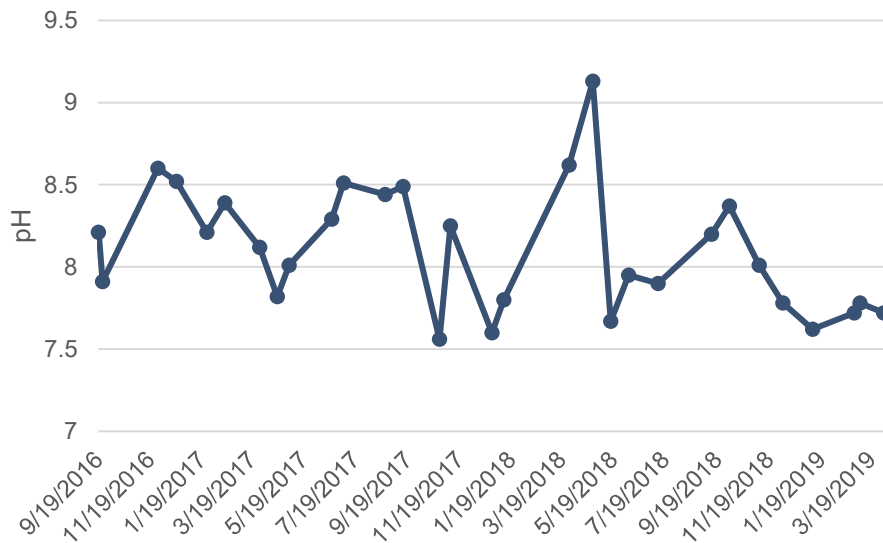


Figure B-27: Bacti Site 30 pH

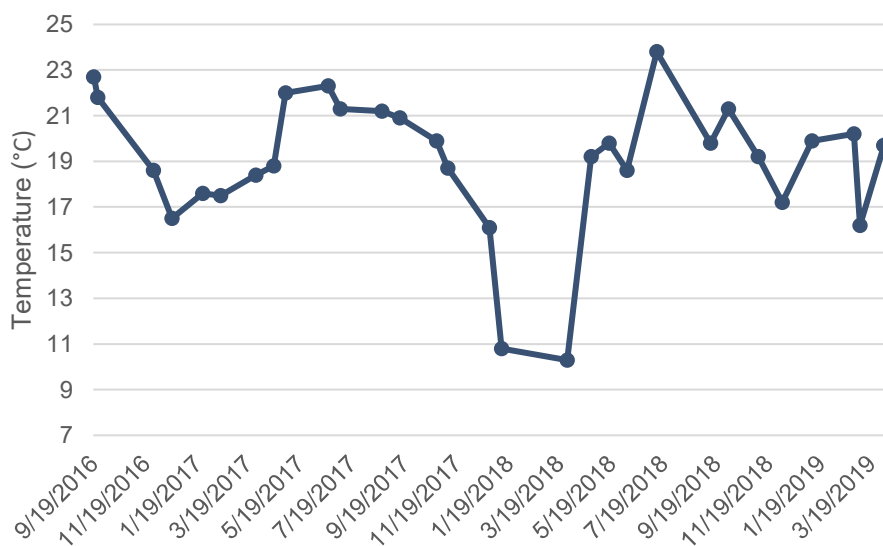


Figure B-28: Bacti Site 30 Temperature

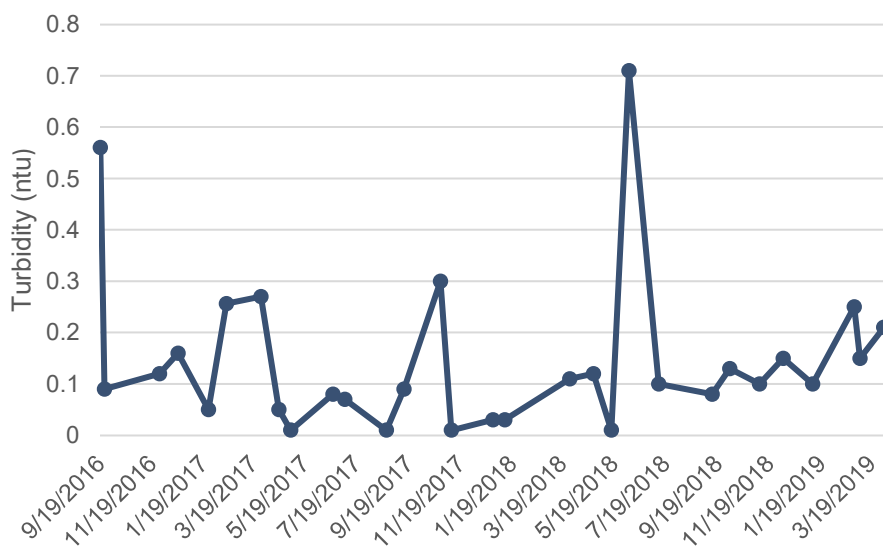


Figure B-29: Bacti Site 30 Turbidity

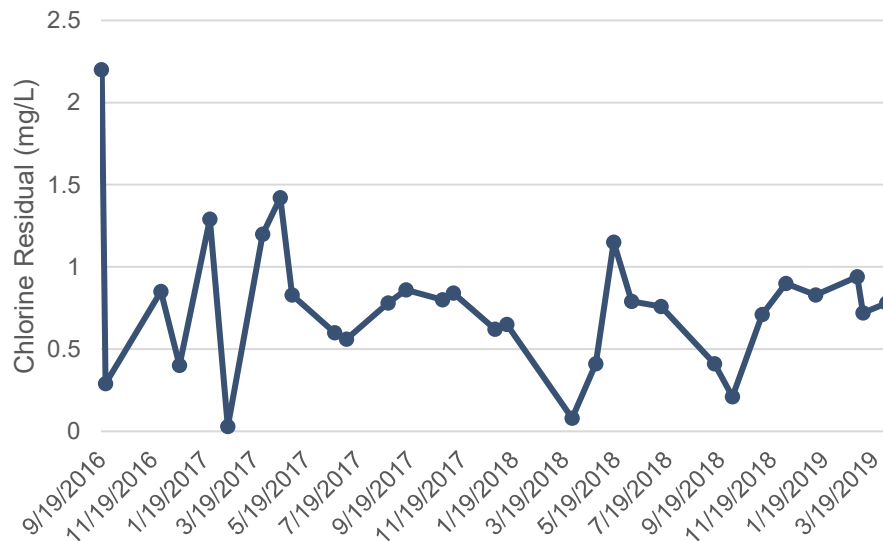


Figure B-30: Bacti Site 30 Chlorine Residual

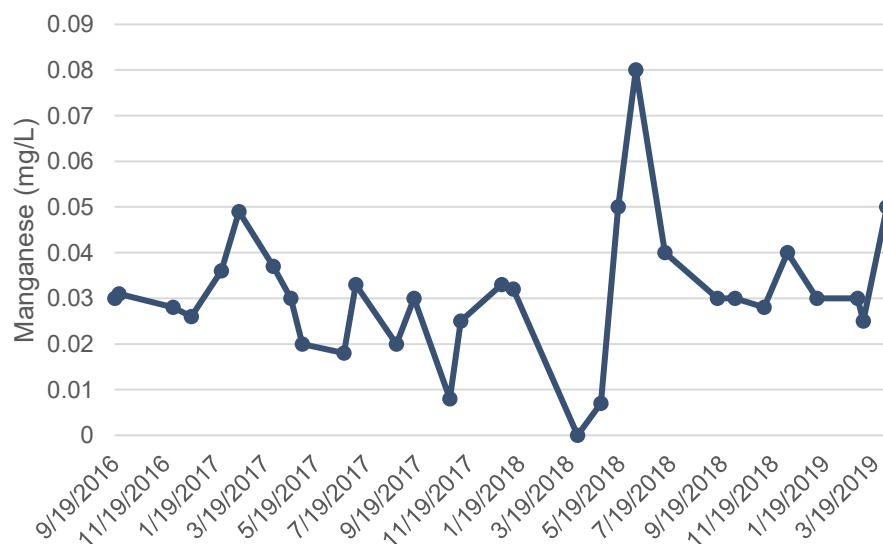


Figure B-31: Bacti Site 30 Manganese

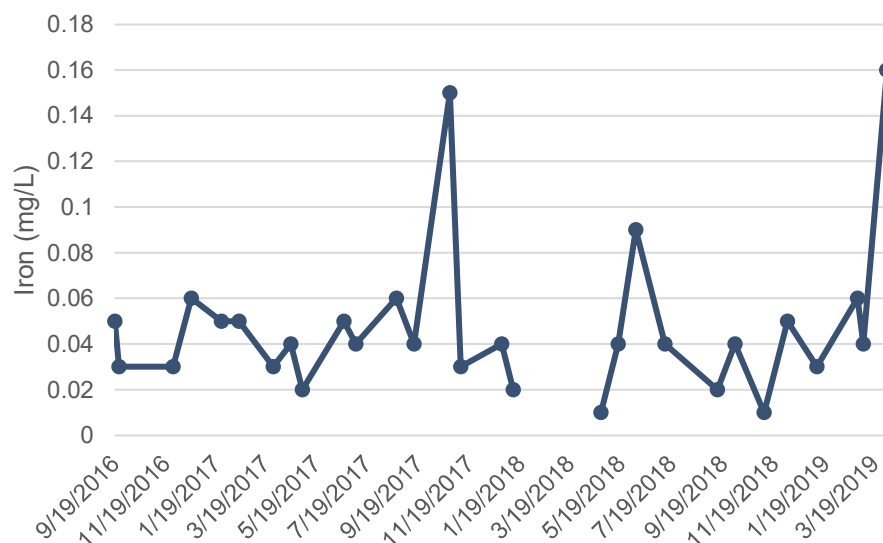


Figure B-32: Bacti Site 30 Iron

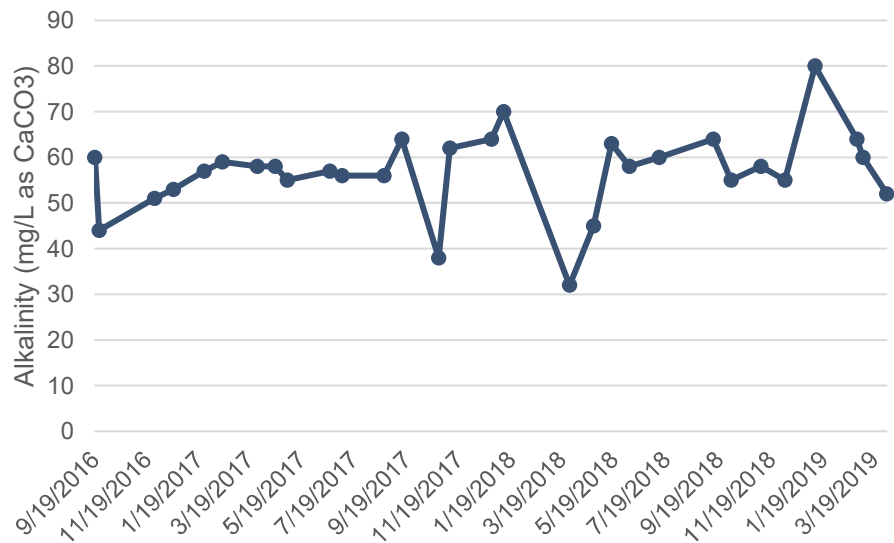


Figure B-33: Bacti Site 30 Alkalinity

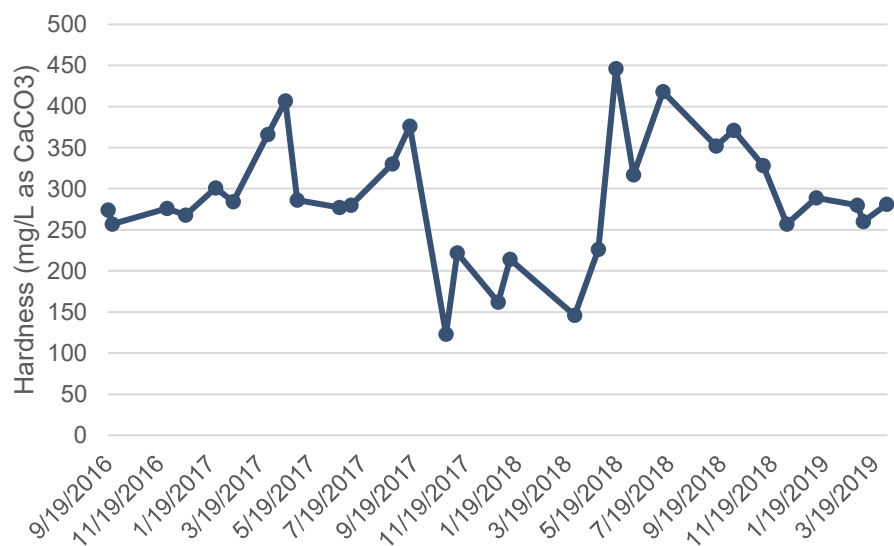


Figure B-34: Bacti Site 30 Hardness

Table A-3: Bacti Site 30 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
4/3/2019	1.29	178

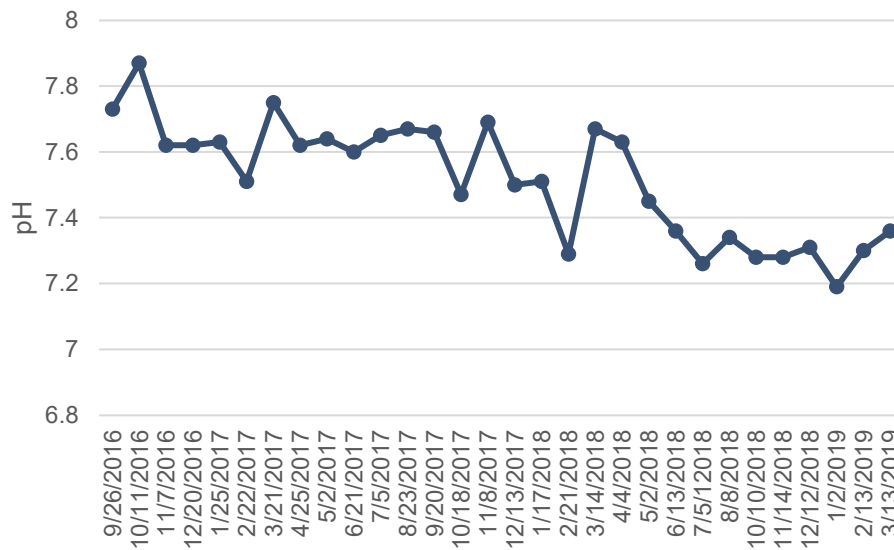


Figure B-35: Bacti Site 40 pH

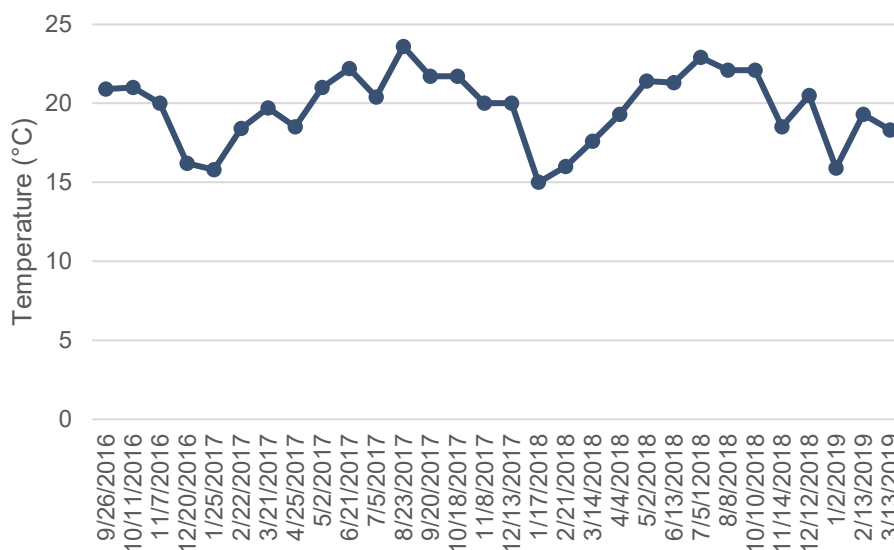


Figure B-36: Bacti Site 40 Temperature

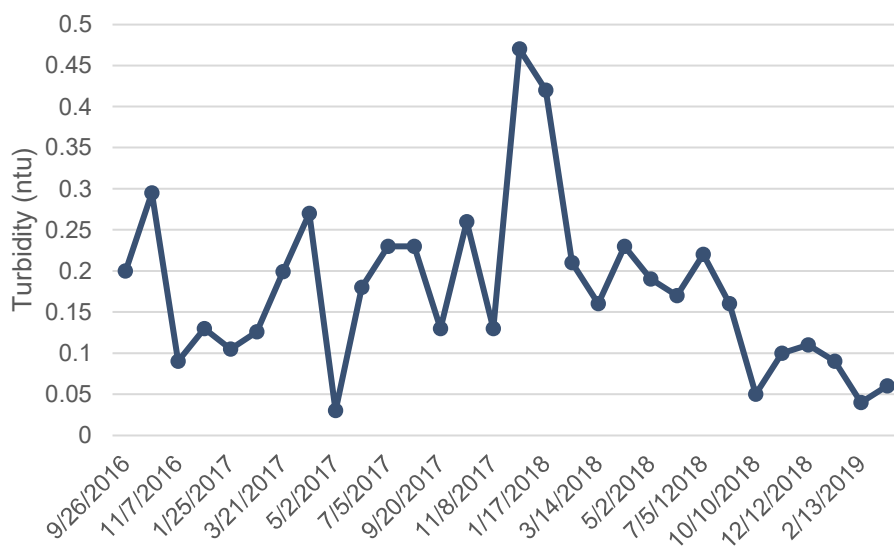


Figure B-37: Bacti Site 40 Turbidity



Figure B-38: Bacti Site 40 Chlorine Residual

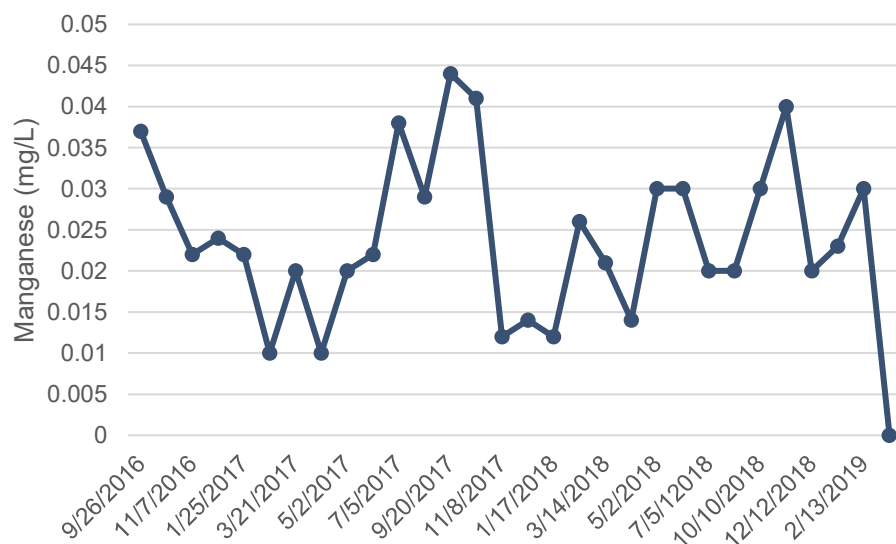


Figure B-39: Bacti Site 40 Manganese

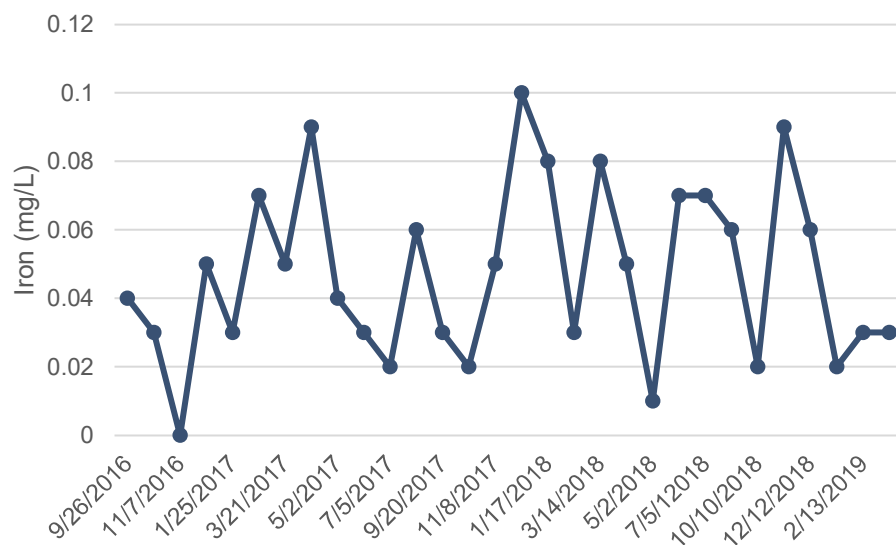


Figure B-40: Bacti Site 40 Iron

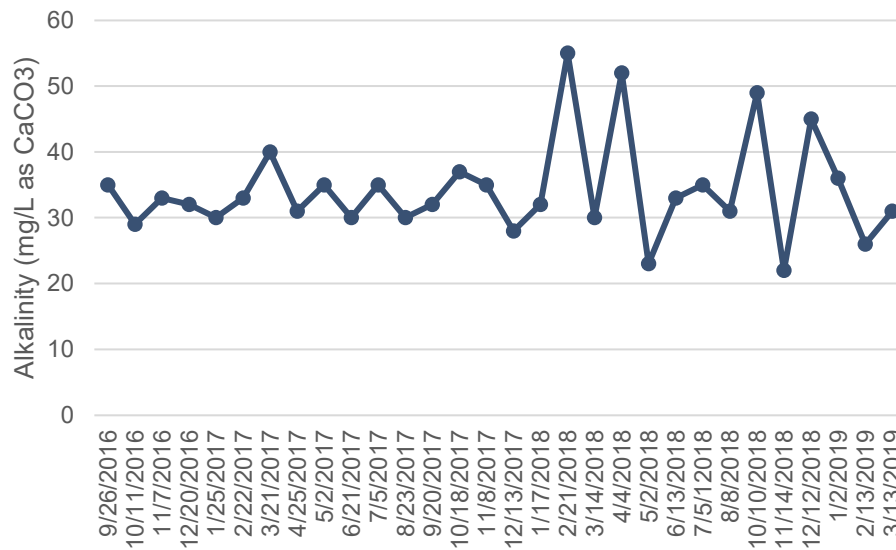


Figure B-41: Bacti Site 40 Alkalinity

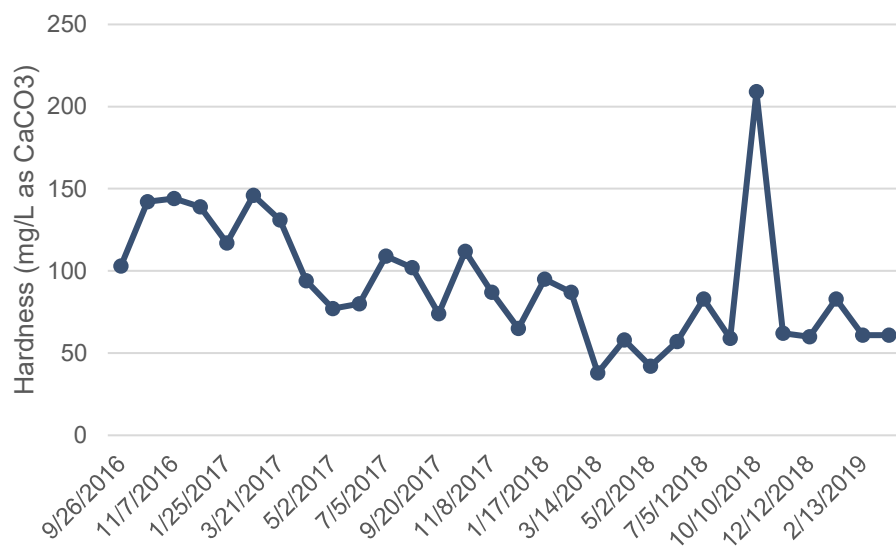


Figure B-42: Bacti Site 40 Hardness

Table A-4: Bacti Site 40 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/13/2019	0.69	124

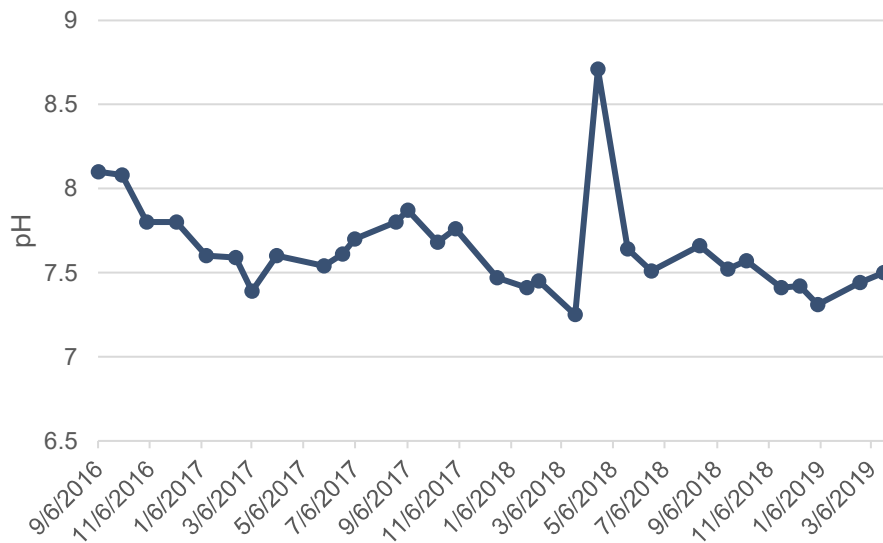


Figure B-43: Bacti Site 50 pH

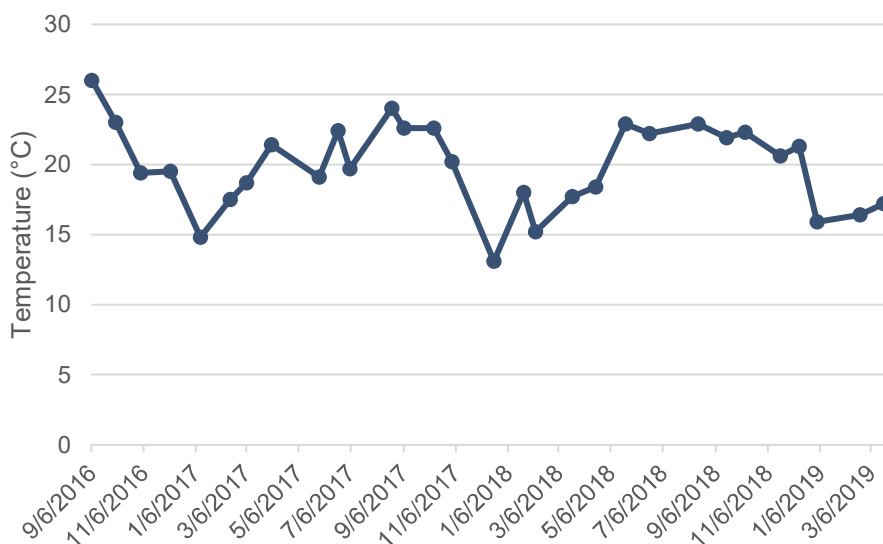


Figure B-44: Bacti Site 50 Temperature

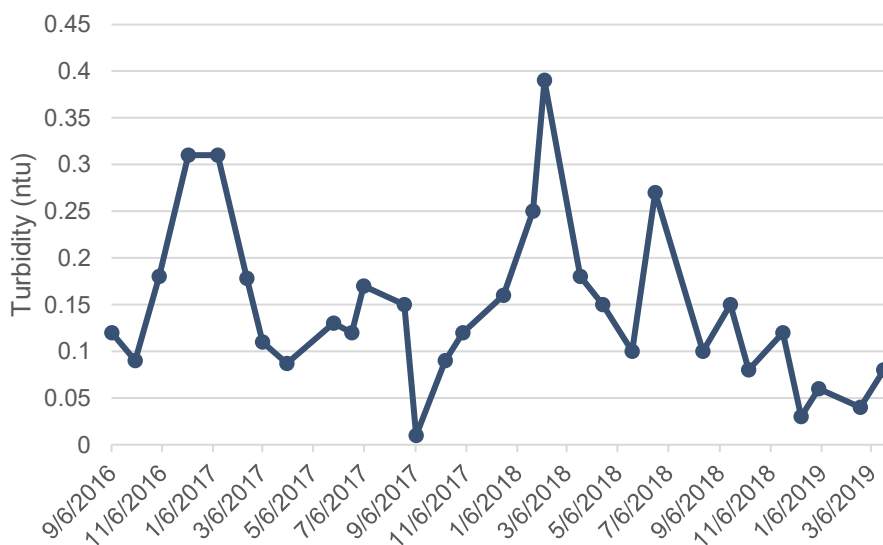


Figure B-45: Bacti Site 50 Turbidity

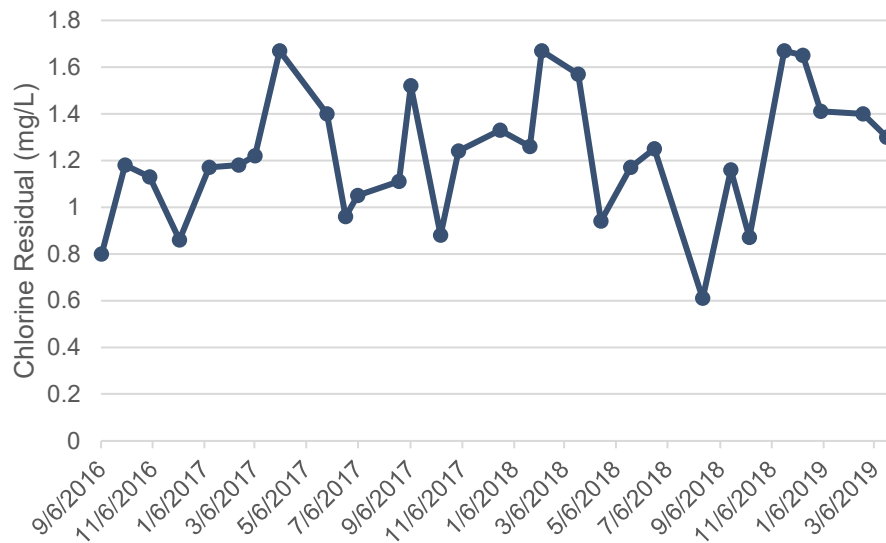


Figure B-46: Bacti Site 50 Chlorine Residual

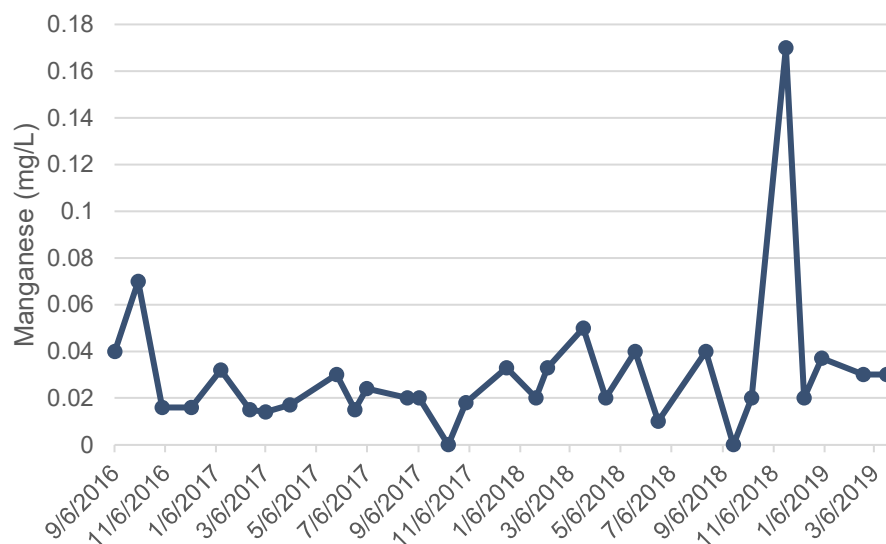


Figure B-47: Bacti Site 50 Manganese

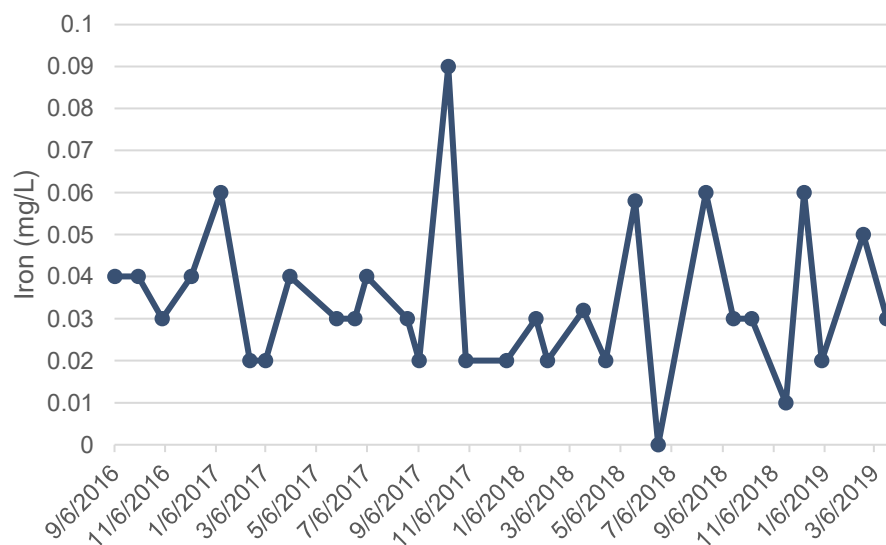


Figure B-48: Bacti Site 50 Iron

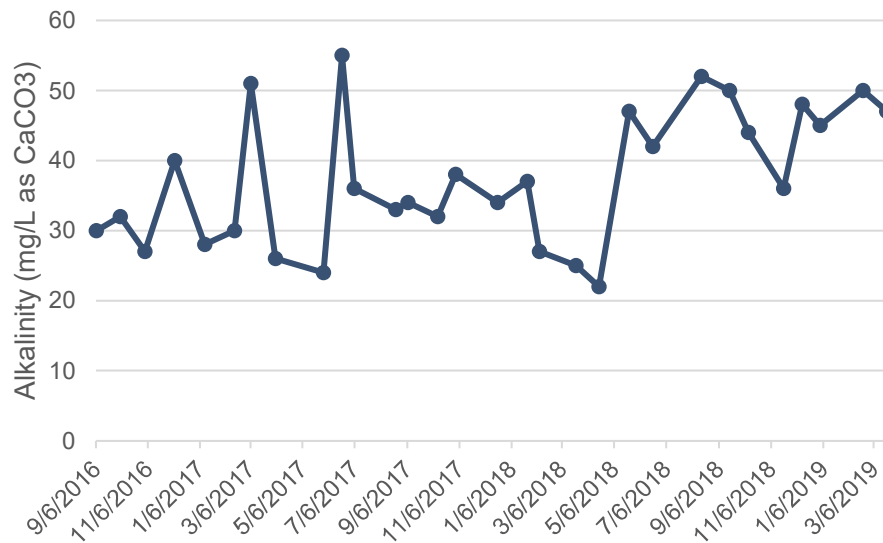


Figure B-49: Bacti Site 50 Alkalinity

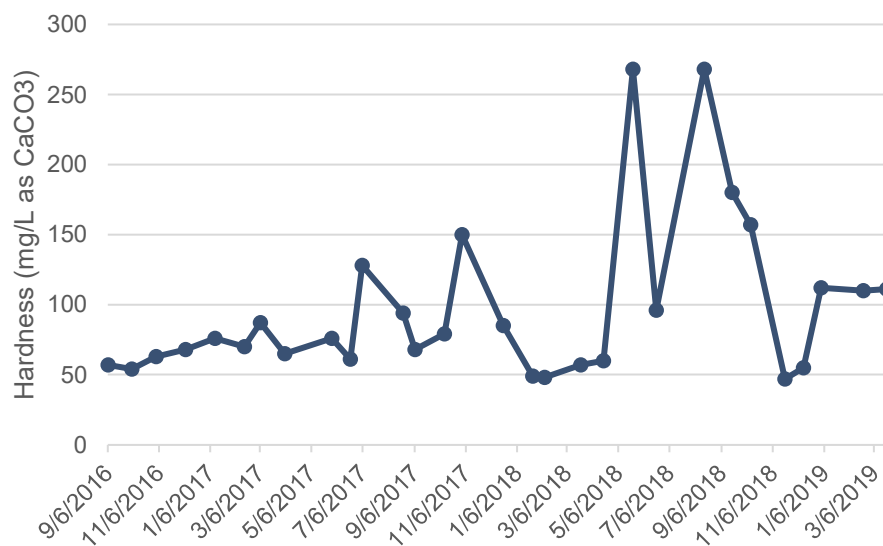


Figure B-50: Bacti Site 50 Hardness

Table A-5: Bacti Site 50 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/21/2019	1.16	106

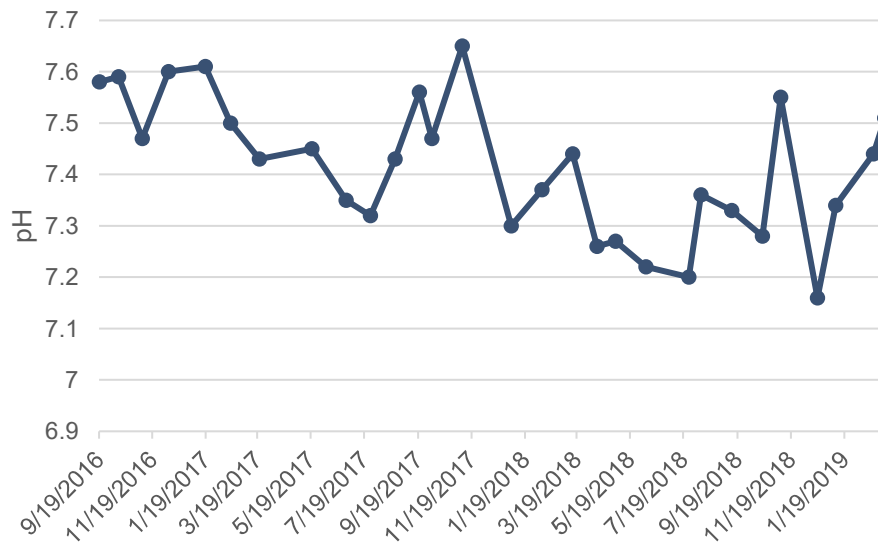


Figure B-51: Bacti Site 60 pH

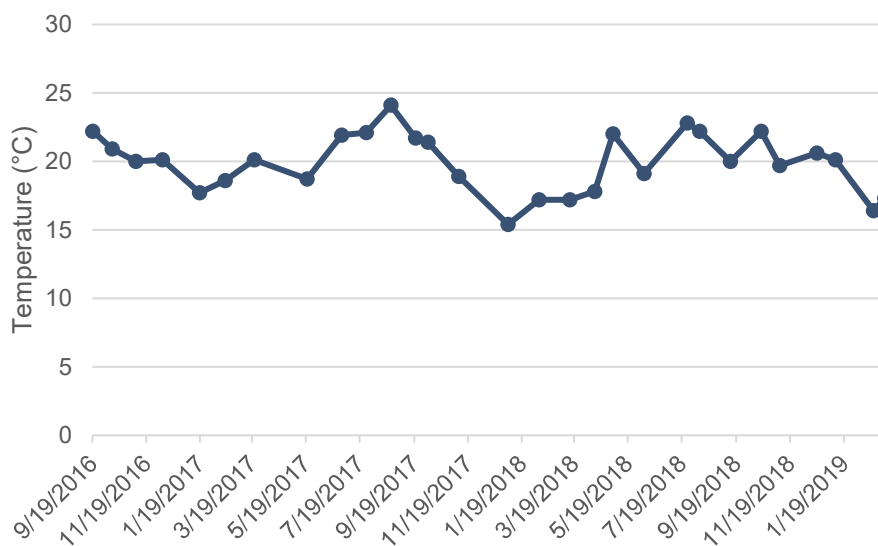


Figure B-52: Bacti Site 60 Temperature

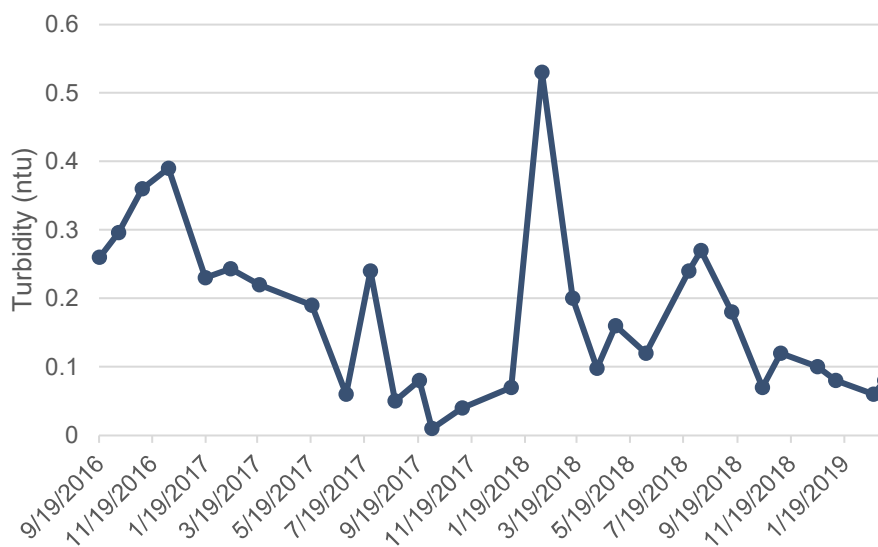


Figure B-53: Bacti Site 60 Turbidity

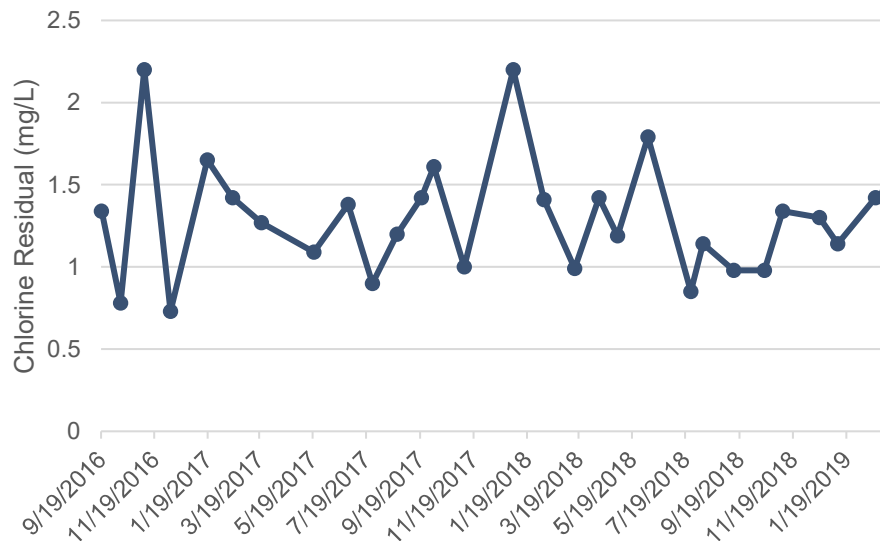


Figure B-54: Bacti Site 60 Chlorine Residual

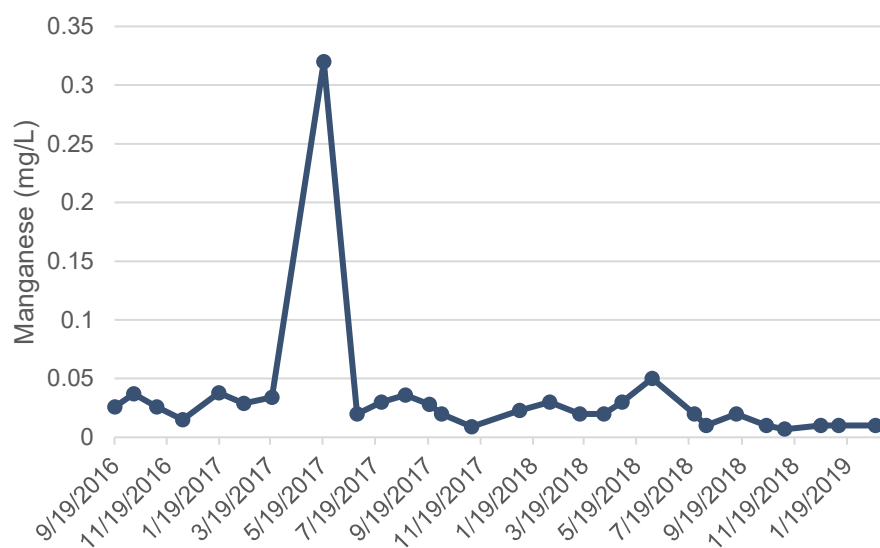


Figure B-55: Bacti Site 60 Manganese

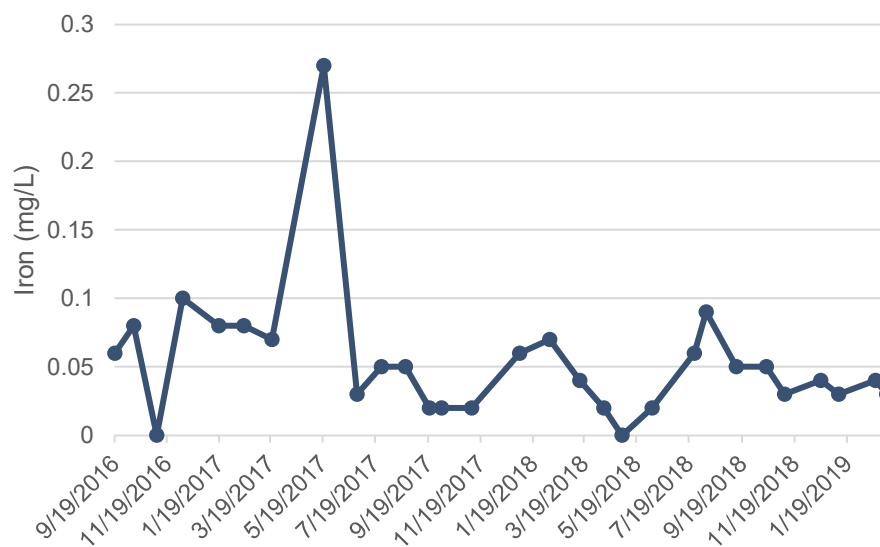


Figure B-56: Bacti Site 60 Iron

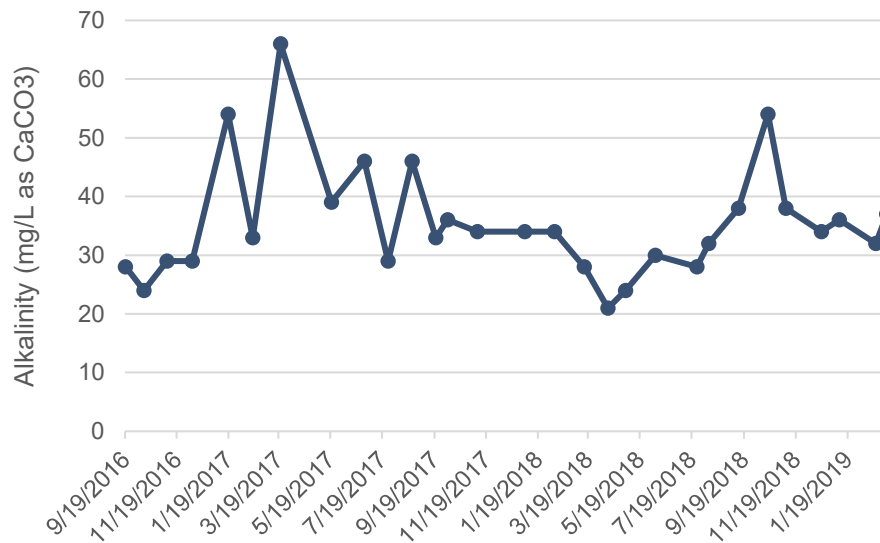


Figure B-57: Bacti Site 60 Alkalinity

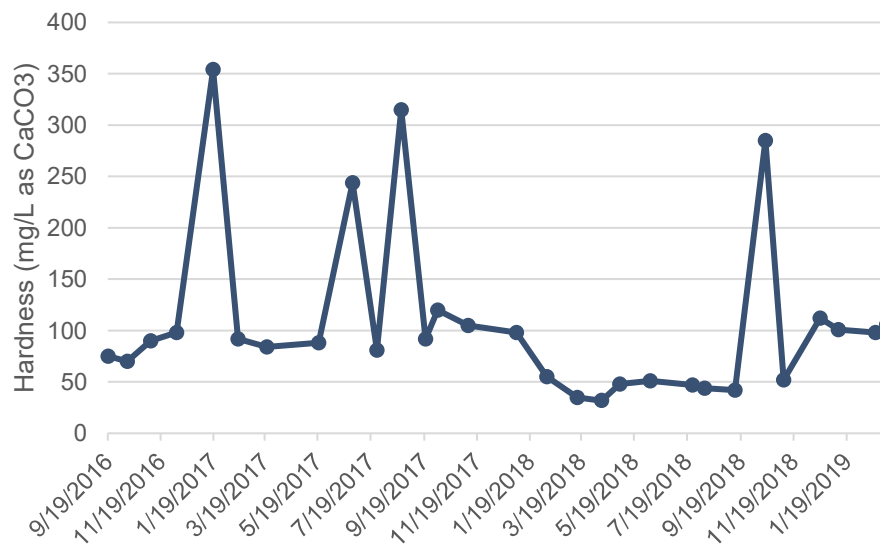


Figure B-58: Bacti Site 60 Hardness

Table A-6: Bacti Site 60 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
NA	NA	NA

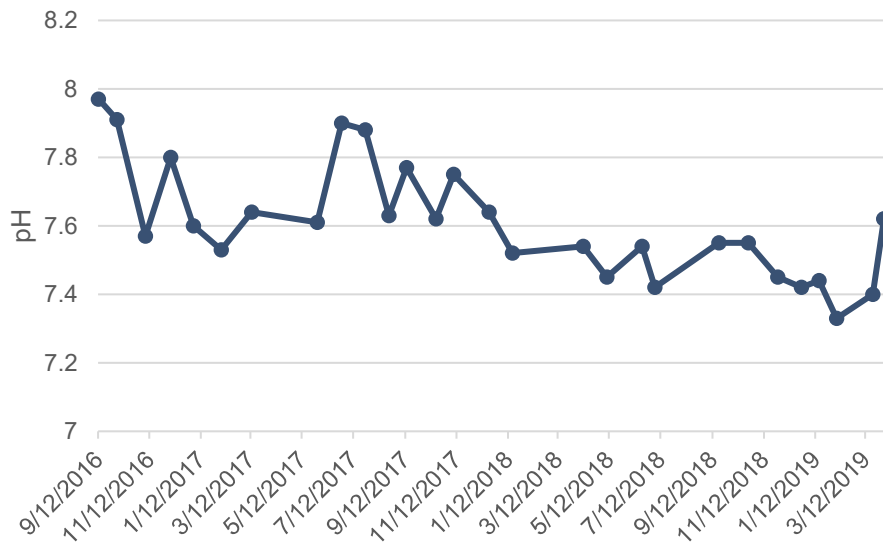


Figure B-59: Bacti Site 70 pH

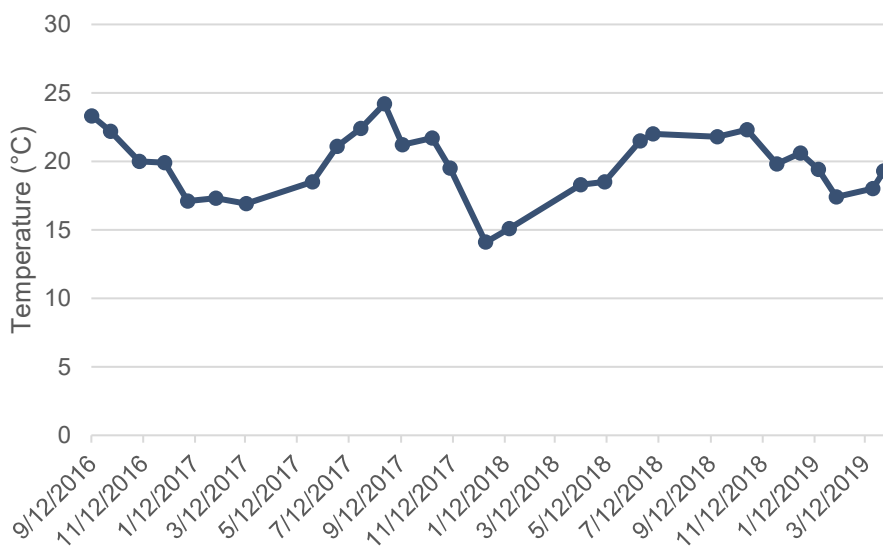


Figure B-60: Bacti Site 70 Temperature

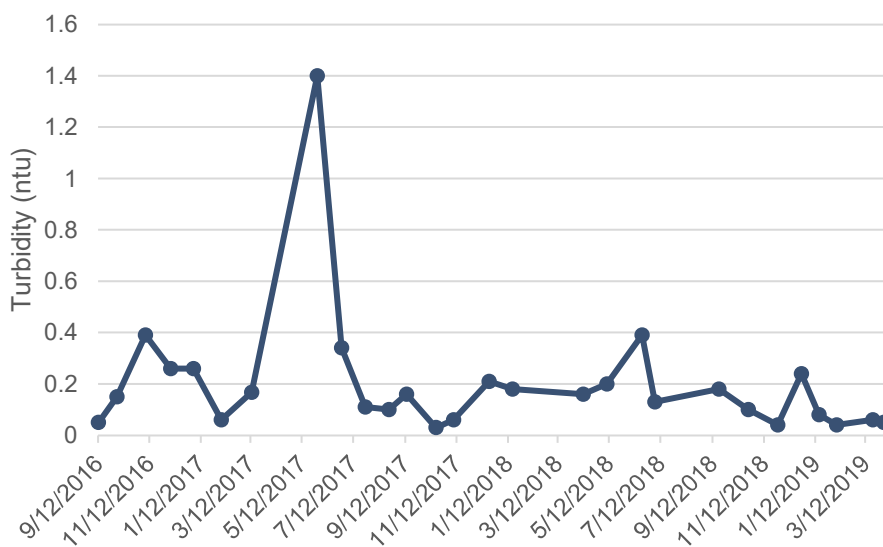


Figure B-61: Bacti Site 70 Turbidity

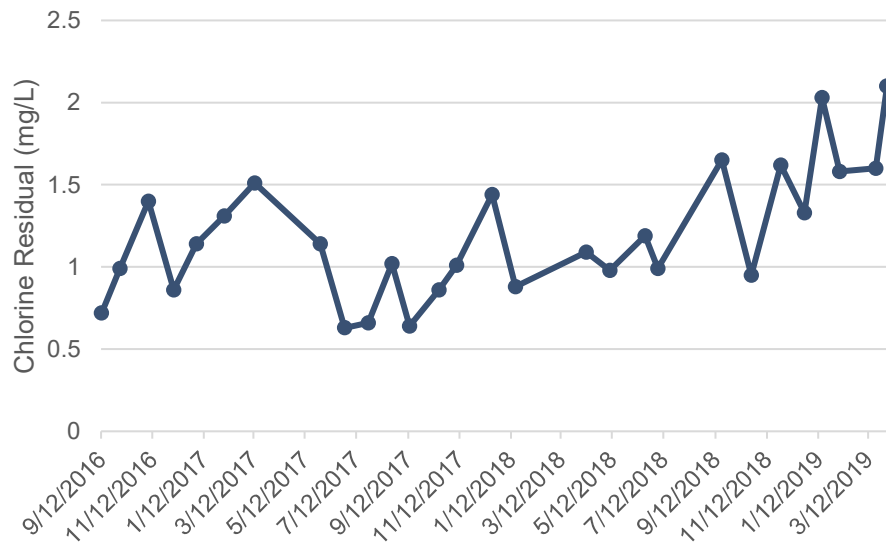


Figure B-62: Bacti Site 70 Chlorine Residual

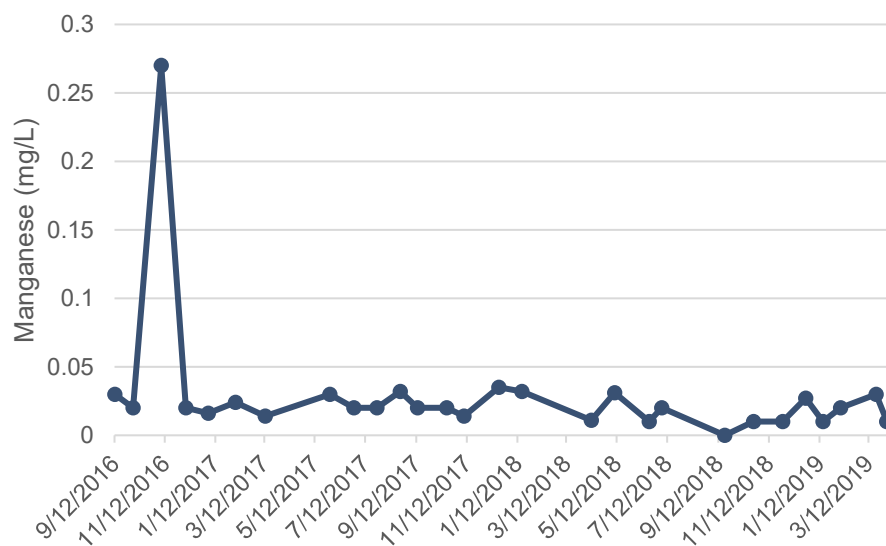


Figure B-63: Bacti Site 70 Manganese

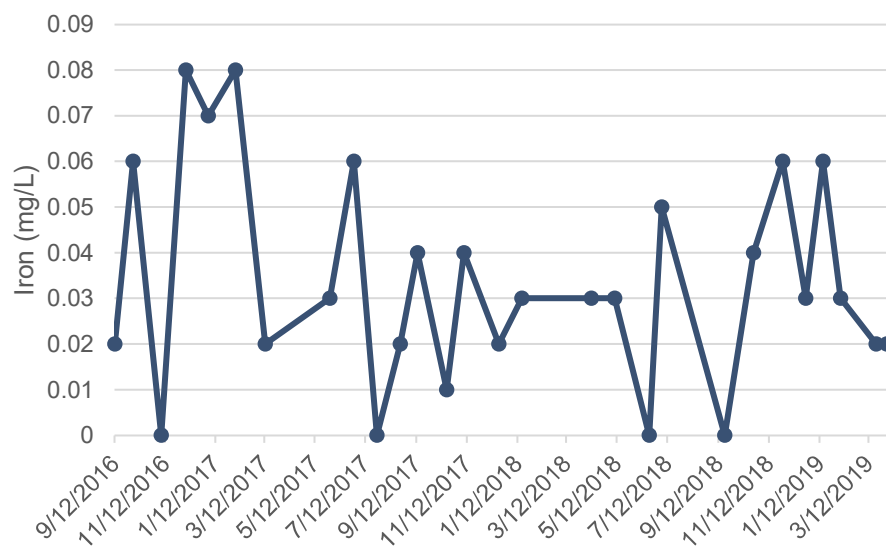


Figure B-64: Bacti Site 70 Iron

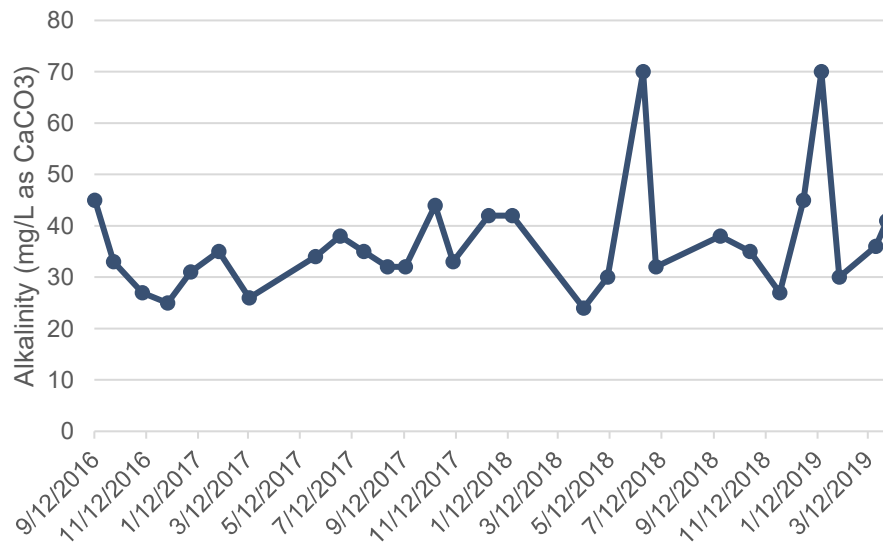


Figure B-65: Bacti Site 70 Alkalinity

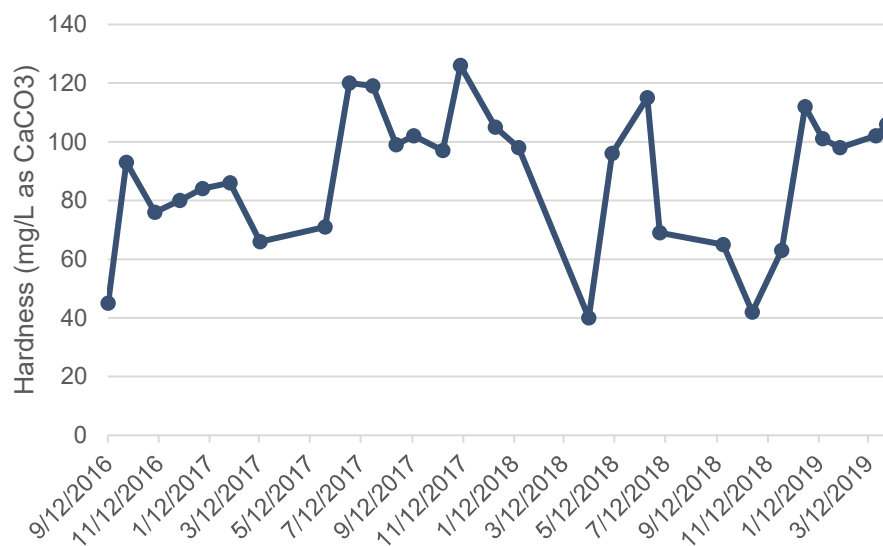


Figure B-66: Bacti Site 70 Hardness

Table A-7: Bacti Site 70 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/21/2019	1.09	137
4/3/2019	1.34	144

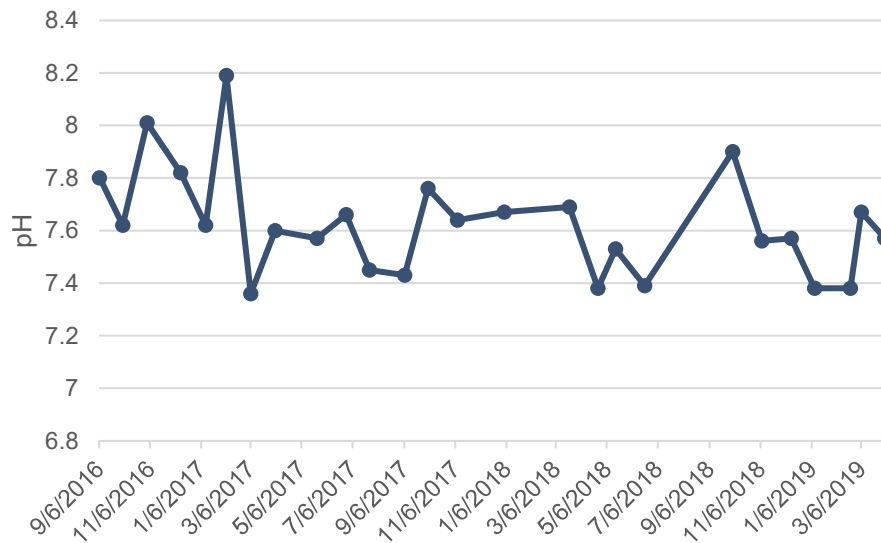


Figure B-67: Bacti Site 80 pH

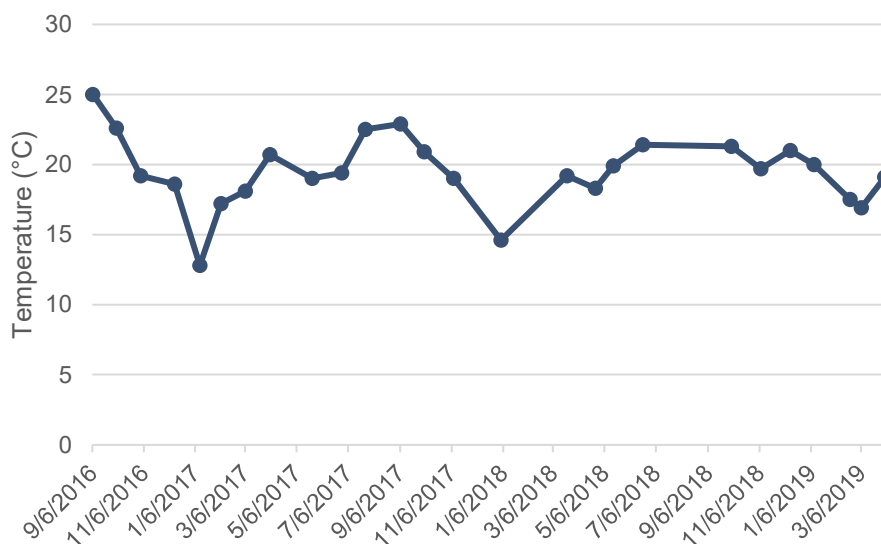


Figure B-68: Bacti Site 18 Temperature

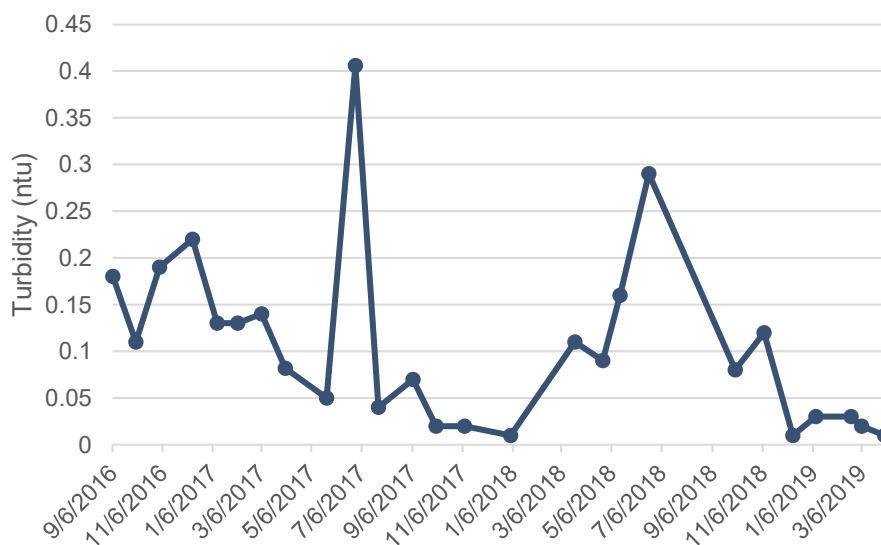
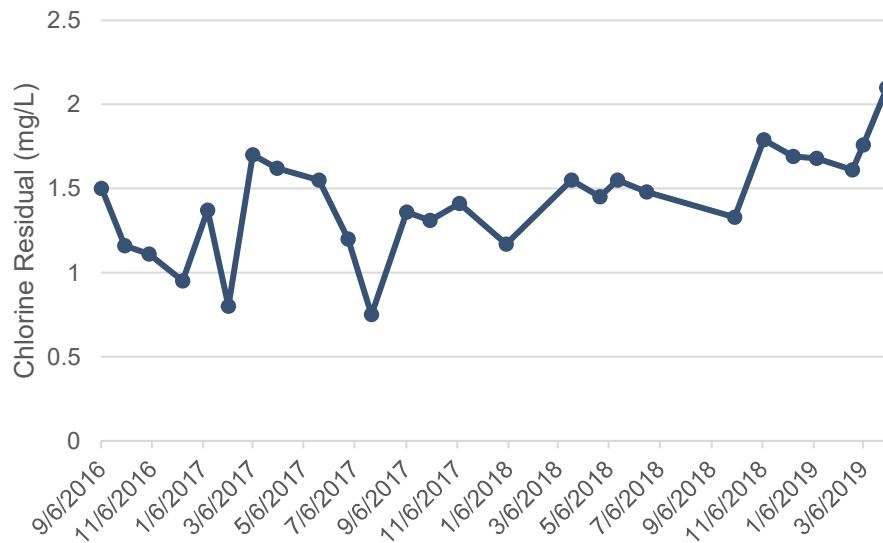


Figure B-69: Bacti Site 80 Turbidity



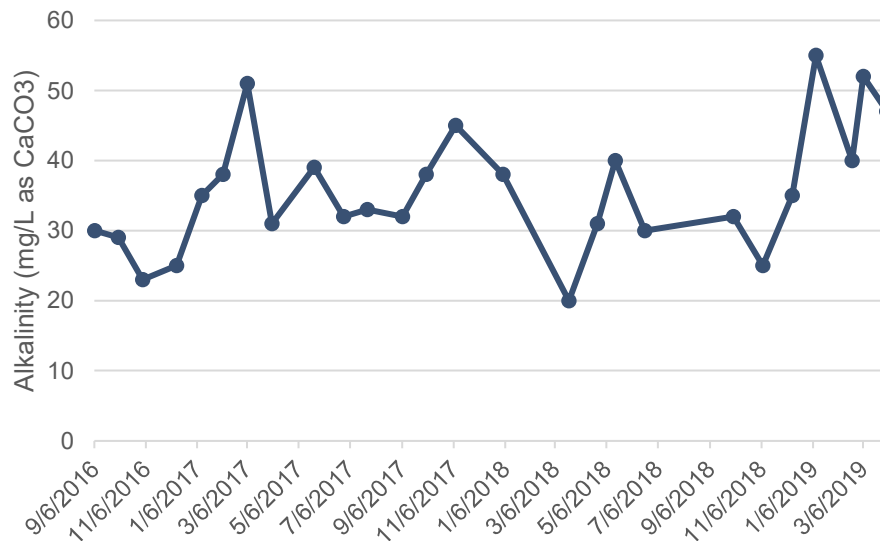


Figure B-73: Bacti Site 80 Alkalinity

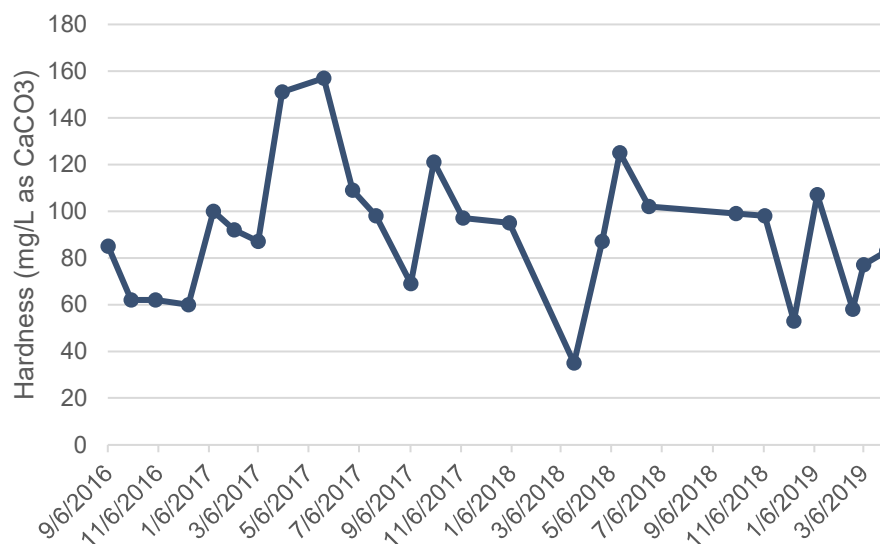


Figure B-74: Bacti Site 80 Hardness

Table A-8: Bacti Site 80 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
4/3/2019	1.36	272

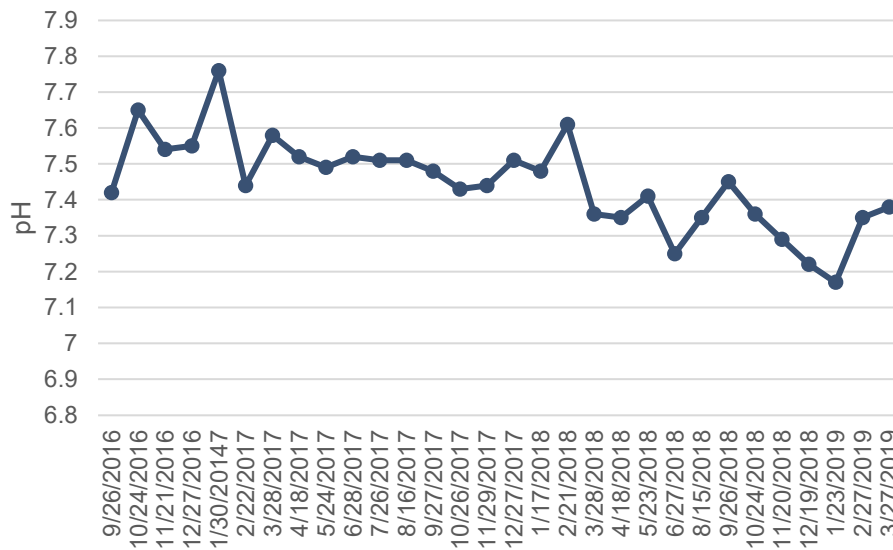


Figure B-75: Bacti Site 90 pH

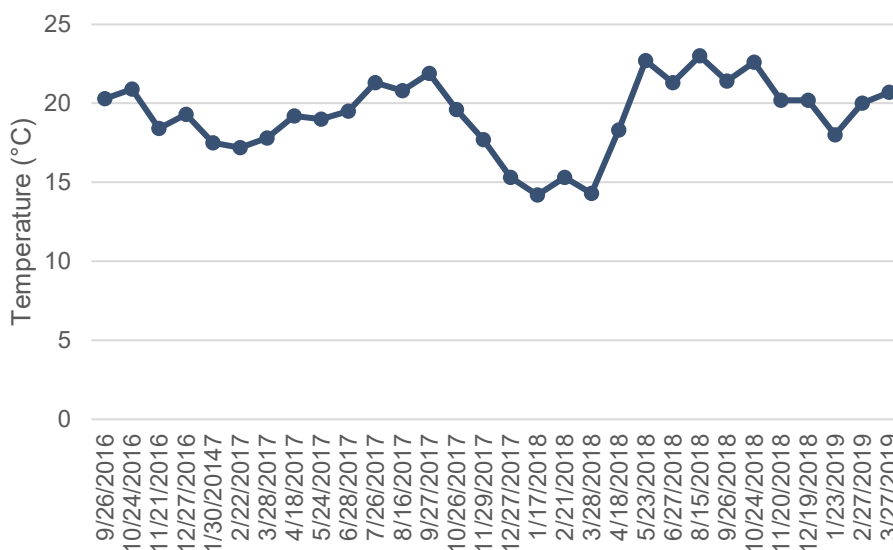


Figure B-76: Bacti Site 90 Temperature

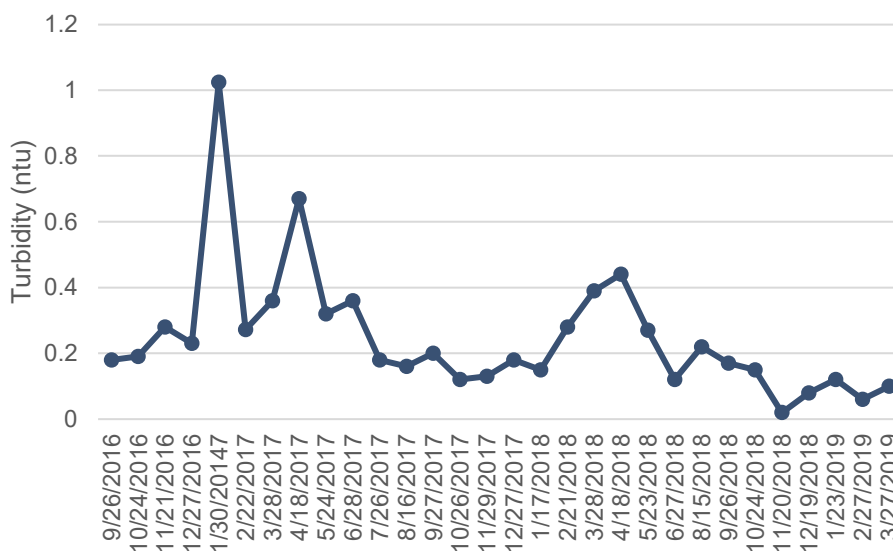


Figure B-77: Bacti Site 90 Turbidity

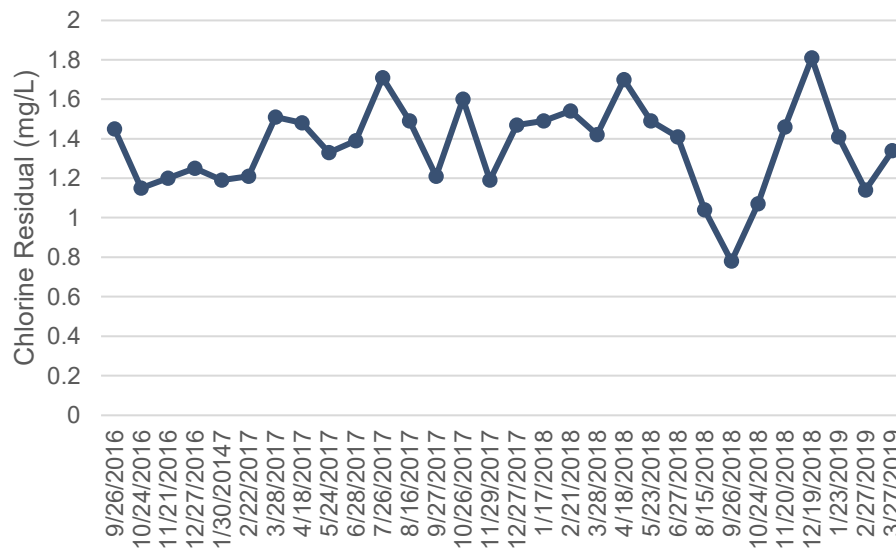


Figure B-78: Bacti Site 90 Chlorine Residual

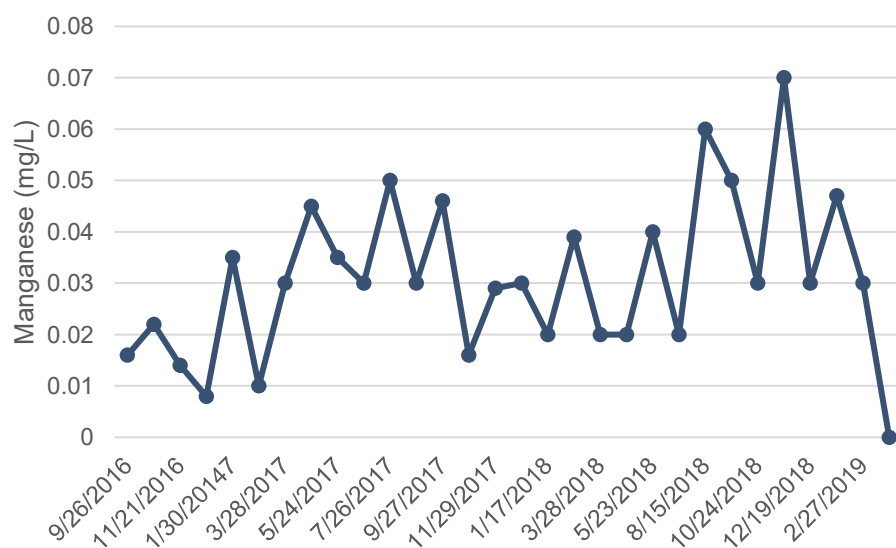


Figure B-79: Bacti Site 90 Manganese

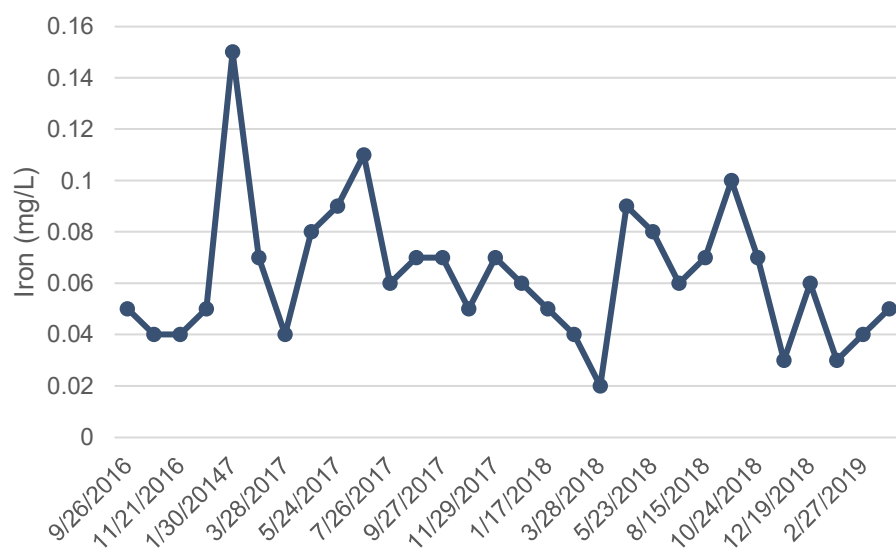


Figure B-80: Bacti Site 90 Iron

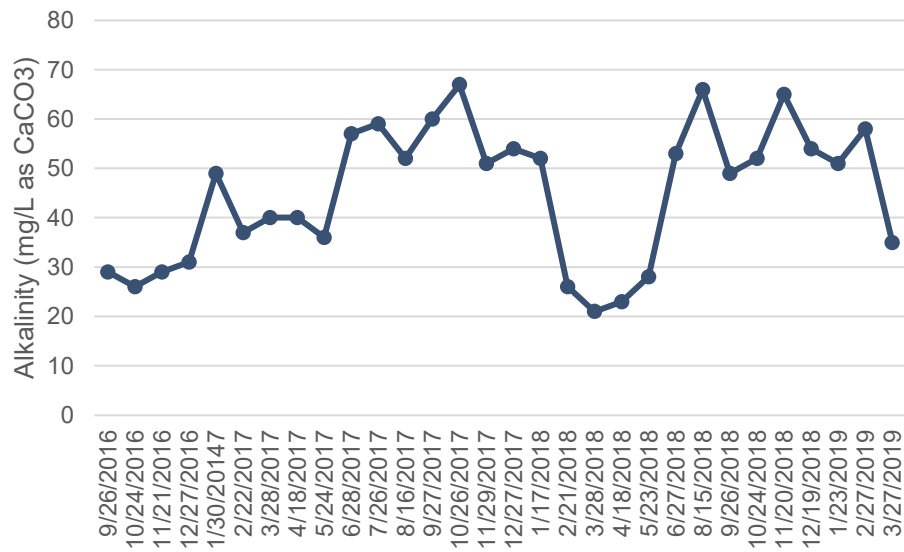


Figure B-81: Bacti Site 90 Alkalinity

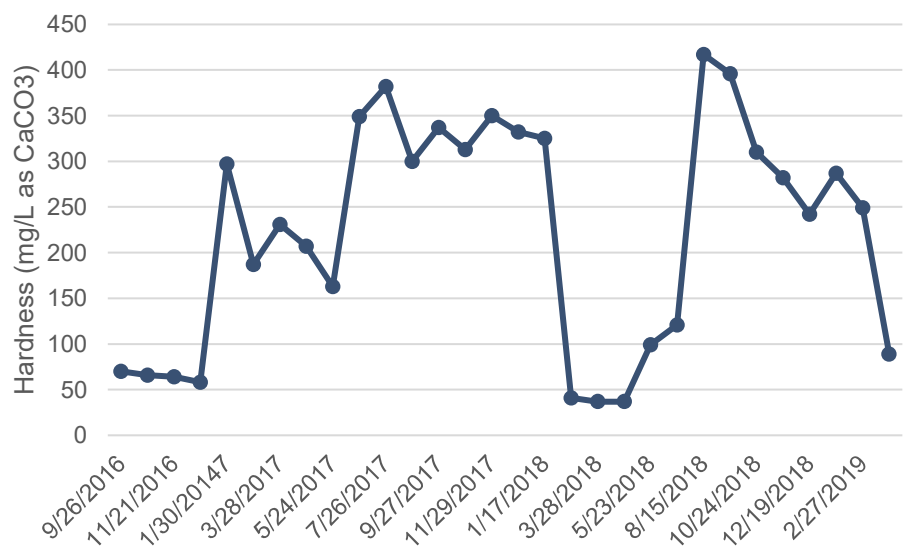


Figure B-82: Bacti Site 90 Hardness

Table A-9: Bacti Site 90 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/27/2019	1.2	128

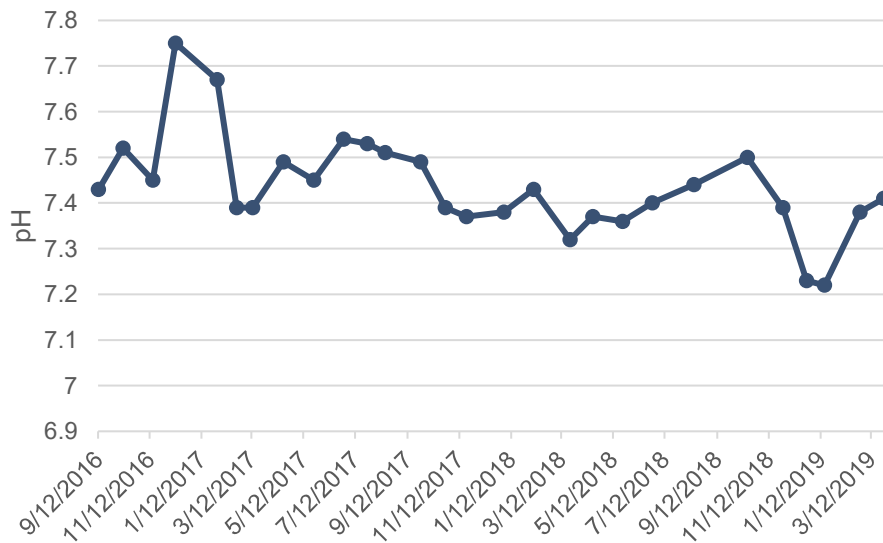


Figure B-83: Bacti Site 100 pH

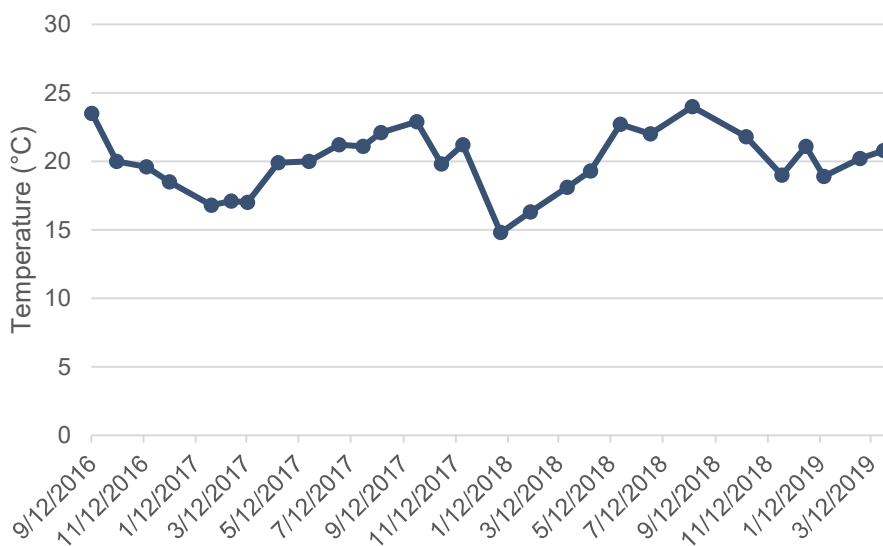


Figure B-84: Bacti Site 100 Temperature

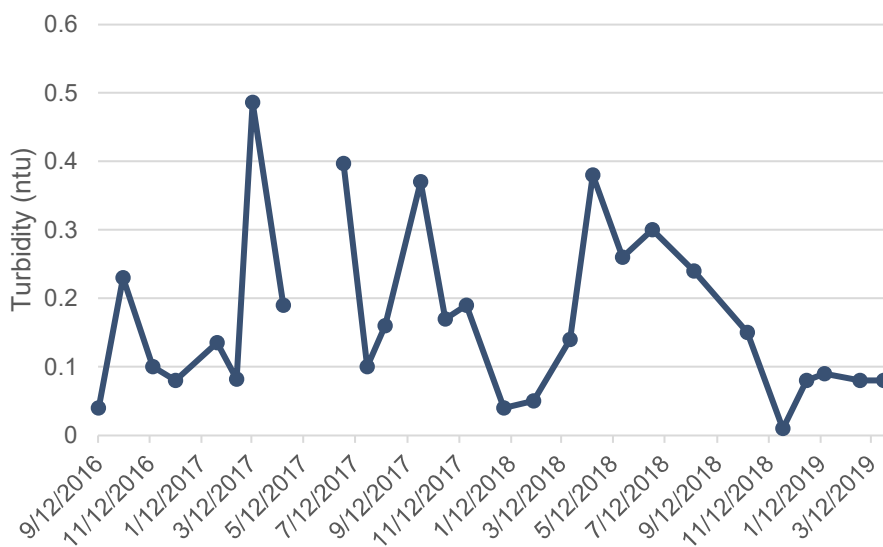


Figure B-85: Bacti Site 100 Turbidity

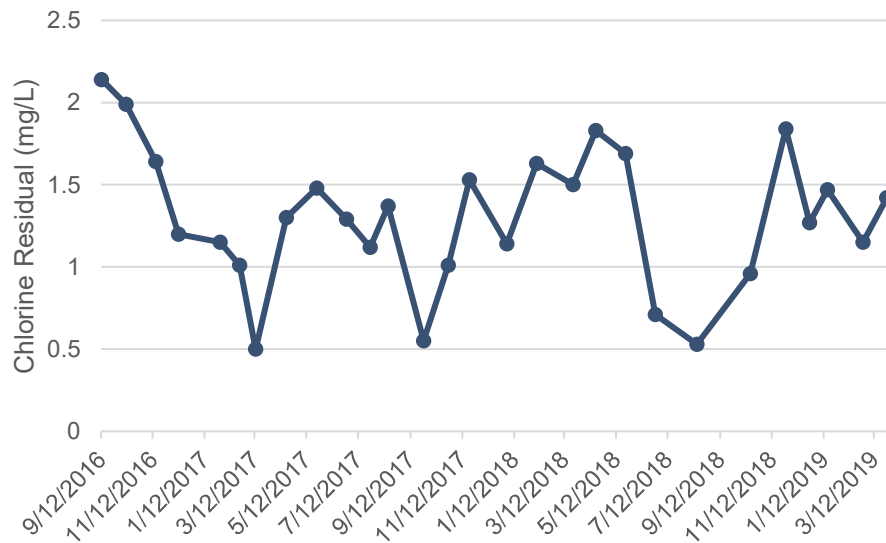


Figure B-86: Bacti Site 100 Chlorine Residual

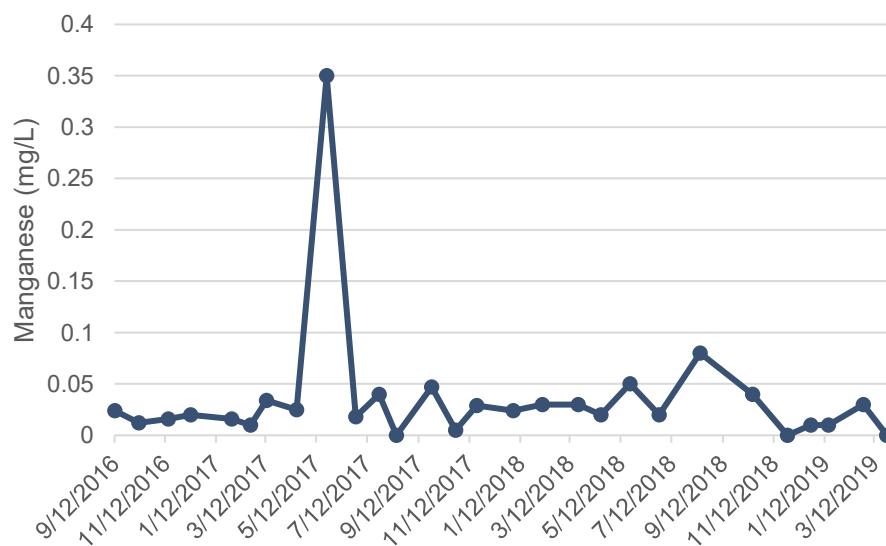


Figure B-87: Bacti Site 100 Manganese

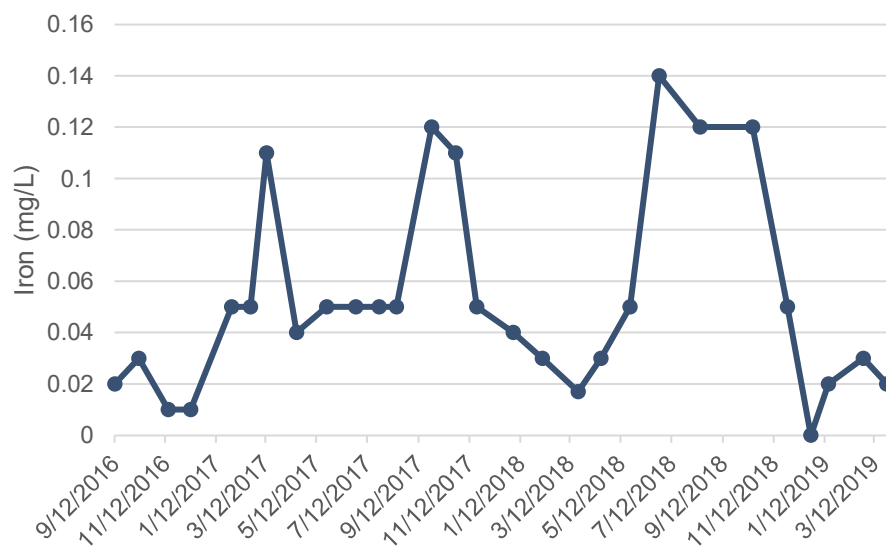


Figure B-88: Bacti Site 100 Iron

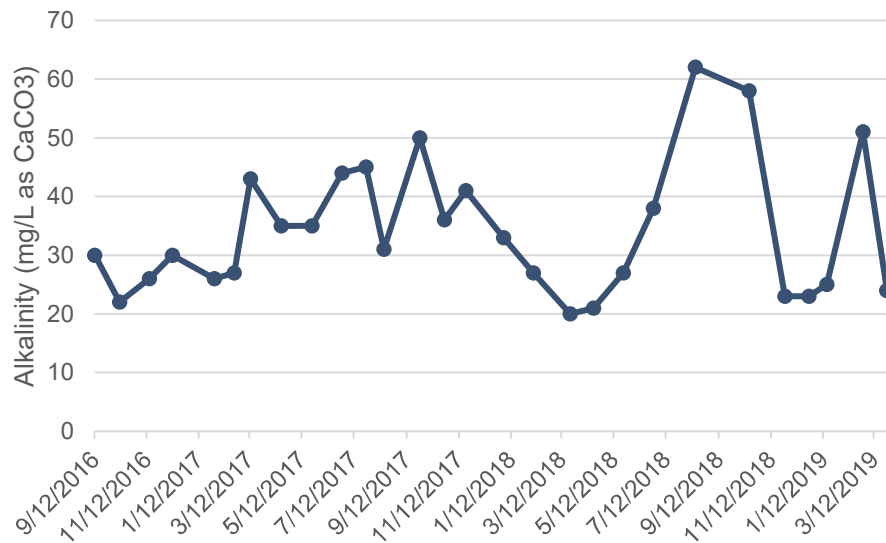


Figure B-89: Bacti Site 100 Alkalinity

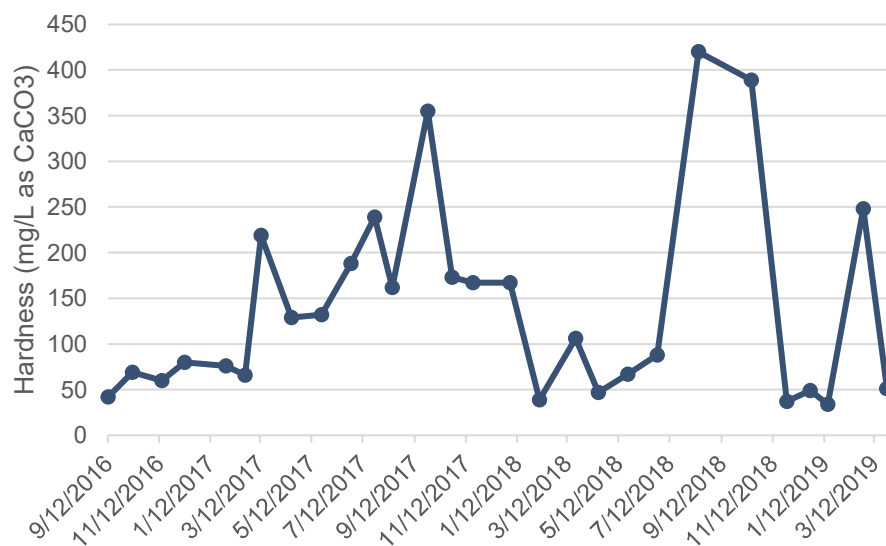


Figure B-90: Bacti Site 100 Hardness

Table A-10: Bacti Site 100 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/27/2019	1.2	81

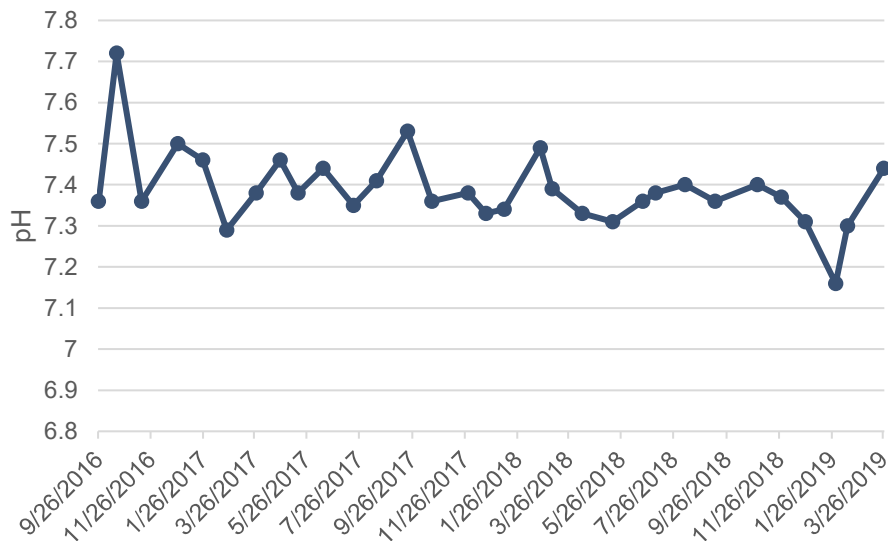


Figure B-91: Bacti Site 110 pH

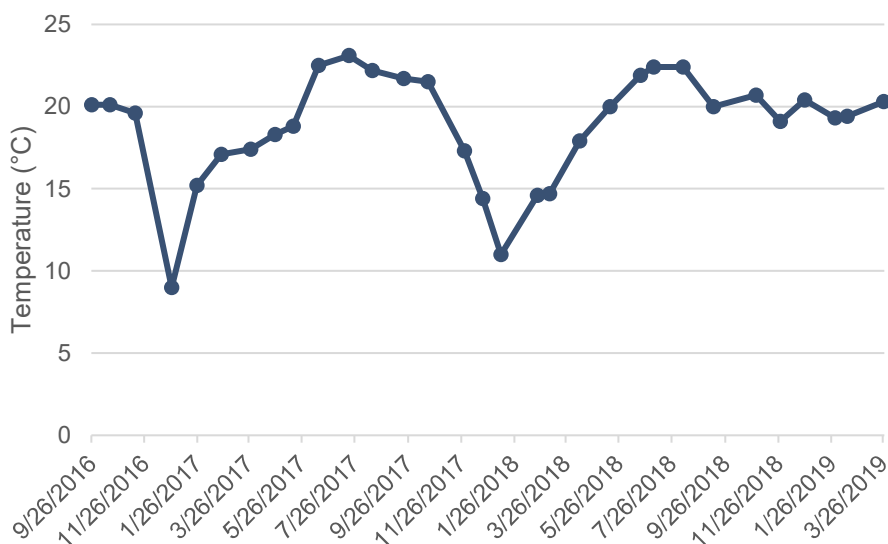


Figure B-92: Bacti Site 110 Temperature

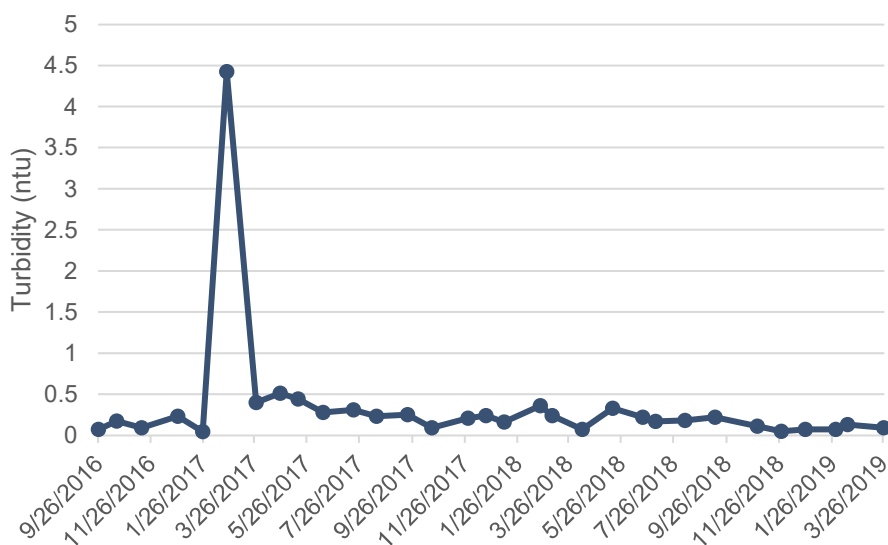


Figure B-93: Bacti Site 110 Turbidity

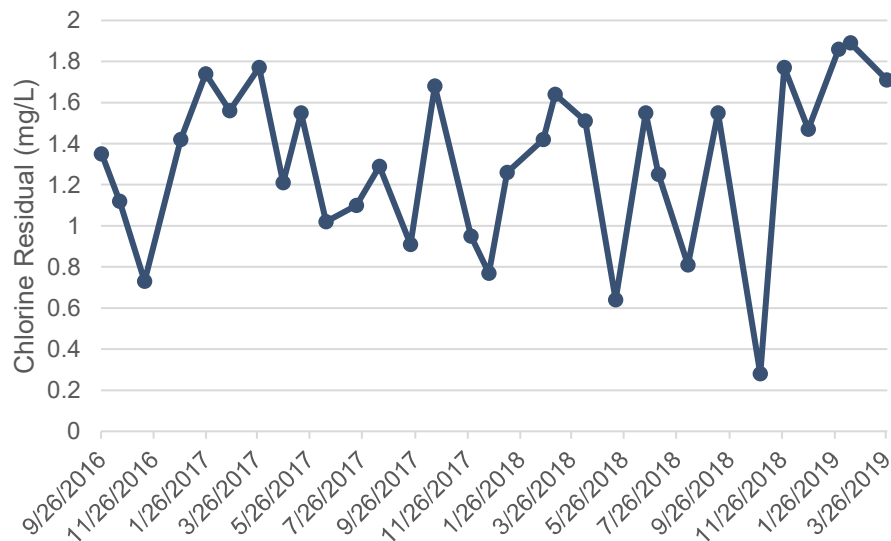


Figure B-94: Bacti Site 110 Chlorine Residual

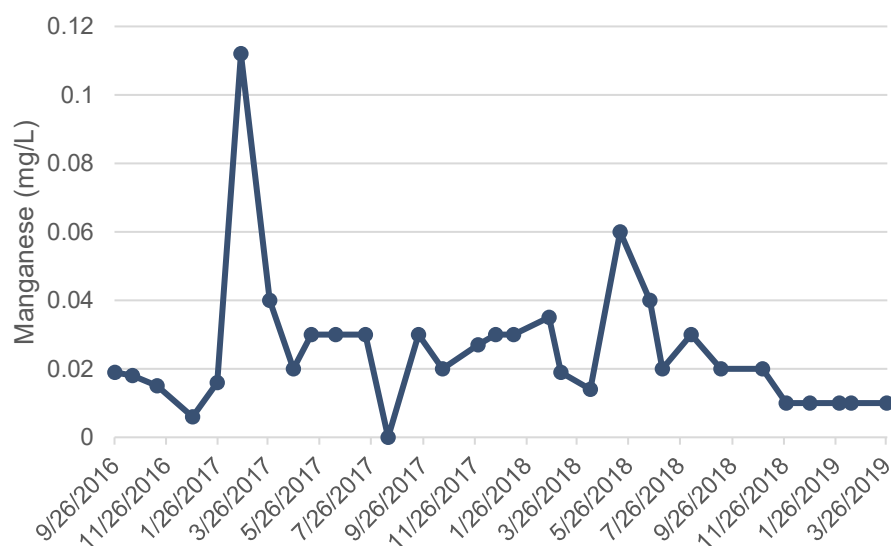


Figure B-95: Bacti Site 110 Manganese

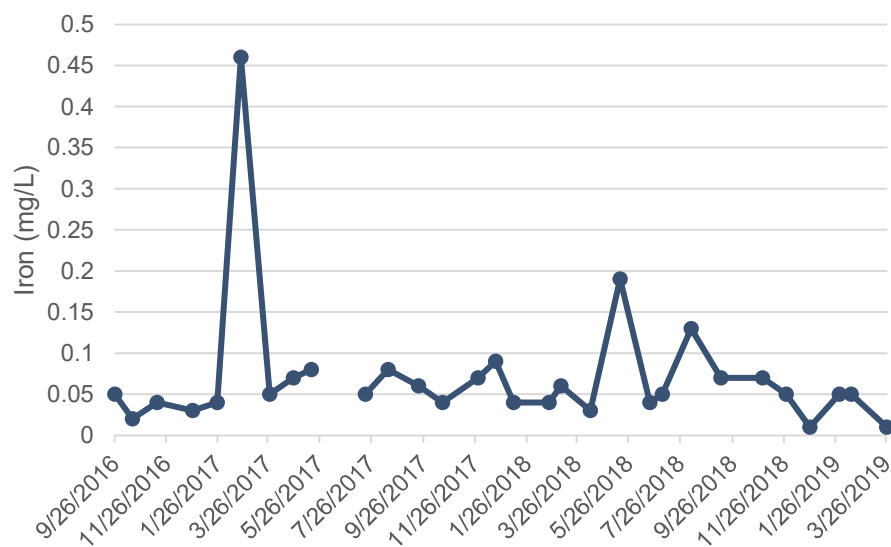


Figure B-96: Bacti Site 110 Iron

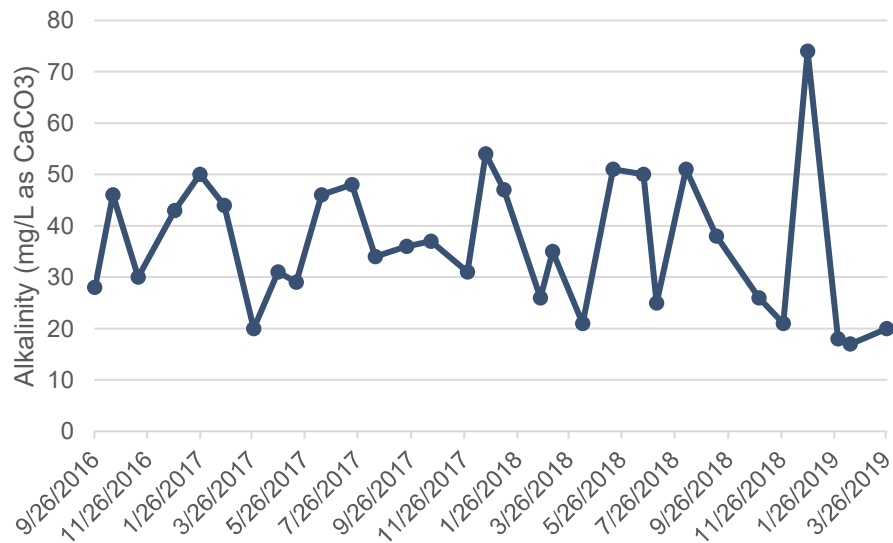


Figure B-97: Bacti Site 110 Alkalinity

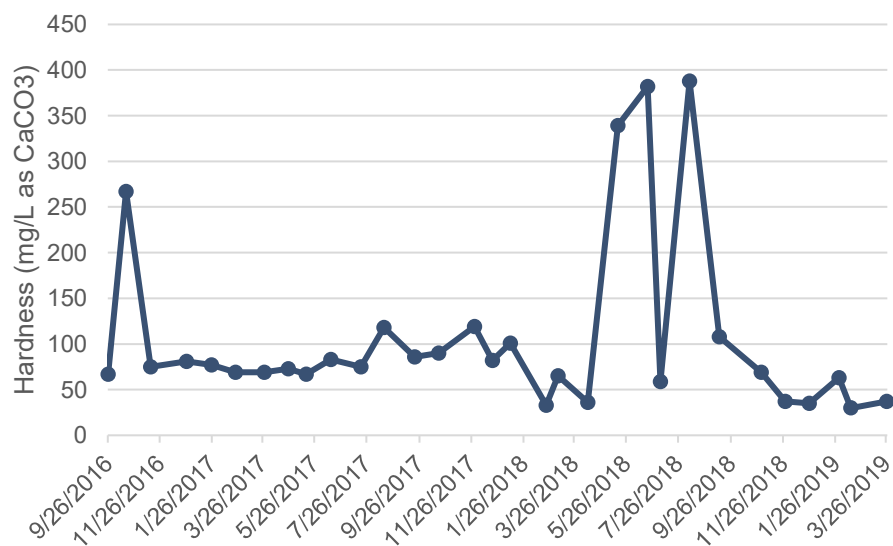


Figure B-98: Bacti Site 110 Hardness

Table A-11: Bacti Site 110 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/27/2019	1.3	62

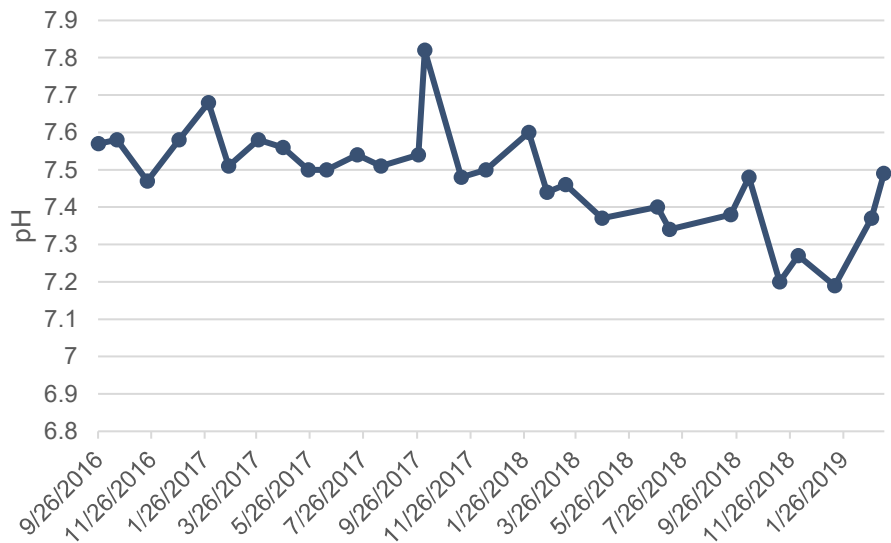


Figure B-99: Bacti Site 120 pH

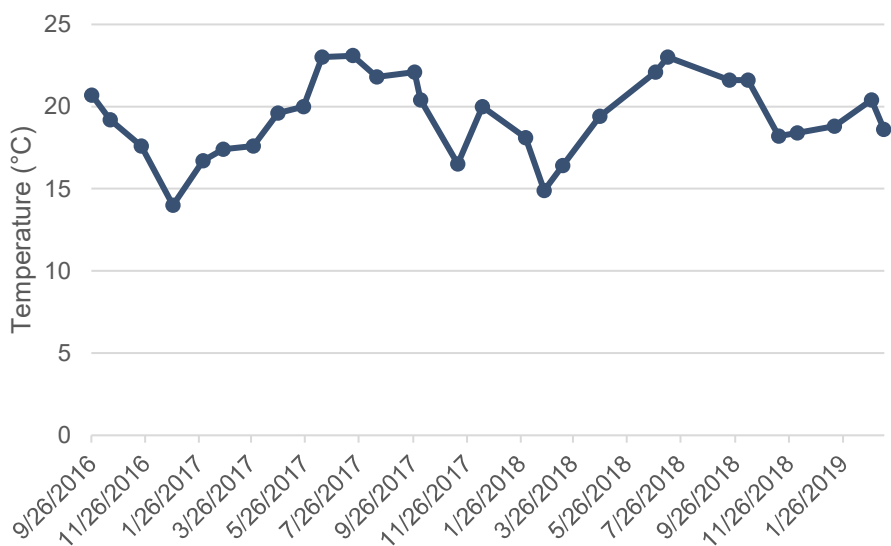


Figure B-100: Bacti Site 120 Temperature

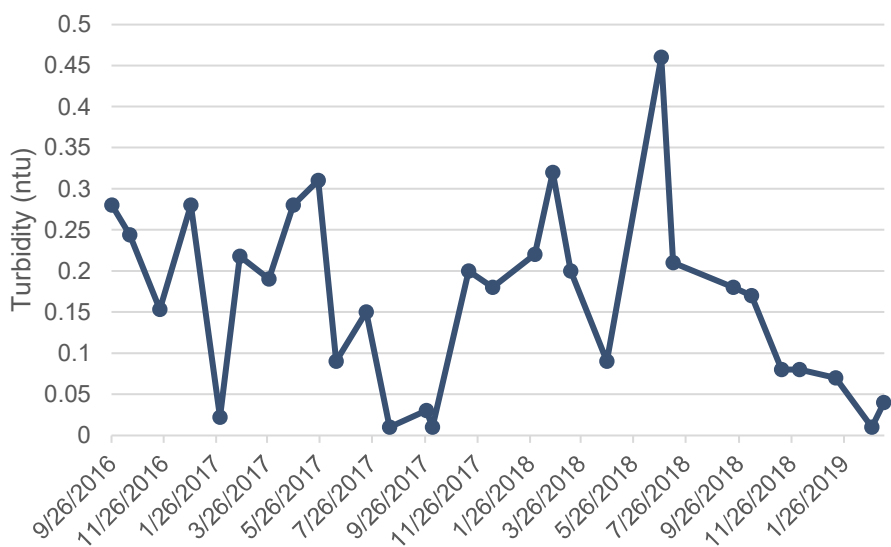


Figure B-101: Bacti Site 120 Turbidity

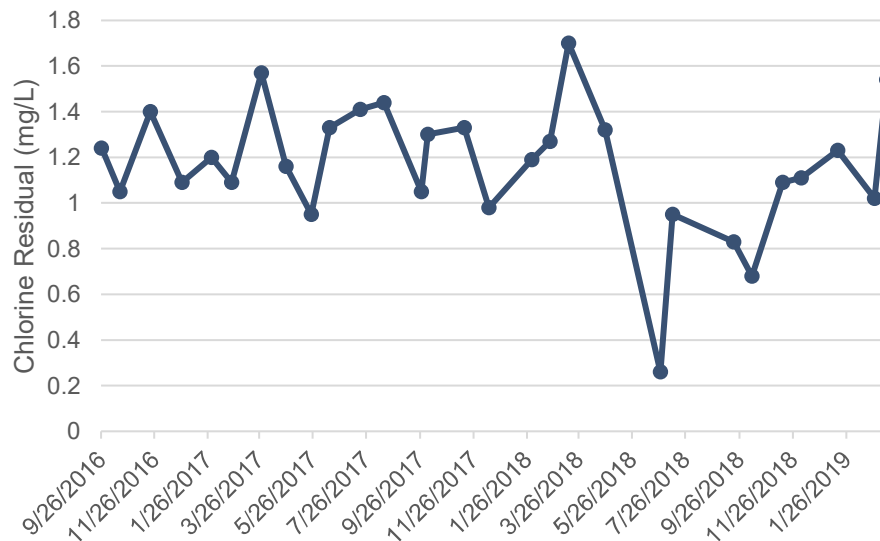


Figure B-102: Bacti Site 120 Chlorine Residual

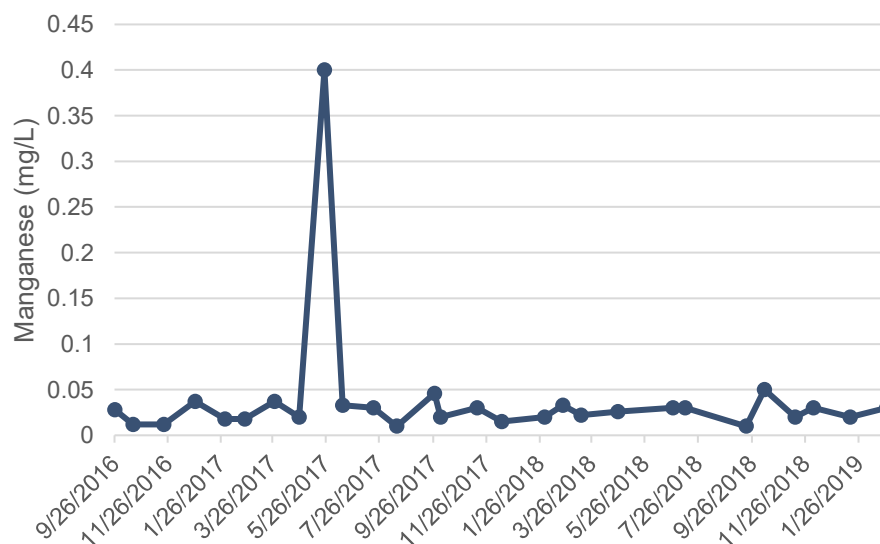


Figure B-103: Bacti Site 120 Manganese

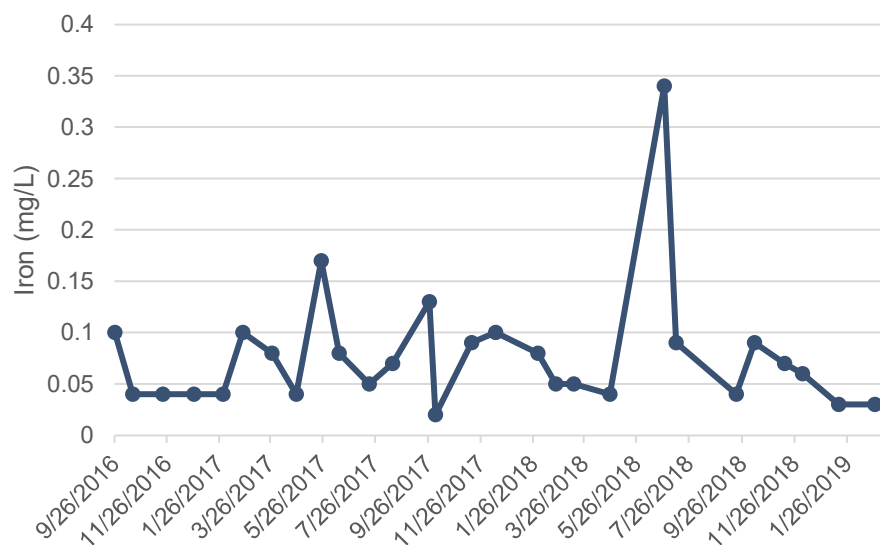


Figure B-104: Bacti Site 120 Iron

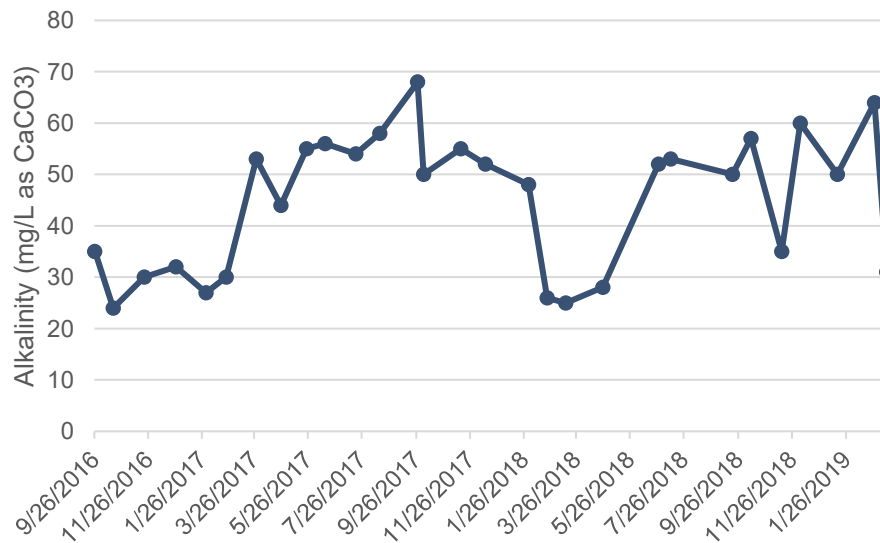


Figure B-105: Bacti Site 120 Alkalinity

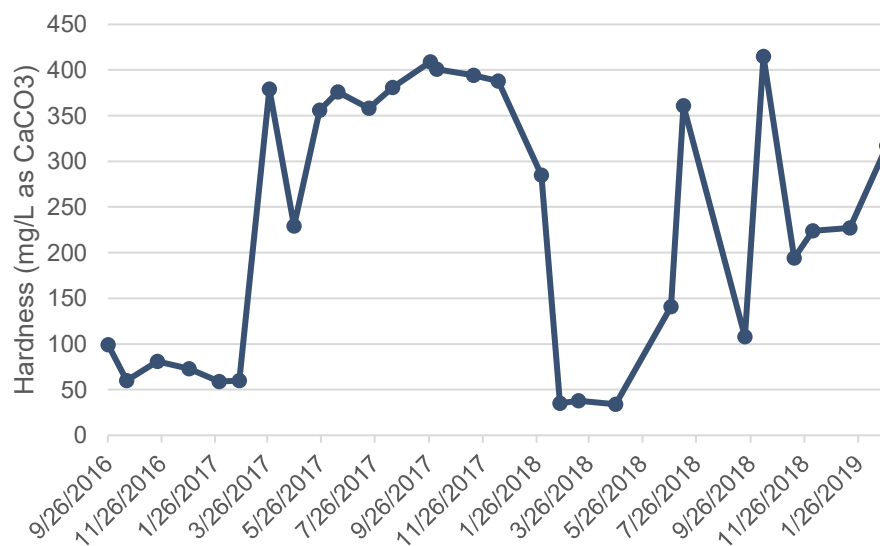


Figure B-106: Bacti Site 120 Hardness

Table A-12: Bacti Site 120 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/13/2019	0.72	84.5

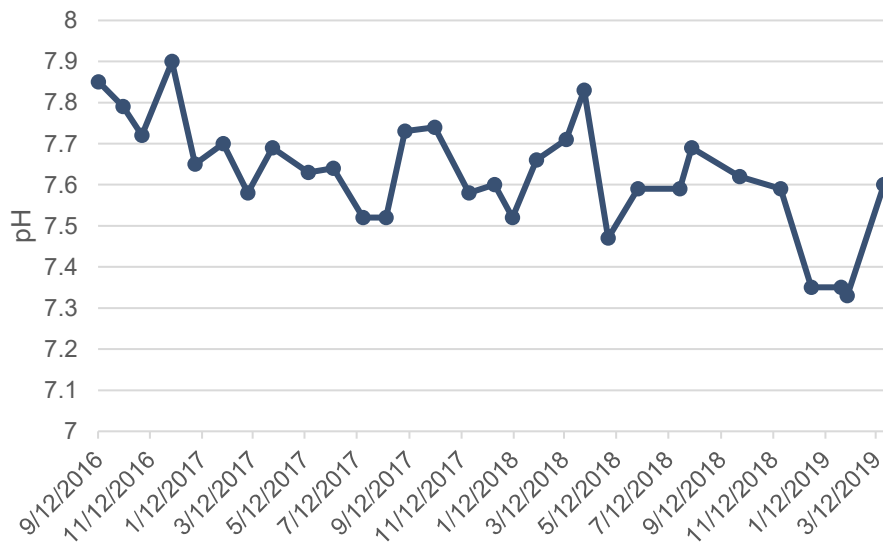


Figure B-107: Bacti Site 130 pH

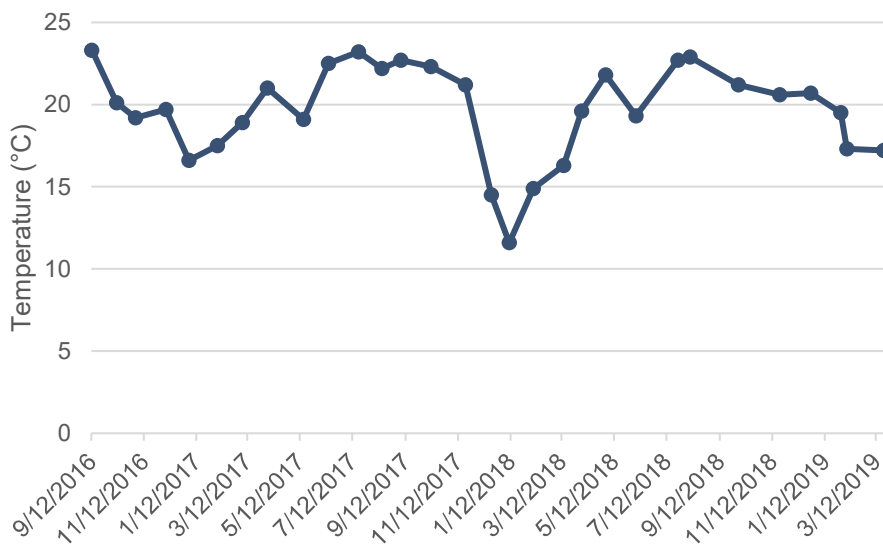


Figure B-108: Bacti Site 130 Temperature

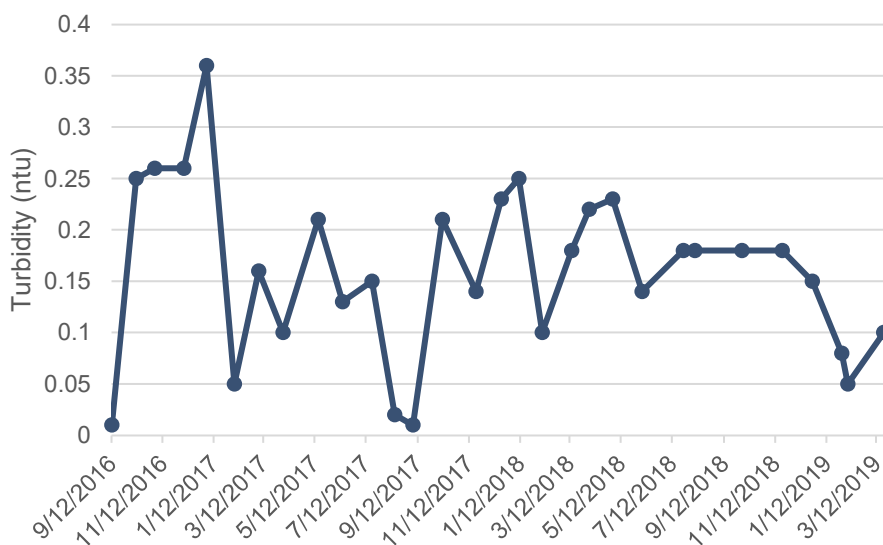


Figure B-109: Bacti Site 130 Turbidity

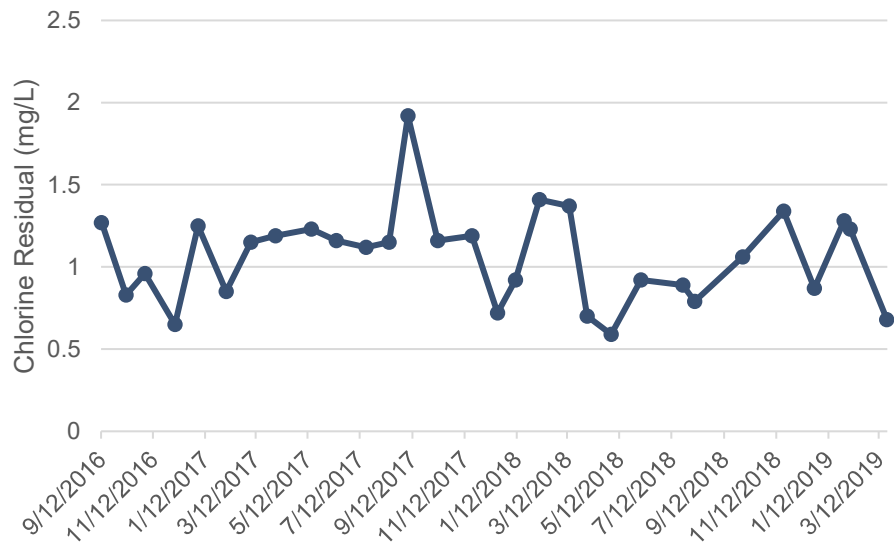


Figure B-110: Bacti Site 130 Chlorine Residual

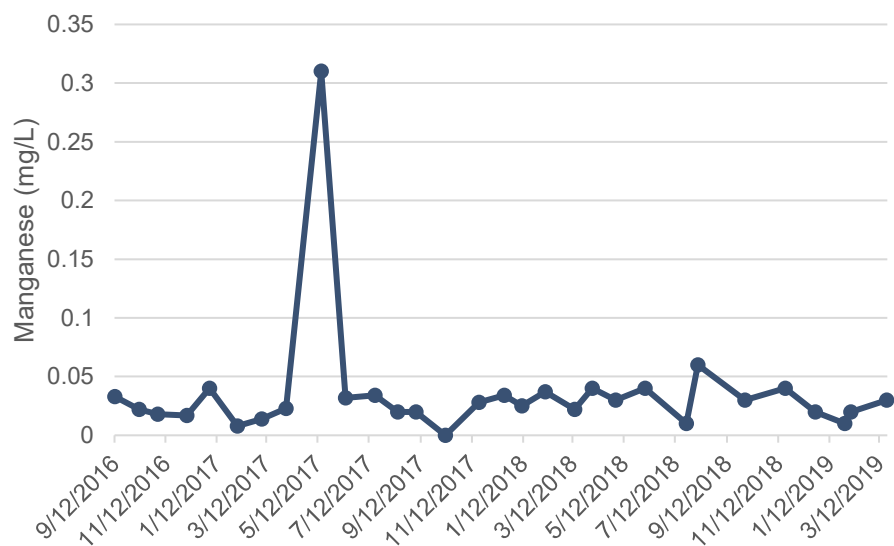


Figure B-111: Bacti Site 130 Manganese

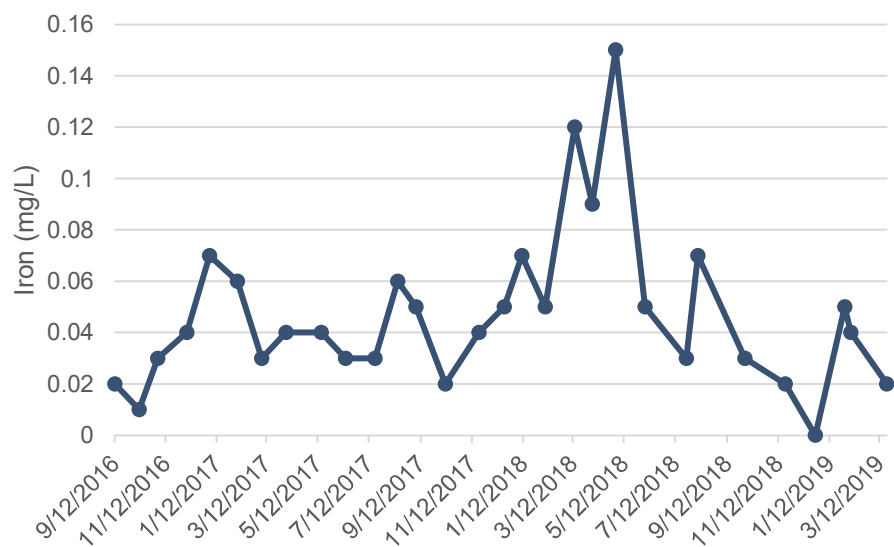


Figure B-112: Bacti Site 130 Iron

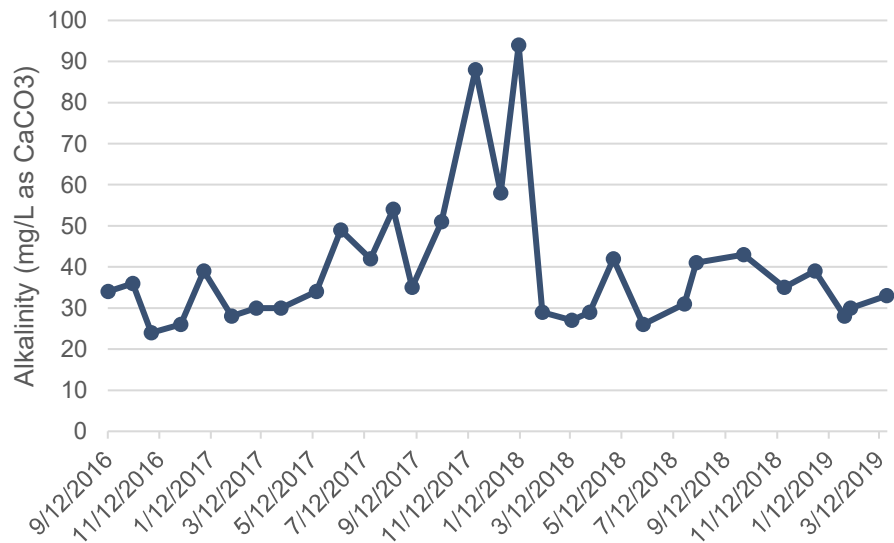


Figure B-113: Bacti Site 130 Alkalinity

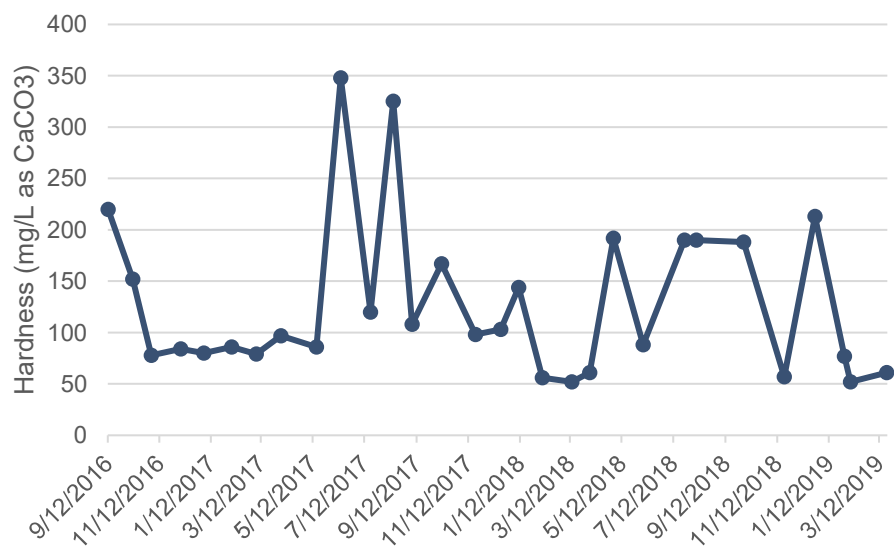


Figure B-114: Bacti Site 130 Hardness

Table A-13: Bacti Site 130 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/21/2019	1.18	133

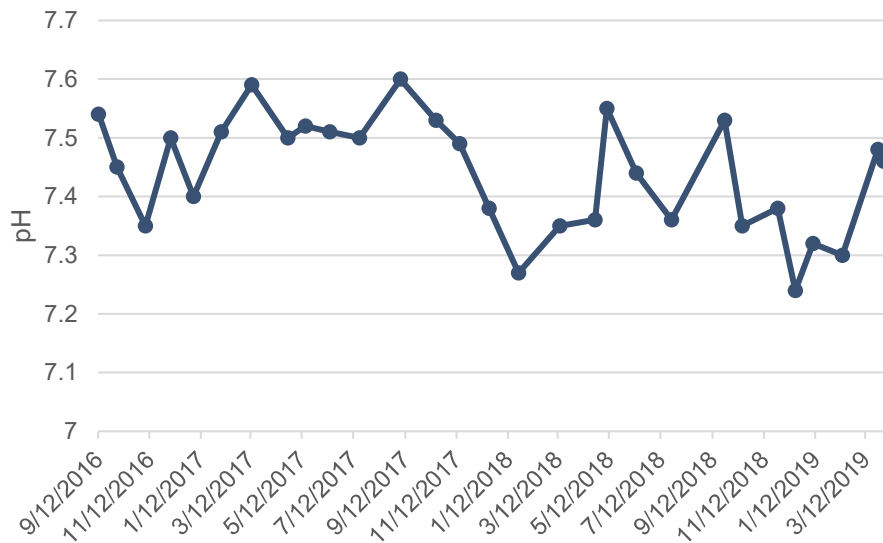


Figure B-115: Bacti Site 140 pH

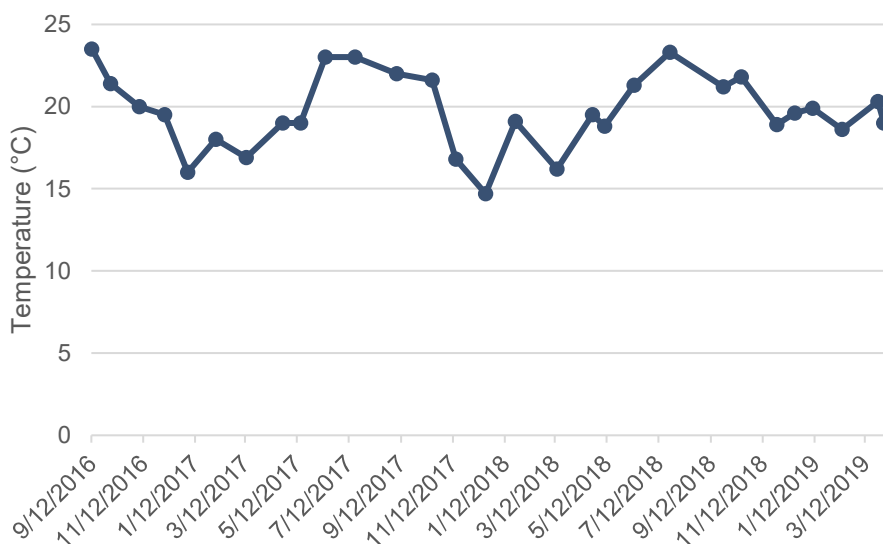


Figure B-116: Bacti Site 140 Temperature

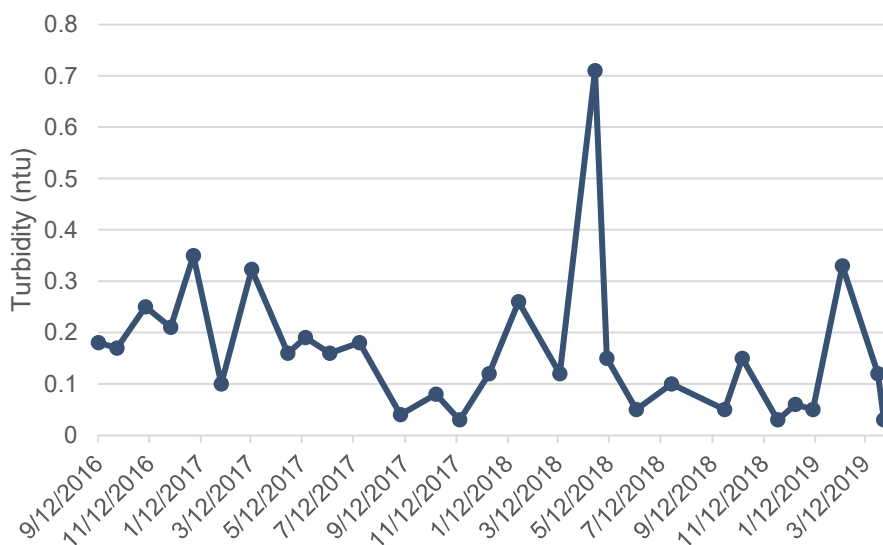


Figure B-117: Bacti Site 140 Turbidity

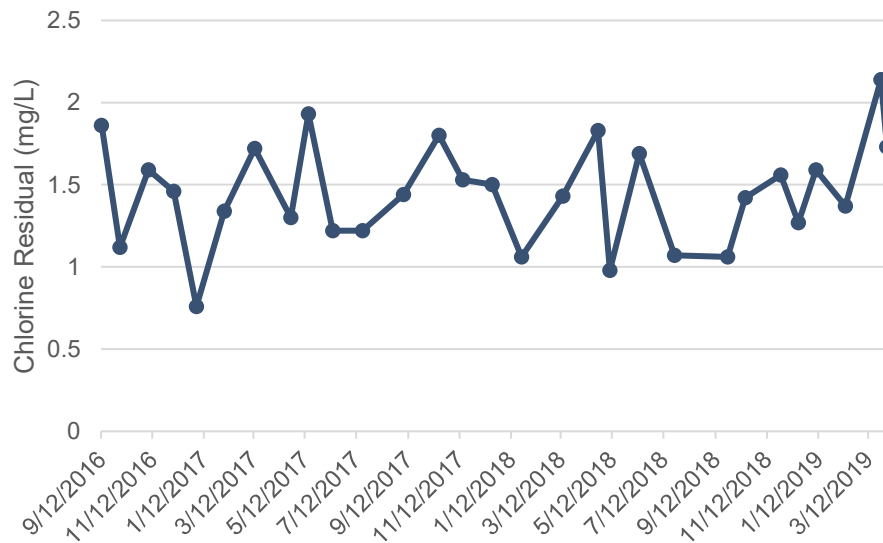


Figure B-118: Bacti Site 140 Chlorine Residual

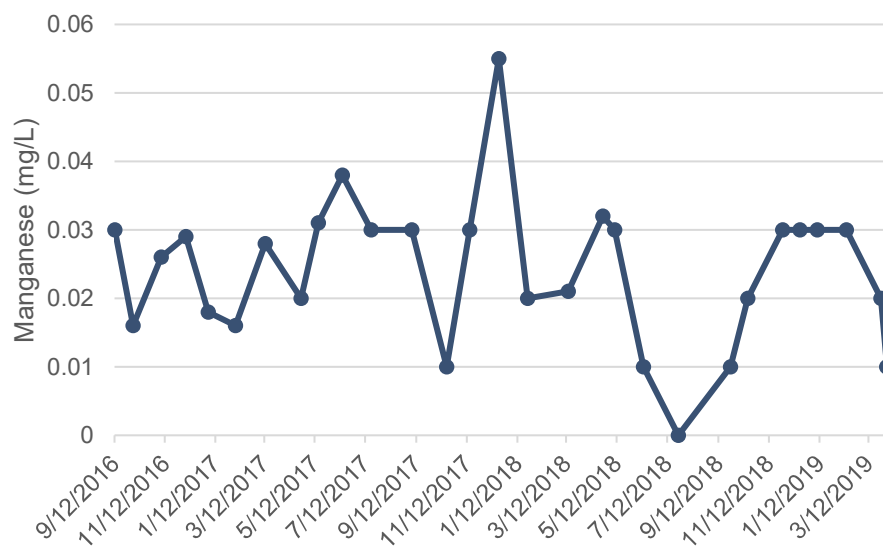


Figure B-119: Bacti Site 140 Manganese

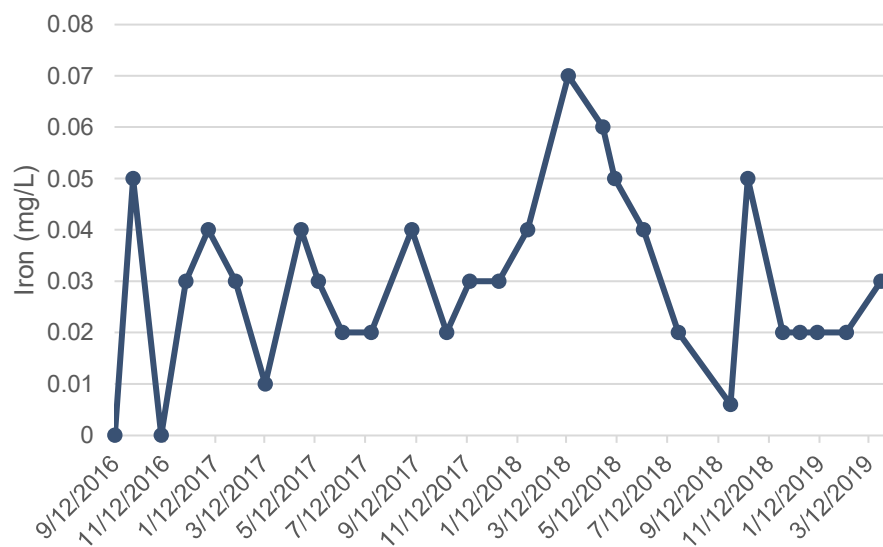


Figure B-120: Bacti Site 140 Iron

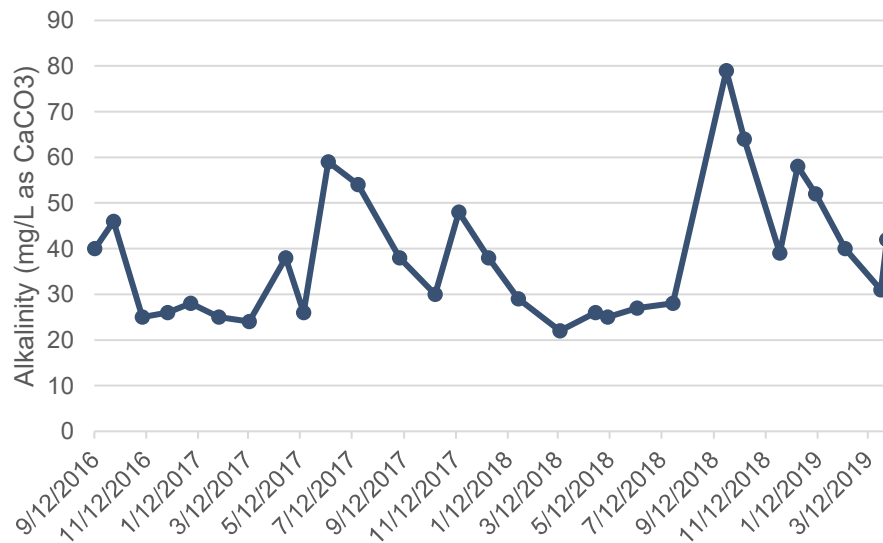


Figure B-121: Bacti Site 140 Alkalinity

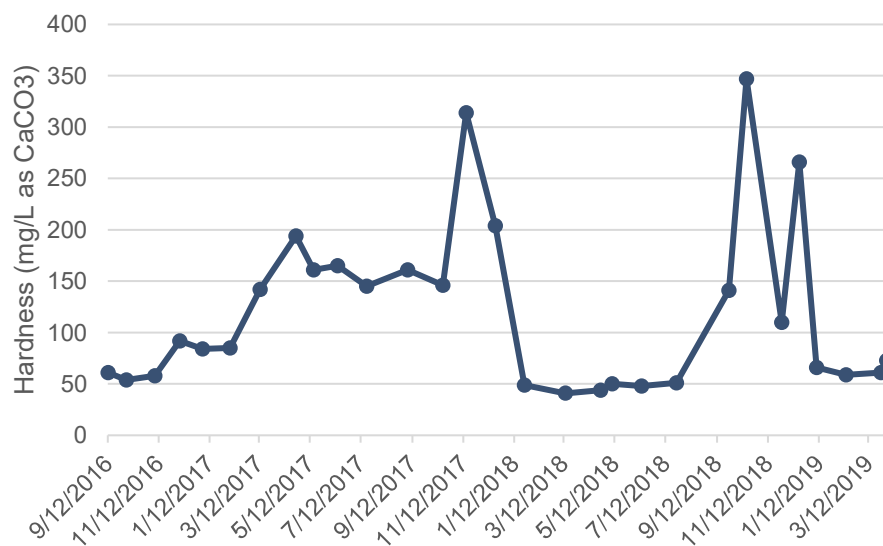


Figure B-122: Bacti Site 140 Hardness

Table A-14: Bacti Site 140 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/27/2019	1.2	88
4/3/2019	1.34	94

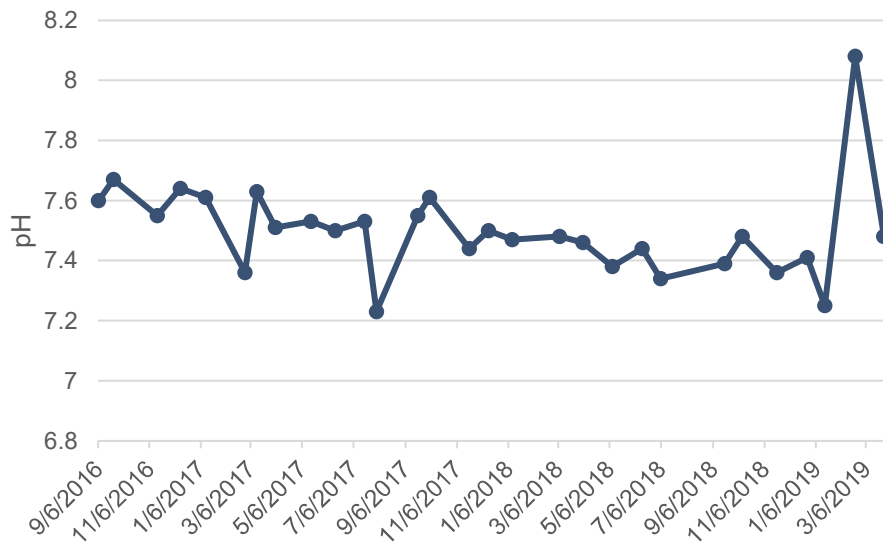


Figure B-123: Bacti Site 150 pH

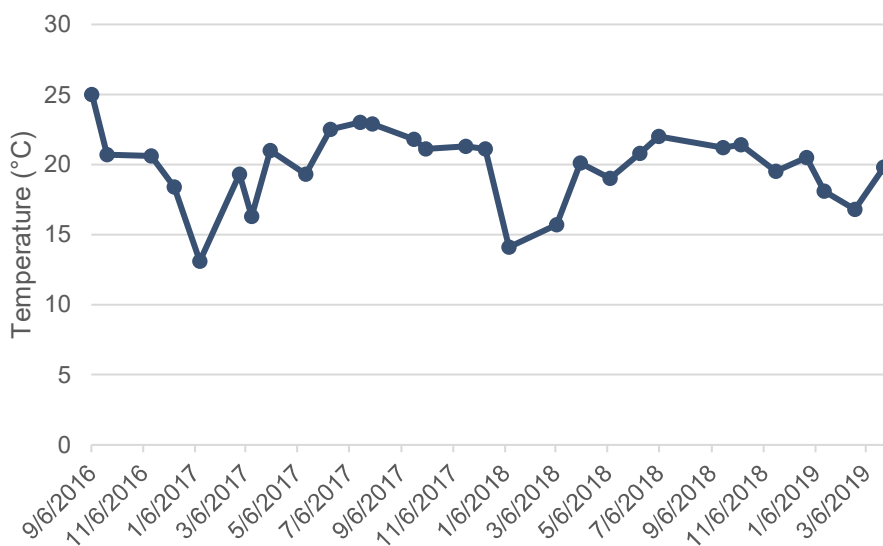


Figure B-124: Bacti Site 150 Temperature

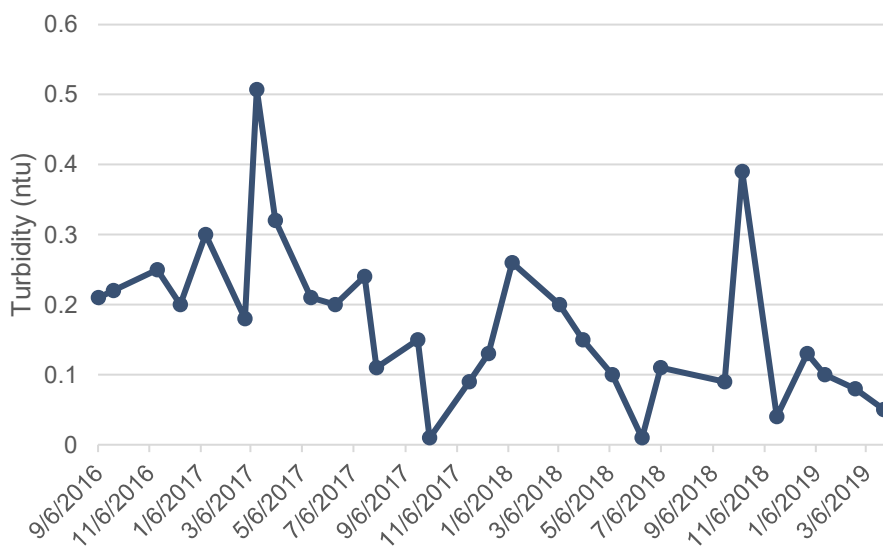


Figure B-125: Bacti Site 150 Turbidity

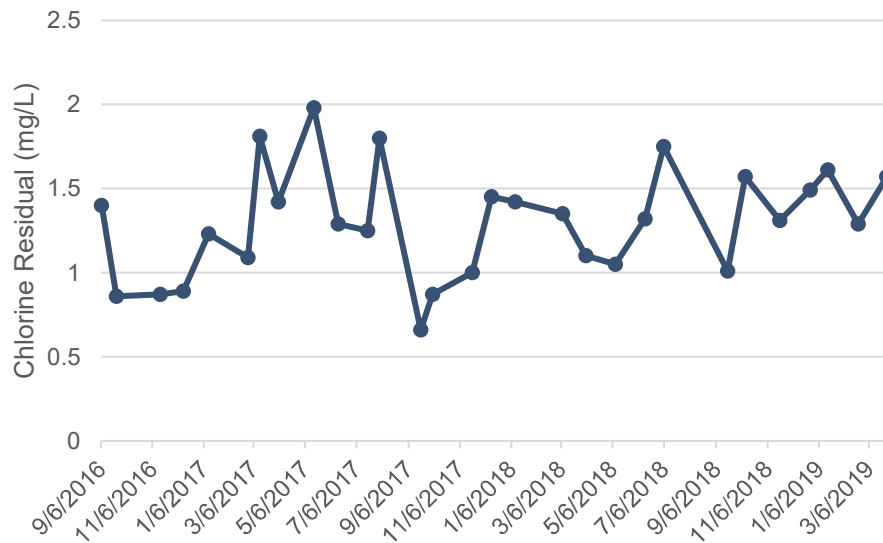


Figure B-126: Bacti Site 150 Chlorine Residual

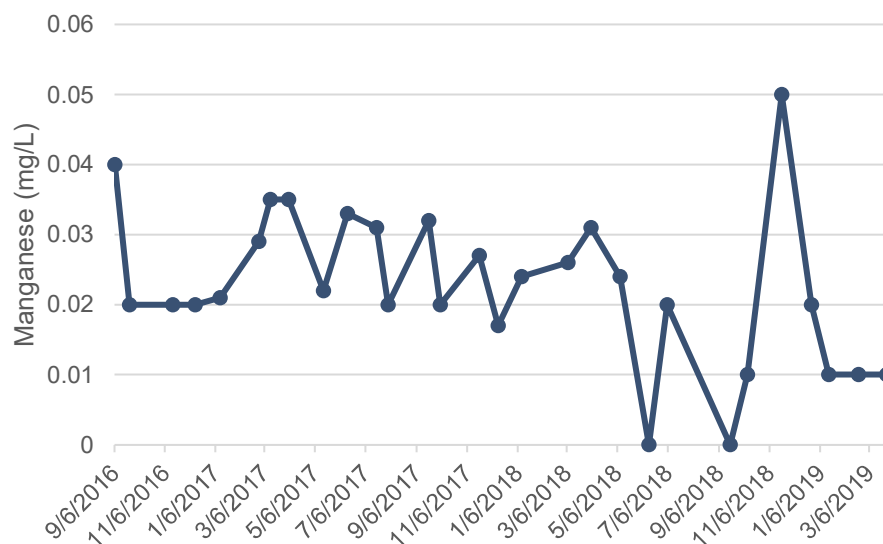


Figure B-127: Bacti Site 150 Manganese

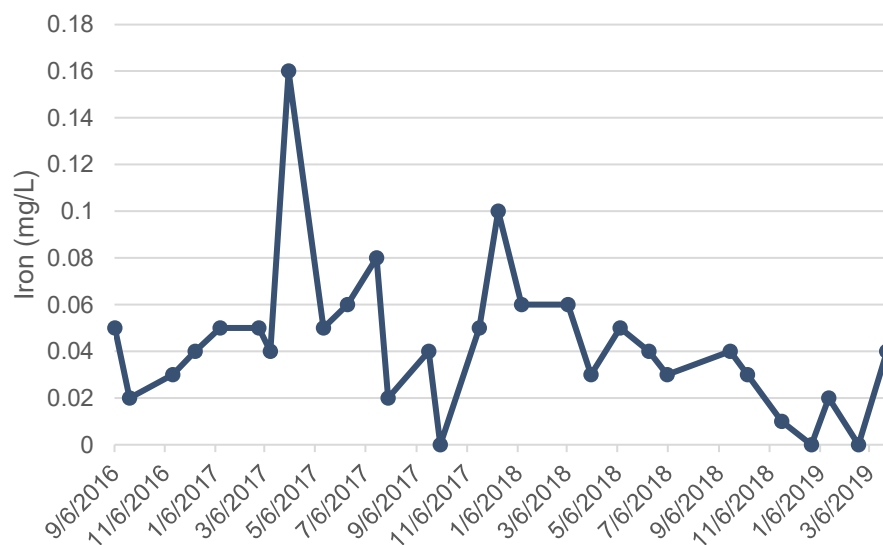


Figure B-128: Bacti Site 150 Iron

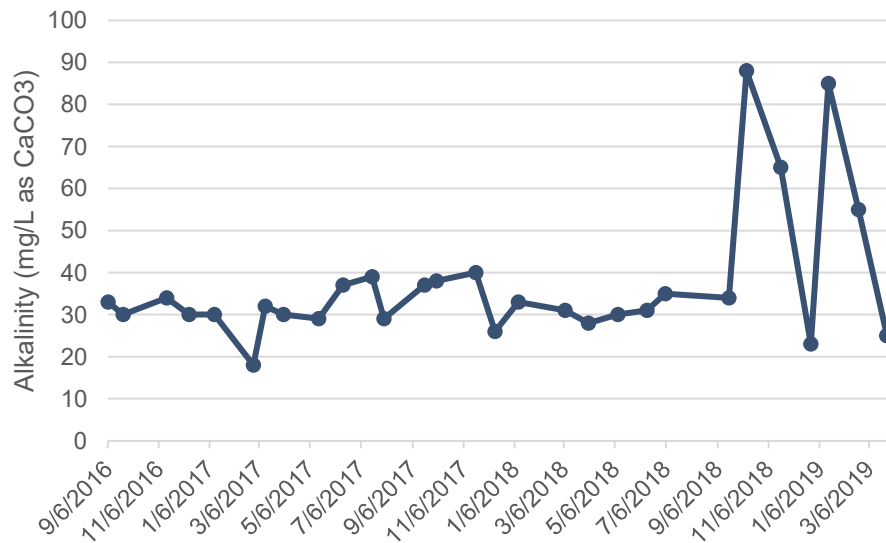


Figure B-129: Bacti Site 150 Alkalinity

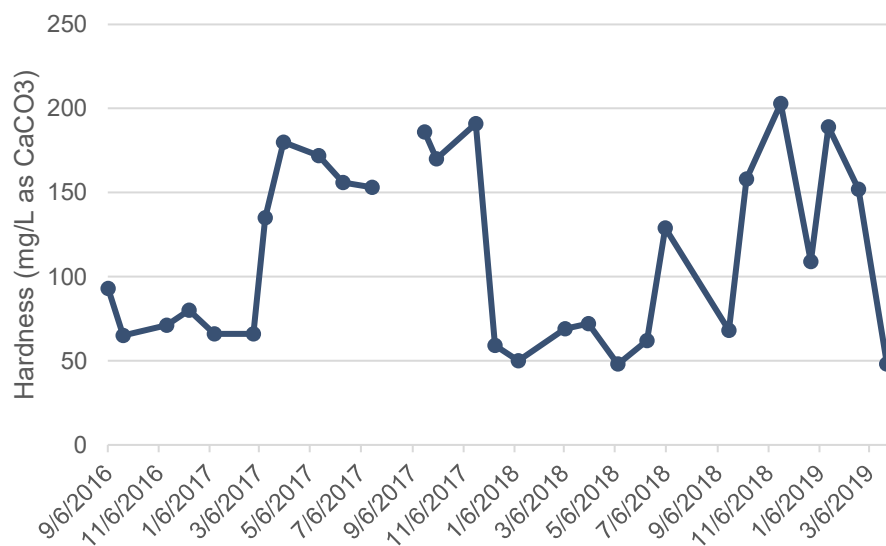


Figure B-130: Bacti Site 150 Hardness

Table A-15: Bacti Site 150 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/27/2019	1.3	78

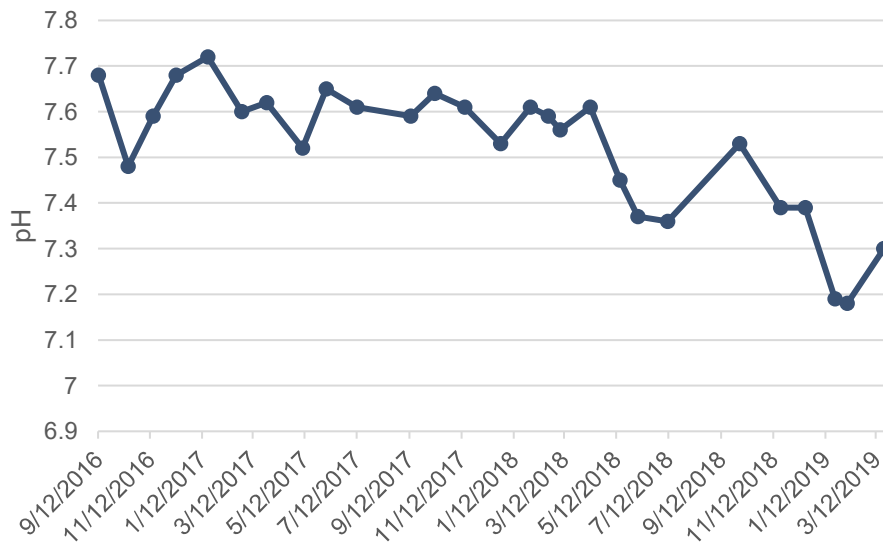


Figure B-131: Bacti Site 160 pH

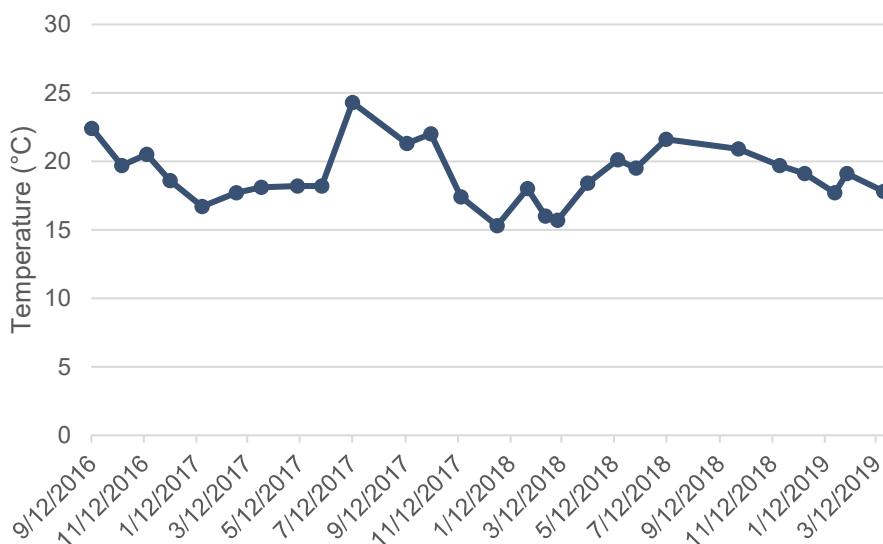


Figure B-132: Bacti Site 160 Temperature

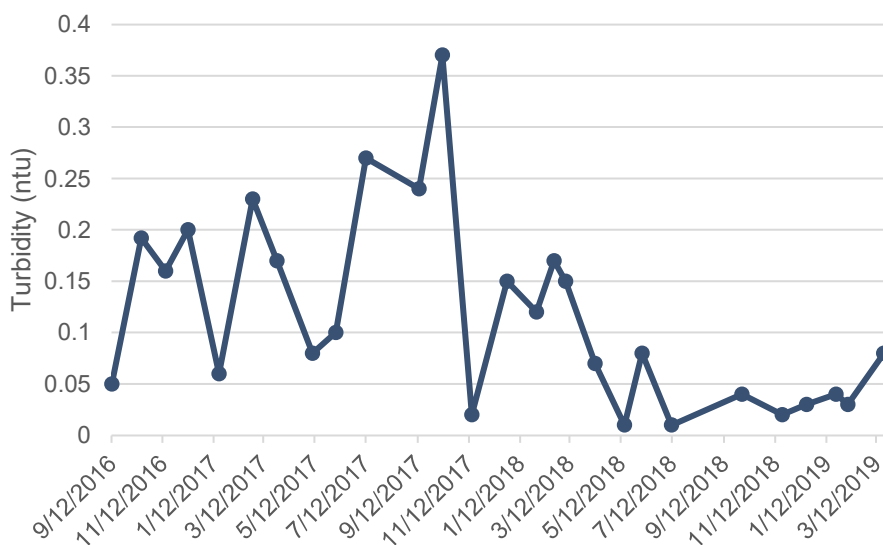


Figure B-133: Bacti Site 160 Turbidity

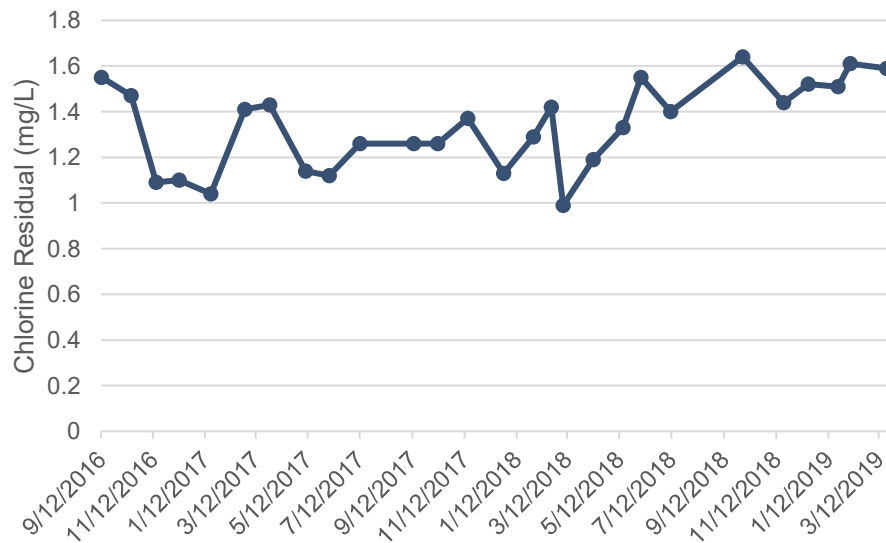


Figure B-134: Bacti Site 160 Chlorine Residual

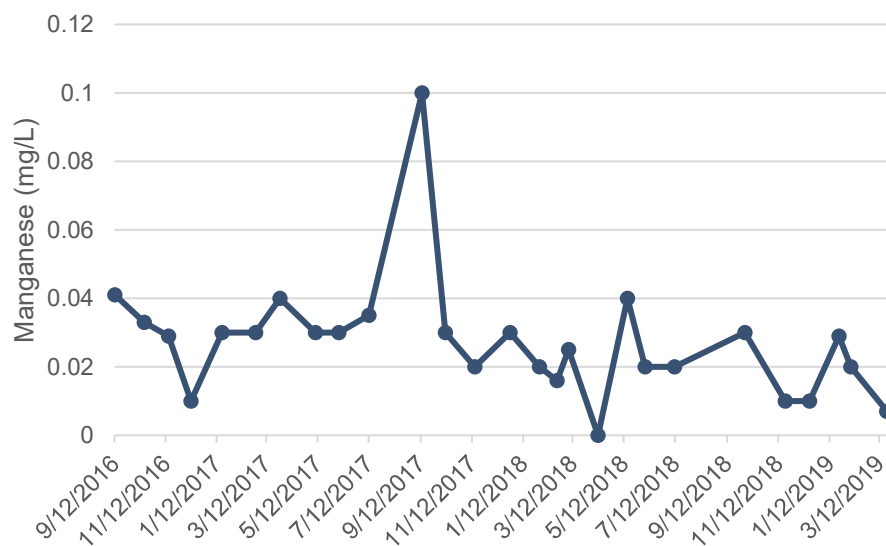


Figure B-135: Bacti Site 160 Manganese

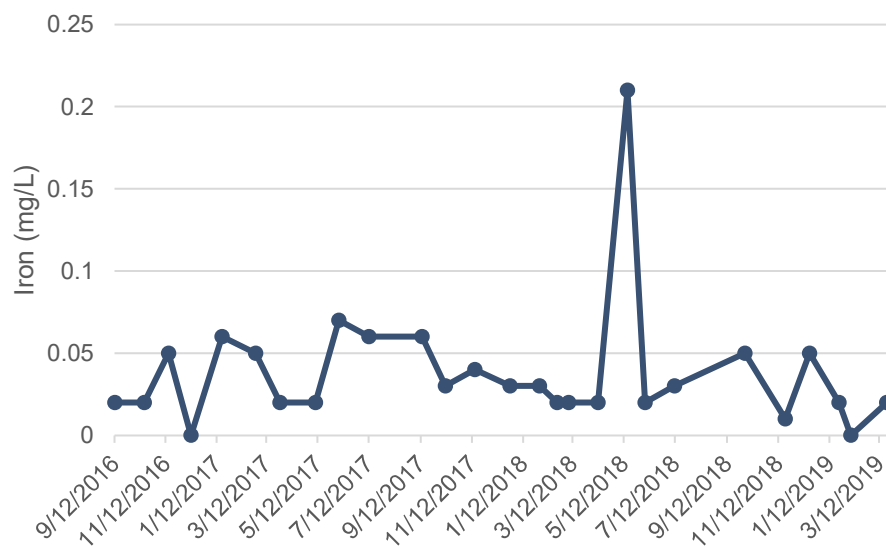


Figure B-136: Bacti Site 160 Iron

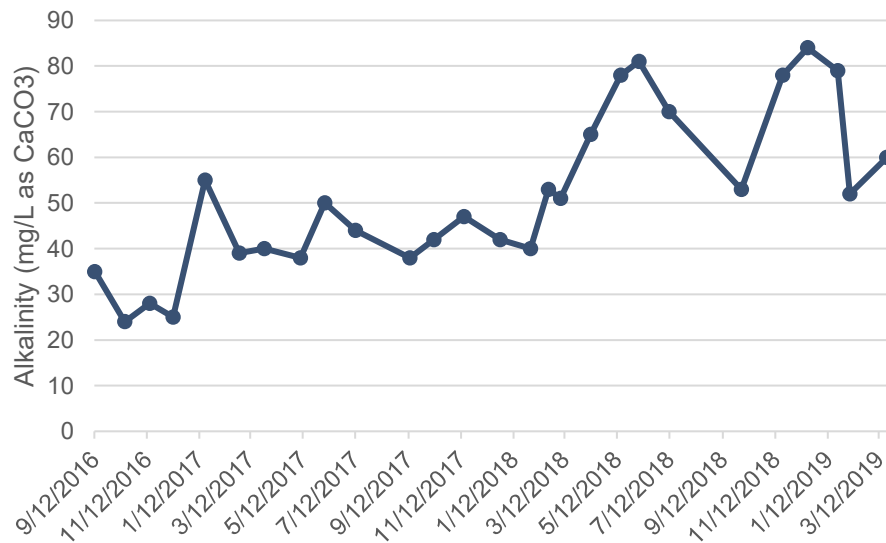


Figure B-137: Bacti Site 160 Alkalinity

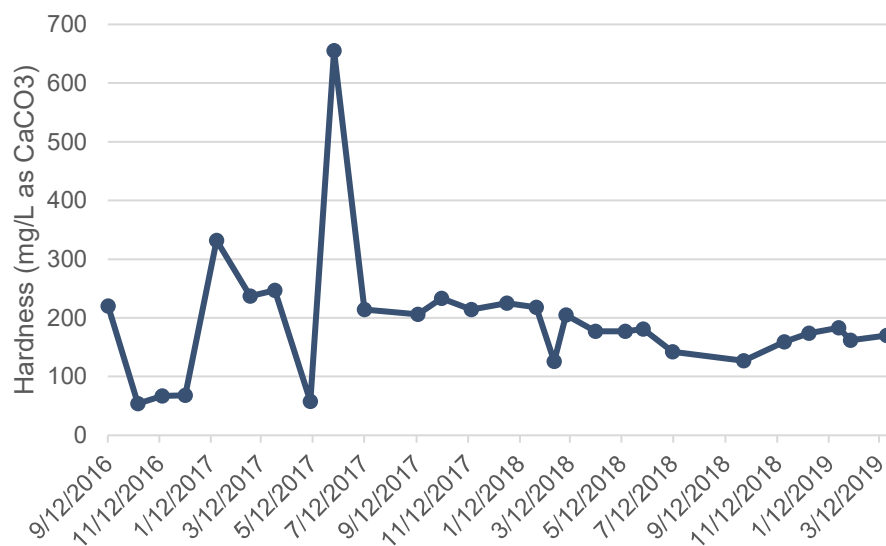


Figure B-138: Bacti Site 160 Hardness

Table A-16: Bacti Site 160 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/21/2019	0.65	207

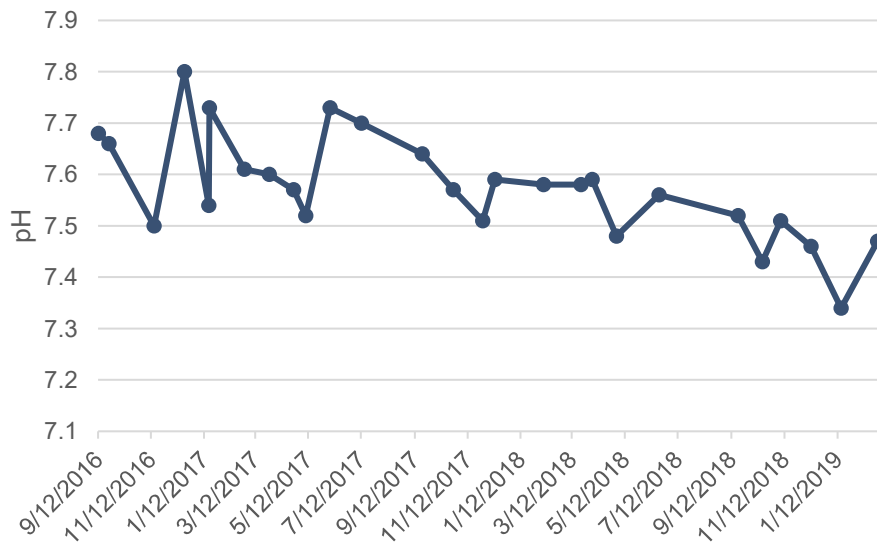


Figure B-139: Bacti Site 170 pH

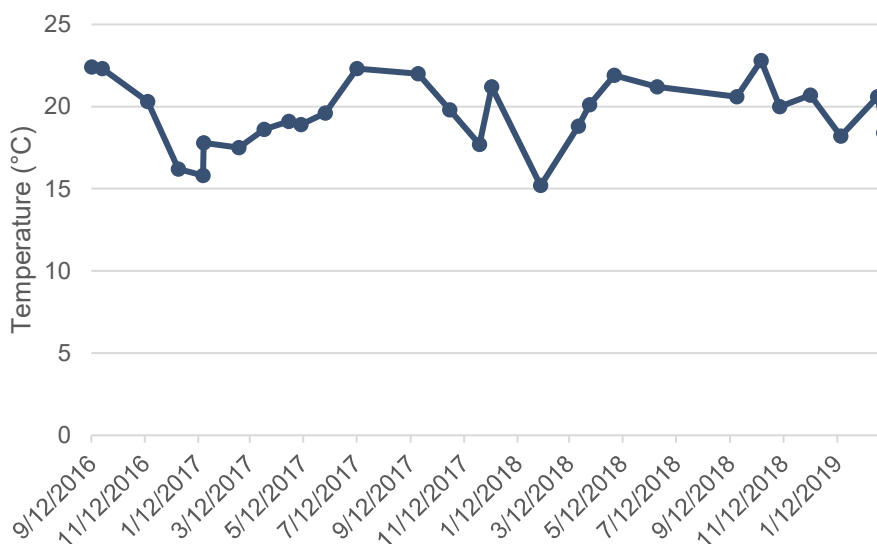


Figure B-140: Bacti Site 170 Temperature

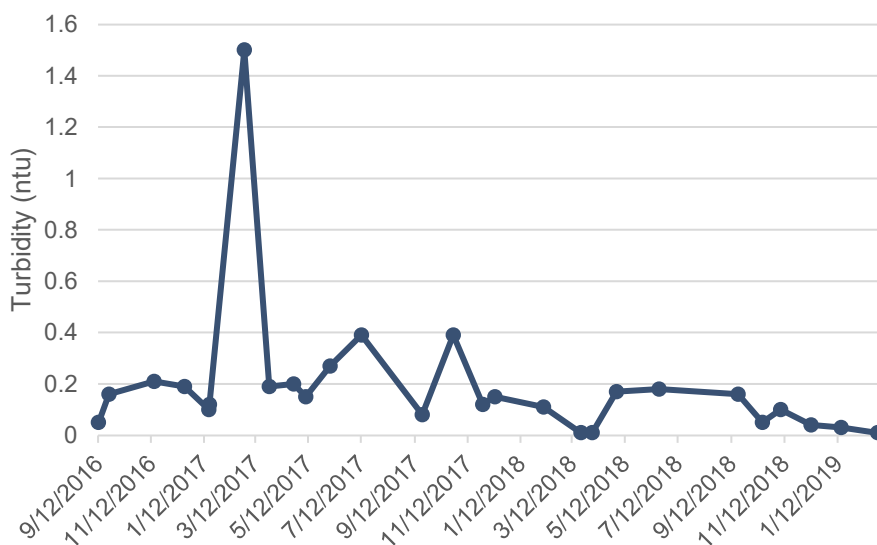


Figure B-141: Bacti Site 170 Turbidity

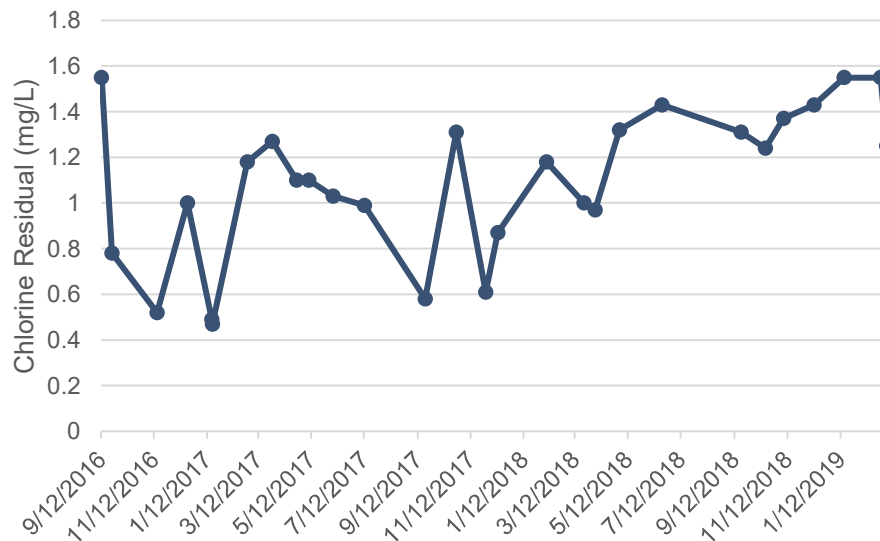


Figure B-142: Bacti Site 170 Chlorine Residual

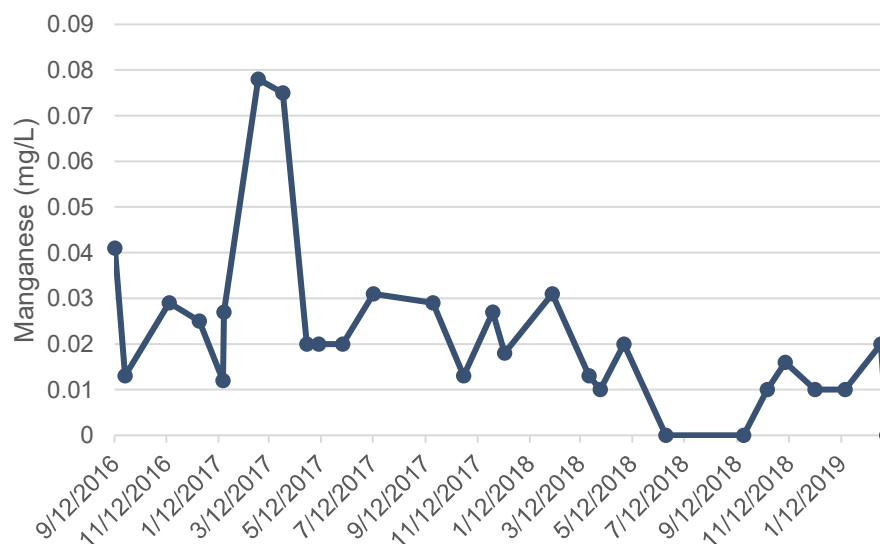


Figure B-143: Bacti Site 170 Manganese

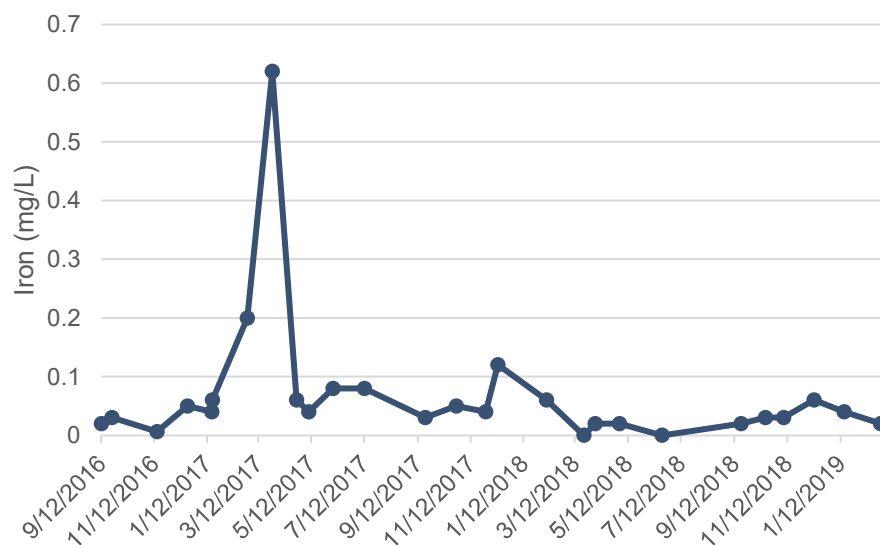


Figure B-144: Bacti Site 170 Iron

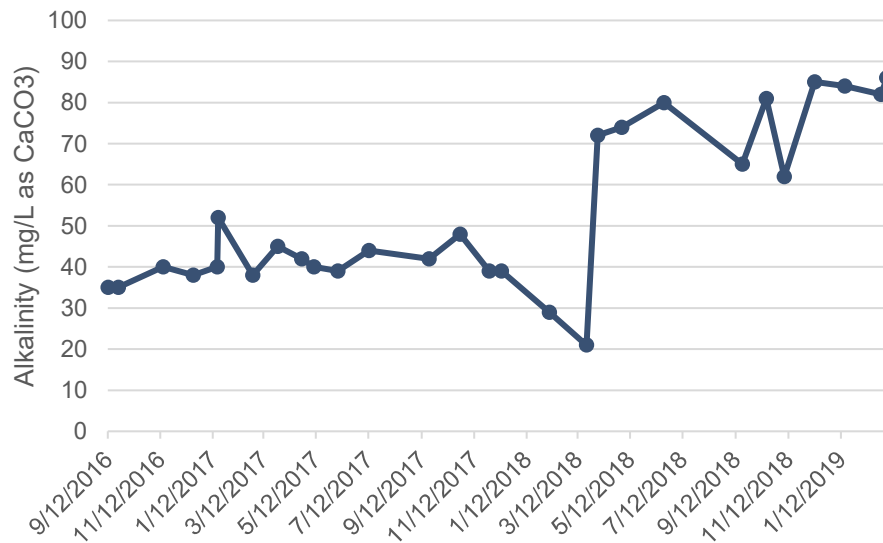


Figure B-145: Bacti Site 170 Alkalinity

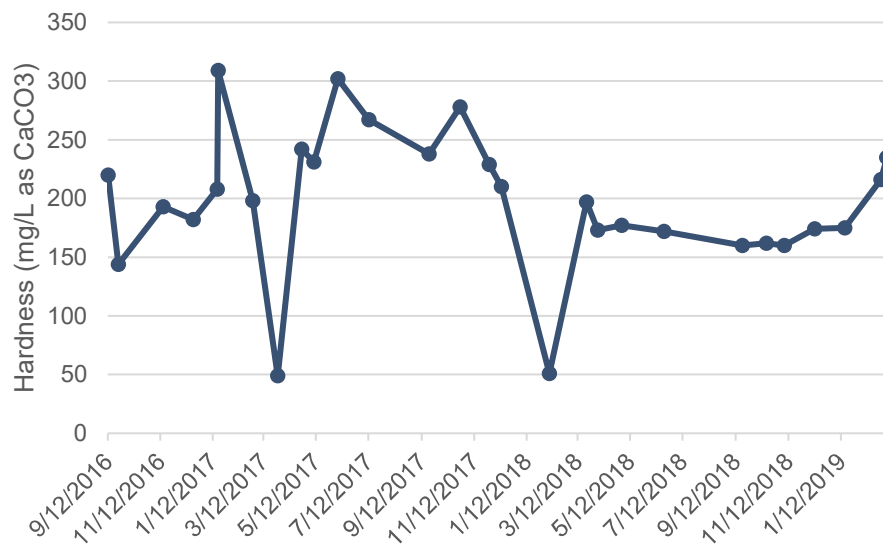


Figure B-146: Bacti Site 170 Hardness

Table A-17: Bacti Site 170 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
NA	NA	NA

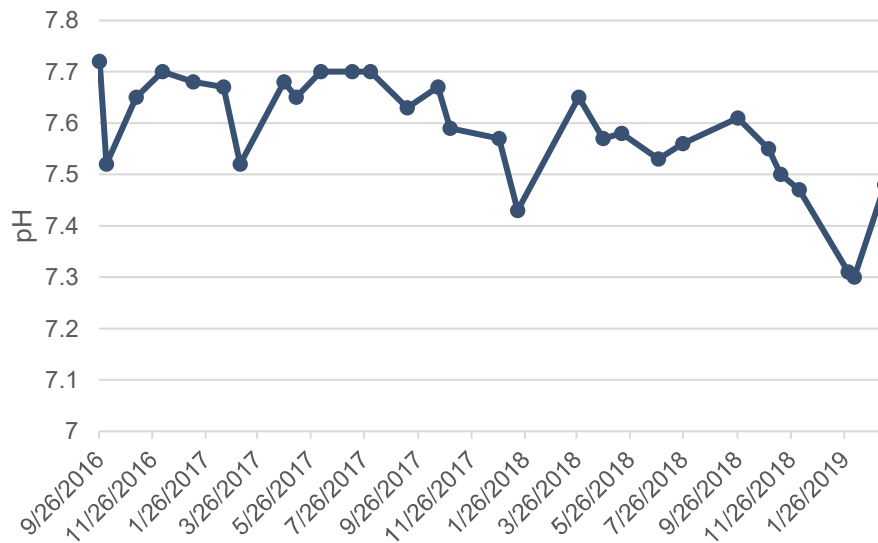


Figure B-147: Bacti Site 180 pH

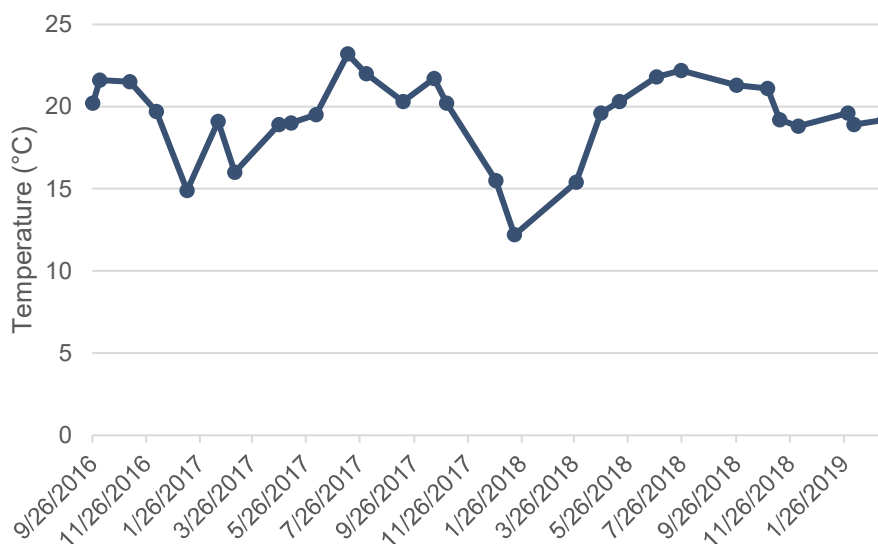


Figure B-148: Bacti Site 180 Temperature

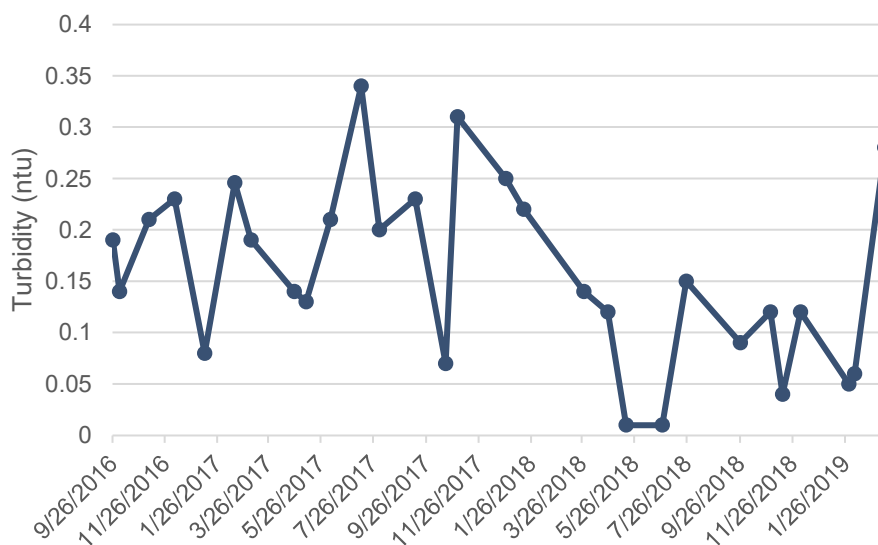


Figure B-149: Bacti Site 180 Turbidity

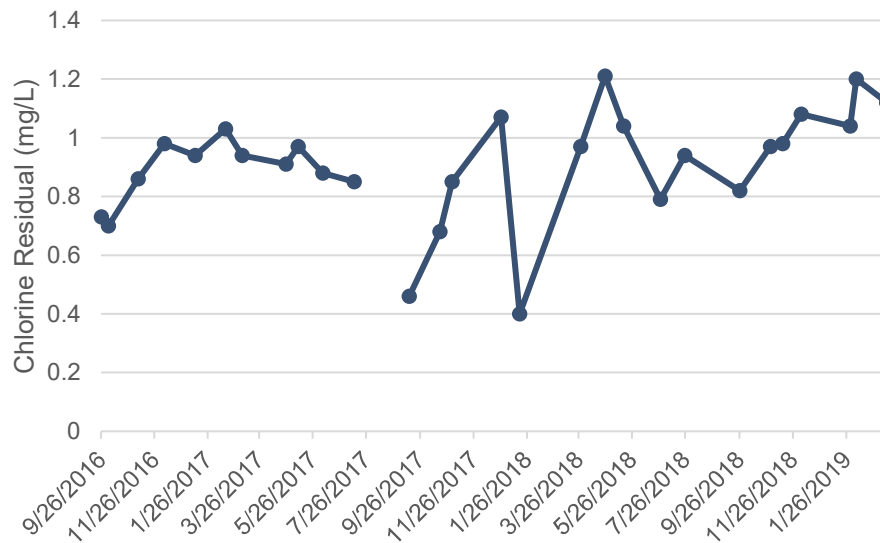


Figure B-150: Bacti Site 180 Chlorine Residual

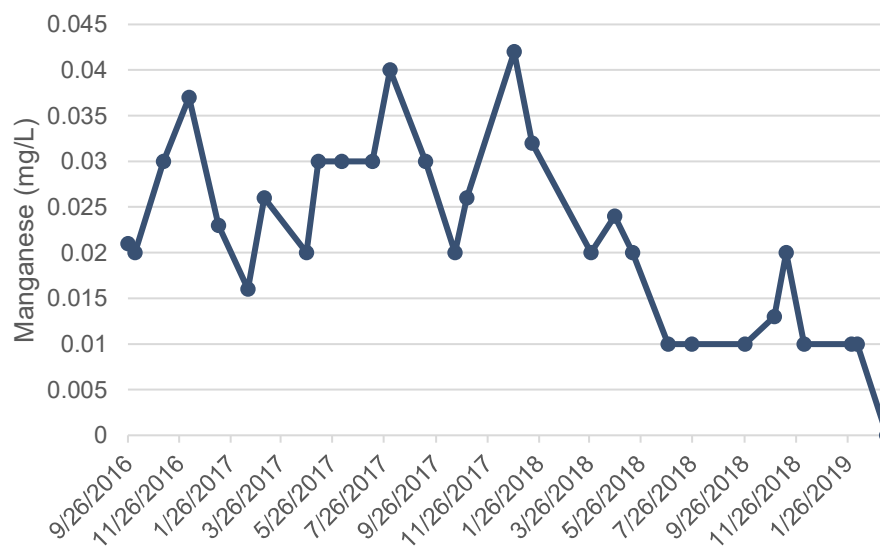


Figure B-151: Bacti Site 180 Manganese

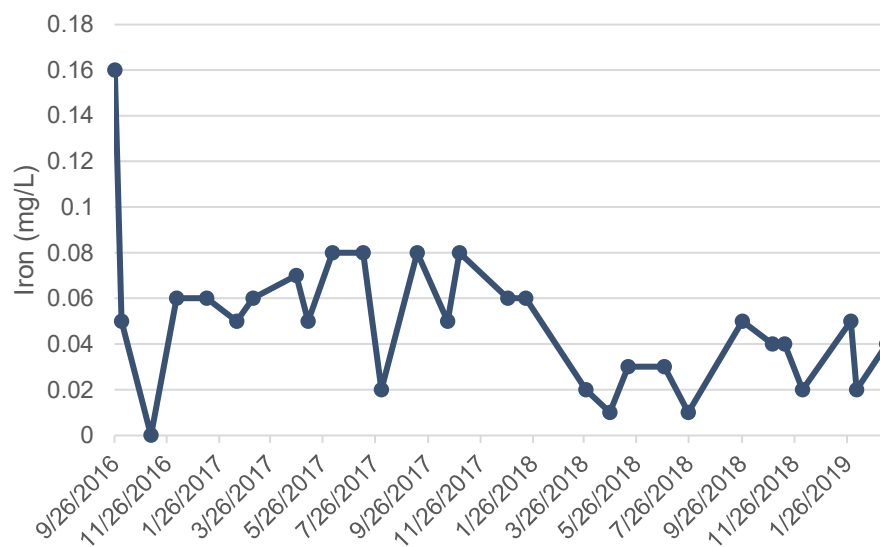


Figure B-152: Bacti Site 180 Iron

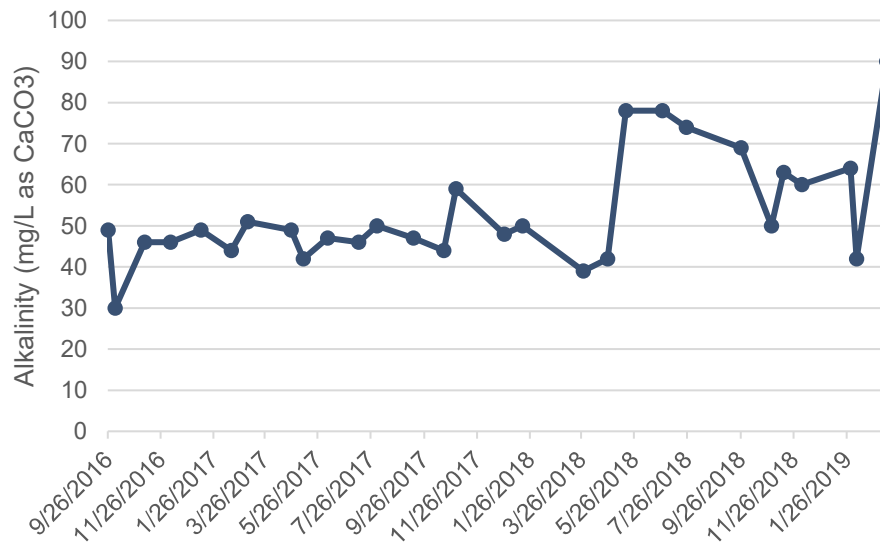


Figure B-153: Bacti Site 180 Alkalinity

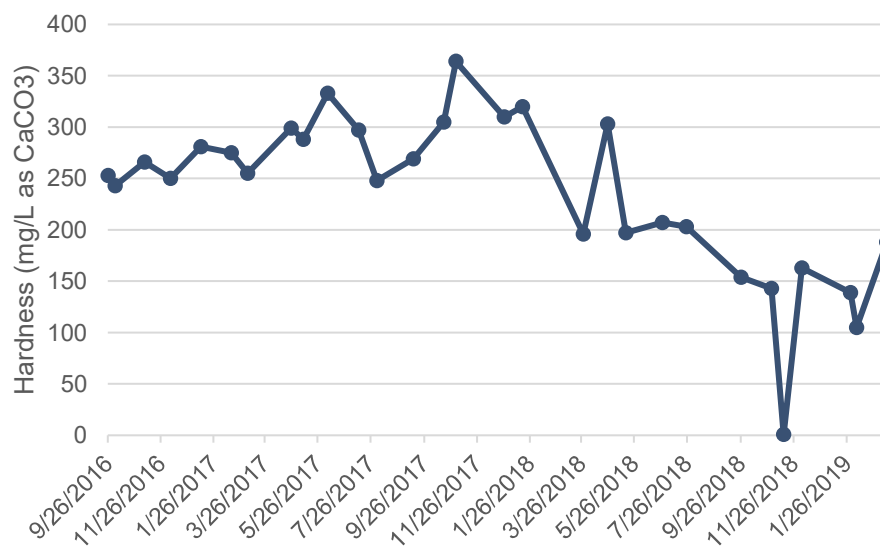


Figure B-154: Bacti Site 180 Hardness

Table A-18: Bacti Site 180 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/13/2019	0.5	210

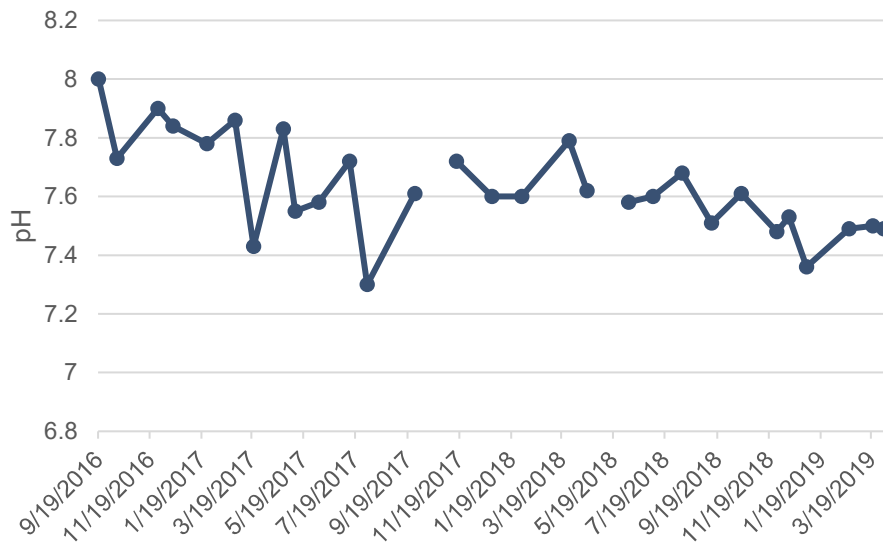


Figure B-155: Bacti Site 190 pH

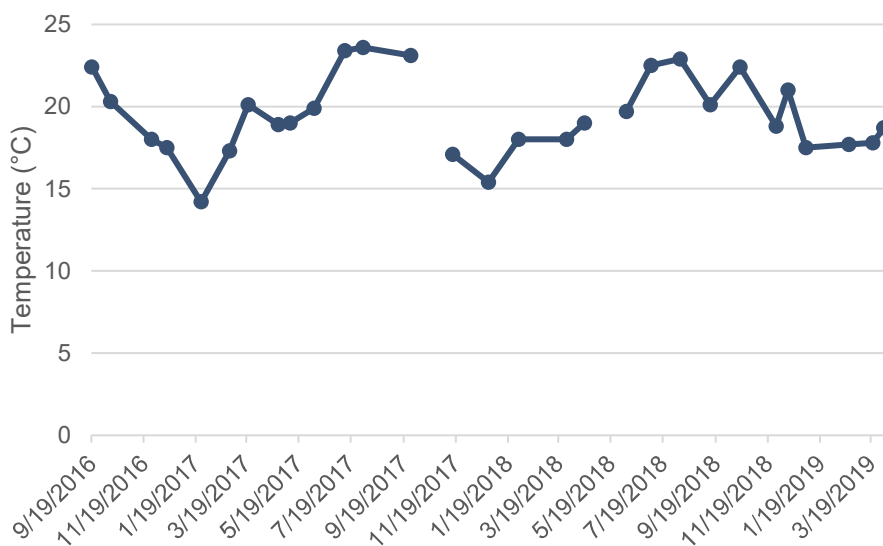


Figure B-156: Bacti Site 190 Temperature

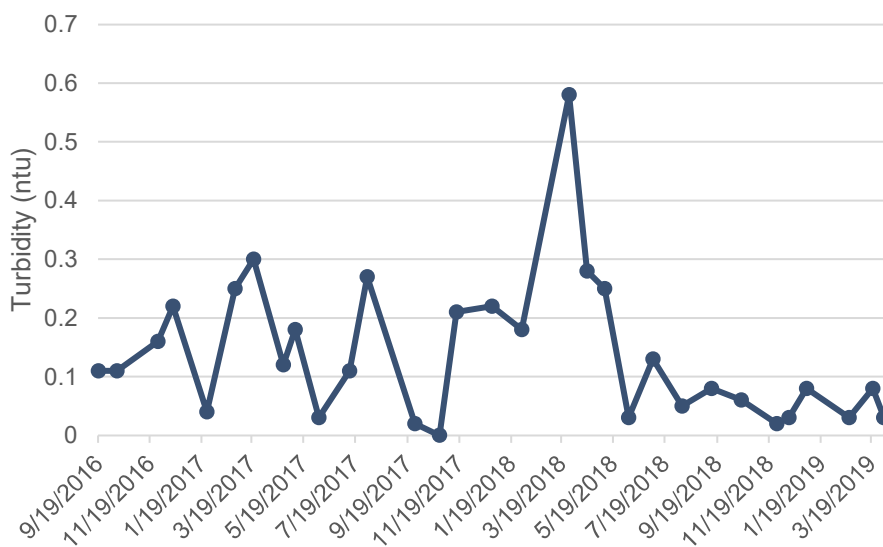


Figure B-157: Bacti Site 190 Turbidity

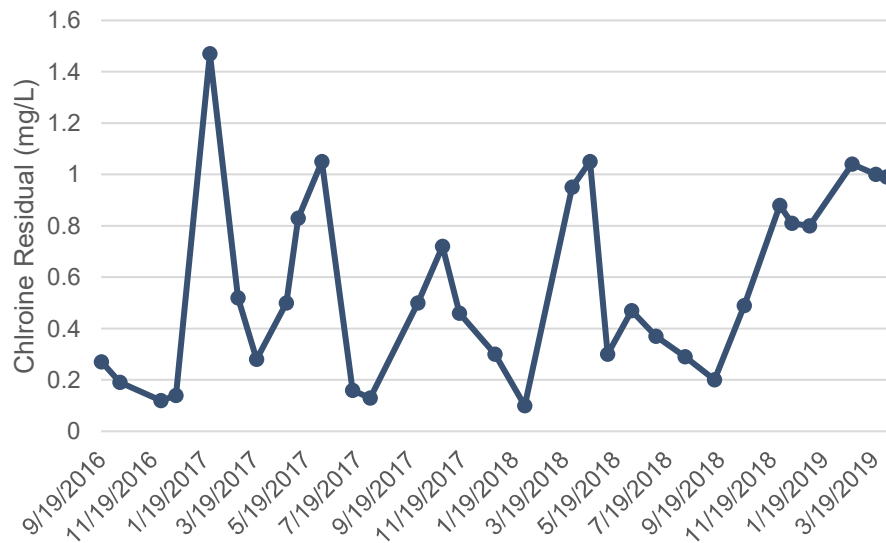


Figure B-158: Bacti Site 190 Chlorine Residual

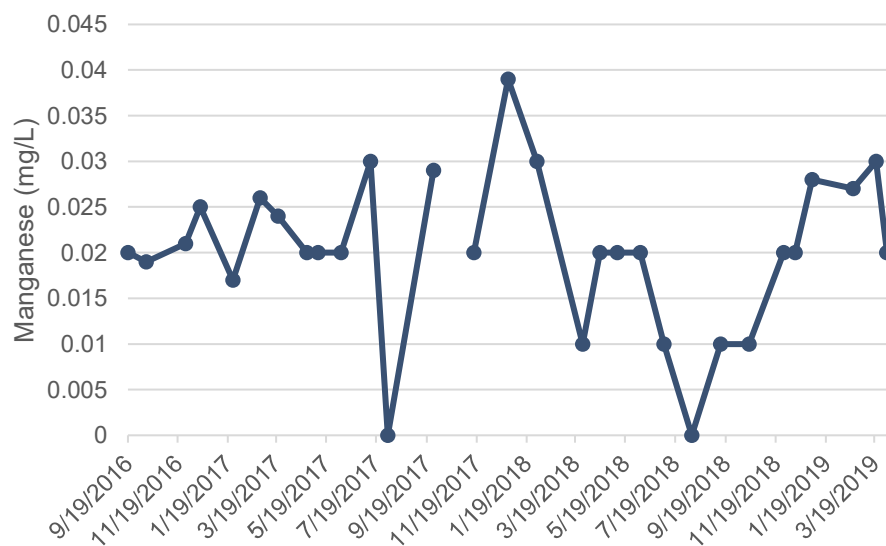


Figure B-159: Bacti Site 190 Manganese

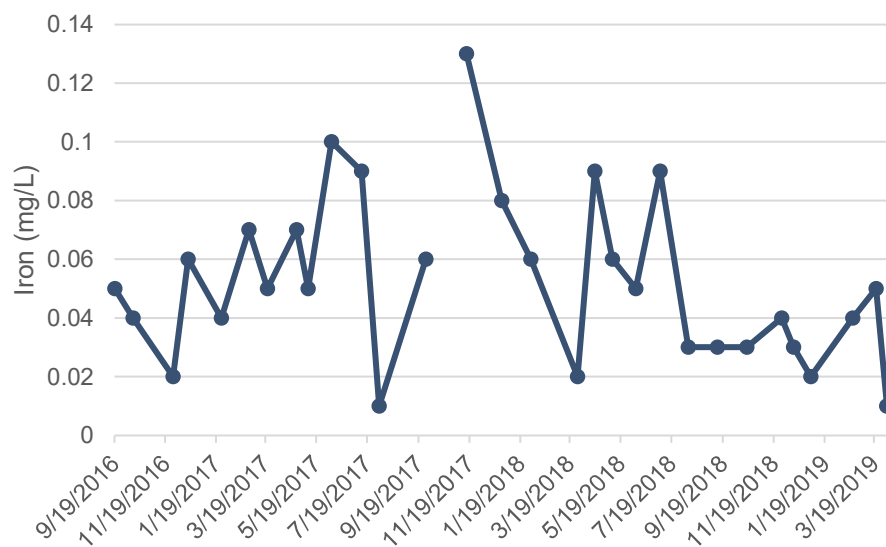


Figure B-160: Bacti Site 190 Iron

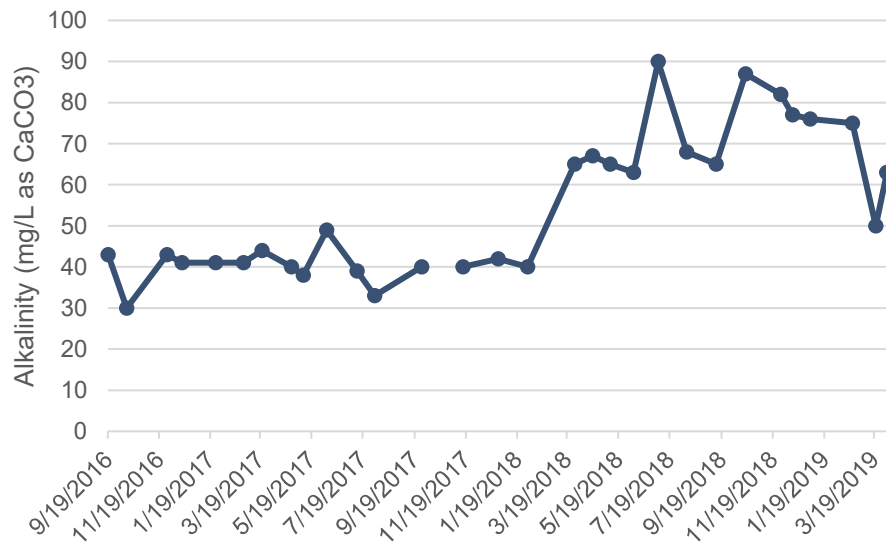


Figure B-161: Bacti Site 190 Alkalinity

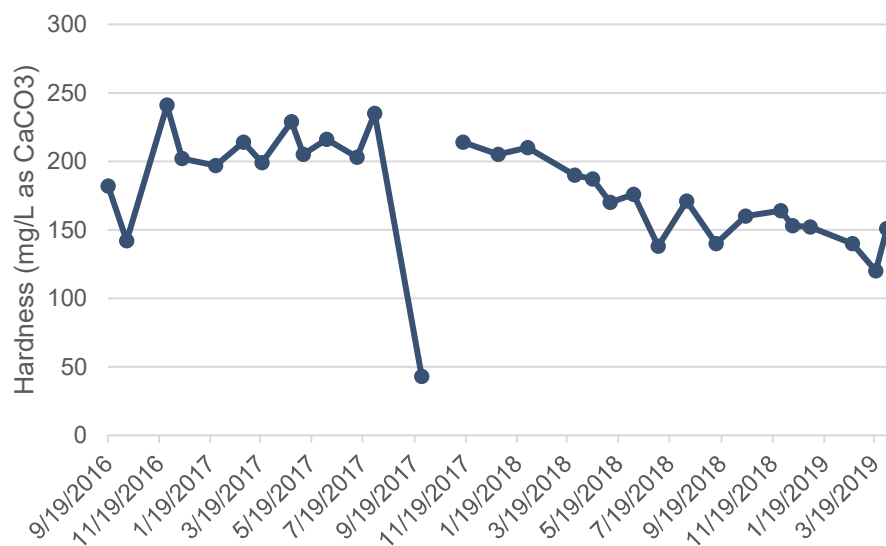


Figure B-162: Bacti Site 190 Hardness

Table A-19: Bacti Site 190 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
3/21/2019	0.58	210
4/3/2019	0.9	236

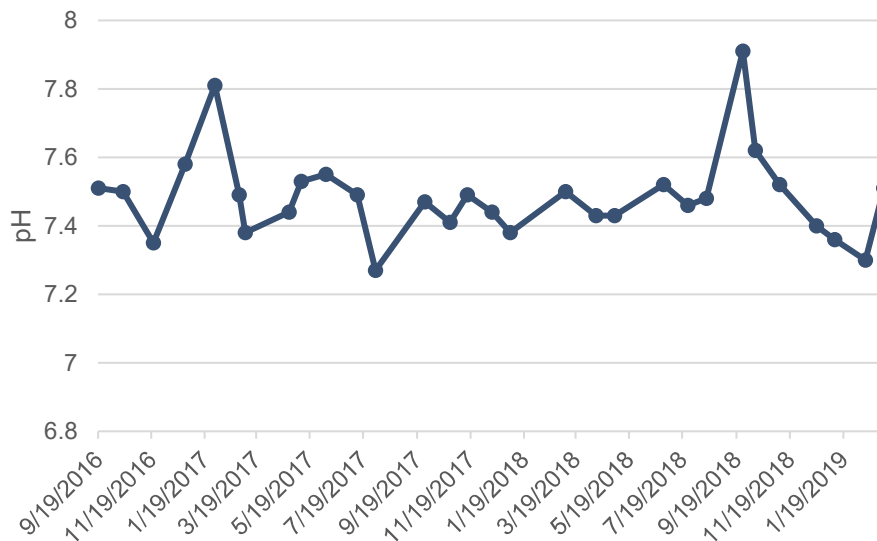


Figure B-163: Bacti Site 200 pH

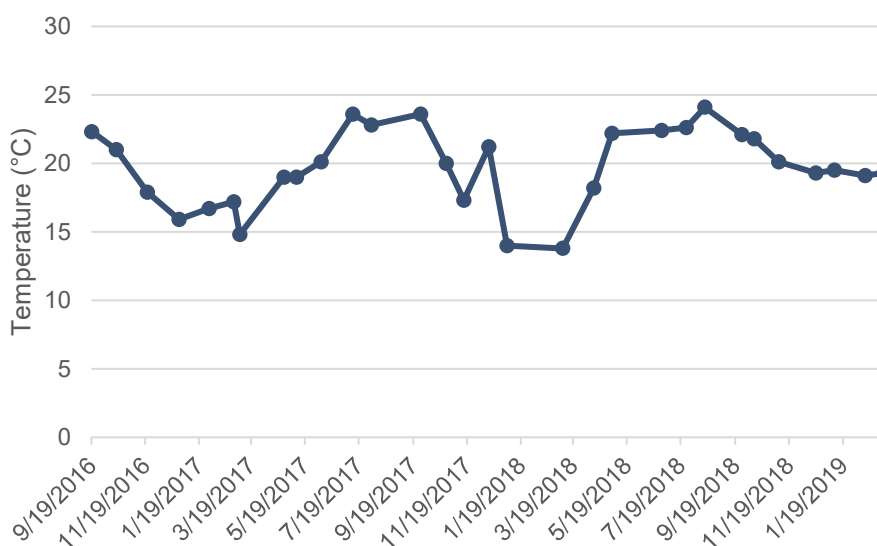


Figure B-164: Bacti Site 200 Temperature

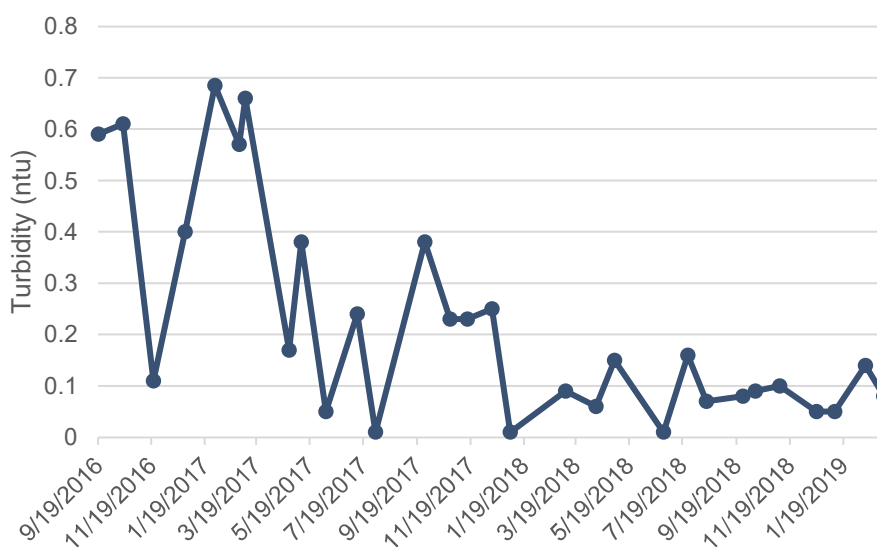


Figure B-165: Bacti Site 200 Turbidity

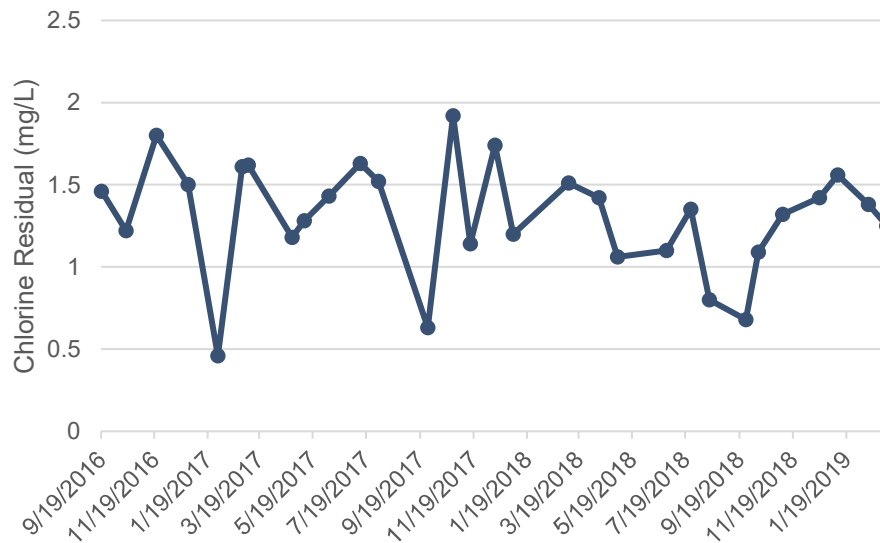


Figure B-166: Bacti Site 200 Chlorine Residual

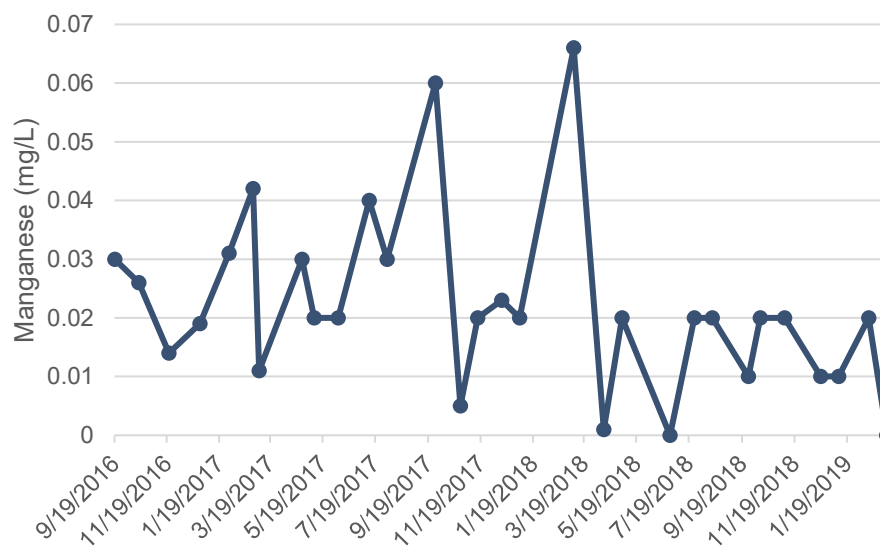


Figure B-167: Bacti Site 200 Manganese

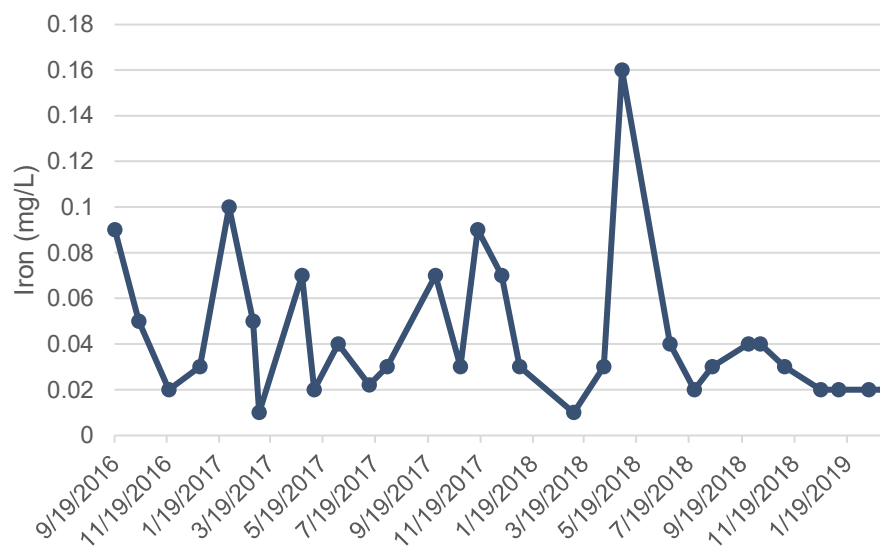


Figure B-168: Bacti Site 200 Iron

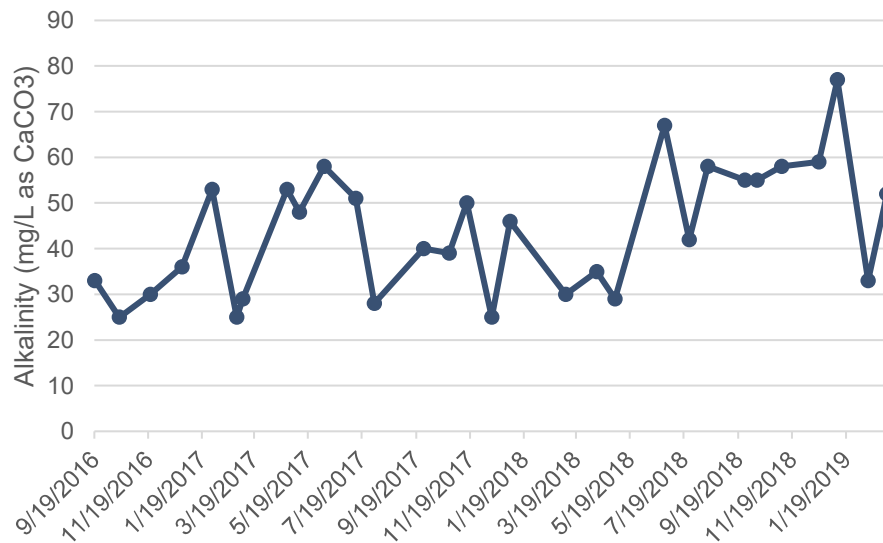


Figure B-169: Bacti Site 200 Alkalinity

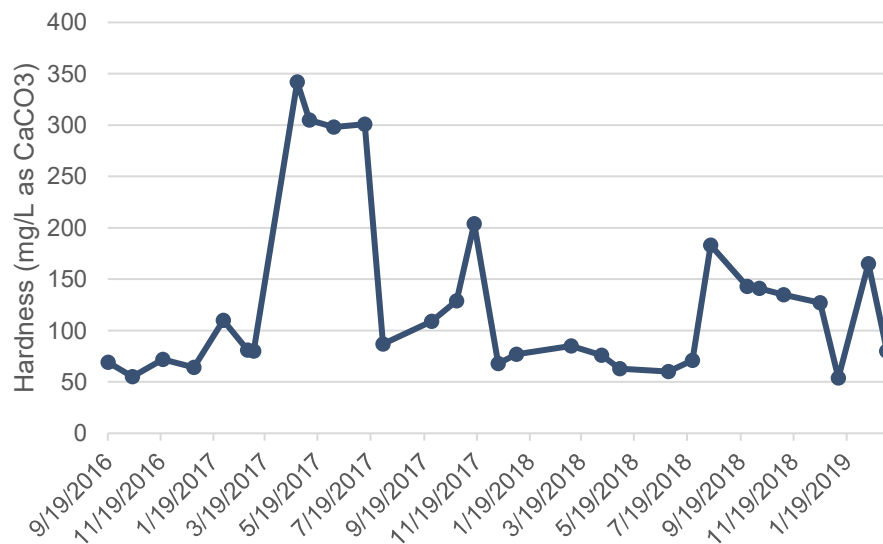


Figure B-170: Bacti Site 200 Hardness

Table A-20: Bacti Site 200 Additional Data

Date	Orthophosphate (mg/L as PO ₄)	TDS (mg/L)
NA	NA	NA

Appendix C: WTP Data

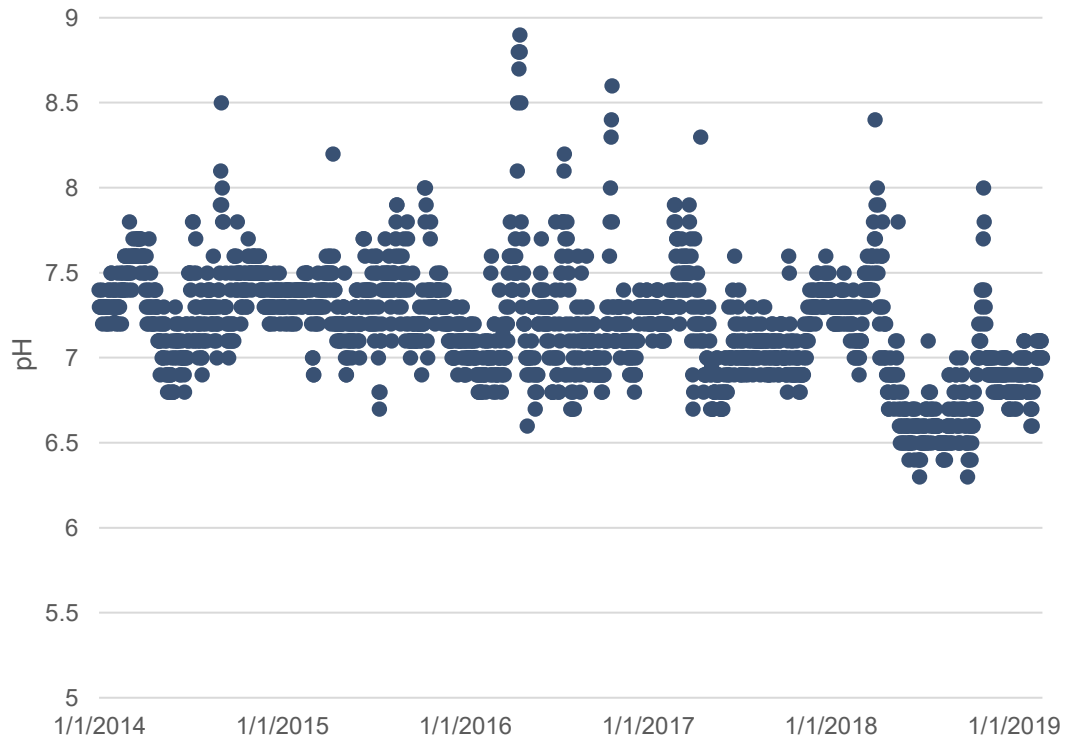


Figure C-1. WTP Raw Water pH

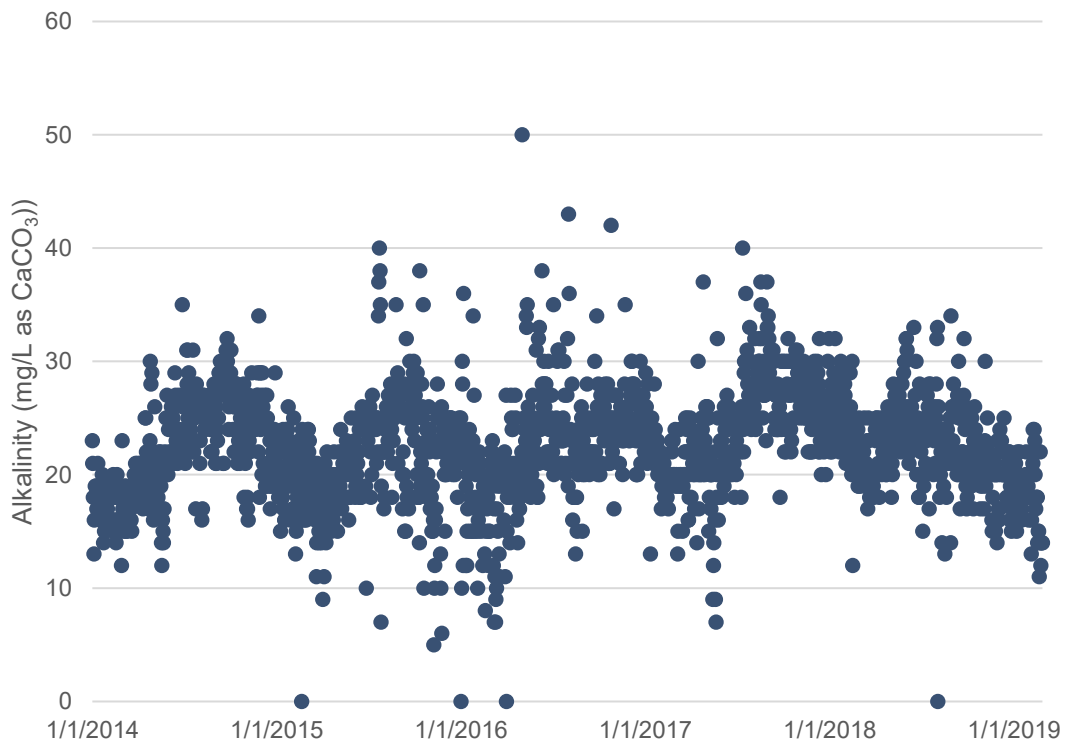


Figure C-2. WTP Raw Water Alkalinity

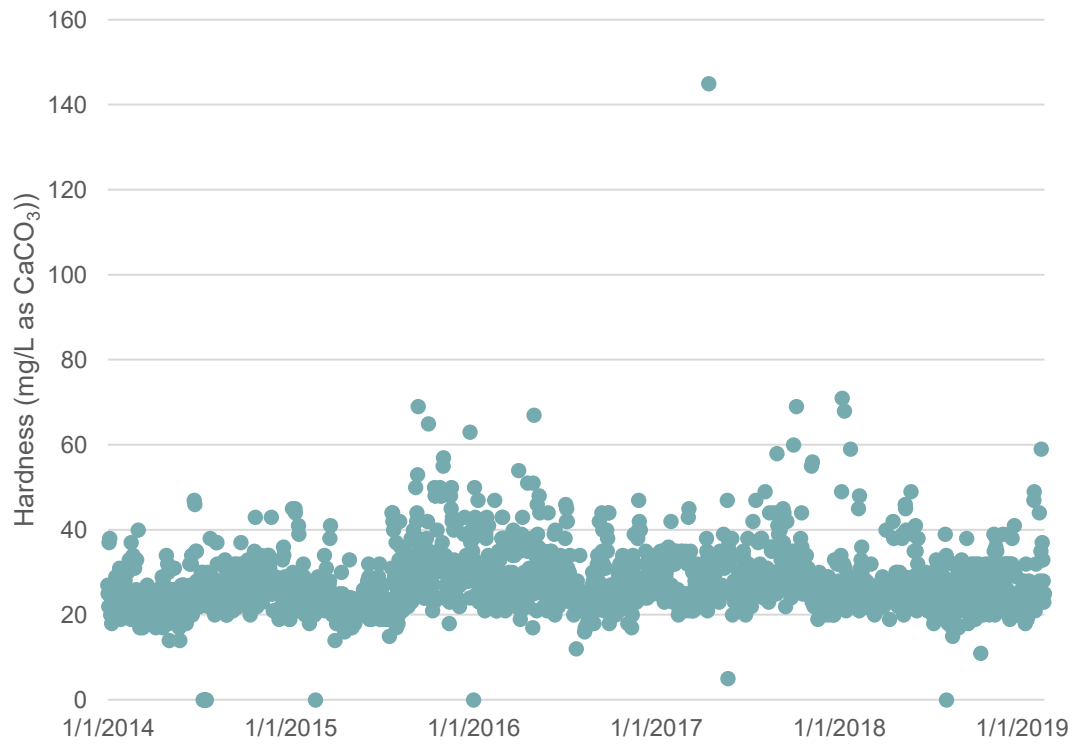


Figure C-3. WTP Raw Water Hardness

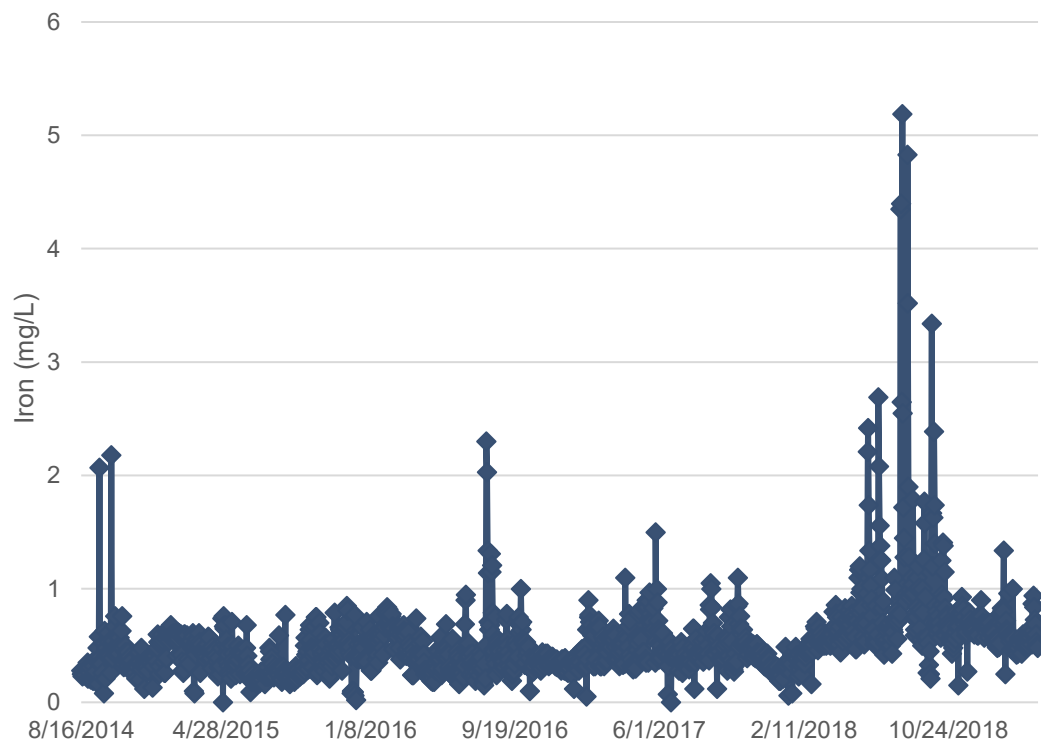


Figure C-4. WTP Raw Water Iron

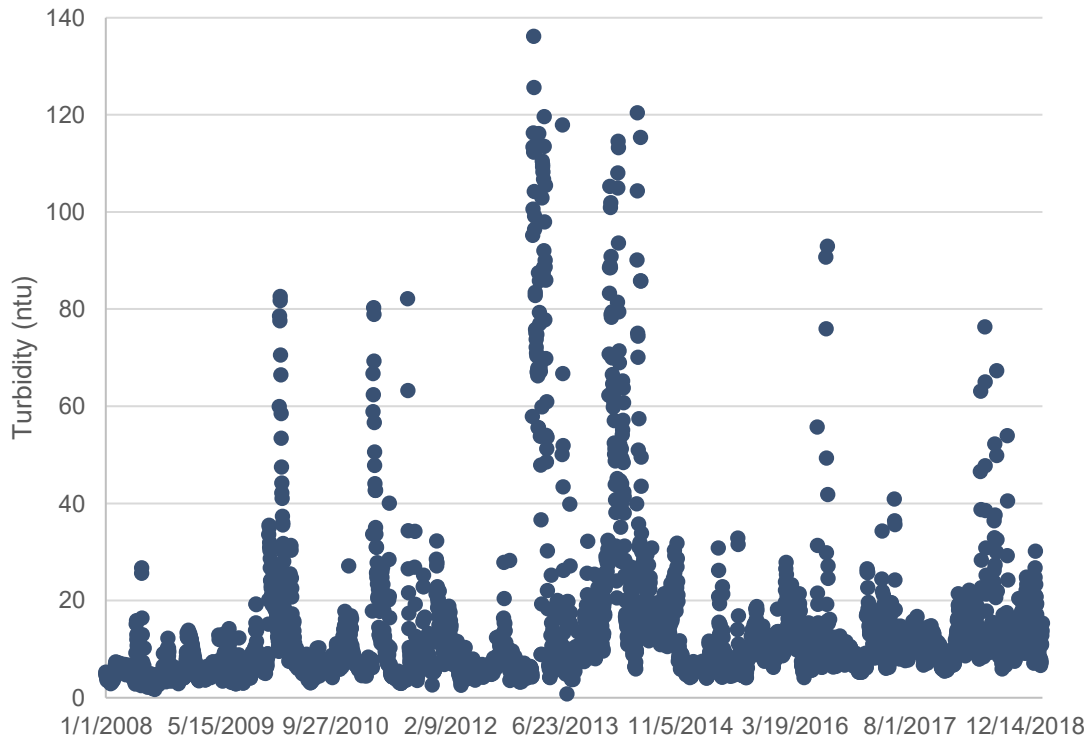


Figure C-5. WTP Average Raw Water Turbidity

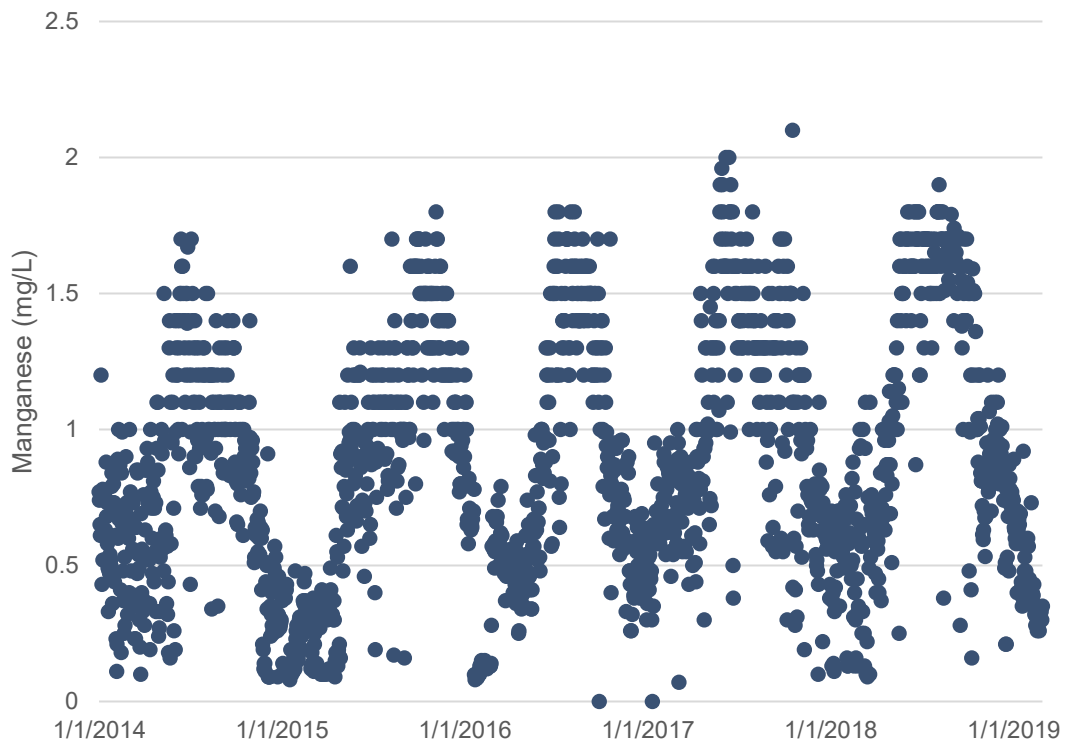


Figure C-6. WTP Raw Water Manganese after Permanganate Addition

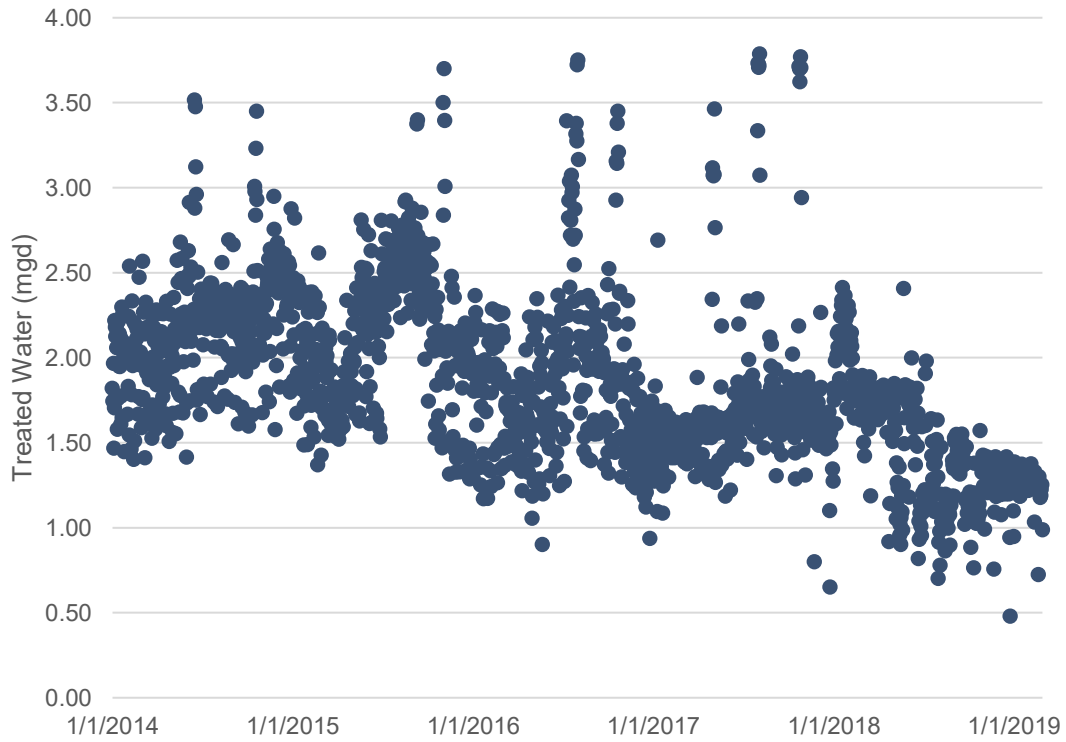


Figure C-7. WTP Total Treated Water

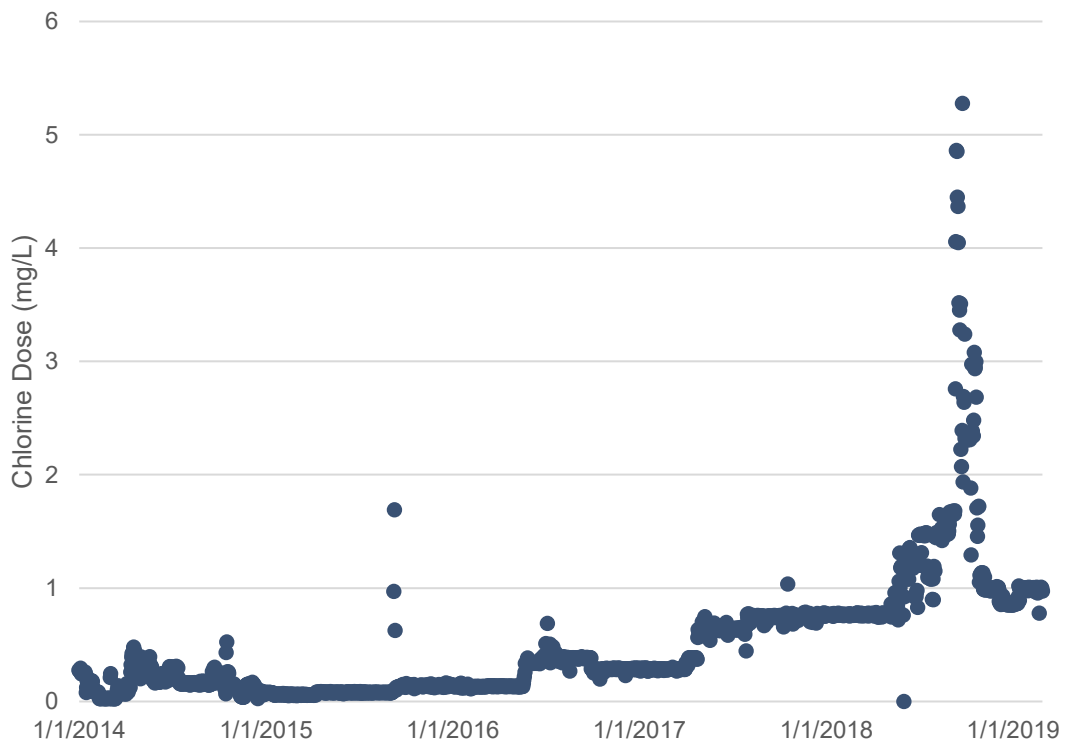


Figure C-8. WTP Applied Chlorine Residual

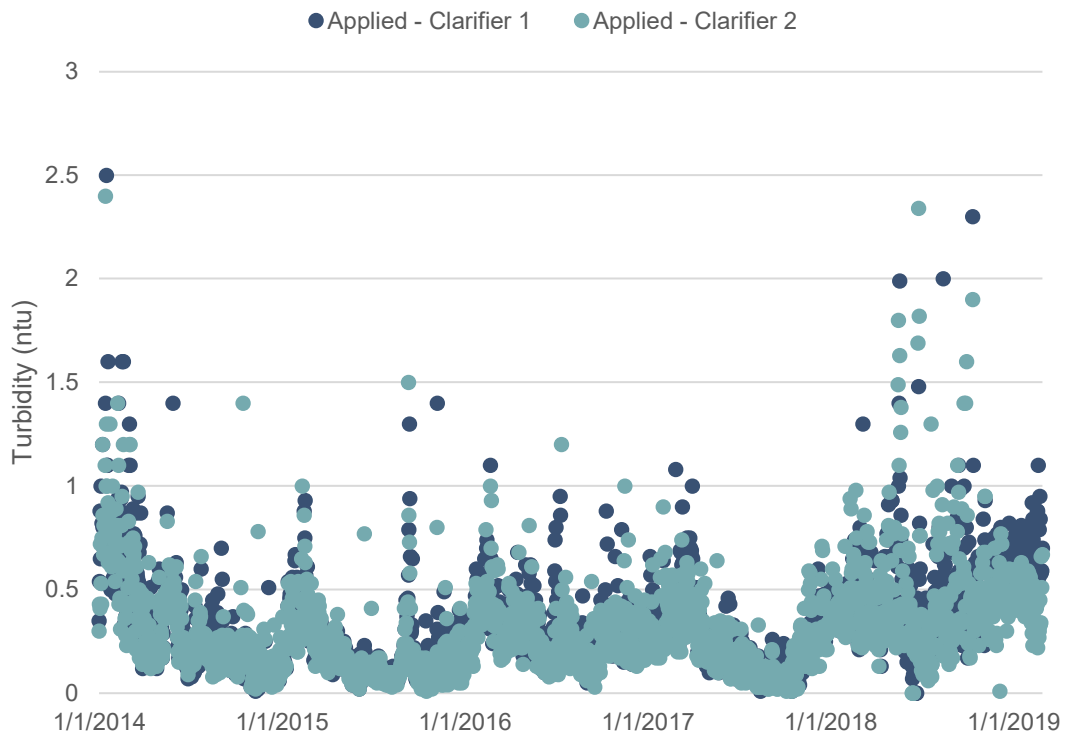


Figure C-9. WTP Turbidity Removal

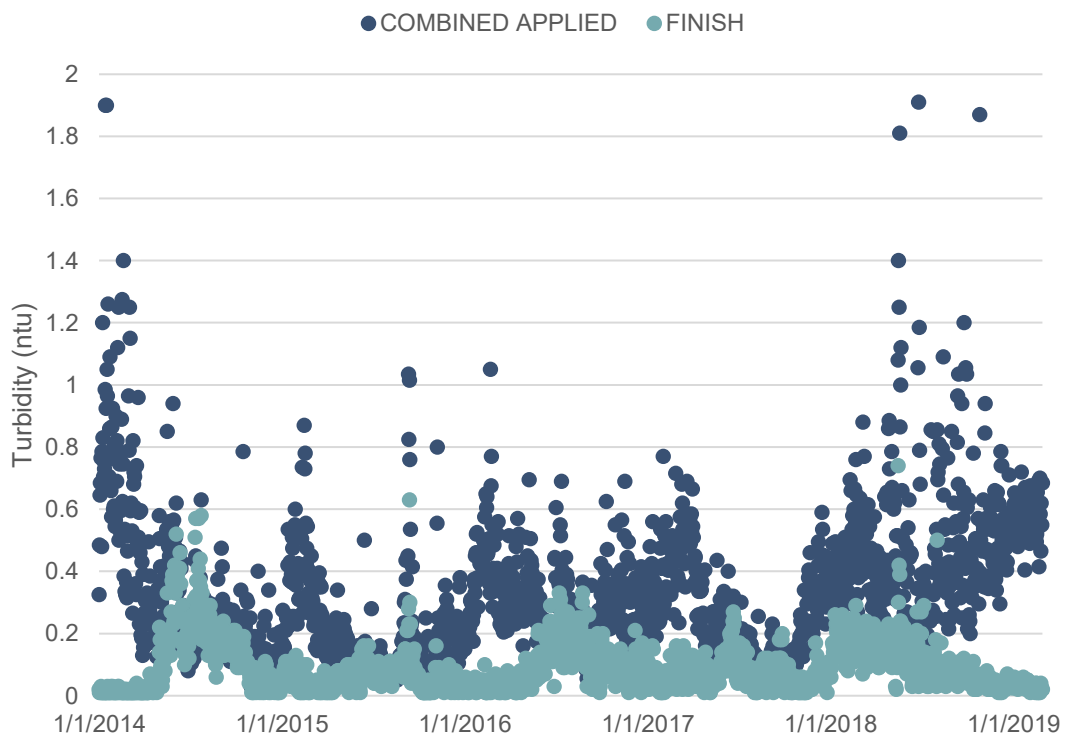


Figure C-10. WTP Turbidity Removal

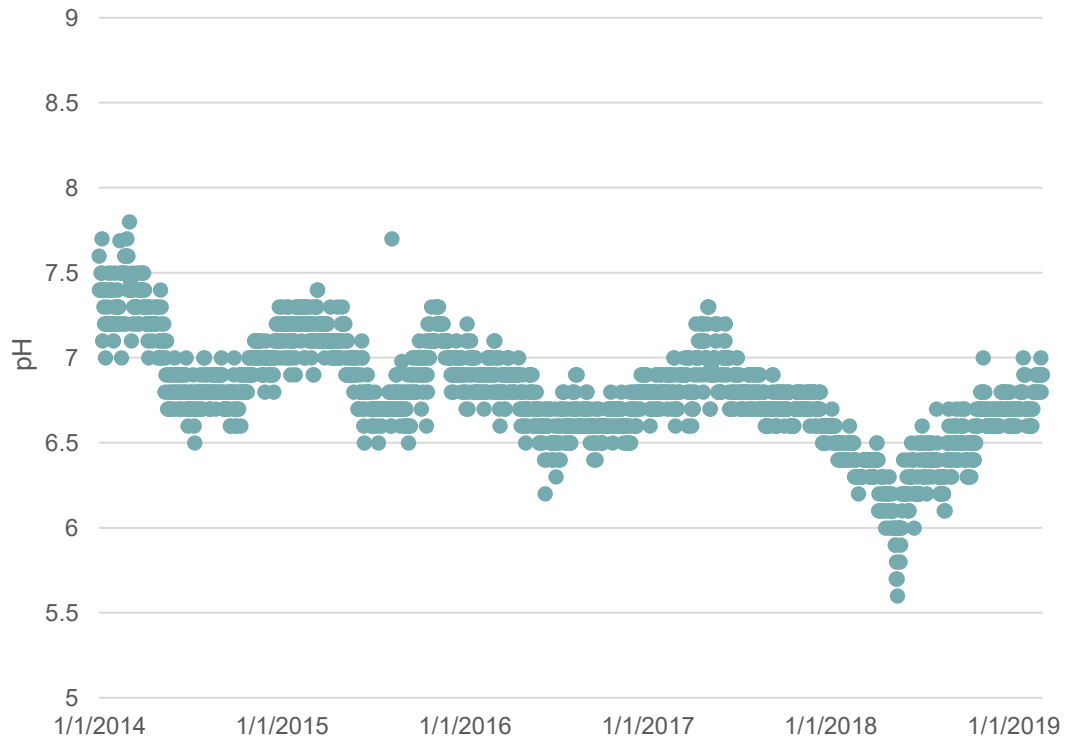


Figure C-11. WTP Applied pH

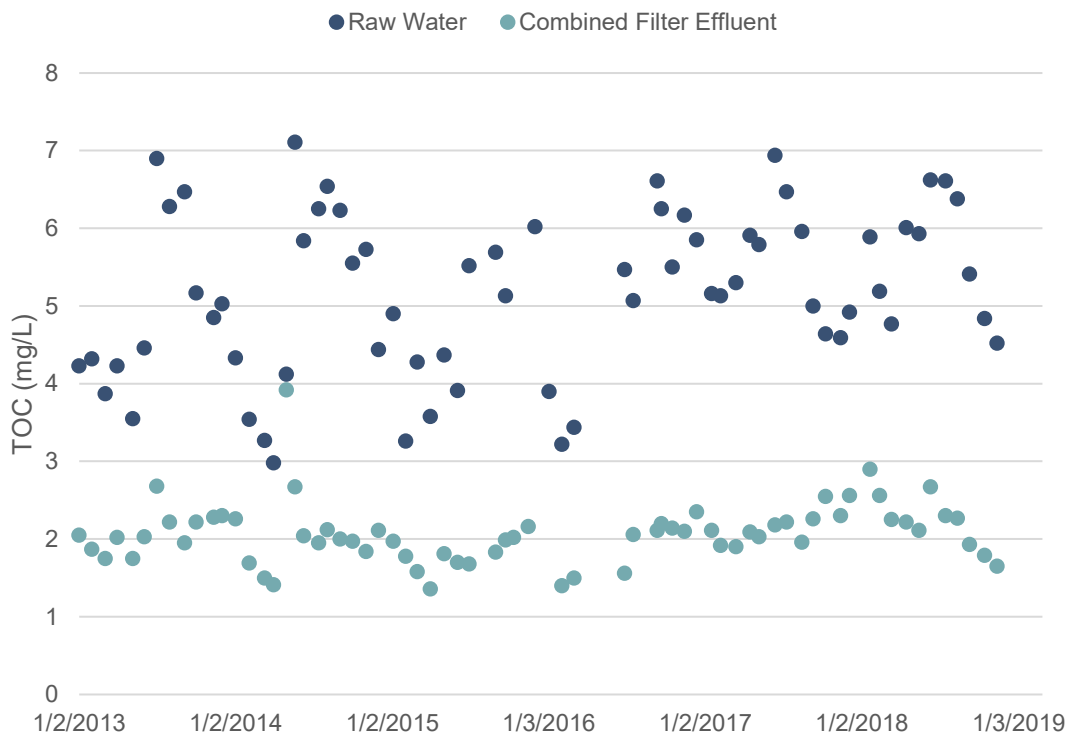


Figure C-12. WTP Total Organic Carbon (TOC) Removal

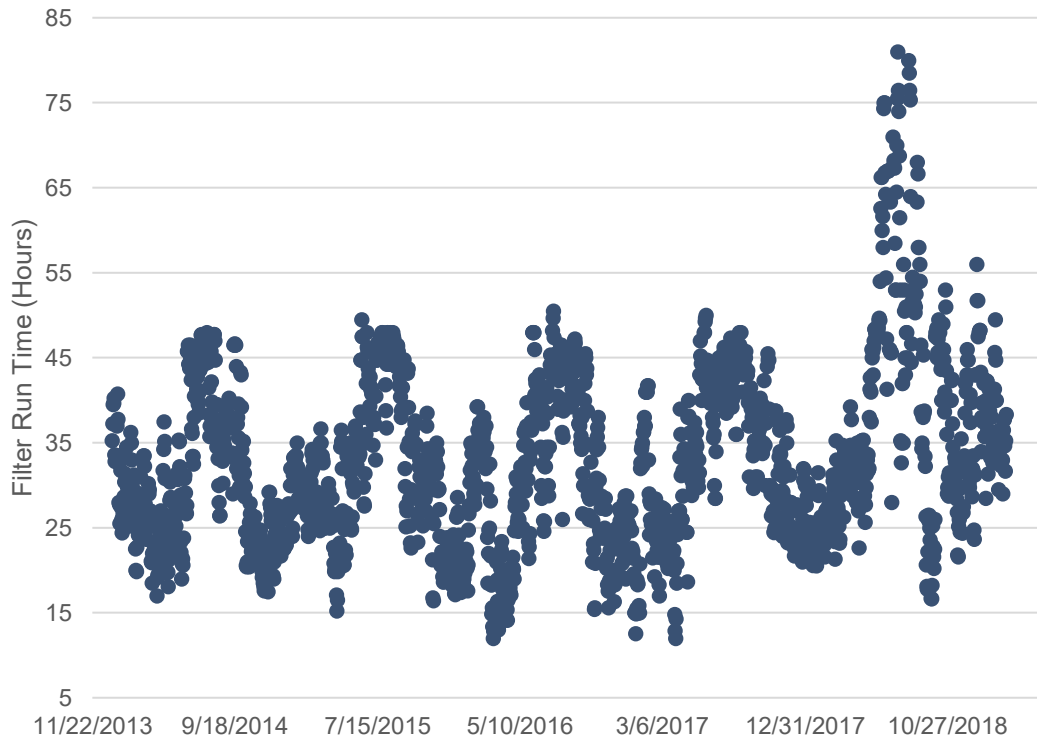


Figure C-13. WTP Average Filter Run Time

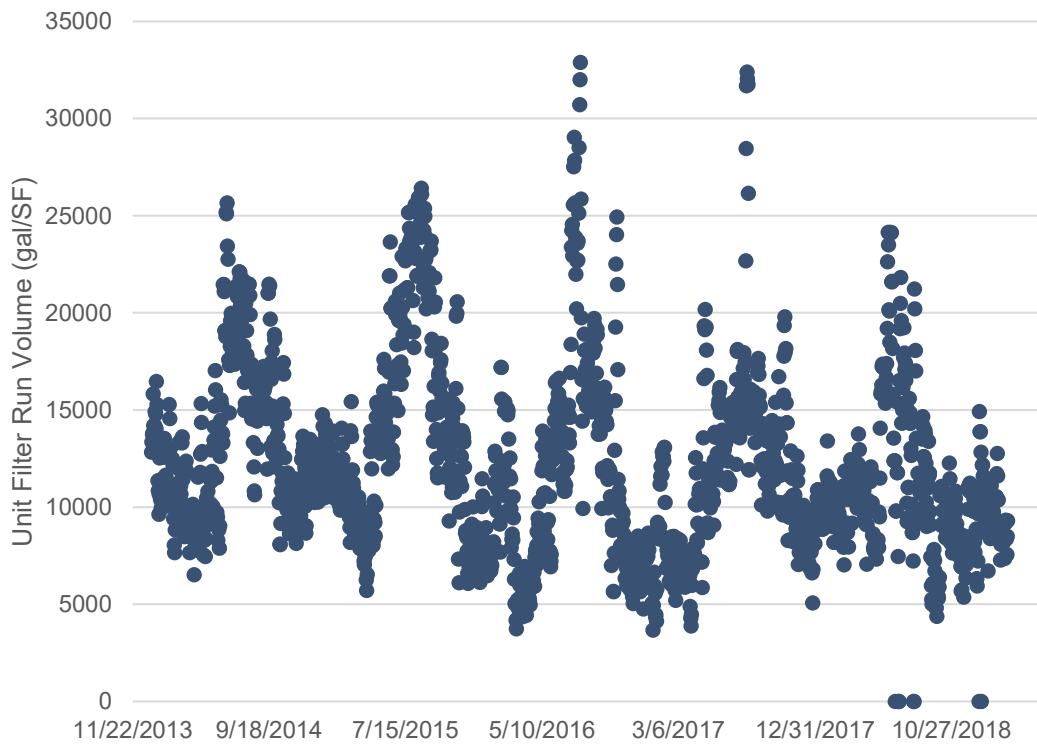


Figure C-14. WTP Average Unit Filter Run Volume

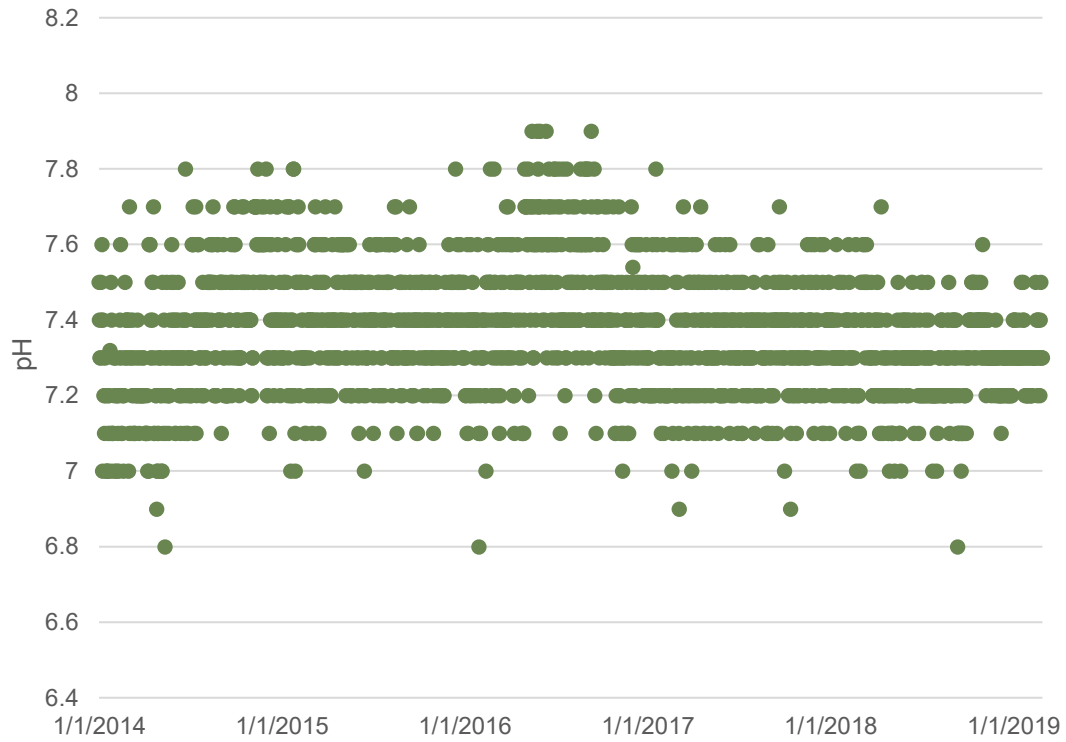


Figure C-15. WTP Finished Water pH

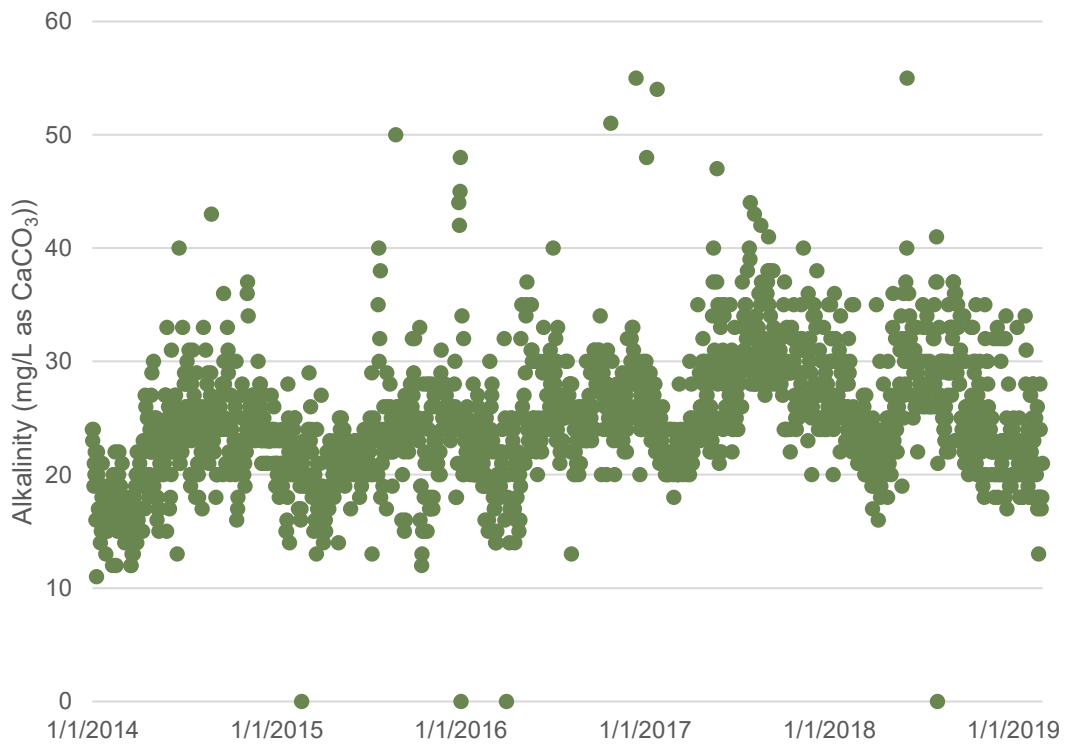


Figure C-16. WTP Finished Water Alkalinity

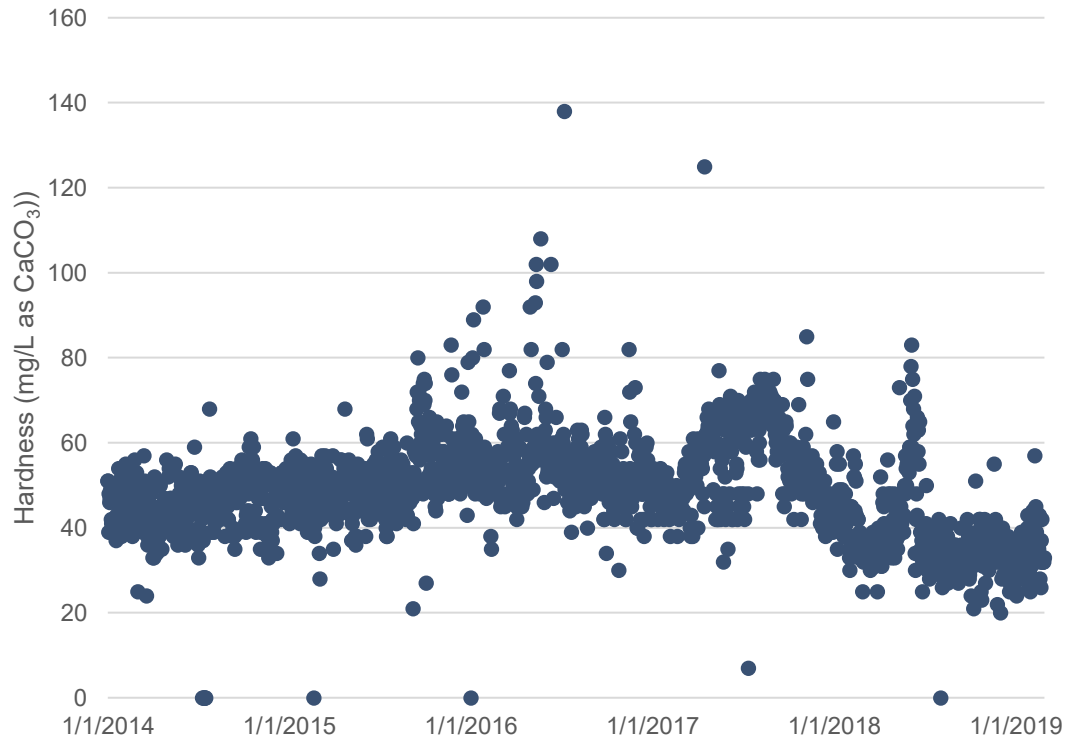


Figure C-17. WTP Finished Water Hardness

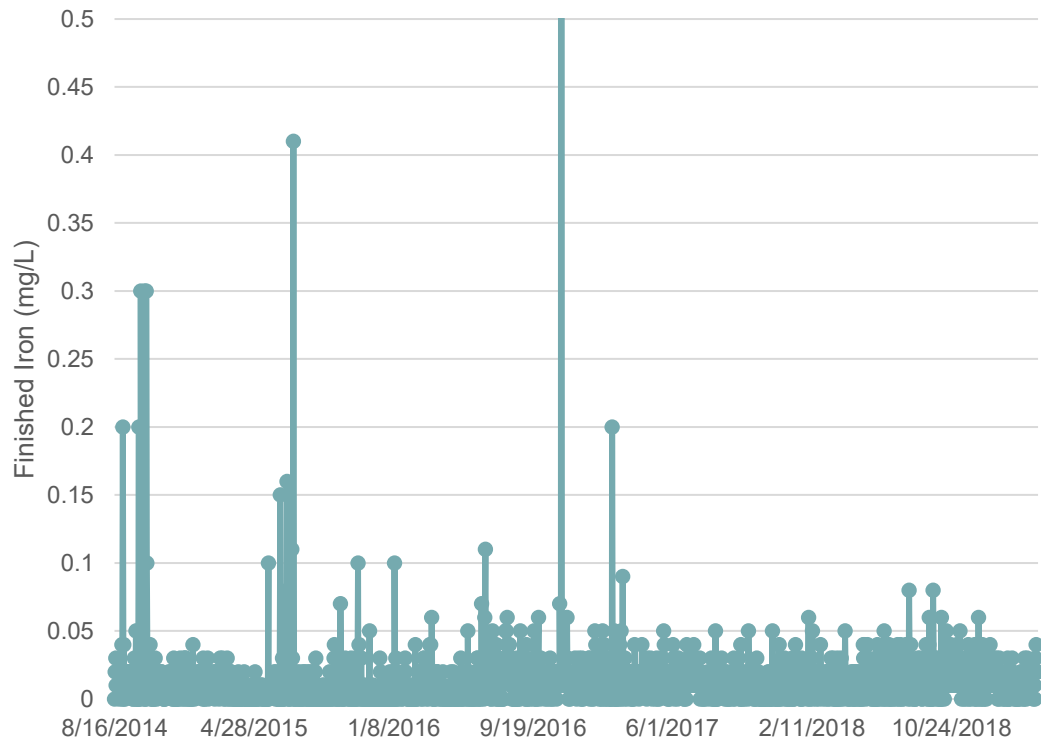


Figure C-18. WTP Finished Water Iron

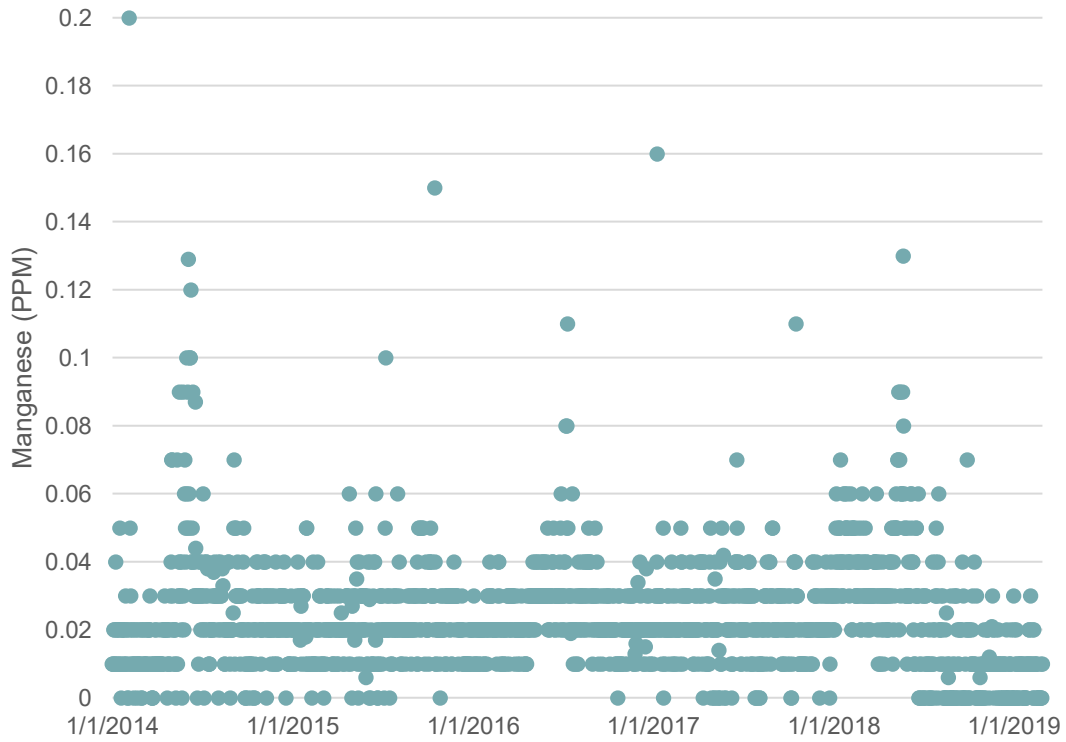


Figure C-19. WTP Finished Manganese

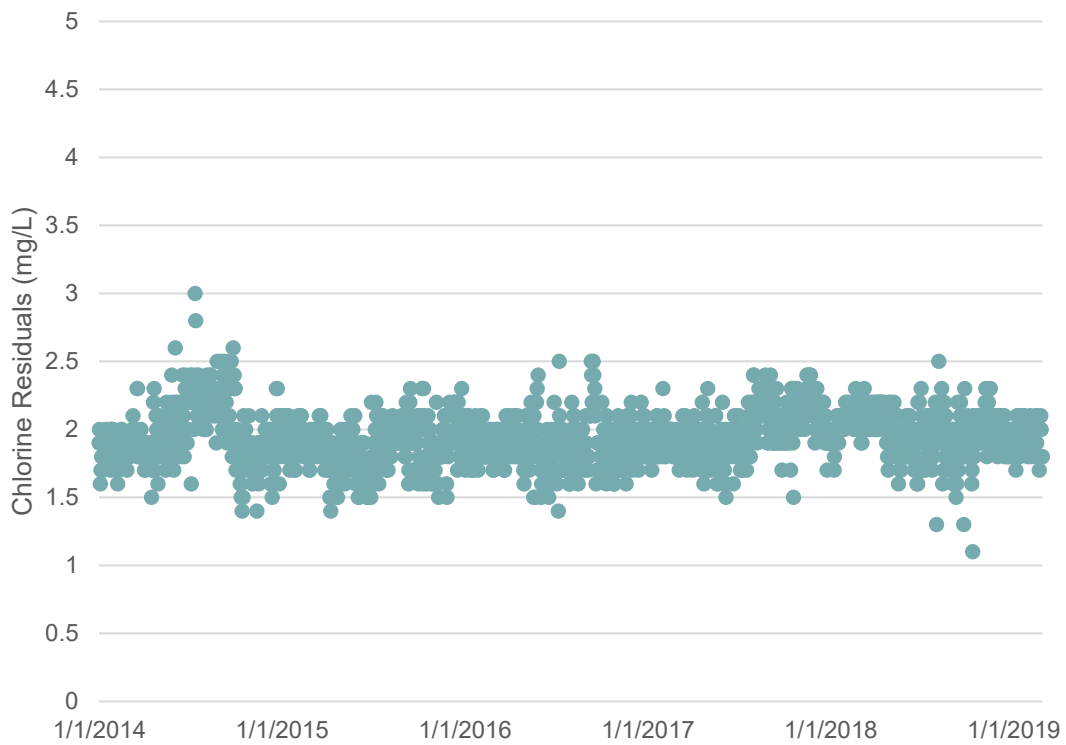


Figure C-20. WTP Finished Chlorine Residual

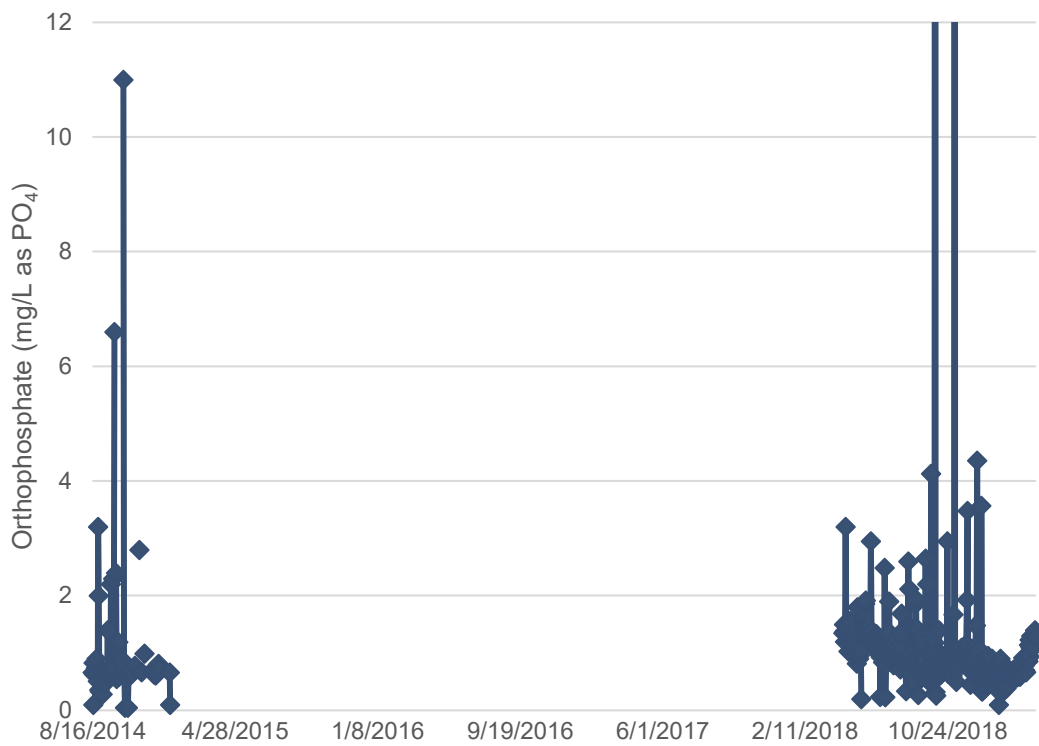


Figure C-21. WTP Orthophosphate Concentrations

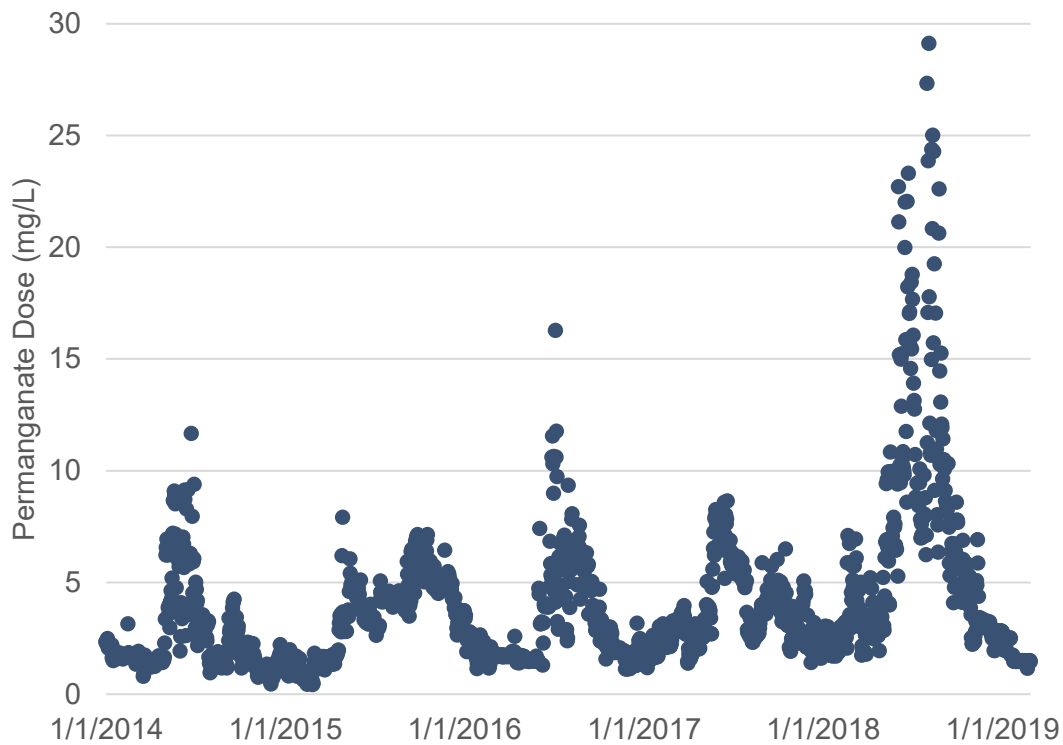


Figure C-22. WTP Permanganate Dose (Added at the Reservoir and/or the WTP)

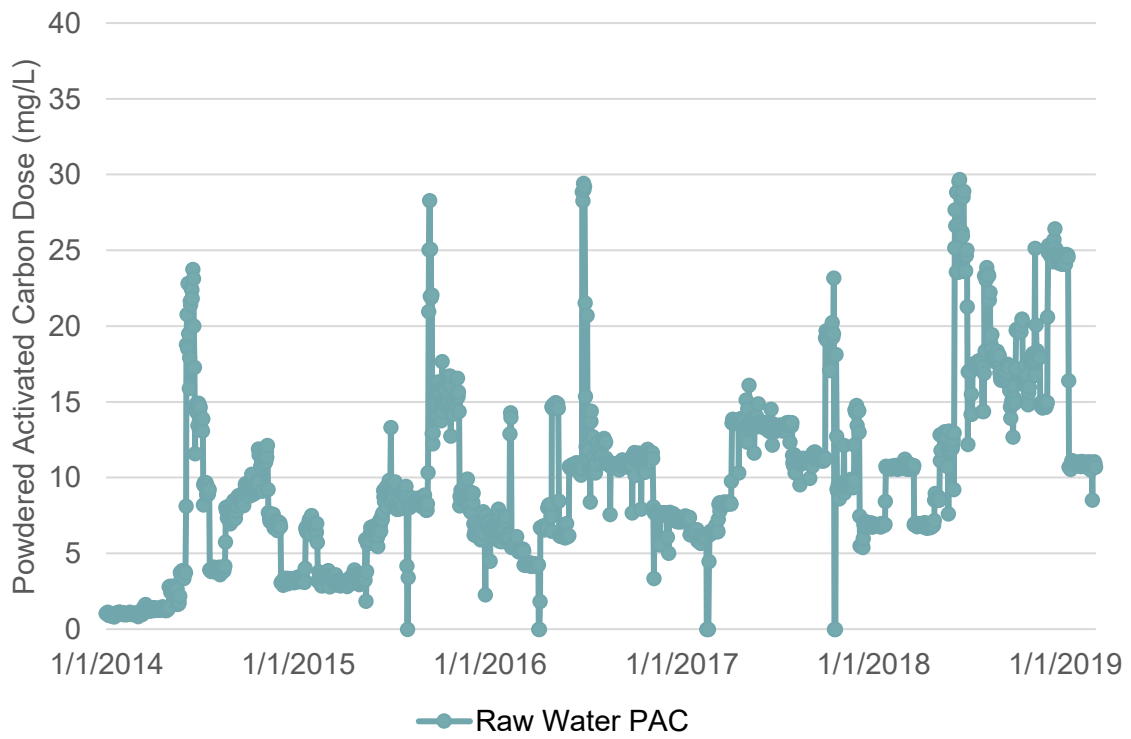


Figure C-23. WTP Raw Water Powdered Activated Carbon Dose

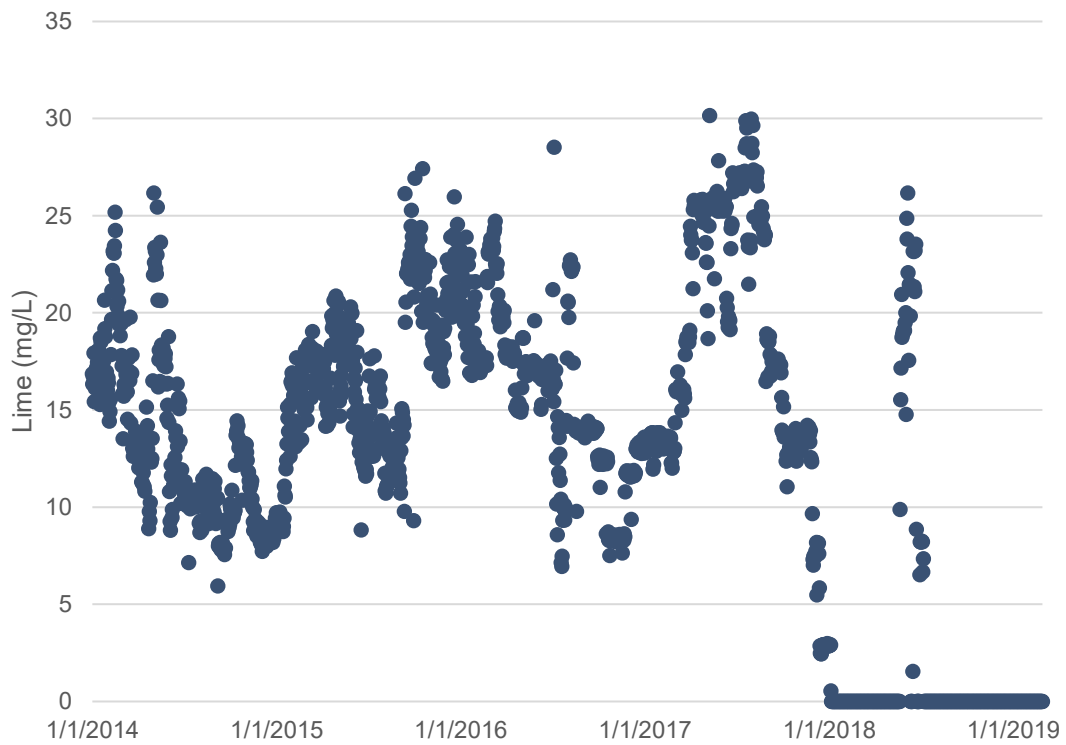


Figure C-24. WTP Raw Water Lime Dose

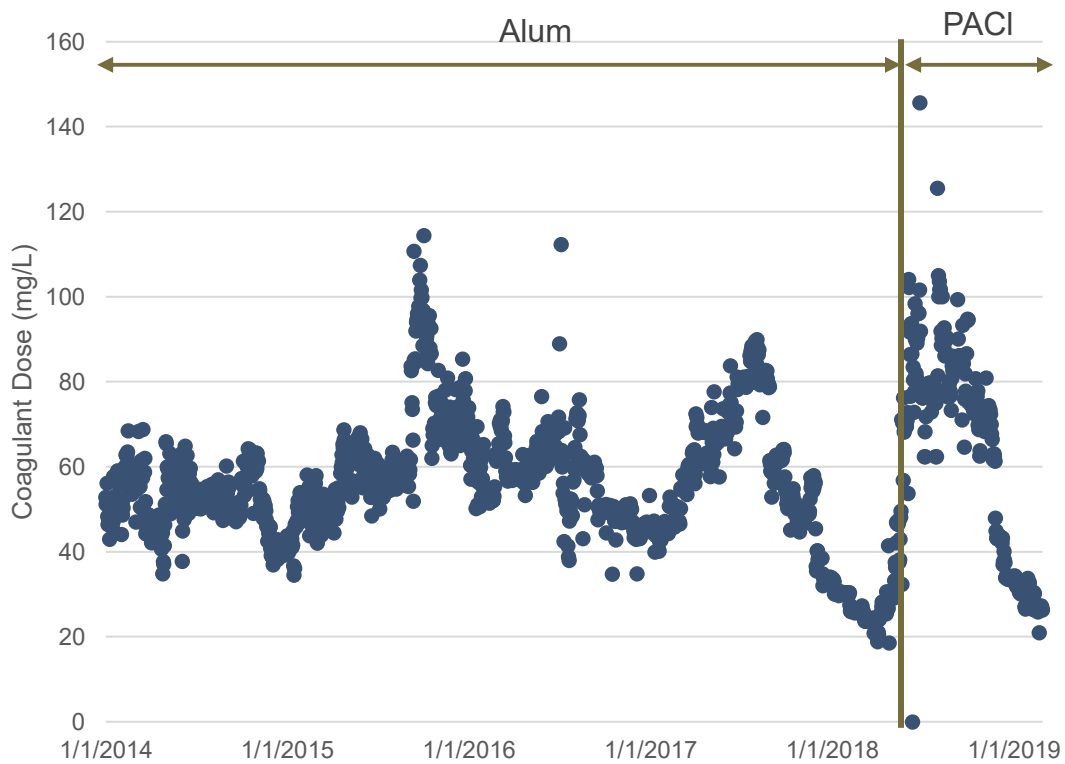


Figure C-25. WTP Coagulant Dose

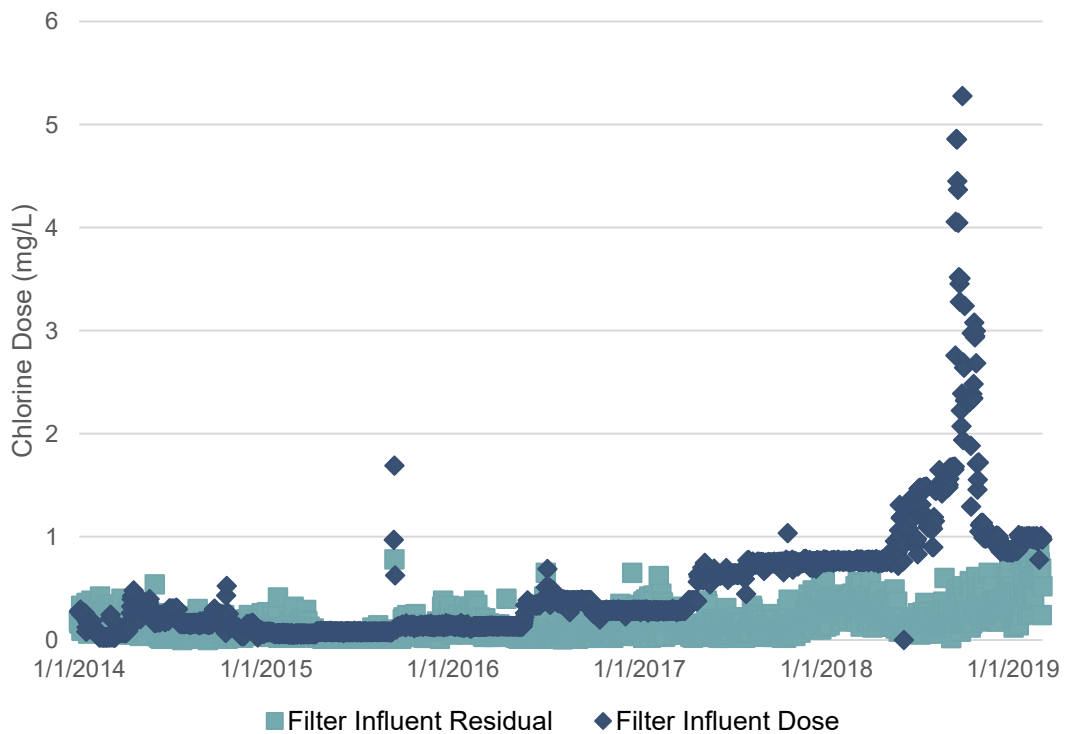


Figure C-26. WTP Applied Chlorine

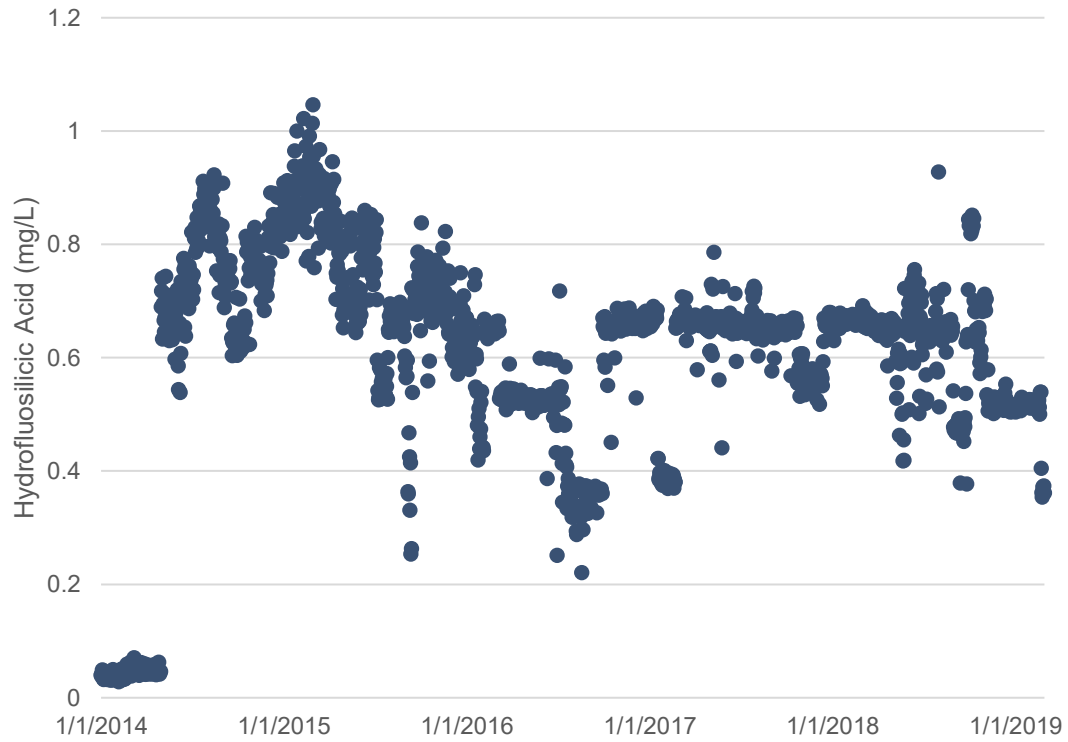


Figure C-27. WTP Fluoride Dose

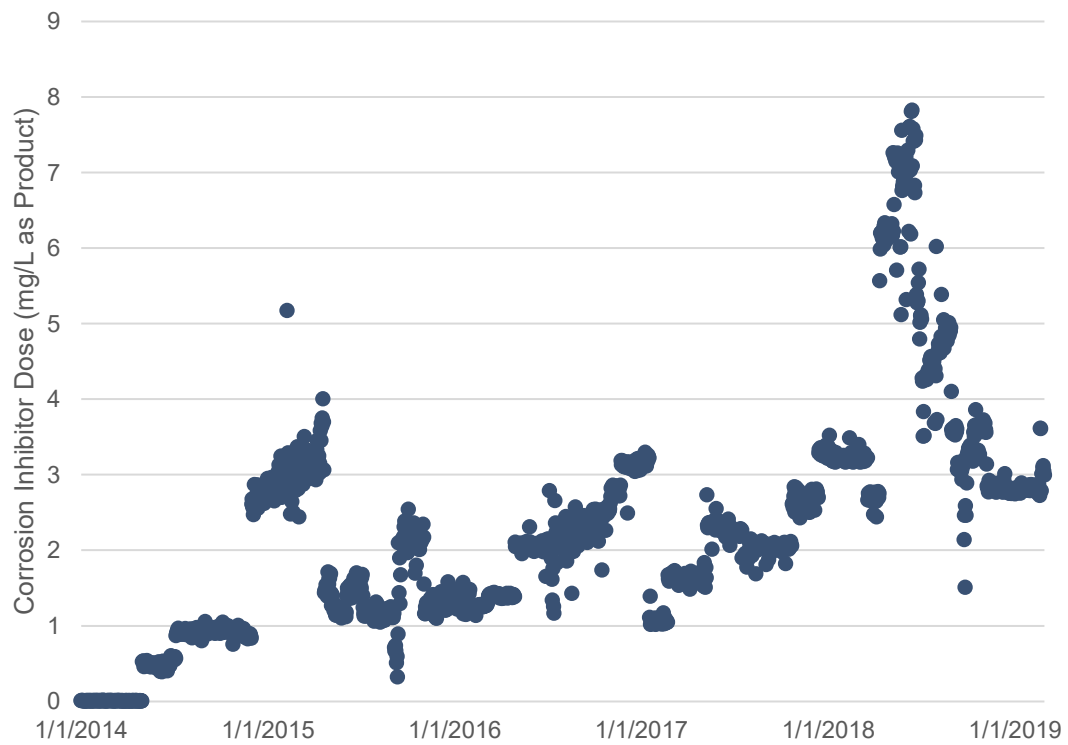


Figure C-28. WTP Corrosion Inhibitor Dose

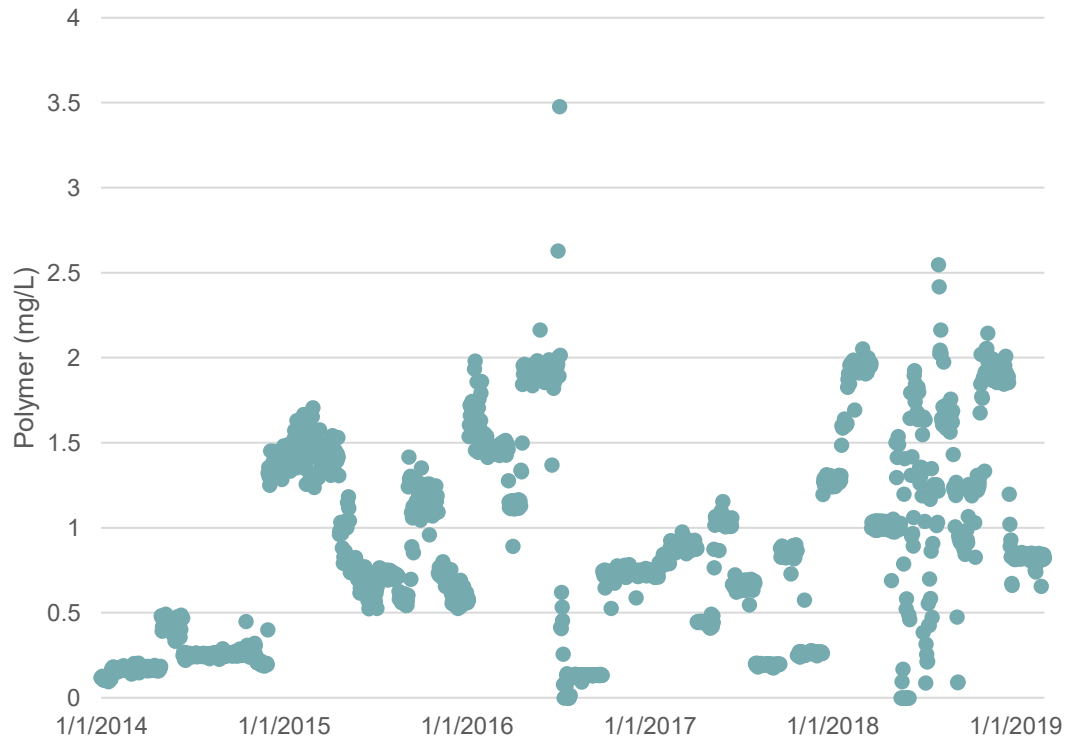


Figure C-29. WTP Polymer Dose

Appendix D: Chandler Street Well Data

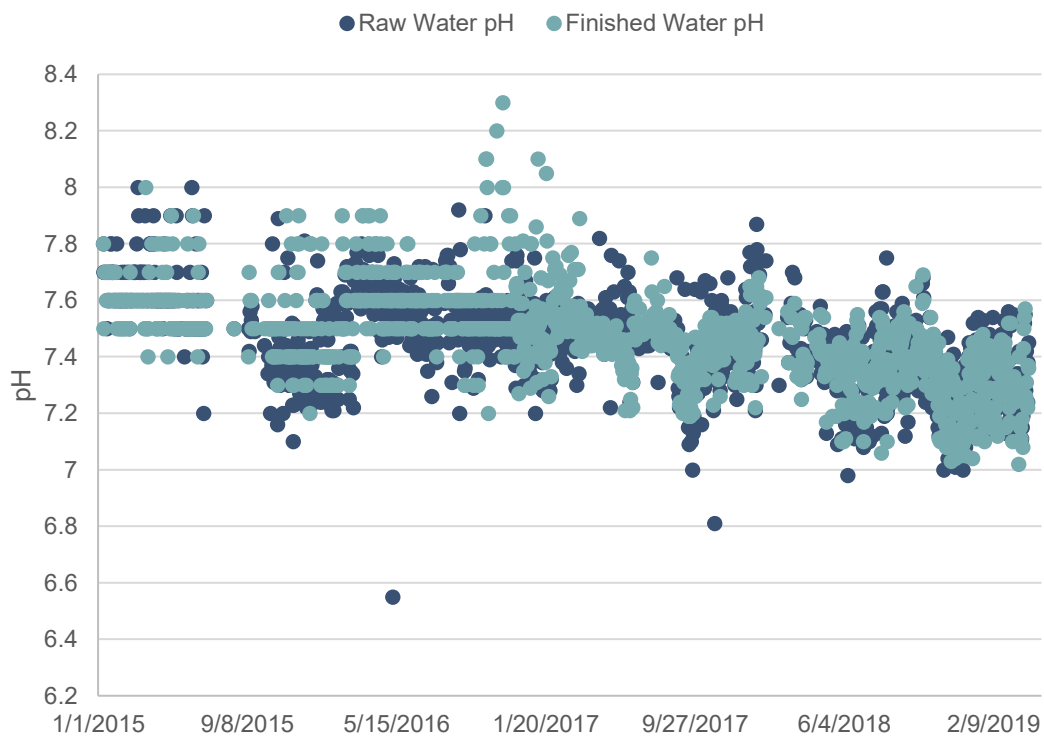


Figure D-1. Chandler Street Well pH

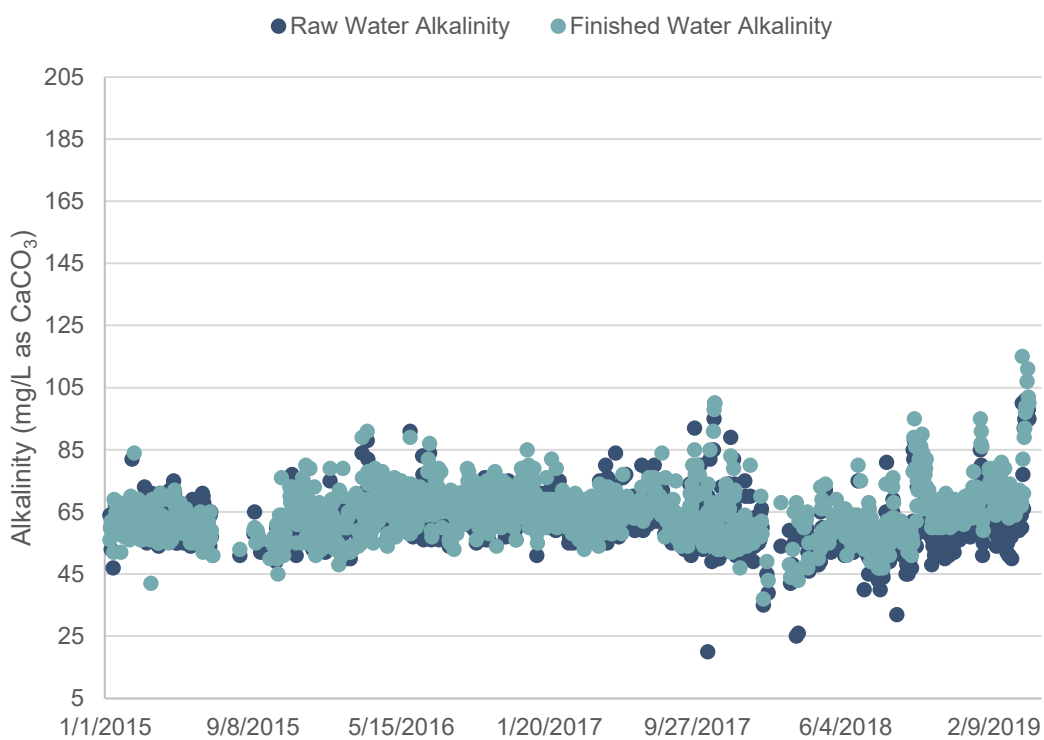


Figure D-2. Chandler Street Well Alkalinity

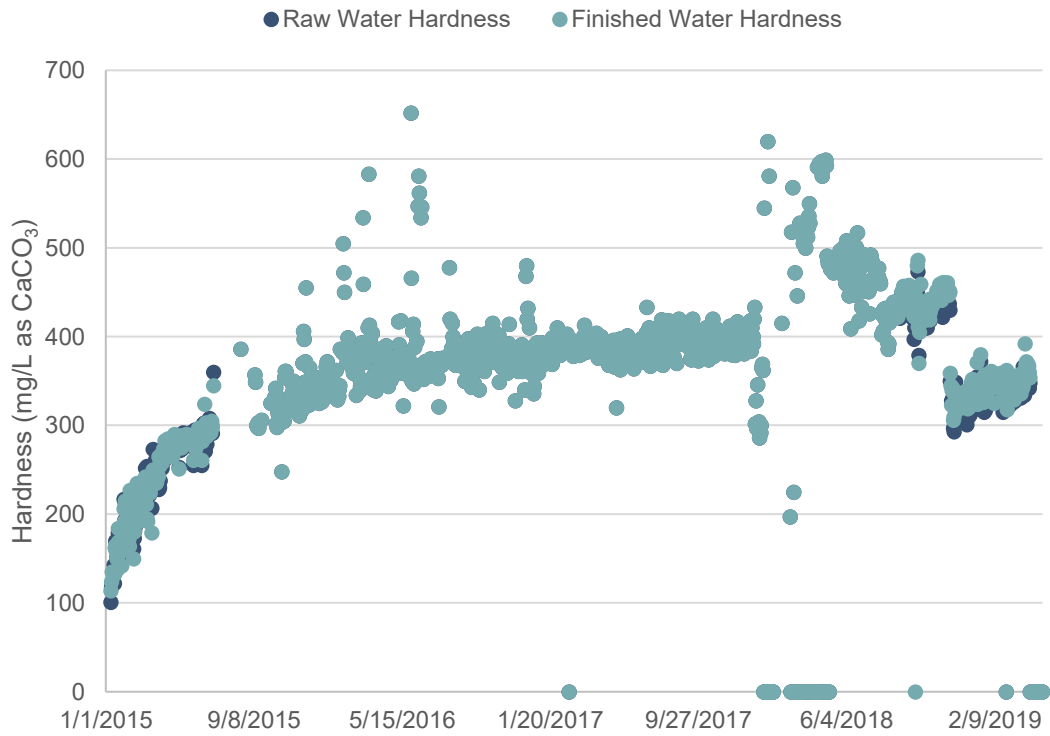


Figure D-3. Chandler Street Well Hardness

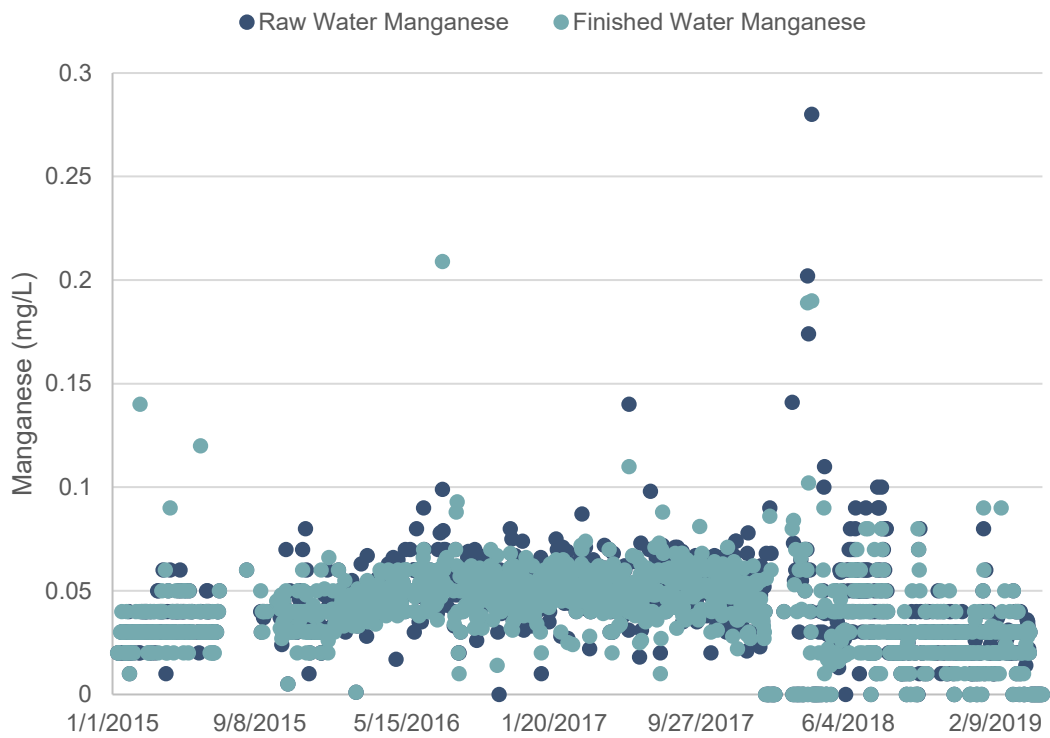


Figure D-4. Chandler Street Well Manganese

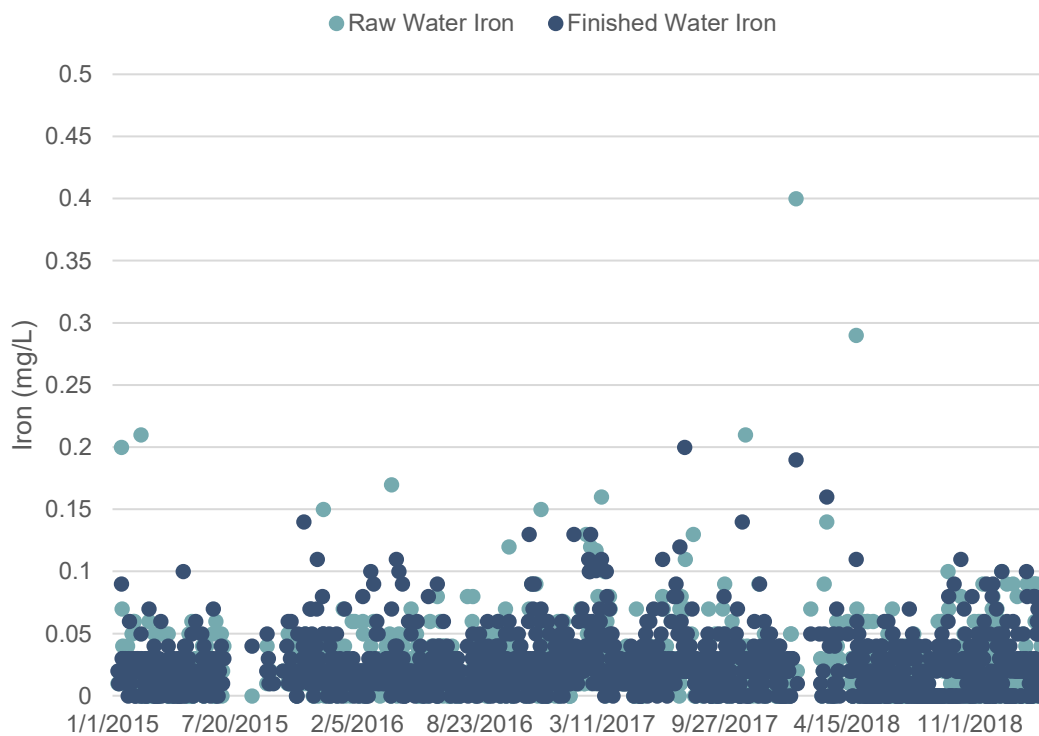


Figure D-5. Chandler Street Well Iron

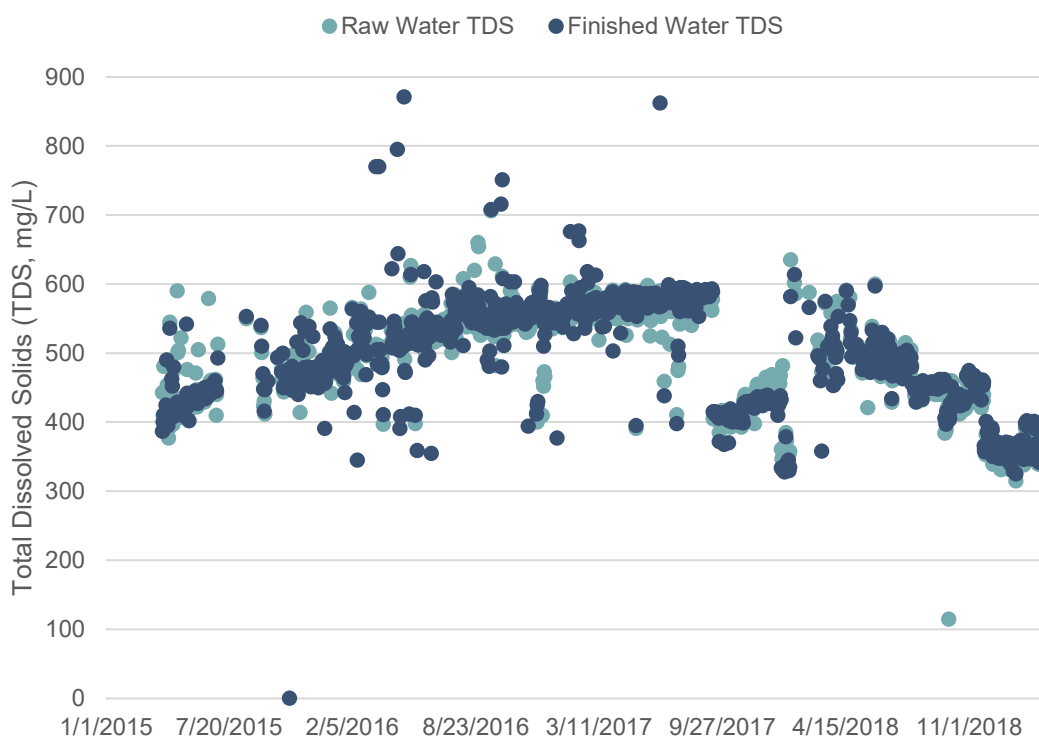


Figure D-6. Chandler Street Total Dissolved Solids

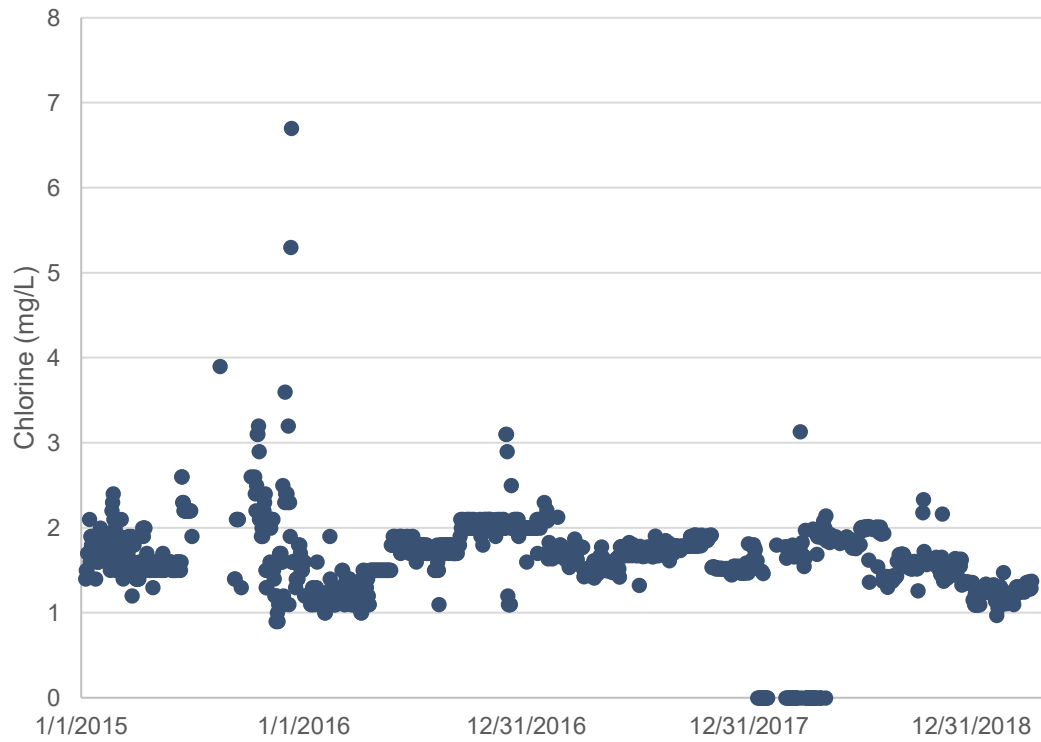


Figure D-7. Chandler Street Well Chlorine Dose

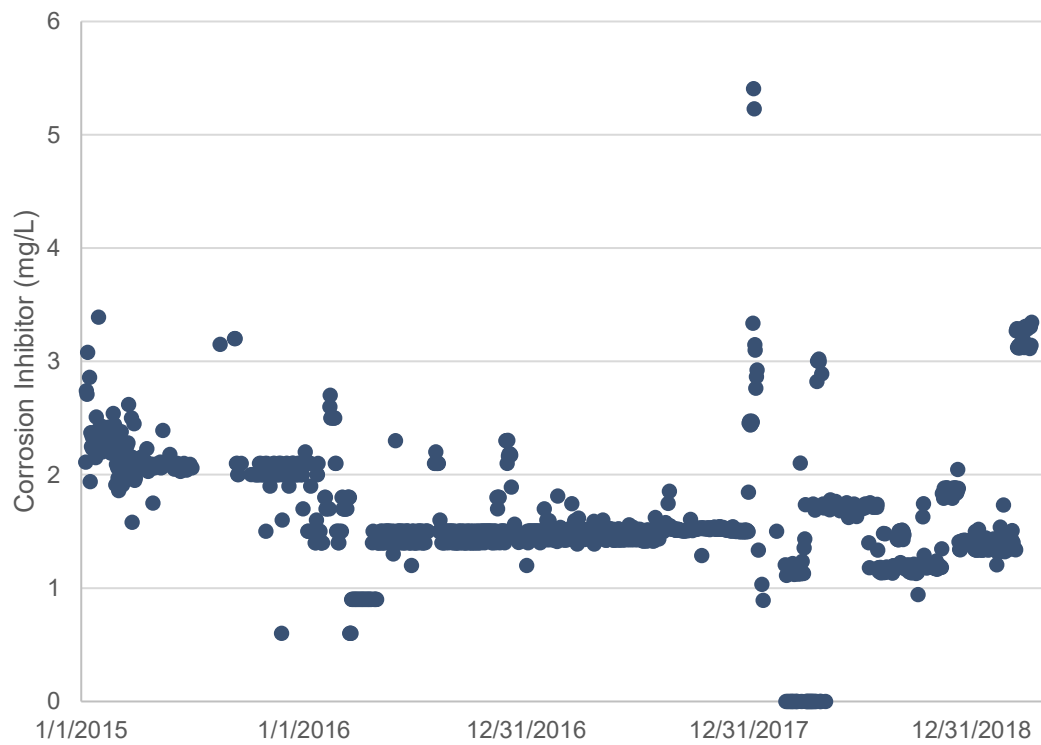


Figure D-8. Chandler Street Well Corrosion Inhibitor Dose

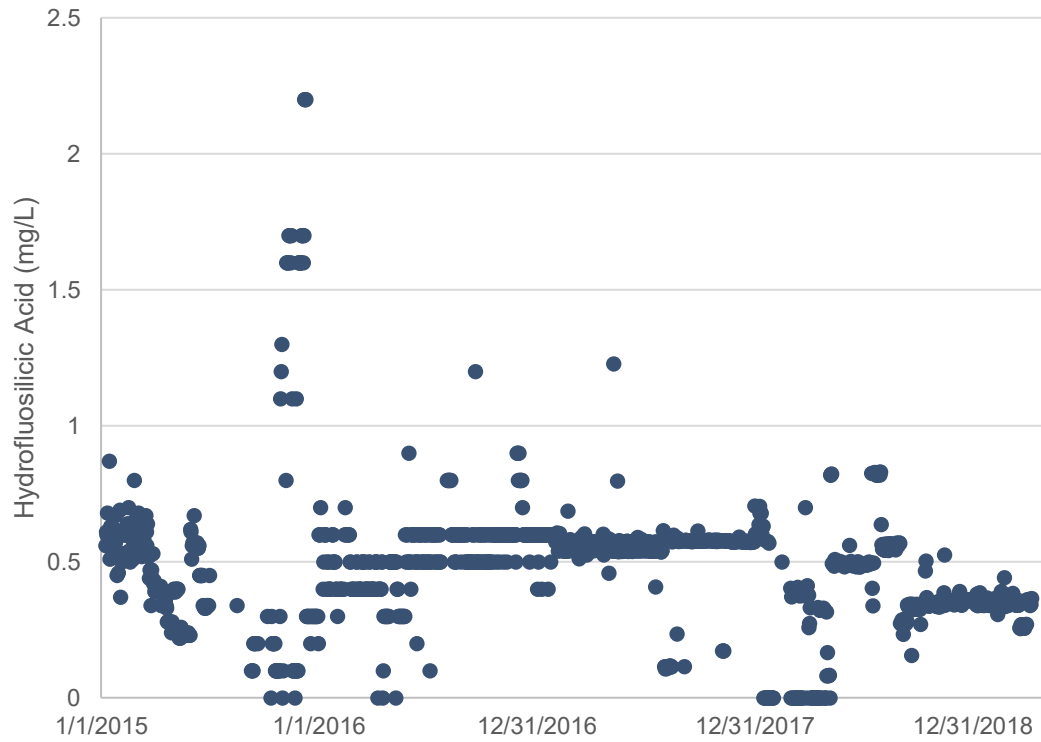


Figure D-9. Chandler Street Well Fluoride Dose

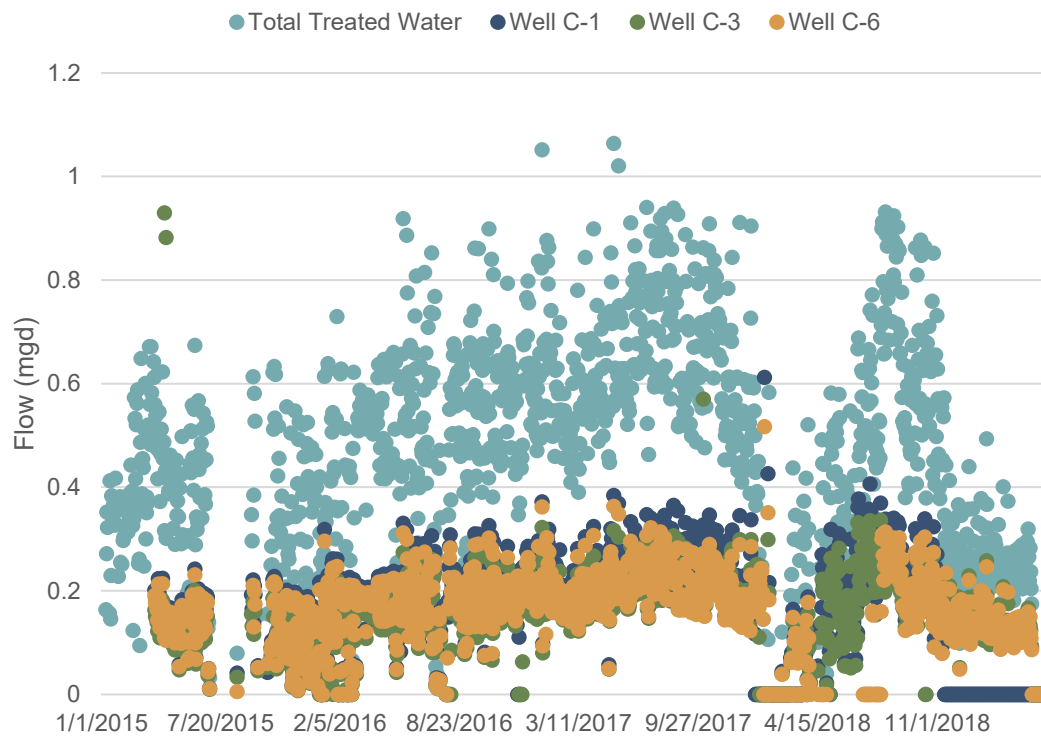


Figure D-10. Chandler Street Well Total Water Treated

Appendix E: Nalles Mill Well Data

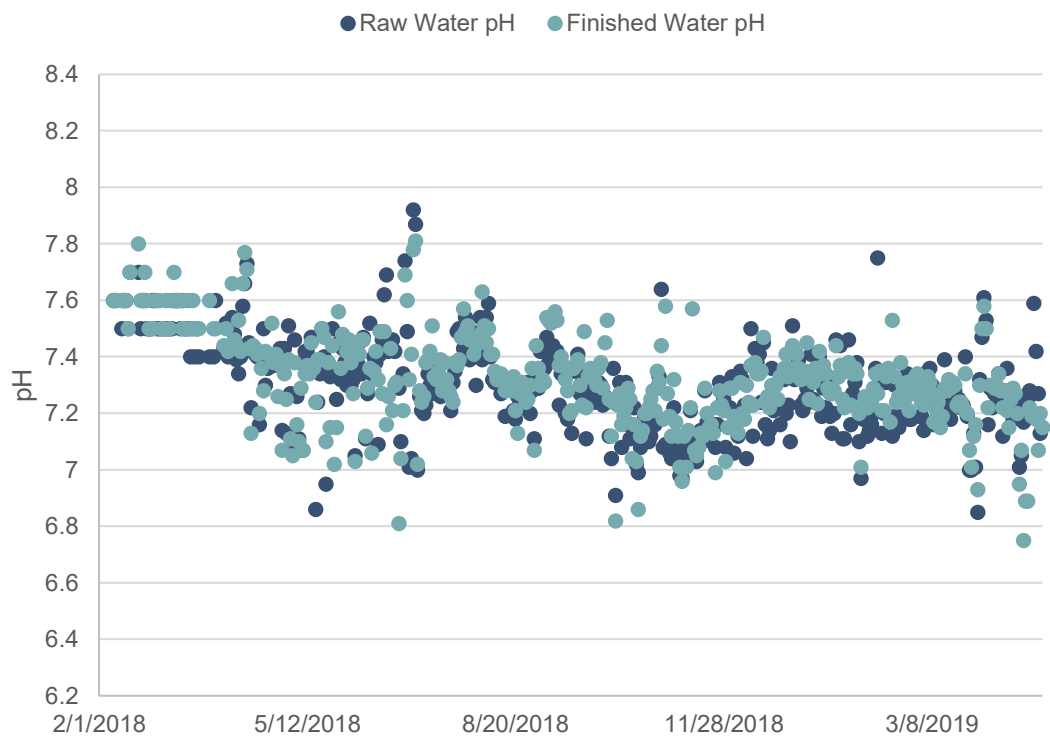


Figure E-1. Nalles Mill Well pH

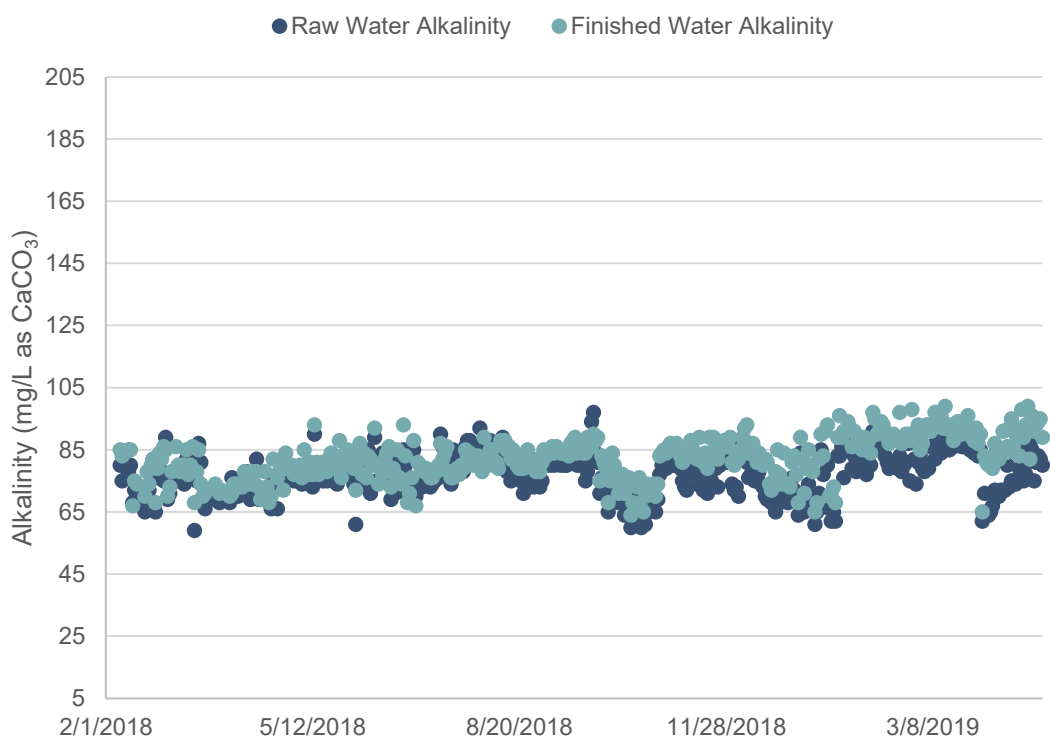


Figure E-2. Nalles Mill Well Alkalinity

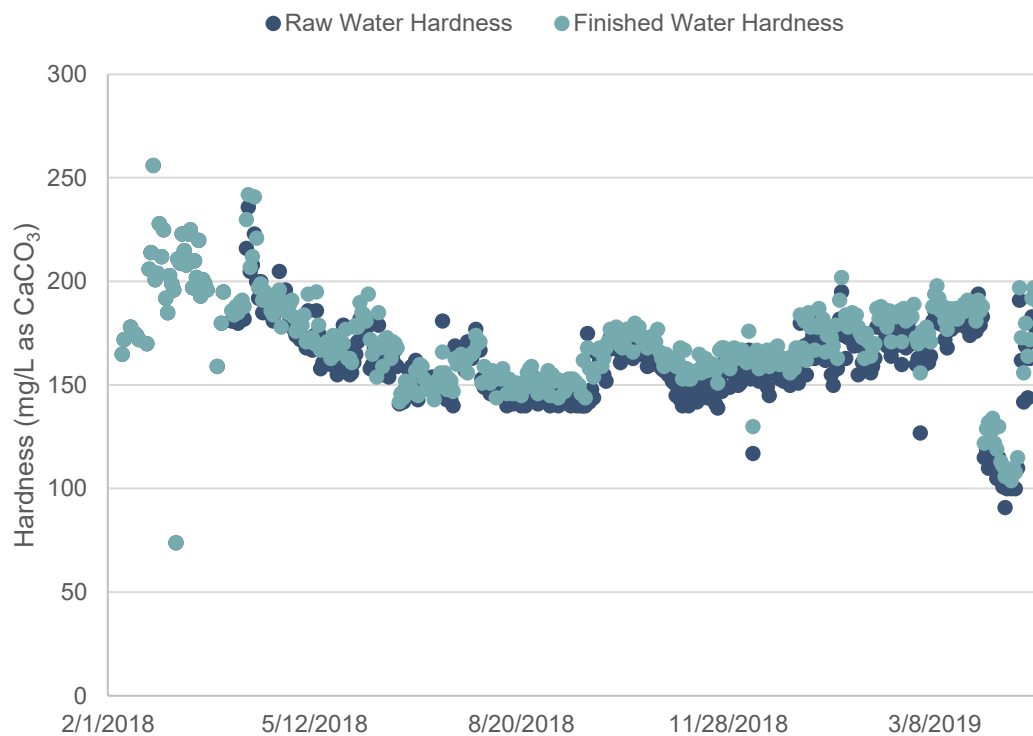


Figure E-3. Nalles Mill Well Hardness

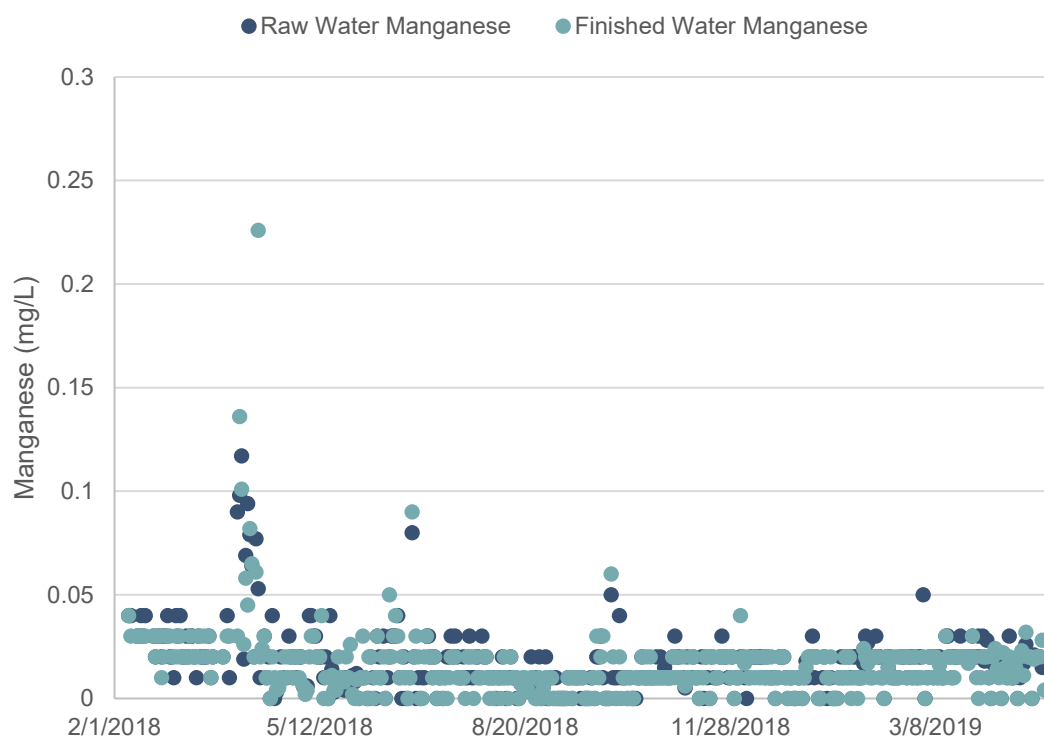


Figure E-4. Nalles Mill Well Manganese

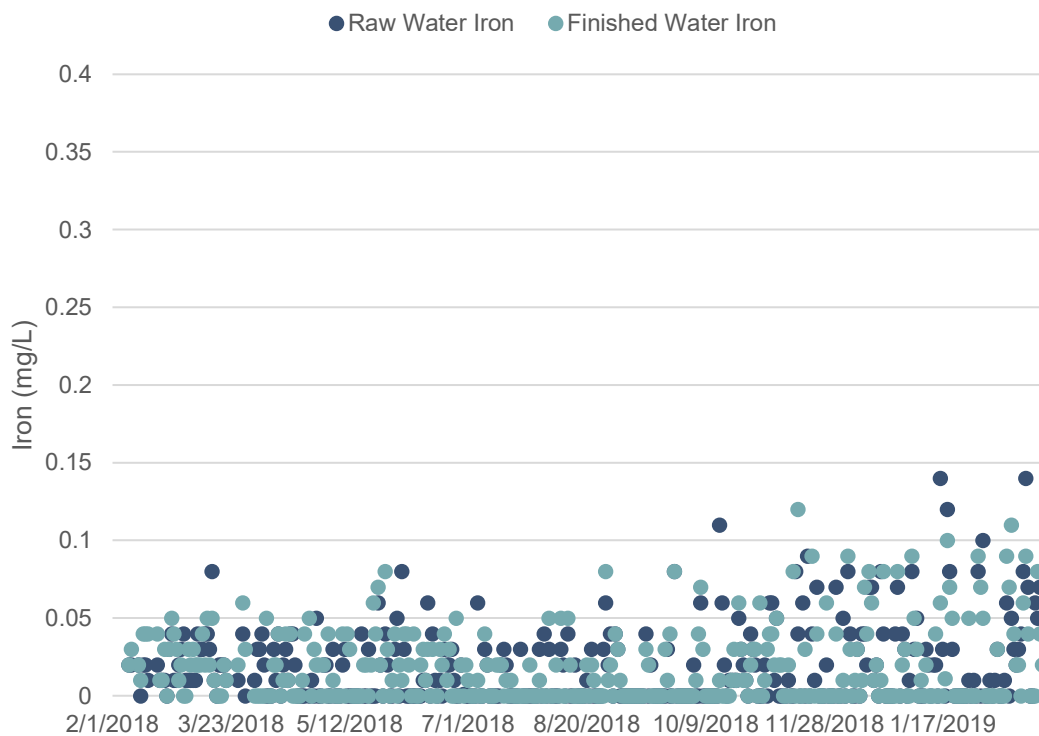


Figure E-5. Nalles Mill Well Iron

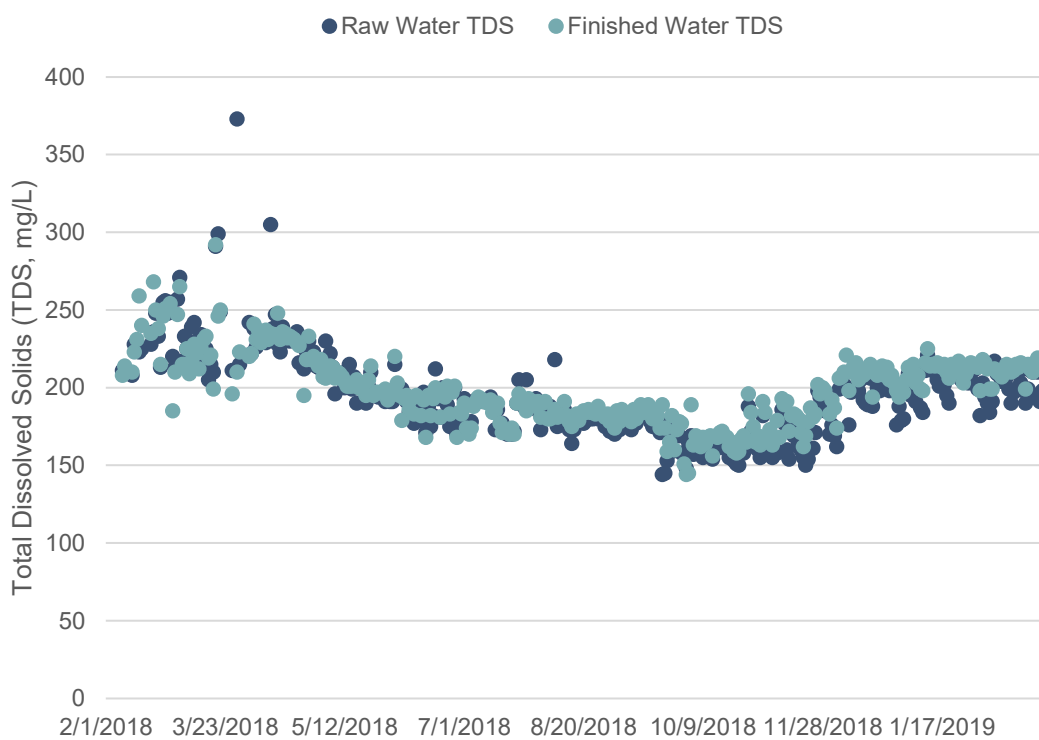


Figure E-6. Nalles Mill Well Total Dissolved Solids

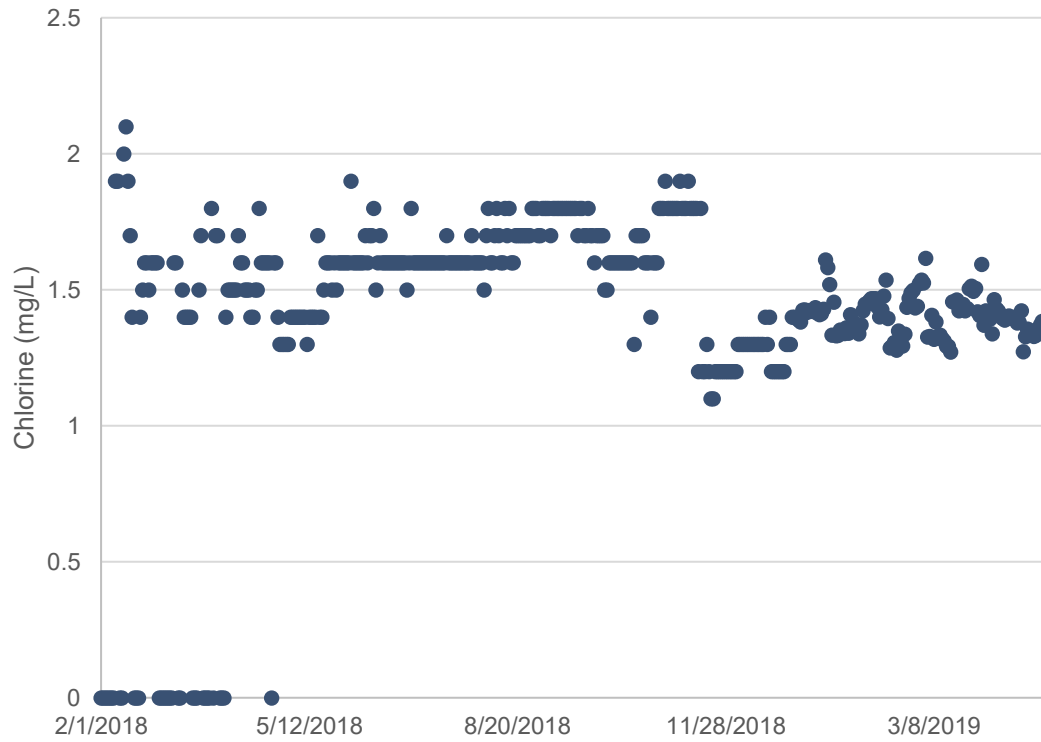


Figure E-7. Nalles Mill Well Chlorine Dose

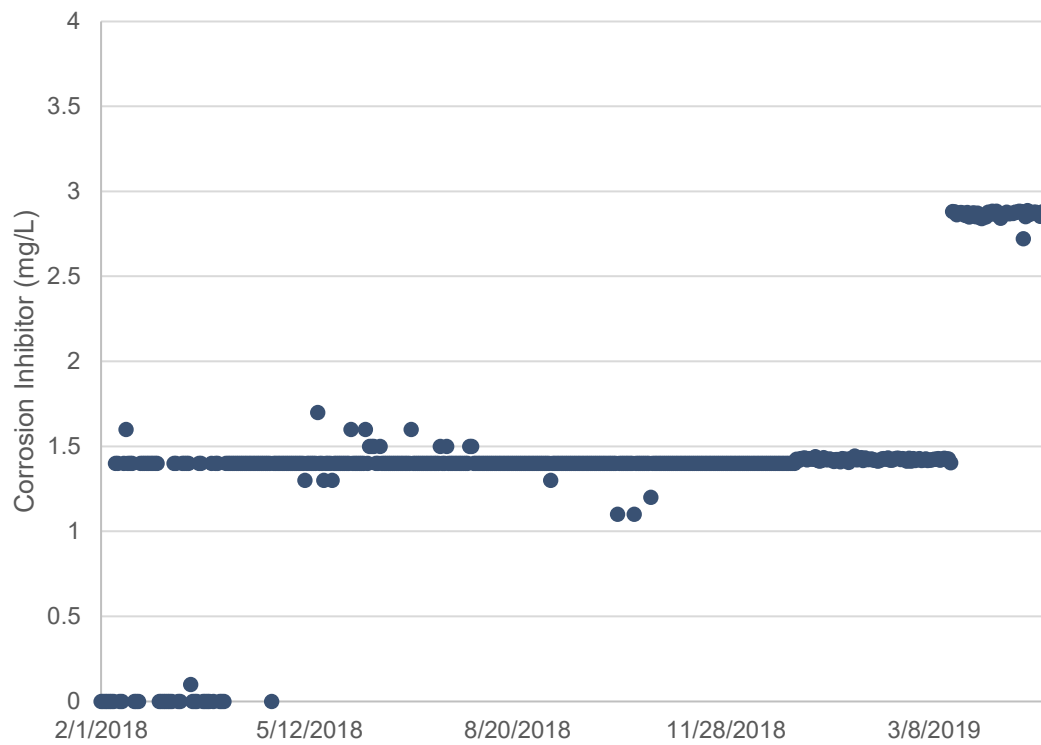


Figure E-8. Nalles Mill Well Corrosion Inhibitor Dose

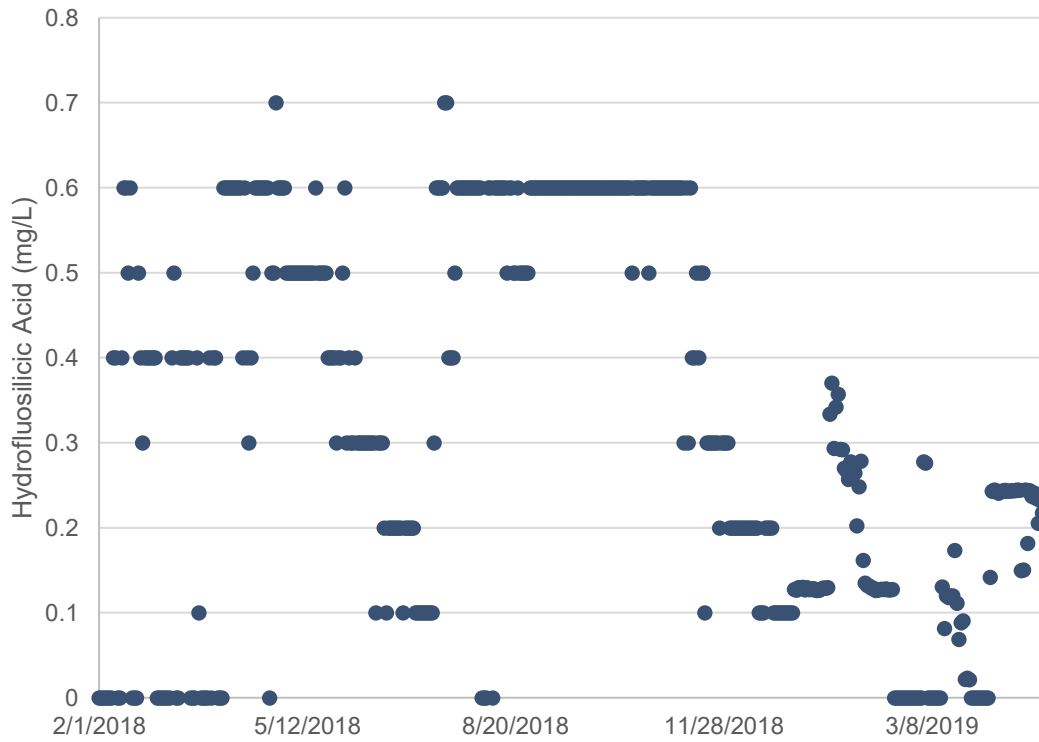


Figure E-9. Nalles Mill Well Fluoride Dose

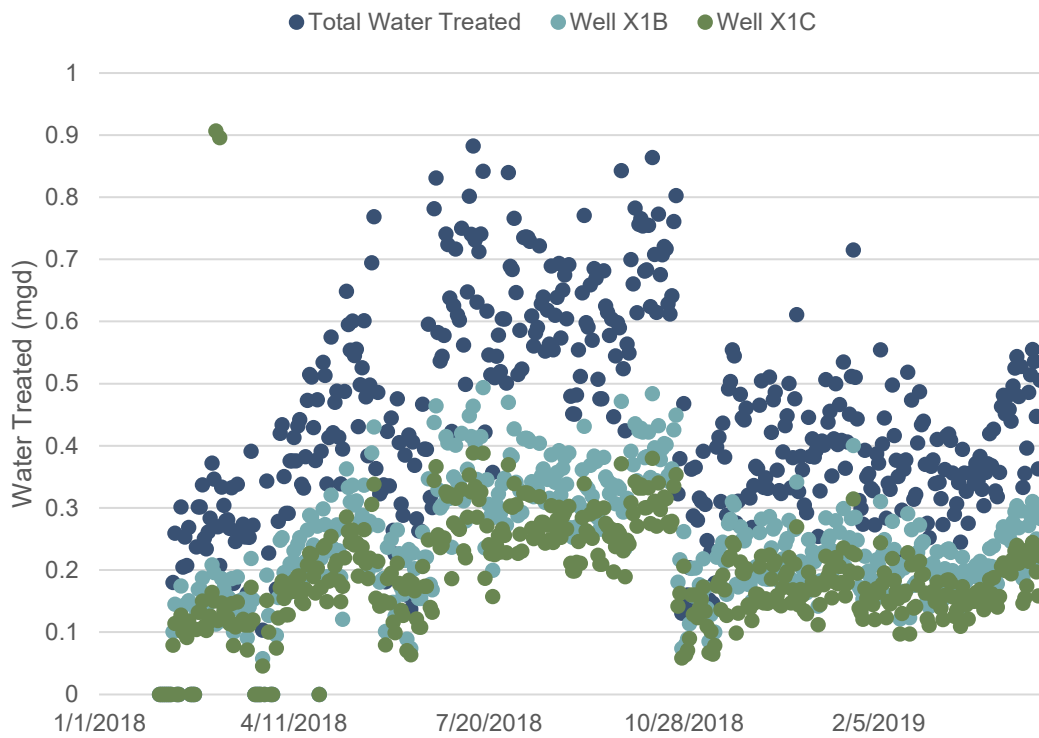


Figure E-10. Nalles Mill Well Total Water Treated

Appendix F: Rockwater Park Well Data

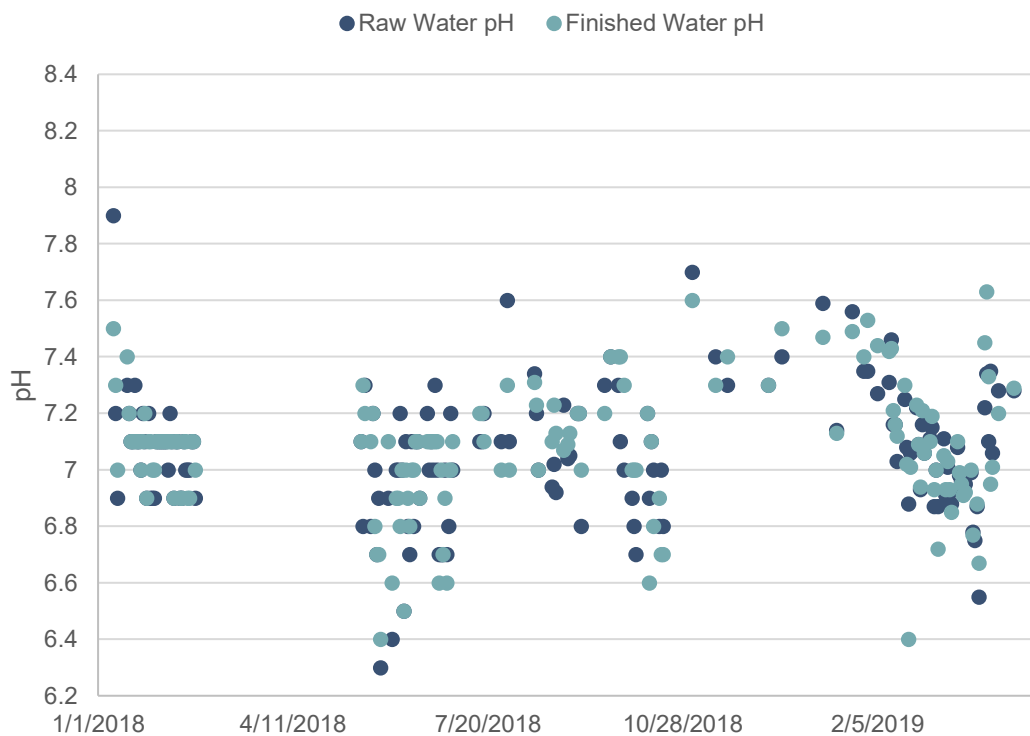


Figure F-1. Rockwater Park Well pH

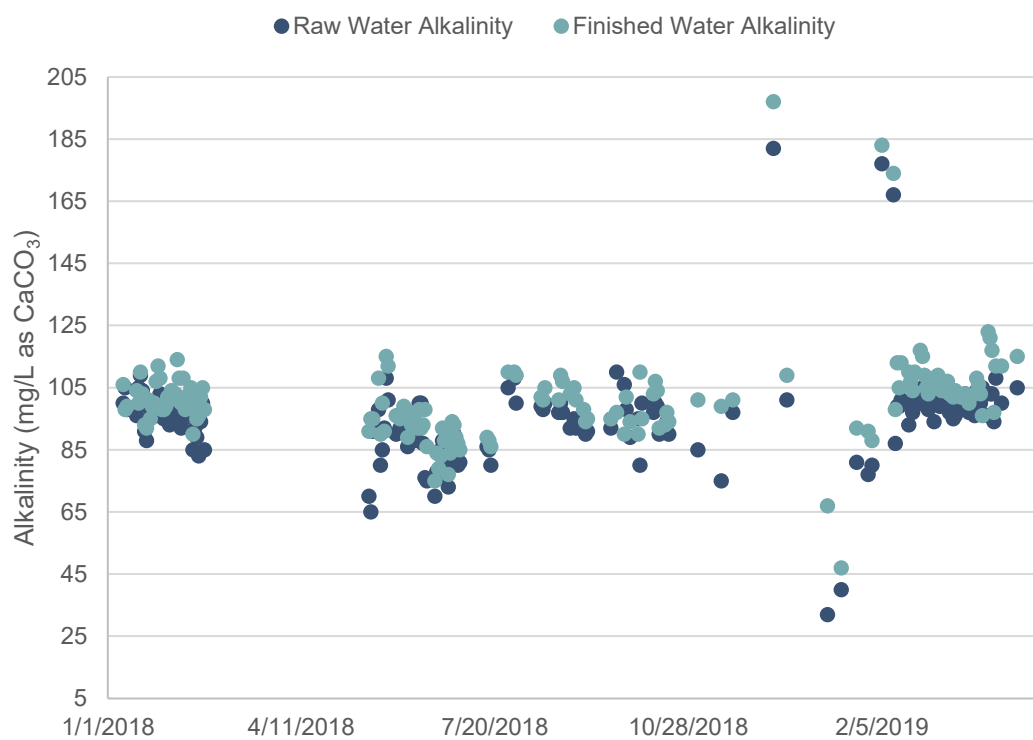


Figure F-2. Rockwater Park Well Alkalinity

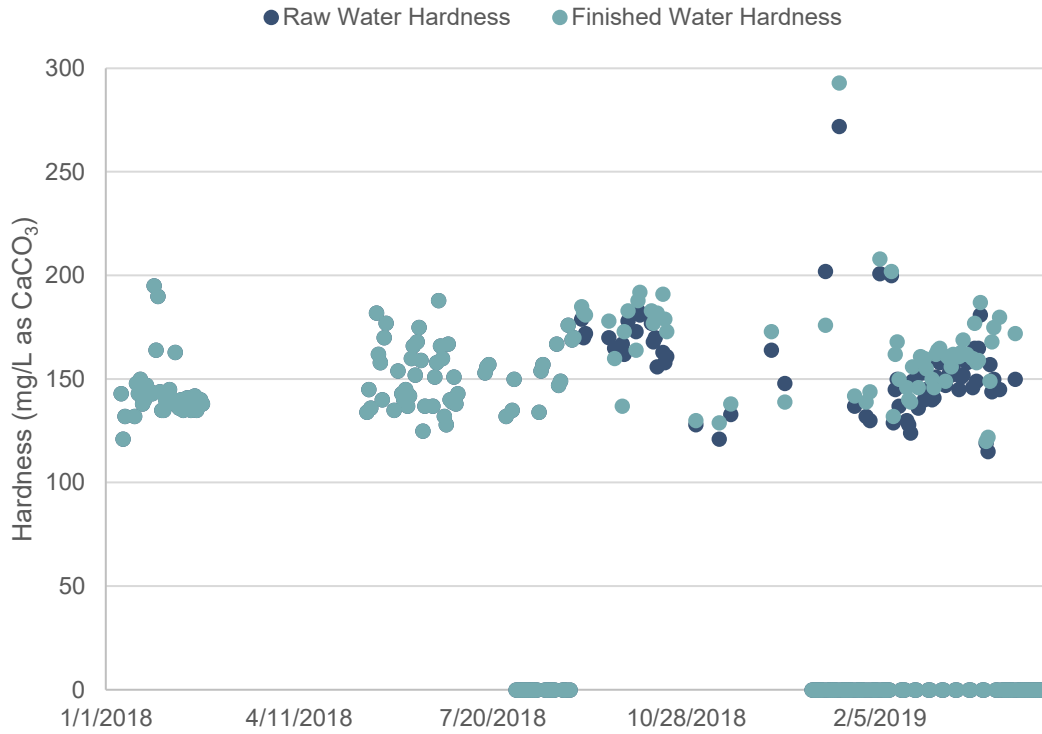


Figure F-3. Rockwater Park Well Hardness

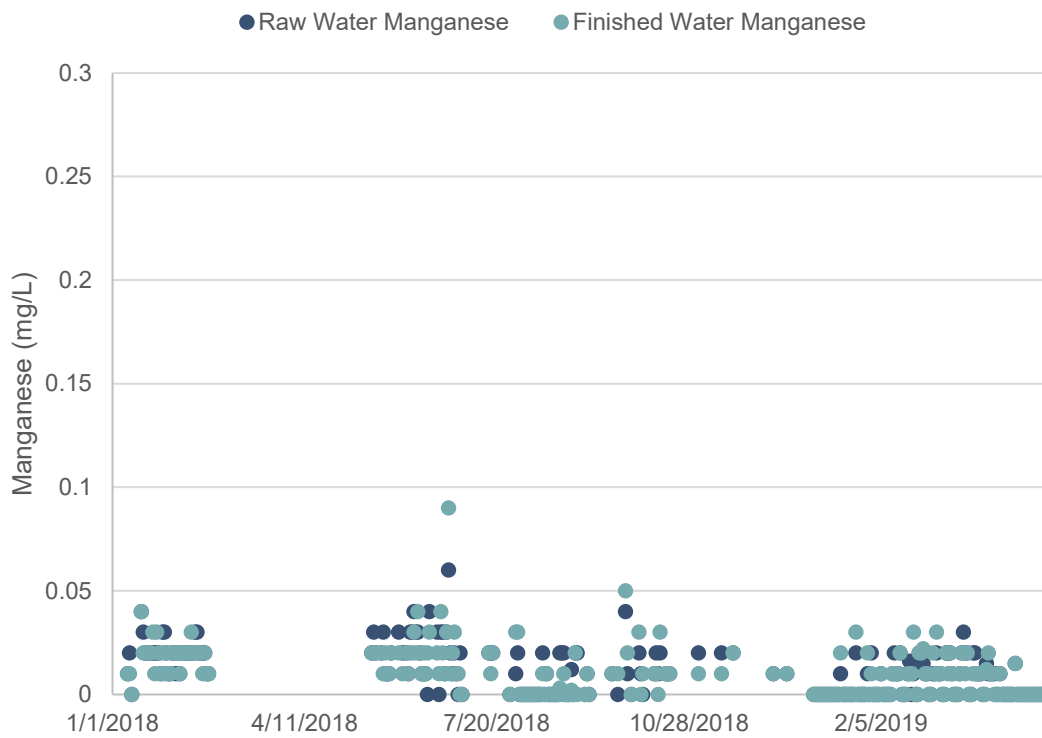


Figure F-4. Rockwater Park Well Manganese

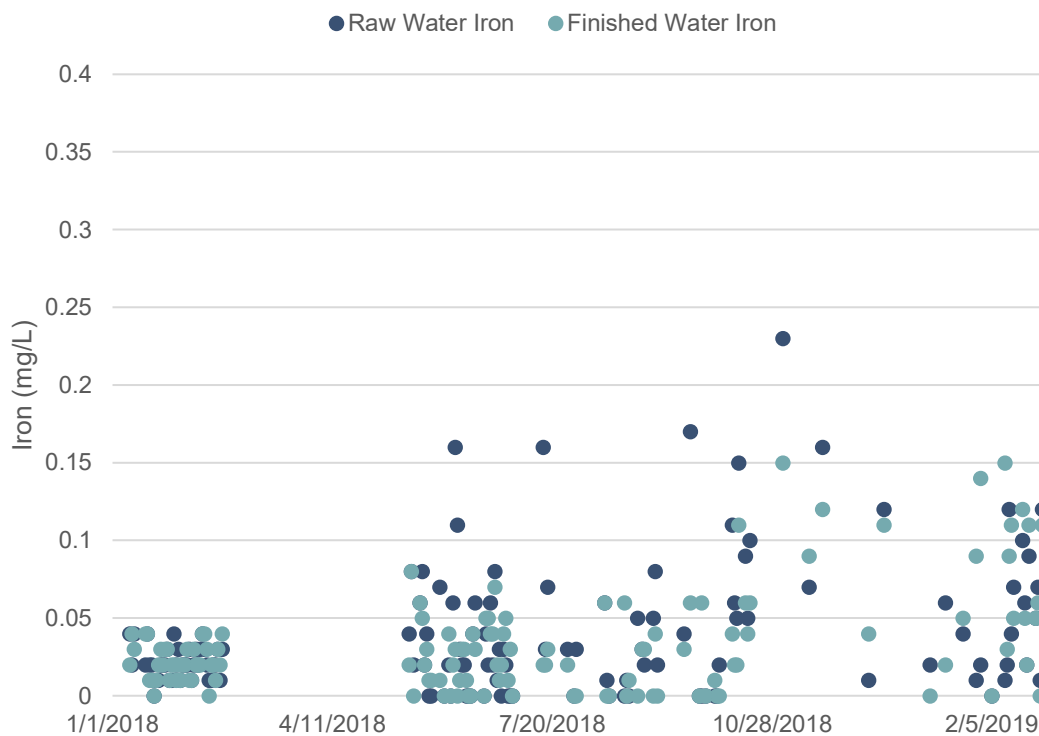


Figure F-5. Rockwater Park Well Iron

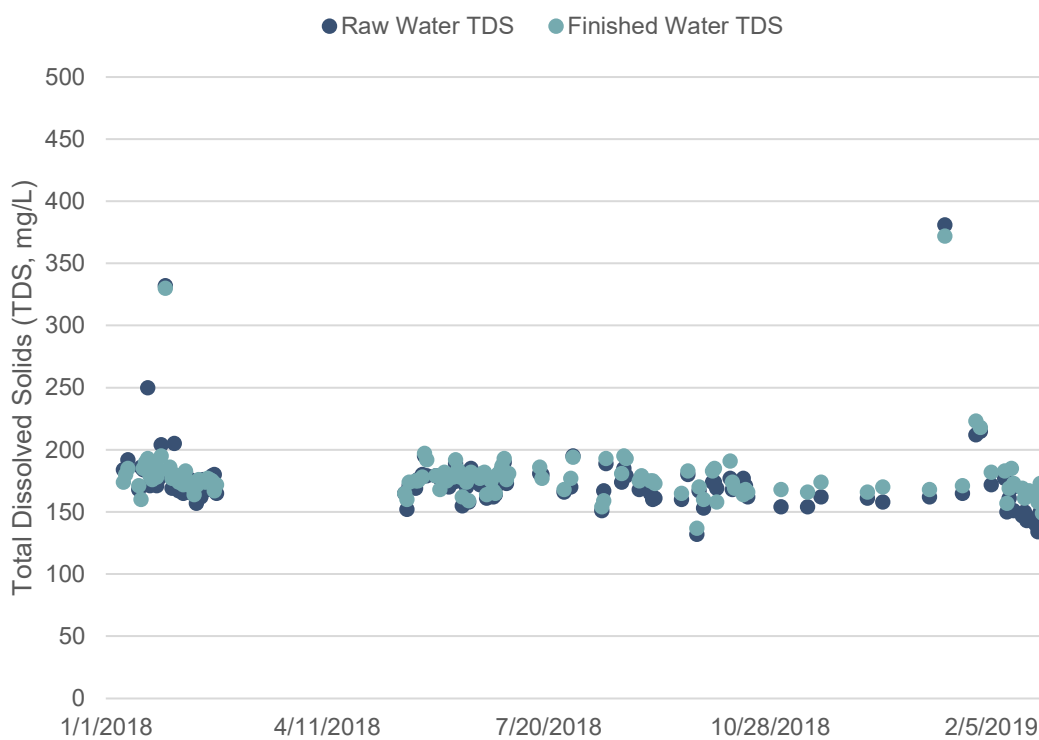


Figure F-6. Rockwater Park Well Total Dissolved Solids

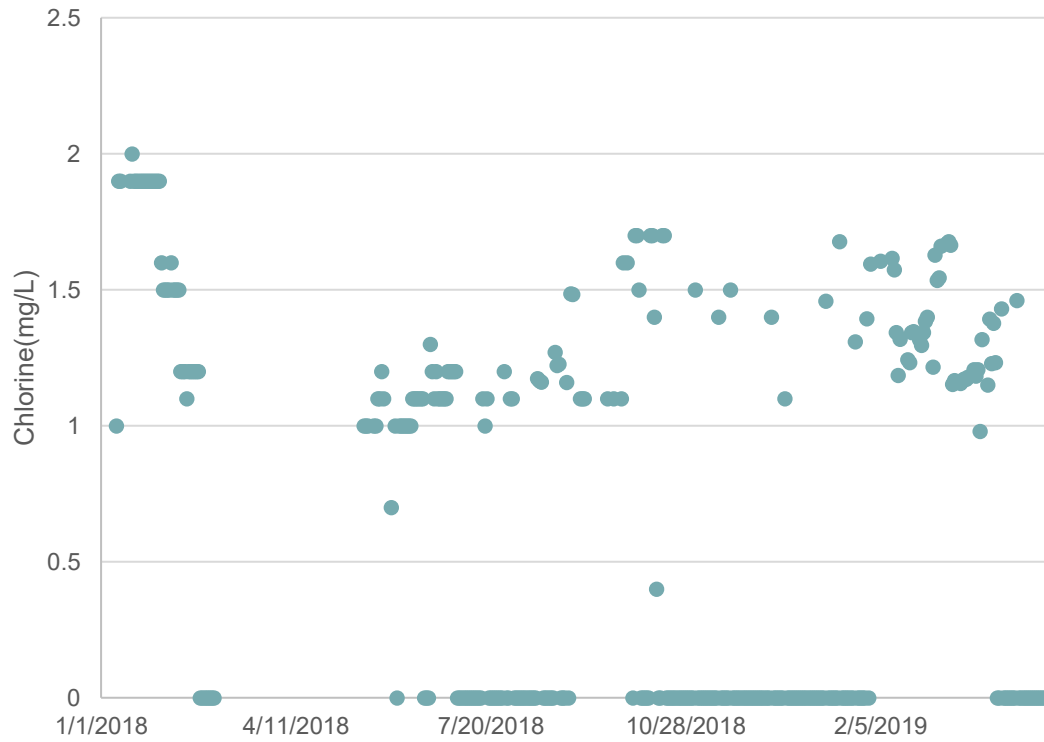


Figure F-7. Rockwater Park Well Chlorine Dose

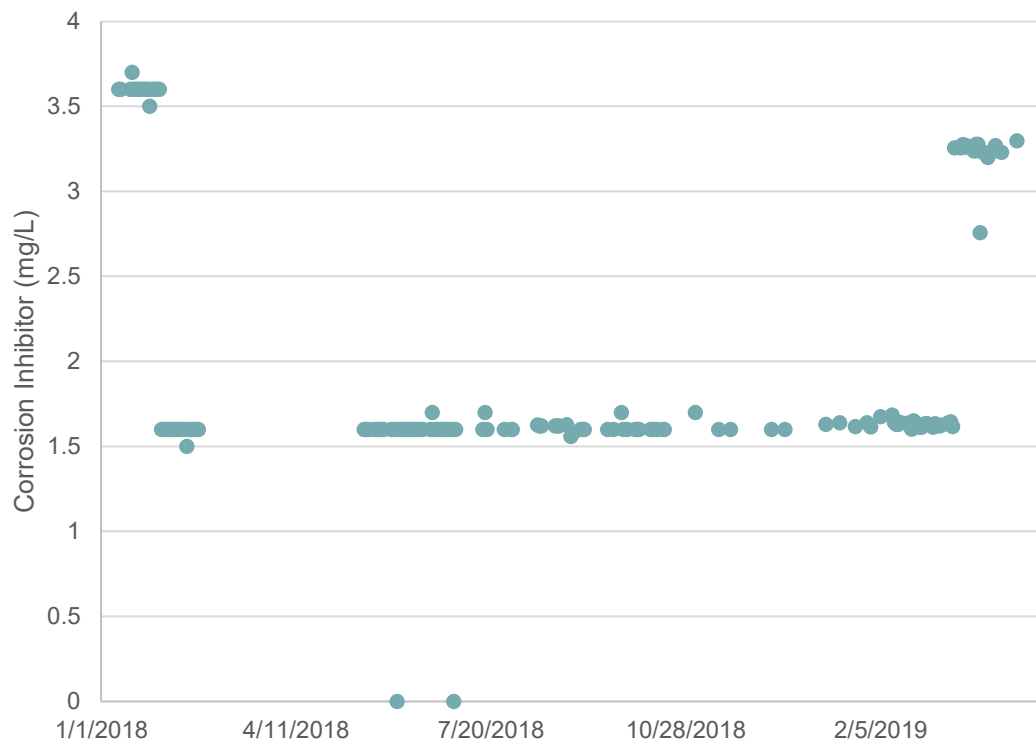


Figure F-8. Rockwater Park Well Corrosion Inhibitor Dose

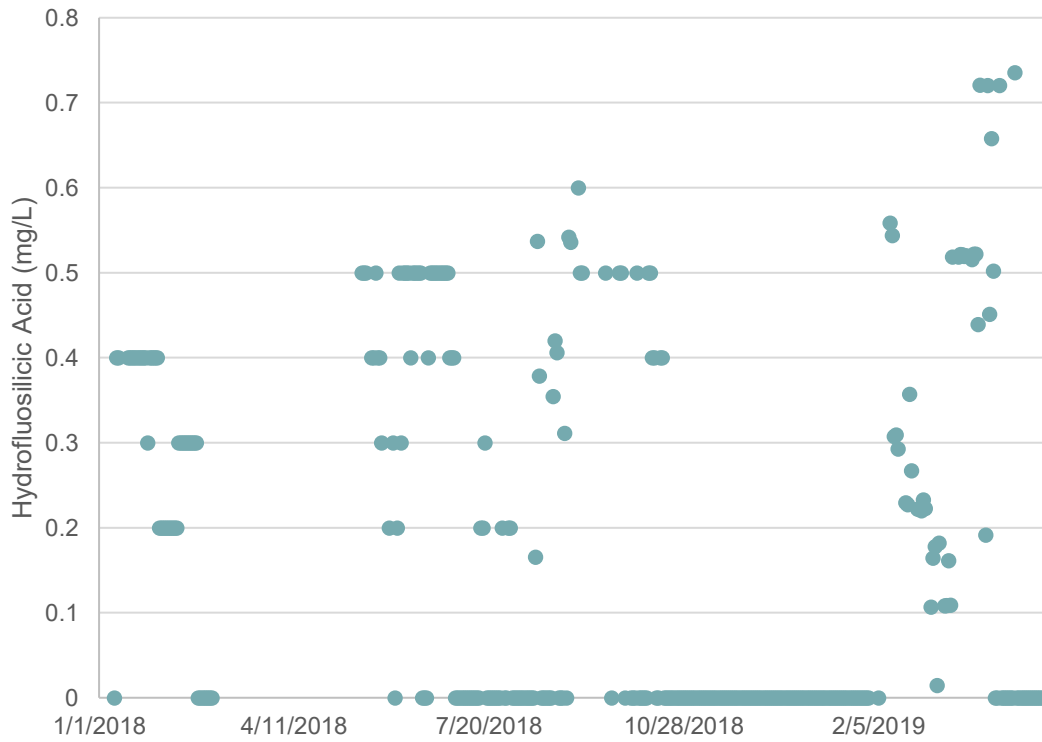


Figure F-9. Rockwater Park Well Fluoride Dose

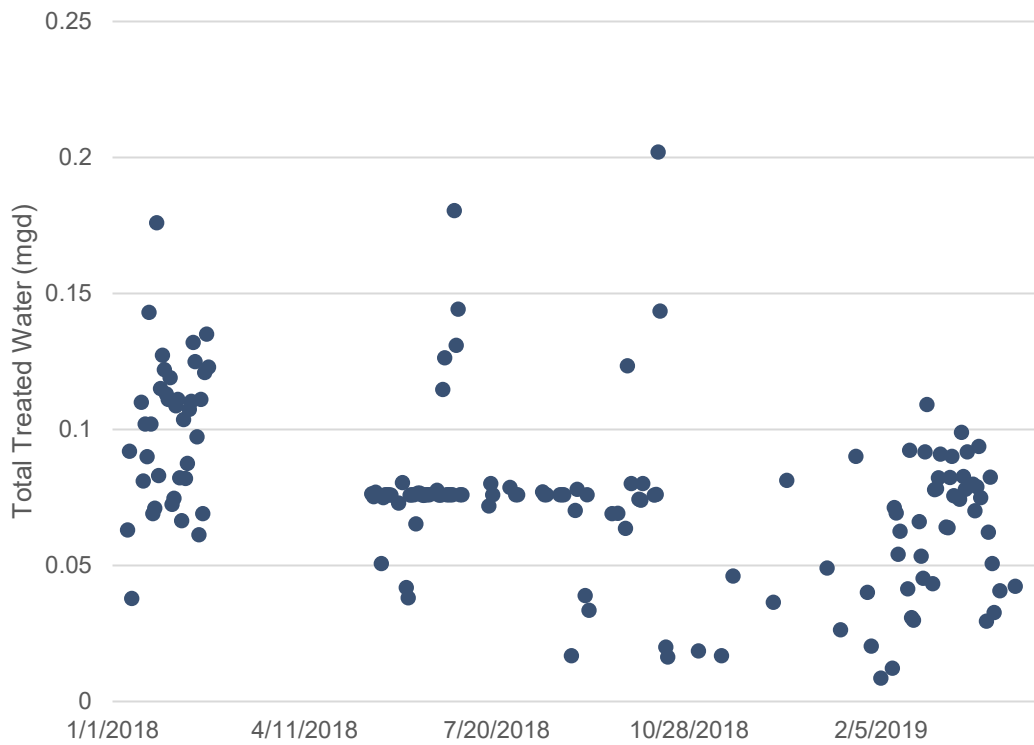


Figure F-10. Rockwater Park Well Total Water Treated