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Spatial and Temporal Variations of Water Quality within the City of Atlanta Water Distribution System, 2012-2013

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Abstract

Spatial and Temporal Variations of Water Quality within the
City of Atlanta Water Distribution System, 2012-2013

By Courtney Weil

To date, evaluation of distribution system water quality has been under-explored, and water utilities, as well as the general public, could benefit from the exploration of water quality deterioration within urban distribution systems. The City of Atlanta water utility serves more than a million customers on a daily basis, and extensively monitors the quality of water at over 80 key sites throughout the distribution system, typically on a quarterly basis. The comparison of these quarterly grab samples to the water quality data that was collected continuously using remote sensors during this study shows that these two sampling methods produce significantly different means and variances over time for a variety of water quality parameters, including conductivity, pH, chlorine, turbidity, and pressure. These infrequent grab samples provide a much less complete characterization of the temporal variation in basic water quality parameters compared to continuous water quality monitoring. In addition, the comparison of water quality data collected continuously displays interesting differences among parameters at the two locations sampled, suggesting water quality changes spatially, as well as temporally, within the City of Atlanta distribution system. Investment in increased capacity to monitor and evaluate real-time water quality data at key locations within a distribution system could lead to improved distribution system water quality oversight, and better public health protection.

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Chapter 1 – Literature Review

Maintaining good drinking water quality is a pivotal aspect in the global effort to protect public health. The vast majority of U.S. citizens consume drinking water from public distribution systems multiple times each day, and the quality of water must be consistently safe in order to prevent an outbreak of illness, and maintain overall health.

1.1 – Total Coliform Rule

The Total Coliform Rule (TCR) was promulgated by the U.S. Environmental Protection Agency (EPA) in 1989 and took effect in 1990. This rule set health goals, legal limits, and monitoring recommendations in order maintain acceptable levels of total coliforms in drinking water ("Total Coliform Rule," 2012). The overall purpose of the TCR is to protect the public health by ensuring adequate, safe, and reliable drinking water by monitoring for the presence of microbial contamination through the presence of coliforms ("Total Coliform Rule," 2012). In December 2012, the EPA submitted final revisions of the TCR to the Federal Register. These proposed revisions include establishing criteria for exemplary drinking water systems to qualify for reduced monitoring, as well as legislation that would require public water systems most vulnerable to contamination to identify and fix problems ("Total Coliform Rule," 2012).

The TCR requires routine monitoring for the presence of total coliforms and fecal coliforms or *E. coli* "at sites representative of water throughout the distribution system" ("A Review of Distribution System Monitoring", 2007). Water utilities can have no more than 5% of monthly samples be coliform positive for systems collecting greater than 40 samples per month, and no more than one sample per month be coliform-positive for systems collecting less than 40 samples per month ("A Review of Distribution System Monitoring", 2007).

The presence of coliforms are indicators of the effectiveness of water treatment and ultimately of the vulnerability of the water distribution system to contamination ("A Review of Distribution System Monitoring", 2007). The frequency of samples is determined by the number of people served by the water utility, and ranges from 1 sample per month for water systems serving 1,000 persons to over 400 samples per month for systems serving close to 4 million persons ("A Review of Distribution System Monitoring", 2007). Ultimately, individual states decide the number and location of monitoring samples taken by water utilities, because the TCR does not set national requirements for the number and location of samples. Thus, sampling protocols vary from state to state. Some states require water utilities to take one sample per month from a large number of sites, while other states collect samples more frequently at fewer sampling sites. Both of these sampling approaches have advantages and disadvantages. Namely, collecting multiple samples at fewer locations provides a more constant history of water quality at these sites, while collecting fewer samples at more locations offers a better picture of the spatial difference of quality throughout these sites in the distribution system ("A Review of Distribution System Monitoring", 2007).

The dispersion of coliforms throughout a distribution system was a key aspect in the design of the TCR because research has shown coliforms are neither randomly nor uniformly dispered within distribution systems (Pipes and Christian, 1982). The TCR requires water utilities to conduct coliform monitoring monthly in order to characterize these long-term changes of water quality throughout the distribution system, as well as protect public health.

1.2 – Remote Sensing of Water Quality Parameters

The TCR emphasizes the importance of coliform monitoring in distribution systems through the requirement of on-site collections; however, these measurements are conducted

through infrequent grab samples, which may be of limited scope to the overall variability of water quality within an entire distribution system. Thus, remote sensing techniques are currently being developed to monitor water quality on a continuous basis to aid in characterizing the spatial and temporal changes of distribution system water quality.

The development of remote sensing technologies for water quality monitoring began in the 1970s with the use of satellite sensors to measure optical and thermal properties of surface waters (Ritchie, Zimba, & Everitt, 2003). Water quality monitoring research with a focus on distribution systems has also increased since the events in September 2011, when the security of the United States' water infrastructure became a national priority (Hall, Szabo, Panguluri, & Meiners, 2009). Subsequently, the United States Environmental Protection Agency (U.S. EPA) has focused on research and evaluation of online water quality monitoring technologies that could serve as an early warning to contaminant intrusion in drinking water supplies (Hall, Szabo, Panguluri, & Meiners, 2009).

Currently, remote sensing is most commonly used at water treatment plants and in water storage tanks. Remote sensing within distribution systems continues to be developed, particularly to fully develop a technically reliable and economically suitable sensor that can be used for mass deployment nationally (Hall, Szabo, Panguluri, & Meiners, 2009). During a portion of the U.S. EPA's assessment of prototype real-time remote sensors, standard parameters measured included free and total chlorine, chloride, specific conductance, dissolved oxygen, oxidation reduction potential, pH, turbidity, temperature, total organic carbon, ammonia, and nitrate (Hall, Szabo, Panguluri, & Meiners, 2009). One of the major challenges sited in this assessment was the unreliability of probes, with probes measuring dissolved oxygen, pH, temperature, ammonia, and nitrate tending to exhibit low specificity (Hall, Szabo, Panguluri, & Meiners, 2009). In addition,

all probes required weekly to monthly calibration, which becomes a large addition to the overall cost of these systems (Hall, Szabo, Panguluri, & Meiners, 2009). The research conducted by the U.S. EPA and online water quality sensor manufacturers concluded that the most effective parameters for detecting contaminants are free chlorine, total organic carbon, conductivity, and pH (Hall & Szabo, 2005). This research also concluded that turbidity was not a good primary indicator of contamination because it can be highly variable (Hall & Szabo, 2005).

The technology of remote sensing is still developing; however, a network of online water quality sensors deployed in distribution systems throughout the United States could significantly aid in the indication of possible contamination, which would allow water utilities to quickly launch appropriate responses, and ultimately better protect the public health (Hall & Szabo, 2005). In addition, remote sensors could potentially save water utilities hours of collection and testing time currently spent on obtaining small grab samples, which are only a small fraction of the same data that can be collected from remote sensors (Hall & Szabo, 2005).

1.3 – The City of Atlanta Water Distribution System

The City of Atlanta (COA) water distribution system serves approximately 1.2 million people with 100 million gallons of treated water per day ("City of Atlanta," 2011). Surface water from the nearby Chattahoochee River is the largest source of water for the COA. The Chattahoochee River is vulnerable to microbial contamination, thus good water treatment is essential to ensure a potable water supply ready for consumers (Tinker et al., n.d.). The urban Atlanta area is a fitting environment to conduct this study, as the conditions for water treatment within the COA are comparable to other cities in the United States.

Six drinking water utilities, operating eleven treatment plants, provide potable water to the five-county metro-Atlanta area. The water treatment plants and the utilities that operate the

plants serving the metro-Atlanta area are displayed in Table 6 in Appendix 1. The treatment methods used in the majority of these plants are conventional and commonly used in most treatment plants across the United States. These practices include coagulation, sedimentation, filtration, disinfection, ultraviolet disinfection, and chlorination, all which comply with industry-wide standards and practices (Tinker et al., 2010). The DeKalb county water utility uses ozone and chlorine disinfection, and thus is the one exception to these standard treatment methods.

The COA monitors and tests water quality on a regular basis, and publishes annual water quality reports available to the public, as required by the TCR ("City of Atlanta Water," 2009; "City of Atlanta Water," 2011; "Watershed Management," 2010). The main regulated contaminants assessed in the most recent report, published in 2011, include total coliform bacteria, turbidity (NTU and % of samples), fluoride (ppm), chlorine (ppm), nitrate (ppm), total trihalomethanes (ppb), haloacetic acids (ppb), and total organic carbon (ratio). Based on the water quality data presented in these recent reports, COA experienced no contaminant level violations during 2011.

During the study period between 2012-2013, one notable advisory warning was experienced within the COA water distribution system. On June 28, 2012, a power outage at the treatment plant resulted in a loss of pressure at the plant ("Media Advisory," 2012). Normal operations were restored in 30 minutes, and the Department of Watershed Management flushed the water system as a precaution against contamination.

1.4 – Water Quality Parameters of Interest

Pressure, chlorine residual, turbidity, pH, oxidation-reduction potential, conductivity, and temperature are the seven key water quality parameters analyzed in this study.

1.4.1 – Pressure

Maintaining adequate pressure within the drinking water distribution system is critical to the process of providing potable piped drinking water, and thus has been one of the most researched aspects of modern drinking water systems. Many studies, within and outside the United States, have shown that low and negative water pressures within a distribution system can potentially lead to microbial intrusions into the drinking water system (Besner et al., 2010; Besner, Prevost, & Regli, 2011; LeChevallier, Gullick, Karim, Friedman, & Funk, 2003; Nygard et al., 2007). Intrusion events are defined by the flow of non-potable water into water mains within the distribution system that occur during a backflow when there is a change in the normal pressure of the system (LeChevallier et al., 2003). These intrusion events are dangerous because they create a pathway for contaminants to penetrate the drinking water supply. Contaminants may include pesticides, detergents, petroleum, wastewater from sewer lines, or soil adjacent to the water line (LeChevallier et al., 2003).

Pressure changes are one of the leading factors linked to intrusion events within drinking water distribution systems (Besner et al., 2011). Pressure changes can be triggered by a variety of reasons, including main breaks, pipe leaks, sudden changes in water demand, uncontrolled pump starting and stopping, use of fire hydrants, system power failures, and flushing operations (Tinker et al., 2009). The COA aims to mitigate these events, which occur intermittently throughout the year, by stabilizing the pressure throughout the distribution system. During normal operation, the water in the distribution system is typically over-pressurized in order to help prevent intrusions. This over-pressurization helps prevent loss of pressure within the pipes that would lead to the movement from the exterior environment into the compromised distribution system pipes. Even during main breaks, and other events that may alter pressure

within the system, most well maintained drinking water systems continue to supply water on a continuous basis. Most low or negative pressure events are transient, with durations typically lasting in the range of seconds to minutes (Besner et al., 2011). However, even during these short periods, intrusion events may occur. Thus, it is necessary to monitor pressure every second, in order to capture the occurrence of these transient events.

1.4.2 – Chlorine

The practice of adding chlorine as a disinfectant to drinking water dates back to the early 1900s ("The History of Drinking Water Treatment", 2000). During this time, chlorination played a large role in reducing waterborne disease outbreaks, and the practice of adding chlorine to drinking water prior to distribution continues to be a common practice that has been globally adopted. Chlorination and other disinfectants inactivate microbial pathogens by breaking down their chemical bonds. As the chlorinated water travels throughout the distribution system, the chlorine residual gradually declines, thus locations farther from the treatment plant typically have lower levels of chlorine residual than locations in close proximity to the treatment plants.

Drinking water distribution systems aim to maintain a level of chlorine residual throughout all points of water usage in a distribution system. A detectable level of chlorine throughout distribution systems is critical to demonstrate that disinfection requirements were properly met at the treatment plant, as well as to aid in the control of biofilm, nitrification, and other water quality problems common in distribution systems (Hall & Szabo, 2005). Many cities and states in the United States have policies requiring 95% of water samples tested to have a measureable amount of chlorine ("Water Quality Terms," 2012). Chlorine is typically concentrated in drinking water at levels of 0.2-1.0 mg/L with the maximum contaminant level (MCL) of 4.00 mg/L ("City of Atlanta," 2011).

1.4.3 – Turbidity

Turbidity is the measure of suspended particles in water, also known as "cloudiness" of water. This cloudiness is caused by the scattering or absorption of light by particles suspended in the water. Turbid water is not only aesthetically displeasing, but can also provide protection to pathogens. A recent study showed a modest positive association between raw water turbidity and emergency department visits for gastrointestinal illness with the Atlanta area, demonstrating the importance of maintaining low levels of turbidity in drinking water (Tinker et al., 2010).

According to the EPA, turbidity levels in drinking water systems using conventional or direct filtration should never exceed 1 NTU, and 95% of samples collected in one month should be equal to or less than 0.3 NTU ("National Primary Drinking Water Regulations," 2012).

1.4.4 – pH

pH is a measure of the acid-base equilibrium in water and is an important parameter in determining the corrosiveness of water ("pH in Drinking Water", 2003). Typically, pH levels do not directly impact water consumers because pH levels will never reach extreme values within the water distribution system. However, pH still remains one of the most vital water quality parameters to measure in a drinking water system ("pH in Drinking Water", 2003). pH is controlled not only for human safety, but also to minimize corrosion in water main lines and pipes throughout the distribution system. The EPA suggests a safe pH level for distribution systems of 6.5-8.5 ("National Primary Drinking Water Regulations," 2012).

1.4.5 – Oxidation-Reduction Potential

Oxidation-Reduction Potential, also known as redox, is a measure of water's ability to oxidize contaminants, with higher redox levels corresponding to higher number of oxidizing agents. Redox measurements within a drinking water system provide valuable information for

drinking water utilities as a measure of disinfectant effectiveness. In addition, these oxidation-reduction reactions can describe the corrosion of materials within the distribution system materials (e.g. pipes), the precipitation of iron and manganese compounds, nitrification, and microbial disinfection ("Water Quality Terms," 2012). Redox levels tend to decrease with an increased pH, and waters with higher levels of chlorine tend to also have higher redox levels (James, Copeland, & Lytle, 2004). Redox levels are not influenced by water temperature ("Oxidation Reduction Potential," n.d.).

Research has shown that at a redox level of about 650 mV – 700 mV, bacteria, including *E. Coli*, are typically killed within a few seconds ("Oxidation Reduction Potential," n.d., Hall & Szabo, 2005). In 1972, the World Health Organization's Standards for Drinking Water stated that water is disinfected instantaneously at a redox level of 650 mV ("Oxidation Reduction Potential," n.d.). Most drinking water from a tap in the United States has a redox between 200-650 mV ("The basics about pH / ORP alteration," n.d.). To date, there are no national drinking water standards for redox in the United States.

1.4.6 – Conductivity

Conductivity is the measure of the ability of water to carry an electrical current and is affected by the presence of inorganic solids dissolved in water ("Conductivity," 2012). In drinking water systems, the measure of conductivity is valuable for monitoring the ionic content of water. In general, water containing higher concentrations of inorganic compounds will have a higher conductivity, and water containing organic compounds that do not dissociate will typically have a lower conductivity ("Causes of Total Coliform-Positive Occurrences," 2006). Conductivity levels between 0-800 are generally considered safe for consumption. To date, there is no national drinking water standard for conductivity in the U.S.

1.4.7 – Temperature

Water temperature affects some of the previously mentioned water quality parameters, including pH, turbidity, and conductivity. Low water temperatures have been associated with increased raw turbidity levels, mainly due to the impairment of microorganism removal during treatment processes in colder months (O'Conner, 2001). However filtered water turbidity varies little by season (Tinker et al., 2010). In addition, as temperature rises, pH tends to decrease as the rising temperature affects the acid-based equilibrium ("pH in Drinking Water", 2003).

Water temperature affects the rates of biological and chemical processes, as well as the oxygen content of the water, thus playing a major role in biological activity and growth within the water system. The rate of chemical reactions typically increases at higher water temperatures ("Water Properties," 2013). For drinking water distribution systems, changes in weather are the main cause of changes in water temperature within the distribution system. Water temperature in a distribution system can range from 0 ºC – 30 ºC, depending on the season and location within the distribution system ("Fundamentals and Control of Nitrification", 2006). The State of Georgia states that drinking water temperatures should never exceed 90ºF (~32.2 ºC) ("Water Use Classifications," n.d.).

1.5 – Hillsborough County, Florida Study

Between 2006-2007, a research study was conducted in Hillsborough County, Florida that used remote sensors to measure real-time physical and chemical water quality parameters. The Hillsborough County study combined pressure monitoring with water sample collection immediately following a pressure transient in order to assess the impact of these pressure transients on microbiological water quality. The study also examined the effect of planned flushing events on microbiological water quality. The major findings of the study demonstrated:

1) the extreme sensitivity of turbidity to fire hydrant valve operations, 2) that large volume water samples (90L) provide a more sensitive characterization of water quality than small volume samples (2L), and 3) *P. aeruginosa*, and *A. hydrophilia* were commonly detected in pre-flushing and flushing water samples and were an indication of re-growth potential within the distribution system (Nilsson, Hooper, Moe, & Uber, 2008).

Chapter 2 – Research Objectives and Rationale

Recent outbreak investigations suggest that a large portion of waterborne diseases in the United States is attributable to problems within water distribution systems (Craun & Calderon, 2001). Since 1996, deficiencies within water distribution system have caused 45% of waterborne disease outbreaks reported in community water systems (Craun & Calderon, 2001). Preventing contamination of the distribution system is a vital public health protection measure (Craun & Calderon, 2001). A large portion of U.S. water distribution system is aging, including the COA distribution system, and this infrastructure aging only increases the vulnerability to disease outbreaks (Craun & Calderon, 2001).

Drinking water in the United States undergoes intensive purification in water treatment plants, which are meticulously monitored for quality, based on stringent treatment requirements. These intensive requirements have led to a large decline in waterborne disease outbreaks due to inadequate treatment of surface water (Craun & Calderon, 2001). In turn, more attention in the current decade has been focused on distribution system water quality rather than treatment plant water quality. Historically, the monitoring of distribution systems has been far less intensive than that of treatment plants, because of fewer regulatory requirements.

In 2004, a team within the Center for Global Safe Water at Emory University examined the relationship between drinking water quality and gastrointestinal illness (GI) in the metropolitan Atlanta area between 1993 and 2004 (Tinker et al., 2009). This team compiled a database of over 4 million emergency department visits from 28 hospitals in the Atlanta area, as well as an extensive water quality dataset that included measurements of water quality indicators from each of the treatment plants and the distribution systems in the study area. Among the results from this study was the association between water residence time and risk of emergency

department visits for GI. About a 5-7% increased risk of GI was observed for the population living in zip codes served by water with long water residence times (in the top 10%) compared to those served by water with intermediate residence times (Tinker et al., 2009). Based on these results, the research team at Emory, sponsored by a Science to Achieve Results (STAR) grant from the U.S. EPA, continued investigating the link between water residence time and water quality, and, a portion of this research is the focus of this study.

In recent years, the COA has not reported a violation of quality in the annual water quality reports. The COA Water Quality bureau monitors more than 40 different sites throughout the distribution system, as required by the TCR, in order to maintain drinking water quality standards. The COA obtains a grab sample of water at each of these locations at least once a quarter to test for physical and chemical water quality parameters in the laboratory.

The overall research objective of this study is to compare seven physical-chemical measures of water quality for spatial and temporal differences at two locations within the COA distribution system. This study will monitor water quality continuously using remote sensors at two sites within the COA distribution system: 1) At the point-of-entry to the distribution system and 2) At a distribution system site with intermediate water residence time.

In addition, a specific objective of this study is to assess how six key physical-chemical measures of water quality differ between two sampling methods: 1) Quarterly grab samples and 2) Continuous monitoring using remote sensors.

These analyses will contribute to our understanding of how the physical quality of water changes as it travels through the distribution system, and how remote sensing data on water quality compares to grab sample data within a distribution system.

Detailed real-time water quality data may aid better operation and management of the distribution system and ensure improved water quality. Eventually, this data may be useful for predicting areas of risk in certain parts of the distribution system due to fluctuations in water quality. This research will examine the value of intensive monitoring of distribution system water quality.

Chapter 3 – Draft Manuscript

3.1 – Introduction and Background

Innovations in water treatment plants (WTP) have led to high standards of water quality leaving these plants and entering the water distribution systems. However, quality control for this water once it enters the distribution system is challenging. Surveillance data for waterborne disease outbreaks in the United States suggests that large portions of waterborne disease outbreaks are attributable to problems within public water distribution systems (Craun & Calderon, 2001).

In 2004, Tinker et al. examined the relationship between drinking water quality and gastrointestinal illness (GI) in the metropolitan Atlanta area between 1993 and 2004 (Tinker et al., 2009). This study compiled an extensive database of emergency department visits in hospitals within the Atlanta area, as well as water quality data from the respective treatment plants and distribution systems serving the metropolitan Atlanta area. A key finding of this study was a significant association between water residence time and risk of GI. A 5-7% increased risk of GI was observed for patients living in zip codes in Atlanta served by water with long water residence times (in the top 10%) compared to those served by water with intermediate residence times (Tinker et al., 2009).

The vast majority of distribution system water quality testing in the United States is on small grab samples collected throughout the distribution system on a routine basis. These small samples are typically collected and processed once a month, sometimes only once per quarter, depending on the site location and the population served by the system. One specific research objective of this study is to compare the COA grab sample data to the data collected continuously using remote sensors as part of this study at two locations in the distribution system.

To collect continuous water quality data, this study installed an Automated Monitoring and Sampling unit (AMS), described in further detail below, at two separate locations: at the Hemphill water treatment plant and at a site with an intermediate water residence time. The AMS collects real time data on seven basic water quality parameters: redox, conductivity, pH, temperature, chlorine, turbidity, and pressure. The data collected at these two sites using the AMS was compared by location in order to examine how water quality parameters change in the distribution system.

Subsequently, this study analyzed the differences between the real time water quality data that was continuously collected using the AMS to the grab samples that were collected less frequently by the COA. This comparison will examine whether grab samples are sufficient to monitor distribution system water quality, or if water utilities would benefit from continuous monitoring via remote sensing devices.

3.2 – Methods

The protocol for sample collection and analysis was developed during a previous study in Hillsborough County, Florida conducted from 2002-2005 (Moe et al., 2009). The AMS used during this study was custom designed and built for the Hillsborough County study. A brief description of the technology and protocol used are included here.

3.2.1 – Automated Monitoring and Sampling Unit

The AMS was designed to continually monitor water quality, and automatically collect large water samples during abrupt changes in water quality. A schematic and photos of the AMS device are located in Appendix 2.

The AMS is connected to a secure monitoring site in the distribution system. Seven different water quality parameters are continually monitored using the probes within the AMS.

The entire system runs on a basic power supply, and the system is also equipped with backup DC batteries that can power the system for up to 12 hours in case of a power failure. A DataTaker DT800 datalogger was also installed within the AMS with a 1GB memory card to store data.

Data logging is based on schedules that can be manually modified within the program that operates the AMS. Every second, water pressure was measured and stored in the data logger. Every five seconds, total chlorine residual and turbidity data was stored. Finally, every minute, data on pH, temperature, conductivity, and oxidation reduction potential (redox) were collected and stored.

3.2.2 – Field site selection

Two field monitoring sites within the COA water distribution system were selected to set up the AMS system. These two field sites were chosen because they shared the following characteristics: 1) Each site was within the COA water distribution system; 2) The COA Department of Watershed Management approved each monitoring site; 3) Each site needed to be secure for the AMS system to be set up and left unattended during the day, which typically involved having a room at the site that could be locked when the study team was not present; 4) Each site also needed to be easily accessible in order to check on the system when needed; 5) These sites needed to connect to the AMS directly to the distribution system and ensure that the water running through the device did not receive any additional treatment. This water connection needed to be used only for research purposes, and not used at the site for any other activities; 6) The sites needed basic amenities including power and Internet access.

The first monitoring site was a steam plant operated by the COA on 14th Street. This site was chosen as the baseline point of entry to the distribution system in order to understand the quality of water shortly after leaving the water treatment plant. A new water treatment plant

recently replaced this steam plant, so this plant was only used as back up for the city. The AMS was connected to a tap within the plant. The COA uses this steam plant for periodic water quality monitoring, so this site allowed direct comparison between the COA's water quality data and the data obtained from the AMS.

The second monitoring site was Fire Station #5 off Old National Highway. This site was chosen particularly because of its distance from the treatment plant and longer water residence time (>40 hours) within the distribution system. This site also met the selection criteria described previously. A map of the City of Atlanta with these two monitoring sites is located in Appendix 3.

3.2.3 – Data analysis

At each visit to both sites, the field operator downloaded the raw data files from the memory card within the datalogger onto a laptop. The downloaded data was then wiped from the memory card, and it was then reinserted back into the AMS device.

This data was saved from the datalogger in a .dxd format and was imported directly into SAS statistical software (SAS Institute Inc., Cary, NC, USA). The data was aggregated into large datasets within SAS. Data was initially cleaned by deleting any "implausible" data among the parameters, based on the following guidelines:

- pH outside range of 0-14
- Redox, conductivity, temperature outside range of 0-1000 (mV, uS/cm, ºC)
- Chlorine residual outside range of 0-20 mg/L
- Turbidity outside range of 0-3 NTU
- Dates outside range of collection period (e.g. 1989 dates)

Scatter plots for each parameter were plotted separately for each month in order to examine the daily range within the parameters. Days with ranges much greater than the typical daily ranges seen for each parameter were deleted. For example, redox variability was typically ~30 mV, and days with ranges of ~600 mV were removed from the dataset, because these readings were considered malfunctions of the AMS probe, and did not represent the true water quality. In addition, the datalogger occasionally went offline for several days at a time due to malfunctions within the system. During this time, no data was logged until the problems were fixed; however, occasionally during these times, small pieces of data would be recorded. These pieces of data were typically only logged for a few minutes in the midst of days with no data. These days were also removed from the datasets when data were not consistent with the ranges recorded within the same month, because validity of these data during times of known malfunctions of the datalogger system could not be ensured. In addition, the turbidity probe was malfunctioning in April, May, and August 2012, so the turbidity data from these entire months were removed from the final datasets. See Appendix 4 for these detailed scatter plots of each parameter. Dates removed from the final datasets are highlighted in red on these scatter plots.

Basic descriptive statistics of the data collected using the AMS at both sites were performed in SAS using these cleaned final datasets. Similar descriptive statistics were produced for the grab samples taken by the COA using Microsoft Excel. Scatter plots and histograms using this clean data were produced in SAS. These plots contained data from both locations separated by color to allow easy comparison.

In order to decrease the sample size of the AMS data while still retaining data quality, a new dataset was created containing only the daily averages recorded by the AMS for each parameter. Using this daily average data, a pooled t-test of equality and an equality of variance

test were conducted for each parameter comparing the continuously monitored data and grab sample data. P-values less than 0.05 were considered significant. In order to graphically display this data, the daily averages of the continuously monitored data and grab sample data were plotted in Excel over time for each parameter at both locations.

In addition, moving averages of the continuously monitored data for each parameter were plotted using SAS. These moving average plots contained both data from the Hemphill WTP and Fire Station sites, and were separated by color. The moving average for these plots was calculated using a span of 1 week. These plots provide a nice visual representation of the spatial and temporal changes in the parameters for the two locations.

Six moving average plots were also produced to display the changes in redox on a randomly chosen day during the collection period (January 17, 2013) using six different ranges for calculating moving averages (1 minute, 30 minutes, 1 hour, 6 hours, 12 hours, 1 day). These plots depict the elimination of the white noise seen in the data as the moving average span increases in time.

3.3 – Results

3.3.1 – Spatial variability of water quality

Water quality parameters measured using the AMS were analyzed spatially by comparing the data from multiple sample sites to assess for any similarities or differences as the water traveled throughout the distribution system. Tables 1 and 2 display the descriptive statistics for the data collected using continuous monitoring at both distribution system locations, including the sample size (N), mean, standard deviation (SD), minimum, maximum, median, and mode.

Table 1 – Physical-chemical water quality parameters collected through continuous remote sensing using the AMS at Hemphill Water Treatment Plant, 2012

Water Quality Parameter	N	Mean (SD)	Min, Max	Median	Mode
Pressure (psi)	9,636,205	106.83 (47.46)	(-65.31, 187.27)	119.84	121.77
Chlorine (mg/L)	1,728,771	1.11 (0.65)	(-0.0049, 3.65)	1.08	0.10
Turbidity (NTU)	1,049,859	0.35 (0.41)	(0.00, 2.99)	0.35	0.16
pH	159,895	7.10 (0.71)	(4.16, 9.99)	7.33	7.38
Conductivity (uS/cm)	161,369	103.91 (14.98)	(43.21, 214.07)	105.37	103.17
Temperature (ºC)	146,579	23.34 (7.09)	(10.50, 35.98)	25.99	11.69
Redox (mV)	160,249	614.97 (13.30)	(348.86, 648.27)	614.9	613.46

Table 2 – Physical-chemical water quality parameters collected through continuous remote sensing using the AMS at the Fire Station distribution system site, 2012-2013

Water Quality Parameter	N	Mean (SD)	Min, Max	Median	Mode
Pressure (psi)	9,473,089	30.97 (27.63)	(-59.74, 81.90)	15.48	5.05
Chlorine (mg/L)	1,467,405	0.90 (0.23)	(0.010, 1.37)	0.95	1.01
Turbidity (NTU)	225,701	1.07 (0.53)	(0.010, 2.99)	1.06	0.98
pH	157,901	8.86 (0.25)	(8.26, 9.56)	8.8	8.72
Conductivity (uS/cm)	157,901	104.25 (18.54)	(51.44, 162.77)	106.9	121.86
Temperature (ºC)	157,901	20.41 (4.32)	(12.04, 32.46)	18.95	17.83
Redox (mV)	157,901	545.32 (69.95)	(204.87, 607.33)	583.79	591.33

Figures 1–14 display scatter plots and histograms of the temporal and spatial variation among seven physical-chemical parameters at both the WTP and Fire Station distribution system locations collected through continuous monitoring by the AMS remote sensor.

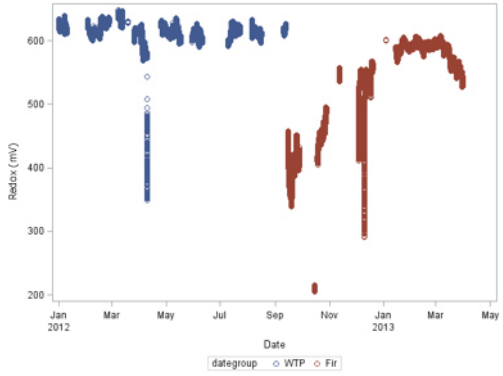


Figure 1 – Comparison of temporal and spatial variation among redox monitored by a remote sensor at WTP & distribution system site, 2012-2013

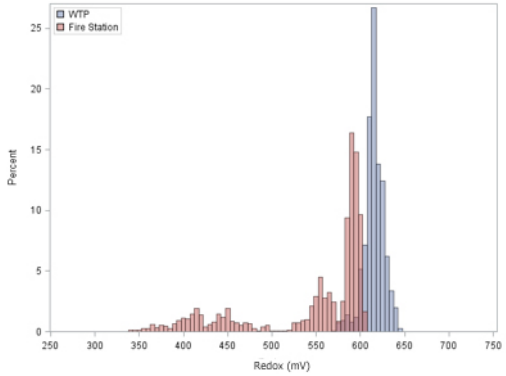


Figure 2 – Distribution of redox monitored by a remote sensor at WTP & distribution system site, 2012-2013

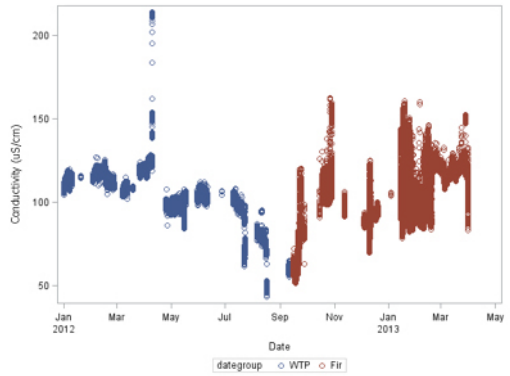


Figure 3 – Comparison of temporal and spatial variation among conductivity monitored by a remote sensor at WTP & distribution system site, 2012-2013

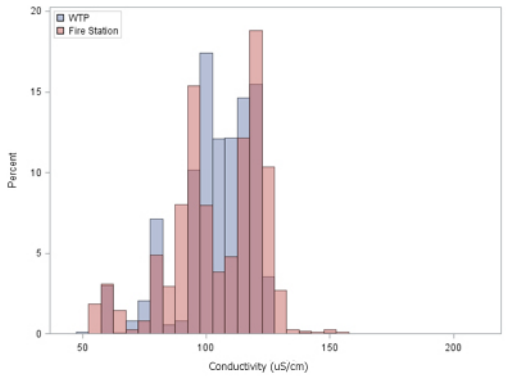


Figure 4 – Distribution of conductivity monitored by a remote sensor at WTP & distribution system site, 2012-2013

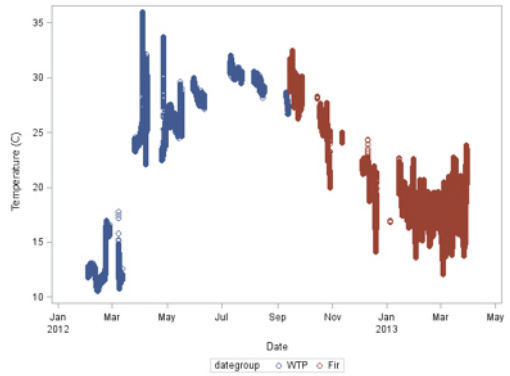


Figure 5 – Comparison of temporal and spatial variation among temperature monitored by a remote sensor at WTP & distribution system site, 2012-2013

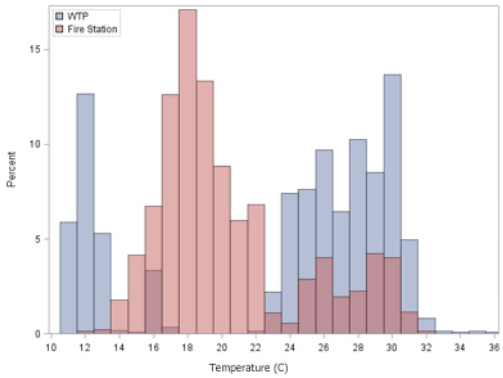


Figure 6 – Distribution of temperature monitored by a remote sensor at WTP & distribution system site, 2012-2013

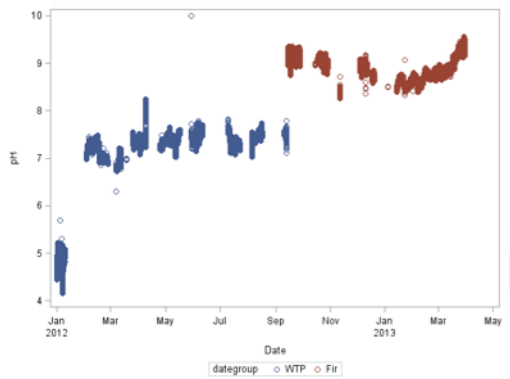


Figure 7 – Comparison of temporal and spatial variation among pH monitored by a remote sensor at WTP & distribution system site, 2012-2013

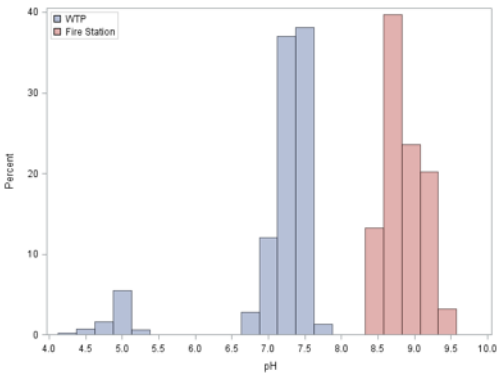


Figure 8 – Distribution of pH monitored by a remote sensor at WTP & distribution system site, 2012-2013

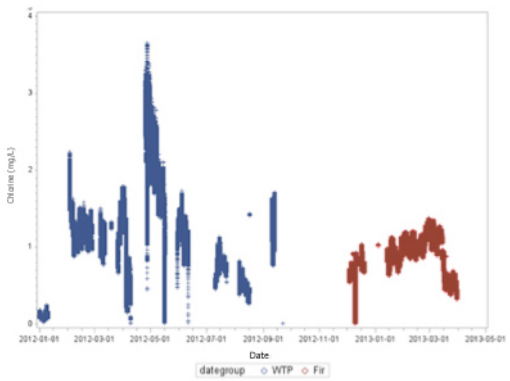


Figure 9 – Comparison of temporal and spatial variation among chlorine monitored by a remote sensor at WTP & distribution system site, 2012-2013

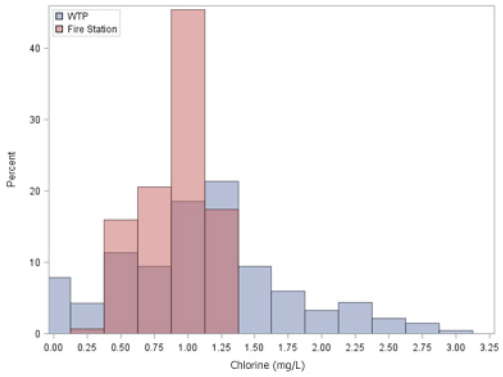


Figure 10 – Distribution of chlorine monitored by a remote sensor at WTP & distribution system site, 2012-2013

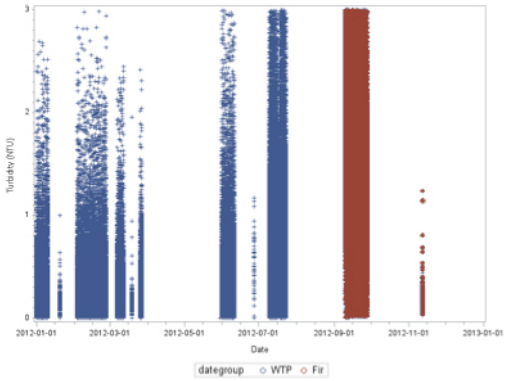


Figure 11 – Comparison of temporal and spatial variation among turbidity monitored by a remote sensor at WTP & distribution system site, 2012-2013

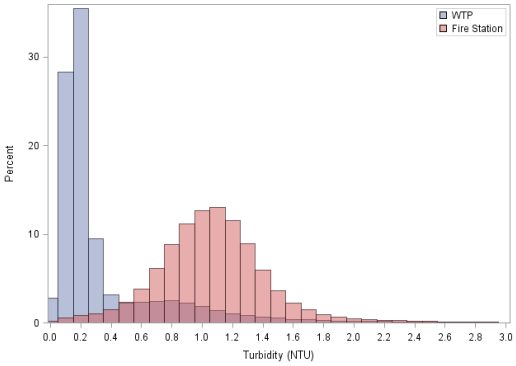


Figure 12 – Distribution of turbidity monitored by a remote sensor at WTP & distribution system site, 2012-2013

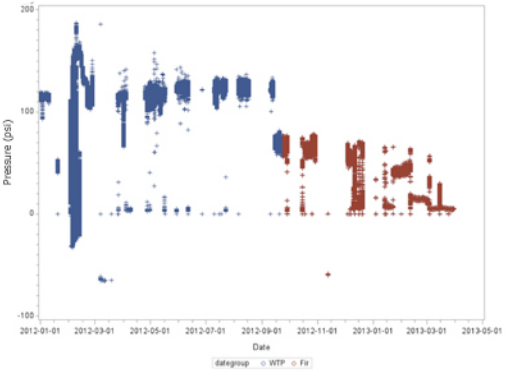


Figure 13 – Comparison of temporal and spatial variation among pressure monitored by a remote sensor at WTP & distribution system site, 2012-2013

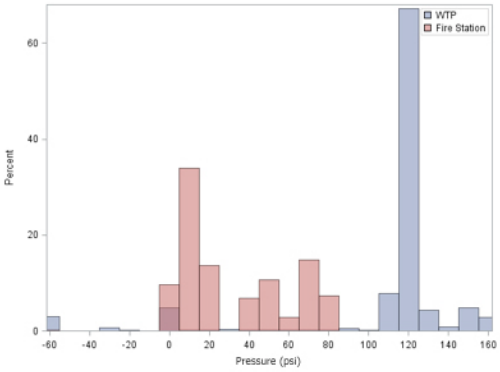


Figure 14 – Distribution of pressure monitored by a remote sensor at WTP & distribution system site, 2012-2013

These scatter plots and histograms display spatial and temporal differences between the two locations, particularly among redox, temperature, pH, and pressure. Figures 1 and 2 show a larger range of redox data collected at the Fire Station than that collected at the WTP. Figure 5 shows that the temperature at the two sites varied over time, which can be expected, as the data from the two locations was collected at different times of the year, thus different seasons. Figures 7 and 8 show the pH ranges from both sites did not overlap, and the pH readings at the Fire Station were much higher. Figures 13 and 14 show the distribution of pressure measurements at the Fire Station was lower than that at the WTP.

Figures 3 and 4 show the conductivity measurements at both distribution locations had a similar range in values but the shapes of distribution curves were different, with the Fire Station having a slightly larger range. Chlorine measurements for both locations, shown in Figures 9 and 10, fluctuated similarly, but with larger range measured at the WTP. Figures 11 displays a similar range in turbidity at both locations. Figure 12 displays a normal distribution of turbidity at the Fire Station, but a right-skewed distribution at the WTP.

3.3.2 – Temporal variability of water quality – Moving averages

There were temporal variations in the distribution system water quality. Figures 15-21 display the fluctuations in the data collected continuously using the AMS for the seven parameters at both locations. The moving average indicates the variations in general trends. The moving average in these figures were calculated using a span of 1 week. These figures display the overall trends without the "white noise" or missing data reported, so overall temporal trends can be more easily assessed.

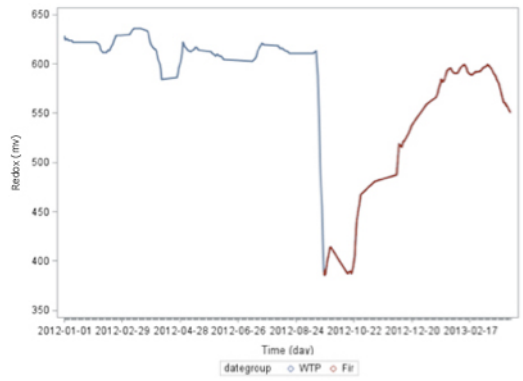


Figure 15 – Temporal variability of redox monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

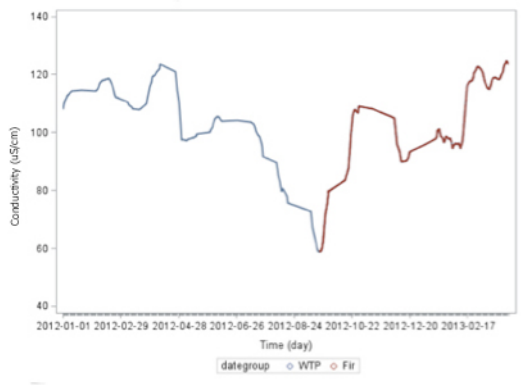


Figure 16 – Temporal variability of conductivity monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

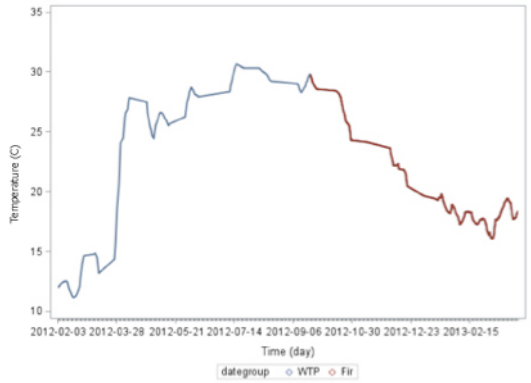


Figure 17 – Temporal variability of temperature monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

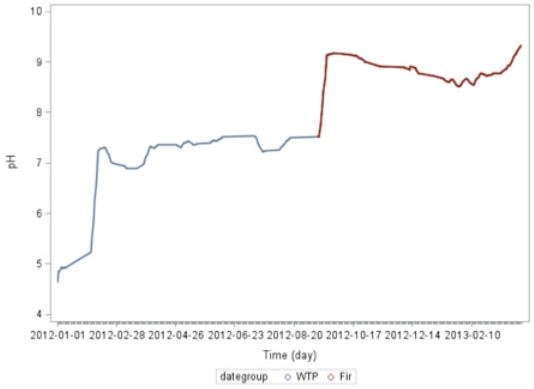


Figure 18 – Temporal variability of pH monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

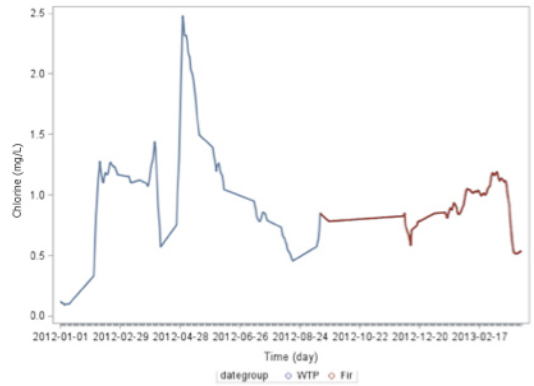


Figure 19 – Temporal variability of chlorine monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

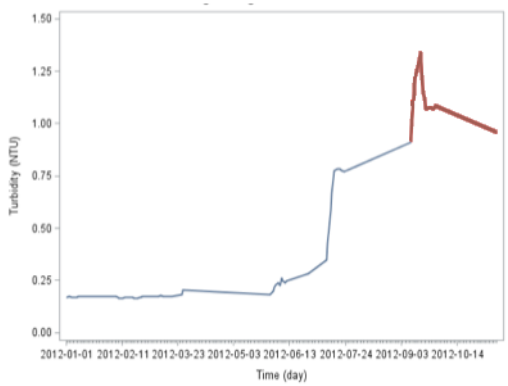


Figure 20 – Temporal variability of turbidity monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

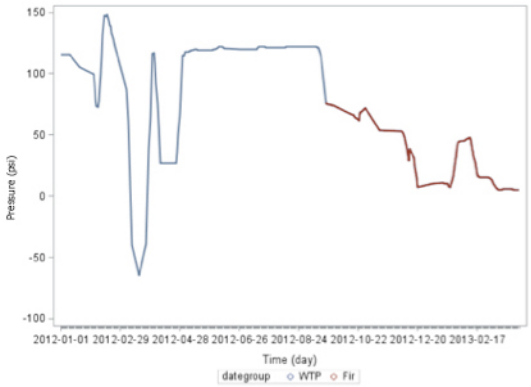


Figure 21 – Temporal variability of pressure monitored by remote sensor displayed as moving averages between WTP and Fire Station distribution site, 2012

Even when using one-week moving averages, there is a surprising amount of temporal variability in the AMS data for some parameters. pH measurements showed the least temporal variability over the course of the study. Redox and turbidity measurements were fairly stable at the WTP site, but both redox and turbidity varied a lot during the time the AMS was at the Fire Station. Temporal variation in turbidity at the Fire Station may be due to probe malfunction. Chlorine measurements at the WTP were extremely variable but somewhat more stable at the Fire Station. Conductivity data demonstrated substantial temporal variability at both sites.

The temporal analyses of water quality changes included examining differences in how the data is represented when the moving average is calculated across various time ranges. Figures 22-27 illustrate temporal variability in redox data collected using continuous monitoring at the WTP, on a single day (chosen at random). The elimination of the white noise as the averaging time span increases was similar for all parameters; so only redox data are presented here as a representation of this pattern.

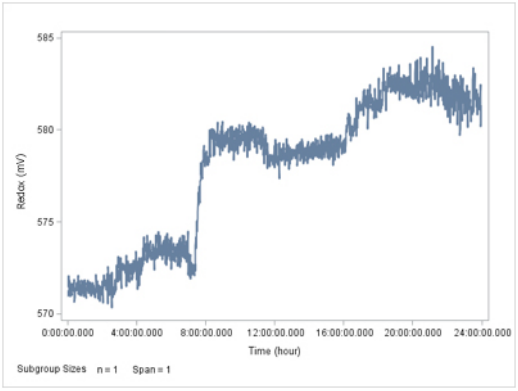


Figure 22 – Temporal variability of redox displayed as a moving average with 1 minute averaging span, Jan. 17, 2013

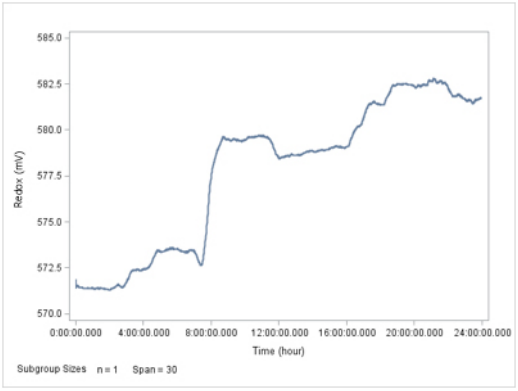


Figure 23 – Temporal variability of redox displayed as moving average with 30 minute averaging span, Jan. 17, 2013

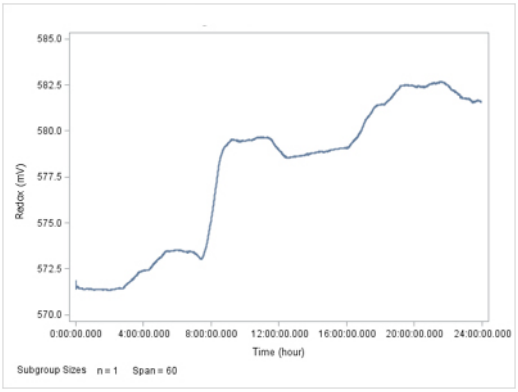


Figure 24 – Temporal variability of redox displayed as a moving average with 1 hour averaging span, Jan. 17, 2013

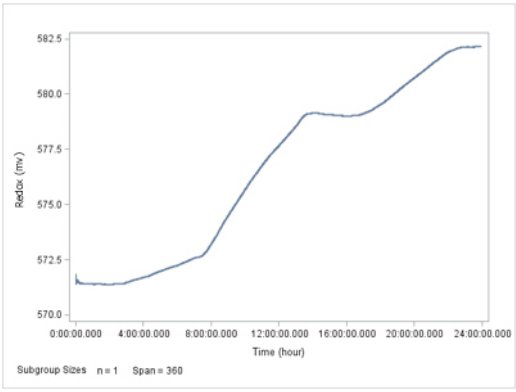


Figure 25 – Temporal variability of redox displayed as moving average with 6 hour averaging span, Jan. 17, 2013

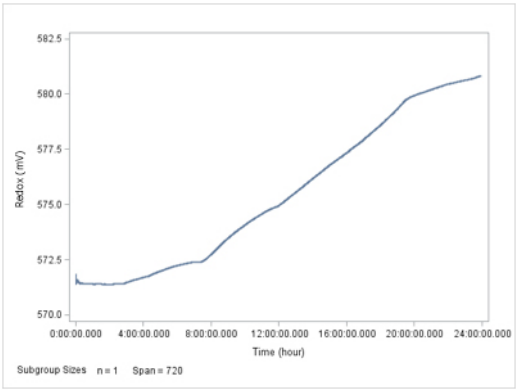


Figure 26 – Temporal variability of redox displayed as a moving average with 12 hour averaging span, Jan. 17, 2013

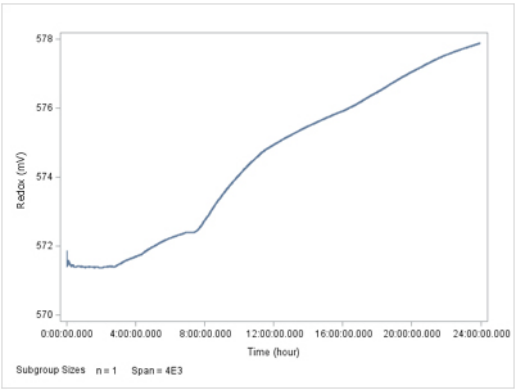


Figure 27 – Temporal variability of redox displayed as moving average with 1 day averaging span, Jan. 17, 2013

3.3.3 – Comparison of continuously monitored data to grab sample data

Table 3 provides descriptive statistics for the seven main water quality parameters (pressure, chlorine, turbidity, pH, conductivity, redox, and temperature) measured through continuous monitoring by the AMS and the grab samples collected by the COA during the first phase of the project, from January 1, 2012 through September 13, 2012. At the Hemphill WTP, the COA collected and analyzed grab samples approximately six times per month during this sampling period.

Table 3 – Comparison of physical-chemical water quality parameters monitored by a remote sensor to measurements on discrete grab samples, Hemphill Water Treatment Plant, 2012

	Continuous Remote Sensing Data collected using AMS at Fire Station			**Grab sample data collected by COA at WTP**		
Water Quality Parameter	**N**	**Mean (SD)**	**Min, Max**	**N**	**Mean (SD)**	**Min, Max**
Pressure (psi)	9,636,205	106.83 (47.46)	(-65.31, 187.27)	128	120.53 (1.15)	(118.16, 124.18)
Chlorine (mg/L)	1,728,771	1.11 (0.65)	(-0.0049, 3.65)	39	1.27 (0.30)	(0.69, 2.08)
Turbidity (NTU)	1,049,859	0.35 (0.41)	(0.00, 2.99)	39	0.10 (0.04)	(0.056, 0.24)
pH	159,895	7.10 (0.71)	(4.16, 9.99)	39	7.29 (0.14)	(6.9, 7.53)
Conductivity (uS/cm)	161,369	103.91 (14.98)	(43.21, 214.07)	39	118.21 (17.79)	(20.6, 144.8)
Temperature (ºC)	146,579	23.34 (7.09)	(10.50, 35.98)	39	22.82 (2.03)	(18.9, 25.7)
Redox (mV)	160,249	614.97 (13.30)	(348.86, 648.27)	*	*	*

*Redox (mV) measurements are not collected by COA

As expected, the continuous sampling using the AMS has a much larger sample size than the grab samples taken by the COA. Despite these large differences in sample size, some of the parameter means are remarkably similar, and statistical tests for comparison are displayed in Table 5. The standard deviation, minimum and maximum values have a larger range for the AMS data compared to the grab sample, particularly for pressure, chlorine, turbidity and

temperature. The low readings in January 2012 at the WTP are potentially due to a malfunction of the AMS probe, as they are uncharacteristic of any of the other pH readings.

Table 4 provides the descriptive statistics for the seven parameters during the second phase of the project, from September 15, 2012 through March 31, 2013, collected at the Fire Station on Old National Highway. COA collected only three grab samples at this sampling site during this phase of the project.

Table 4 – Comparison of physical-chemical water quality parameters monitored by a remote sensor to measurements on discrete grab samples, Fire Station distribution system site, 2012

	Continuous Remote Sensing Data collected using AMS at Fire Station			**Grab sample data collected by COA at Fire Station**		
Water Quality Parameter	**N**	**Mean (SD)**	**Min, Max**	**N**	**Mean (SD)**	**Min, Max**
Pressure (psi)	9,473,089	30.97 (27.63)	(-59.74, 81.90)	**	**	**
Chlorine (mg/L)	1,467,405	0.90 (0.23)	(0.010, 1.37)	3	0.79 (0.29)	(0.46, 1.00)
Turbidity (NTU)	225,701	1.07 (0.53)	(0.010, 2.99)	3	0.15 (0.030)	(0.12, 0.19)
pH	157,901	8.86 (0.25)	(8.26, 9.56)	3	7.98 (0.30)	(7.73, 8.31)
Conductivity (uS/cm)	157,901	104.25 (18.54)	(51.44, 162.77)	3	124.83 (15.08)	(109.20, 139.30)
Temperature (ºC)	157,901	20.41 (4.32)	(12.04, 32.46)	3	16.10 (1.22)	(14.70, 16.90)
Redox (mV)	157,901	545.32 (69.95)	(204.87, 607.33)	*	*	*

*Redox (mV) measurements are not collected by COA
**Pressure (psi) measurements are not collected at this location by the COA

One major difference in between the data collected continuously and that collected through grab samples at the Fire Station was in turbidity. The AMS turbidity probe was not functioning properly for the majority of the sampling period at the Fire Station, so this data should be interpreted with caution.

3.3.4 – Variability between water quality measurements measured through continuous monitoring and grab samples

The COA collects grab samples at least quarterly, if not more frequently, for water quality testing at each sampling site in the COA. During this study, sampling at the Hemphill WTP (n=39) was much more frequent than the Fire Station location (n=3). The AMS device measures water quality parameters every second, every 5 seconds, or every minute, as described previously. For this comparison, the daily averages of the AMS data for each parameter were calculated and plotted below, in an effort to create smaller datasets for comparison.

Table 5 displays the descriptive statistics for data from the sampling methods using the AMS daily average data and the grab samples conducted by the COA. In addition, the results from the test of equality (pooled t-test) and equality of variances tests are reported. P-values less than 0.05 are considered significant in this test. Pressure data was not measured by the COA at the Fire Station, thus no pressure data is reported for the Fire Station in these tables.

Statistical comparisons were not performed for the continuous sampling and grab sample data at the Fire Station because the sample size for the COA grab samples was too low (N=3) to produce interpretable results from these statistical tests.

Table 5 – Comparison of statistical tests of equality on variations in physical-chemical water quality parameters monitored by a remote sensor to measurements on a discrete grab sample, Hemphill Water Treatment Plant, 2012

	Conductivity (uS/cm)	**Temperature (ºC)**	**pH**	**Chlorine (mg/L)**	**Turbidity (NTU)**	**Pressure (psi)**
AMS - Mean (SD) (n)	103.3 (15.7) (n=125)	23.33 (7.1) (n=114)	7.30 (0.3) (n=115)	1.11 (0.6) (n=124)	0.37 (0.37) (n=75)	103.0 (49.9) (n=124)
COA - Mean (SD) (n)	118.21 (17.79) (n=39)	22.82 (2.03) (n=39)	7.29 (0.14) (n=39)	1.27 (0.30) (n=39)	0.10 (0.04) (n=39)	120.53 (1.15) (n=128)
Pooled t-test	t= -4.59, p<0.0001	t= 0.45, p=0.65	t=0.05, p=0.96	t=-1.77, p=0.078	t=4.18, p<0.0001	t=-3.97, p<0.0001
Equality of Variances	f'=1.36, p=0.23	f'=11.33, p<0.0001	f'=3.29, p<0.0001	f'=4.19, p<0.0001	f'=81.01, p<0.0001	f'=1872.18, p<0.0001

The pooled t-test indicates there were significant differences in the means for conductivity (t=-4.59, p<0.0001), turbidity (t=4.18, p<0.0001), and pressure (t=-3.97, p<0.0001) between the daily average data continuous monitored data and the grab sample data. However, the means were not significantly different for temperature, pH, and chlorine. As expected because of the differences in sample sizes, the variance in the data was significantly different between the two monitoring methods for all the parameters, excluding conductivity (f'=1.36, p=0.23).

Figures 28-33 graphically display the temporal variance for each parameter measured at the WTP, using daily averages of the continuous monitored data, and all of the COA data for the respective dates of collection. In addition, U.S. EPA or State of Georgia water quality guidelines are included in each graph when applicable ("Water Use Classifications," n.d., "National Primary Drinking Water Regulations," 2012, "City of Atlanta," 2011).

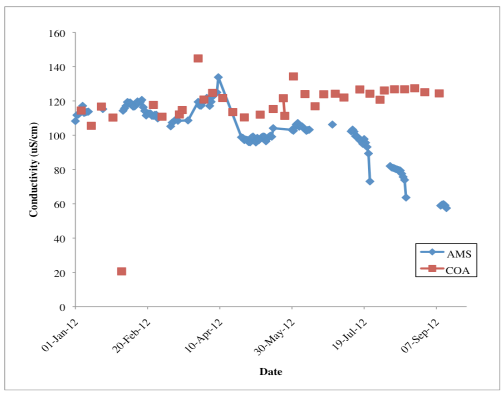


Figure 28 – Comparison of conductivity monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), WTP, 2012

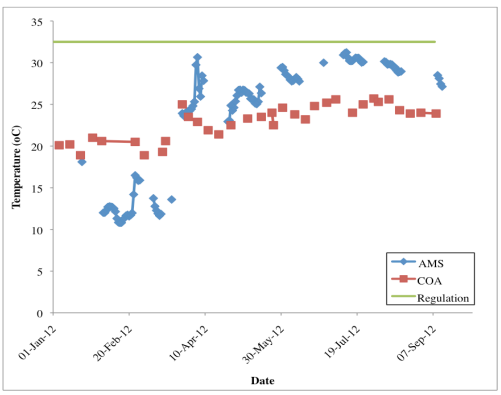


Figure 29 – Comparison of temperature monitored by remote sensor (AMS) to measurements on discrete grab samples (COA) with regulations, WTP, 2012

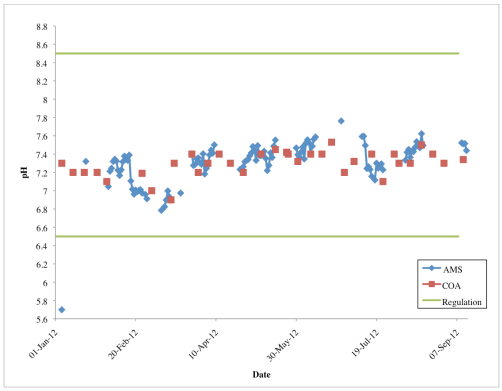


Figure 30 – Comparison of pH monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), with regulations WTP, 2012

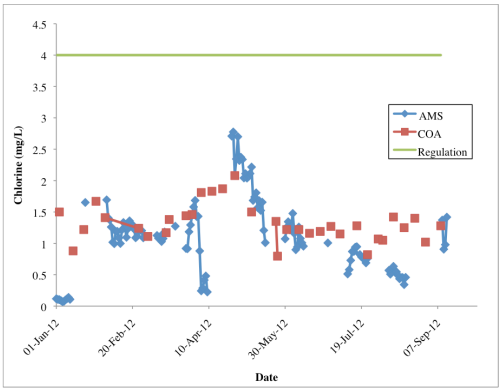


Figure 31 – Comparison of chlorine monitored by remote sensor (AMS) to measurements on discrete grab samples (COA) with regulations, WTP, 2012

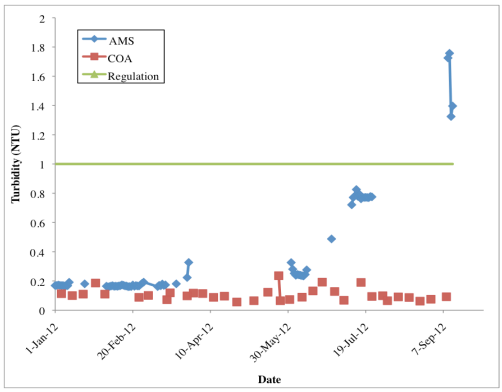


Figure 32 – Comparison of turbidity monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), with regulations WTP, 2012

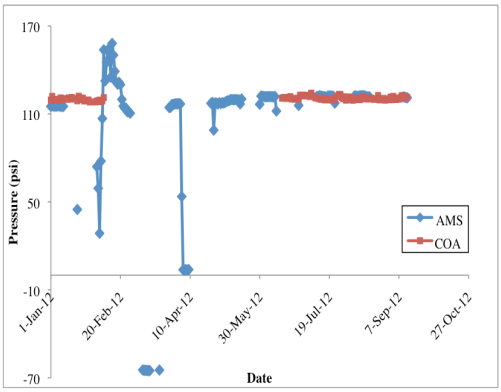


Figure 33 – Comparison of pressure monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), WTP, 2012

COA grab sample data always fell within the guidelines for temperature, pH, chlorine, and turbidity (Figures 29-32). Violations were observed in the continuously monitored data for pH and turbidity on a few occasions; however, as mentioned previously, the AMS probes may have been malfunctioning during these times. In addition, there was little temporal change for pH and chlorine for either sampling method. The continuously monitored data on conductivity shows a moderate decrease over time, in contrast to the general stability of the grab sample data on conductivity, with the exception of a low spike in February. Temporal changes in temperature are expected as seasons change, and Figure 29 shows that the temporal trends measured by through continuously monitoring were similar to those for the grab samples. Pressure measured through continuously monitoring varied greatly during the first four months of collection, then smoothed to similar levels measured by grab sample data at the WTP. The validity of these AMS pressure measurements in the early months is unknown; there was almost no temporal variability in the COA grab sample pressure data.

Similar figures comparing data collected continuously with the AMS at the Fire Station to grab samples collected by the COA at the Fire Station are displayed in Figures 34-37. As stated previously, pressure and turbidity data from the Fire Station were not measured and only three grab samples were collected during this time.

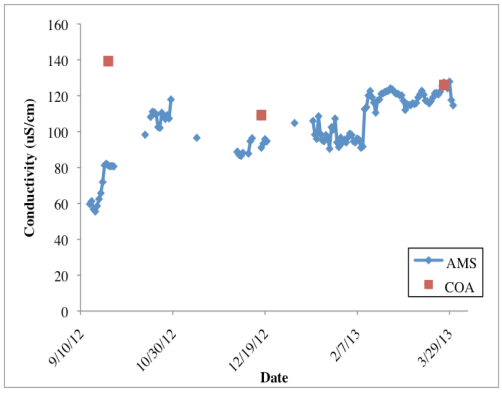


Figure 34 – Comparison of conductivity monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), Fire Station distribution site, 2012

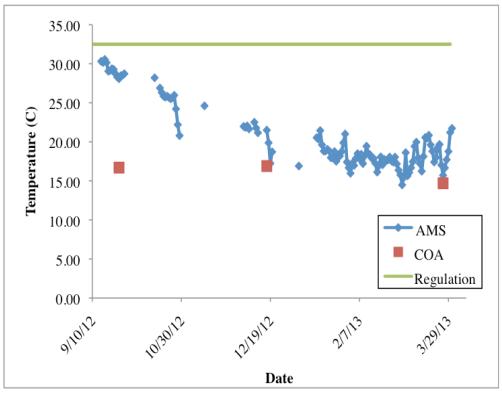


Figure 35 – Comparison of temperature monitored by remote sensor (AMS) to measurements on discrete grab samples (COA) with regulations, Fire Station distribution site, 2012

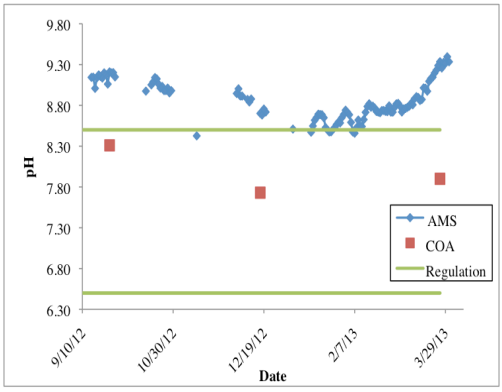


Figure 36 – Comparison of pH monitored by remote sensor (AMS) to measurements on discrete grab samples (COA), with regulations at Fire Station distribution site, 2012

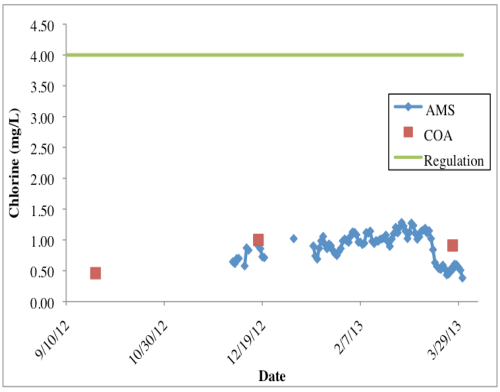


Figure 37 – Comparison of chlorine monitored by remote sensor (AMS) to measurements on discrete grab samples COA) with regulations, Fire Station distribution site, 2012

Guidelines for temperature and chlorine were met using both sampling methods at the Fire Station (Figures 35 and 37). Almost all the pH data collected through continuous monitoring was above the 8.5 guideline, but the pH data from grab samples were within the recommended range of 6.5 to 8.5 (Figure 36).

3.4 – Discussion

The overall research objective of this study was to compare seven physical-chemical measures of water quality for spatial and temporal differences at two locations within the COA

distribution system. Another specific objective of this study was to assess how these key physical-chemical measures of water quality differ between two distinct monitoring methods: 1) Grab samples, and 2) Continuous monitoring using remote sensors.

3.4.1 – Spatial Variability

Comparing key physical-chemical parameters at the two site locations indicates a distinct difference in water quality within the distribution system compared to the point of entry (Figures 1-14). Interestingly, the pH ranges at the two sites overlap for a very small fraction of the data collected, showing that the pH may change significantly as water residence time increases. The U.S. EPA states that the corrosion of pipes within a distribution system can increase pH, especially in portions of the distribution system with increased water age (United States Environmental Protection Agency, 2002). This is consistent with our research findings of the increased pH with increased water age at the Fire Station, which has an estimated water age of 42 hours (Figure 7).

National standards take into consideration spatial variability of water quality, particularly for chlorine standards. Water treatment plants aim to maintain a chlorine level of 1-2 mg/L to ensure chlorine residual level does not decay to 0 mg/L at the points of longest water residence time within the distribution system. Chlorine decay is expected in water distribution systems as water travels spatially, due to the mass-transfer of chlorine with the pipe walls (Rossman, Clark, & Grayman, 1994). The presence of chlorine in distribution systems is one of the key, reliable factors in the control of biofilm growth within pipes, and to serve to mitigate microbial contamination from intrusion events (Hall & Szabo, 2005). Thus, the monitoring of chlorine at sites with long water residence times is key to protecting the public health of the residents in those areas.

Spatial and temporal change of water quality is important because of the potential impact on health from degraded quality at sites with long water residence time. This relationship between drinking water quality and gastrointestinal illness (GI) in the metropolitan Atlanta area was examined between 1993 and 2004 (Tinker et al., 2009). This study showed a significant association between water residence time and risk of GI, with a 5-7% increased risk of GI observed for patients living in zip codes served by water with long water residence times compared to those served by water with intermediate residence times (Tinker et al., 2009). Monitoring changes in physical-chemical parameters of water as it moves through the distribution system to these more distant locations will provide greater understanding of the nature of the risks associated with these sites and inform preventative measures to protect public health at all sites within a distribution system.

3.4.2 – Temporal Variability

All water utilities likely experience different levels of temporal white noise in physical-chemical data. This may be especially true for continuous data collected by remote sensors. However, once the categorization of these variations is achieved, any outliers outside of this normal variation can be more easily detected and compared to state and national standards (Figures 28-37). The times when parameters exceed standards can be flagged for investigation by the water utility. Potentially, a water utility could track these temporal changes in real time, and could develop methods for correcting these spikes in certain parameters, or even preventing them from occurring altogether, so guideline violations will be virtually eliminated. Research and development of affordable remote sensors would be of value to better characterize temporal variability in water quality in the distribution system.

During the continuous monitoring periods, there were occasional temporal variations across multiple parameters concurrently. For example, redox and conductivity at the WTP were fairly stable and tended to fluctuate with a magnitude of about 30 mV and 80 uS/cm (Figures 1 and 3). One exception to this normal fluctuation was recorded on April 9, 2012 for both parameters at the WTP, where the fluctuation of redox was about 350 mV, and over 100 uS/cm for conductivity in a single day. The cause of these large fluctuations in two parameters is unknown, but this provides evidence of an event that should be flagged for further investigation. Examining the WTP activities on this day would be of interest, in the event that such a spike could be predicted based on events occurring internally in the plant. The fact that multiple parameters experienced large fluctuations on a single day is interesting, because it is unlikely that both probes malfunctioned simultaneously.

Better characterization of temporal variation does not explain the cause of these fluctuations, but it can establish the baseline water quality that can be used to identify potential contamination events that are outside the normal fluctuations. Developing the benchmark is cited as the key first action for detecting deviant water quality changes, and ultimately securing public health (Skadsen et al., 2008).

3.4.3 – Comparison of Continuous Monitoring and Grab Samples

Grab samples to monitor water quality required through the Total Coliform Rule do not provide adequate information on water quality within a distribution system, especially in the event of a serious threat to the water supply (Hall, Szabo, Panguluri, & Meiners, 2009). The need for continuous collection of water quality data at various locations throughout the distribution system is critical to ensure adequate quality standards are met as water changes due to spatial and temporal variations. The ultimate purpose of shifting from grab samples to continuous

monitoring is to increase the likelihood of detecting uncharacteristic changes in water quality from the normal background operating conditions, and ultimately to decrease response time of water utilities to correct the water quality changes (Skadsen et al., 2008). A quick response time to intrusion events is greatly facilitated by the use of continuous remote sensors rather than grab samples (Skadsen et al., 2008).

In this study, the variances for the continuous monitoring and grab sample data at the WTP were significantly different for all parameters, except conductivity (Table 5). This may be expected because continuous logging captures more of the daily white noise in the measurements (Figures 22-33). Interestingly, only three of the six parameters measured at the WTP had means that were significantly different between the two sampling methods (Table 5). Daily temporal variations are not captured in the grab samples that are taken by the COA on a quarterly basis. Based on these results, continuous water quality monitoring provides a more comprehensive description of the variability in the conductivity, turbidity, and pressure parameters than grab samples, but grab samples was just as effective for providing representative means for temperature, pH, and chlorine. These results show that investing in continuous water quality monitoring may be more effective in characterizing overall temporal variability for some parameters more than others.

The U.S. EPA has investigated commercially available online water quality monitoring technologies, similar to the AMS used in this study, that could be used as early indicators of an intrusion into water supplies (Hall, Szabo, Panguluri, & Meiners, 2009). The remote sensor technologies investigated by the U.S. EPA focused on sensors that could detect uncharacteristic changes from baseline water quality data in distribution systems, which would ultimately serve as a call to action to the water utility to identify and remediate any contaminant intrusion (Hall,

Szabo, Panguluri, & Meiners, 2009). During this evaluation, the sensors were challenged with select contaminants, and the sensors that responded to the most contaminants were free chlorine, TOC, redox, specific conductance, and chloride probes (Hall et al., 2007). The U.S. EPA also concluded that the specific technology or manufacturer of the sensor used did not affect the overall results of the challenge (Hall et al., 2007).

Trends in research and national interest are shifting towards implementing continuous remote monitoring over grab samples to track water quality within distribution systems. However, the United States is still in the process of identifying the most useful and practical remote sensing technology to implement.

3.4.4 – Strengths

The AMS used in this study is innovative in that it is one of the first successful models of a portable, continuous remote sensing device which measures multiple key parameters concurrently, and can be easily setup and maintained within a distribution system. To-date, most remote sensors for water quality are implemented in storage tanks, or for large bodies of source water, rather than focusing on drinking water distribution systems (Hall, Szabo, Panguluri, & Meiners, 2009). The amount of data collected by this system was incredible; especially considering the field team only travelled to the field site a maximum of once per week to maintain the device.

3.4.5 – Limitations

This study does have limitations in terms of internal and external validity. The AMS collection device used in the study is a new technology custom-built for these specific research purposes. During its use in the Hillsborough County study in Florida, the accuracy of the probes within the AMS was determined to be high. The probes were calibrated and monitored before

data collection began in Atlanta, and the AMS collected data for about a week before January 1, 2012, when the first “official” day of data collection was recorded for this study. During the course of this study, several probes, including the chlorine and turbidity probes, malfunctioned, leading to weeks of missing data and the ultimate replacement of these probes within the AMS. The probes within the AMS device are very sensitive to small changes, which makes them useful for measuring continuous changes in water quality; however, the potential for malfunction is high if an external event affects the probe. Based on notes taken from field visits, the time periods when there was evidence of probe malfunction were removed from the dataset. However, the starting point of these malfunctions is difficult to pinpoint, causing some concern for the validity of data specifically around the times of probe malfunctions. Due to these malfunctions, the data sets from the remote sensors contain sections of missing data, and unfortunately the data for June 28, 2012 is missing, which was the day of the boil-water advisory at the WTP ("Media Advisory," 2012). In addition, only one remote sensor was available for use during this study, thus the data collected at both locations was not done concurrently, which decreases the internal validity when directly comparing data at both sites. Ideally, a water utility could set-up remote sensors to record data at multiple sites in a distribution system simultaneously.

The AMS used in this study was custom-built for research purposes, thus this system is not market-ready. Research and development into an easily maintainable and reliable remote sensor is critical for the real-world application of this research.

In addition, extrapolation of specific data collected during this study may not be appropriate for every water utility. A multitude of factors influence water quality in the distribution system, including pipe age, soil type, and weather; thus, not all water distribution systems will experience the spatial and temporal variations in the parameters reported in this

study in Atlanta. However, the overarching distinction established in this study between continuous monitoring and grab sampling is important, and should be replicated in other cities in order to test the external validity of the differences in these two water quality monitoring methods.

One main limitation of the data analyses performed in this study was that all of the parameters measured had a non-normal distribution (Figures 1-14), which is an assumption when performing tests of equality. This assumption of normality can be violated when the sample sizes are large, but the results of these tests should be interpreted with caution. Further analyses of these data should try non-parametric approaches. Finally, due to the immense amount of data collected, it was difficult to distinguish between actual changes in water quality from probe malfunctions, thus cleaning this large data set was extremely challenging.

3.5 – Conclusion

Spatial differences for seven key water quality parameters were observed between the point of entry and a site of intermediate water residence time monitored in the COA distribution system. Temporal differences were also observed at both locations. The ability to capture the variation in temporal and spatial trends increases when data is collected continuously using a remote sensor, rather than collected through routine, but infrequent, grab samples.

The technology for continuous water quality measurement is cutting-edge and needs continued investment in research in order to develop an affordable, reliable system. Metropolitan water utilities could better protect the quality of water piped throughout their distribution system by actively monitoring water quality using remote sensors and taking prompt action to address sudden changes. This monitoring will increase the knowledge base about the typical variance for key water quality parameters, and could eventually lead to the development of more specific

distribution system water quality standards. Overall, the temporal and spatial variability in water quality within drinking water distribution systems has to-date been under-reported. The development and use of a real-time water quality monitoring system could be of value to improve consistency and overall quality of water throughout the drinking water distribution system. Further research is needed to describe a link between short-term temporal changes in water quality and potential resulting health effects among the consumers of this water to determine which water quality parameters are most effective for predicting risk to public health.

Chapter 4 – Lessons learned and recommendations

The maintenance of the AMS device used in this study was delicate. During the course of our study, both the chlorine and turbidity probes malfunctioned for long periods of time. In the end, the probes were completely replaced. In a similar future study, I would recommend more pro-active investigation if a similar malfunction occurs, so as not to lose entire days or weeks of potential data. If a probe is malfunctioning for an entire day or two, a serious effort to fix the problem should be taken immediately by field staff, because rarely did a probe fix itself without extensive effort. The AMS system was equipped with an off-site log-in feature, in order to view the data-logging in real time at a remote location. However, due to poor Internet signals at the second site in our study, we were unable to remotely access this data; thus, making it more difficult to continuously monitor for any malfunctions. Sometimes an entire week (or two) would pass before our team knew of any problems with probes or in the datalogging. If remote log-in is not an option, then I would recommend devoting a team member to visit the site at least once a week to check on the system and download the data. Our team typically visited sites every other week due to scheduling conflicts, but I would recommend visiting more frequently in order to stay on top of any problems that may occur. In addition, I would recommend importing the downloaded data immediately into SAS, or a similar data analysis program, in order to produce basic plots of the data on a weekly or bi-weekly basis. These figures will help flag any missing data, and ultimately ensure the extent to which the datalogger is recording data. These quick plots will aid tremendously in finding and fixing any problems in the datalogging device.

During each site visit, I would recommend doing basic hand measurements of water quality parameters, such as pH, turbidity, and chlorine. These hand measurements could provide valuable information on the validity of the data measured by the AMS, or other continuous

monitoring equipment. Our team randomly performed these measurements, but a more intentional effort would produce an additional dataset that would be of interest for future studies.

In addition, frequent probe calibration could significantly aid in the quality of data collected, as well as the confidence in the data collected. Continuous remote sensors are difficult to maintain, and calibrating probes every week, or every other week, is another key aspect to improve overall data quality.

If possible, I would recommend meeting with a member of the water quality team at the local water utility and discussing how the particular water utility measures quality standards set by the State and the U.S. EPA. The formalization of this knowledge at the forefront a project would be of great value, in order to better understand the significance of the parameter levels being measured.

Appendix

Appendix 1 – List of City of Atlanta Water Treatment Plants

Table 6 – Major Drinking Water Treatment Plants, and the Counties that they Serve, Primarily Five-County Metro-Atlanta*

County	*Primary Drinking Water Treatment Plants Serving County*	*Utility Operating Treatment Plant*
Clayton	Terry R. Hicks Water Production Plant	Clayton County Water Authority
	J. W. Smith Water Production Plant	
	W. J. Hooper Water Production Plant	
Cobb	Hugh Wyckoff Treatment Plant	Cobb County-Marietta Water Authority
	James E. Quarles Treatment Plant	
DeKalb	Scott Candler Water Filter Plant	DeKalb County Department of Watershed Management
Fulton	Atlanta-Fulton County Water Treatment Plant	Atlanta-Fulton County Water Resources Commission
	Chattahoochee Treatment Plant	City of Atlanta Bureau of Drinking Water
	Hemphill Treatment Plant	
Gwinnett	Lanier Filter Plant	Gwinnett County Department of Public Utilities
	Shoal Creek Plant	

*Table retrieved from Unpublished Environmental Protection Agency STAR Grant submitted by Emory University, and used with permission

Appendix 2 – AMS device schematic and photos

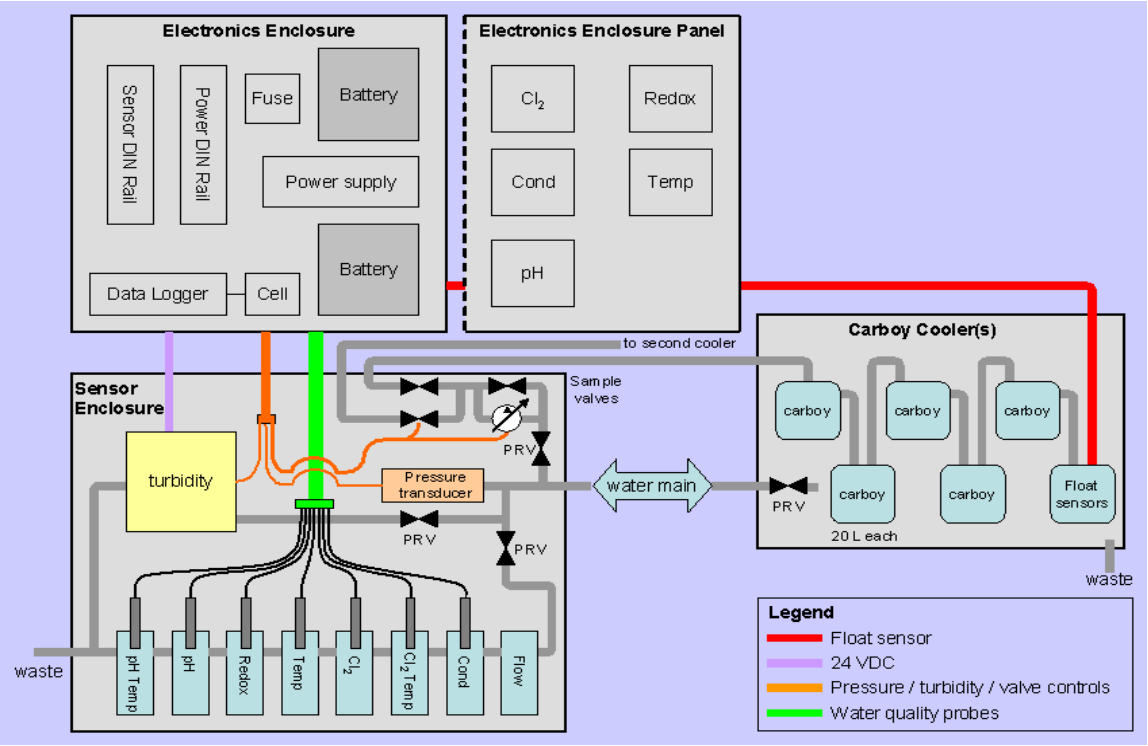


Figure 38 – Schematic of Automated Monitoring and Sampling (AMS) unit*

*Schematic retrieved from Hillsborough County study and used with permission (Moe et al., 2009).

Figure 39 – AMS controller box, probe box, and laptop inside Fire Station field site #2

Figure 40 – AMS probe box

Figure 41 – AMS controller box display panel

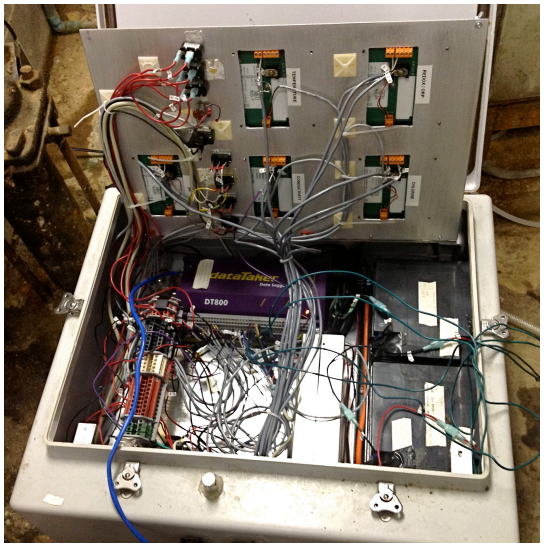
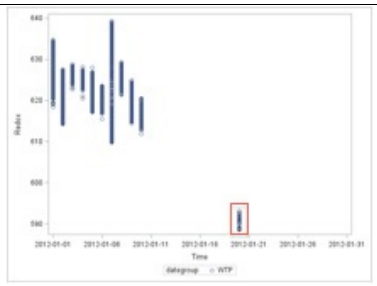


Figure 42 – AMS controller box inside-panel

Appendix 3 – Monitoring site locations with the City of Atlanta

Figure 43 – Map of City of Atlanta with study sites highlighted

Appendix 4 – Data cleaning: Raw scatter plots of parameters separated by month with dates removed highlighted in red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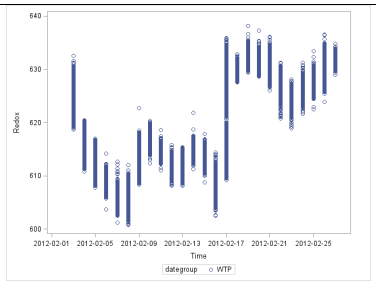
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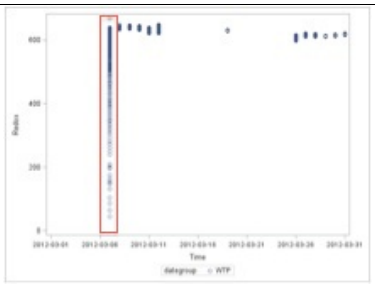
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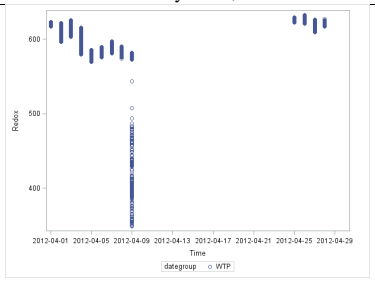
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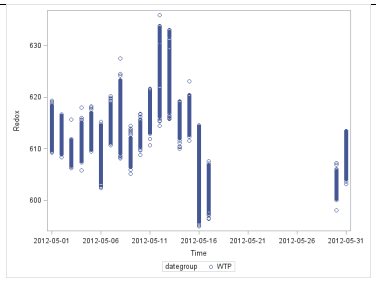
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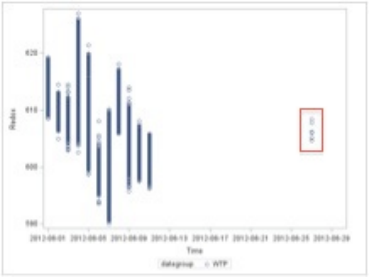
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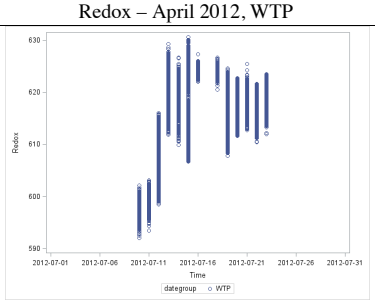
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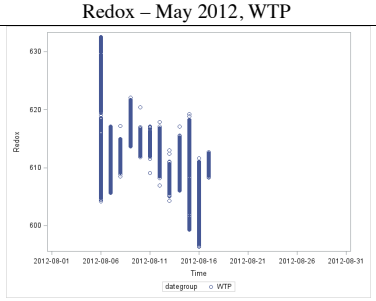
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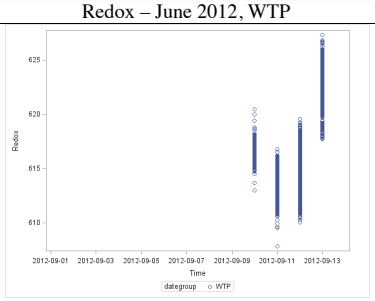
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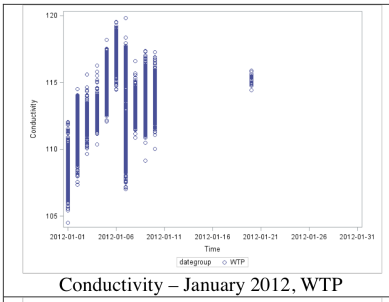
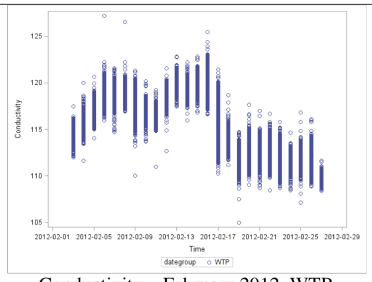
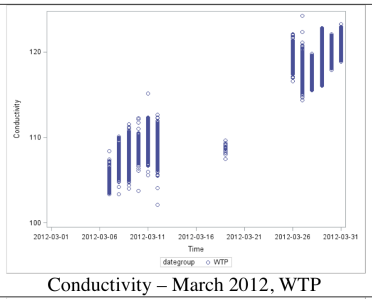


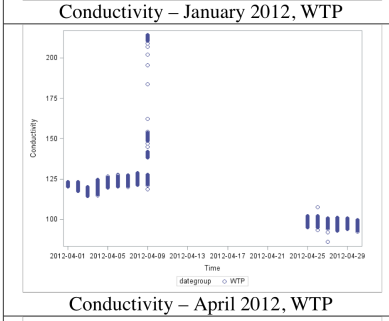
Conductivity – January 2012, WTP



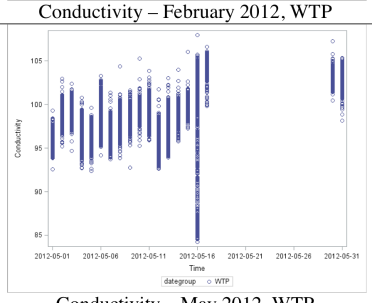
Conductivity – February 2012, WTP



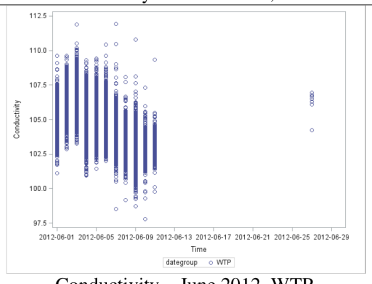
Conductivity – March 2012, WTP



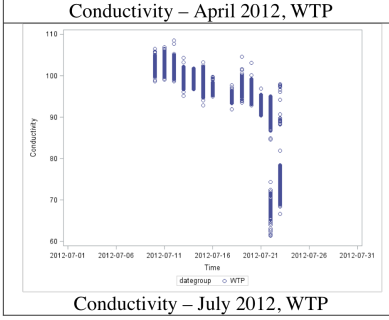
Conductivity – April 2012, WTP



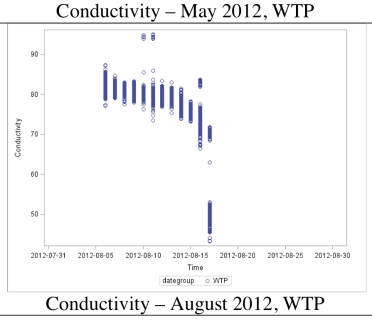
Conductivity – May 2012, WTP



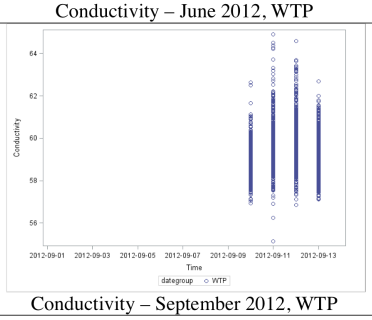
Conductivity – June 2012, WTP



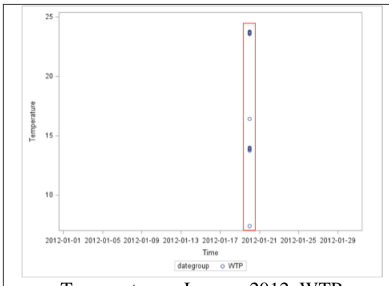
Conductivity – July 2012, WTP



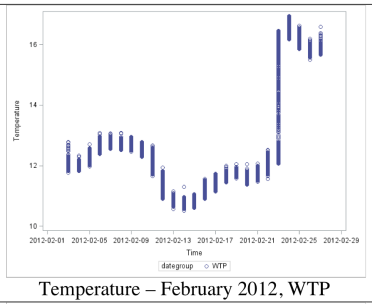
Conductivity – August 2012, WTP



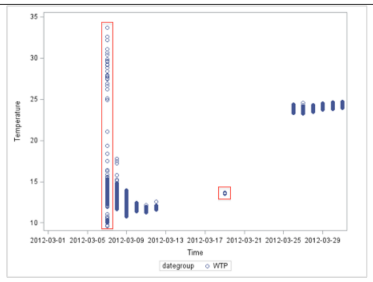
Conductivity – September 2012, WTP



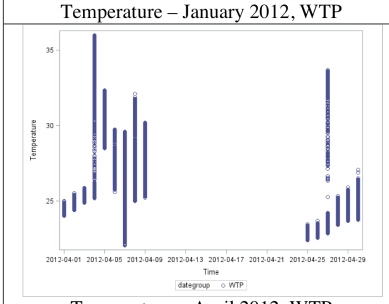
Temperature – January 2012, WTP



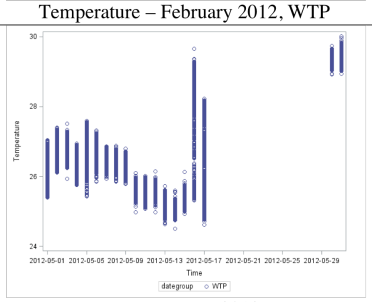
Temperature – February 2012, WTP



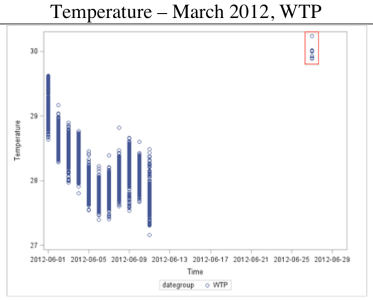
Temperature – March 2012, WTP



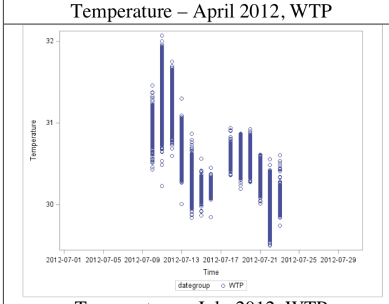
Temperature – April 2012, WTP



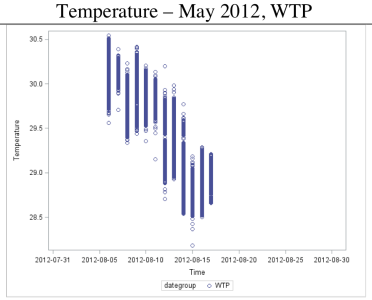
Temperature – May 2012, WTP



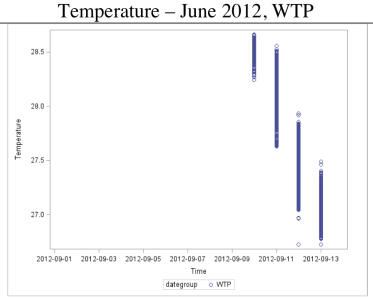
Temperature – June 2012, WTP



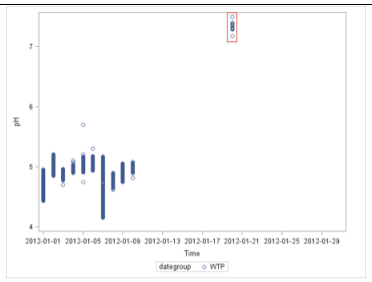
Temperature – July 2012, WTP



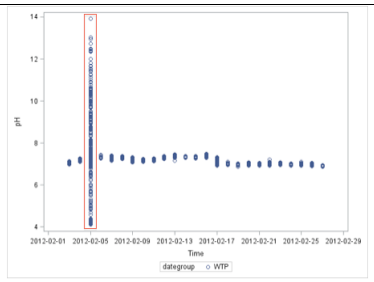
Temperature – August 2012, WTP



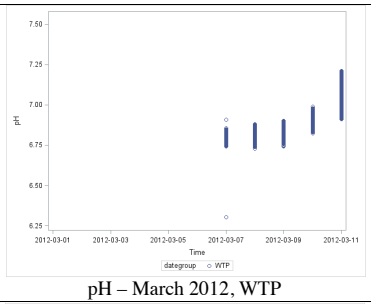
Temperature – September 2012, WTP



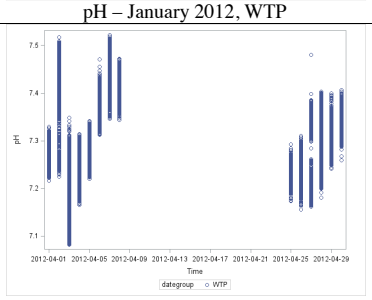
pH – January 2012, WTP



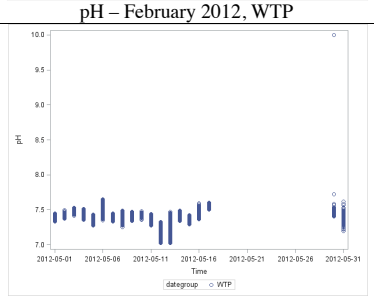
pH – February 2012, WTP



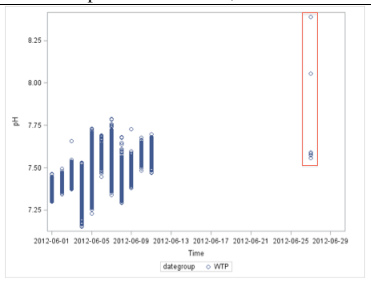
pH – March 2012, WTP



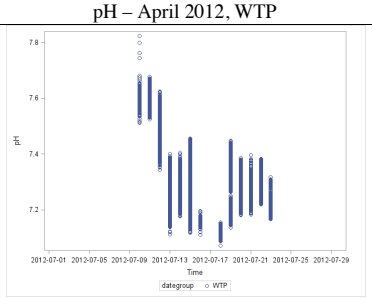
pH – April 2012, WTP



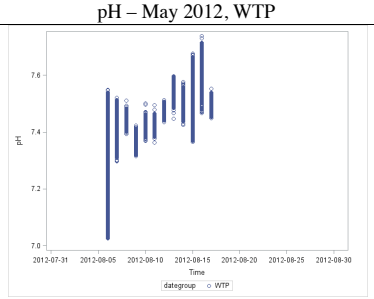
pH – May 2012, WTP



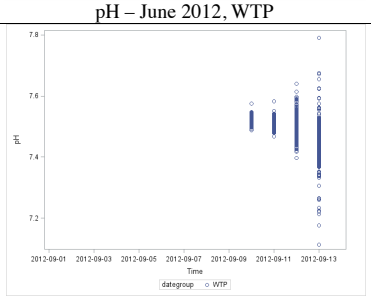
pH – June 2012, WTP



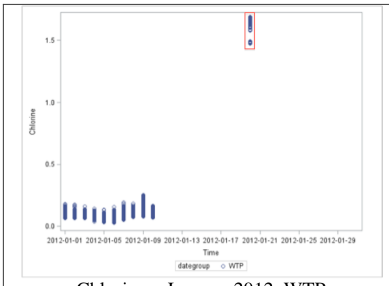
pH – July 2012, WTP



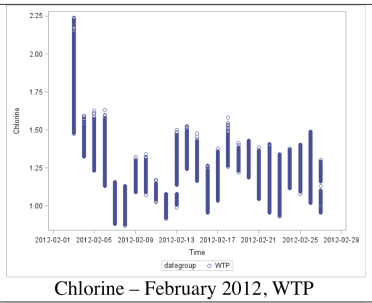
pH – August 2012, WTP



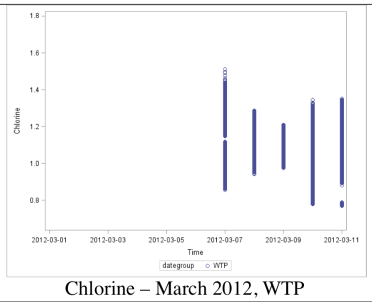
pH – September 2012, WTP



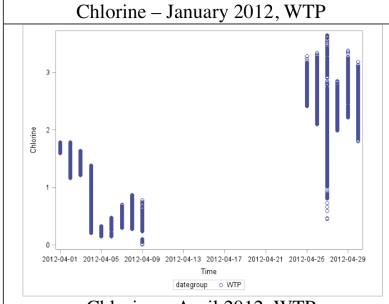
Chlorine – January 2012, WTP



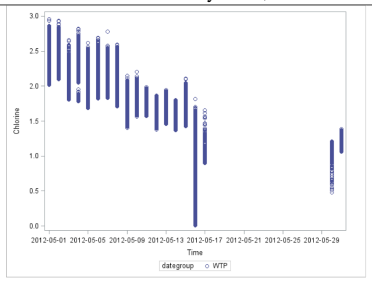
Chlorine – February 2012, WTP



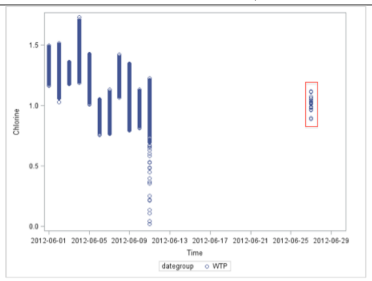
Chlorine – March 2012, WTP



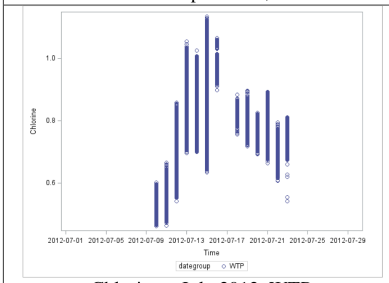
Chlorine – April 2012, WTP



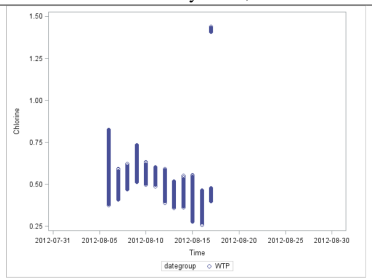
Chlorine – May 2012, WTP



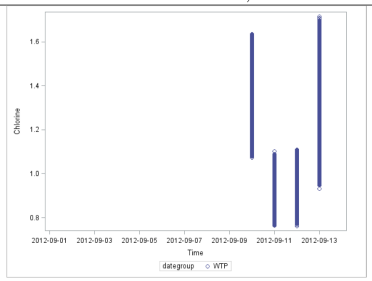
Chlorine – June 2012, WTP



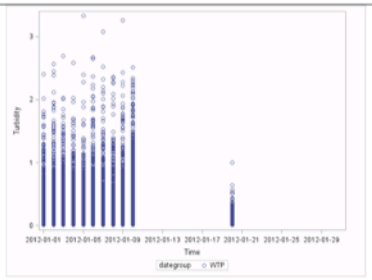
Chlorine – July 2012, WTP



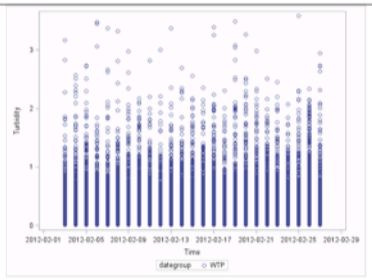
Chlorine – August 2012, WTP



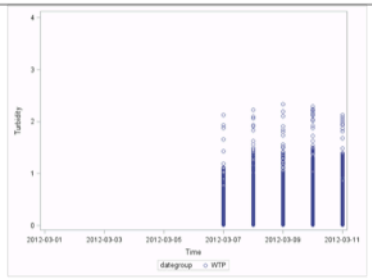
Chlorine – September 2012, WTP



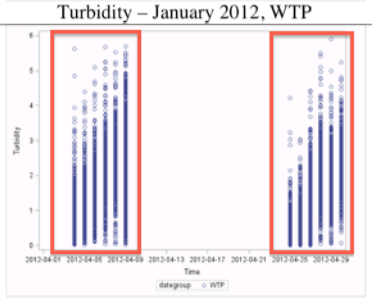
Turbidity – January 2012, WTP



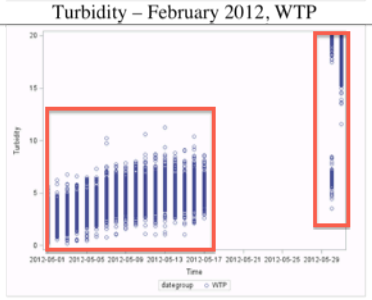
Turbidity – February 2012, WTP



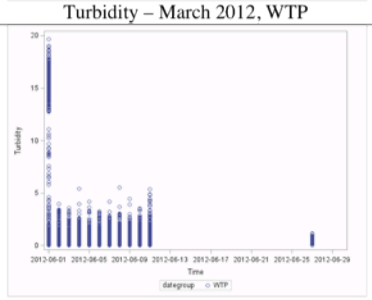
Turbidity – March 2012, WTP



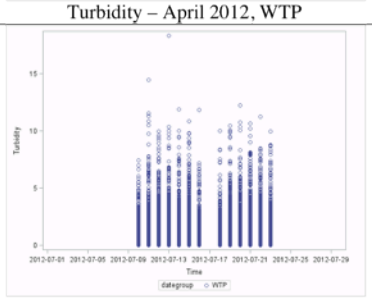
Turbidity – April 2012, WTP



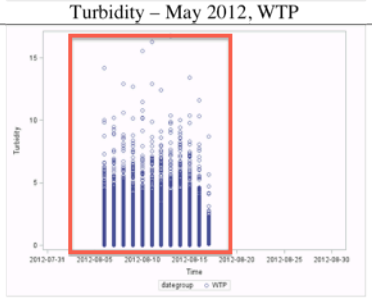
Turbidity – May 2012, WTP



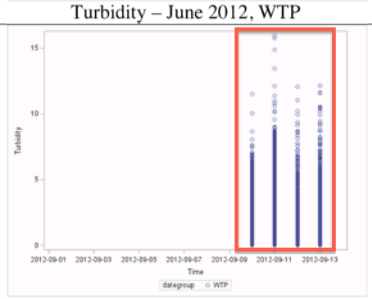
Turbidity – June 2012, WTP



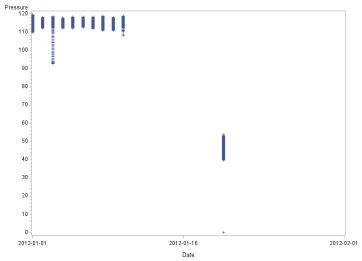
Turbidity – July 2012, WTP



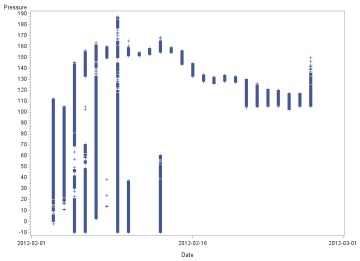
Turbidity – August 2012, WTP



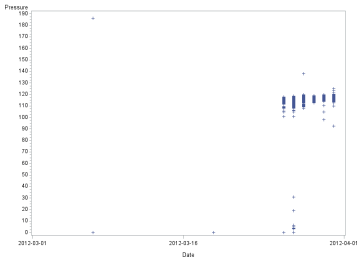
Turbidity – September 2012, WTP



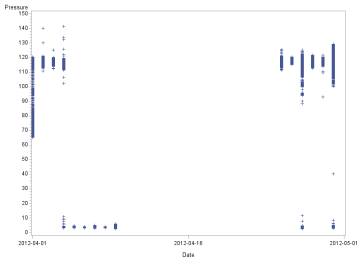
Pressure – January 2012, WTP



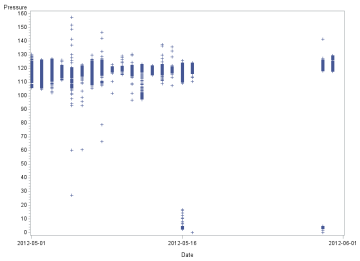
Pressure – February 2012, WTP



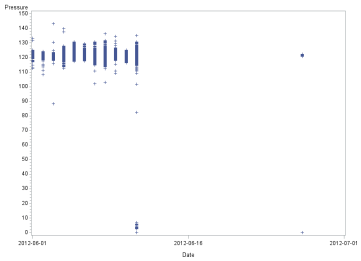
Pressure – March 2012, WTP



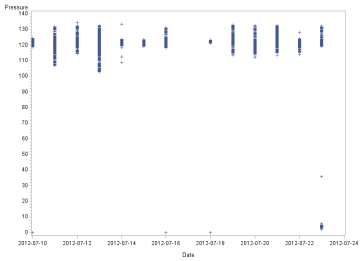
Pressure – April 2012, WTP



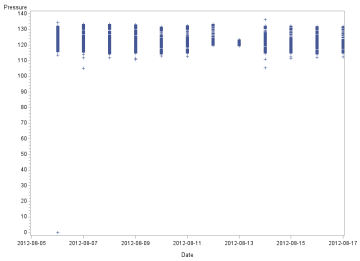
Pressure – May 2012, WTP



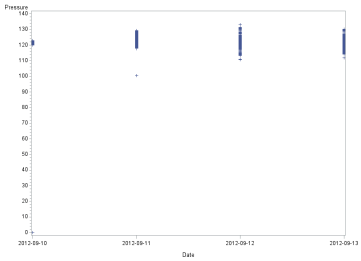
Pressure – June 2012, WTP



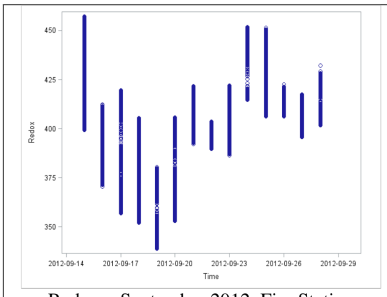
Pressure – July 2012, WTP



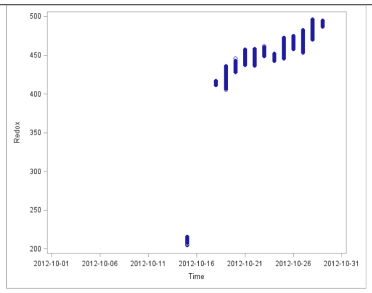
Pressure – August 2012, WTP



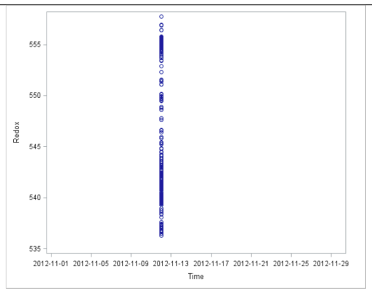
Pressure – September 2012, WTP



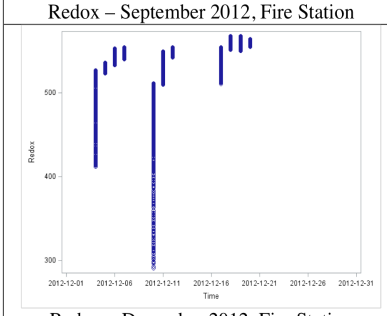
Redox – September 2012, Fire Station



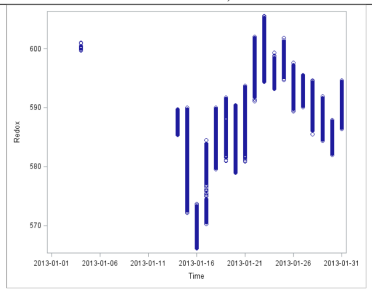
Redox – October 2012, Fire Station



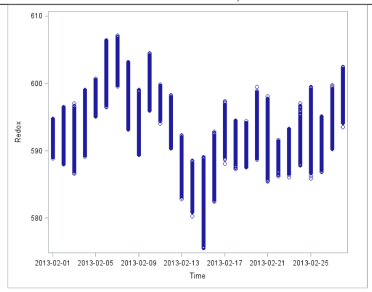
Redox – November 2012, Fire Station



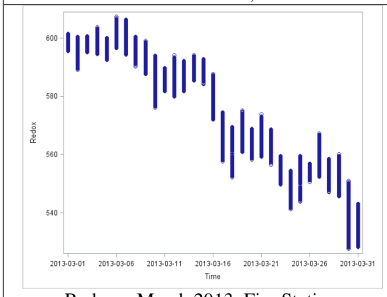
Redox – December 2012, Fire Station



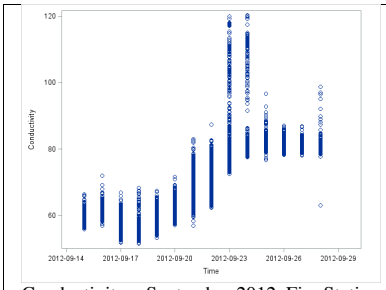
Redox – January 2013, Fire Station



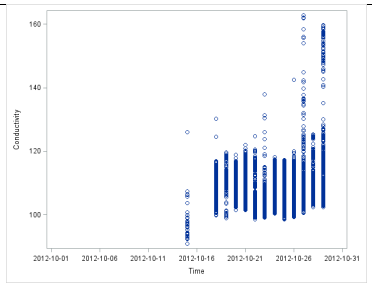
Redox – February 2013, Fire Station



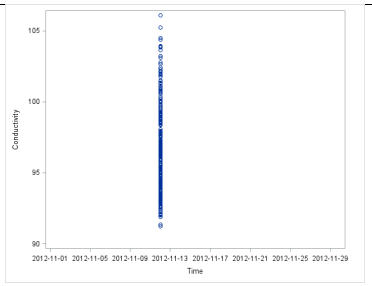
Redox – March 2013, Fire Station



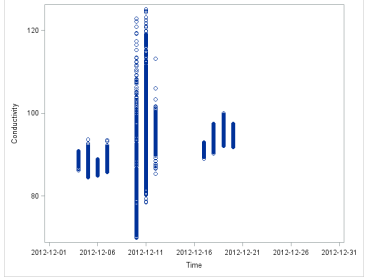
Conductivity – September 2012, Fire Station



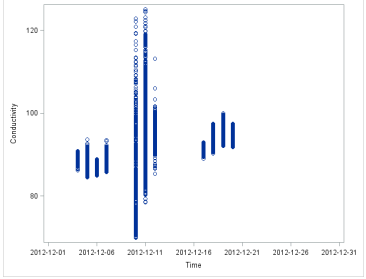
Conductivity – October 2012, Fire Station



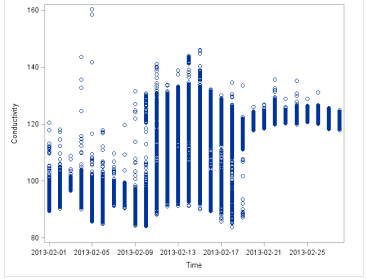
Conductivity – November 2012, Fire Station



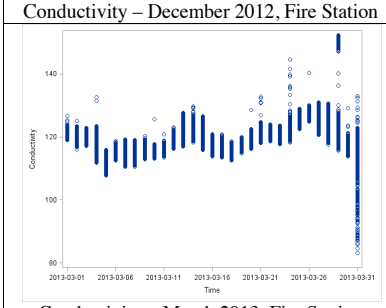
Conductivity – December 2012, Fire Station



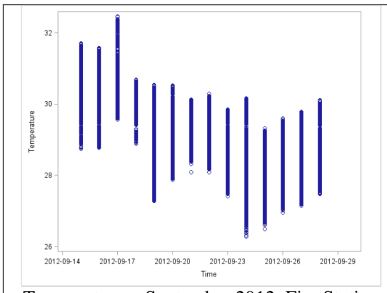
Conductivity – January 2013, Fire Station



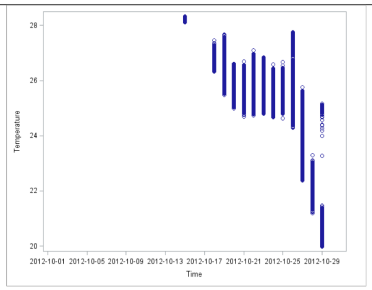
Conductivity – February 2013, Fire Station



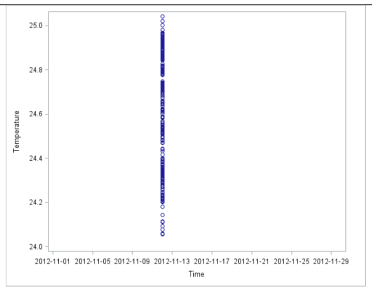
Conductivity – March 2013, Fire Station



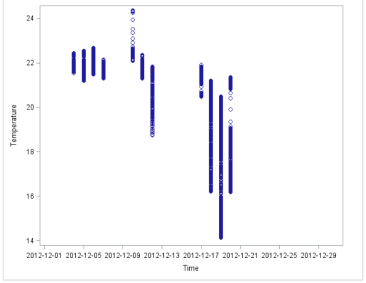
Temperature – September 2012, Fire Station



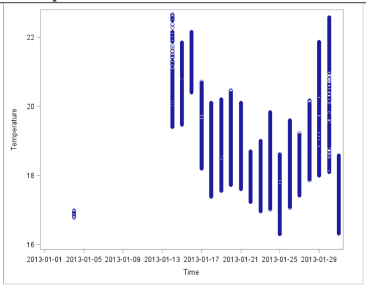
Temperature – October 2012, Fire Station



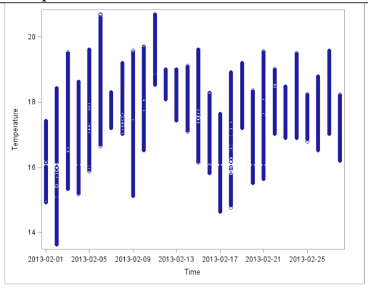
Temperature – November 2012, Fire Station



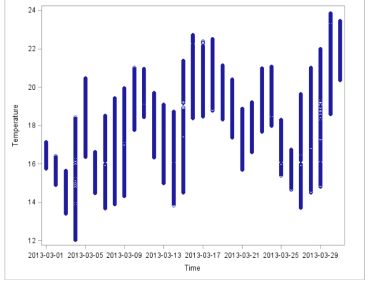
Temperature – December 2012, Fire Station



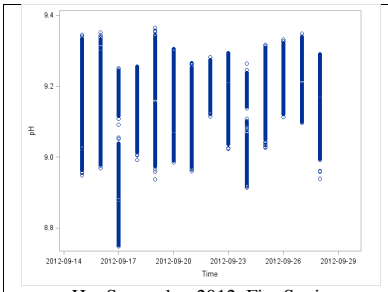
Temperature – January 2013, Fire Station



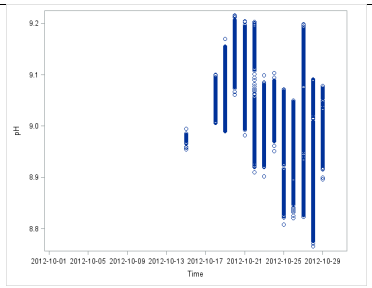
Temperature – February 2013, Fire Station



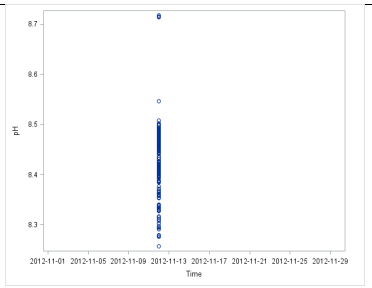
Temperature – March 2013, Fire Station



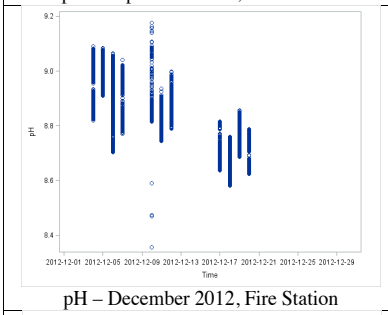
pH – September 2012, Fire Station



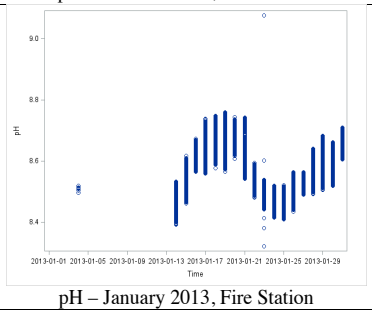
pH – October 2012, Fire Station



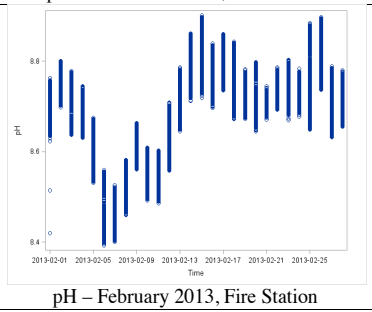
pH – November 2012, Fire Station



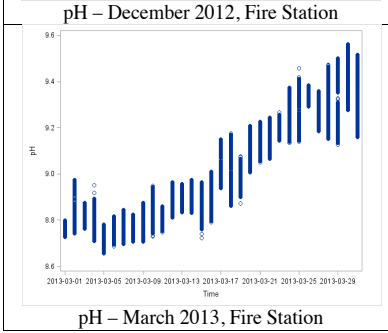
pH – December 2012, Fire Station



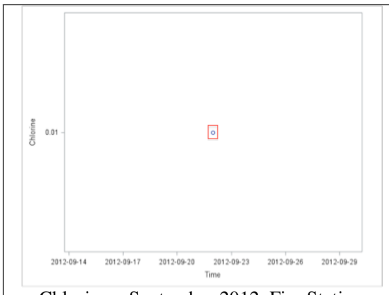
pH – January 2013, Fire Station



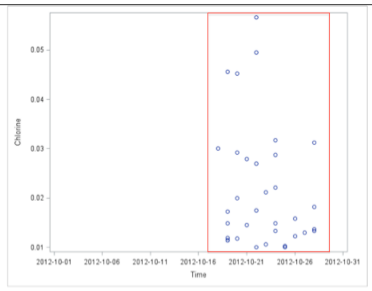
pH – February 2013, Fire Station



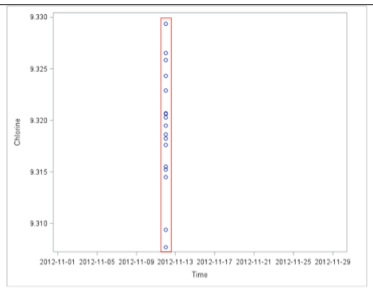
pH – March 2013, Fire Station



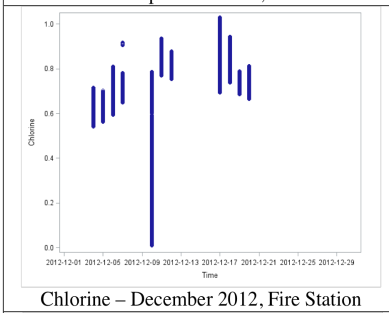
Chlorine – September 2012, Fire Station



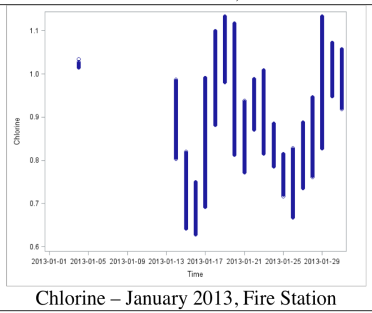
Chlorine – October 2012, Fire Station



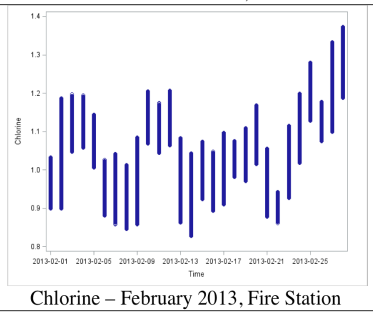
Chlorine – November 2012, Fire Station



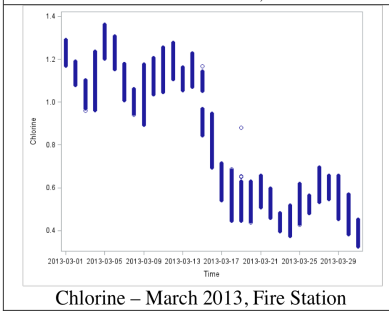
Chlorine – December 2012, Fire Station



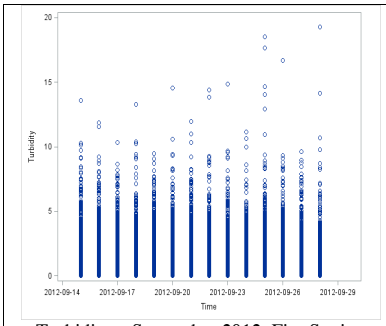
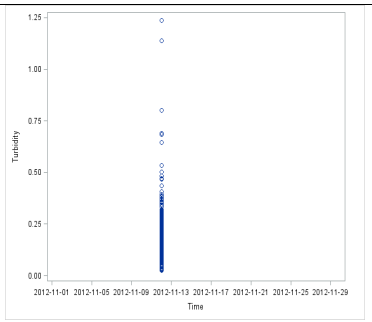
Chlorine – January 2013, Fire Station

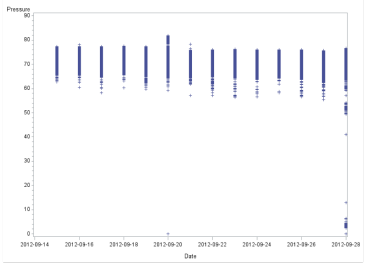


Chlorine – February 2013, Fire Station

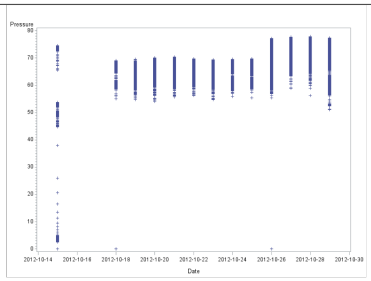


Chlorine – March 2013, Fire Station

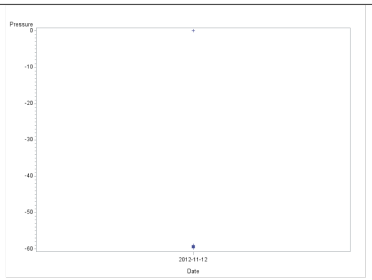
 Turbidity – September 2012, Fire Station	Turbidity probe not functioning – No turbidity data recorded in October Turbidity – October 2012	 Turbidity – November 2012, Fire Station
Turbidity probe not functioning – No turbidity data recorded in December Turbidity – December 2012	Turbidity probe not functioning – No turbidity data recorded in January Turbidity – January 2013	Turbidity probe not functioning – No turbidity data recorded in February Turbidity – February 2013
Turbidity probe not functioning – No turbidity data recorded in March Turbidity – March 2013		



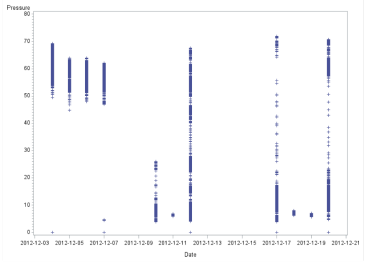
Pressure – September 2012, Fire Station



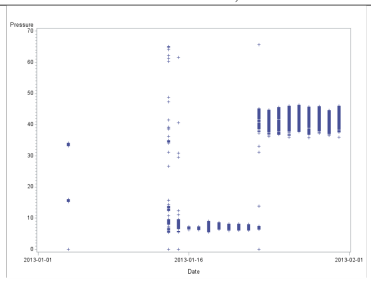
Pressure – October 2012, Fire Station



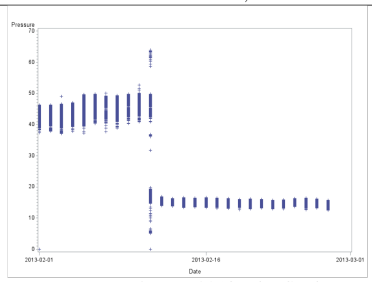
Pressure – November 2012, Fire Station



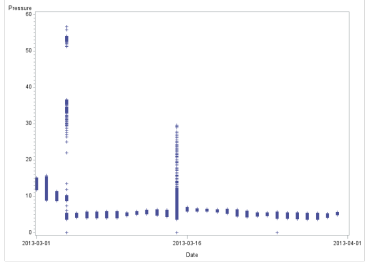
Pressure – December 2012, Fire Station



Pressure – January 2013, Fire Station



Pressure – February 2013, Fire Station



Pressure – March 2013, Fire Station

Appendix 5 – Relationships between selected pairs of parameters

We performed a limited analysis of the temporal relationship between selected pairs of water quality parameters. The temporal relationship between water quality parameters has been examined in several previous studies. O'Conner observed that low water temperatures were associated with increased raw turbidity levels, mainly due to impaired removal of microorganism during biological treatment processes in colder months (2001). In addition, as temperature rises, pH tends to decrease as the rising temperature affects the acid-based equilibrium ("pH in Drinking Water", 2003).

The relationships between water quality parameters described in Chapter 1.4, were explored visually through scatter plots with fit lines for the pairs of variables. These plots were produced using the clean datasets from the WTP. These plots included comparisons of: 1) pH and chlorine; 2) pH and pressure; 3) pH and redox; 4) chlorine and redox; and 5) chlorine and pressure. Fit lines and 95% confidence limits were also included on these graphs.

The relationship of the impact of pressure changes on pH and chlorine was explored on February 11, 2013 to investigate if a pressure change might directly impact chlorine and pH readings. February 11, 2013 was chosen because there is a large pressure change during the course of this day that appears to be due to a true pressure drop, rather changes that may be due to white noise or probe failure. These pressure changes also occur on other dates throughout this study, and the data presented on February 11, 2013 is consistent with these other dates.

Figures 44-48 display the scatter and fit lines of the parameter pairs identified previously.

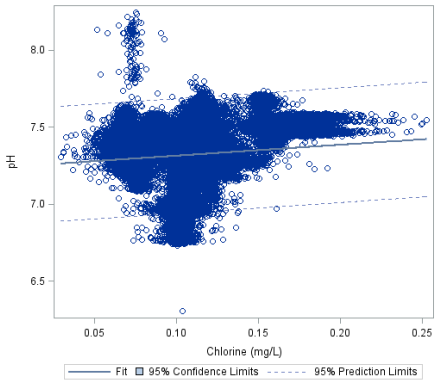


Figure 44 – Correlation between pH and chlorine monitored using remote sensors, WTP, 2012

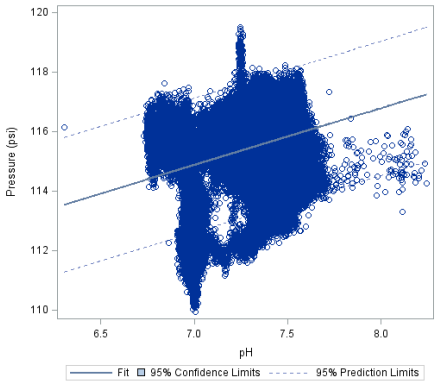


Figure 45 – Correlation between pressure and pH monitored using remote sensors, WTP, 2012

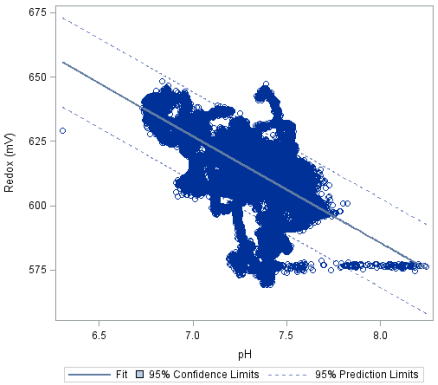


Figure 46 – Correlation between pH and redox monitored using remote sensors, WTP, 2012

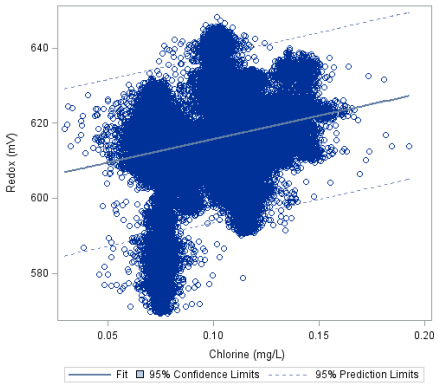


Figure 47 – Correlation between redox and chlorine monitored using remote sensors, WTP, 2012

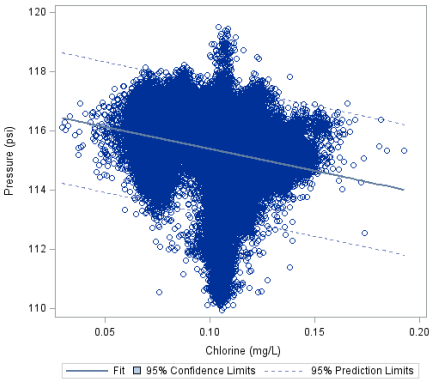


Figure 48 – Correlation between pressure and chlorine monitored using remote sensors, WTP, 2012

Figure 44 displays the relationship between pH and chlorine, and shows a small positive correlation. Interestingly, at the extreme high and low pH readings (greater than 7.6 and less than 6.8), the range of chlorine concentration became much more compact,

with a range of approximately 0.5 mg/L, as opposed to a range of about 1.5 mg/L for the middle range of pH levels between 7.0-7.5.

Figures 45 and 47 display weak positive correlations between pressure and pH, and redox and chlorine, respectively. Figure 48 displays a slight negative correlation between pressure and chlorine. However, a lot of variability exists in these fit lines, and because all three plots exhibit small correlations, it is difficult to infer a strong relationship between these variables. Redox and pH appear to have a strong negative correlation, and Figure 40 displays this decrease in redox as pH increases.

The relationship between redox and pH appears to be the strongest correlation between the pairs investigated in this study, and supports this same relationship previously described in James, Copeland, & Lytle (2004) (Figure 46).

Figures 49-51 display scatter plots of pressure, chlorine, and pH data over time for February 11, 2013 to examine the effect of short-term pressure change chlorine and pH. At approximately 11:30 AM, the pressure changed from fluctuations of approximately 50 psi to below 20 psi (Figure 49). Figure 50 shows that the chlorine readings at this time suddenly increased from a normal variation of 0.2 mg/L to 0.3 mg/L for a short time, before returning again to a 0.2 mg/L variation. Figure 51 displays the pH data collected during this occurrence, and no obvious difference in variation exists through visual inspection.

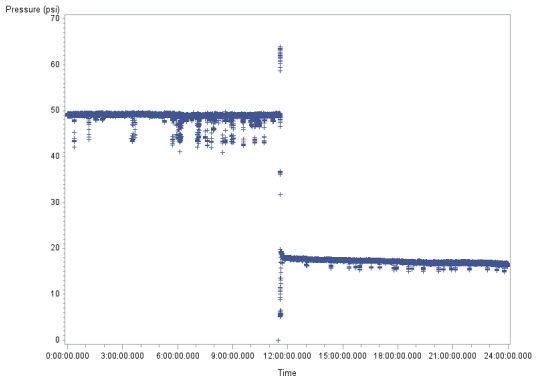


Figure 49 – Daily pressure variation on February 11, 2013 at the Fire Station distribution system location, with pressure drop occurring at 11:30 AM

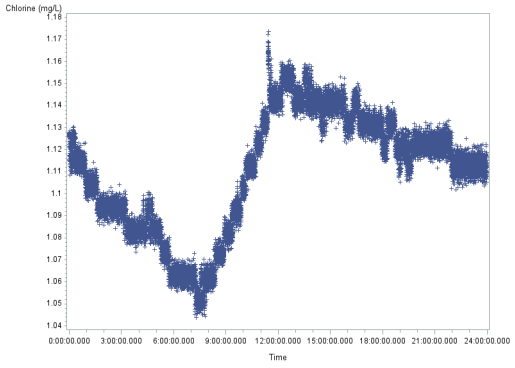


Figure 50 – Daily chlorine variation on February 11, 2013 at the Fire Station distribution system location, while pressure drop occurred concurrently at 11:30 AM

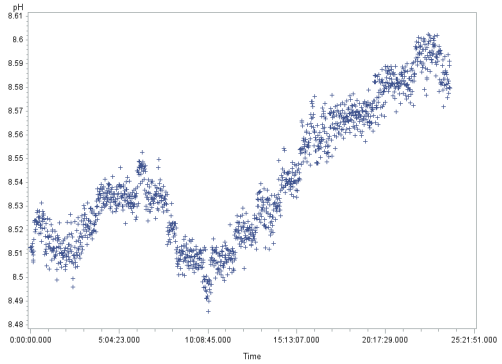


Figure 51 – Daily pH variation on February 11, 2013 at the Fire Station distribution system location, while pressure drop occurred concurrently at 11:30 AM

The effect of short-term pressure changes on pH and chlorine was examined visually in Figures 49-51. During a sudden 20 psi pressure drop, the chlorine

measurements also spiked briefly, then continued to fluctuate with an overall decreasing trend.

These relationships between parameters are important to characterize because, if there were consistent correlations between pairs of parameters, they could become predictors for one another. In the event of a probe malfunction for one parameter in a pair (which happened frequently for the remote sensors in this study), the second parameter may be used to model and predict the levels of the first parameter. Ultimately, the characterization of these relationships could serve as a back up when remote sensor probes might malfunction.

Appendix 6 – References

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