

Linkage Between Characteristics of Premise Plumbing Systems and
Microbial Quality of Stagnant Drinking Water

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ABSTRACT

The length of pipe between the water main and the point of use (POU), known as premise plumbing, has a direct impact on public health. However, relatively little is known about factors that affect the microbial quality in premise plumbing. Although microbial quality typically degrades during stagnation, little research is present linking factors such as building age and level of usage to the extent to which stagnation occurs.

To gain insight into the effect of premise plumbing service age on the level of microbial contamination in stagnant drinking water, water at the POU was analyzed. It was observed with statistical significance ($p < 0.05$) that as service age of a premise plumbing system increased so did microbial concentration in stagnant drinking water. Results also indicated that partially re-piping premise plumbing systems may greatly reduce the abundance of microorganisms, again demonstrating the impact of service age on microbial quality of stagnant drinking water in premise plumbing and suggesting re-piping as a potential risk-mitigating strategy.

Two rapidly measurable parameters (free chlorine and temperature) were analyzed for their suitability in use for indicating the extent of drinking water stagnation at the POU. Because of the seasonal variability of temperature in water supply, water temperature was not found to be a suitable indicator of stagnancy. Free chlorine, however, was found to be a suitable indicator of stagnancy. Free chlorine concentrations were also linked to heterotrophic plate counts. Additionally, the effect of pipe size on free chlorine concentration after overnight stagnation was analyzed. These results were used to show flushing tap water for 15s for every 100ft of 0.5in copper piping in order to reduce microbial contamination is a simple potential risk-mitigation strategy for premise plumbing users.

Further analyses focused on the chlorine decay rates in copper pipes. Chlorine was found to decay faster in newly built premise plumbing systems than old systems and fastest in unused copper pipes. The effect of increased usage was also analyzed; increasing the usage in older premise plumbing systems decreased the chlorine decay rate while the same increase in usage in newer systems increased the chlorine decay rate.

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ABBREVIATIONS AND SYMBOLS

A.....	Arrhenius Reaction Opportunity
ANOVA.....	Analysis of Variance
ANCOVA	Analysis of Covariance
C.....	Concentration (mass volume ⁻¹)
C ₀	Initial Concentration (mass volume ⁻¹)
CFU.....	Colony Forming Unit
d.....	Inner Pipe Diameter (length ⁻¹)
DWDS.....	Drinking Water Distribution System
E	Activation Energy (volume pressure mole ⁻¹)
E&PS.....	Earth and Planetary Sciences
EPA.....	Environmental Protection Agency
HPC	Heterotrophic Plate Count
HSD	Honestly Significant Difference
k	Total Decay Constant (time ⁻¹)
k _b	Bulk Water Decay Constant (time ⁻¹)
k _w	Pipe Wall Solution Decay Constant (time ⁻¹)
K _w	Pipe Wall Decay Constant (length time ⁻¹)
S/V.....	Surface Area to Volume Ratio (length ⁻¹)
POU	Point of Use
PVC.....	Poly-Vinyl Chloride
R	Gas Constant (volume pressure temperature ⁻¹ mole ⁻¹)
R ²	Coefficient of Determination

SERF.....	Science and Engineering Research Facility
t.....	Time
t_s	Stagnation Time
T	Temperature
T_w	Initial Water Temperature
WHO.....	World Health Organization
WTP.....	Water Treatment Plant

CHAPTER 1: Introduction

1.0 LITERATURE REVIEW

1.0.1 Drinking Water Distribution System

The drinking water distribution system (DWDS) includes all of the water utility components needed for the distribution of potable water by mean of pumps or gravity storage feed through distribution networks to users (AWWA 1974). Several of these components consist of the water treatment plant (WTP), the water main, and premise plumbing systems. The publically owned portion of the DWDS, was estimated to have spanned nearly 1 million miles in the United States in 2005, and is projected to expand by 13,200 miles a year (Kirmeyer et al. 1994; Grigg 2005). Premise plumbing, which is largely privately owned, has been estimated to span over 6 million miles in length (Edwards et al. 2003).

The DWDS is a vitally important part of infrastructure; the importance of which lies in its close contact with individuals, its ability to transport clean water, and potentially waterborne pathogens. In fact, problems within the DWDS have recently been labeled the cause of many outbreaks of waterborne diseases (Craun and Calderon 2001; Blackburn et al. 2004). In order to mitigate the risk of waterborne diseases, disinfectant residuals are often present in drinking water (e.g. free chlorine, chloramines, etc.). However, when these residuals decay to low levels, microbial concentration can rise wherein lies the risk of DWDS (Clark et al. 1994; Pepper et al. 2004; Ayoub and Malaeb 2006; Manuel et al. 2010). Many of the negative impacts of the DWDS can be attributed to premise plumbing (Council 2006).

1.0.2 Premise Plumbing

Premise plumbing is the section of the DWDS that consists of piping between the water main and the point of use (POU). It is in this portion of the DWDS that many issues negatively impacting public health may originate. This occurrence is due to the fact that premise plumbing water quality is not currently monitored by the U.S. Environmental Protection Agency (EPA) (Council 2006). There are a myriad of factors that characterize premise plumbing systems that make them susceptible to potential public health risks (e.g. increased retention times, small pipe diameter, fluctuating temperatures) (Haider et al. 2002; Zietz et al. 2003; Zietz et al. 2007).

1.0.2.1 Pipe Diameter

One factor of premise plumbing that makes it susceptible to public health risks is its characteristically small pipe diameter (< 0.5 in) in comparison to the main DWDS (3 in) (Edwards et al. 2003). Because of the small pipe diameters, the ratio of surface area to volume in premise plumbing systems is much higher than the rest of the distribution system. The high surface area to volume ratio results in increased biological and chemical leaching and permeation, as well as higher disinfectant residual decay rates (Rossman et al. 1994; Council 2006). The release of lead into bulk water in premise plumbing has been documented in several studies (Deshommes et al. 2010; Elfland et al. 2010; Gagnon and Doubrough 2011). Additionally, opportunistic pathogens may be released from biofilms that can grow on pipe walls (Parsek and Singh 2003; Lehtola et al. 2007).

1.0.2.2 Fluctuating Temperatures

Premise plumbing is also characterized by fluctuating temperatures which can attribute to public health risks. Beyond the seasonal variation of temperature that all of the DWDS undergoes, water in premise plumbing undergoes greater fluctuation in temperature than that of the water main (Rushing and Edwards 2004). This greater fluctuation can be attributed in part to hot, cold, and refrigerated water lines (Council 2006). These fluctuating temperatures affect the rate at which disinfectant residuals decay and thus, the rate at which stagnation occurs (Hua et al. 1999).

1.0.2.3 Residual Decay Kinetics

Both pipe diameter and temperature have effects on the kinetics of disinfectant residual decay. In order to reduce the microbial concentration in DWDS, a disinfectant residual must be present. Therefore, the rate at which residual decays is a very important parameter. The parameter that is used to represent the rate of decay is called the decay rate constant (k). The k -value has two parts in DWDSs; that which is related to the bulk water (k_b ; time^{-1}), and that which is related to the water at the wall (k_w ; time^{-1}) (Biswas et al. 1993b; Clark et al. 1994; AWWARF 1996; Beatty et al. 1996).

$$(1) \quad k = k_w + k_b$$

Residual decay is often modeled by a first-order decay reaction (Jadas-Hécart et al. 1992; Zhang et al. 1992; Rossman et al. 1994),

$$(2) \quad C = C_0 \cdot e^{-kt}$$

where C is the concentration at a given time (mass volume^{-1}), C_0 is the initial concentration (mass volume^{-1}), and t is the time. This model becomes somewhat convoluted as more factors

that affect the decay rate are added. A few of the factors are as follows: temperature, plumbing age, pipe diameter, and pipe material.

The effect of temperature on reaction rate has been well documented and can be modeled with the Arrhenius equation (Sawyer 1994; Beatty et al. 1996; Hua et al. 1999),

$$(3) \quad k = A \cdot e^{-E/RT}$$

where A is the Arrhenius reaction opportunity, E is the activation energy (volume pressure mole⁻¹), R is the gas constant (volume pressure temperature⁻¹ mole⁻¹), and T is the temperature. Using this equation decay rates can be adjusted to a common temperature in order to facilitate comparison.

Pipe diameter has an effect on decay rate that can be modeled using the surface area to volume ratio (S/V; length⁻¹). In circular pipes, S/V can be estimated with the expression 4/d, where d is pipe diameter (Rossman et al. 1994). Using this addition, the expression for the overall k becomes

$$(4) \quad k = \frac{S}{V} K_w + k_b$$

where K_w is the pipe wall reaction constant (length time⁻¹) (Rossman et al. 1994). Utilization of this expression allows for better comparison of wall related decay constants from pipes of different diameters.

Piping age and material have also been shown experimentally to affect the decay rate of chlorine in a variety of ways (Al-Jasser 2007; 2011). Some materials were shown to have increased k-values as age increased while others showed decreased k-values. Al-Jasser (2007 & 2011) tested several pipe materials typically seen in the water main. However, the studies did not test small gauge pipes that are commonly present in premise plumbing or copper piping. In addition to different pipe materials reacting to aging differently, pipe material has been shown to

be an important factor in decay when the pipes are of similar age (Hallam et al. 2002). Although Hallam et al (2002) did not use copper pipes, chlorine was later shown to react with $\text{Cu}(\text{OH})_2$ in copper pipes and greatly increase the decay rate (Nguyen et al. 2011). Because copper is a commonly used premise plumbing piping material in commercial buildings, it is valuable to analyze the rate at which disinfectant residuals decay in a system made of copper (Edwards et al. 2003). It is also necessary to study the factors that affect the residual decay rates.

1.0.3 Stagnation

Because the water in premise plumbing systems is used at varying frequencies, often with long intermissions, increased retention times (i.e. stagnation) usually occur in premise plumbing (Haider et al. 2002). Stagnation may occur in a house when the users are at work or school; it may also occur for schools during nights, weekends, or summer breaks. Extended periods of stagnation allow disinfectant residuals such as free chlorine (Cl_2) to undergo decay to potentially undetectable levels (Jadas-Hécart et al. 1992; Clark et al. 1994). Due in part to the reduction in disinfection residuals, stagnation has been shown to be linked to increased microbial levels in the water distribution system in general (Pepper et al. 2004; Ayoub and Malaeb 2006; Manuel et al. 2010). Higher bacterial concentration, in turn, may lead to a myriad of issues including: infections (Huang et al. 2002), aesthetic issues such as taste, color, and odor (Mallevalle and Suffet 1987; Hoehn 1988), pipe corrosion (Lee et al. 1980), and biofilm formation (van der Kooij 2003).

In order to compare stagnant and non-stagnant premise plumbing water quality, it is helpful to have a useful indicator of the level of stagnation. Typically, temperature has been used as an indicator (Lautenschlager et al. 2010; van der Wielen and van der Kooij 2010).

Therefore, there is currently a need for an experimentally backed indicator of stagnation. This indicator should be quickly and economically determinable.

1.0.4 Biofilm and Microbial Population

As stated earlier, when chlorine residual is allowed to decay to low levels, microbial concentration can increase (Pepper et al. 2004; Ayoub and Malaeb 2006; Manuel et al. 2010). The fact that higher microbial concentrations in drinking water occur after stagnation at the POU has been observed several times (Pepper et al. 2004; Lautenschlager et al. 2010). It is during these times of decreased residual and increased microbial concentrations that biofilms have an increased tendency to form (van der Kooij 2003). It has been estimated that biofilms can contain more than 95% of a drinking water distribution system's (DWDS) microorganisms (Flemming 2002). When the disinfection residual increases biofilms can protect and nourish many types of microorganisms including opportunistic pathogens (Parsek and Singh 2003; Lehtola et al. 2007). These pathogens include *Legionella spp.* and non-tuberculosis *Mycobacterium spp.* (Pryor et al. 2004; Tobin-D'Angelo et al. 2004; Vaerewijck et al. 2005; Thomas et al. 2006; Tsitko et al. 2006). In addition to these opportunistic pathogens, the EPA has proposed a list of other microbial contaminants that it is concerned may be present in the drinking water supply (EPA 2004). This list includes the bacteria: *Mycobacterium avium*, *Helicobacter*, and *Aeromonas*; the viruses: *Caliciviruses*, *Echovirus*, *Coxsackieviruses*, and *Adenovirus*; the protozoa: *Microsporidium*; and the toxins: *Cyanobacterial toxins* (EPA 2004). The risk of presence of these microbes emphasizes the importance of understanding the factors that affect stagnation in premise plumbing, as well as the effect of premise plumbing systems have on microbial growth during stagnation. However, there have been relatively few studies that have investigated the

microbial ecology of various premise plumbing systems (Council 2006). Similarly, there have been no studies determining effect that premise plumbing service age has on the microbial concentration in stagnant drinking water.

1.1 RESEARCH OBJECTIVES

I. Linkage Between Service Age and Increased Microbial Concentration in Stagnant Premise Plumbing

Objective I.1: Verify the effect of stagnation on microbial concentration

Hypothesis I.1: If the drinking water in a premise plumbing system is allowed to stagnate overnight, an increase in microbial concentration will occur.

Objective I.2: Determine the presence of a relationship between premise plumbing service age and microbial concentration.

Hypothesis I.2.1: As the service age of a premise plumbing system increases, so will the microbial concentration during stagnation.

Hypothesis I.2.2: Partial re-piping of a premise plumbing system will mitigate the increase in microbial concentration that occurs during stagnation.

II. Free Chlorine Residual as an Indicator of Stagnation in Premise Plumbing

Objective II.1: Experimentally validate a parameter for the use of indicating the extent of stagnation in premise plumbing systems.

Hypothesis II.1: Free Cl_2 concentration, since it is regulated by water treatment plants and avoids changes due to seasonal variations, will be a rapidly determinable and useful indicator of the level of stagnancy in premise plumbing systems.

III. Factors Affecting Chlorine Decay Kinetics in Copper Premise Plumbing

Objective III.1: Determine the effect of a copper premise plumbing system's service age on the decay rate of chlorine residual.

Hypothesis III.1: As the service age increases, the decay rate will decrease due to oxidation of the copper pipe wall.

Objective III.2: Determine the effect of increased usage of a premise plumbing system on the decay rate of chlorine residual.

Hypothesis II.2: By increasing the usage of a copper premise plumbing system, the decay rate in older systems will decrease, and the decay rate in newer systems will either increase slightly or stay the same.

CHAPTER 2: Linkage between Service Age and Increased Microbial Concentration in Stagnant Premise Plumbing

2.0 INTRODUCTION

Although one defining characteristic of a developed country is access to a system of water treatment and distribution, such access does not provide immunity to the potential risks of unclean drinking water (Semenza et al. 1998; Craun et al. 2010; Wingender and Flemming 2011). It has been shown that the section of plumbing between the water main and the POU, known as premise plumbing, has several inherent qualities that may increase this risk such as increased retention time, fluctuating temperatures, narrow pipe diameters, and more direct contact with individuals (Haider et al. 2002; Zietz et al. 2003; Zietz et al. 2007). During periods of increased retention time, also known as stagnation, disinfection residuals such as chlorine can decay below detectable levels (Clark et al. 1994). Due in part to the reduction in disinfection residuals, stagnation has been shown to be linked to increased microbial levels in the water distribution system in general (Pepper et al. 2004; Ayoub and Malaeb 2006; Manuel et al. 2010). Higher bacterial concentration, in turn, may lead to a myriad of issues including: infections (Huang et al. 2002), aesthetic issues such as taste, color, and odor (Mallevalle and Suffet 1987; Hoehn 1988), pipe corrosion (Lee et al. 1980), and biofilm formation (van der Kooij 2003). Of these issues, premise plumbing has an additional risk for biofilm formation which is fostered by its small diameter piping (Bartram et al. 2003). Biofilms, which can contain more than 95% of a drinking water distribution system's (DWDS) microorganisms, both protect and nourish microorganisms during times of increased disinfection residual (Flemming 2002; Parsek and Singh 2003; Lehtola et al. 2007). Therefore, when the water becomes stagnant, microbial levels increase and, aided by small pipe diameters, foster biofilm formation. The biofilms in turn

protect the microorganisms when the stagnant water is replaced by fresh drinking water and the disinfection residual increases. When the water again becomes stagnant, the microbial levels rise once more and biofilms are able to continue forming. This cycle may be further enhanced by the effect of plumbing service age on chlorine residual decay rates.

As the service age of pipes increases, the decay rate of disinfectant residuals related to the reaction with the pipe wall can increase (Al-Jasser 2007). As chlorine decay increases, stagnation and the resulting bioaccumulation can commence earlier (Ayoub and Malaeb 2006). Additionally, biofilms grow and become more stable and mature as they get older (Martiny et al. 2003).

From these two points, it becomes apparent that premise plumbing service age may have an important impact on the microbial quality of drinking water at the POU. Although several papers have documented that stagnation leads to higher bacterial concentrations in drinking water at the POU, there are currently few studies that have detailed the factors that affect the microbial contamination during premise plumbing stagnation, and no studies have determined the effect of premise plumbing service age on microbial contamination at the POU after stagnation (Pepper et al. 2004; Lautenschlager et al. 2010). Therefore, the purpose of this study is to show how the service age of a premise plumbing system impacts the presence of microorganisms in stagnant drinking water.

2.1 MATERIALS AND METHODS

2.1.1 Site Location and Sampling

Tap water from eleven randomly selected premise plumbing systems served by the same water treatment plant (WTP) in Knoxville, Tennessee was studied in August and September of 2012 (Table 1 and Figure 1). Water was allowed to remain stagnant in pipes overnight (>8 hrs.) which allowed the chlorine residual to decay and the HPC to increase. Additionally, fresh water samples were taken after the tap was allowed to run for approximately 5 minutes. Each sample site was tested on three different days to ensure that neither adverse weather nor water treatment plant conditions affected the outcome of the results. To minimize the effect of changing conditions, sampling for the three replicates only occurred on three days. For each sample, the

Table 1: Sampling Site Information

System ID	System Age, yr	Pipe Material	Age Group	HPC, CFU mL ⁻¹ ‡
C	1	PVC	1	348 (59.8)
A	2	PVC	1	203 (65.7)
I	2	PVC	1	683 (108.3)
B	4	PVC	1	748 (130.0)
D	20	Cu	2	1499 (333.0)
E	45	Cu	2	2508 (374.3)
G	67	Cast Iron	2	2406 (327.7)
K	88	Cast Iron	3	2994 (262.0)
J	103	Cast Iron	3	3296 (221.1)
F	127	Cast Iron	3	3932 (515.1)
H*	132	Cast Iron	-	1423 (306.4)

*Premise plumbing system H was partially re-piped within 5 years prior to this study and was therefore not included in any ANOVA testing.

‡(Standard Deviations)

first 50 mL of tap water was discarded in order to eliminate potential contamination from the ambient environment. The second 50 mL was then poured into a sterile polypropylene centrifuge tube. From each tube, 5 mL was tested to determine whether chlorine residual less than 0.2 mg L⁻¹ using the method the DPD method (Orbeco-Hellige; L147050) (Wang and Gardinali 2013). The tubes were then placed in a cooler packed with ice packs. Once all of the samples were taken, they were taken to the lab for immediate analysis. All samples were analyzed the day they were taken.

All samples were tested according to standard method 9215C, the heterotrophic plate test spread plate method (Eaton et al. 2005). For each sample, 0.2 mL were pipetted onto triplicate plates of pre-dried R2A Agar. The plates were allowed to incubate for seven days at 28°C. After incubation, the colonies were hand counted.

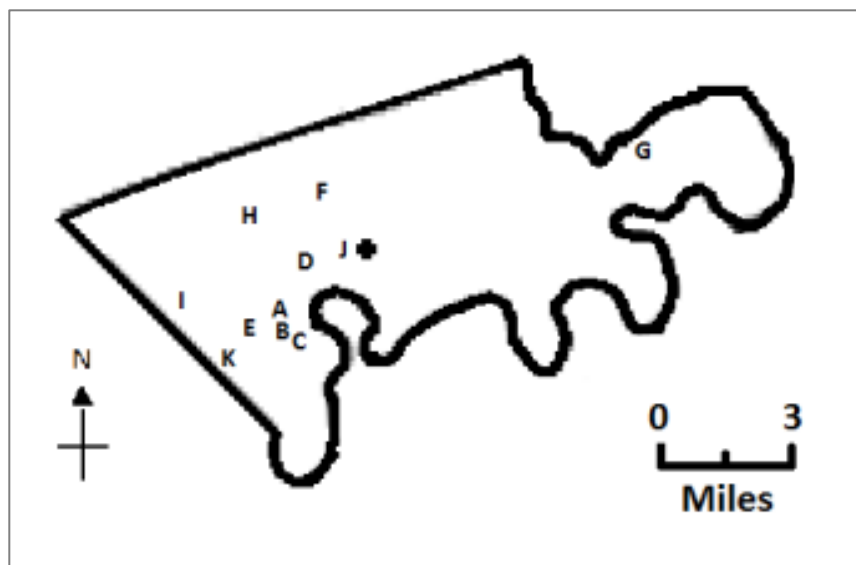


Figure 1: Map of West Knoxville, TN. Each letter represents a sample site (Table 1) and the black dot (●) represents the water treatment center that supplies West Knoxville.

2.1.2

Statistical Analysis

All statistical analysis were performed in SPSS statistical software package (IBM SPSS Statistics Version 21) using an α of 0.05. Samples were divided into separate age and pipe material groups (Figure 1) and then compared using an analysis of variance (ANOVA). Tukey's HSD test was performed post-hoc to determine how the means of each group compared to one another. Prior to running the ANOVA the assumptions of normality and equality were checked with the Shapiro-Wilk test and Levene's test, respectively. Linear regressions and correlations were performed to determine relationships between age and HPC in specific pipe materials.

2.2 RESULTS AND DISCUSSIONS

2.2.1 Impact of Stagnation on Microbial Water Quality

Fresh water HPC counts were consistently below detectable limits ($<5 \text{ CFU mL}^{-1}$) (data not shown). This occurrence was expected since chlorine residual was present (e.g. $> 1.0 \text{ mg /L}^{-1}$). Stagnant water samples, however, had a HPC with a mean of $1822 \pm 1253 \text{ CFU mL}^{-1}$. Although samples were taken on the same days, the range of values was high ($110 - 4815 \text{ CFU mL}^{-1}$). The high variation in values was consistent with stagnant water in samples from other studies (Lautenschlager et al. 2010). The reason for the high level of microbial contamination in the stagnant water samples was due in part to the longer retention times common in premise plumbing (Pepper et al. 2004; Ayoub and Malaeb 2006; Manuel et al. 2010). Once the disinfectant residual completely decays, there is a greater tendency for biofilms to develop (van der Kooij 2003). As the service age of the premise plumbing increases, so does the age and maturity of the biofilm (Martiny et al. 2003). It is from this biofilm that bacteria can enter the drinking water during periods of stagnation (LeChevallier et al. 1987; van der Wende et al.

1989). If the rate at which bacteria enters the bulk water from the biofilm is constant, then when the water is constant and flow is negligible, the concentration in the bulk water per unit length of pipe will be much higher than when the flow is higher. This statement is intuitive because if the bulk water is moving each liter of water will receive only a small portion of the bacteria from the biofilm than if it were not moving. Hence, there is a return to lower microbial concentrations when the water is allowed to run for several minutes and become “fresh”.

2.2.2 Factors Contributing to Variation in Water Quality

Upon closer inspection, it was reasoned that the variation in HPC could be accounted for predominately by two factors: premise plumbing service age and pipe material. The data was therefore divided into three service age groups. Service age groups were divided so that the range of premise plumbing system service ages never exceeded 50 years (Table 1). Each group was significantly different from the other two. Also, as the service age groups increased so did the mean HPC (Figure 2).

The data was also divided into three groups by the following pipe materials: PVC, copper, and cast iron. PVC was significantly different from the other two groups which were not significantly different from one another. (Figure 2, Inset). PVC had the lowest average HPC values (495.6 ± 262.2 HPC mL⁻¹). Cast iron pipes had the highest average HPC values (3407.2 ± 478.7 HPC mL⁻¹).

Because of substantial overlap between the service age and material groupings the ANOVA and Tukey's HSD tests could not be used to conclude which factor contributed more to the variation in HPC. In the geographic area of study, pipe material appears to coincide, to a large extent, with the service age of premise plumbing.

2.2.3 Linkage of Service Age to Bacterial Levels

In order to differentiate the effects of premise plumbing service age and pipe materials, linear regressions and correlations were performed between HPC and service age for PVC and cast iron premise plumbing systems. Copper systems were omitted because of the small sample size. The slope of the PVC regression line was 27.45 CFU L⁻¹ Yr⁻¹ and the R²-value for the correlation was 0.42 (Figure 3, inset). The small R²-value was likely due to the fact that the service age range of the premise plumbing systems was only three years, which was very short. At such a small service age gap, variation was dominated by the myriad of other factors that can affect the microbial quality of premise plumbing (e.g. stagnant water temperature, house temperatures, water usage patterns, etc.). The large slope could be attributed the initial growth and maturing of the biofilm that can occur during the first 3 years of service (Martiny et al. 2003).

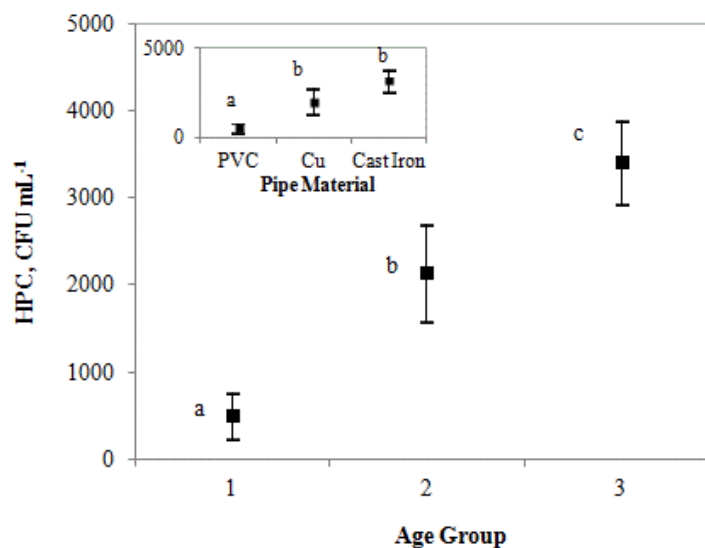


Figure 2: HPC of stagnant water in stagnant water of premise plumbing systems at point of use. Data grouped by age of premise plumbing system (Table 1). (Inset) Data grouped by premise plumbing material. Data are means of grouped data with error bars representing standard deviations. Means that are significantly different are labeled with different lowercased letters (ANOVA, Tukey's HSD, $p < 0.05$)

The slope of the regression line for cast iron piping was $5.04 \text{ CFU L}^{-1} \text{ Yr}^{-1}$. When the correlation was performed on premise plumbing systems with cast iron piping (service age range 60 years), an R^2 -value of 0.89 was determined (Figure 3). From this larger R^2 -value, it was gathered that as the service age range increased the effect of service age on stagnant water microbial quality increased and the other effects became secondary. The slope indicated that age still had an effect on microbial concentration after the biofilm had matured for the initial 3 years of service. Furthermore, the smaller value of the slope in cast iron pipes suggested that after maturation, the rate at which HPC increased was greatly reduced. Both linear regressions showed that age had an effect on the microbial concentration.

2.2.4 Re-piping Effect

Premise plumbing system H underwent partial re-piping 5 years prior to this study. Although, the premise plumbing system was originally constructed 132 years ago, it consisted of sections that were much younger. The HPC was compared to both the premise plumbing system closest

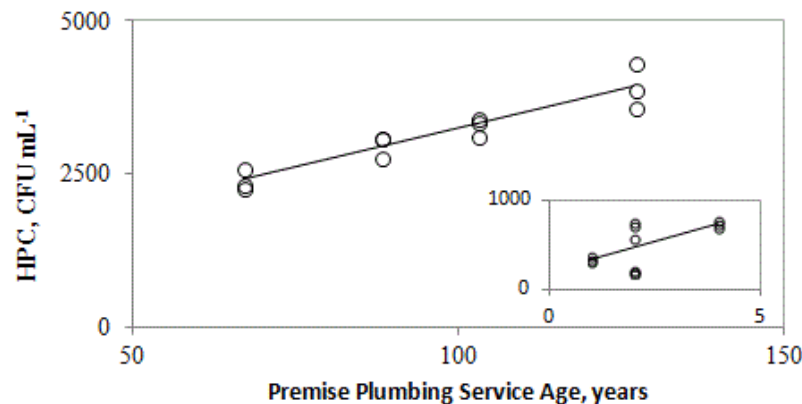


Figure 3: Linear regressions between the age of the premise plumbing system and HPC in stagnant water. Cast iron premise plumbing systems with (inset) PVC premise plumbing systems. Slopes are 5.04 for Cast Iron and 27.45 for PVC premise plumbing data ($p < 0.05$). R^2 -values for Cast Iron and PVC are 0.89 and 0.42, respectively ($p < 0.05$).

to premise plumbing system 132 years in service age (premise plumbing system F) and the premise plumbing system with the most similar HPC (premise plumbing system D) (Figure 4). System H had a HPC approximately 36% of premise plumbing system F. System D which was 112 years younger than the original premise plumbing system H only differed than the partially re-piped system by 77 HPC mL^{-1} . This difference in HPC again demonstrated the impact of service age on microbial quality of stagnant drinking water in premise plumbing. It also suggested that partial re-piping of premise plumbing system could be a potential strategy for reducing microorganism concentrations in premise plumbing system and the risk associated with elevated microorganism concentrations.

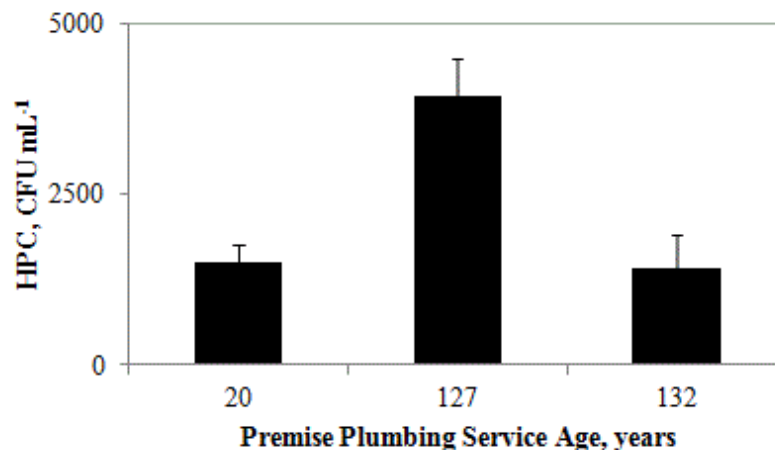


Figure 4: CFU mL^{-1} of three premise plumbing systems. The oldest premise plumbing system has been partially re-piped within the last 5 years. The data columns are means of three days of data with the bars representing the upper standard deviations.

2.3 SUMMARY

As the service age of premise plumbing systems increase, so did the microbial concentration that occurred during stagnation. This pattern was observed within and across different pipe material groups. Additionally, partially re-piping a premise plumbing system may mitigate the increase of microbial concentration that occurs during stagnation.

CHAPTER 3: Free Chlorine Residual as an Indicator of Stagnation in Premise Plumbing

3.0 INTRODUCTION

Stagnation is the occurrence of water ceasing to flow in drinking water distribution systems (DWDS) for extended periods of time. This often occurs in sections of the DWDS with increased retention time such as dead end areas or premise plumbing. Premise plumbing is the section of the DWDS between the water main and the POU. Increased levels of stagnation at times such as night or the work day can often occur in premise plumbing (Haider et al. 2002). Extended periods of stagnation allow disinfectant residuals such as free chlorine (Cl_2) to undergo first-order decay to potentially undetectable levels (Jadas-Hécart et al. 1992; Clark et al. 1994). Depletion of Cl_2 residual may facilitate microbial survival and growth and allow biofilm formation to occur. Biofilm has been shown to potentially harbor opportunistic pathogens that can be released during stagnation (Parsek and Singh 2003; Lehtola et al. 2007).

In order to compare the quality and parameters of stagnant and fresh water, it is imperative to establish a quickly determinable parameter as an indicator of drinking water stagnation. Typically, temperature has been used as an indicator (Lautenschlager et al. 2010; van der Wielen and van der Kooij 2010); the use of which, however, has not been supported by experimental evidence. Since water temperature may be variable depending on premise temperature and seasonal effects, it needs to be further analyzed. One purpose of this paper is to compare two quickly determinable parameters (temperature as well as chlorine concentration) to blueprint data in order to establish a reliable indicator of stagnation in drinking water distribution systems. Additionally, it attempts to give a mitigation strategy for minimizing the amount of microbial concentration to an acceptable level of stagnation.

3.1 MATERIALS AND METHODS

3.1.1 Site Locations and Sampling

Samples were taken from buildings of various ages on the campus of the University of Tennessee, Knoxville. All buildings are serviced by the same conventional water treatment plant. The treatment plant's source water is the Tennessee River. The premise plumbing for all buildings was comprised of copper. The sample taps were located in custodial rooms that were locked unless being used by custodians or experiments. The experimenter was therefore able to ensure that water at the POU was stagnant when testing occurred. Flow rate was determined for each tap. Water was allowed to remain stagnant in pipes overnight (>8 hrs.) which allowed the chlorine residual to decay, water temperature to equilibrate to the building temperature, and the HPC to increase. Samples were taken throughout the seasons of winter, spring, and summer.

3.1.2 Premise Plumbing Volume Determination

Blueprints for the buildings Min Kao, Haslam, and Baker Center were used in order to determine the nominal pipe diameters and lengths present in the respective premise plumbing systems. These values were, in turn, used to determine the volume of water in each section of the premise plumbing system and the premise plumbing system as a whole. In order to determine the volume of water between in the pipes between the floor piping and the POU the blue prints and measurements of the taps were used. Measurements at the site also had to be made to determine the lengths of pipes between floors for some buildings when the heights of floors were not specified in the blueprints.

3.1.3 Free Chlorine and Temperature Profiles

In order to develop profiles, taps that had been allowed to stagnate overnight were flushed, and chlorine concentrations and temperatures were monitored as they returned to fresh levels (Appendix). Water samples of 5 mL were tested incrementally as water was allowed to flush from the tap using the DPD method (Orbeco-Hellige; L147050) (Wang and Gardinali 2013). Temperature profiles were determined by placing a digital thermometer in the flowing tap water. The temperature was continually monitored and incrementally recorded.

3.1.4 Heterotrophic Plate Counts

Samples were taken while water was stagnant and when the water was fresh. For stagnant water 15 mL was filtered, and for fresh water 1 L was filtered. Fresh and stagnant samples were taken in 15 mL sterile polypropylene centrifuge tubes and 1 L sterilized (by autoclave) polypropylene bottles, respectively. Once samples were taken, they were placed in a cooler packed with ice packs. All HPC analyses were performed within 8 hours of sampling. Samples were tested according to standard method 9215D, the heterotrophic plate test membrane filter method (Eaton et al. 2005). The plates were allowed to incubate for seven days at 28°C. After incubation, the colonies were hand counted.

As an addition, four extra samples were taken in which HPC profiles were determined as water was allowed to flush. For HPC profiles, the first 50 mL of flushed water was discarded then the next 15 mL was sampled. Subsequently, 1 L samples were taken after the following volumes of water had been flushed from the system: 1 L, 2 L, 5 L, 10 L, 20 L, and 50 L.

3.1.5 Statistical Analysis

All statistical analysis were performed in SPSS statistical software package (IBM SPSS Statistics Version 20) using an α of 0.05. Heterotrophic plate counts were divided into groups based on the chlorine concentration recorded at the volume at which they were taken. The groups were those concentrations greater than 0.2 mg L^{-1} or those less than or equal to 0.2 mg L^{-1} . In order to take into account HPC lower than the detection limit ($< 67 \text{ CFU L}^{-1}$), several steps were taken. First, all values that were below the limit of detection, were considered observed at the limit of detection. Next, the left censored data set transformed into a right censored data set using the “flipping method” (Zhang et al. 2009). Where the value over which the data set was flipped was 80000 CFU L^{-1} . The two flipped data sets were then compared using a Wilcoxon rank sum test. The p-value determined for the right censored data is equal to the left censored data set (Zhang et al. 2009).

3.2 RESULTS AND DISCUSSIONS

3.2.1 Chlorine and Temperature as Indicators of Stagnancy

When water was allowed to flush so that Cl_2 concentrations, temperatures, and HPC were approximately equal to those in the main, the water was considered fresh. In the data, these levels were assumed to be met when the water flushed was greater than 100 L and the Cl_2 concentration plateaued. Using blueprints of several premise plumbing systems, the limit of 100 L was determined to be a very conservative value that allowed sufficient sampling of the volume of water present between the POU and the point at which the premise plumbing system entered the building. This conservative value was chosen for two reasons: Because blueprints were not

available for all of the buildings sampled and the premise plumbing systems were not ideal plug flow systems.

Chlorine concentration plateaued at $1.30 \pm 0.50 \text{ mg L}^{-1}$ (N=39) and temperature had an absolute change of $5.6 \pm 3.2 \text{ }^{\circ}\text{C}$ (N=45). In several instances, final plateaus were not reached until well beyond the volume capacity of the premise plumbing system being tested. There were several reasons for these observances. For Cl_2 concentration, decay can occur while water is flowing through the premise plumbing system. The Cl_2 concentration in the water main may not be completely static either and could have a certain level of stagnancy after a night of lower use. Water temperature is affected by pipe temperature, which is, in turn, affected by ambient temperature. The time to reach this equilibrium may be slower, depending on the temperature differential of the ambient and water temperature, than the time it takes to flush the premise plumbing water capacity one time over.

Between Cl_2 concentration and temperature, Cl_2 was determined to be a more precise indicator of the extent of stagnation. This inference was made because depending on outdoor and indoor temperatures, the water temperature could have increased, decreased, or have stayed the same during the transition from stagnant to fresh water (Figure 5; Appendix). However, no matter the season, Cl_2 concentration always increased when the system was flushed, and it

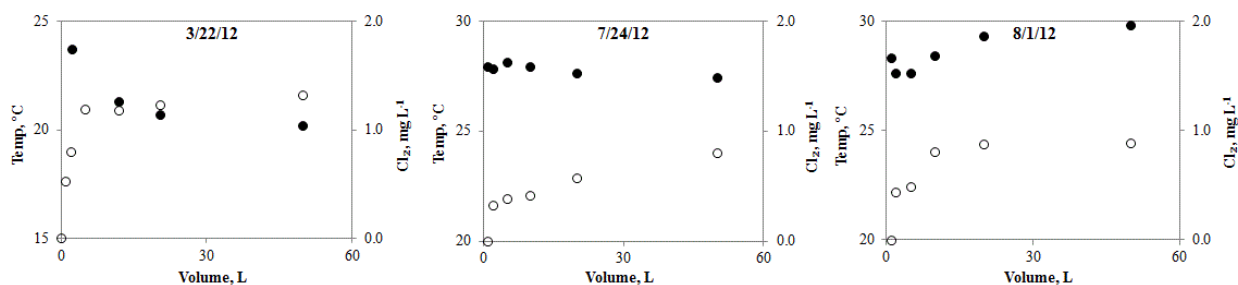


Figure 5. Chlorine (○) and Temperature (●) profiles for E&PS. From left to right, the temperature decreased, stayed roughly the same ($\Delta T = -0.5^{\circ}\text{C}$), and increased during tap flushing. However, the Cl_2 concentration increased on all three dates.

increased to approximately the same level ($1.30 \pm 0.50 \text{ mg L}^{-1}$). Therefore, although it is a slightly more difficult parameter to measure, Cl_2 is a good indicator of the extent of stagnation.

3.2.2 Relationships Between Chlorine Concentration and HPC

This indication is relatively useless, however, if our measure of freshness has no impact on HPC. Therefore, HPC was taken at the beginning and end of the flushing periods. The HPC was then compared to the chlorine concentration using the Wilcoxon rank sum test. HPC was divided into two groups: samples collected at Cl_2 concentrations less than or equal to 0.2 mg L^{-1} and those collected at Cl_2 concentrations greater than 0.2 mg L^{-1} (Figure 6). The Wilcoxon rank sum test determined the two means to be significantly different. However, the potentially large volumes that needed to be flushed to reach fresh levels of water (upwards of 500 L), and therefore low HPC levels, were unreasonable from a public health standpoint.

For that reason, HPC profiles were developed in tandem with Cl_2 profiles to determine if HPC shared the same sharp levels of change during the first 2 L of flushing as Cl_2 concentration. Visually, it was apparent that both HPC and Cl_2 concentrations had sharp levels of change (Figure 7). In fact, HPC underwent an 80% decrease within $1.5 \pm 0.58 \text{ L}$ and Cl_2 increased past 0.2 mg L^{-1} (approximately 15%) after $1.25 \pm 0.5 \text{ L}$ (Figure 7). Taking into account the upper standard deviation of both of these values, an individual needs only to

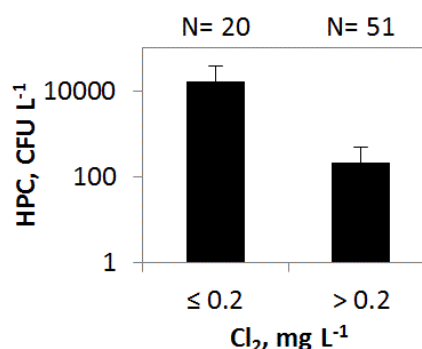


Figure 6. Mean values with standard deviation bars for HPC sampled when Cl_2 concentrations were less than or equal to 0.2 mg L^{-1} and greater than 0.2 mg L^{-1} . The Wilcoxon rank sum test shows that the means are significantly different ($p < 0.05$)

flush 2.08 L of water in order to greatly reduce the HPC content in their otherwise stagnant and potentially unhealthy water.

3.2.3 Effect of Pipe Size on Rate of Stagnancy

In order to better determine the applicability of the data for residential application, it was important to study the cause of the sharp change in Cl_2 concentration and HPC during the first 2 L of water flow. Pipe size was hypothesized to be the main contributing factor to this change. Therefore, blueprints were analyzed and compared to the Cl_2 profiles (Figure 8). It was noted that inflection points on the chlorine profile often occurred at pipe size change locations. A possible reason that there were transition periods instead of constant concentrations in pipes of constant sizes is the fact that the distribution systems were not perfect plug flow reactors. This

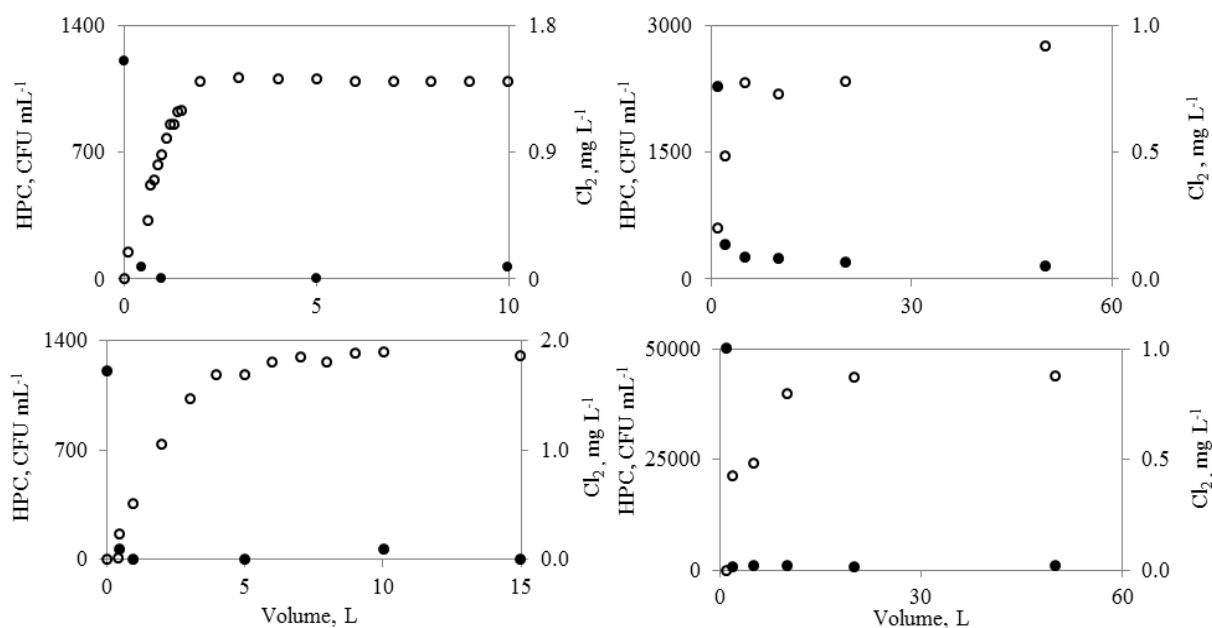


Figure 7. Chlorine (○) and Heterotrophic Plate Count (●) profiles. The volume at which Cl_2 is increased by 10% on each graph is top left 1 L, top right 2 L, bottom left 2 L, bottom right, 1 L. The volume at which HPC is reduced by 80% is top left 1 L, top right 2 L, bottom left 1 L, and bottom right 2 L.

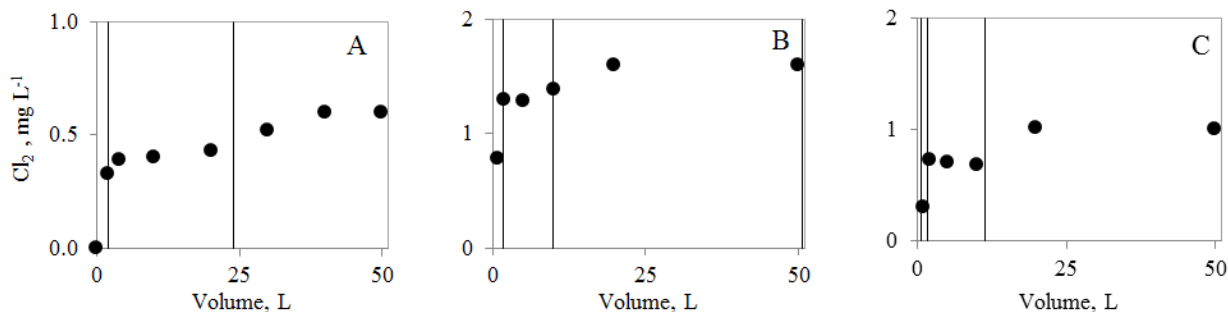


Figure 8. Chlorine profiles with vertical lines representing pipe diameter increases. (A) Sample taken from Min Kao on 2/8/12. (B) Sample taken from Haslam on 3/13/12. (C) Sample taken from the Baker Center on 7/26/12. More profiles for these buildings are in the Appendix.

fact was due to imperfections in the system such as: friction at the pipe wall, pipe connections, expansions and contractions in the pipes, etc.

It was to be expected that large changes in Cl₂ concentration occurred at pipe diameter changes when decay kinetics were taken into account. Cl₂ decay, which can be modeled as a first order decay, can be attributed to two factors: bulk decay and wall decay (Jadas-Hécart et al. 1992; Zhang et al. 1992; Rossman et al. 1994). Wall decay is dependent on pipe diameter (Rossman et al. 1994). S/V in circular pipes is nominally 4/d. This means that as pipes double in diameter, reaction rate is cut by half. The blueprints in the study showed an increase from 0.5 in to either 1.25 in or 1.5 in which further increased this difference in decay rate, and therefore Cl₂ concentration, after overnight stagnation.

3.2.4 Residential Application for Stagnation Mitigation

In order to analyze how long it took to flush different volumes of water, the flow rates of the sample buildings were determined. The mean flow rate was $0.26 \pm 0.06 \text{ L s}^{-1}$. In order to flush 2.08 L of water at this rate, only 8 s were needed. However, 50 L, the typical volume of the

premise plumbing systems sampled in this study, needed approximately 3 min of flushing. In order to flush 500 L, which was the highest volume at which a final plateau of Cl_2 or temperature was recorded, water needed to be flushed for over 30 min. In the case of individual (non-experimental) use, it may be more likely to flush for 8 s and achieve 80 % HPC reduction and still have technically stagnant water.

Relating this information to residential application, there are two potential options for stagnation mitigation. The first option is to reduce the use of small diameter pipes. However, this can quickly become costly, especially when using materials such as copper. The second option is to increase the amount of flush time before water use after extended stagnation times. If the residence is comprised solely of 0.5 in diameter piping, and the tap has a flow rate equal to earlier stated 0.26 L s^{-1} , then 15 s of flushing for every 100 ft of premise plumbing would be required to obtain water from the main.

3.3 SUMMARY

Because of its relationship to seasonal variation, the use of temperature as an indicator of premise plumbing stagnation was determined to not be as reliable as chlorine. However, it may still be useful for residential water users because it can be determined without instrumentation. Free chlorine was determined to be a reliable and precise indicator of premise plumbing stagnation because its maximum value was not affected by factors outside of the distribution system. Also, free chlorine concentration is regulated at the water distribution system and therefore the levels in the water main were much more consistent than the unregulated temperature.

After comparing the fresh and stagnant values of HPC and Cl_2 concentration, as well as the profiles observed when water was flushed from stagnant to fresh, it was determined that there was a strong relationship between Cl_2 concentration and HPC. The sharp increase in Cl_2 and the sharp decrease in HPC were related to pipe diameter. This relationship may be due to the increased value of the chlorine decay constant that was predicted by the standard decay model. A potential mitigation strategy for high microbial concentrations in premise plumbing systems that are made of 0.5 in piping is to flush taps for 15 s at 0.26 L s^{-1} for every 100 ft of piping between the POU and the water main.

CHAPTER 4: Factors Affecting Chlorine Decay Kinetics in Copper Premise Plumbing

4.0 INTRODUCTION

Disinfectant residual is an important key to maintaining biological integrity in drinking water distribution systems (DWDS). It is therefore vital in keeping water safe to drink at the POU.

Chlorine is a common disinfectant residual in the United States, and the World Health Organization recommends maintaining a level above 0.2 mg L^{-1} ((WHO) 1993). This is because when the Cl_2 concentration is below this level, microorganisms can begin to grow and produce biofilm which coat pipe walls and provide a protective reservoir for microorganisms (LeChevallier et al. 1987; (WHO) 1993; van der Kooij 2003; Lehtola et al. 2007).

In order to reduce the microbial concentration in DWDS, Cl_2 must be present. The parameter that is used to represent the rate of decay is called the chlorine decay rate constant (k). The k -value has two parts in DWDSs: That which is related to the bulk water (k_b) and that which is related to the wall (k_w) (Biswas et al. 1993b; Clark et al. 1994; AWWARF 1996; Beatty et al. 1996).

$$(1) \quad k = k_w + k_b$$

As the diameter of pipes decrease, k_w becomes the predominant form of decay. This wall related decay is often modeled by a first-order decay reaction (Jadas-Hécart et al. 1992; Zhang et al. 1992; Rossman et al. 1994),

$$(2) \quad C = C_0 e^{-kt}$$

where C is the concentration at a given time, C_0 is the initial concentration, k is the decay rate, and t is the time.

This model becomes somewhat convoluted as more factors that affect the decay rate are added. A few of these factors are as follows: temperature, plumbing age, pipe material, and water usage. The effect of temperature on reaction rate has been well documented and can be modeled with the Arrhenius equation (Sawyer 1994; Beatty et al. 1996; Hua et al. 1999),

$$(3) \quad k = A \cdot e^{-E/RT}$$

where k is the decay rate, A is the Arrhenius reaction opportunity, E is the activation energy, R is the gas constant, and T is the temperature. Using this equation, decay rates can be adjusted to a common temperature in order to facilitate comparison. Pipe material has been shown to be an important factor in decay (Hallam et al. 2002). Although Hallem et al. (2002) did not use copper pipes, chlorine was later shown to react with $\text{Cu}(\text{OH})_2$ in copper pipes and greatly increase the decay rate (Nguyen et al. 2011). Piping age has also been shown to affect the decay rate in a variety of ways (Al-Jasser 2007; 2011). This study tested the effect of service age on chlorine decay rate in copper piping, which has not previously undergone this type of testing.

Although several papers studying the decay rate in the DWDS have been published, few study pipes *in situ*, and most study larger gauged pipes (Jadas-Hécart et al. 1992; Biswas et al. 1993a; Rossman et al. 1994; Beatty et al. 1996; Al-Jasser 2007). This study focuses on small diameter copper pipes in premise plumbing. Additionally, the testing is largely *in situ*. This study aims to clarify the effects of premise plumbing age and differing usage patterns on chlorine decay rate.

4.1 MATERIALS AND METHODS

4.1.1 Sampling Sites

Samples were taken from 7 different custodial rooms on the University of Tennessee, Knoxville Campus. All buildings were serviced by the same conventional water treatment plant. The treatment plant's source water was the Tennessee River. All piping in the buildings was made of copper and the pipe size connecting to the custodial rooms was 0.5 in nominal size. The sample taps were located in custodial rooms that were locked unless being used by custodians or experiments. The use of custodial rooms ensured that taps were used minimally outside of experimentation. Three of the buildings were built after 2005 and four buildings were built before 1960.

4.1.2 Decay Constant Determination

Water was flushed for approximately 30 minutes. As stated in chapter 2, this allowed approximately 500 L to be flushed. It also ensured that Cl_2 concentration was at a maximum level. A 5 mL sample of water was then taken, and the tap was turned off. 5 mL samples were taken every 30 minutes. For each sample, free chlorine was measured using the DPD method (Orbeco-Hellige; L147050) (Wang and Gardinali 2013). In order to determine k , the natural log of the chlorine concentration was plotted against stagnation time. A linear regression was then performed. The slope of the regression was k (Figure 9).

4.1.3 Chlorine Decay Progression

The effect of premise plumbing usage was monitored by repeated flushing of taps. For six taps (three old and three new), the procedure in section 3.1.2 was performed three consecutive times in one day (Table 2). The procedure in section 3.1.2 was later performed three times over a period of several days for three old and three new buildings (Figure 10 and Table 3).

4.1.4 New Pipe Decay Determination

The chlorine decay rate was determined in unused 0.5 in. nominal diameter copper pipes. The length of each pipe was 1 ft and both ends were capped with copper tube caps. The chlorine decay rate was determined by filling the tube with tap water from a tap that had been flushed for 30 min. Then the free chlorine concentration was monitored every 10 min using the DPD method (Orbeco-Hellige; L147050) (Wang and Gardinali 2013). Ten minute increments were used because the decay rate was much faster than the pipes in the buildings. Both ends of the

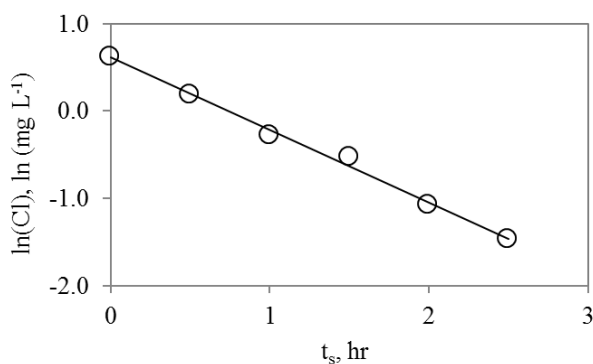


Figure 9. Natural log of the chlorine decay constant over time in Min Kao on Nov-12-2012. The k-value was determined to be 0.829 hr^{-1} with an R^2 of 0.995.

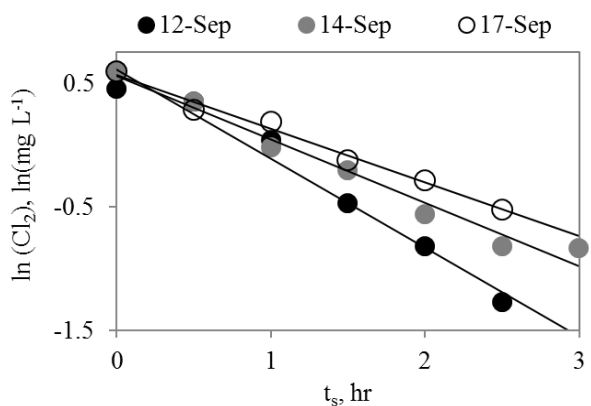


Figure 10. Natural log of the chlorine concentration over time on 3 different days in Perkins Hall. The respective k-values are 0.72 hr^{-1} , 0.51 hr^{-1} , and 0.43 hr^{-1} .

copper pipe were capped during stagnation in order to protect the chlorine from light that could increase the rate of decay.

4.1.5 Temperature Adjustment

In order to adjust the k-values to a common temperature of 20°C the Arrhenius equation was used. The equation was then modified so that solving for A would become unnecessary.

$$(4) \quad k_2 = k_1 \div \exp(-E/R (T_1^{-1} - T_2^{-1}))$$

All the k-value data were then adjusted to 20°C using an E/R that minimized the R^2 value on a linear regression (Figure 11). This process insured that any scatter left in the data was most likely due to sources other than temperature variation.

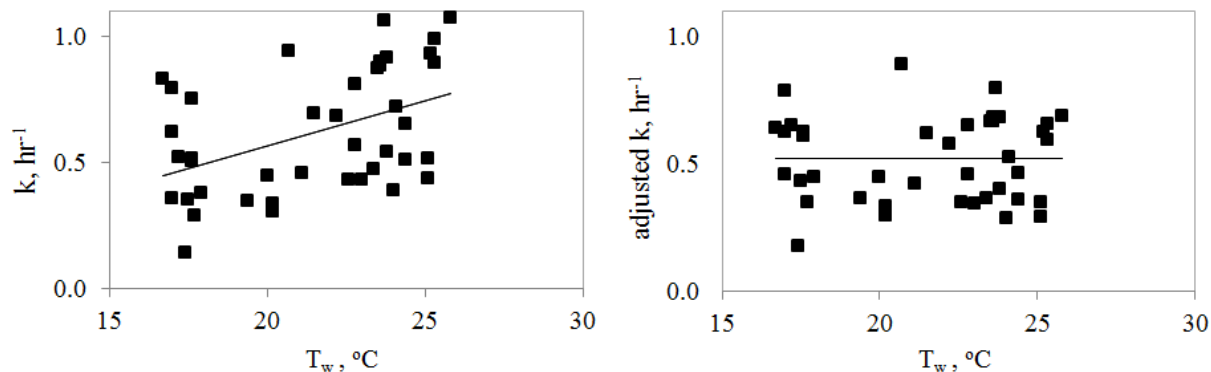


Figure 11. k-values at different initial water temperatures. (left) original k-values. Slope is 0.0353 and R^2 is 0.1991. (right) adjusted k-values. Slope is $2 \cdot 10^{-5}$, and R^2 is $1 \cdot 10^{-7}$.

Table 2: Single Day Testing

Building Name	Premise Plumbing Construction Year	Sampling Date	k-values †			Tw‡, °C
			1	2	3	
Ayers Hall	1921	14-Nov-12	0.379 (0.309)	0.290 (0.434)	0.200 (0.559)	17.7 (0.25)
Earth and Planetary Sciences Building	1929	3-Dec-12	0.938 (0.313)	0.620 (0.417)	0.360 (0.542)	18.2 (2.14)
Ferris Hall	1930	1-Oct-12	0.650 (0.403)	0.509 (0.452)	0.474 (0.508)	24.0 (0.49)
Howard H. Baker Jr. Center for Public Policy	2007	7-Nov-12	0.504 (0.319)	0.518 (0.426)	0.521 (0.531)	22.0 (4.25)
James A. Haslam II Business Building	2009	24-Aug-12	0.808 (0.285)	0.874 (0.403)	0.917 (0.521)	23.0 (0.68)
Min H. Kao Electrical Engineering & Computer Science	2012	12-Nov-12	0.751 (0.323)	0.792 (0.448)	0.829 (0.573)	22.2 (0.65)

† () represents sample time in days (I.E. 0.0 = 12:00 AM and 0.5 = 12:00PM)

‡ Average temperatures and (standard deviations)

Table 3: Multiple Day Testing

Building Name:	Premise Plumbing Construction Year:	k-values [†]			Tw [‡] , °C
		1	2	3	
Earth and Planetary Sciences Building	1929	- (-)	- (-)	- (-)	- (-)
Perkins Hall	1949	0.722 (0.000)	0.514 (1.960)	0.435 (4.971)	24.8 (0.58)
<u>Estabrook</u>	1955	0.347 (0.000)	0.338 (1.984)	0.304 (3.938)	19.9 (0.46)
Howard H. Baker Jr. Center for Public Policy	2007	0.896 (0.000)	0.931 (0.972)	0.987 (2.056)	25.3 (0.06)
James A. Haslam II Business Building	2009	0.900 (0.000)	0.882 (3.077)	1.063 (4.201)	23.7 (0.07)
Min H. Kao Electrical Engineering & Computer Science	2012	0.696 (0.000)	0.569 (0.892)	0.685 (1.007)	22.2 (0.65)

[†] () represents sample time in days (I.E. 0.0 = initial time and 1.5 = 1 day and 12 hours after initial)

[‡] Average temperatures and (standard deviations)

4.1.6 Statistical Analysis

All statistical analysis were performed in SPSS statistical software package (IBM SPSS Statistics Version 21) using an α of 0.05. Samples were divided into two groups: Old (> 20 yr) and New (< 5 yr). They were then compared on a basis of their k-value and initial temperature using analysis of covariance (ANCOVA). An analysis of variance (ANOVA) paired difference test was used in subsequent sections. In these sections, samples were divided into groups based on their age and whether flushing repetitions happened over the span of one day (single) or over more than one day (multi). Additionally, pairs were assigned in two fashions. K-values were paired with the k-value of the repetition immediately following (1 run), and initial k-values were assigned with final k-values (2 run).

4.2 RESULTS AND DISCUSSIONS

4.2.1 Effect of Premise Plumbing Age on Chlorine Decay Rate.

There are a myriad of factors that can affect the chlorine decay rate in premise plumbing systems. Although many of those factors were controlled for in this system (e.g. Premise plumbing material and size, source water, etc), initial water temperature and building age were two variables that were not held constant in this experiment. In order to determine the effect of premise plumbing age on chlorine decay rate without neglecting the effect of temperature, an ANCOVA was performed (Figure 12). After the initial assumptions that temperature had the same effect on old and new building chlorine decay rates (as determined by slope) and that age had no effect on the temperature of the premise plumbing (analysis not shown), the final ANCOVA was performed. This analysis showed that age had a significant impact on the chlorine decay rate ($p < 0.05$) with new buildings having a higher decay rate of $0.54 \pm 0.10 \text{ hr}^{-1}$

and old building having a decay rate of $0.32 \pm 0.11 \text{ hr}^{-1}$ (after adjusting temperature to 20°C). In fact, the partial eta squared was 0.552. This value indicated that up to 55.2% of the variation of the k-value can be contributed to building age.

The adjusted k-value determined for unused copper piping was $0.99 \pm 0.03 \text{ hr}^{-1}$. If microbial contamination was the primary cause of chlorine decay, then, based on the data from chapter 1 showing that there was more microbial contamination in older premise plumbing systems, the data should have shown that older buildings had higher decay rates than new buildings, and unused pipes had the lowest decay rate. However, the opposite trend was observed. It could therefore be inferred that microbial contamination was not the primary cause of chlorine decay.

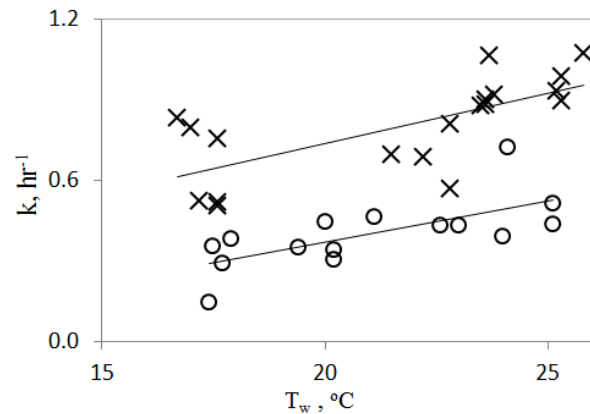


Figure 12. Chlorine decay rate versus Initial water temperature. The regression line for k-values in new premise plumbing systems (X) has a slope of 0.038 and a y-intercept of (0, -0.01). The regression line for k-values in old premise plumbing systems (O) is 0.0308 and a y-intercept of (0, -0.25). An ANCOVA found the slopes to not be significantly different, but the y-intercepts were found to be significantly different.

4.2.2 The Effect of Increased Water Usage on Chlorine Decay Rate

4.2.2.1 Effect in Old vs. New Buildings

The effect of increased water usage was initially tested on old and new buildings (Table 4). Using a paired difference test k-values in old buildings were found to significantly decrease starting at the one additional repetition by a mean of $0.076 \pm 0.070 \text{ hr}^{-1}$. As expected, with a

second repetition, this value, with respect to initial, doubled to a decrease of $0.152 \pm 0.123 \text{ hr}^{-1}$. While the chlorine decayed slower with increased usage in old buildings, new buildings showed the opposite effect and increased. However, the mean increase of new building k-values was not significant until the second run when the mean increase reached the value of $0.05 \pm 0.123 \text{ hr}^{-1}$. The results showing that the decay rates of old buildings decreased with increased usage while new buildings' decay rates increased was somewhat counterintuitive and seemed initially to have been incompatible with the observance that the copper piping was the driving force of chlorine decay. This was because if copper piping was the sole driving force, then with increased usage and, therefore, increased oxidation, old, new, and unused piping decay rates would fall somewhat equally. However, not only did old and new premise plumbing decay rates show opposite patterns, unused piping did not decrease or increase with increased usage. It could therefore be inferred that there was a second driving force to chlorine decay.

The pattern observed could be reconciled with the knowledge of bioaccumulation in premise plumbing. In new buildings, where copper piping was the primary driving force, biofilm covered the pipe walls and inhibited chlorine decay. As usage increased, the biofilm was decayed and more chlorine could react with the pipe walls. However, in older premise plumbing, much more of the pipe wall was oxidized and biofilm became the driving force of chlorine decay. Therefore, as usage increased and more biofilm was decayed, the oxidized pipe wall was exposed and chlorine decay fell. In unused pipes, where no biofilm was present, the decay constant remained

Table 4: Mean k-difference due to increased flushing repetition

	1 run	2 run
Old	-0.076 (0.070)*	-0.152 (0.123)*
New	0.025 (0.055)	0.050 (0.046)*

* significant at $p < 0.05$

constant. It also remained constant because the amount of chlorine added to the pipes was not sufficient to oxidize the pipe wall to a level that would affect the decay rate.

4.2.2.2 Effect of Increasing Usage in Shorter vs. Longer Time Spans

In order to further explore the effects of increased usage, buildings were tested by flushing them 3 times in the same day and, later, 3 times over the course of several days. The buildings that were flushed 3 times in a single day simulated a higher level of use than those that were flushed over several days. A paired difference test was used to compare consecutive runs (Table 5). Accordingly, both old and new buildings had significant levels of change when flushed 3 times in the same day. Neither old nor new, however, had significant levels of change when flushed 3 times over several days.

The results here further showed the effects of biofilm with relation to chlorine decay. When both the new and old premise plumbing systems had increased usage in the same day, the effects were significant. However, when the usage of the premise plumbing system increased by the same amount but was spread over several days the results were no longer significant. This could be explained by biofilm re-growth. When the pipes were flushed within the same day the water was never completely stagnant (i.e. $< 0.05 \text{ mg L}^{-1} \text{ Cl}_2$) for very long which prohibited the re-growth of biofilm in the system. When the pipes were flushed on separate days, stagnation occurred and biofilm was allowed to occur. Although the effects of increased usage were still seen, they were reduced because of the biofilm re-growth.

Table 5: Mean k-value difference due to increasing time between repetitions

1 run	1 day	Multi day
Old	-0.108 (0.074)*	-0.043 (0.052)
New	0.028 (0.018)*	0.022 (0.079)

*** significant at $p < 0.05$**

4.3 SUMMARY

The observed Cl_2 decay rate in copper pipes was closely related to premise plumbing service age. As age increased, decay rate decreased accordingly. Additionally, unused copper pipes had a higher decay rate than premise plumbing systems that were less than five years in use, suggesting that the reaction between free chlorine and copper might have been responsible for the decay of chlorine in copper premise plumbing systems.

The usage pattern of a premise plumbing system also had an effect on the rate of Cl_2 decay. For buildings older than 50 years, increased usage decreased the decay rate, while in newer buildings increased usage resulted in greater chlorine decay rate. This may have been due to the presence of a layer of bioaccumulation in the form of biofilm on the pipe walls that could be reduced by flushing the system. A reduction in this biofilm resulted in an increase in the decay rate in newer buildings because the reaction between the wall and chlorine was higher than the reaction between the biofilm and chlorine. In older buildings, a reduction in the biofilm caused a reduction in the decay rate because sufficient oxidation of the copper tubing had lowered the reaction rate between chlorine and the pipe wall such that it was lower than chlorine and the biofilm. Furthermore, in unused pipes, the decay rate remained constant with increased usage. This consistency was because the unused pipe had not had adequate time to develop any bioaccumulation. Additionally, allowing 24 hrs between flushings decreased the variability in the decay constant so that there was no longer a significant difference due to increased usage. This observance may be attributed to a wall-related layer that can undergo re-growth or replenishment.

CHAPTER 5: Future Research

This study, in addition to answering several questions, opens up the possibility for future research. Since many of the tests in the study focused on copper piping, one possible research direction is to investigate some of the research objectives of this study in different pipe materials such as PVC, other polymers, or cast iron. These studies could include a more specific look at the effect premise plumbing service age has on stagnant water microbial concentration. In particular, the rate at which stagnant water microbial concentration increases with premise plumbing service age. A more focused and expansive study on the effect of partially re-piping premise plumbing systems is also an option.

An additional area of focus relates to objectives involving chlorine decay. Exploring the effect of age and usage rate on chlorine decay constants in buildings with different pipe materials is one research direction. Also, in order to expand the research on how usage effects decay rate, lab tests of k-values could be performed. In these tests, any wall-related layers in pre-used piping could be removed by chemical, biological, and physical means in order to determine the makeup of the layer. Biological and chemical layers could be analyzed using advanced techniques in order to determine their exact composition. All of these tests could also be performed with different pipe materials. Additionally, all of the study areas in this test used free chlorine as a residual. Future research could be performed in areas with disinfectant residuals other than free chlorine or with no disinfectant residual at all.

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APPENDIX

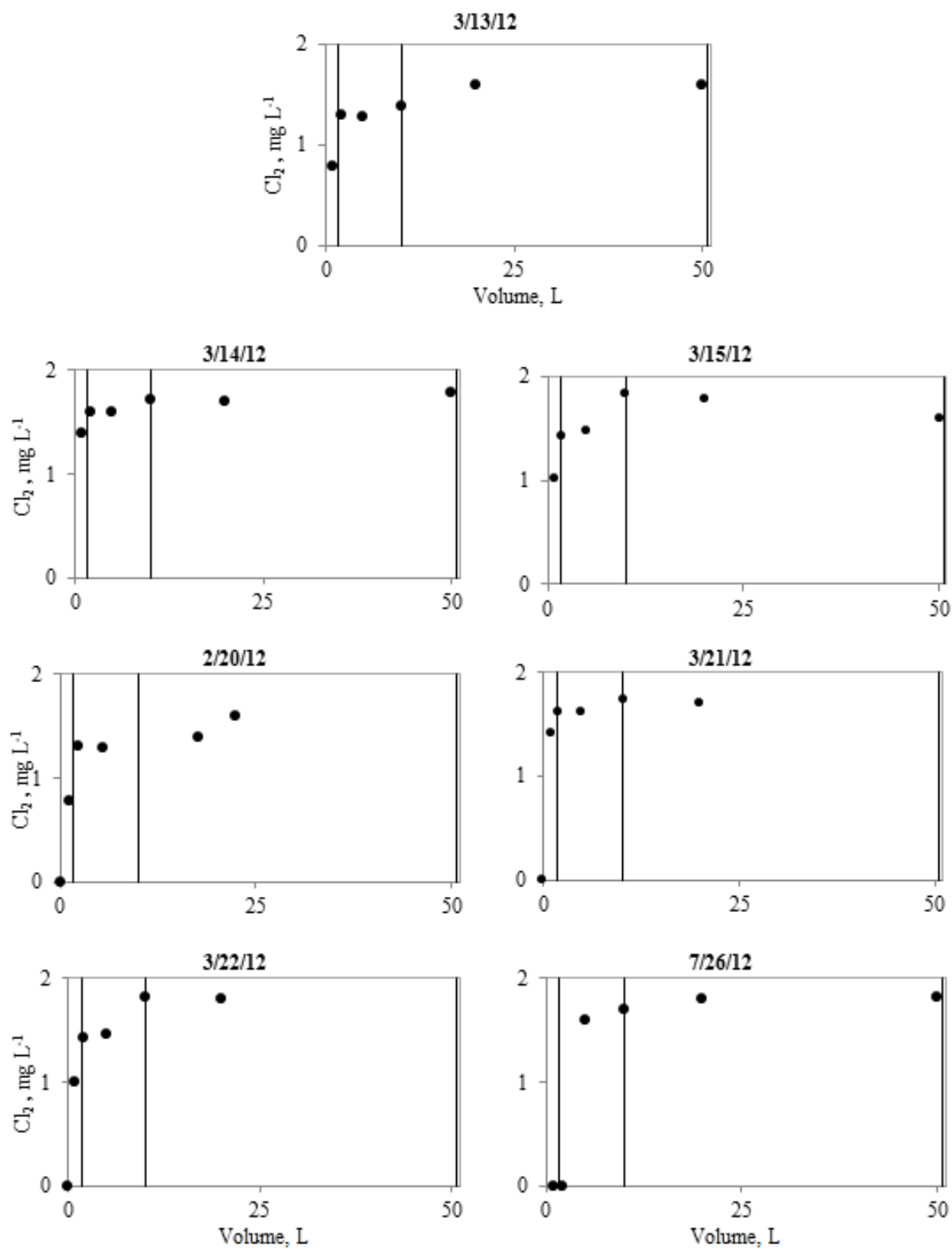


Figure A-1. Samples taken from Haslam. Pipe diameter increases at 1.7 L, 10 L, and 50.6 L.

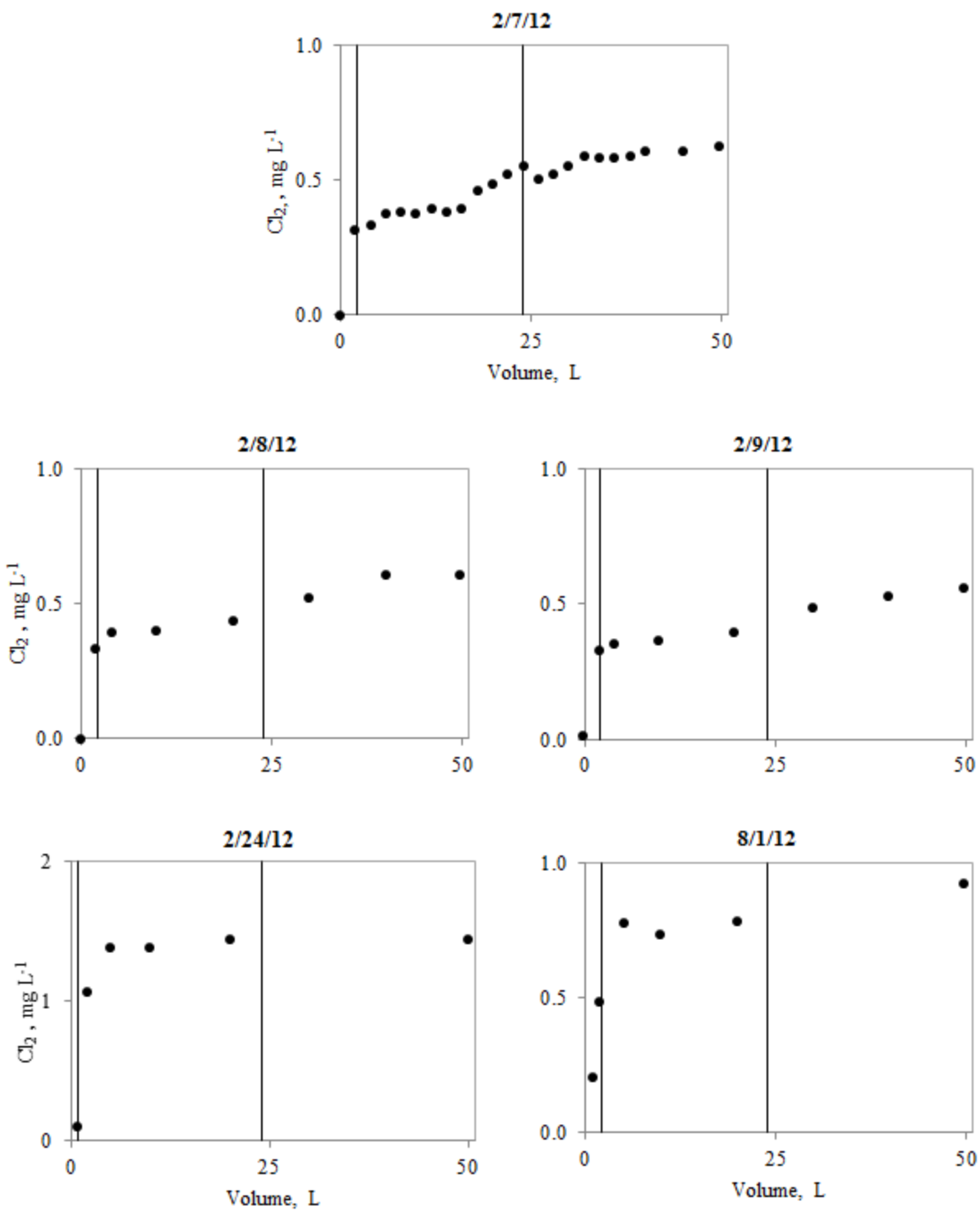


Figure A-2. Chlorine profiles from Min Kao. Pipe diameter increases at 1 L and 24 L.

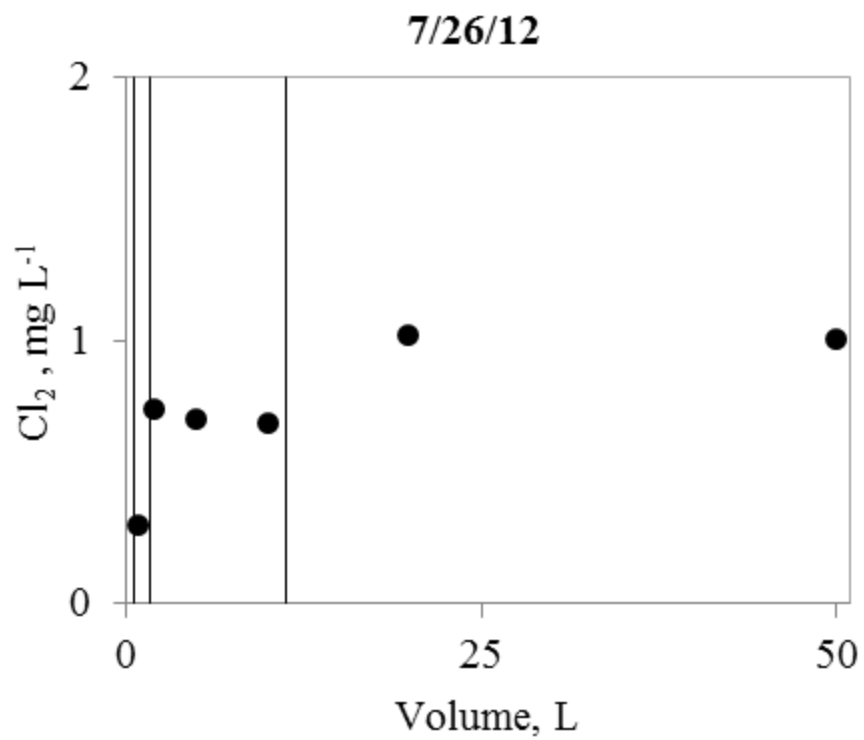


Figure A-3. Chlorine profile from Baker Center. Vertical lines represent changes in pipe diameters. Pipe diameter increases at 0.58 L, 1.65 L, and 11.3L.

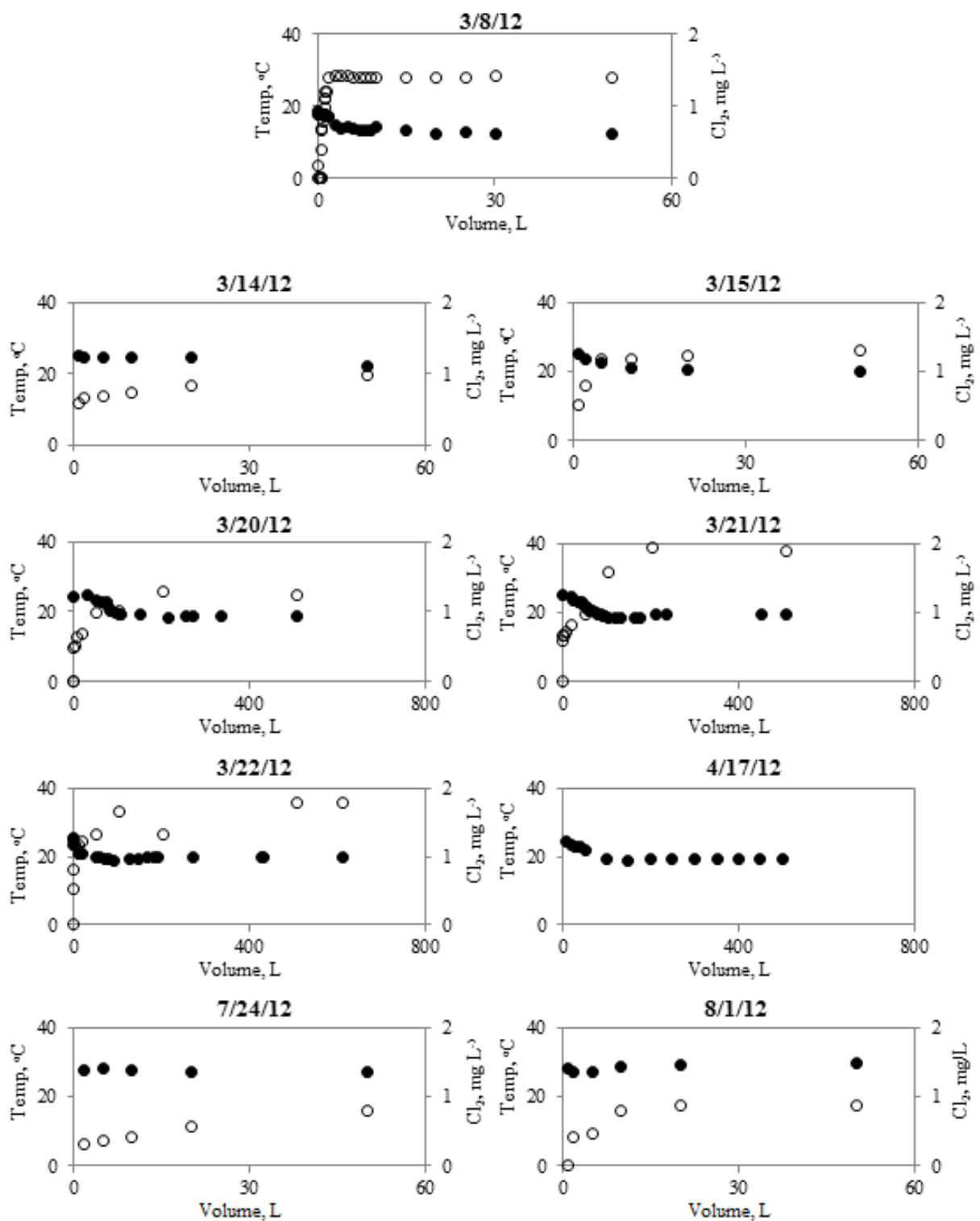


Figure A-4. Samples taken in Earth and Planetary Sciences. White dots (○) represent free chlorine concentration in mg/L . Black dots (●) represent temperature in $^{\circ}\text{C}$

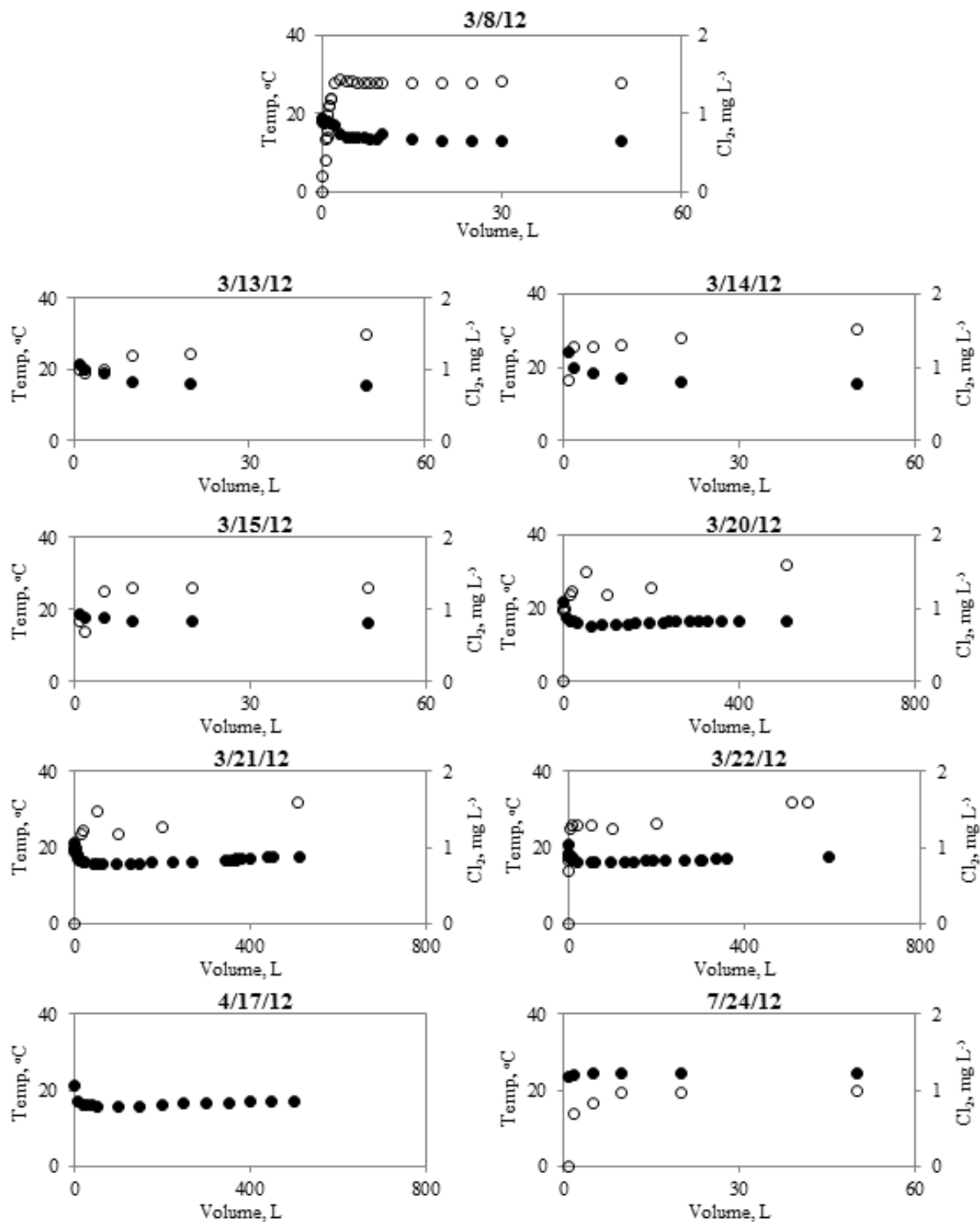


Figure A-5. Samples taken in Ferris Hall. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

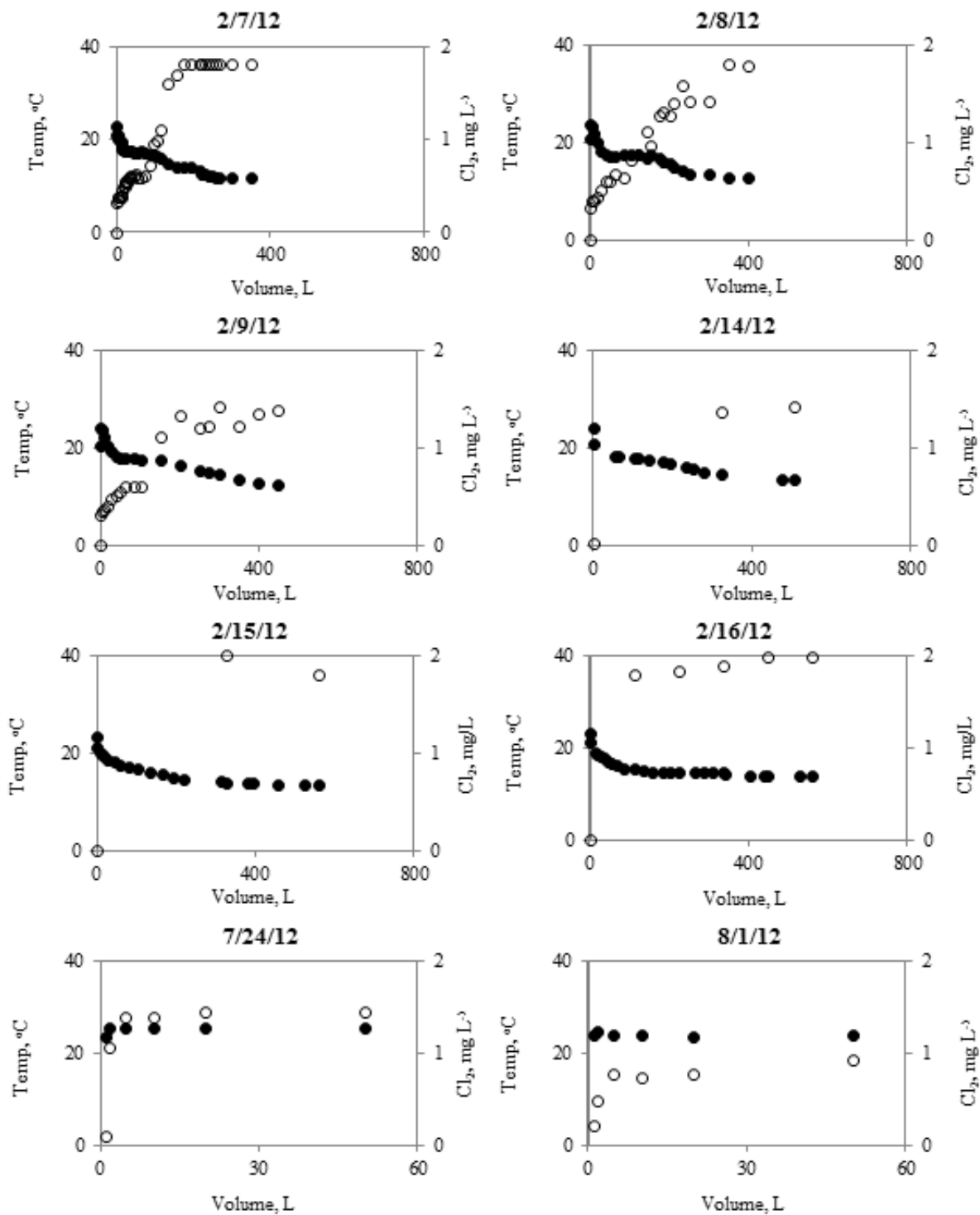


Figure A-6. Samples taken in Min Kao Electrical Engineering building. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

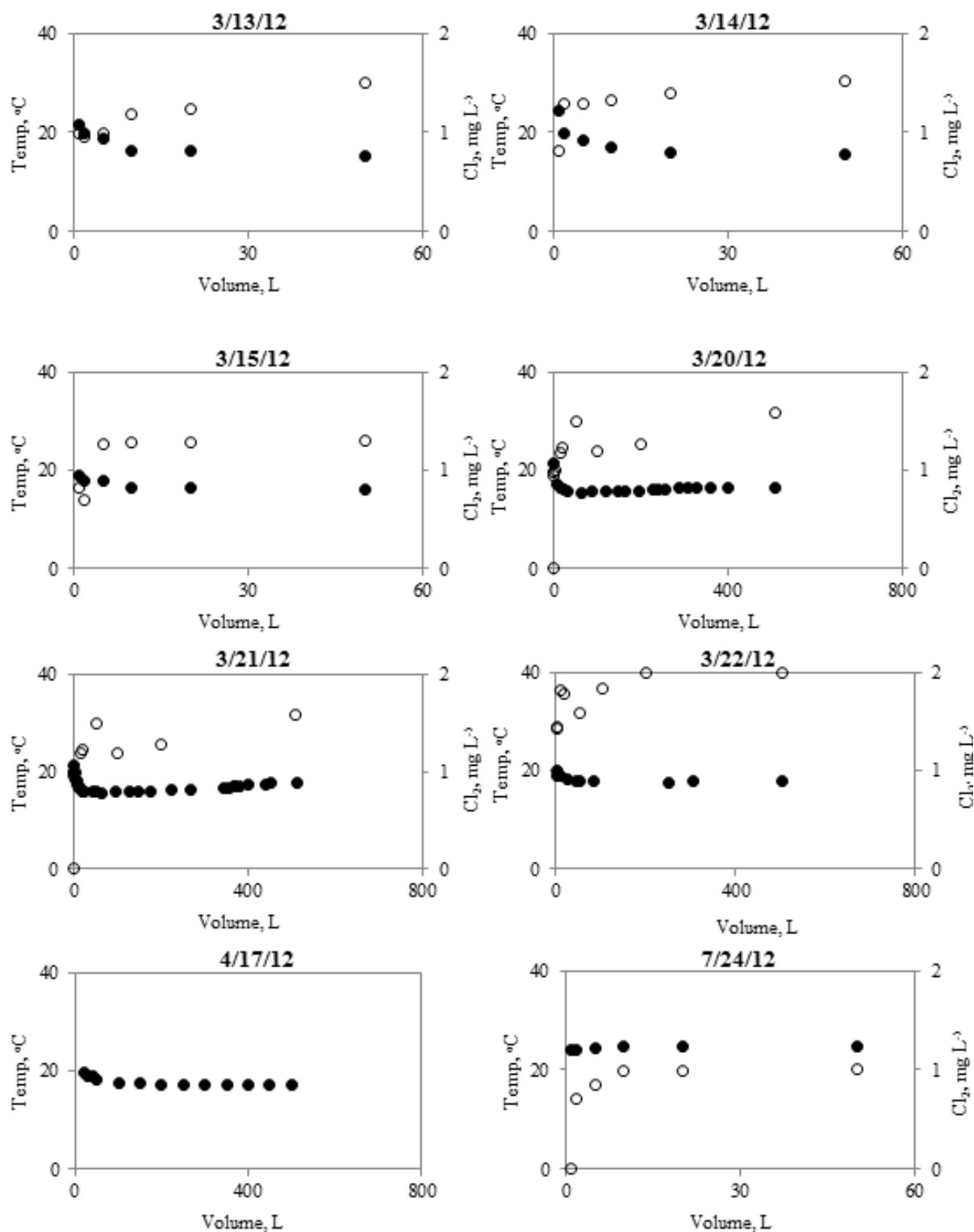


Figure A-7. Samples taken in Haslam Hall. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in oC.

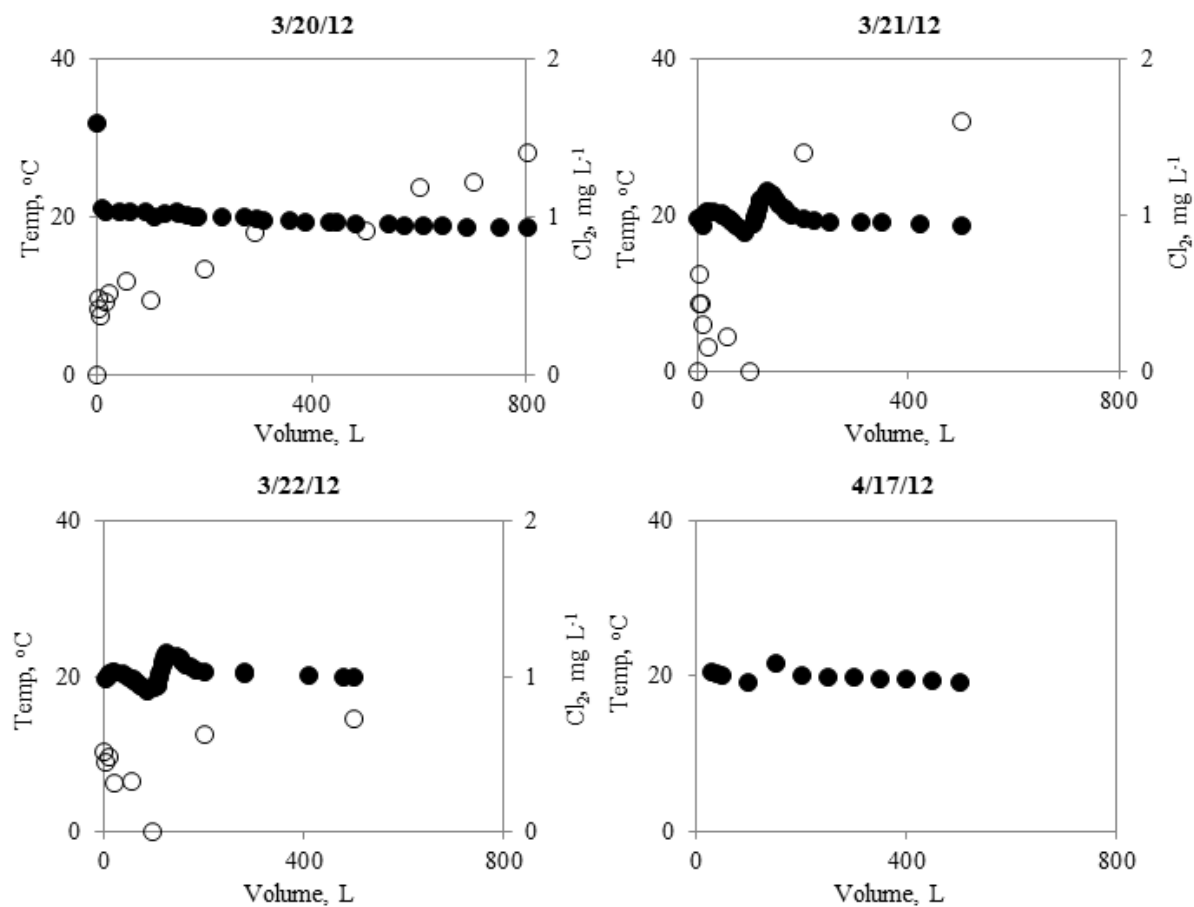


Figure A-8. Samples taken in Pasqua Hall. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

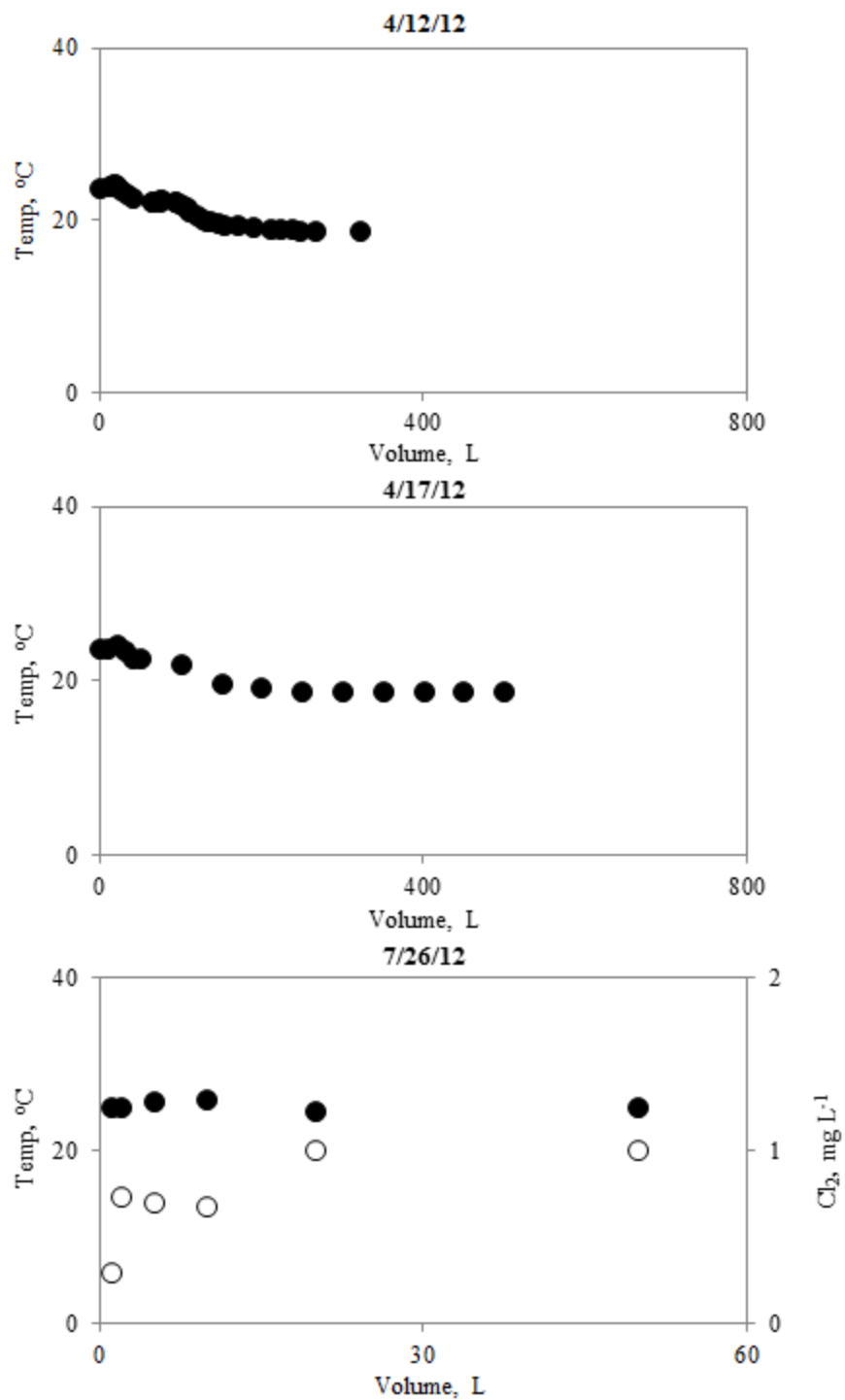


Figure A-9. Samples taken in the Baker Center. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

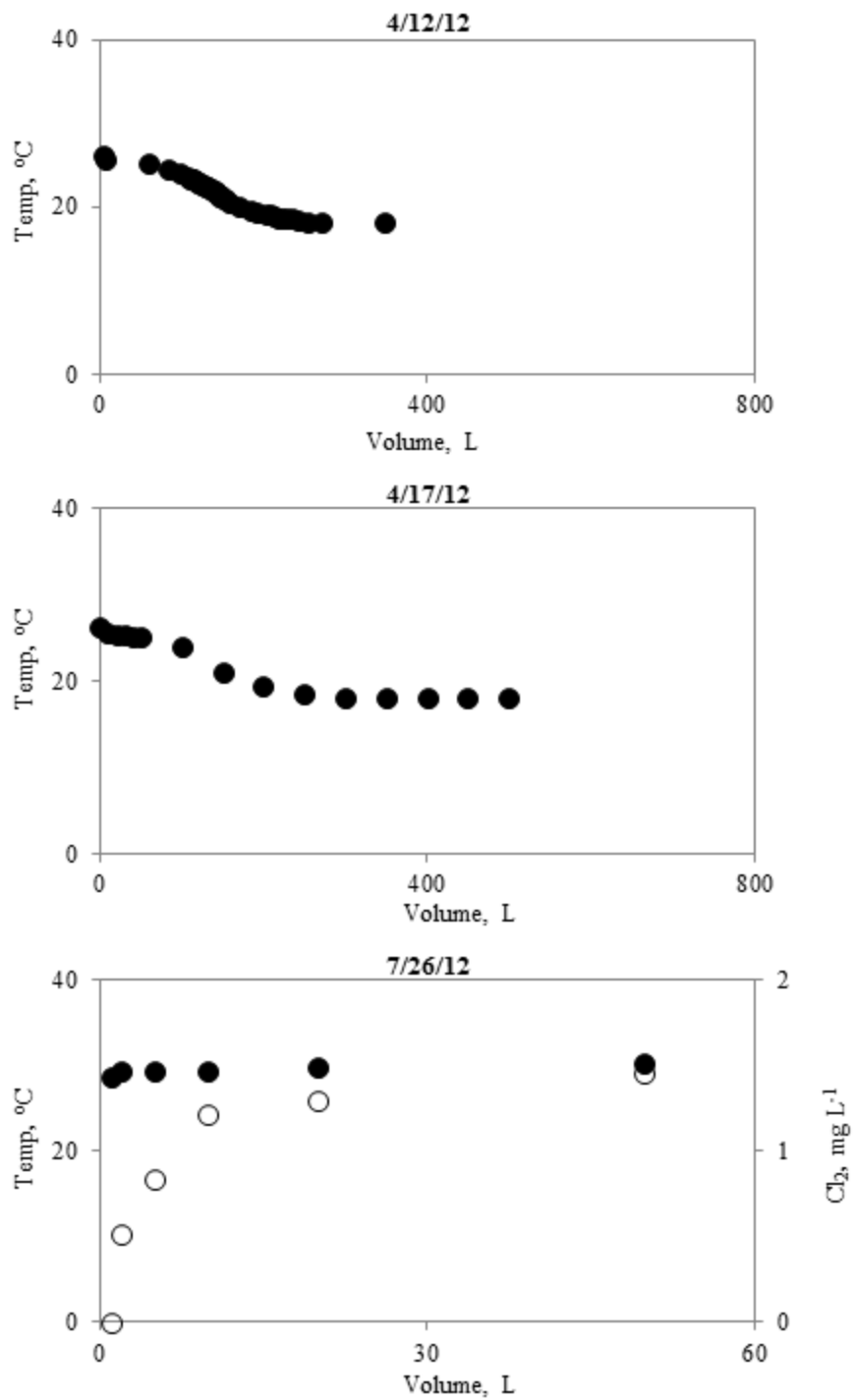


Figure A-10. Samples taken in Perkins Hall. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

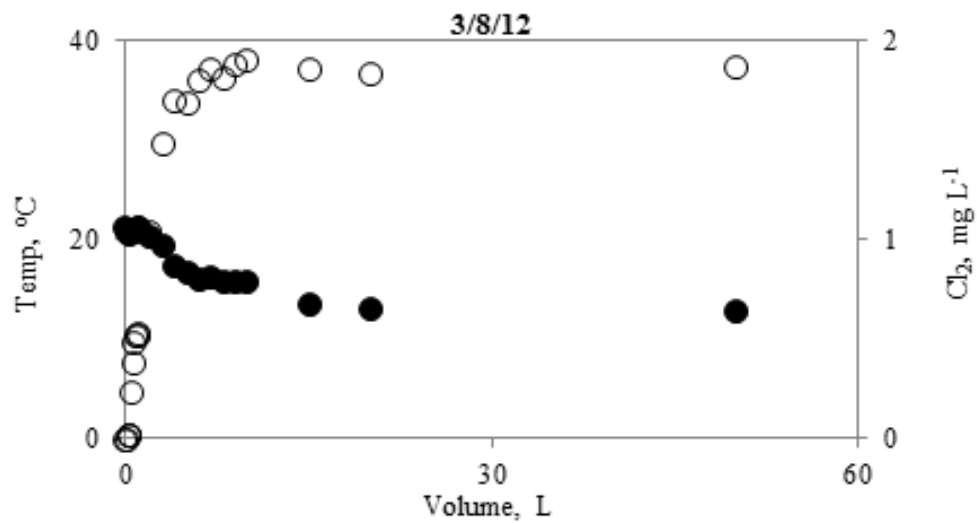


Figure A-11. Samples taken in the Science and Engineering Research Facility. White dots (○) represent free chlorine concentration in mg/L. Black dots (●) represent temperature in °C.

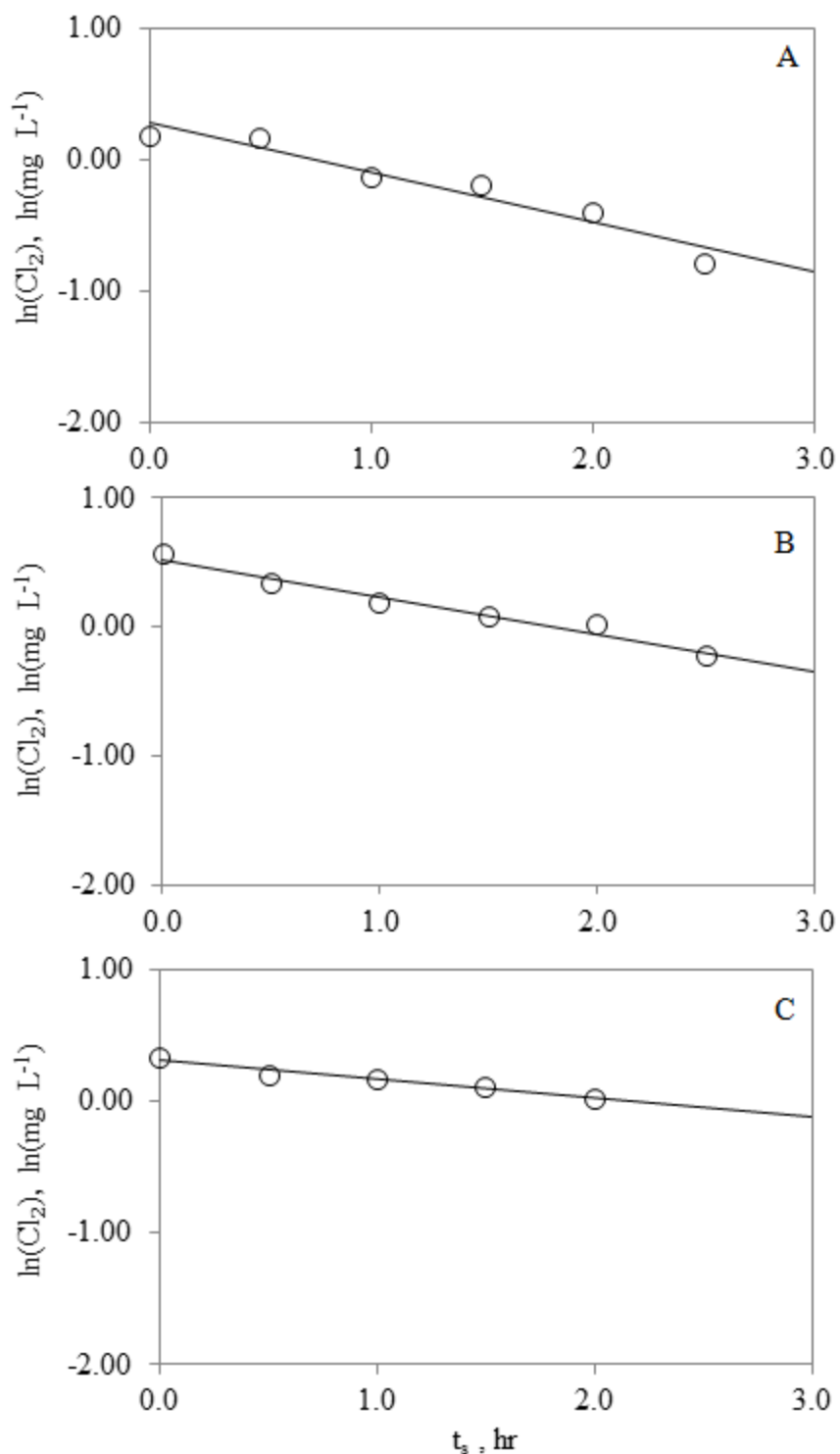


Figure A-12. Natural log of the concentration of free chlorine over time for Ayers Hall on November 14, 2012. Samples A, B, and C have initial times of 7:25AM, 10:25AM, and 1:25PM, respectively. The respective R^2 values of the linear regressions are 0.929, 0.969, and 0.942. The k -values (hr^{-1}) are 0.379, 0.290, and 0.143.

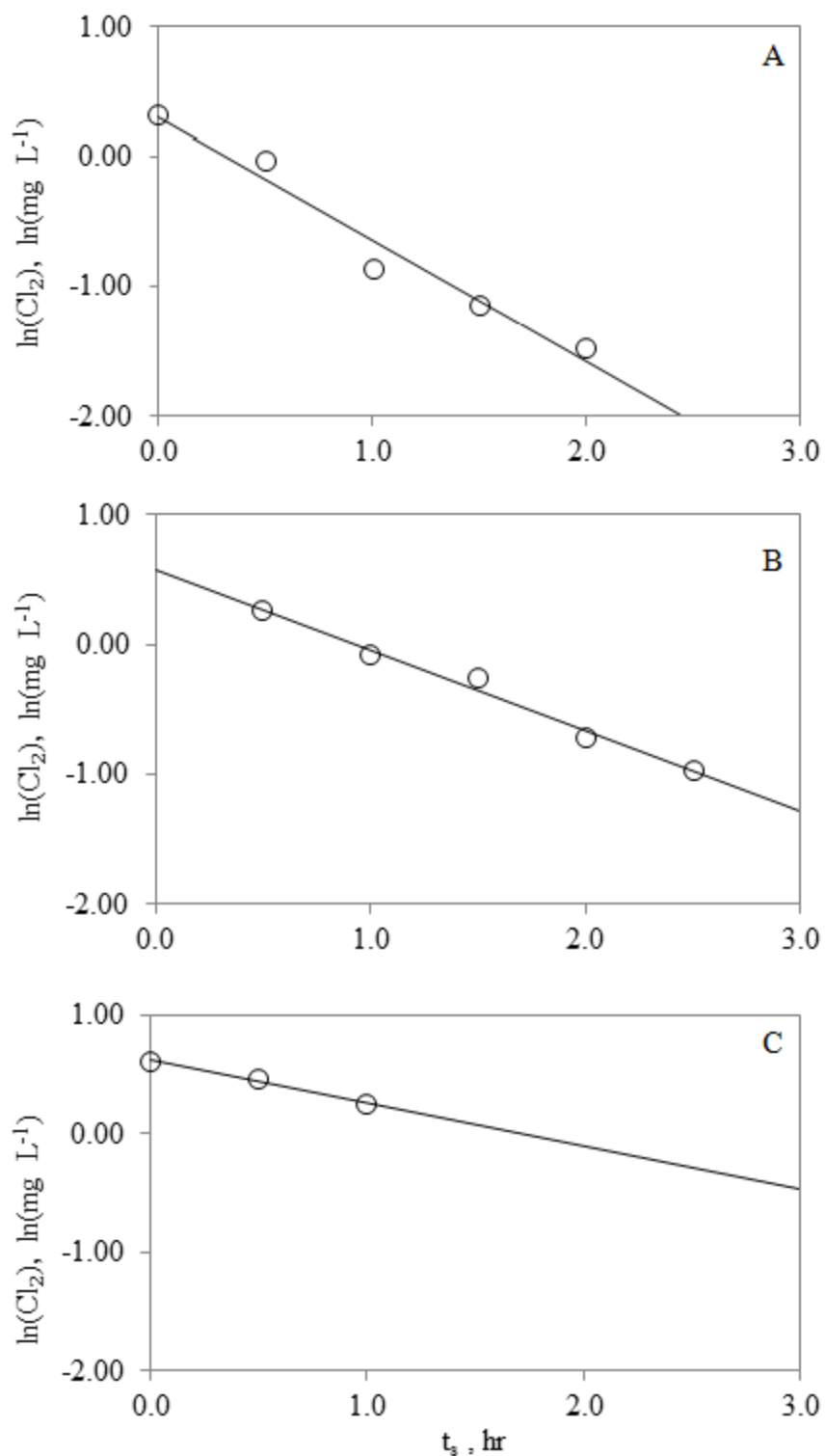


Figure A-13. Natural log of the concentration of free chlorine over time for Earth and Planetary Science Building on December 3, 2012. Samples A, B, and C have initial times of 7:30AM, 10:00AM, and 1:00PM, respectively. The respective R^2 values of the linear regressions are 0.963, 0.988, and 0.988. The k -values (hr^{-1}) are 0.939, 0.620, and 0.360.

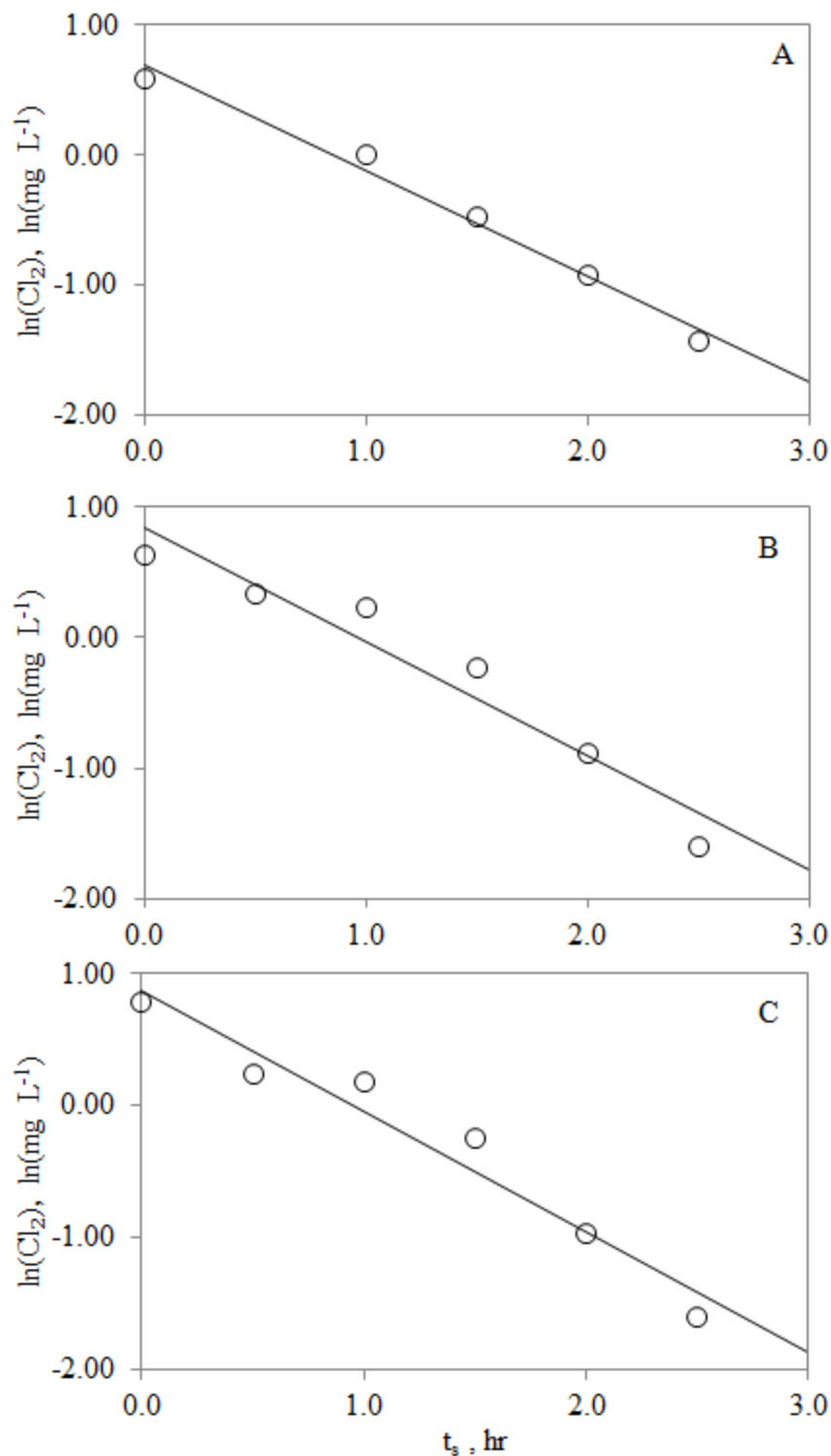


Figure A-14. Natural log of the concentration of free chlorine over time for the James A. Haslam II Business Building on August 21, 2012. Samples A, B, and C have initial times of 6:50AM, 9:40AM, and 12:30PM, respectively. The respective R^2 values of the linear regressions are 0.986, 0.929, and 0.951. The k-values (hr^{-1}) are 0.808, 0.874, and 0.917.

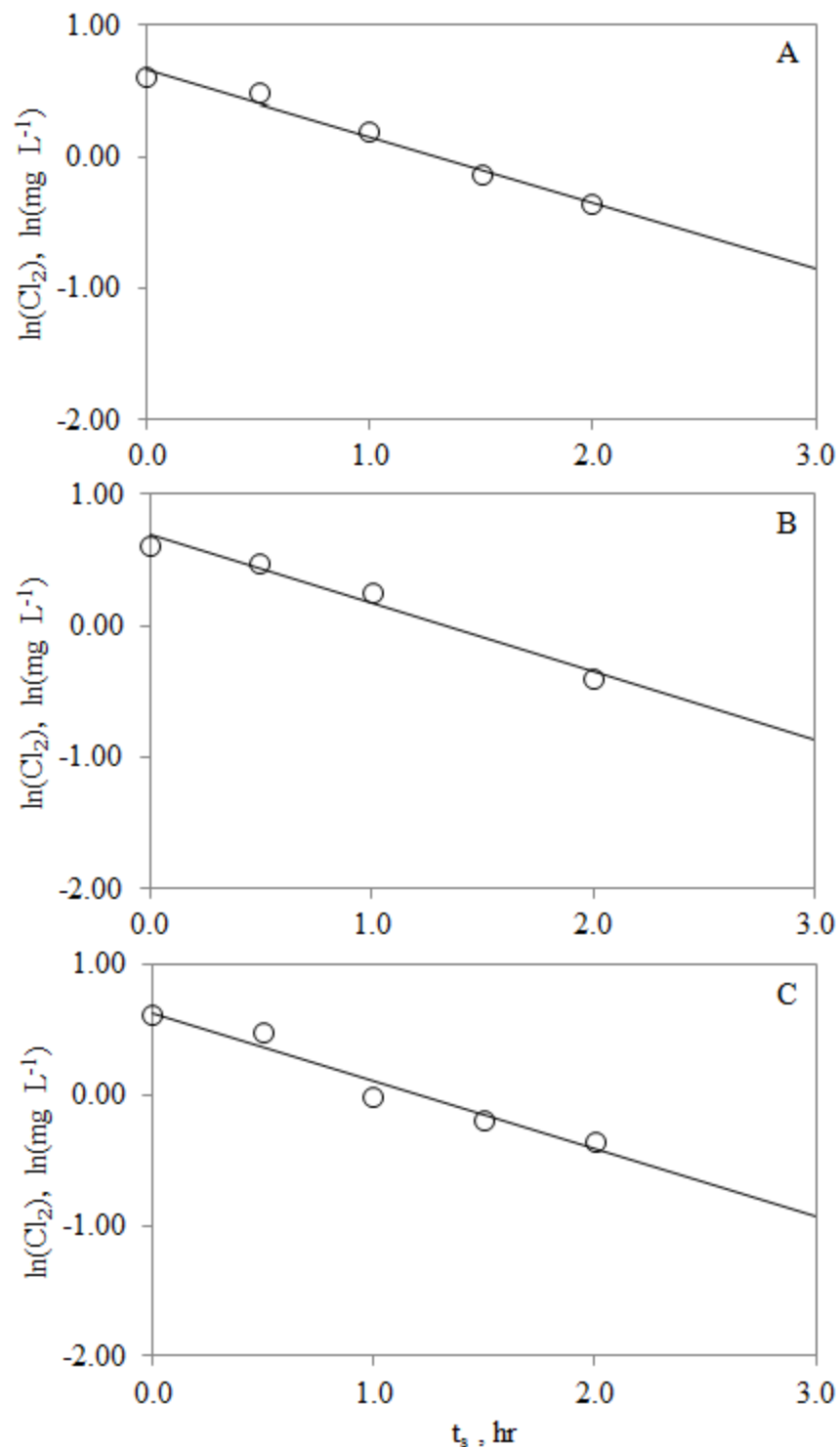


Figure A-15. Natural log of the concentration of free chlorine over time for the Howard H. Baker Jr.Center for Public Policy on November 7, 2012. Samples A, B, and C have initial times of 7:40AM, 10:14AM, and 12:45PM, respectively. The respective R^2 values of the linear regressions are 0.983, 0.972 and 0.954. The k -values (hr^{-1}) are 0.504, 0.518, and 0.954.

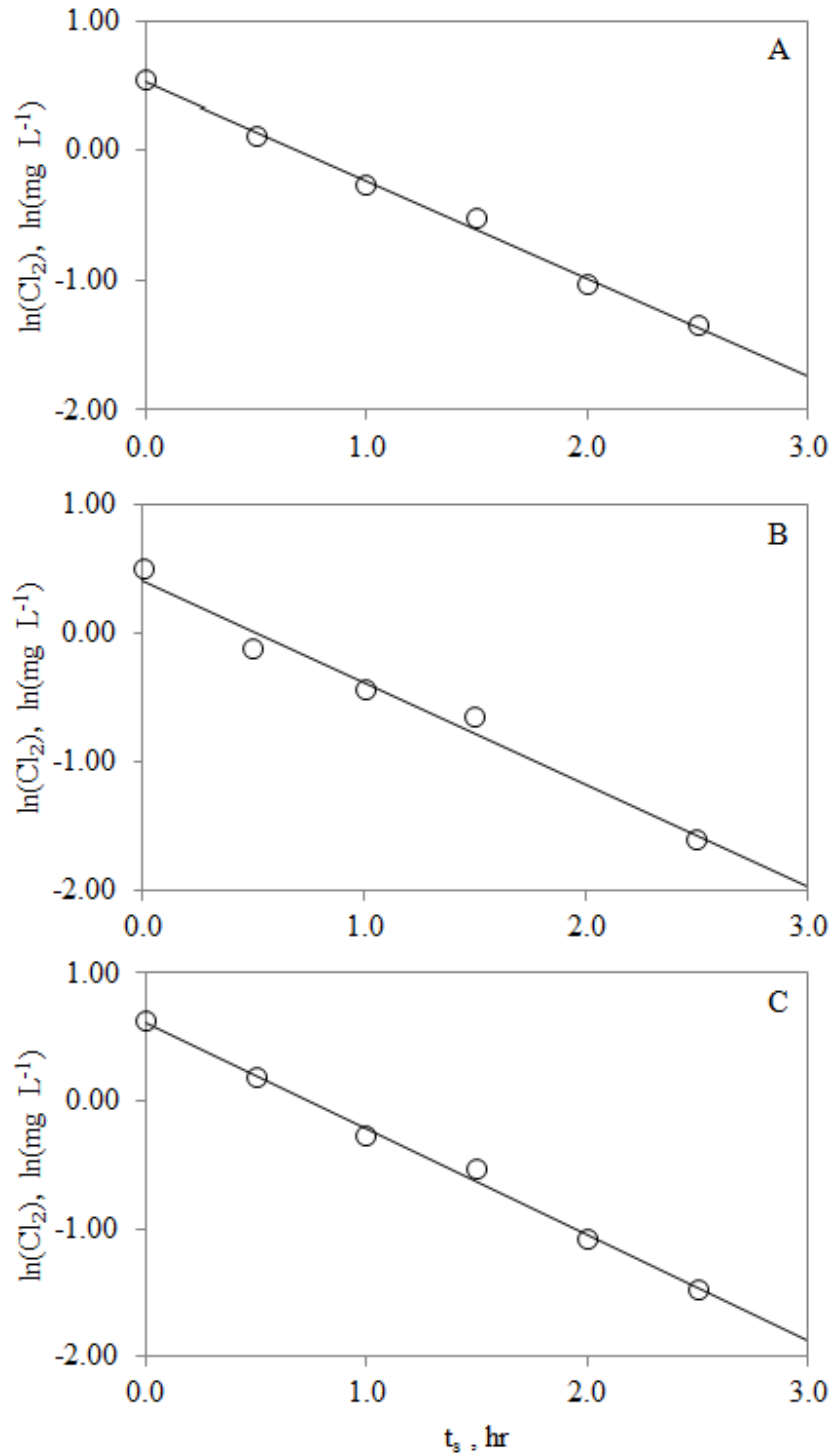
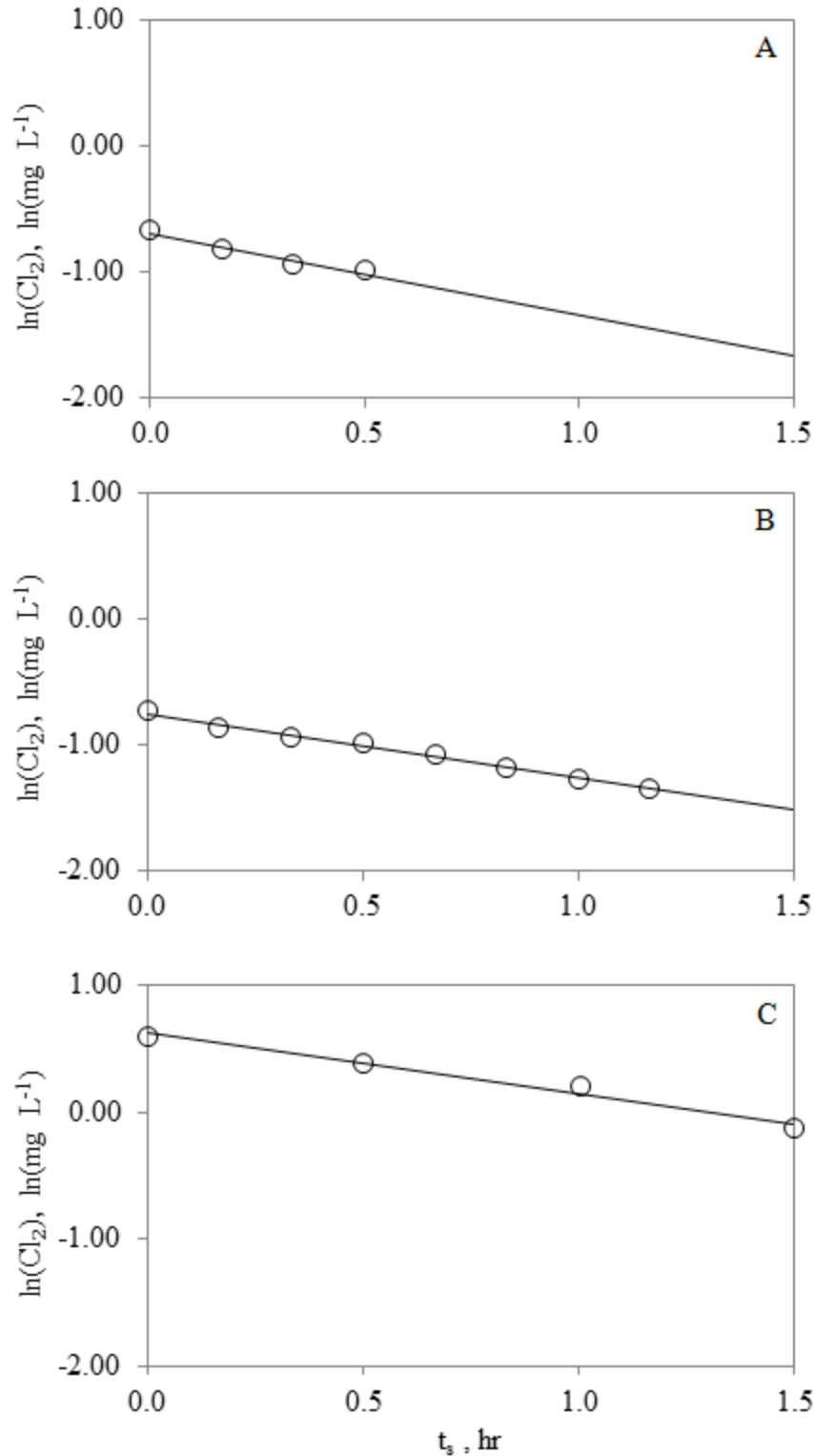


Figure A-16. Natural log of the concentration of free chlorine over time for the Min H. Kao Electrical Engineering & Computer Science Building on November 12, 2012. Samples A, B, and C have initial times of 7:45AM, 10:45AM, and 1:45PM, respectively. The respective R^2 values of the linear regressions are 0.996, 0.980 and 0.995. The k-values (hr^{-1}) are 0.751, 0.792, and 0.823.



A-17. Natural log of the concentration of free chlorine over time for Ferris Hall on October 1, 2012. Samples A, B, and C have initial times of 9:41AM, 10:51AM, and 12:11PM, respectively. The respective R^2 values of the linear regressions are 0.962, 0.993 and 0.981. The k-values (hr^{-1}) are 0.650, 0.509, and 0.474.

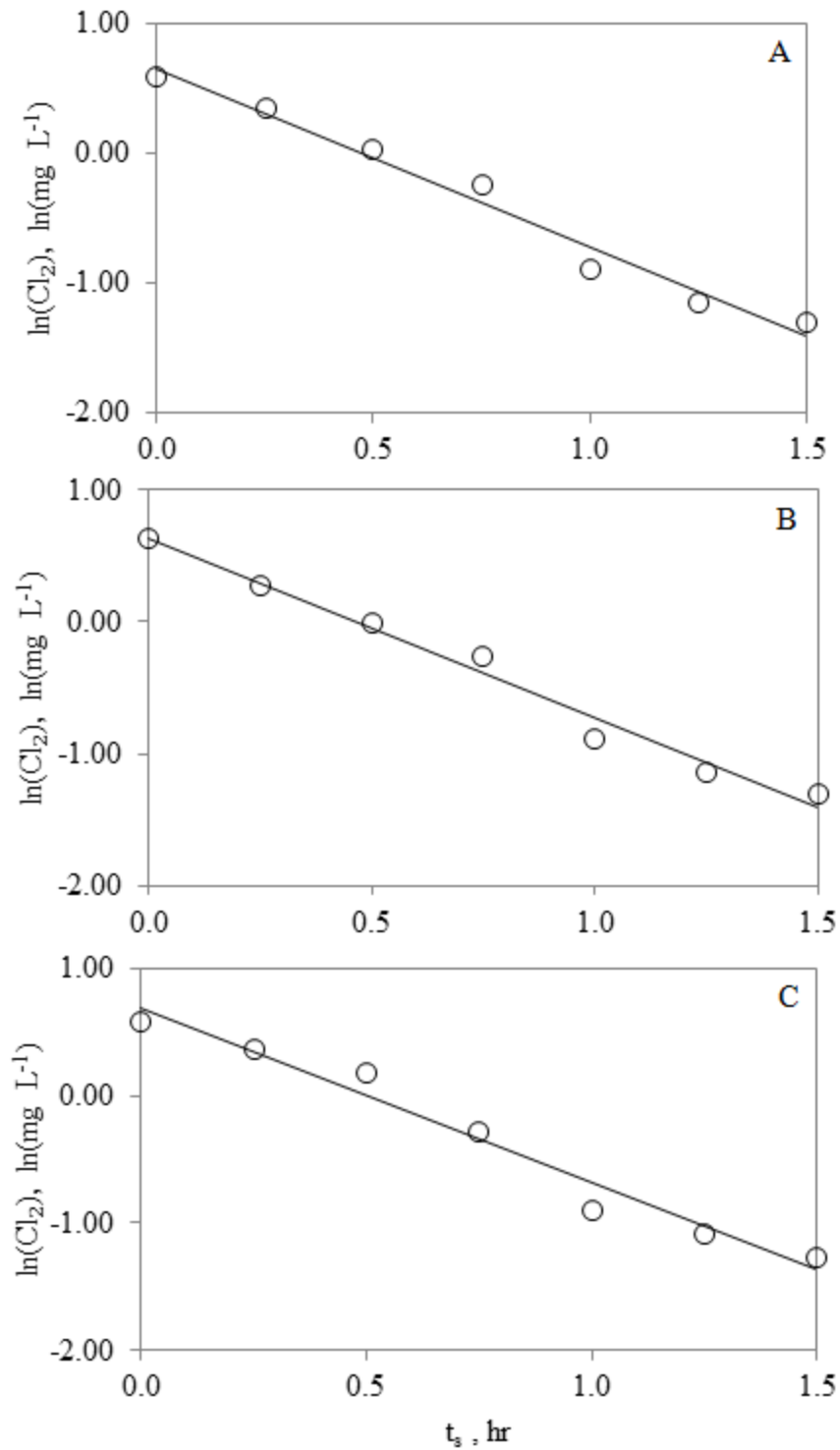


Figure A-18. Natural log of the concentration of free chlorine over time for an unused copper pipe with a 0.5 in nominal diameter. Samples A, B, and C have respective R^2 values of 0.979, 0.982 and 0.969. The k-values, (hr^{-1}) are 1.373, 1.362, and 1.362.

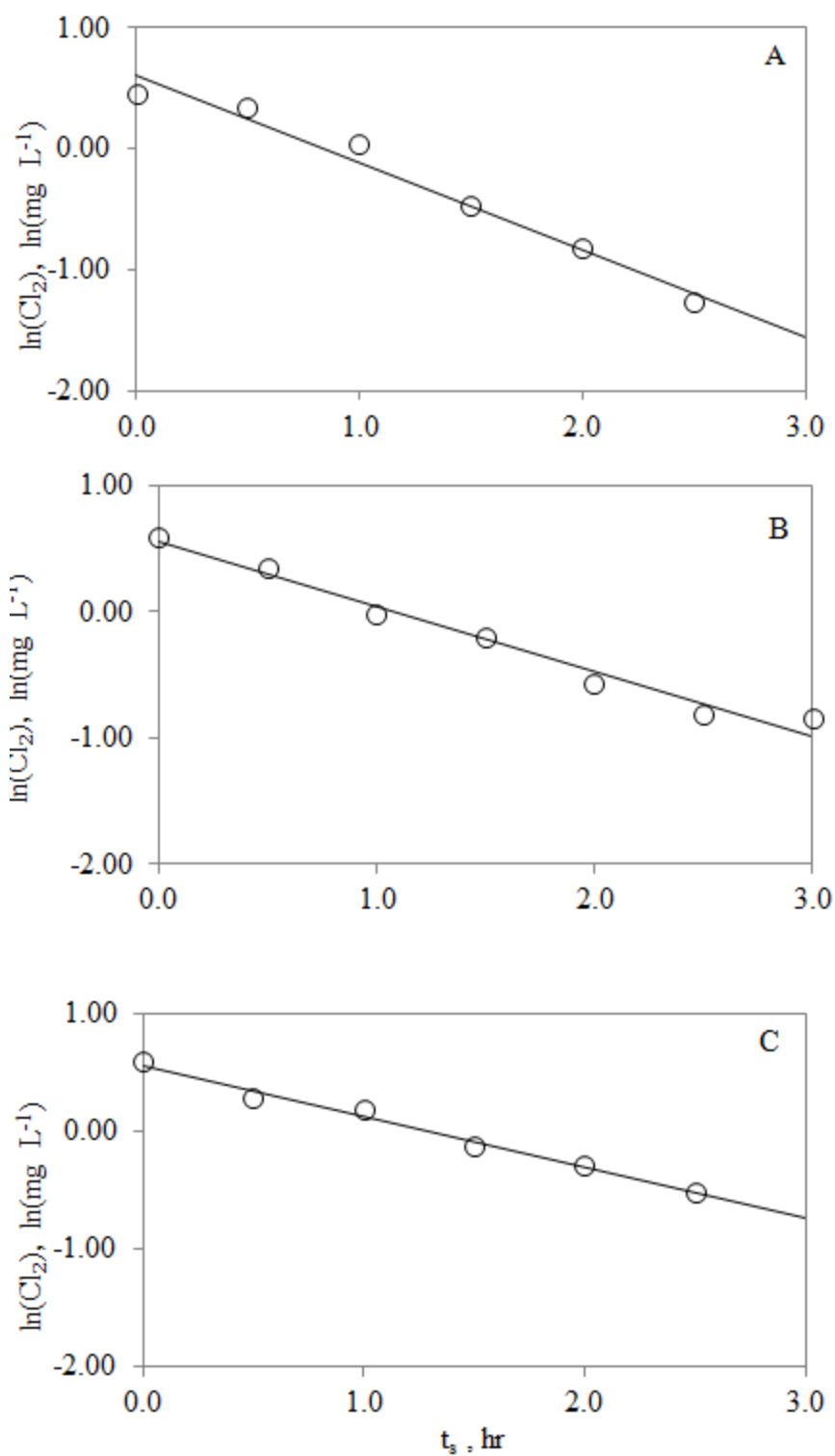


Figure A-19. Natural log of the concentration of free chlorine over time for Perkins 57B-a on September 12, 14, and 17 respectively. Samples A, B, and C have respective R^2 values of 0.97, 0.98, and 0.99. The k -values (hr^{-1}) are 0.722, 0.514, and 0.435.

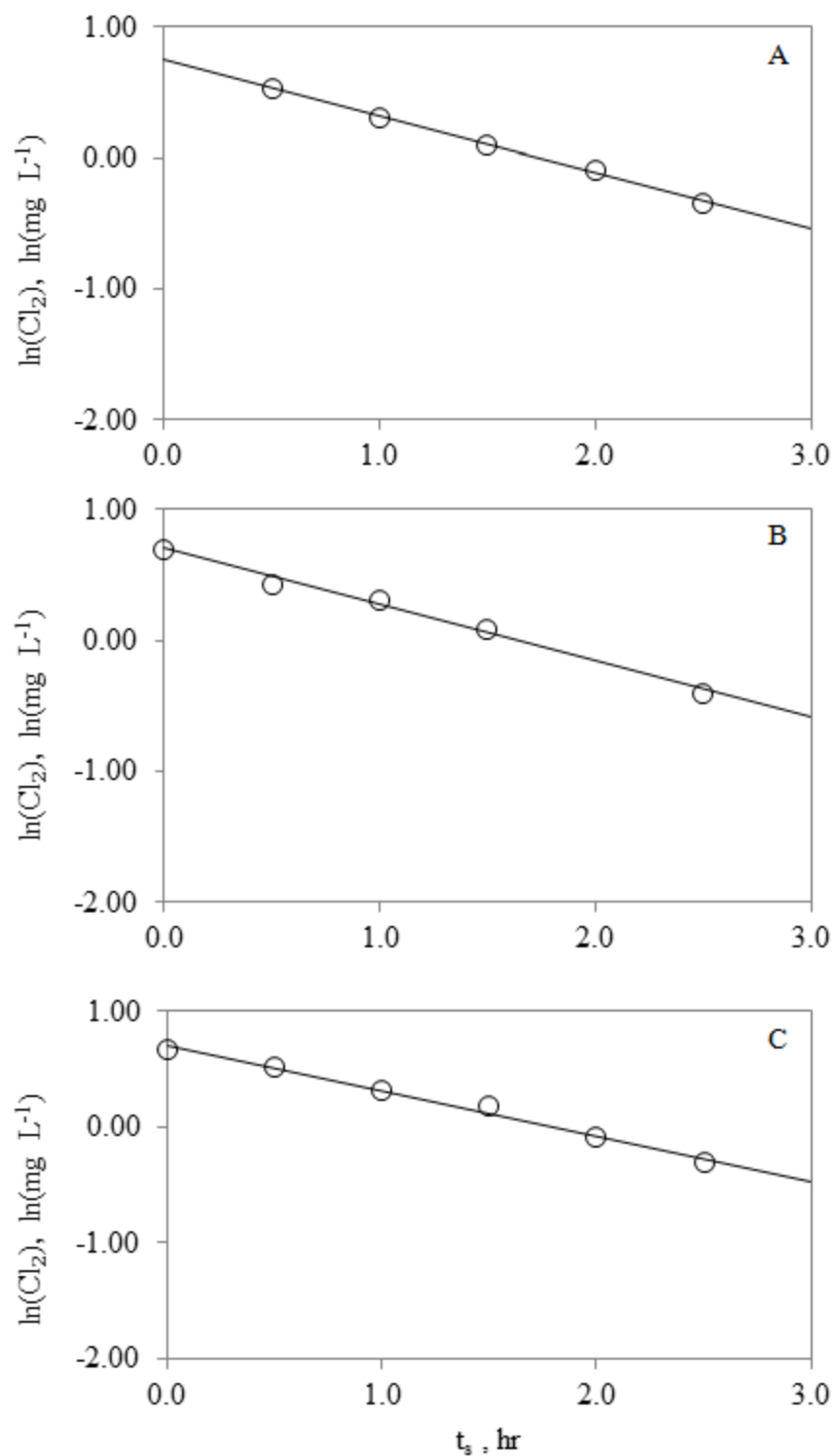


Figure A-20. Natural log of the concentration of free chlorine over time for Perkins 57B-a on September 24, 26, and 28, respectively. Samples A, B, and C have respective R^2 values of 1.00, 0.99, and 0.99. The k -values (hr^{-1}) are 0.432, 0.431, and 0.393.

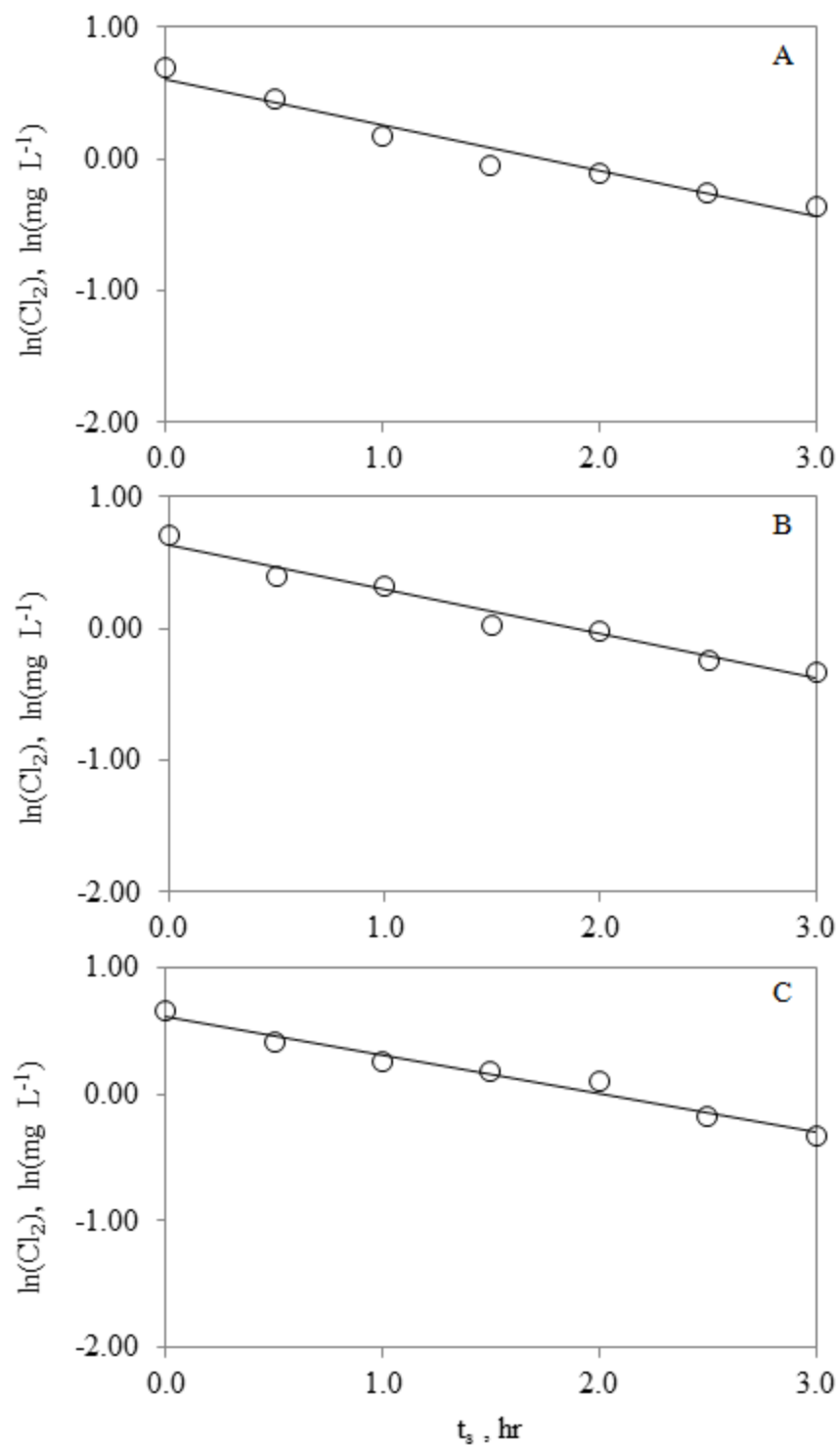


Figure A-21. Natural log of the concentration of free chlorine over time for Estabrook room 001B on October 22, 24, and 26, respectively. Samples A, B, and C have respective R^2 values of 0.96, 0.97, and 0.98. The k -values (hr^{-1}) are 0.347, 0.338, and 0.304.

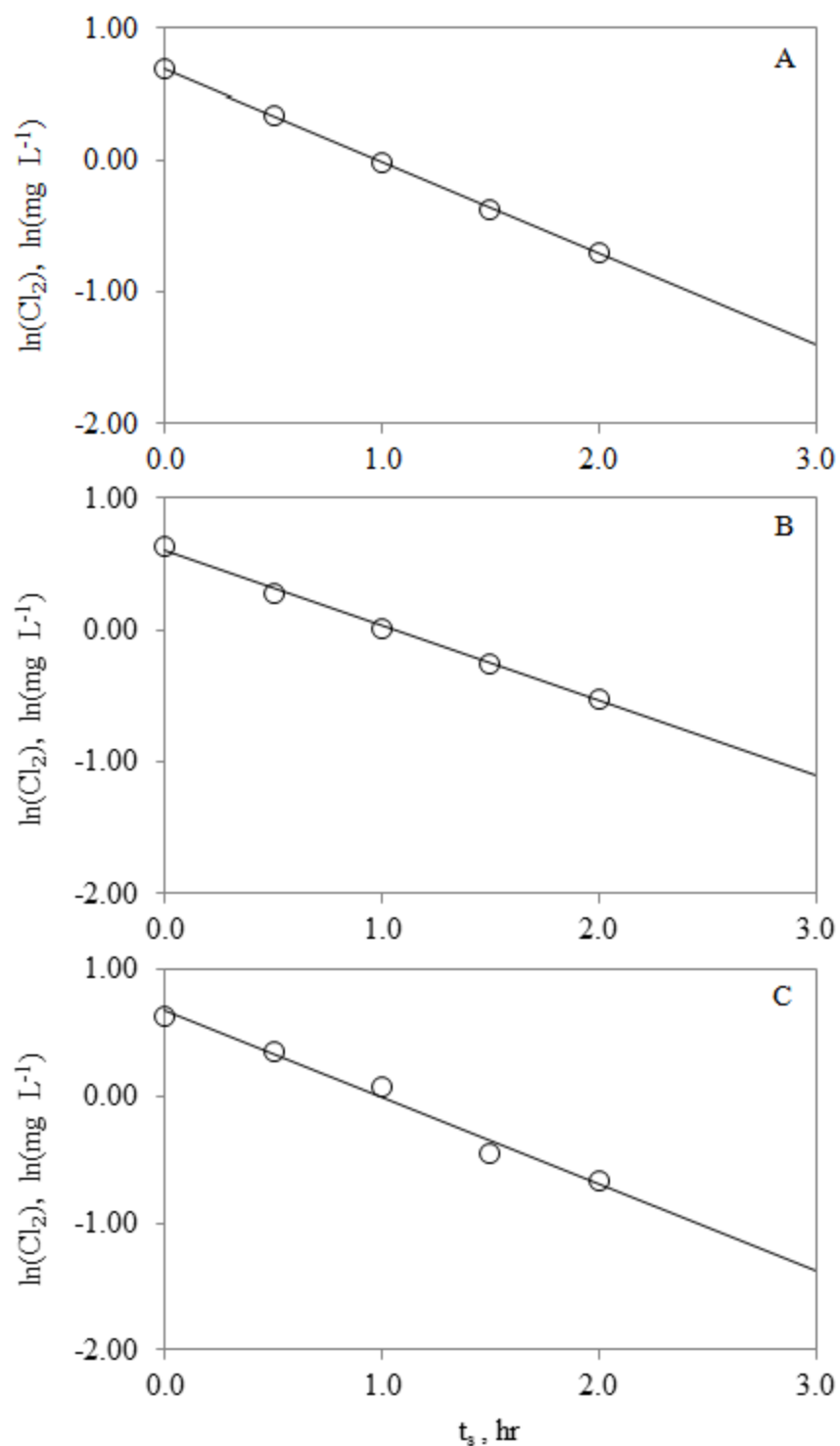


Figure A-22. Natural log of the concentration of free chlorine over time for Min Kao on September 24 and September 25 at (b) 7:10AM and (c) 10:10AM, respectively. Samples A, B, and C have respective R^2 values of 1.00, 1.00, and 0.99. The k -values (hr^{-1}) are 0.696, 0.569, and 0.685.

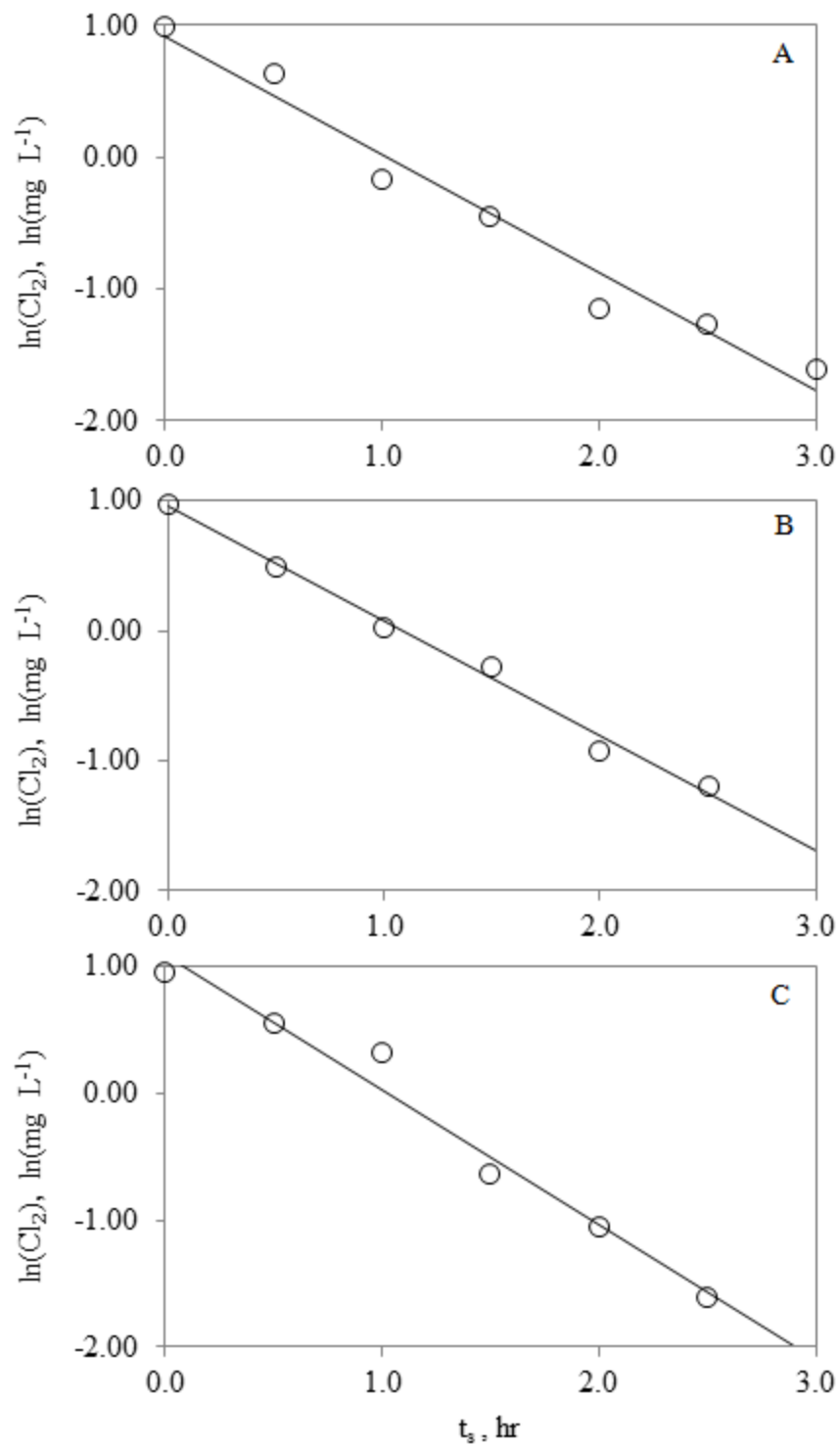


Figure A-23. Natural log of the concentration of free chlorine over time for Haslam on August 17, 20, and 21, respectively. Samples A, B, and C have respective R^2 values of 0.97, 0.99, and 0.97. The k -values (hr^{-1}) are 0.900, 0.993, and 1.063.

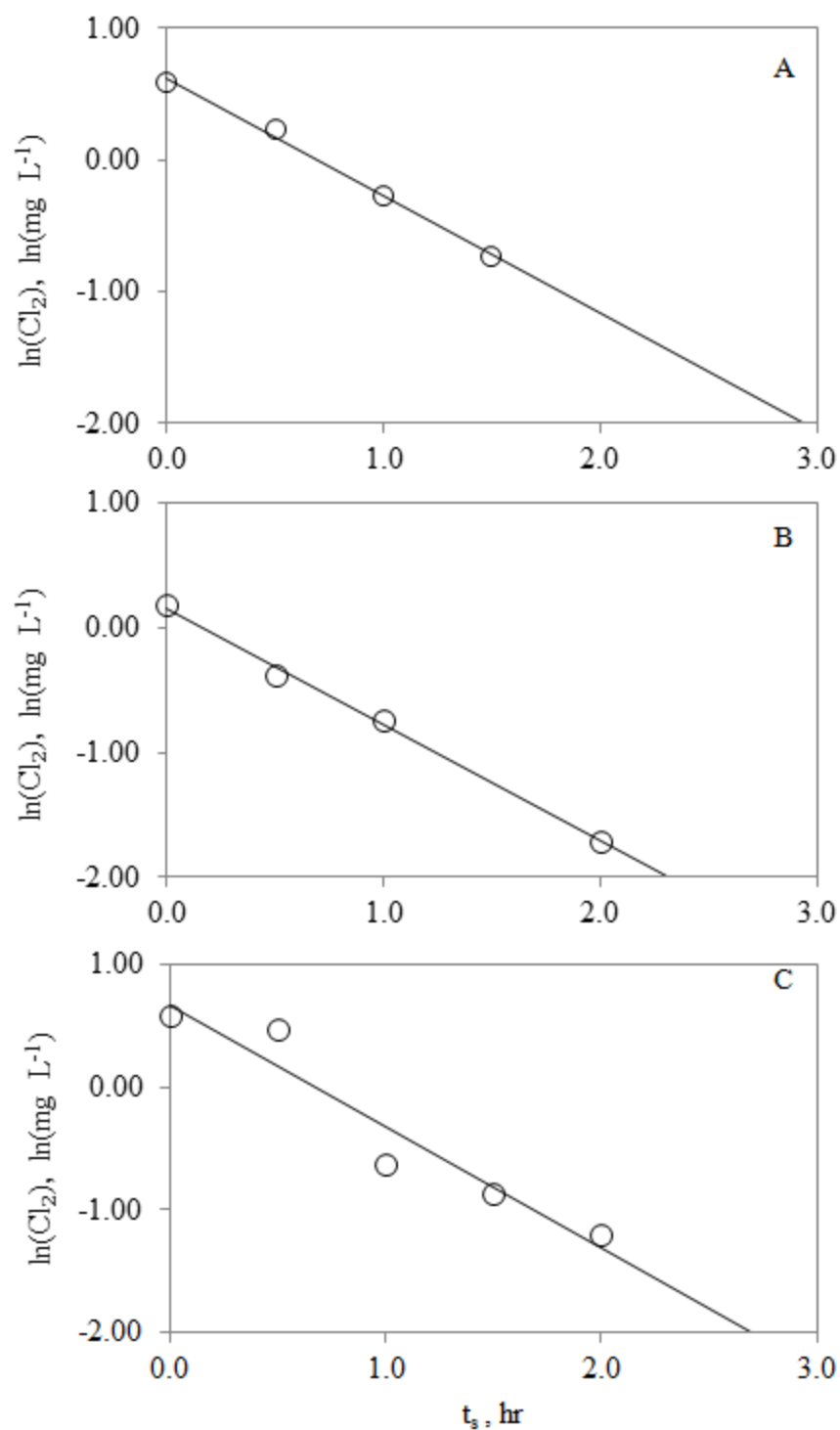


Figure A-24. Natural log of the concentration of free chlorine over time for Baker on August 21, 22, and 23, respectively. Samples A, B, and C have respective R^2 values of 0.99, 1.00, and 0.92. The k -values (hr^{-1}) are 0.896, 0.931, and 0.987.

VITA

Joshua Thomas Frerichs was born in Kingsport, Tennessee on December 26, 1987 to his parents Rue Delano and Cindy Faye Frerichs (Frays). He is the youngest of four: Melanie, Neil, and Leslie. Soon after birth his family moved to Huntsville, Alabama where he attended Riverton Elementary School until the 3rd grade. In 1997, he moved to Maryville, Tennessee and continued his elementary school career at Foothills Elementary School. He subsequently attended Maryville Middle and High school. Joshua graduated high school with honors in 2006.

In the fall of 2006, Joshua enrolled in the University of Tennessee, Knoxville. He marched in the Pride of the Southland Marching Band for three years. He was the Editor for Chi Epsilon, the civil engineering honors society, during 2010 and 2011. He was captain of the Concrete Canoe Team for the American Society of Civil Engineers (ASCE) in 2010 and the President of ASCE in 2011. He received a strong chemistry background during his first four years of his undergraduate program while obtaining the entrance requirements for dental school. Desiring to apply his science classes in his career, Joshua decided to pursue a career in environmental engineering rather than entering dental school. He received his Bachelor of Science in Civil Engineering with Magna Cum Laude honors in 2011.

After graduating from his undergraduate studies, Joshua began an internship at Oak Ridge National Laboratory where he co-authored two papers. The following school year he received a fellowship to attend the University of Tennessee in order to earn his Master's Degree. During his studies, he co-authored yet another paper. After his first year of graduate school he married Lauren Rene Hartweg. Joshua graduated with a Master of Science in Environmental Engineering in August 2013.