PIPE MATERIAL'S INFLUENCE ON CHLORINE RESIDUALS IN A MUNICIPAL DRINKING WATER DISTRIBUTION SYSTEM

By

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DRINKING WATER DISTRIBUTION SYSTEM

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Title of Study: Pipe Material's Influence on Chlorine Residuals in a Municipal Drinking Water Distribution System

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Abstract: Drinking water must be treated chemically in order to eliminate pathogenic microbes. Fully treated water is legally required to contain a certain concentration of disinfectant to prevent recontamination in the distribution system. This additional disinfectant is called disinfectant residual. The U.S. Environmental Protection Agency (EPA) regulation mandates that municipalities monitor residual concentrations throughout the distribution system to ensure that safe water is delivered to consumers. An Oklahoma municipality detected multiple sites throughout their distribution system with substandard residual concentrations during routine monitoring. The Oklahoma State Environmental Science Graduate program sampled 119 sites throughout the distribution system with a HACH SL 1000 portable analyzer. The HACH unit was used to measure free chlorine, total chlorine, monochloramine, free and total ammonia, total alkalinity, nitrite, and ph. Laboratory research generally supports the idea that pipe material can influence residual concentrations. Data were analyzed to determine if there were any significant differences in water quality between 4 different pipe materials that are used in the city's distribution system (asbestos-cement, cast-iron pipe, ductile-iron pipe, and PVC). Results do not indicate that pipe material influences total chlorine, monochloramine, free ammonia, total ammonia, total alkalinity, nitrite, and pH. Increased distance from the treatment facility was found to result in lower residual concentrations. Increased residual concentration resulted in decreased bacterial presence as measured by heterotrophic plate counts.

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

The city of Stillwater, Oklahoma sources drinking water from Kaw Lake. Kaw Lake was constructed by the United States Army Corps of Engineers in 1976. The lake is located 8 miles east of Ponca City, Oklahoma. It covers 17,000 surface acres. Kaw Lake is fed by the Arkansas river and is used for hydroelectric power, water supply, recreation, and wildlife conservation (Alemayehu, 2016).

Raw water must be treated prior to distribution to remove pathogens and other potential sources of human illness. Stillwater's water supply was originally treated with chlorine-based purification methods. The city of Stillwater switched to using chloramine to treat its drinking water supply in order to comply with disinfection byproduct (DBP) regulations. There are human health risks associated with both the use of chorine and chloramine in municipal water supplies. DBPs produced by both disinfection methods have been found to be carcinogenic (Bartsch, 1989; Lijinsky, 1970; McDonald, 2005; Wang, 2007). Degradation of these disinfectants can allow for regrowth of pathogens which cause human illness such as *E. coli* (Allen, 2018; Craun, 2001).

Human health risks can be exacerbated by stagnation, passing through degraded infrastructure, or improper water treatment (Allen, 2018, Craun, 2001). Stillwater's drinking water infrastructure has been installed and updated over the course of several decades. A significant proportion of these components are significantly aged and are most likely substantially degraded. Seasonal nitrification issues have been observed through water quality data collection. An analysis of the city of Stillwater's water treatment methods, known water quality issues, and infrastructure can help shed light on areas that pose elevated risks to human health and warrant additional study/monitoring.

1.2 A BASIC OVERVIEW OF WATER TREATMENT METHODOLOGY

Raw water treatment methodology varies between facilities. Most utilities perform the same basic steps. The first step is generally coagulation and flocculation. Positively charged chemicals are added to the water which neutralize negatively charged sediment particles suspended in the water column. Neutralized particles then bind with the added chemicals to form larger particles referred to as floc. Sedimentation occurs in the next step. Floc particles settle to the bottom of the water column due to their increased weight (CDC, 2022).

The third step is referred to as filtration. Water above the sediment layer is clear and contains much less particulate matter once the floc settles to the bottom. This water is then passed through filters in order to remove whatever remains after the first two treatment steps. Filters vary in pore size and material in order to most effectively remove contaminants. The last step in the treatment process is disinfection. Disinfection is typically performed by adding some type of biocidal agent such as chlorine, chloramine, or ozone to kill any microbiota which remain after the other treatment measures (CDC, 2022.).

The city of Stillwater's water treatment methodology follows the same basic process described above. Ferric sulfate is added to raw water as a flocculating agent. Polymer is also added to promote increased coagulation and sedimentation. Calcium oxide (lime) is used to cause dissolved hardness particles to precipitate and settle to the bottom of the water column. Carbon dioxide additions adjust pH and halt the softening process. Ozone is then used as a biocidal disinfection agent which also improves taste and odor. Fluoride is added to promote oral health. Chloramines are then added to serve as a disinfectant residual to prevent microbial recontamination within the distribution system. Samples are collected and analyzed throughout the water treatment process and finished water samples are tested six times daily (Stillwater.org, 2022.).

1.3 RESEARCH OBJECTIVES

The city of Stillwater's distribution system is made up of 8 different pipe materials. They were installed gradually over the course of the last 70 years. These materials are: asbestos-cement (transite), cast iron, concrete, copper, ductile iron, galvanized pipe, HDPE (high-density polyethylene), and PVC. Pipes vary in diameter from less than 6 inches to 42 inches. The objective of this study was to determine if there were any significant differences in residual concentration in samples taken from sites with differing pipe materials. A secondary objective was to determine whether targeted replacement of certain distribution system materials would be a feasible remediation option for areas with substandard water quality. The only material types with adequate sample size for comparison were cast iron, ductile iron, PVC, and asbestos-cement. We hypothesized that samples taken from PVC sites would have higher average chlorine residuals than those taken from cast or ductile iron sites.

CHAPTER II

2.1 LITERATURE REVIEW

HUMAN HEALTH RISKS ASSOCIATED WITH CHLORINATED DRINKING WATER

Chlorine is currently the most widely utilized water treatment method due to its low implementation cost. Chlorine is generally added at two points in the disinfection process (pre/post treatment). It persists in detectable levels in fully treated drinking water (Deborde, 2008). The biocidal properties of chlorine have been well documented. Chlorine-based disinfection methods have been implemented extensively (Hoff, 1981). It has been found to produce disinfection by-products (DBPs). DBPs are produced whenever chlorine reacts chemically with organic matter present in raw water. The two primary DBPs associated with chlorine treatment are trihalomethanes (THMs) and haloacetic acids (HAAs) (Westerhoff, 2004).

Trihalomethanes are generally formed when organic matter present in raw water supplies is chlorinated (WHO, 2005). Trihalomethanes and other DBPs associated with chlorination have been found to be carcinogenic (McDonald, 2005; Wang, 2007). A 1998 study found a positive association between consumption of chlorinated drinking water and rectum, lung, bladder, and kidney cancer (Yang, 1998). Chlorine DBPs can be minimized by effective removal of natural organic matter. Organic matter removal methods such as enhanced coagulation and activated carbon filtration can minimize DBP production in municipal water supplies. Both filtration techniques are effective and pose no known human health-risks. They are one of the most expensive ways to reduce formation of DBPs (Sedlak 2011).

2.2 HUMAN HEALTH RISKS ASSOCIATED WITH CHLORAMINATED DRINKING WATER

Chloramine can be substituted for chlorine to minimize DBP formation. Chloramine is less expensive to implement than advanced filtration techniques. Chloramines refer to three chemicals that form when chlorine and ammonia are combined in aqueous solution: monochloramine (NH_2CL), dichloramine ($NHCL_2$), and trichloramine (NCL_3). Monochloramine is preferred for water treatment due to its biocidal properties in conjunction with minimal taste and odor compared to dichloramine and trichloramine (Kirmeyer, 2004).

The primary advantage of switching from chlorine to chloramine is that chloramine is significantly less reactive with organic matter. This hypothetically means that DBPs can be reduced with less filtration of organic matter required. Chloramine is less reactive with organic matter overall than chlorine, but still produces its own potentially hazardous DBPs. Safety hazards associated with the storage of chlorine gas can also be minimized by switching to chloramine (Sedlak, 2011).

One of the most hazardous Chloramine DBPs is nitrosamines. Nitrosamines form when chloramines react with nitrogen-containing organic compounds (Sedlak, 2011).

Laboratory testing has shown nitrosamines to be potent carcinogens (Lijinsky, 1970, Bartsch, 1989).

Chloramine is also thought to be responsible for increased levels of lead in several municipal water supplies. Lead present in pipes remains relatively stable in the presence of chlorine which forms the less soluble compound lead dioxide ($Pb0_2$). Chloramine is not as strong an oxidant as chlorine. The layer of lead dioxide ($Pb0_2$) is reduced to Pb (II) containing minerals whenever chloramine is substituted in municipal water supplies. These minerals are far more soluble. They result in increased lead levels in drinking water for systems that contain lead (Liu, 2009). Increased chloride levels under lowered pH conditions have also been found to promote lead release in drinking water (Ng, 2015).

Disinfection by-products produced by chloramination have been found to be relatively stable in both laboratory tests and samples taken from actual distribution systems. Systems treated with free chlorine were found to have increased concentrations of various DBPs compared to chloramine. Over 500 disinfection by-products have been identified for the most common disinfectants used (chlorine, ozone, chlorine dioxide, chloramines) (Deborde, 2008). Human health effects of many of these are unknown. Only a small proportion of these DBPs have been quantified in drinking water. This effectively means that there is a great deal of uncertainty over which DBPs consumers are exposed to, as well as levels of exposure (Weinburg, 2002). The EPA currently only has mandatory DBP regulations in place for trihalomethanes and five acetic acids (Safe Drinking Water Act, 2019).

2.3 HUMAN HEALTH RISKS ASSOCIATED WITH AGING INFRASTRUCTURE

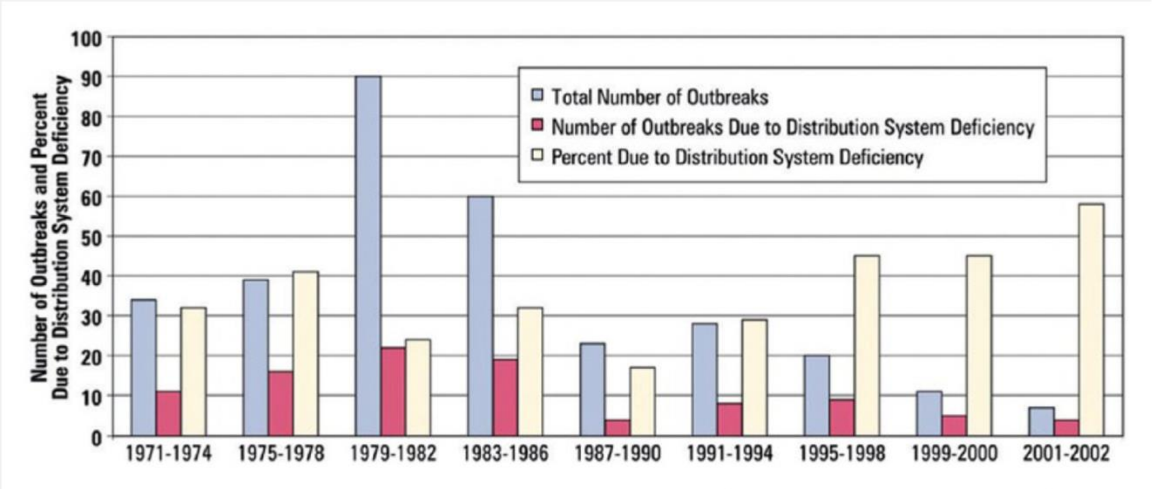
Age of water infrastructure piping in the U.S. ranges greatly. Some lines over 100 years of age are still in use today. National infrastructure installation data indicates a large proportion of pipe currently in use is around 60 years of age (Grigg, 2019). Aging infrastructure currently poses one of the largest threats to consumers of public water supplies. Utilities are legally required to monitor drinking water at the point of entry into the distribution system. This means that drinking water is microbiologically safe prior to entering the distribution system. Potential exists for microbial recontamination within the distribution system and in plumbing (Allen, 2018).

One hundred and thirteen waterborne disease outbreaks were attributed to distribution system deficiencies between 1971-1998. A total of 21,000 cases of illness were reported for all 113 outbreaks with an average of 186.4 illnesses per outbreak (Craun, 2001). Distribution system pipes are subject to corrosion over time. Cracks and fissures which form serve as routes by which microbes and contaminants may enter the distribution system (Allen, 2018). Recontamination can also occur from bacterial colonies which grow on pipe wall surfaces (Berry, 2006).

The total number of waterborne disease outbreaks in the United States decreased between 1971-2002 (Panguluri, 2005). This decrease is most likely attributable to improvements in water treatment methodology and monitoring requirements. The percentage of outbreaks caused by distribution system deficiency has increased steadily.

The percentage of outbreaks caused by distribution system failure is presumed to have continued to increase after 2002 as infrastructure components continue to age and fail (Allen, 2018).

Figure 1. Waterborne disease outbreaks in the United States (Panguluri, Grayman, & Clark, 2005).



2.4 ECONOMIC IMPACTS OF AGING INFRASTRUCTURE

It was estimated that water infrastructure in the United States would require around $300 billion dollars in order to meet current standards in 2008 (USEPA, 2013). Drinking water systems in the U.S. are also thought to face an annual shortfall of roughly $11 billion annually (ASCE, 2013). The American Society of Civil Engineers (ASCE) publishes a report card which assigns infrastructure a letter grade based off physical condition and necessary monetary inputs. U.S. drinking water and wastewater infrastructure have consistently received “D” ratings during the most recent evaluations.

These issues will only be exacerbated by population increase and subsequent increases in drinking water demand. Leaking pipes are also estimated to result in the loss of 7 billion gallons of treated drinking water daily in the United States (ASCE 2009, 2013). Funding for infrastructure updates is not currently sufficient to address total needs. Federal funding is particularly deficient. Roughly two-thirds of capital investment in water infrastructure since the 1980s has been from state and local governments. The federal government invested 63% of total capital spending in the water sector in 1977. Water infrastructure received only 9% of total capital spending in 2017 (ASCE, 2021).

Limited federal support exists in the form of the EPA’s Drinking Water State Revolving Fund (DWSRF). It provides low-interest loans to state and local drinking water infrastructure projects. The EPA conducts a Drinking Water Needs survey every four years which determines overall allotment for each state. States are required to provide a 20% funding match to DWSRF loans. The median size of DWSRF loans was $1 million in 2018. One-fourth of projects were co-funded by the U.S. Department of Agriculture’s (USDA) Rural Development program (ASCE 2021).

User fees are currently the largest source of funding for infrastructure updates nationally. The average monthly drinking water rate increased 31% from 2012-2018. Utilities still report widespread underfunding despite rate increases. Only 21% of U.S. utilities report being able to fully cover the cost of providing drinking water services.

Replacement of degraded water infrastructure and financing for capital improvements are the two most commonly reported causes of shortfalls. (ASCE, 2021).

2.5 DISINFECTANT RESIDUALS

Providing completely sterile drinking water at the distribution system level is not feasible for several reasons. Certain pathogens and other microbiota have varying levels of disinfectant resistance. Disinfectant resistance is influenced by microbial community diversity and interspecies resistance (Servais, 2004). Biofilms are thin films of bacteria which adhere to a surface. They tend to form within distribution systems on pipe surfaces and have been found to contain 25 times more bacterial cells per unit length than the adjacent bulk water (Servais, 2004). Multispecies biofilms are generally thought to be more resistant to disinfecting agents than single species films. Biofilms are generally thought to be the primary source of bacterial recontamination in distribution systems which are adequately treated and have no line breaches (Berry, 2006).

A key component of preventing microbial recontamination is chlorine/chloramine residuals in treated water (Neden, 1992). Adequate amounts of disinfectant are required to treat microbes that can grow on the surface of corroded pipes or enter through line breaks. The loss of residual disinfectant serves to increase the likelihood of recontamination. Several factors have been found to influence persistence of monochloramine in distribution systems.

Chloramine loss is affected by at least five different groups of chemical reactions: autodecomposition (decay), reactions with organic matter, oxidation reactions, nitrification and other environmental reactions. The rate of these reactions are influenced by a wide range of environmental factors such as: chloramine dose, temperature, pH, atmospheric exposure, nitrification, organics, bromide, nitrite and iron levels (Kirmeyer, 2004). Pipe wall material, extent of corrosion, pipe diameter and water velocity also influence chloramine persistence (Clark, 2011, Clark, 2012).

Water age has also been found to significantly influence chloramine residuals (Wang, 2014). Water that has had longer to stagnate within the distribution system generally contains lower residual levels than newer water. The amount of time water remains in the distribution system prior to reaching the consumer is referred to as residence time. Consumer water use and distance from the water treatment plant influence residence time within distribution systems (Wang, 2014).

Residence times vary greatly. Any time greater than 2 days is considered long. Residence times of 30 days and greater have been observed in municipal systems with low water demand (Zlatanović, 2017). Longer residence times have been found to promote microbial growth in distribution systems (Bartram, 2003). Increased microbial growth in stagnated water can be influenced by a variety of factors such as disinfectant type, pipe wall material, temperature, and bacterial community. It is not well understood due to the complexity of these interactions.

2.6 NITRIFICATION OF DRINKING WATER

Nitrification is the process by which ammonia is oxidized by bacteria to form nitrates and nitrites (Wolfe, 1988). Nitrification has been found to break down chlorine and ammonia residuals. This leads to increased nitrite and bacterial concentrations within the distribution system (Lieu, 1993). Elevated levels of nitrates/nitrites are undesirable in municipal water supplies due to their potential to cause water quality deterioration, corrosion, and difficulties maintaining disinfectant residuals (Zhang, 2009). Nitrification is a common issue in chloraminated water supplies due to the ammonia molecules which make up monochloramine. Ammonia is released whenever chloramine decomposes. Chloramine decomposition is affected by a variety of environmental factors such as chloramine dose, temperature, pH, atmospheric exposure, nitrifying bacteria, organics, bromide, nitrite and iron levels (Kirmeyer, 2004).

Ammonia-oxidizing bacteria (AOB) are generally the primary cause of nitrification. These bacteria derive exogenous energy from ammonia or nitrite (Zhang, 2009). AOB require certain environmental and chemical conditions in order to grow (Wolfe, 2003). Variation in these environmental conditions leads to nitrification frequently occurring as a seasonal issue in both drinking water and wastewater distribution systems (Ferrara, 1985). Some evidence suggests that AOB are more resistant to disinfectants such as chlorine and chloramine which allows them to persist in distribution systems even in the presence of residual disinfectants. Ammonia-oxidizing bacteria are not well understood by scientists. Individual species responsible for nitrification episodes are often difficult to identify (Wolfe, 1988).

Laboratory testing has generally found that common AOB should be rendered inactive at typical chloramine exposure times/dosage but nitrification is still frequently observed within these systems (Regan, 2002). A survey of municipalities that use chloramine found that 63% of utilities have found evidence of nitrification (Suffet, 1996). Additional study of complex ammonia-oxidizing bacterial reactions and additional characterization of unknown AOB species is still necessary to account for the discrepancy between laboratory testing and field observations (Regan, 2002).

2.7 PIPE WALL MATERIAL

Pipe wall material can influence disinfectant residual decay, rate of nitrification reactions and bacterial regrowth in distribution systems. Several studies have shown that the most important factors influencing biofilm formation in distribution systems is organic carbon availability and pipe wall material (Clement, 2004). Community structure of the bacterial species present in biofilms can also be influenced by pipe material (Wang, 2014).

Substantial amounts of research have been performed on biofilm accumulation on iron surfaces. Less is known about PVC, cement and epoxy. Findings generally support that idea that biofilm accumulation is greatest on ferrous materials and least on plastics such as PVC. Taste and odor issues and coliform violations are commonly observed in distribution systems that contain large amounts of unlined iron pipes. This is presumably due to elevated levels of regrowth. (Clement, 2004). It is not known whether differences in biofilm accumulation between pipe wall materials are due to differing chemical reactions at wall surfaces, or as a result of differing porosity and textures between these materials.

The high likelihood of bacterial reinfection in the distribution system creates the need for detecting and measuring bacteria within the distribution system. Heterotrophic plate counts (HPC) are used to detect and quantify bacteria present in drinking water. Plate counts are performed by placing small amounts of a water sample under conditions that are favorable for bacterial growth in a laboratory setting. The number of colonies which form in the bacterial culture are counted and serve as an index for overall amount of bacteria present. There is not currently a known direct correlation between HPCs and human safety, but they have been used historically as a human safety indicator in drinking water supplies (Bartram, 2003).

2.8 RELEVANT DRINKING WATER LAWS AND REGULATIONS

All public drinking water systems in the United States are subject to the Safe Drinking Water Act (SDWA). The SDWA was passed in 1974. It has been amended several times to address additional water quality concerns. The SDWA authorizes the EPA to set water quality standards designed to protect public health. The National Primary Drinking Water Regulations specifically set enforceable maximum contaminant levels for public water supplies. Water quality standards include requirements for testing and monitoring of contaminants. It also provides for the distribution of annual consumer confidence reports that inform the public about contaminants detected in their water (Safe Drinking Water Act, 1974).

Disinfection by-products standards are specifically addressed by the Stage 1 and Stage 2 Disinfectant and Disinfection By-products Rules. Stage 1 specifically states monitoring requirements for disinfection by-product precursors as well as state and consumer reporting requirements. Stage 2 sets maximum allowable concentrations of the following DBPs: Chloroform, Bromodichloromethane, Dibromochloromethane, Bromoform, and Monochloroacetic, Dichloroacetic, Trichloroacetic, Bromoacetic and Dibromoacetic acids which are collectively referred to as trihalomethanes (EPA, 2020).

The EPA Lead and Copper Rule was introduced in 1991 to protect public health by reducing lead and copper levels in drinking water. The rule requires utilities to monitor lead and copper levels at taps. Lead concentrations are not to exceed 15 ppb. Copper concentrations may not be more than 1.3 ppm in more than 10% of customer taps sampled. Utilities are required to perform additional corrosion control activities to lower lead or copper levels if allowable levels are exceeded. Requirements are also given for informing the public if elevated lead/copper levels are detected, and measures that should be taken to protect their health (EPA, 2020).

The Oklahoma Department of Environmental Quality (ODEQ) is the state authority tasked with ensuring municipalities abide by the Safe Drinking Water Act. The Water Quality Division of ODEQ deals directly with water quality standards in Public Water Systems (PWS). The PWS program has five areas of focus: compliance monitoring, technical assistance and enforcement, drinking water state revolving fund, capacity development and sanitary surveys. These elements are designed to ensure water quality standards are met and safe drinking water is delivered to consumers throughout the state.

ODEQ divides the state into multiple districts. A compliance coordinator is assigned to each district to ensure that the counties in their jurisdiction are found to be in compliance. ODEQ requires public water systems utilizing chloramines for secondary disinfection to maintain a minimum total chlorine residual of 2 mg/L as Cl_2 at the point of entry (POE) and 1 mg/L as Cl_2 at the most distant points in the distribution system. This is found under Title 252, Chapter 631 Public Water Supply Operation, Section 3-3 Disinfection Requirements.

The Total Coliform Rule (TCR) requires utilities to perform monthly distribution system sampling for total coliforms. Compliance is determined by the presence or absence of coliforms in the monthly samples. The rule states that no more than 5 percent of all routine and repeat samples in a month may test positive. Positive samples must be analyzed for the presence of fecal coliform (*E. coli*). Detection of fecal coliform in a sample results in an acute violation. An acute violation necessitates rapid notification of state and the public as it constitutes a direct health risk. Acute violations often result in the issuance of a “boil water” notice to consumers. Utilities are also required to perform at least 5 routine samples during the next month of operation following any positive sample for total coliforms (EPA, 2013).

2.9 DRINKING WATER MONITORING AND SAMPLING

Regulations and monitoring requirements in place from the EPA and ODEQ effectively ensure that drinking water is bacterially safe when it leaves the treatment facility. Samples taken at the point of entry (POE) to the distribution system serve to determine finished water quality prior to entering the distribution system. POE monitoring is performed for the following parameters: water temperature, pH, total alkalinity, free ammonia, total chlorine residual, total trihalomethanes, haloacetic acids, chlorine and bromate.

ODEQ requires monthly distribution system monitoring for both chlorine residuals and total coliforms. The number of sampling sites is determined by the size of the population served. Stillwater is required to monitor 50 sites per month for both chlorine residual and total coliforms. Sites are required to rotate every other month to ensure a better representation of the entire distribution system. Ongoing nitrification issues have also prompted the city undergo voluntary monitoring for parameters that serve as indicators of nitrification. These parameters are: monochloramine, free and total ammonia, nitrite, pH, total alkalinity, and temperature. This sampling is performed at five locations located in different parts of the distribution system. Nitrification monitoring allows city staff to quantify the extent to which nitrification may negatively influence chlorine residuals. This is necessary in order to remain in compliance with ODEQ regulation.

2.10 DRINKING WATER DISTRIBUTION SYSTEM AND WATER QUALITY DATA

Previous data was collected by City of Stillwater and analyzed by Black and Veatch. There are 107 sites listed in the city's total coliform rule (TCR) sampling plan. These locations are sampled for both total coliforms and chlorine residual monthly to remain in compliance with ODEQ monitoring requirements. ODEQ regulation also mandates that these sampling sites must be rotated every other month. The city was able to remain in compliance with the TCR rule for 2020 and 2021 with less than 5% of samples testing positive for total coliforms (Black&Veatch, 2022).

Between January 2018 and January 2022, 31 monitoring sites had an average chlorine residual below the ODEQ requirement of 1 mg/L. Figure 2 displays differences in systemwide chlorine residuals between the POE and the distribution system. It also illustrates seasonal influence on residual decay rates. Figure 3 shows the locations that were not in compliance, as well as how many years each site was below mandatory Cl_2 levels. Chlorine residual decay is seasonally influenced. The highest rates of decay were observed between July and November. A systemwide recovery period was observed in the winter months with peak residuals occurring in February and March. The eastern and southwestern portions of the distribution system were found to have the highest rates of chlorine residual decay (Black&Veatch, 2022).

Figure 2. City of Stillwater's systemwide monthly average drinking water chlorine residuals (Black and Veatch, 2022).

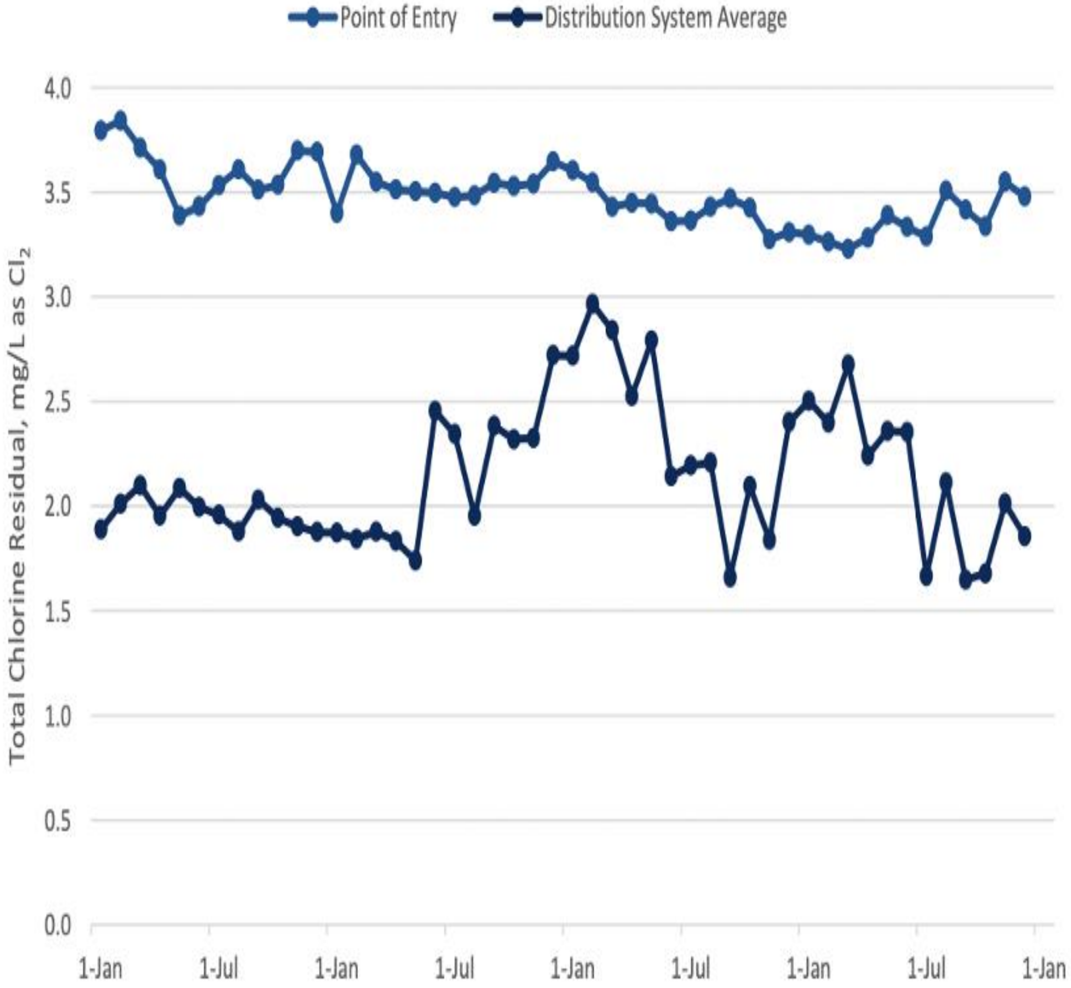
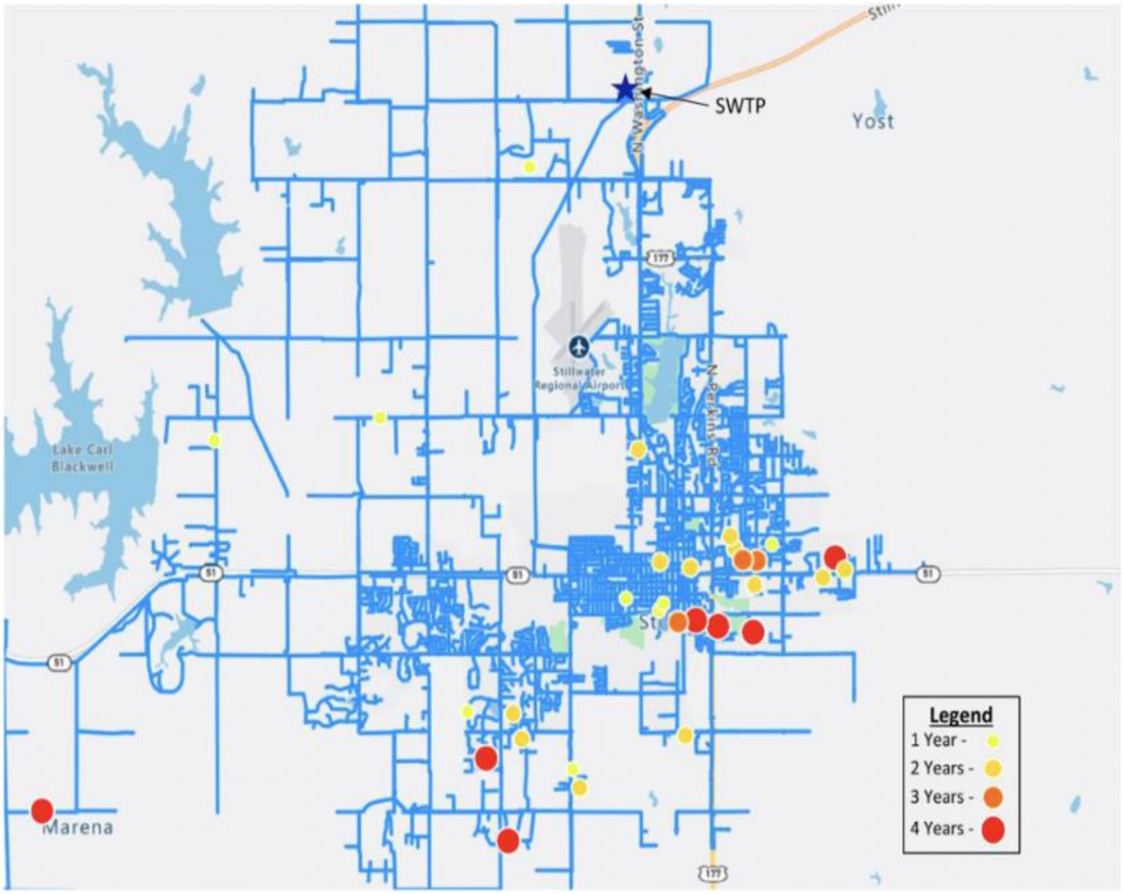


Figure 3. Monitoring Sites With <1.0 mg/L total chlorine residual (annual average) (Black and Veatch, 2022).



CHAPTER III

METHODOLOGY

3.1 DATA COLLECTION METHODS

All field data gathered for this study were collected using the same sampling protocol employed by City of Stillwater personnel. Water quality is monitored within the distribution system primarily through the use of HACH SL1000 portable analyzers. Samples are generally sourced from outdoor taps or fire hydrants. Lines are flushed for a minimum of five minutes to ensure that samples are taken from within the distribution system rather than plumbing or from inside the hydrant.

Water quality parameters are then evaluated with the use of single-use reagent “chemkeys” which are loaded into the HACH SL1000. The following field parameters were tested for this analysis: free chlorine, total chlorine, monochloramine, free and total ammonia, total alkalinity, and nitrite. Samples for pH were measured using chemkeys or with a standalone unit (HACH HQ411D). City of Stillwater field staff measures pH with a separate probe which attaches to SL1000 analyzers.

Heterotrophic plate count (HPC) and nitrate samples were also collected. They were not processed in the field. All HPC and nitrate samples were analyzed off site by Accurate Environmental Laboratory in Stillwater. Data were collected between 5/23/22-6/30/22. A total of 119 sites were sampled. Each site was sampled once for free chlorine, total chlorine, monochloramine, pH, nitrite, total alkalinity, free ammonia, and total ammonia. Nitrate and HPC samples were only collected for 74 sites.

Distance is another important factor in determining potential reasons for poor water quality. Distance from the treatment facility was measured using ArcGIS. All distances were measured linearly from the plant to the sampling location. They did not account for the additional distance gained from passing through the pipe network.

3.2 STATISTICAL ANALYSIS

Our specific objective was to determine if water quality parameters tested in the field (free chlorine, total chlorine, monochloramine, free ammonia, total ammonia, total alkalinity, nitrite, and pH) differed between pipe types (cast iron, ductile iron, PVC, and asbestos-cement). Sites with recorded values below detection limit were converted to zero for each variable (ex. all total chlorine recorded as “under range” were converted to 0).

Each variable was checked for normality using Kolmogorov-Smirnov tests. A Kruskal-Wallis test was used to determine differences in variables between the four pipe types. HPC analysis was only performed on three pipe types due to inadequate sample size for ductile iron pipe (n=3). Regression analysis was used to determine the relationship between water quality parameters and modeled water age and distance of the sample site from the water treatment facility. All statistical analyses were run in Minitab v.21.1. Dunn’s post hoc comparison test was performed on nitrite data.

CHAPTER IV
FINDINGS

4.1 RESULTS

Average total chlorine concentration for all sites was 1.1 mg/L and 63/119 sites were less than the 1 mg/L mandated by ODEQ regulation. Mean distance from the treatment facility was 9891.77 m. All variables with the exception of total alkalinity were not normally distributed.

Table 1 shows mean sample values plus standard deviation and P and H values for each water quality parameter and material type. Material types are abbreviated as follows: cast iron pipe (CIP), ductile iron pipe (DIP), asbestos-cement (ACP) and PVC. None of the water quality parameters tested differed based on pipe material except nitrite (Table 1). The Dunn's post-hoc comparison test for nitrite showed that none of the pipe types differed between each other at P=0.05.

Table 1. Mean sample values by pipe type, P values determined using Kruskal-Wallis test.

Variable	ACP	CIP	DIP	PVC	P Value (H Value)
Total Cl	1.222 ± 1.111	0.924 ± 1.193	1.354 ± 1.285	1.026 ± 1.195	0.576 (1.98)
Monochloramine	1.134 ± 1.080	0.894 ± 1.155	1.296 ± 1.284	0.949 ± 1.159	0.455 (2.61)
Free Ammonia	0.249 ± 0.178	0.158 ± 0.140	0.246 ± 0.154	0.239 ± 0.158	0.337 (3.38)
Total Ammonia	0.475 ± 0.343	0.386 ± 0.431	0.499 ± 0.362	0.427 ± 0.346	0.592 (1.91)
Total Alkalinity	44.72 ± 10.70	48.21 ± 8.62	44.22 ± 6.83	43.71 ± 11.43	0.547 (2.13)
pH	7.746 ± 0.307	7.787 ± 0.196	7.897 ± 0.209	7.803 ± 0.253	0.528 (2.22)
Nitrite	0.138 ± 0.222	0.058 ± 0.068	0.036 ± 0.038	0.083 ± 0.076	0.030 (8.79)

Total chlorine (Figure 4), total ammonia (Figure 5), and monochloramine (Figure 6) were found to be significantly related to distance from the water treatment facility. None of the other parameters tested were related to distance. Total chlorine and monochloramine tended to decrease in concentration with increased distance. All samples taken within 5,000 meters or less of the treatment facility were above the mandated 1.0 mg/L. Average distance from the treatment facility for all 119 sample sites was 9891.77 meters (6.15 miles). Total ammonia was also found to decrease in total concentration with increased distance. Heterotrophic plate counts were generally found to decrease with higher concentrations of chlorine residual (Figure 7). The majority of HPC counts greater than 100 CFU/ml occurred at chlorine concentrations below 0.5 mg/L.

Figure 4. Chlorine residual concentration and distance (meters) from treatment facility.

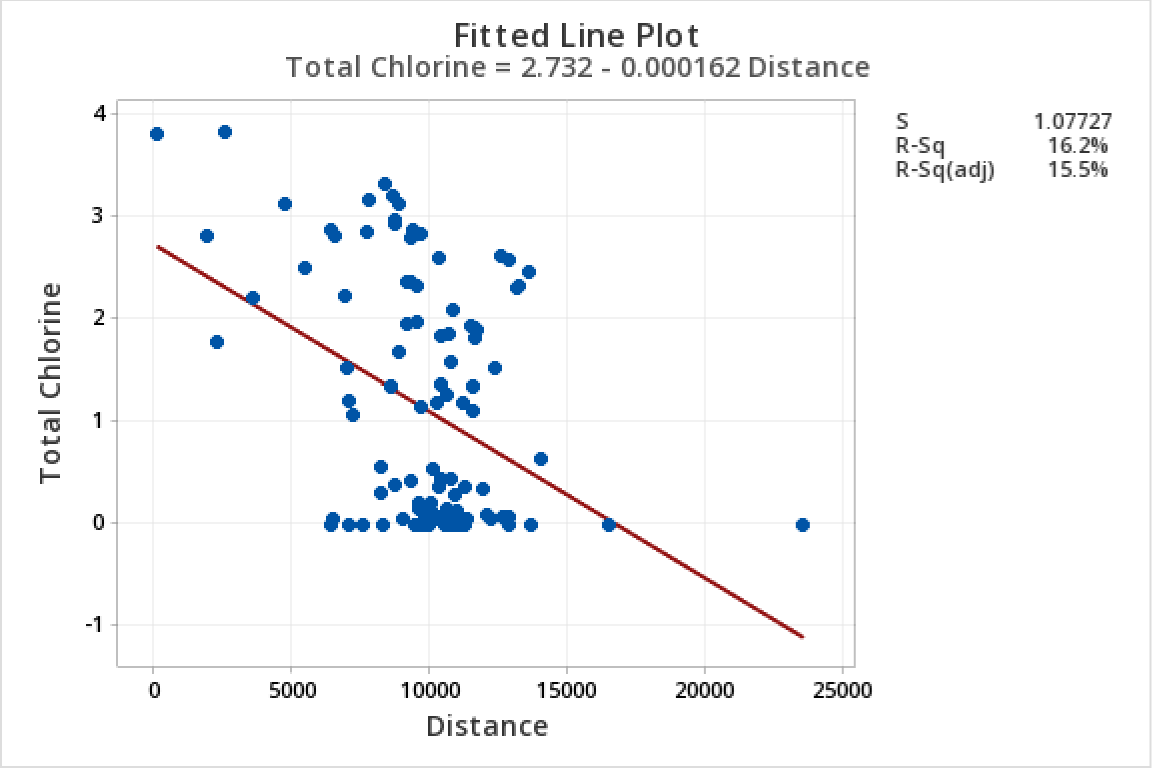


Figure 5. Monochloramine residual concentration and distance (meters) from treatment facility.

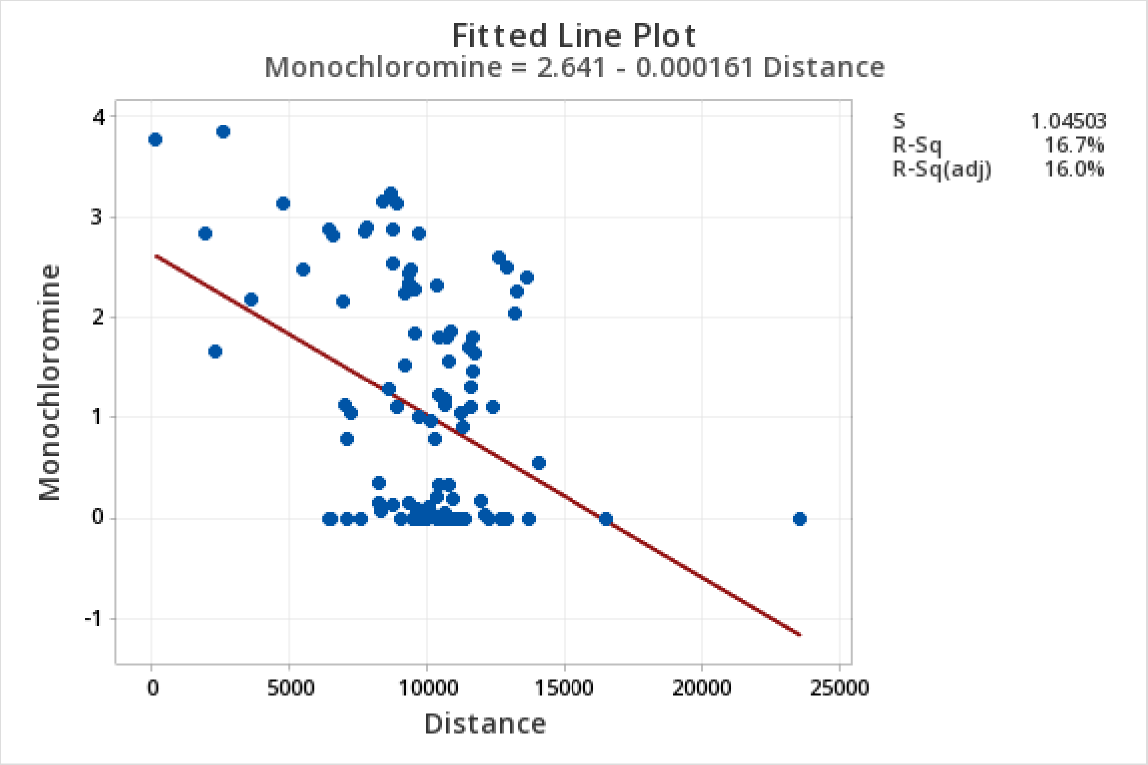

Fitted Line Plot
Monochloromine = 2.641 - 0.000161 Distance
S 1.04503
R-Sq 16.7%
R-Sq(adj) 16.0%
Monochloromine
4
3
2
1
0
-1
0
5000
10000
15000
20000
25000
Distance

Figure 6. Total ammonia concentration and distance (meters) from treatment facility.

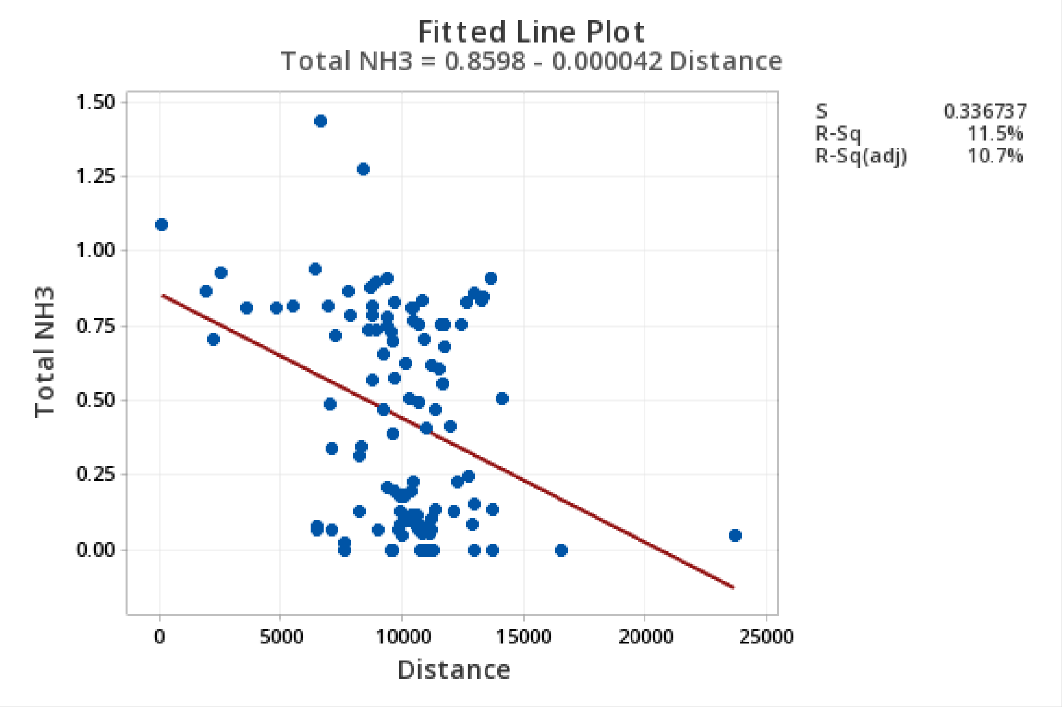
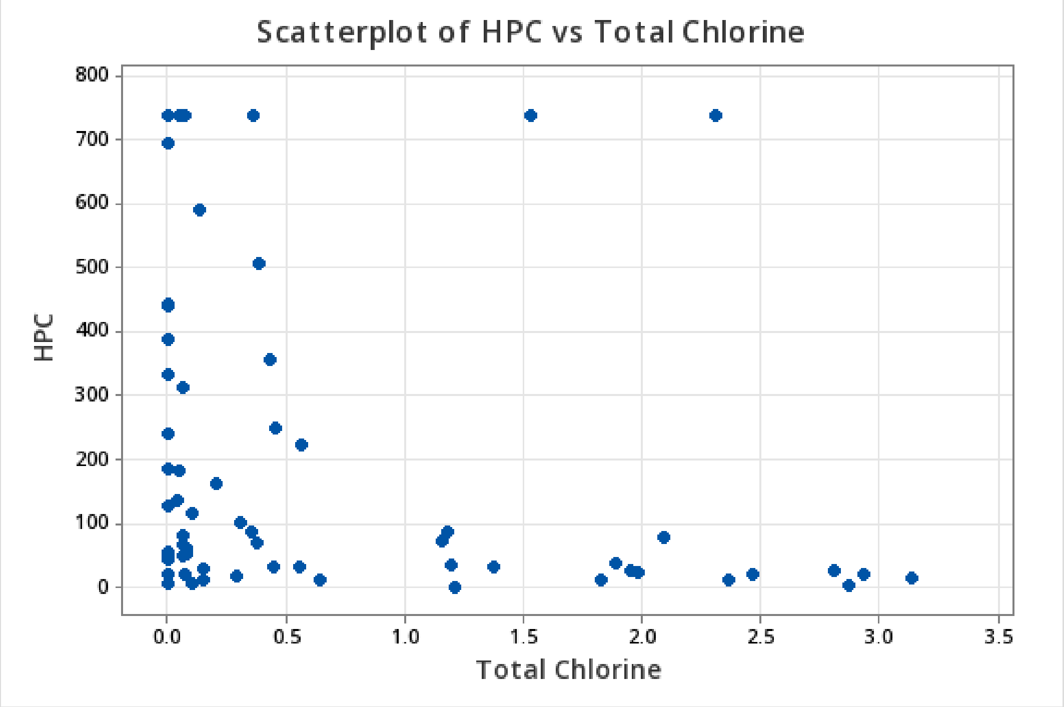


Figure 7. HPC counts and total chlorine concentration.



4.2 DISCUSSION

Multiple laboratory studies support the idea that pipe wall material influences biofilm accumulation and residual levels (Clement, 2004; Wang 2014). We hypothesized that pipe material would have significant influence on residual concentration and could potentially affect the other water quality parameters sampled. Cast iron and ductile iron pipes specifically were predicted to have lower concentrations of total chlorine and monochloramine than PVC. Our analysis does not support this hypothesis as no significant differences were detected between material types for any of the water quality parameters sampled.

These results rule out only replacing certain material types to remediate substandard residual levels. It is far more likely that distance, water age, and nitrification are the more influential factors on chlorine/monochloramine residuals. Significant potential for line breaches exists throughout the distribution system due to the age and material type of some of the components. These breaches can influence residual levels and serve as the primary sources of microbial recontamination. Not all material types are equally susceptible to line breaches. Cast iron pipes are generally thought to be less prone to cracks and leaks than other materials (Ecrumen, 2014). The greatest risk to consumers of waterborne illness occurs when line breaches occur in conjunction with substandard residual levels and increased water age (Egorov, 2002).

All samples for this dataset were taken in May and June. City of Stillwater personnel reported that this timeframe is generally when nitrification issues begin to occur throughout the distribution system (Black and Veatch, 2022). These claims are substantiated by studies which show nitrification to primarily be a warm season occurrence (Ferrara, 1985; Wolfe, 2003). Nitrification could also account for a significant proportion of low residual observations (Kirmeyer, 2004).

Total chlorine and monochloramine decay with increased distance is a well-documented phenomenon and is expected in a drinking water distribution system (Wang, 2014). Total ammonia concentrations would also be expected to decrease with increased distance from the treatment facility. Monochloramine (NH_2CL) is made up of chlorine and ammonia molecules. Chloramine decay causes the release of both chlorine and ammonia into the distribution system. Reduced chloramine levels means that less total ammonia from chloramine decay can be released into drinking water (Kirmeyer, 2004, Clark, 2012).

Increased distance from the treatment facility was shown to be related to water quality parameters but with relatively low R^2 values (16.2). The relationships did not follow strong linear trends. High levels of variation were observed between 5000 and 15,000 m from the facility. No substandard total chlorine levels (< 1 mg/L) were observed within 5,000 m of the treatment facility. The observed variation at distances greater than 5,000 m indicates that distance is not the only factor which influences chlorine residuals.

HPC counts were observed to increase sharply at total chlorine residual concentrations less than 0.5 mg/L. All but two HPC counts taken from sites with 1 mg/l or greater total chlorine were less than 100 CFU/ml. Decreased HPC counts in the presence of elevated chlorine residuals demonstrates the efficacy of chlorine as a disinfectant (Hoff, 1981). A general trend of lower HPC counts above the 0.5 mg/L threshold and increased counts at less than 0.5 mg/L also shows the importance total CL_2 concentration has on bacterial survival rates.

4.3 REMEDIATION OPTIONS

It is not feasible to determine which specific factor, or combination of factors are responsible for substandard residual levels on a site-by site basis for the entire distribution system. Potential causes for low residual observations could be nitrification, line breaches, long residence times, distance from treatment facility, biofilm accumulation or some combination thereof. Historic monitoring data indicates that nitrification is an influential factor on chloramine residuals during the warmer months in Stillwater's distribution system. Two common methods for dealing with nitrification issues within the distribution system are rechlorination/rechloramination and line flushing.

Rechlorination is the addition of chlorine post treatment somewhere within the distribution system. Rechloramination is the addition of chlorine and ammonia. One strategy to combat nitrification is the introduction of additional disinfectant retroactively once nitrite levels reach a predetermined threshold. This strategy is called breakpoint chloramination (or chlorination depending on the disinfectant used) (Karthic, 2022).

Line flushing is frequently utilized by utilities to cycle water through the distribution system to improve water quality. Stillwater currently utilizes flushing when substandard residual levels are detected through routine monitoring. Routine line flushing in areas which consistently have water quality issues is a tool that utilities can use to proactively prevent issues caused by long residence times. Line flushing does result in additional water usage that some consumers can perceive as wasteful (Cohen, 2000). Successful remediation would be contingent on the extent and frequency of line flushing practices, and would necessitate significant data collection to determine efficacy.

The addition of another treatment facility to provide fresh water to the more distant points in the distribution system could also improve residual concentrations. This could very likely remediate many of the issues associated with long residence times. Increased residual levels could also help reduce nitrification, but would likely not eliminate its occurrence entirely. The addition of another treatment facility would come at significant cost which would vary in accordance with the sophistication of the facility installed. The addition of a new facility would take years to plan, budget, and install meaning that substandard residuals would likely remain until then.

4.4 TARGETED DISTRIBUTION SYSTEM REPLACEMENT MATERIALS AND COSTS

Laboratory testing has shown that pipe material can influence residual concentration and biofilm accumulation (Clement, 2004, Wang, 2014). This hypothetically means that by specifically targeting material types which accumulate more biofilm for replacement, residual levels could be raised if pipe material was an influential factor. Pipe replacement and maintenance is a necessary part of infrastructure maintenance but generally comes at substantial cost. Budgets for infrastructure updates and replacement are often severely limited with shortfalls being reported nationwide (ASCE, 2021).

Cost of line replacement is highly variable and is affected by several key factors. These are: pipe material, pipe diameter, trenching costs, soil type, bedding material, backfill material, fittings valves, and hydrants, pavement removal and replacement, utility interference, and traffic control. Figure 8 below shows the estimate from Clark et al. (2002) for the installation of 7000 feet of new cast iron pipe.

Figure 8. Example of cost modeling of distribution line installation (Clark et al. 2002).

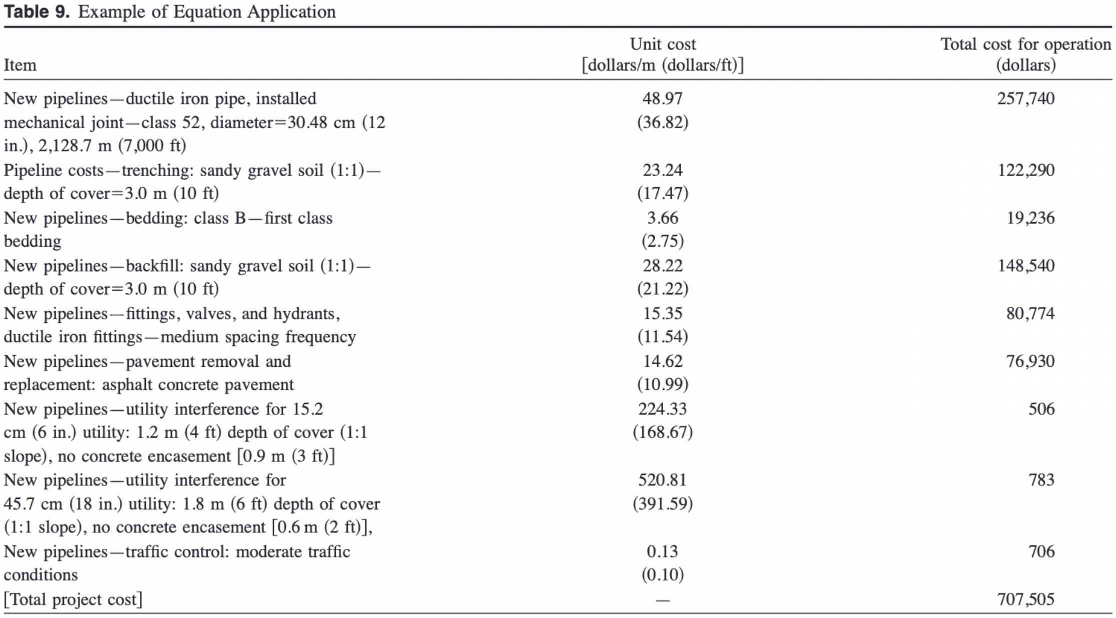


Table 9. Example of Equation Application

Item	Unit cost [dollars/m (dollars/ft)]	Total cost for operation (dollars)
New pipelines—ductile iron pipe, installed mechanical joint—class 52, diameter=30.48 cm (12 in.), 2,128.7 m (7,000 ft)	48.97 (36.82)	257,740
Pipeline costs—trenching: sandy gravel soil (1:1)—depth of cover=3.0 m (10 ft)	23.24 (17.47)	122,290
New pipelines—bedding: class B—first class bedding	3.66 (2.75)	19,236
New pipelines—backfill: sandy gravel soil (1:1)—depth of cover=3.0 m (10 ft)	28.22 (21.22)	148,540
New pipelines—fittings, valves, and hydrants, ductile iron fittings—medium spacing frequency	15.35 (11.54)	80,774
New pipelines—pavement removal and replacement: asphalt concrete pavement	14.62 (10.99)	76,930
New pipelines—utility interference for 15.2 cm (6 in.) utility: 1.2 m (4 ft) depth of cover (1:1 slope), no concrete encasement [0.9 m (3 ft)]	224.33 (168.67)	506
New pipelines—utility interference for 45.7 cm (18 in.) utility: 1.8 m (6 ft) depth of cover (1:1 slope), no concrete encasement [0.6 m (2 ft)],	520.81 (391.59)	783
New pipelines—traffic control: moderate traffic conditions	0.13 (0.10)	706
[Total project cost]	—	707,505

Utilizing the same cost estimates from Figure 8 and adjusting for inflation can be used to provide an order of magnitude estimate of cost per-foot for the replacement of ductile iron pipe in Stillwater's distribution system under the same conditions. The cumulative cost of the above installation is roughly $101 per linear foot. Cost rises to $170 per linear foot after adjusting for inflation. Inflation was calculated using the U.S. bureau of labor statistics CPI inflation calculator. The above example is for the installation of new pipe, additional expenses can be expected for line replacement as the old pipe would also necessitate removal and disposal. The lack of differences between chlorine in the different pipe types studied in this project suggest that pipe type alone is not influential enough to warrant targeted replacement of certain pipe materials in order to improve residual concentration. Replacement of specific pipe is unlikely to generate enough improvement in water quality to justify the substantial amount of capital expenditure necessary to perform it.

4.5 STUDY LIMITATIONS AND FUTURE RESEARCH

Small sample size and narrow range of sample dates hindered our ability to isolate certain variables in our analysis. Comparison of sites with the same distance and water age would allow a better picture of the influence of pipe material on residuals. There were not adequate sample sites to allow for this type of comparison in this dataset. The timing of sampling during the summer means that nitrification could have potentially accounted for many low residual observations. Comparing data collected during warmer months with that from colder months, could help better estimate the extent of nitrification. A similar analysis of data collected during February or March (when nitrification is least prevalent) may offer a more accurate representation of pipe material’s influence.

Line flushing and rechloramination both effectively serve to combat low residuals caused by both nitrification and long residence times. This means that additional study isn’t necessary to begin to treat areas in which low residuals are consistently observed. Continued monitoring would allow for efficacy of flushing or rechlorination to be determined. Eliminating low residuals caused by nitrification and stagnation could also aid in helping the utility locate line breaches in areas which consistently remain at substandard levels.

CHAPTER V
CONCLUSION

5.1 CONCLUSIONS

Pipe material influences disinfectant residuals in laboratory research. The objective of this study was to determine whether this influence could be detected in field settings, and to determine if targeting certain material types for replacement could be used to increase disinfectant residuals. Residual data was gathered throughout various points in the distribution system and was then compared by pipe material type. A statistical analysis of this data allowed for a simple analysis of the influence of pipe material without accounting for any other factors such as nitrification or water age which are difficult to quantify on a site-by site basis. Pipe material was not found to have a significant influence on disinfectant residuals or any of the other water quality parameters which were sampled.

Delivering microbially safe water to consumers is a difficult task but one which is imperative. Disinfectant residuals are crucial for protecting people who rely on municipal water supplies. The complexity of the biochemical reactions at play, and the myriad of unknown bacterial species responsible, frequently result in drinking water which is substandard in quality. Continued study of those factors which cause low residual concentration are steps forward in protecting human health. Factors like nitrification, residence time, and degraded infrastructure are known to result in low residual levels. A means of empirically identifying causality on a site-by-site basis is not readily available to utilities and highlights the need for additional study and technique development. Analysis of all the factors which potentially influence the persistence of residuals is the first step in developing new techniques which could ultimately result in safer water for everyone.

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