2014

Dishwashing Water Recycling System and Related Water Quality Standards for Military Use

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Church, Jared, "Dishwashing Water Recycling System and Related Water Quality Standards for Military Use" (2014). *Electronic Theses and Dissertations, 2004-2019*. 655.
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DISHWASHING WATER RECYCLING SYSTEM AND RELATED WATER QUALITY STANDARDS FOR MILITARY USE

by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2015

Major Professor: Woo Hyoung Lee

ABSTRACT

As the demand for reliable and safe water supplies increases, both water quality and available quantity are being challenged by population growth and climate change. Greywater reuse is becoming a common practice worldwide; however, in remote locations of limited water supply, such as those encountered in military installations, it is desirable to expand its classification to include dishwashing water to maximize the conservation of fresh water. Given that no standards for dishwashing greywater reuse by the military are currently available, the current study determined a specific set of water quality standards for dishwater recycling systems for U.S military field operations.

A tentative water reuse standard for dishwashing water was developed based on federal and state regulations and guidelines for non-potable water, and the developed standard was cross-evaluated by monitoring water quality data from a full-scale dishwashing water recycling system using an innovative electrocoagulation and ultrafiltration process. A quantitative microbial risk assessment (QMRA) was also performed based on exposure scenarios derived from literature data. As a result, a specific set of dishwashing water reuse standards for field analysis (simple, but accurate) was finalized as follows: turbidity (<1 NTU), *E. coli* (<50 cfu mL^{-1}), and pH (6–9). UV_{254} was recommended as a surrogate for organic contaminants (e.g., BOD_5), but requires further calibration steps for validation.

The developed specific water standard is the first for dishwashing water reuse and will be expected to ensure that water quality is safe for field operations, but not so stringent that design complexity, cost, and operational and maintenance requirements will not be feasible for field use. In addition the parameters can be monitored using simple equipment in a field setting with only modest training requirements and real-time or rapid sample turn-around. This standard may prove useful in future development of civilian guidelines.

ACKNOWLEDGMENTS

I thank all who contributed in the completion of this thesis in one way or another. First, I would like to give thanks to God without whom nothing is possible.

I am so grateful for my advisor, Dr. Woo Hyoung Lee, who guided me with understanding and generous guidance and support. With his ambitious attitude, I was able to immerse myself in a broad range of research involvement. I would also like to thank my master thesis committee, Dr. Andrew Randall and Dr. Steven Duranceau for their guidance and encouragement during this work.

I express deep gratitude to Mainstream Engineering Corporation for funding this research. I especially thank Ted Amundson, Dustin Zastrow and Joseph Dixon for their cooperation and support.

I express my thanks to Maria Real-Robert for her guidance in the lab, from whom I learned the analytic techniques needed for the completion of this research, and to Matt Verbyla for his expertise on QMRA. His determination and professionalism was deeply appreciated. I would also like to thank my research group friends: Xiangmeng Ma, Faris Munshi and Xiaochen Wang for their help with laboratory work and support.

Finally, I dedicate this work to my wife, Haillie, for her devotion and endless support. I thank my parents and family and parents-in-law and their family members for their love, support and endless encouragement.

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LIST OF ACRONYMS

ANSI	American National Standards Institute
BOD	biochemical oxygen demand
CBOD	carbonaceous biochemical oxygen demand
CFU	colony forming unit
COD	chemical oxygen demand
CWA	Clean Water Act
DALY	disability adjusted life years
DBP	disinfection by-product
DBPFP	disinfection by-product formation potential
DBAA	dibromoacetic acid
DCAA	dichloroacetic acid
DO	dissolved oxygen
DOC	dissolved organic carbon
DPR	direct potable reuse
EDC	endocrine disrupting compounds
USEPA	U.S. Environmental Protection Agency
FAC	Free available chlorine
FC	Fecal Coliform
FOB	forward operating base
FSIS	U.S. Food Safety and Inspection Service
FDEP	Florida Department of Environmental Protection

HAA	haloacetic acids
IPC	International Plumbing Code
IPR	indirect potable reuse
MBAA	monobromoactic acid
MCAA	monochloroacetic acid
MCL	maximum contaminant level
MDGs	Millennium Declaration Goals
MPN	most probable number
NDMA	N-nitrosodimethylamine
NOM	natural organic matter
NPDES	National Pollutant Discharge Elimination System
NSF	National Sanitation Foundation
NTU	nephelometric turbidity unit
O&G	Oil and Grease
OSHA	U.S. Occupation Safety & Health Administration
QMRA	quantitative microbial risk assessment
SDWA	Safe Drinking Water Act
SUVA	specific ultraviolet absorbance
TB MED	Technical Bulletin Medical
TCAA	trichloroacetic acid
TDS	total dissolved solids
THM	trihalomethanes

TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
UF	ultrafiltration
UPC	Uniform Plumbing Code
USACE	U.S. Army Corps of Engineers
USAPHC	U.S. Army Public Health Command
WHO	World Health Organization

CHAPTER ONE: INTRODUCTION

The demand for reliable and safe water supplies for municipal, agricultural, industrial, and military use has been continuously growing over the last few decades with population growth, economic development, climate change, and depletion of traditional freshwater supplies (USEPA 2012). Greywater is spent water from bathroom and kitchen sinks, showers/bathtubs, and laundry facilities (Scholze and Page 2011) and is typically reused as irrigation and cooling water in urban settings. Greywater reuse has attracted plenty of attention as a water conservation strategy and many greywater reuse systems have been developed and implemented in commercial and residential facilities to achieve significant water savings indoors and outdoors (Yu et al. 2013). However, in remote locations of limited water supply, like those encountered in military installations, greywater applications are expanded to showering and firefighting. For these remote places, it is desirable to expand potential uses to include the recycle of dishwashing water to maximize the conservation of fresh water.

This thesis sought to develop a specific water reuse standard for a dishwashing water recycling system for military field operations in fresh water-limited locations and to validate the developed water standard by cross-evaluating the water quality data from a greywater recycling system. For the current scope of work, this study focused on water reuse within the United States (U.S.) military; however, the results of this study may be applicable for a number of other settings involving traveling individuals in remote and water-scarce locations, such as Peace Corps volunteers.

For the reuse of greywater in the U.S., many regulations and standards have been developed based on the U.S. Environmental Protection Agency (USEPA) Secondary Treatment

Standard. Water quality standards for greywater reuse should satisfy the following four criteria: hygienic safety, aesthetics, environmental tolerance, and economic feasibility (Nolde 2000). Typical greywater standards are regulated at the state level and exclude greywater generated from dishwashing because of the relatively large concentration of pollutants (USEPA 2012; Friedler 2004; Li et al. 2009). However, these standards vary from state to state and there are currently no guidelines or regulations regarding dishwashing water reuse at either the federal or state level or in the U.S. Army Public Health Command (USAPHC) guidelines (USAPHC 2011). Guidelines for water reuse in military field operations set by U.S. Army Technical Bulletin (TB) MED 577: "Sanitary Control and Surveillance of Field Water Supplies" differ from state-regulated standards and include standards for shower and laundry water recycling (US Army 2010); but there are no standards for dishwater recycling. The gap between state greywater regulations and military guidelines, along with the lack of guidelines for dishwater reuse standards make the deployment of a dishwater recycling system difficult (Lazarova et al. 2003).

Given the need to further develop military guidelines for dishwater recycling, the objective of this thesis is to recommend standards for the use of reclaimed dishwashing water, based on federal, state, and USAPHC regulations and guidelines for non-potable water use. Various water quality data (e.g., BOD_5, COD, TOC, pH, Turbidity, TSS, TDS, TP, UV_{254}, and SUVA), along with chlorine demand and disinfection by-product formation potential, were assessed using a full-scale dishwashing water recycling system with electrocoagulation (EC) and ultrafiltration (UF). A quantitative microbial risk assessment (QMRA) model was used to develop recommendations for the maximum tolerable concentrations of *E. coli*, *Salmonella*, and human norovirus in reclaimed dishwashing water.

CHAPTER TWO: DEVELOPMENT OF INTIAL WATER QUALITY STANDARDS FOR DISHWATER RECYCLING

2.1 Water Reuse Regulations, Guidelines and Applications

As natural water sources become strained from population growth, water utilities have been looking to reduce freshwater demands through the reuse of greywater for non-potable uses (USEPA 2012). The most common practice for water reuse is agricultural irrigation (WHO 2006). However, the applications also include industrial, environmental, and urban reuse. Greywater constitutes almost 70% of all domestic wastewater, but only contains 30% of the organic pollutants making it a common source for water reuse (Pidou et al. 2007). Currently, regulations controlling the quality of treated and/or untreated water for reuse are only controlled at the state or local level (Figure 1).

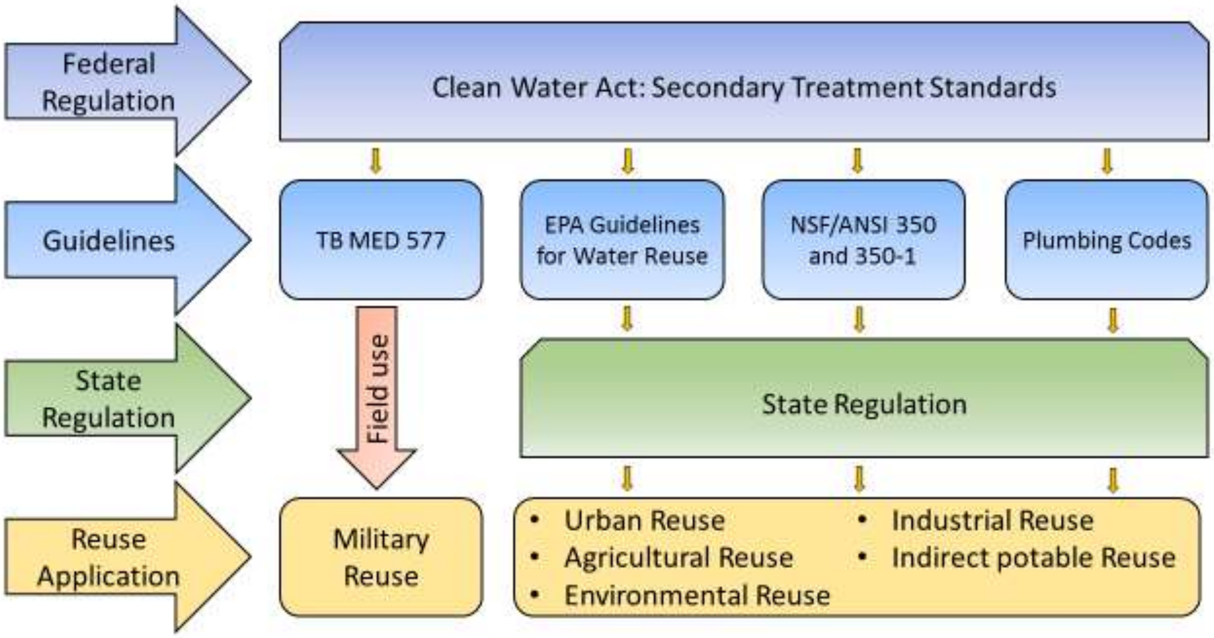


Figure 1. Guidelines, regulations and applications of greywater reuse.

The state of California was the first to generate water reuse standards for irrigation in 1918 and as interest continued to increase, the U.S. EPA drafted guidelines to offer support to states who wished to develop their own regulation (USEPA 2012). Today, more than 30 states have some form of legislation governing water reuse (Yu et al. 2013). As shown in Figure 1, greywater reuse applications are generally governed by state regulation or TB MED 577 "Sanitary Control and Surveillance of Field Water Supplies" during military field applications. State regulated water quality standards are typically adopted from nationally recognized guidelines including U.S. EPA Guideline for Water Reuse, NSF International/American National Standards Institute (NSF/ANSI) 350 and 350-1, and plumbing codes, all of which fall under the national standards set by the Clean Water Act (CWA).

Greywater reuse is growing rapidly worldwide, especially in areas of high water stress like Israel, Spain and Australia (Oron et al. 2014). Approaches to and stringency of greywater regulations vary greatly from country to country. Greywater reuse standards from around the world generally exclude kitchen greywater, only governing water from bathtubs, showers, handwashing basins, and washing machines. In some Australian states, untreated greywater can be used for toilet flushing, subsurface irrigation, or both; in others, greywater must be treated (Allen et al 2010; Radcliffe 2010). In Israel, Spain, Japan and Germany, greywater cannot be reused for cleaning dishes (Allen et al. 2010; Gross 2015), and plumbing codes in Canada prohibit the distribution of reclaimed greywater through faucets (Allen et al 2010). In Great Britain, Standard BS 8525-1:2010 specifies water quality guidelines for reclaimed greywater used for doing laundry, washing cars, power-washing outdoor areas, flushing toilets, and watering gardens (Table 1); it does not allow this water to be used for drinking, food preparation, cooking, dishwashing or personal hygiene (British Standards Institution 2010). The World

Health Origination (WHO) published *Guidelines for the safe use of wastewater, excreta and greywater* in response to the Millennium Declaration Goals (MDGs) set at the special session of the United Nations General Assembly in 2000. The guidelines are based on a health target of a Disability-adjusted Life Year (DALY) loss of $<10^{-6}$ per person per year. The guidelines deal mostly with agricultural irrigation and do not include dishwater recycling standards (WHO 2006).

Table 1. A selection of greywater reuse standards, guidelines and regulations from around the world

Parameter	pH	Turbidity[a] (NTU)	TSS (mg/L)	$CBOD_5$[a] (mg/L)	BOD_5[a] (mg/L)	Free Chlorine (mg Cl_2/L)	*Fecal Coliform*[b] (FC/100ml)
U.S. Secondary Treated Wastewater	6.0–9.0	<5	<30	<25	<30	-	<16
British Standard BS 8525-1:2010	5–9.5	<10 (n/a for garden watering)	-	-	-	<2.0 (<0.5 for garden watering)	Varies [f]
International Plumbing Code	-	<2	-	-	-	-	<2.2 [g]
US EPA and NSF Guidelines	6.5–8.5	<5	<30	<25	<25	0.5–2.5	<14
U.S. State Regulations	-	<2–<5	<5–<30	<8–<30	<5–<30	N.R.[c] - 5	<14
TB MED 577 (U.S. Army)	5 - 9	<10[d]	-	-	-	1 mg/L	N.D.[e]

[a] 30 day avg.; [b] 7 day avg.; [c] N.R.: not regulated; [d] < 1 NTU if filtered; [e] N.D.: non detectable; [f] For spray applications and washing machine use, guideline is for *E. coli* (not detected in 100 mL), intestinal *Enterococci* (not detected in 100 mL), *Legionella pneumophila* (spray applications only, <10/100 mL), and total coliforms (<10/100 mL); for non-spray applications (toilet flushing and garden watering), guideline is for *E. coli* (<250/100 mL), *Enterococci* (100/100 mL), and total coliforms (<1,000/100 mL). [g] Total coliforms per 100 mL (7-day median)

2.2 Greywater Regulations and Guidelines in the United States

2.2.1 Federal Regulations

In the U.S., greywater applications and standards are enforced at the state level and fall under the specifications set by the Federal Clean Water Act (USEPA 2012). Under the Clean Water Act, the U.S. EPA Secondary Treatment Standards (40 CFR 133.102) provide national standards for the disposal of wastewater. These standards are as follows; BOD < 30 mg/L, TSS < 30 mg/L, pH 6–9, and Turbidity < 5 NTU (Table 1). Because these standards regulate the disposal of all wastewater, they also become the minimum requirements for water reuse regulations and guidelines (USEPA 2012).

2.2.2 National Guidelines

2.2.2.1 United States Environmental Protection Agency (USEPA)

The U.S. EPA first developed *Guidelines for Water Reuse* in 1980 when a need for national guidance on regulations first became apparent (USEPA 2012). The most recent version in 2012 has gained a large influence over regulation with 30 states and several countries utilizing the guidelines. The document contains information on water reuse including; reuse applications, current regulatory programs, treatment technologies, public and environmental health concerns and recommended water quality standards. Although dishwater reuse does not fall into the U.S. EPA guidelines, many water reuse applications are included in the guidelines. These are as follows:

- Irrigation (Agricultural, golf course, and residential)
- Seawater barrier
- Industrial use

- Groundwater recharge
- Geothermal/energy production
- Natural system restoration
- Toilet flushing

The water quality guidelines set by the U.S. EPA vary depending on application. The largest factor determining the water standard is human exposure. For example, the U.S. EPA recommends that biological oxygen demand (BOD_5) for water used to irrigate non-food crops remain less than 30 mg/L and *fecal coliforms* stay less than 200/100ml, while water used to irrigate food crops needs a BOD less than 10 mg/L and no detectable fecal coliform/100ml. Table 2 shows an example of standards set by the EPA *Guidelines for Water Reuse*.

Table 2. EPA guidelines for water reuse (2012): unrestricted urban reuse

Parameter	pH	BOD_5	Turbidity	*Fecal coliform*	Free chlorine residual
Standard	6.0-9.0 (weekly)	< 10 mg/L (weekly)	< 2 NTU (continuous)	Non detectable (daily)	1 mg Cl_2/ L (continuous)

2.2.2.2 NSF International/American National Standards Institute (NSF/ANSI)

NSF/ANSI recently came out with guidelines for water reuse which has quickly gained popularity (NSF 2010). The NSF/ANSI Standard 350: *On-site Residential and Commercial Water Reuse Treatment Systems* and the NSF/ANSI Standard 350-1: *On-site Residential and Commercial Graywater Treatment Systems for Subsurface Discharge* provide guidance on water quality standards, methods of evaluation, product specifications, and product literature for greywater treatment systems. Along with guidelines, NSF/ANSI attempts to eliminate discrepancies between state regulations by certifying treatment systems. NSF/ANSI certification does not necessarily meet all state regulations, but it does provide a consistent standard recognized nationwide. The NSF/ANSI guidelines/certifications are split into two categories: ***Class R***: single-family residential and ***Class C***: multifamily and commercial. Both categories have standards that are unique their class. NSF/ANSI 350-1, like NSF/ANSI 350, is separated into Class R and C but only allows for subsurface irrigation. None of the NSF/ANSI standards allow for the use of dishwater.

2.2.2.3 Plumbing Codes

Plumbing codes often have water reuse guidelines and regulations built into their policies. Although most states develop their own regulations for water reuse, there are several cases where state departments (e.g., Department of Environmental Protection [DEP] and the Department of Health) have not developed water reuse standards and leave regulation to the plumbing codes (Yu et al. 2013). Plumbing codes do not normally contain quantitative water quality parameters, but regulate by installing certain treatment requirements (e.g., disinfection, pipe coloring, filtering). States typically adopt nationally or internationally recognized plumbing codes with the Uniform Plumbing Code (UPC) and the International Plumbing Code (IPC) being the most popular.

2.2.3 State Regulation

Water reuse regulations are controlled by state or local regulatory agencies (e.g. DEP, Plumbing Codes, and Department of Health) (Yu et al. 2013). The U.S. EPA recognizes 30 states that allow for the reuse of greywater. The other states do not regulate or do not allow greywater reuse. Yu *et al.* (2013) examined all state regulations for greywater reuse and found that of 29 states that promote greywater reuse, 22 states had internal inconsistencies in regulation. Discrepancies in greywater reuse stems from the adoption of plumbing codes like the UPC (8 states) or the IPC (10 states), both of which include greywater regulations. These codes often differ from regulations found within environmental, health, or sewage disposal codes. For example, West Virginia's health codes do not allow for greywater reuse, but it has adopted the IPC which contains regulation for the use of greywater. In this example, precedence is given to the stricter regulation (Glenn 2012). Regulations depend on the reuse application; Table 3 provides greywater reuse standards for the state of Florida in the U.S., showing how greywater quality standards differ between different applications.

Table 3. Florida's greywater regulations

Application	Turbidity (NTU)	TSS (mg/L)	$CBOD_5$ (mg/L)	*Fecal coliforms* (/100mL)	Free chlorine (mg Cl_2/L)	Other
Urban-unrestricted	**2-2.5** (continuous online monitoring)	**5** (max.)	**30** (avg. 30 day) **60** (max.)	75% of samples below detection **25** (max.)	> **1.0** for 15 min	*Giardia* and *Cryptosporidium* sampling once every 2 years
Agricultural reuse (for food crops)	**2-2.5** (continuous online monitoring)	**5** (max.)	**30** (avg. 30 day) **60** (max.)	75% of samples below detection **25** (max.)	> **1.0** for 15 min	*Giardia* and *Cryptosporidium* sampling once every 2 years
Agricultural reuse (for non-food crops)	N.S.	**30** (avg. 30 day) **60** (max.)	**30** (avg. 30 day) **60** (max.)	**200** (avg.) **800** (max.)	> **0.5** for 15 min	-
Groundwater recharge	N.S.	**30** (avg. 30 day) **60** (max.)	**30** (avg. 30 day) **60** (max.)	**200** (avg.) **800** (max.)	> **0.5** for 15 min	Nitrate (g N/L) < **12**

Source: U.S. EPA *Guidelines for Water Reuse 2012*

2.2.4 Military Guidelines

The U.S. Army is guided by state, federal, or international regulations when not in deployment or in the presence of any host nation requirements (U.S. Army 2010). In areas of active military operations, greywater regulation is guided by TB MED 577 (*Sanitary Control and Surveillance of Field Water Supplies*) (U.S. Army 2010). Guidelines of TB MED 577 are less stringent than regulations at the state level (Table 2) and include water standards for applications like showering, laundry, and firefighting for field water reuse. These applications are not typically regulated within the states. Although TB MED 577 regulations may be less strict than at the state level, they do comply with the CWA, in particular with Section 402, which pertains to the National Pollutant Discharge Elimination System (EPDES).

The guidelines set by TB MED 577 have water quality standards for the recycling of showering water (Table 4) which provided a reasonable set of standards for the current study due to the characteristics between showering and dishwashing being similar in terms of potential human contact and the use of detergent. Standards for shower water recycling are as follows (TB MED 577): pH 5-9, turbidity <1 NTU, hardness < 500 mg/L, TDS < 1,500 mg/L, Free chlorine residual 1 mg Cl_2/L after 30 minutes and no presence of coliforms. This guideline was selected as the best candidate for developing dishwater recycling standards.

Table 4. U.S. military showering water standards

	1980	1984	1986	2010
pH	6.5–7.5	4.5–9.5	6.4–7.5	5-9
Turbidity (NTU)	<1 desirable < 5 permissible	<1	<5	<1

	1980	1984	1986	2010
Free available chlorine residual	5 mg/L (>20°C) 10 mg/L (<20°C)	5 mg/L (>20°C) 10 mg/L (<20°C)	5 mg/L (>20°C) 10 mg/L (<20°C)	1 mg/L after 30 minutes
Hardness	-	-	500 mg/L	500 mg/L
Total dissolved solids (TDS)	-	5,000 mg/L	-	1,500 mg/L

Source: Engelbrecht 1986, U.S. Army 2010

2.3 Dishwater Characteristics

Greywater is domestic wastewater from non-toilet sources like showers, bathtubs, sinks, and washing machines. The wastewaters from kitchen sinks and dishwashers are referred to as dark greywater and are rarely used for urban reuse (Yu et al. 2013). Currently, there are no developed standards for dishwater recycling. Therefore, it is important to consider the potential health risks associated with dishwater reuse for the development of water quality standards for dishwater recycling. Contaminants of dishwater include chemical and microbial components. A large contributor to chemical contamination of dishwater is from the use of detergents. Chemicals in commercial dish detergents include anionic/nonionic surfactants, salts, dyes, perfumes and ethanol (Erickson 2007). Microbiological contaminants are also a major problem with kitchen greywater. *Fecal coliforms* levels as high as 2,400,000/100ml have been found in samples of kitchen sink water (Burrows et al. 1991). Table 5 shows examples of various dishwasher water quality. The characteristics of dishwater are highly variable depending on the type of detergent (e.g., non-ionic and anionic), foods, components of surfactant (e.g., ingredients), and the dishwashing habits of the people involved (e.g., amount of surfactant use) (Eriksson et al. 2002).

Table 5. Examples of dishwater quality

Parameter	Friedler 2004	Siegrist et al. 1976
pH	8.2	-
EC (electrical conductivity)	2,721 µS/ cm	-
TSS (total suspended solids)	1,045 mg/L	440 mg/L
COD (chemical oxygen demands)	1,296 mg/L	-
BOD (biological oxygen demands)	699 mg/L	1,040 mg/L
TOC (total organic carbon)	234 mg/L	600 mg/L
Total oil	328 mg/L	-
NH_4-N	5.4 mg/L	4.5 mg/L
P	537 mg/L	68 mg/L
Cl	716 mg/L	-
B	3.8 mg/L	-
Na	641 mg/L	-
FC (*fecal coliform*)	6.0×10^4/100ml	-

2.4 Health Concerns Associated with Dishwater

2.4.1 Chemical Components

2.4.1.1 Detergents

Detergents are a major source of chemical contamination in dishwater. In general, dish detergents contain surfactants, salts, perfumes, ethanol, and dyes. Due to the diversity of chemicals (e.g., acidic or basic compounds) used in detergents, the pH of dishwater is highly variable. Detergents are also sources of nitrates, sulfates, and phosphates which, when dissolved in water, may lead to formation of disinfection by products (DBP) (Pidou et al. 2007). Triclosan, an antibacterial agent found in some detergents, is a DBP precursor, a known endocrine disrupter, and could produce drug resistance bacteria (Rule et al. 2005). Most surfactants used in detergents are sulphonate and sulphate based which have been shown to have harmful biological effects on health and the environment. A major concern is endocrine disrupting properties of surfactants. A study by Tripathi et al. showed sexual disruption in rainbow trout with surfactant levels as low as 0.1 mg/L (Tripathi et al. 2013).

2.4.1.2 Organic Matter

Food particulates, fats, and oils cause dishwater to have organic concentrations as high as 880 mg/L TOC (Eriksson et al. 2002). In addition to promoting growth of pathogenic bacteria and other microorganisms, organic pollutants can have an effect on human health. It is difficult to predict human effects of exposure to a complex mixture of organics; however, there are studies involving the health effects of specific organic molecules found in greywater. Phthalates, for example, are commonly found in greywater and have toxicological properties including the disruption of the endocrine system (Hamlyn-Harris 2001).

2.4.1.3 Disinfection Byproducts (DBP)

Chlorination is a popular disinfection method because the residual concentration in the system maintains safe levels of microbial contamination (Najm et al. 1994); however, chlorine can form a broad range of DBP by reacting with natural organic matter (NOM). A study from Kim *et al*. (2002) shows the strong relationship between total organic carbon and disinfection byproducts. Although the dishwater will not be ingested, DBP are volatile, leading to inhalation and dermal adsorption (Florentin et al. 2011). Studies have shown that prolonged exposure to volatile DBP (>250 hours) can cause asthma (Weisel et al. 2009), reproductive issues, and bladder cancer (Villanueva et al. 2007). In addition, only a fraction of DBP have been studied leaving uncertainty to the true scale at which health can be affected (LaKind et al. 2010).

2.4.2 Microbiological Components

Microbiological quality of water is directly related to human health making it a primary concern for most water reuse regulations. Dishwater contains large amount of microbes with concentrations ranging from 6.0×10^4 cfu (colony forming units)/100ml to 2.3×10^6 cfu/100ml (Eriksson et al. 2002). These microorganisms are capable of causing severe illness, requiring disinfection of reused water to eliminate any potential health effects. Waterborne microorganisms can fall into four categories; viruses, bacteria, protozoa, and Helminths (Burrows et al. 1991).

- Viruses: *Hepatitis A* and *Norwalk virus*
- Bacteria: *E. Coli*, *Salmonella*, *Listeria*, *Bacillus cereus* and *Staphylococcus aurous*
- Protozoa: *Cryptosporidium*, *Giardia*, *Endameba*, *Cyclospora* and *Microsporidia*
- Helminths: Roundworms and flatworms

Microbial quality of greywater depends on the types of treatment level, as follows:

Types of reclaimed water by treatment level	***Microbial Quality of Greywater (# of organisms per 100 ml)***
Potable Reuse	None
Disinfected Tertiary Reclaimed Water	< 2.2
Disinfected Secondary Reclaimed Water	< 23
Undisinfected Reclaimed Water	20 to 2,000
Greywater	100 to 100 million
Dishwater	Thousands to billions
Raw Wastewater	Millions to billions

2.5 Parameters for Water Quality Standards

There are many physical, chemical and biological water quality parameters for evaluating water after greywater treatment. While there are water parameters which can easily be measured (e.g., pH and turbidity), others are time-consuming, complicated, and not applicable for field use. For the purpose of this thesis, several water parameters were evaluated to find correlations between one or two easily measurable parameters for field use and parameters that need to be measured in the laboratory. Particularly, water quality parameters for field testing need to be quick and simple to measure, while also providing valuable information on water quality.

2.5.1 Field Parameters

2.5.1.1 pH

pH is an important water quality parameter that influences the effectiveness of a treatment system (e.g., electrocoagulation and chlorination). It is normally kept in a narrow window, between 6-8, to prevent corrosion and problems with disinfection. Using pH as a parameter for water quality is particularly useful for field application because measurement is taken using a simple pH meter or strips. An example of pH as a parameter is the U.S. EPA guidelines for water reuse which requires a pH between 6-9 (USEPA 2012).

2.5.1.2 Turbidity

Turbidity is the measure of cloudiness of water. Materials responsible for the cloudiness of water include algae, planktonic microbes and soil particles. Turbidity can shield pathogens from disinfection which makes it a common parameter in water treatment. It is generally accepted that turbidity needs to be below 1 NTU for effective disinfection. Turbidity is easily measured with a nephelometer and is a good indicator of treatment effectiveness (USEPA

2012). One example of turbidity being used as a standards parameter is that U.S. EPA requires 95% of drinking water samples to have a turbidity of less than 0.3 NTU in a 30 day period (USEPA, 2012).

2.5.1.3 Free available chlorine (FAC)

FAC is the measure of chlorine available for disinfection. Free available chlorine is a popular water reuse parameter because it maintains disinfection. Typical greywater applications require FAC levels to fall between 0.5 mg Cl_2/L and 5 mg Cl_2/L (USEPA, 2012).

2.5.1.4 Conductivity

Conductivity is the measure of water's ability to pass an electrical current. A water's conductivity is affected by the presence of anions (e.g., Cl^-, SO_4^{2-}, NO_3^-, and PO_4^{3-}) or cations (e.g., Na^+, Al^{3+}, and Fe^{3+}). Conductivity closely relates to total dissolved solids (TDS) which is commonly used in water quality standards (USEPA 2012, WHO 2006, and US Army 2010). Conductivity measurements are simple and immediate with the use of a conductivity meter.

2.5.1.5 UV_{254}

UV_{254} is a method for determining the amount of organics in a sample by measuring UV adsorption at 254nm. Aromatic compounds tend to absorb light at this wavelength which can be used to determine the concentration of aromatic containing molecules in the water. UV_{254} is a useful field parameter because it is relatively simple to perform and only needs a UV spectrometer. In addition, UV_{254} absorption is strongly related to DBP (Najm et al 1994).

2.5.2 Non-Field Parameters

2.5.2.1 Biological Oxygen Demand (BOD)

BOD is the measure of oxygen consumed by microorganisms and is directly related to concentration of biodegradable substances in water. BOD is common parameter used in waste water regulation which has been used since 1908 (Hamlyn-Harris 2001). BOD has been included in greywater regulation including standards set by the U.S. EPA, WHO and state level regulation.

2.5.2.2 Chemical Oxygen Demand (COD)

COD is similar to BOD except COD measures the amount of all chemicals that can be oxidized, not just biologically oxidized substances (Hamlyn-Harris 2001). An example of COD in regulation is the city of Windhoek, Namibia, which requires their drinking water COD to be less than 20mg/L (du Pisani 2006).

2.5.2.3 Total Organic Carbon (TOC)

TOC is the amount of carbon incorporated into to organic matter. A report produced by Gutteridge Haskins & Davey Pty Ltd (Hamlyn-Harris 2001) recommended TOC as a parameter for water quality of direct potable reuse because of its establishment as a surrogate of health risk associated with organic compounds present in water. An example of TOC in water reuse regulation is standards set by the state of Florida, requiring a monthly average for indirect potable reuse to have a TOC less than 0.3 mg/L.

2.5.2.4 Total Dissolved Solids (TDS)

TDS measures the substances, inorganic and organic, found in water. TDS are usually salts including calcium, magnesium, sodium, sulfates and nitrates. No recent data shows a relationship between TDS in drinking water and serious health effects, however, excessive TDS (i.e., greater than 1,500 mg/L) can lead to scaling (Hamlyn-Harris 2001). An example of TDS in greywater regulation is that TB MED 577 requires TDS to be less than 2,000 mg/L for water reuse (U.S. Army 2010).

2.5.2.5 Nitrogen

Nitrogen exists in many forms including nitrate, nitrite, and ammonia. Ammonia levels can have a negative effect on aquatic life because of its toxic nature. Nitrate and nitrite levels can promote growth of bacteria and algae causing eutrophication. An example of nitrogen as a parameter in water reuse regulation is Arizona's urban reuse regulation requires less than 10 mg/L total nitrogen (TN).

2.5.2.6 Phosphorous

Phosphorus is typically the limiting nutrient for plant growth, meaning a sudden increase in phosphorus levels can cause eutrophication. Therefore, phosphorus is typically controlled for environmental water reuse applications. An example of phosphorous in water reuse regulation is Florida's environmental reuse regulation requiring less than 2 mg/L phosphorous.

2.5.2.7 Surfactants

Buildup of surfactant could be a concern if not properly monitored. Although the risk is small, surfactants have been shown to disrupt endocrine systems of humans and animals. Studies have found that surfactants can have harmful environmental impacts at concentrations above 0.1 mg/L (Tripathi et al. 2013).

2.5.2.8 Oil and Grease (O&G)

Dishwater is known to contain large amounts of oil and grease. O&G is a common parameter for wastewater treatment because of public health and pipe clogging problems. An example of O&G in water regulation is Philippine class C wastewater requires O&G to be below 5 mg/L (USEPA 2012).

2.5.2.9 *Fecal Coliforms/E. Coli*

Fecal coliforms and *E. coli* are used as an indicator of pathogenic bacteria, viruses, and protozoans. High levels of *fecal coliform* can mean high levels of pathogenic bacteria that can pose a serious threat to human health. Recently, U.S. EPA recommended the use of *E. coli* as an indicator and states are beginning to change their standards accordingly (Hamlyn-Harris 2001). *E.coli* can easily be measured using Colilert/Quanti tray system (IDEXX) using only a few pieces of equipment and a turnaround time of 24 hours. Many greywater standards required the absence of *fecal coliform* per 100mL.

2.6 Initial Water Quality Standards for Dishwater Reuse

Available literature on the development of greywater reuse regulation was extensively reviewed to obtain the overall understanding of existing water quality parameters and standards. The driving force behind all the standards seems to be human health. One parameter directly dealing with human health is microbial contaminates, thus requiring chlorine disinfection. BOD_5 is widely used for state regulation to prevent biological growth. The shower reuse standards from TB MED 577 most closely regulate in the scope of dishwater recycling; however, it has no requirements on BOD_5, but limits coliforms to absent per 100 mL.

There are many physical, chemical and biological water quality parameters for evaluating water after greywater treatment (Salgot et al. 2006). While some water parameters can easily be measured (e.g., pH and turbidity), some are time-consuming, complicated, and not applicable for field use. For the scope of the project, various water quality parameters were evaluated to recommend for field use. Particularly, the field testing methods need to be rapid and simple to measure, while also providing accurate information on water quality.

Turbidity, pH, and UV_{254} were selected as important parameters for field use of dishwasher recycle based on literature review. In addition, chlorine residual was also considered as an important parameter to ensure disinfection. For public safety, there should be no detectable coliforms or *E. coli* present in the treated greywater. By removing or inactivating most microbes, the risk of waterborne illness is significantly reduced (Schneider 2009).

Many microbial containments will be removed by ultrafiltration (Hagen 1998). As an additional barrier for potential pathogenic hazards, a chlorine residual of at least 1 mg Cl_2/L will help achieve a high level of inactivation. It is recommended that BOD_5 should be maintained at values below 30 mg/L for water reuse; 30 mg/L is the limit set by the U.S. EPA Secondary Standards as well as other state regulations for greywater reuse. High BOD_5 (e.g., above 20 mg/L) is expected to produce DBP and promote bacteria growth (e.g., biological contamination). Since BOD_5 and other organic parameters (e.g., TOC and COD) are not easily measured in field environments, UV_{254} will ensure proper levels of organics.

Turbidity and pH are easily measured parameters that can provide information on the effectiveness of the recycling treatment. High turbidity above 5 NTU or outranged pH values (< pH 6 or > pH 9) could indicate a failure in the system. Below is the summary of recommended standards for dishwater reuse based on available literature.

- ***Lab test: General water quality requirement***
    - pH 6–9
    - Turbidity < 5 NTU
    - Free chlorine (in the storage tank) : 1–5 mg Cl_2/L
    - UV_{254} (to provide the correlation with organic parameter such as BOD_5)
    - BOD_5 < 30 mg/L
    - TSS < 30 mg/L
    - Total coliform < None (CFUs/100 mL or MPN/100 mL)

- ***Field application: Minimum water quality requirement***
    - pH 6–9
    - Turbidity < 5 NTU
    - Free chlorine (in the storage tank): 1–5 mg Cl_2/L
    - UV_{254} (as surrogate for organics such as BOD_5)
        - The correlation with BOD_5 should be evaluated in the laboratory and calibration curves should be created to use UV_{254} in field

CHAPTER THREE: EVALUATION OF A DISHWASHING WATER RECYCLING SYSTEM

3.1 Dishwashing Water Recycling System

A full-scale prototype dishwashing water recycling system was constructed and operated by Mainstream Engineering Corporation (Rockledge, FL, USA) over the course of year (Figure 2). Water collected from three 20 gallon (76 L) sinks (wash, rinse, and sanitize) was first treated by electrocoagulation using zinc electrodes to destabilize emulsions and precipitate suspended particles from the high-pH greywater (due to detergents used in dishwashing). Then the water was further processed by ultrafiltration (UF) using a hollow fiber, cross-flow, and modified polyethersulfone membrane (WaterSep, Marlborough, MA, USA) with a molecular weight cutoff of 750 kDA (Amundsen et al., 2013). A standard issue powdered detergent soap (NSN 7930-00-281-4731, NuGentec, Emeryville, California) was supplied as a detergent and a preliminary analysis showed that the detergent's pH was 9.4 and includes sodium phosphate derivative anionic surfactant (Appendix A). The electrocoagulation (EC) system was constructed with PVC with dimensions of 27cm (H)×5 cm(L)×6 cm(W). The electrodes were constructed with zinc, measuring 27 cm(H)×5 cm(L)×0.3 cm(W), and were separated by 0.6 cm. The seven electrode plates were placed in the cell with one electrode as the anode, one electrode as the cathode (the anode and cathode were located at opposite ends of the reactor) and five inner plates operating in a bipolar fashion. The total electrode area was 810 cm^2 with an applied potential of 20V (AC). The current density was 1.85 mA/cm^2 and the cell residence time was 7 min. The UF membrane was operated at 25°C with a transmembrane pressure of 0.10 MPa and a feed flow rate of 400 mL/min. The filter was back flushed for 30 sec every 3 min at 0.14 MPa using permeate. The filter was also cleaned, alternating between white vinegar and 1.0 M NaOH for 10 min for every 4 hrs of runtime. Samples were collected weekly for testing.

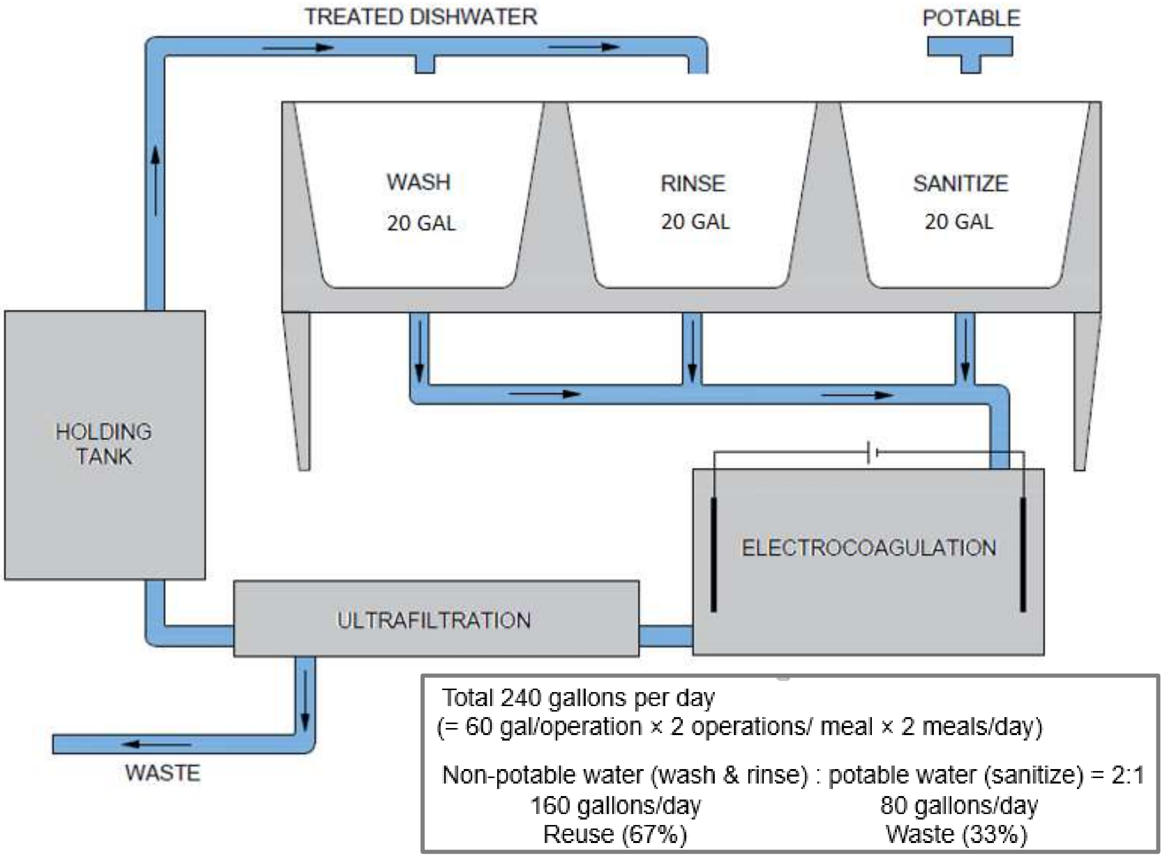


Figure 2. Schematic diagram of a greywater recycling process for dishwashing water.

A synthetic surrogate dishwashing water used during the system operation as a representative sample of U.S. Army field dishwashing water. Concentrated food mixture (3 kg baked beans, 1.28 kg chili con carne and 1.9 L of water) (8.3 mL), vegetable oil (2.5 mL) and NSN 7930-00-281-4731 dishwashing soap (20.0 g) were combined with 3.79 L (1 gallon) of fresh tap water to produce the synthetic greywater with a BOD_5 of 1,000 mg/L and TSS of 850 mg/L (Natick Soldier Center, 2007).

3.2 Methodology

3.2.1 Water Quality Analysis

On-site samples were collected from the dishwater recycle device at 25°C and analyzed in the UCF laboratories within 3-6 hrs. Sample collection was performed in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 1998). The parameters measured included BOD_5, COD, TSS, TDS, total phosphorus (TP), pH, temperature, total organic carbon (TOC) (SM 5310), UV_{254} (EPA 415.3), SUVA (EPA 415.3), trihalomethanes (THMs) (SM 6232 B), and haloacetic acids (HAAs) (EPA 552.2). HAAs were analyzed by a certified external lab (Advanced Environmental Laboratories, Inc. Altamonte Springs FL, USA).

3.2.2 Potential Microbial Growth: The Effect of Surfactant and Ultrafiltration Treatment of Dishwashing Water on E. Coli.

The current water recycling system contains multiple barriers to remove microbial contaminants: zinc electrocoagulation, ultrafiltration, and chlorination. However, under specific (or undesirable) circumstances in field operations (e.g., hot weather condition), it may not be easy to maintain the chlorine residuals required for bacterial control in the chlorinated holding tank. In this case, the presence of surfactants may inhibit bacterial growth, or cause their decay, during the event of the absence of free chlorine. Therefore, the degree of disinfection by contacting with the surfactant only (without chlorination) was evaluated in batch experiments.

E. coli was selected as a model bacteria for microbiological testing because of its use as an indicator organism in U.S. greywater regulations (USEPA 2012). *E. coli* (K-12 strain S 4362, ATCC 29181) was propagated in tryptic soy broth (Difco, Detroit, MI), following manufacturer's specifications, and incubated for 48 hrs at 37°C. After allowing the *E. coli* to stabilize (5 days at 37°C), 0.5 mL of the liquid culture (3.6×10^{8} CFU/100ml) was added to five beakers with 500 mL of sterilized (autoclaved) UF/EC treated synthetic dishwater and different detergents and surfactants (1) no detergent, 2) powdered detergent (NSN 7930-00-281-4731, NuGentec, Emeryville, California,) 3) anionic surfactant (sodium lauryl sulfate), 4) cationic surfactant (cethyl trimethylammonium chloride (CTAC)), and 5) nonionic surfactant (Triton X-100)). The UF/EC synthetic dishwater was produced by treating synthetic dishwashing water (recipe described in section 4.1) with the developed UF/EC treatment system (i.e., one-cycle system operation) without detergent. Surfactant was then added to produce a 0.05 N solution which is typical of U.S. dishwashing water (Lai 2012). The manufacturer recommended amount of standard issued powdered detergent (5.3 g/L) was used which contains an unknown amount of surfactant. Treated greywater without surfactant or detergent was used as a control. The dishwater environments were maintained at 37°C ±1°C and continuously stirred using a hot plate and magnetic stirrer. Triplicate samples were aseptically withdrawn from each environment at 5, 60, 120, and 240 minutes for quantification of *E. coli*. *E. coli* concentrations were determined using spread plate technique with dilutions on Nutrient Agar (Difco, Detroit, MI). Colony forming units (cfu) were counted after a 48-hour incubation period and *E. coli* was verified through inspection of colony morphology (Johansson et al. 2005).

3.2.3 Chlorine Demand and Disinfection by-Product Formation Potential (DBFP) of Treated Dishwashing Water

Most regulations, including the U.S. EPA Guidelines for Water Reuse, NSF/ANSI 350-1 and many state regulations, require a hydraulic retention time (HRT) of less than 24 hrs for a water storage tank. Therefore, it is recommended to set a HRT of 24 hrs for the chlorinated holding tank of the dishwater recycling system. This will retain water quality by limiting the time for residual depletion and bacterial growth. A HRT of 48 hrs or more is also sometimes recommended in some state regulations (USEPA 2012) and plumbing codes (IPC 1302.1). Therefore, batch tests for chlorine demand were conducted for HRT periods of 24 and 48 hrs. The treated greywater chlorinated holding tank could be a potential source of bacterial growth if the desired chlorine residuals are not maintained; however, chlorine can also react with NOM to form a broad range of DBP which are a concern to human health (Jumpatong and Buddhasukh 2003). Not only are DBP a concern if ingested, they are also volatile and can be inhaled or adsorbed dermally (Hagen 1998). Although the dishwater will not be ingested, chlorine demands for the treated water, along with DBP formation potential (DBPFP), was evaluated because of the relatively high organic levels (100 mg C/L). The treated dishwashing water (pH 9.6±0.1) was dosed with sodium hypochlorite (SS290-1, Fisher Scientific) and incubated at 32^{o} C for different times (2, 4, 6, 24, and 48 hrs). 32^{o} C was used to simulate hot water usage. A preliminary test with a single dose of 50 mg Cl_2/L showed chlorine depletion within 24 hrs; assumed to be due to high TOC (data not shown). In this study, chlorine doses were also increased to 60, 70, and 75 mg Cl_2/L and chlorine residuals were measured over time during 48 hrs.

3.2.4 Quantitative Microbial Risk Assessment (QMRA)

Dishwashing water could become contaminated with pathogens when dishes and other kitchen utensils become contaminated during food preparation (Ståhl Warnersson et al. 2004). The use of electrocoagulation, ultrafiltration and chlorination to treat contaminated dishwater should eliminate pathogens present; however, there may be some exceptions. For example, Westrell et al. (2003) reported that virus removal in single-membrane ultrafiltration systems can be as low as one log10 unit, due to micro-defects in filter construction, partially-damaged membranes, and leaky seals (Westrell et al. 2003). Also, bacteria may be able to form biofilms on the product side of membranes (Jacangelo et al. 1989), and pathogens could persist or, in the case of bacteria, grow within the holding tank. There are also many viruses known to have a high resistance to chlorination (Black et al. 2009).

The QMRA model for this study was designed with the help of Mr. Matt Verbyla at the University of South Florida to estimate the maximum tolerable concentrations of three reference pathogens (human norovirus, *Salmonella spp*. (non-typhi), and *E. coli O157:H7*) in the recycled dishwater. The assumptions for the parameters used in the QMRA model are provided in Table 6. Human norovirus was chosen as a reference viral pathogen because it is non-enveloped, highly infectious (Le Pendu et al. 2006), and has been known to cause both water- and food-related outbreaks (Goodgame 2007). *Salmonella spp*. was chosen as a reference pathogen group because they have been widely associated with foodborne outbreaks and some serotypes are very hazardous to humans (USEPA 2010). Finally, Shiga toxin-producing *E. coli* strain *O157:H7* was chosen as a reference pathogen since it has been implicated in many foodborne outbreaks (FSIS 2001), and therefore is potentially present in food preparation materials and utensils. For human norovirus, a small proportion of the population may have genetic resistance to infection; however, for the purposes of this QMRA, it was assumed that all individuals may be susceptible (Soller et al. 2010). The same assumptions were made for *Salmonella* and *E. coli O157:H7*.

Not all microbial infections will result in an illness. The percentage of norovirus infections resulting in illness was determined using a dose-dependent model proposed by Teunis et al. (2008) (see Table 6). For *Salmonella* and *E. coli O157:H7*, it was assumed that 20% and 28% of all infections would result in illness (Soller et al. 2010).

Table 6. QMRA model parameter assumptions

Parameter	Units	Value or Distribution	References
Acceptable Risk of Illness			
Maximum tolerable cases of illness	ratio	1 in 50,000 exposures	Two orders of magnitude less than the current estimated disease incidence for military field personnel (Riddle et al. 2006)
Exposure to Pathogens			
Volume ingested for direct potable reuse	mL/person/day	$V = 3{,}000$	(USEPA 2011)
Volume accidentally ingested during reuse for irrigation	mL/person/day	$V = 1$	(Ottoson and Stenstrom 2003)
Volume accidentally ingested during reuse for dishwashing	mL/person/day	$V = 1$	Assumed to be the same as irrigation
Volume accidentally ingested during reuse for showering	mL/person/day	$V = 1.9$ (assumes two 7-minute showers per person per day)	(Ahmed et al. 2010)
Dose-Response Models			
Norovirus (based on best fit parameters for 8fIIa & 8fIIb inocula)		Hypergeometric model: $\alpha = 0.04$, $\beta = 0.055$, $\eta_{NV} = 0.00255$, $r_{NV} = 0.086$, $a = 0.9997$	(Teunis et al., 2008)
Salmonella spp.		Approximate Beta-Poisson model: $\alpha = 0.3126$, $\beta = 2884$	(Soller et al., 2010)
E. coli O157:H7		Approximate Beta-Poisson model: $\alpha = 0.1705$, $\beta = 1.61 \times 10^6$	(Soller et al., 2010)
Probability of Infection Resulting in Illness			
Illness:Infection (I)	probability; proportion	NoV: $p_{ill\|inf} = 1 - (1 + \eta_{NV} c_{NV} V)^{-r_{NV}}$ *Salmonella*: 0.2 *E. coli*: 0.28	(Soller et al., 2010; Teunis et al., 2008)

3.3 Results

3.3.1 Effluent Water Characteristics

Table 7 shows the effluent characteristics of the dishwashing water recycling system. BOD_5, and COD were significantly reduced after ultrafiltration with average concentrations of 65 (93.5% removal) and 708 (64.6% removal), respectively. The system also produced water with TSS, TDS, and turbidity of 16 mg/L (98.1% removal), 2,650 mg/L, and 0.3 NTU (99.6% removal), respectively, with a pH of 9.5. The value of the SUVA was relatively low indicating that the large aromatic molecules are being adsorbed and filtered out by coagulation and ultrafiltration (de la Rubia et al. 2008). The values of effluent water quality still exceeded typical greywater reuse standards (Table 3), but fresh potable water at an elevated temperature will be used for the sanitization step, resulting in the dilution of any treated water droplets which are carried over when dishes are transferred from the rinse stage to the sanitation (final) stage of the dishwashing process.

Table 7. Developed dishwashing water recycling system effluent characteristics

Parameter	Influent	Effluent from the developed system	Typical greywater reuse standards
BOD_5 (mg/L)	1,000	65[a]	30
COD (mg/L)	2,000	708[a]	100
TOC (mg/L)	-	92.5±5.2	No standard
pH	-	9.5±0.4	6.0–9.0
Turbidity (NTU)	450	0.325±0.014	5

Parameter	**Influent**	**Effluent from the developed system**	**Typical greywater reuse standards**
TSS (mg/L)	850	16[a]	30
TDS (mg/L)	-	2,650[a]	450
TP (mg P/L)	-	88[a]	5
UV 254 ($cm^{-1)}$	-	0.68±0.02	0.03–0.07
SUVA (L mg^{-1} m^{-1})	-	0.71±0.10	No standard
Total coliform (MPN/100ml)	-	Not detectable	Not detectable

[a] Analyzed by Mainstream Engineering Co.

3.3.2 Chlorine Demands and the Formation of Disinfection by-Products

Chlorine is typically used as a secondary disinfectant because chlorine residual in the system permit the continued inactivation of microbes (Salgot et al. 2006). To retain chlorine residuals in the holding tank at acceptable levels, the treated greywater was chlorinated and the chlorine consumption and the associated DBP formation were investigated for 24 and 48 hrs. As shown in Figure 3, the chlorine demand of the treated dishwater was relatively high due to high TOC.

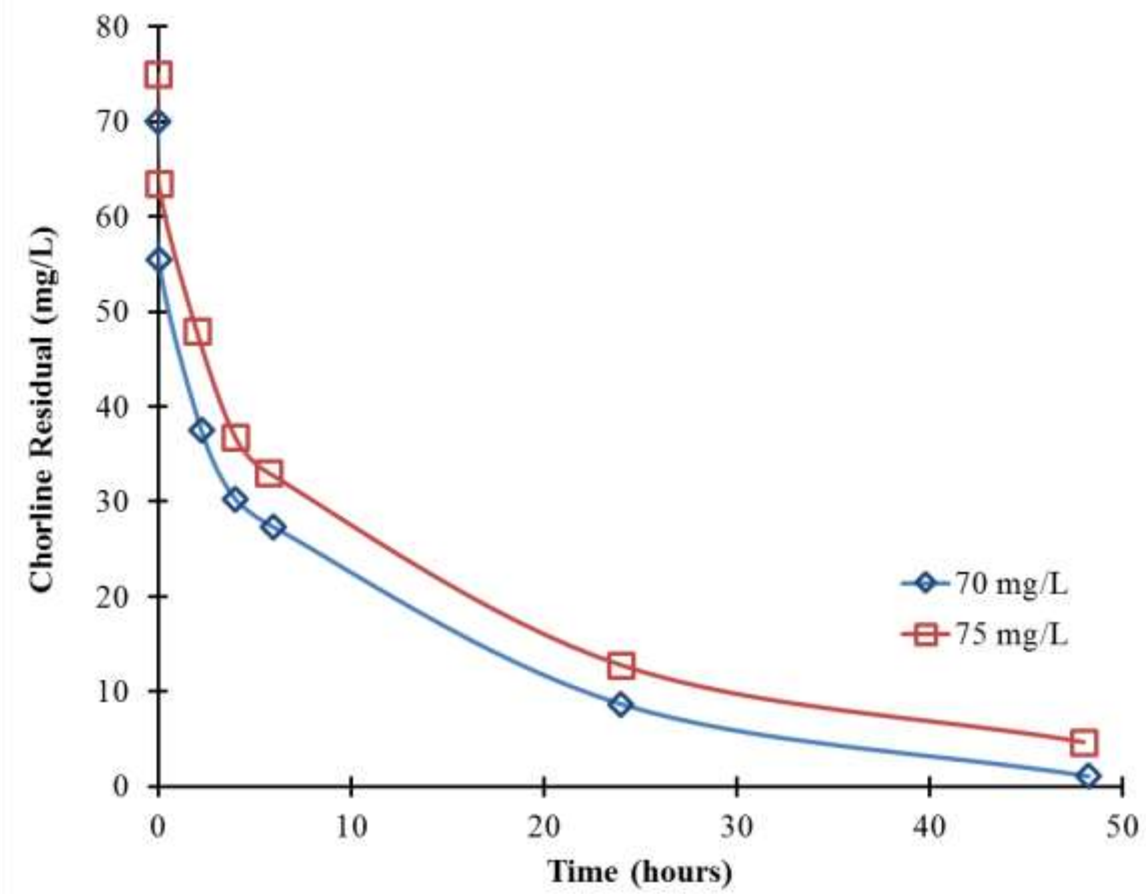


Figure 3. Chlorine demands for treated dishwashing water (pH 9.5) at 32°C with chlorine doses of 60, 70, and 75 mg Cl_2/L.

For the treated water, a chlorine dose of 60 mg Cl_2/L resulted in a residual of 2.8 mg Cl_2/L at 24 hrs but was unable to maintain a concentration above 1 mg Cl_2/L after 48 hours. However, both dosages of 70 and 75 mg Cl_2/L maintained a concentration above 1 mg/L after 48 hours (1.1 and 4.7 mg Cl_2/L of chlorine residual, respectively). As a result, a 60 mg/L was sufficient for maintaining the recommended chlorine residual in a holding tank with a 24 hrs HRT, but a dosage of 70 or 75 mg/L would be required at a 48 hrs HRT depending on what factor of safety was decided upon. However, the high chlorine dosages used resulted significant DBP formation because of precursors found in the UF permeate/effluent.

Most of these organics were small enough to pass through the UF membrane which removes particulates via size exclusion. It is well known that chlorine reacts with NOM to form a broad range of DBP (Jumpatong and Buddhasukh 2003). Table 8 shows the DBP formation after chlorination of the effluents. The species analyzed were chloroform ($CHCl_3$), dichlorobromomethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$) for THMs and monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), and dibromoacetic acid (DBAA) for HAAs. Given that U.S. drinking water standard for DBP are 80 ppb for total THMs and 60 ppb for total HAAs (40 CFR Parts 9, 141, and 142), the DBP formation potential was relatively high. As shown in Table 8, after 24 hrs total THMs of 1,789 and 1,685 ppb were generated with chlorine doses of 70 and 75 mg Cl_2/L, respectively. The THMs formed were mostly chloroform ($CHCl_3$). Total HAAs were 966 and 1,027 ppb after 24 hrs with chlorine doses of 70 and 75 mg Cl_2/L, respectively.

DBP levels were similar between the different chlorine doses, inferring that organic concentration and reaction time were major factors in the formation of DBP. Even though the water from the system was not designed for ingestion, exposure to these concentrations of DBP via accidental ingestion, dermal adsorption, or inhalation of vaporized DBP could lead to health effects. Extensive research on the health effects of THMs have been published due to the volatile nature of this class of DBP. Even at levels as low as 100 ppb, THMs can cause adverse respiratory and allergy related effects (Kabsch-Korbutowicz, 2005).

Table 8. THM and HAA formation potential of UF/EC treated dishwater

	Chlorine dose (mg Cl_2/L)	Time (hrs)	$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)		Total (µg/L)
THM	60	24	1562	125	6.25	2.24		1696
	70	24	1661	125	2.77	<1		1789
		48	2025	106	<1	<1		2132
	75	24	1577	106	1	<1		1685
		48	2078	135	<1	<1		2213
	Chlorine dose (mg Cl_2/L)	Time (hrs)	MCAA (µg/L)	MBAA (µg/L)	DCAA (µg/L)	TCAA (µg/L)	DBAA (µg/L)	Total (µg/L)
HAA	70	2	26.7	4	286	123	4.60	443
		4	29.5	4	321	149	4.95	509
		6	34.2	4	361	165	5.30	570
		24	53.4	ND	621	285	6.50	966
		48	70.2	ND	644	349	ND	1064
	75	2	22.3	4	223	106	2.80	359
		4	31.2	5	335	199	5.00	575
		6	36.3	5	365	211	4.75	622
		24	62.4	ND	647	317	ND	1027
		48	57.2	ND	633	282	ND	971

Given that chloroform production reached 1,661 µg/L after 24 hours of the exposure to chlorine, a dynamic model software (STELLA, isee systems, Lebanon, NH, USA) was used to predict potential accumulation of chloroform ($CHCl_3$) in the air within military field tents. The model was developed based on rate constants derived from experimental data under worst case scenarios (i.e., high temperature water [55°C], minimal ventilation [0.2 air exchanges per hr], and high doses of chlorine [70 mg Cl_2/L every 24 hrs]). Additional details on DBP vaporization are provided in Appendix E. If volatilized, chloroform concentrations spiked at 1.16 ppm shortly after dosing the holding tank with chlorine and fell to 0.47 ppm over the remainder of the day (Appendix E). The U.S. Occupational Safety & Health Administration (OSHA) requires chloroform concentrations to be below 50 ppm, but recommends that the permissible exposure limit be reduced to 2 ppm within an hour. Although the model predicts chloroform concentrations will not exceed the OSHA standards, proper ventilation (especially after adding chlorine) will protect the safety of the dishwashing personnel.

3.3.3 Effects of Surfactants of Microbial Growth

The effect of surfactants on *E. coli* disinfection is presented in Figure 4. The data shown represents the mean values of triplicate samples. Among the surfactants tested, the presence of cationic surfactant resulted in more than 6-$\log_{10}$ reduction within 5 min (data not shown); however, cationic surfactants are generally not used in dishwashing detergents. The control test (i.e., treated water without detergent or surfactant) showed inhibited microbial growth which is likely linked to zinc residuals during EC. The greywater with the standard issued detergent (NSN 7930-00-281-4731, NuGentec, Emeryville, California) effectively reduced the *E. coli* concentration in the synthetic dishwater along with the anionic and nonionic surfactants. The presence of surfactants showed 97.8–99.8 % reduction of *E. coli* within 1 hr and the rate of microbial decay was 2.5 times faster compared to the water without any detergent or surfactant. With the exception of the cationic surfactant, the effect of surfactant type on the survival of *E. coli* was insignificant in this batch test. All surfactants at a concentration of 0.05 N significantly reduced *E. coli* concentrations within the 4 hrs experiment (the HRT of the storage tank is approximately 1 day), indicating that the detergent used can provide an additional barrier against microbial growth. The pH for surfactant tests were in the range of 6.8–8.6, which meet typical greywater reuse standards.

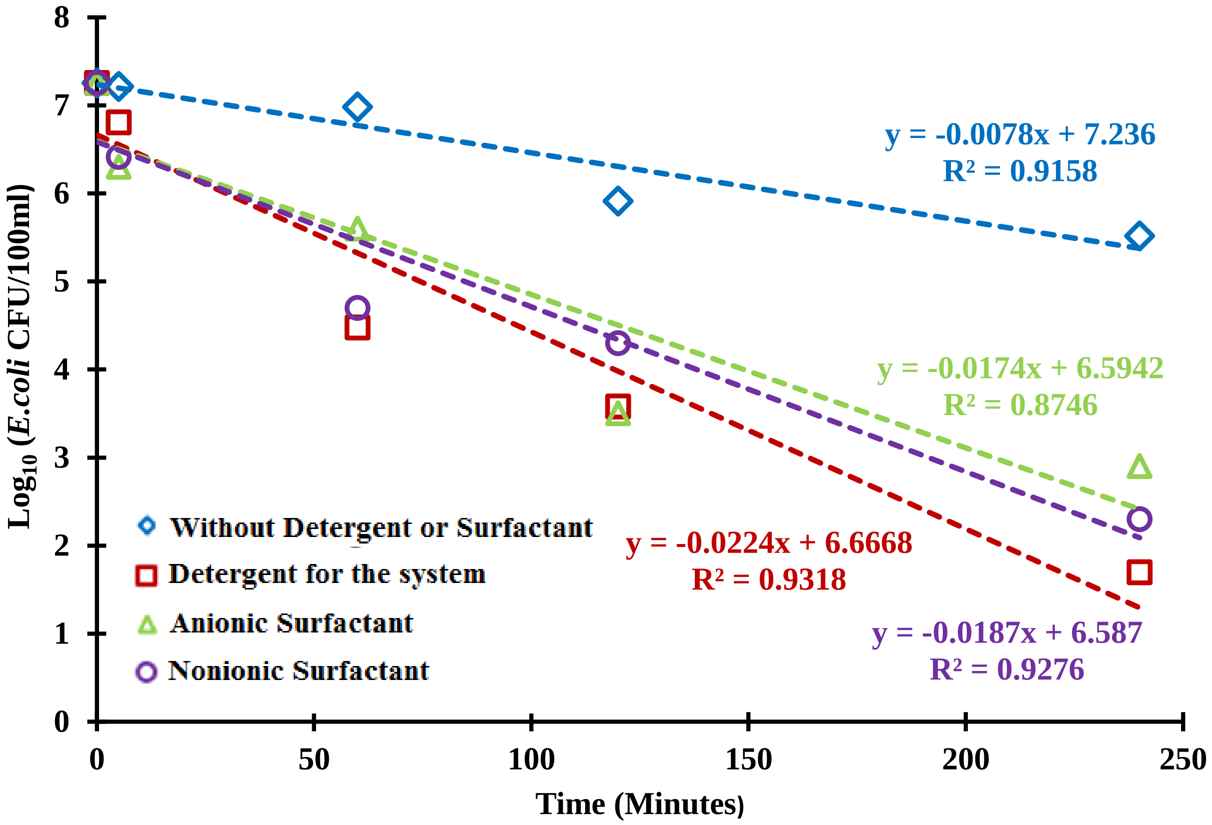


Figure 4. Effect of surfactants on *E. coli* decay.

3.3.4 Quantitative Microbial Risk Assessment

The results of the QMRA are displayed in Figure 5. If the reclaimed dishwashing water is recycled for dishwashing with the assumption of 1 mL ingestion of this water by accident, the concentrations of norovirus, *Salmonella spp*., and *E. coli O157:H7* in the holding tank should not exceed 8.7, 0.92, and 8.2×10^{-3} per mL, respectively. If the water is reused for showering with the assumption of accidental ingestion of 1.9 mL per day, the concentrations of norovirus, *Salmonella spp*., and *E. coli O157:H7* should be no greater than 5.4×10^{3}, 576, and 5.1 per mL, respectively. With further treatment to remove chemical contaminants and improve aesthetics, the reclaimed dishwashing water could even be reused for direct potable use, if concentrations remained below 2.9×10^{-3} noroviruses per mL, 3.1×10^{-4} *Salmonella* per mL, and 2.7×10^{-6} *E. coli O157:H7* per mL.

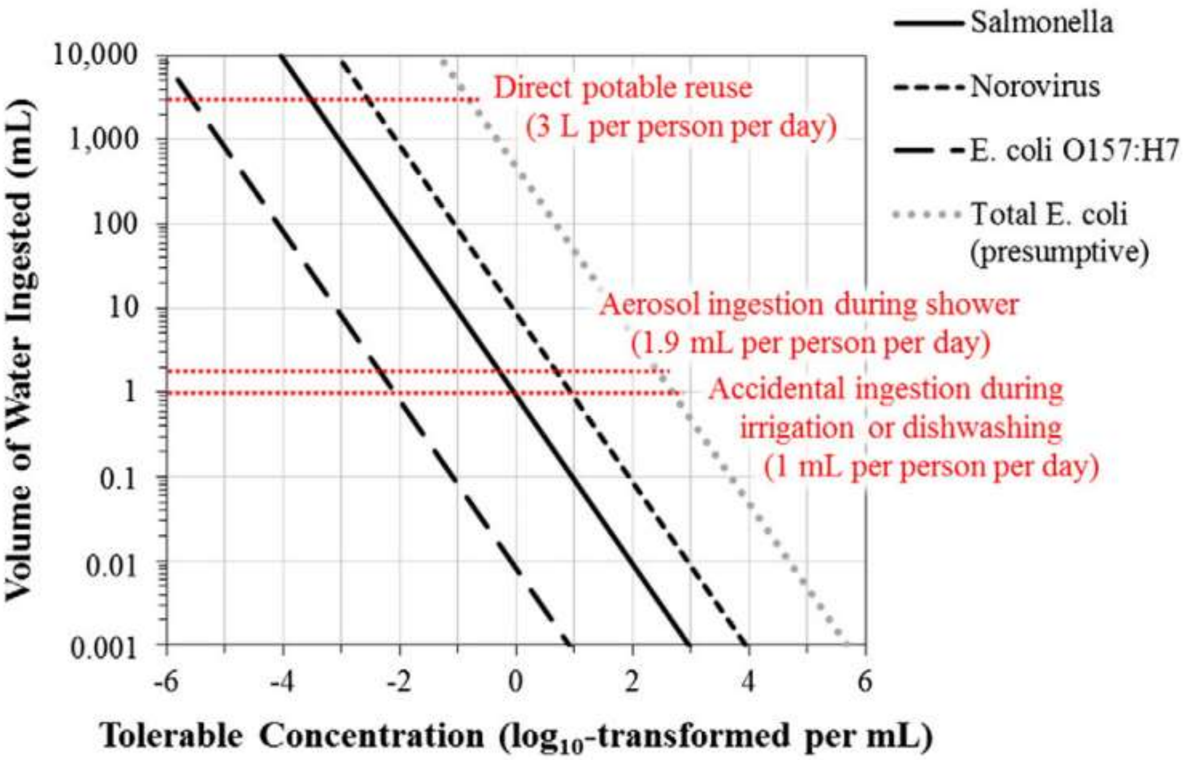


Figure 5. Maximum tolerable concentration of reference pathogens vs. volume of recycled dishwater ingested (accidentally or intentionally) per person per day, based on a limit of one illness per 50,000 exposures, assuming that exposure occurs daily.

Routine monitoring for *E. coli O157:H7*, *Salmonella*, and human norovirus in water samples may not be practical or economically feasible in military field settings. However, as evidenced by Figure 5, the microbial risk posed by *E. coli O157:H7* is greater than the risks posed by *Salmonella* and human norovirus. It is not typical to monitor concentrations of individual strains of *E. coli* in the field, therefore, a ratio of pathogenic *E. coli* strains to total *E. coli* will be used to roughly estimate the maximum recommended concentration of total *E. coli* in dishwashing water, which can be used to establish water reuse guidelines for this particular context. Currently, there is no accepted value for such a ratio in dishwashing water. Thus, the ratio of *E. coli O157:H7* to total *E. coli* in ground beef may be the closest approximation to the ratio of pathogenic *E. coli* to total *E. coli* in dishwashing water.

The ratio of *E. coli O157:H7* to total *E. coli* in ground beef (and the assumed ratio in dishwashing water) would be between 2.3×10^{-7} and 1.7×10^{-5} (refer to calculations in the appendix F). Using the higher of the two estimated ratios, the presumptive concentration of total *E. coli* in reclaimed dishwashing water would be five orders of magnitude greater than the concentration of pathogenic *E. coli*. Since the ratio of pathogenic *E. coli* to total *E. coli* may be even greater than assumed here, it would be sensible to use a factor of safety equal to one additional order of magnitude in proposed maximum concentrations.

Since the tolerable concentration of total *E. coli* is ~500 per mL according to the results of the QMRA (see Figure 5), the recommended concentration of total *E. coli* in reclaimed dishwashing water is 50 per mL. Even without chlorination, this should be easily achieved with the treatment system described in this thesis, especially given the anticipated decay of *E. coli* in the presence of dishwashing surfactants in the holding tank (Figure 4). It is important to note that coliform bacteria (such as *E. coli*) may not always be the most adequate indicators of contamination by all foodborne pathogens in treated dishwashing water (Sheikh 2010), and more research may be needed to determine the typical concentrations of foodborne pathogens in dishwashing water, as well as the fate and transport of other pathogens (such as viruses) in the treatment system.

CHAPTER FOUR: DEVELOPMENT OF DISHWATER RECYCLING STANDARDS

4.1 Recommended Water Quality Standards for Dishwashing Water Recycling

There are many physical, chemical, and biological water quality parameters for evaluating greywater treatment (Mollah et al. 2004). While some water parameters (e.g., pH and turbidity) can easily be monitored using simple measurements (e.g., potable pH meter and turbidity meter); others, like BOD, COD, and TOC, are time-consuming, complicated, and not applicable for field use. Field testing methods need to be rapid and simple while also providing accurate information on water quality. Turbidity, pH, and UV_{254} were selected as indispensable water quality parameters for field use of dishwasher recycling based on parameters used in TB MED 577 and due to the effectiveness of UV_{254} as a surrogate for organic monitoring (Potter and Wimsatt 2012; Reckhow et al. 1990).

If the treated dishwashing water is used for dishwashing, irrigation, or showering, it is recommended that maximum *E. coli* concentrations should not exceed 50 per mL. As demonstrated by QMRA (Figure 5), maximum norovirus concentrations should also not exceed ~1 per mL, and maximum *Salmonella* concentrations should not exceed ~0.1 per mL (using a factor of safety of one log10 unit). Reducing the concentration of these pathogens beyond these recommended levels would require additional expenses, and may not be necessary to ensure a level of health protection that is suitable for individuals in this setting. Concentrations of water- and food-borne pathogens, including bacteria, protozoa and viruses, should be sufficiently removed by ultrafiltration and electro-coagulation (Blyth et al. 2007).

A chlorine residual of at least 1.0 mg Cl_2/L is often recommended in water reuse guidelines to maintain microbial inactivation in the water reuse systems (e.g., prevent bacterial growth in reclaimed water holding tanks); however, the use of chlorine in this context may not be necessary unless bacterial growth is observed because it may cause unintended health risks (due to the formation of DBP) and unnecessary costs. If chlorine is used, it is recommended to implement further treatment strategies for the removal of organics to prevent DBP formation.

Currently, TB MED 577 sets guidelines for water quality during field operation but lacks regulation of organic contaminates (U.S. Army 2010). On the other hand, U.S. state and federal agencies carefully monitor and regulate organic pollutants in drinking and wastewater treatment because of the contribution of organic compounds to microbial growth, oxygen consumption, and chlorine residual depletion (USEPA 2012). The gap between water quality standards from state regulations and TB MED 577 is likely due to the difficulty in monitoring organic contaminates in field operation. It is recommended that BOD_5 be monitored and maintained at values of below 30 mg/L for dishwater reuse which is the same limit set by the U.S. EPA Secondary Standard as well as other state regulations for greywater reuse. While BOD_5 measurements may be unsuitable for field operation, several optical techniques have been developed for quick and simple monitoring of organic contaminates (e.g., UV_{280}, UV_{254}, $color_{436}$, and $color_{400}$) (Uyguner et al. 2011). UV_{254} has gained significant attention because of its strong correlation with DBP formation potential (Becker and Wattier 1985; Pifer and Fairey 2014), thus enabling the use of UV_{254} for chlorinated water systems. It is expected that the parameter can also be useful for monitoring organics and DBP in military operations with the aid of commercially available spectroscopy devices. Currently, TB MED 577 has no regulation on the DBP formation from chlorine disinfection; but, it is recommended to monitor the organic contaminants for public safety.

Table 9. Developed water quality standard of the dishwashing water recycling system for military use

Parameter	Recommended water standard
pH	6-9
Turbidity	<1 NTU
UV_{254}	Surrogate[a] for organics (e.g., BOD_5 below 30 mg/L)
E. coli	< 50 cfu per mL[b]

[a] The correlation with BOD_5 for the dishwashing water to be recycled needs to be evaluated in the laboratory and calibration curves should be constructed before the use of UV_{254} in field.

[b] This recommended standard is proposed for reuse of recycled dishwashing water for dishwashing in military field settings

Measurement of UV_{254} can be a useful tool for providing a simple monitoring parameter for water quality of treated dishwater during field operation. Dishwater quality varies from meal to meal, which could pose a problem for using UV_{254} for organic regulation. To employ UV_{254} as a parameter of organic contaminants, the relationship between UV_{254} and other organic parameters needs to be further investigated. Turbidity and pH are easily measured parameters that can also provide information on the effectiveness of the treatment.

Based on the results and discussion above, a final set of dishwashing water reuse standards for field analysis was proposed as follows (Table 6): pH 6–9, turbidity <1 NTU, and *E. coli* <50 cfu mL^{-1}.

4.2 Environmental Discharge Considerations

For environmental discharge in the U.S., the dishwater recycling system requires a BOD_5 less than 30 mg/L and pH between 6 and 9. These standards could also be adopted for military dishwater recycling. This practice would also be beneficial for DBP reduction if chlorine disinfection is used. .

CHAPTER FIVE: CONCLUSIONS

A preliminary water reuse standard for dishwashing water was developed based on federal, state, and military regulations for non-potable water and on the evaluation of an existing electrocoagulation/ultrafiltration dishwater recycling treatment device. The specific set of dishwashing water reuse standards for field analysis (simple, but accurate) has then been finalized as follows: pH 6–9, turbidity <1 NTU, UV_{254}, and *E. coli* <50 cfu mL^{-1}. QMRA established that *E. coli* concentrations less than 50 cfu mL^{-1} will reduce risk of illness to less than 1 in 50,000 exposures, which is two orders of magnitude less than the current estimated disease incidence for military field personnel.

The developed specific water standard is the first for dishwashing water reuse and will be expected to maintain water quality that is safe for field operations, but not so stringent as to induce undue design complexity, cost, and operational/maintenance requirements. In addition, the parameters can be monitored using simple equipment in a field setting with only modest training requirements and real-time or rapid sample turn-around. The standard is expected to provide the military with a simple, compact, maintainable, integrated system to reliably process water quality data with variable mixtures of food, oil, and detergents from dishwashing water. This study may also prove useful in future development of civilian dishwashing guidelines.

APPENDIX A: DETERGENT ANALYSIS

detergent(2)

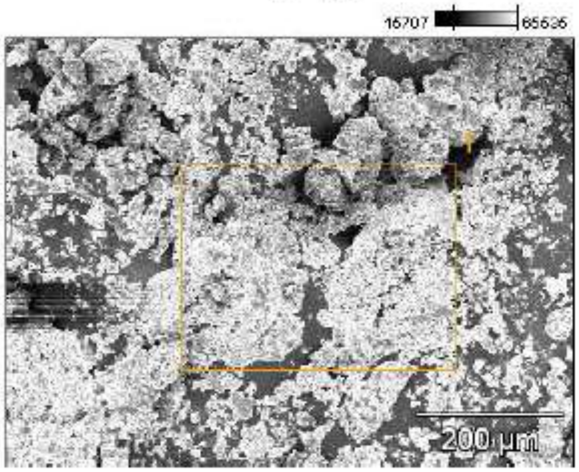
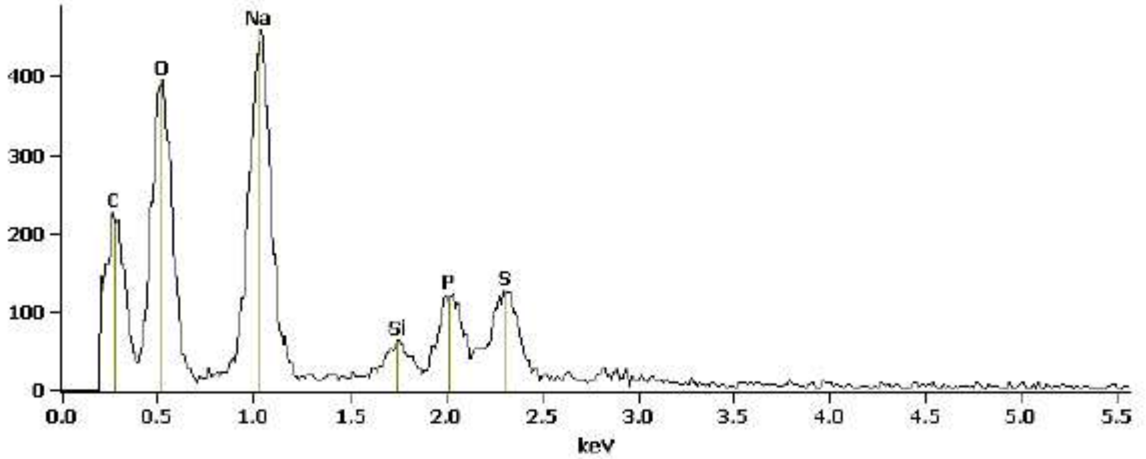
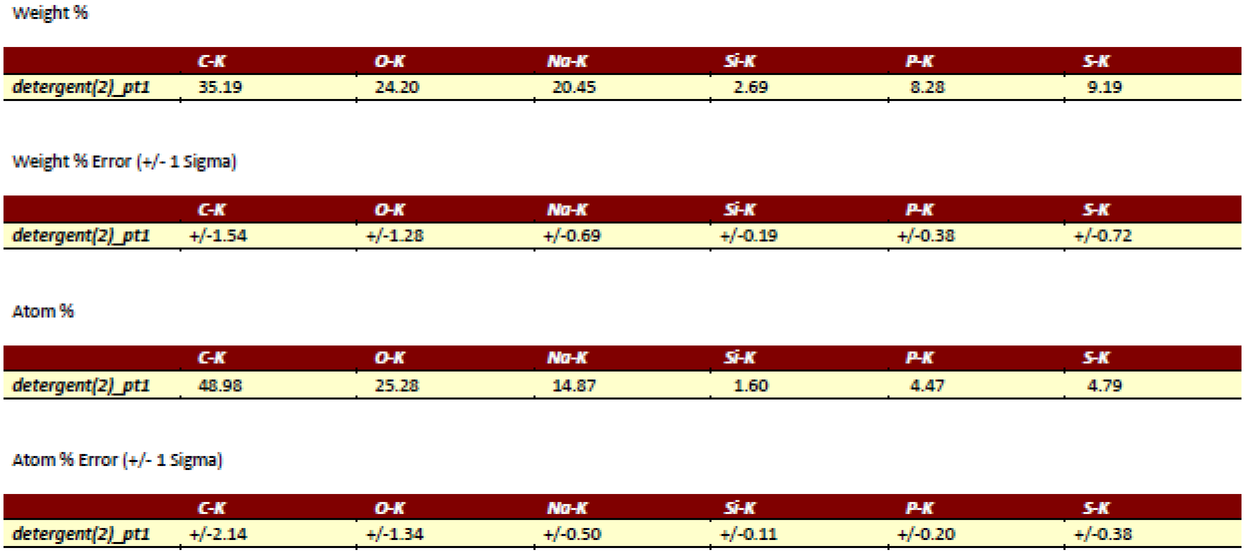


Image Name:	detergent(2)
Image Resolution:	512 by 384
Image Pixel Size:	1.52 µm
Acc. Voltage:	10.0 kV
Magnification:	145

Full scale counts: 459

detergent(2)_pt1





Weight %

	C-K	O-K	Na-K	Si-K	P-K	S-K
detergent(2)_pt1	35.19	24.20	20.45	2.69	8.28	9.19

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Na-K	Si-K	P-K	S-K
detergent(2)_pt1	+/-1.54	+/-1.28	+/-0.69	+/-0.19	+/-0.38	+/-0.72

Atom %

	C-K	O-K	Na-K	Si-K	P-K	S-K
detergent(2)_pt1	48.98	25.28	14.87	1.60	4.47	4.79

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Na-K	Si-K	P-K	S-K
detergent(2)_pt1	+/-2.14	+/-1.34	+/-0.50	+/-0.11	+/-0.20	+/-0.38

APPENDIX B: ADDITIONAL WATER REUSE STANDARDS

Table B1. Selected Greywater Reuse Standards

Application	Agency	pH	Turbidity (NTU)	BOD	*F. coli*	Free chlorine ($mgCl_2/L$)	Other
Urban-Unrestricted	Arizona-Class A	-	<2 (24hr) <5 (Max)	-	none/100ml[b] 3/100ml- Max	-	Nitrogen <10mg/L
	California-Tertiary	-	<2 (24hr) <10 (Max)	-	2.2/100ml[a] 23/100ml (Max)	-	-
	Florida	-	<2-2.5 (continuous)	CBOD <20mg/L[a]	75% samples below detection 25/100ml (Max)	> 1 for 15 min	-
	Hawaii-R1	-	<2 (95%) <10 (Max)	<30mg/L	2.2/100ml[a]	> 5 (90 min)	-
	Nevada-Category A	-		<30mg/L[c]	2.2/100ml[c] 23/100ml (Max)	-	-
	New Jersey-Type I	-	<2 (Max)	-	2.2/100ml[a] 14/100ml (Max)	> 1 (15 min)	Nitrogen <10mg/L
	North Carolina-Tier 1	-	<10 (Max)	<10mg/L[c] <15mg/L (Max)	14/100ml[c] 25/100ml (Max)	-	-
	Texas- Type I	-	<3	<5mg/l	20/ 100ml[c] 75/ 100ml (Max)	-	-
	Oregon	-	-	<10mg/L	2.2/ 100ml [c]	-	-
	Virginia-Level 1	-	<2[b]	<10mg/L[c]	14/100ml [c]	-	-
	Washington-Class A	-	<2[b] <5 (Max)	<30mg/L	2.2/100ml[a] 23/100ml- Max	-	-
	EPA-Unrestricted	6.0 - 9.0	<2	<10mg/l	None/ 100ml	1	-
	NSF/ANSI 350 Class R	6.0 - 9.0	<5 10- Max	<10mg/l 25mg/l (Max)	E.Coli-14/ 100ml 240 (Max)	>0.5 <2.5	-
	NSF/ANSI 350 Class C	6.0 - 9.0	<5 10- Max	<10mg/l 25mg/l (Max)	E. Coli- 2.2/ 100ml* 200 (Max)	>0.5mg/L <2.5	-
	TB MED 577-Unrestricted	6.5 -10	<10 <1 (filtered)	-	E. Coli- None/ 100ml 10(Max)	1 (30 min)	-
Urban-Restricted	Arizona-Class B	-	-	-	200/100ml 800/100ml (Max)	-	Nitrogen < 10mg/L
	California-Tertiary	-	-	-	23/100ml[a] 240/100ml- Max	-	-
	Florida[1]	-	-	-	-	-	-
	Hawaii-R2	-	-	30mg/L or 60mg/L depending of design	23/100ml[a] 200/100ml (max)	> 5 (90 min)	-

[a.] Weekly Average, [b.] Daily Average, [C.] Monthly Average

Table B1 *continued*

Application	Agency	pH	Turbidity (NTU)	BOD$_5$	*F. coli*	Free chlorine (mgCl$_2$/L)	Other
Urban-Restricted	Nevada-Category B	-	-	30mg/L^b	2.2/100ml^b 23/100ml (Max)	-	-
	New Jersey-Type II	-	-	-	200/100ml^c 400/100ml (Max)	> 1 (15 min)	Nitrogen < 10mg/L
	North Carolina-Tier 1	-	<10 (max)	<10mg/L^c <15mg/L (max)	14/100ml^c 25/100ml (Max)	-	-
	Texas- Type II	-	-	<20mg/l without pond system	200/ 100ml^c 800/ 100ml (Max)	-	-
	Virginia-Level 2	-	-	<30 mg/L^c <45mg/L (max)	200/100ml^c	-	-
	Washington-Class C	-	-	<30mg/L	23/100ml^a 240/100ml (Max)	> 1 (30 min)	-
	EPA-Restricted	6.0 - 9.0	-	-	< 200/100ml	-	-
	TB MED 577-Restricted	-	<5^a <10 (Max)	-	E. Coli- 150/ 100ml 600 (Max)	-	-
Groundwater Recharge	Florida	-	-	CBOD <30mg/L^c <45 mg/L^a <60mg/L (max)	200/100ml 800/100 (max)	> 0.5 (15 min)	Nitrate <12mg/l
	Washington	-	<2^b <5 (Max)	<5mg/L	2.2/100ml^a 23/100ml- Max	> 1 (30 min)	-
	EPA-Recharge	6.5 - 8.5	<2	-	-	1	-
Potable	TB MED 577 (Short term Potable)	5.0 - 9.0	<1	-	None/ 100ml	-	

$^{a.}$ Weekly Average, $^{b.}$ Daily Average, $^{C.}$ Monthly Average
Source: U.S. EPA's Guidelines for Water Reuse

APPENDIX C: THM ANALYSIS QUALITY ASSURANCE/QUALITY CONTROL

The QA/QC results for this study are presented in Tables C1 and C2. Sample duplicates are within the acceptable variation range of 10% RSD. The sample spikes were assessed by %Recovery and the acceptable range is 80 – 120% Recovery. All reported analyses are within this range. The haloacetic acid analysis was conducted by an external laboratory and analytical QA/QC was not provided. However, the experimental dupe for samples dosed with 70 and 75 mg/L and incubated at 24 hours showed a %RSD of 9% and 8% total haloacetic acids, respectively. This is still within the acceptable 10% limit.

Table C1. QA/QC Checks: Chlorine Residual

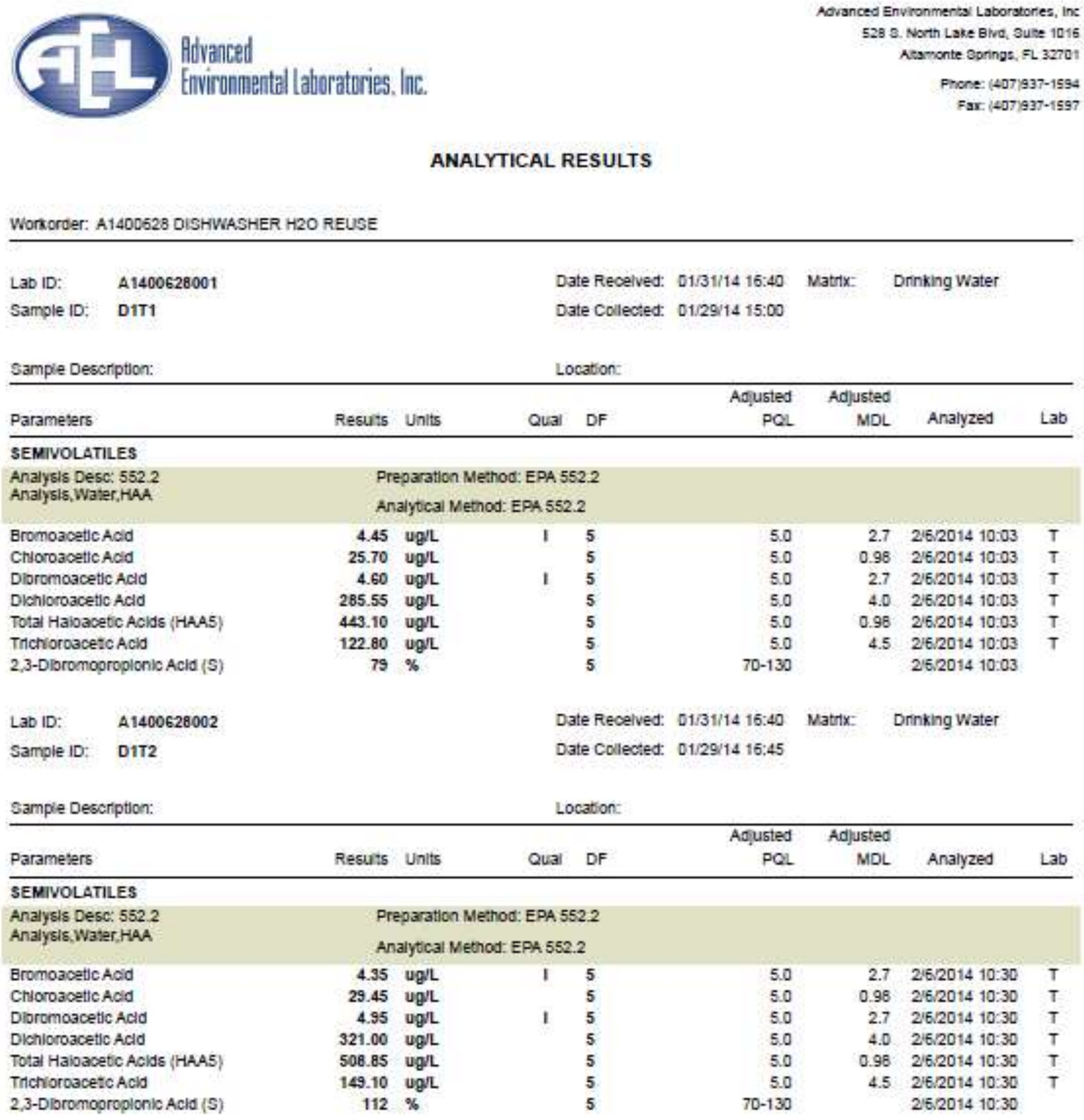
QA/QC	Sample ID Chlorine Dose (mg/L) @ Time (h)	Chloride Residual (mg/L)		%RSD
		Sample 1	Sample 2	
Analytical	60 @ 24	2.8	2.8	1
	70 @ 24	8.7	8.4	3
	75 @ 24 Dupe	13.0	13.0	<1
Experimental	70 @ 0.03	55.5	60.0	7
	75 @ 24	12.8	13.0	1

Table C2. QA/QC Checks: Trihalomethanes

Sample	Chlorine Dose (mg/L)	Incubation Time (hr)	Dilution	THM (μg/L)*			
				$CHCl_3$	$CHCl_2Br$	$CHClBr_2$	$CHBr_3$
ANALYTICAL							
Chlorinated Dishwater	70	24	1:10	166.09	12.51	<1	<1
Dupe				170.59	12.16	<1	<1
Spike (+30 μg/L)				191.36	44.80	35.14	30.55
%RSD				2	3	<1	<1
%Recovery				84	108	116	102
Chlorinated Dishwater	60	24	1:20	76.09	5.01	<1	<1
Dupe				76.40	5.26	<1	<1
Spike (+50 μg/L)				123.88	59.85	56.70	50.32
%RSD				<1	4	<1	<1
%Recovery				96	110	113	101
EXPERIMENTAL							
Chlorinated Dishwater	70	24	1:10	154.46	11.74	<1	<1
%RSD				6	6	<1	<1

*Diluted sample concentrations.

APPENDIX D: ADVANCED ENVIRONMENTAL LABORATORIES' HAA REPORT



Advanced Environmental Laboratories, Inc.

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Altamonte Springs, FL 32701
Phone: (407)937-1594
Fax: (407)937-1597

ANALYTICAL RESULTS

Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID: **A1400628001** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D1T1** Date Collected: 01/29/14 15:00

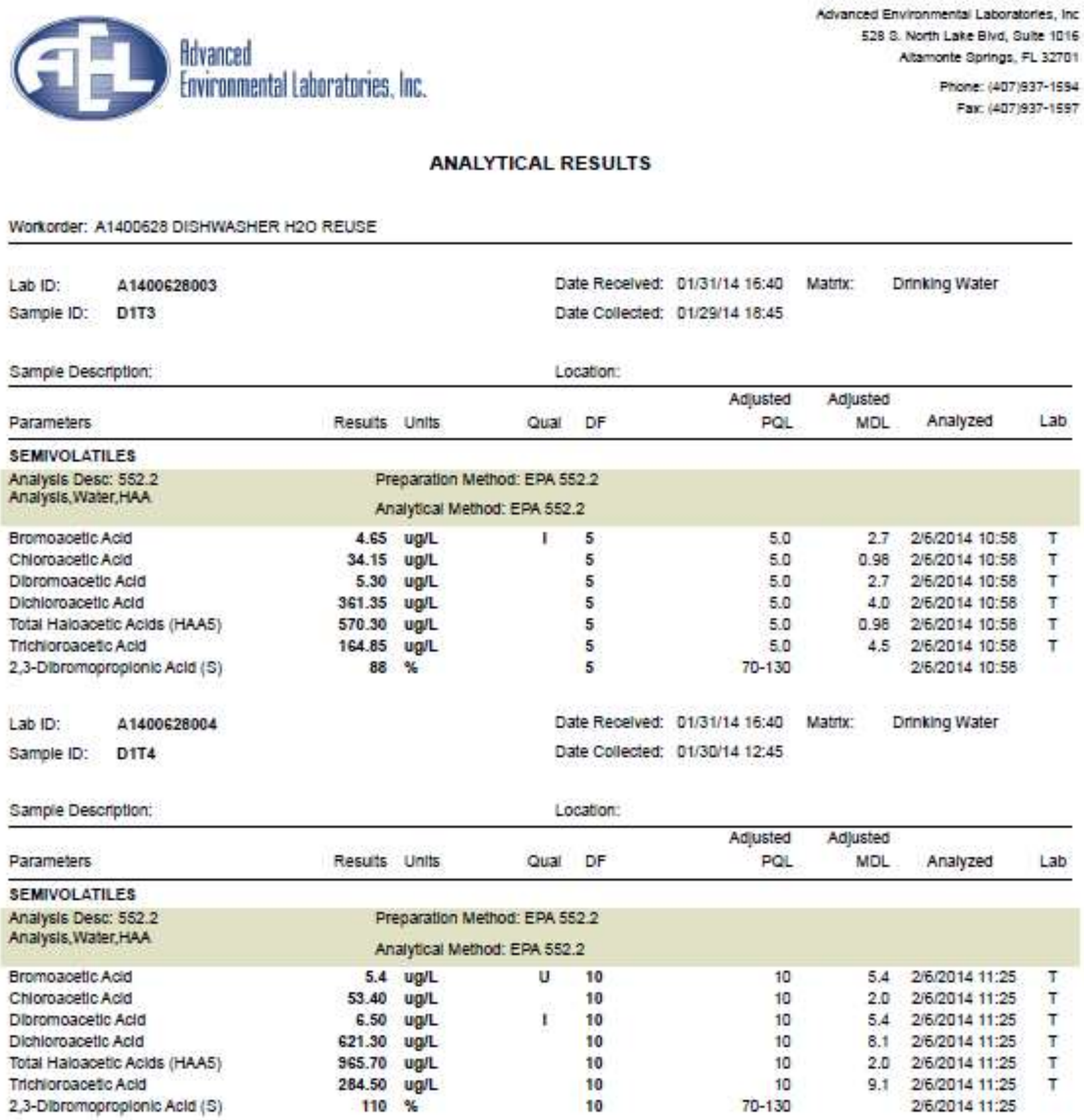
Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**4.45**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 10:03	T
Chloroacetic Acid	**25.70**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:03	T
Dibromoacetic Acid	**4.60**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 10:03	T
Dichloroacetic Acid	**285.55**	**ug/L**		**5**	5.0	4.0	2/6/2014 10:03	T
Total Haloacetic Acids (HAA5)	**443.10**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:03	T
Trichloroacetic Acid	**122.80**	**ug/L**		**5**	5.0	4.5	2/6/2014 10:03	T
2,3-Dibromopropionic Acid (S)	**79**	**%**		**5**	70-130		2/6/2014 10:03	

Lab ID: **A1400628002** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D1T2** Date Collected: 01/29/14 16:45

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**4.35**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 10:30	T
Chloroacetic Acid	**29.45**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:30	T
Dibromoacetic Acid	**4.95**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 10:30	T
Dichloroacetic Acid	**321.00**	**ug/L**		**5**	5.0	4.0	2/6/2014 10:30	T
Total Haloacetic Acids (HAA5)	**508.85**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:30	T
Trichloroacetic Acid	**149.10**	**ug/L**		**5**	5.0	4.5	2/6/2014 10:30	T
2,3-Dibromopropionic Acid (S)	**112**	**%**		**5**	70-130		2/6/2014 10:30	



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ANALYTICAL RESULTS

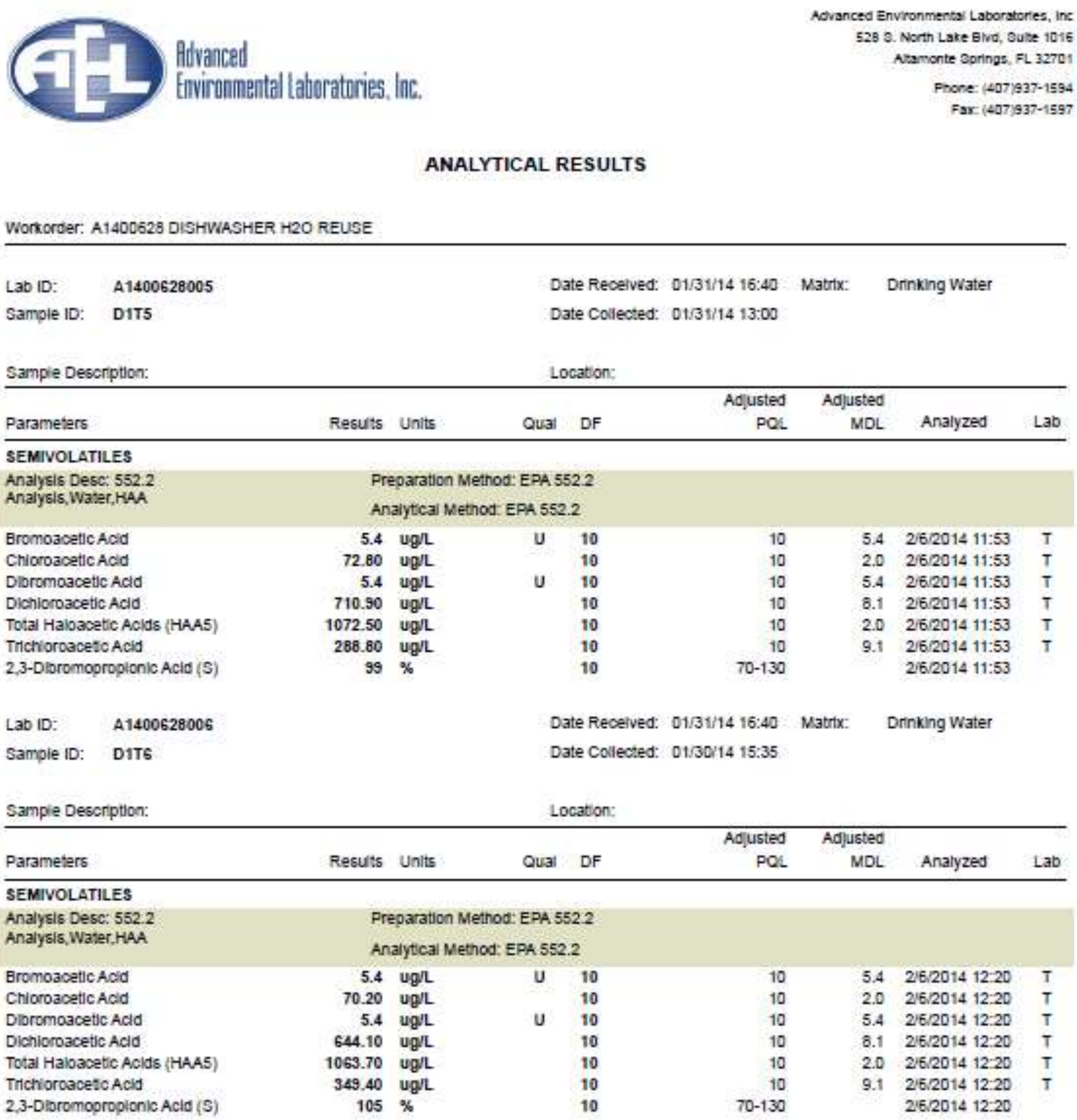
Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID:	**A1400628003**	Date Received: 01/31/14 16:40	Matrix: Drinking Water
Sample ID:	**D1T3**	Date Collected: 01/29/14 18:45	
Sample Description:		Location:	

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**4.65**	**ug/L**	**I**	**5**	5.0	2.7	2/6/2014 10:58	T
Chloroacetic Acid	**34.15**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:58	T
Dibromoacetic Acid	**5.30**	**ug/L**		**5**	5.0	2.7	2/6/2014 10:58	T
Dichloroacetic Acid	**361.35**	**ug/L**		**5**	5.0	4.0	2/6/2014 10:58	T
Total Haloacetic Acids (HAA5)	**570.30**	**ug/L**		**5**	5.0	0.98	2/6/2014 10:58	T
Trichloroacetic Acid	**164.85**	**ug/L**		**5**	5.0	4.5	2/6/2014 10:58	T
2,3-Dibromopropionic Acid (S)	**88**	**%**		**5**	70-130		2/6/2014 10:58	

Lab ID:	**A1400628004**	Date Received: 01/31/14 16:40	Matrix: Drinking Water
Sample ID:	**D1T4**	Date Collected: 01/30/14 12:45	
Sample Description:		Location:	

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	**U**	**10**	10	5.4	2/6/2014 11:25	T
Chloroacetic Acid	**53.40**	**ug/L**		**10**	10	2.0	2/6/2014 11:25	T
Dibromoacetic Acid	**6.50**	**ug/L**	**I**	**10**	10	5.4	2/6/2014 11:25	T
Dichloroacetic Acid	**621.30**	**ug/L**		**10**	10	8.1	2/6/2014 11:25	T
Total Haloacetic Acids (HAA5)	**965.70**	**ug/L**		**10**	10	2.0	2/6/2014 11:25	T
Trichloroacetic Acid	**284.50**	**ug/L**		**10**	10	9.1	2/6/2014 11:25	T
2,3-Dibromopropionic Acid (S)	**110**	**%**		**10**	70-130		2/6/2014 11:25	



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ANALYTICAL RESULTS

Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID: **A1400628005** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D1T5** Date Collected: 01/31/14 13:00

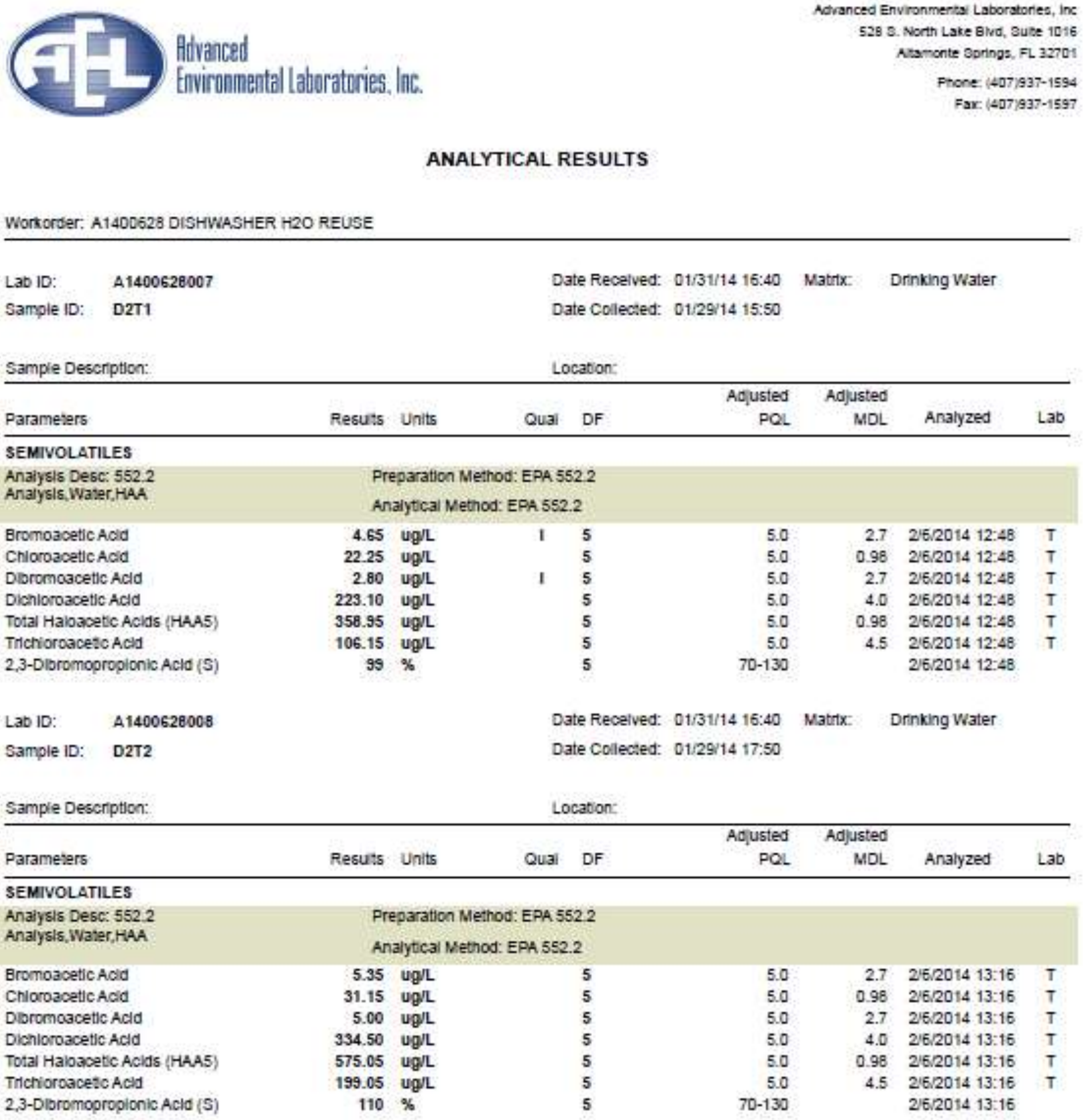
Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	**U**	**10**	10	5.4	2/6/2014 11:53	T
Chloroacetic Acid	**72.80**	**ug/L**		**10**	10	2.0	2/6/2014 11:53	T
Dibromoacetic Acid	**5.4**	**ug/L**	**U**	**10**	10	5.4	2/6/2014 11:53	T
Dichloroacetic Acid	**710.90**	**ug/L**		**10**	10	6.1	2/6/2014 11:53	T
Total Haloacetic Acids (HAA5)	**1072.50**	**ug/L**		**10**	10	2.0	2/6/2014 11:53	T
Trichloroacetic Acid	**288.80**	**ug/L**		**10**	10	9.1	2/6/2014 11:53	T
2,3-Dibromopropionic Acid (S)	**99**	**%**		**10**	70-130		2/6/2014 11:53	

Lab ID: **A1400628006** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D1T6** Date Collected: 01/30/14 15:35

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	**U**	**10**	10	5.4	2/6/2014 12:20	T
Chloroacetic Acid	**70.20**	**ug/L**		**10**	10	2.0	2/6/2014 12:20	T
Dibromoacetic Acid	**5.4**	**ug/L**	**U**	**10**	10	5.4	2/6/2014 12:20	T
Dichloroacetic Acid	**644.10**	**ug/L**		**10**	10	6.1	2/6/2014 12:20	T
Total Haloacetic Acids (HAA5)	**1063.70**	**ug/L**		**10**	10	2.0	2/6/2014 12:20	T
Trichloroacetic Acid	**349.40**	**ug/L**		**10**	10	9.1	2/6/2014 12:20	T
2,3-Dibromopropionic Acid (S)	**105**	**%**		**10**	70-130		2/6/2014 12:20	



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ANALYTICAL RESULTS

Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID: **A1400628007** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D2T1** Date Collected: 01/29/14 15:50

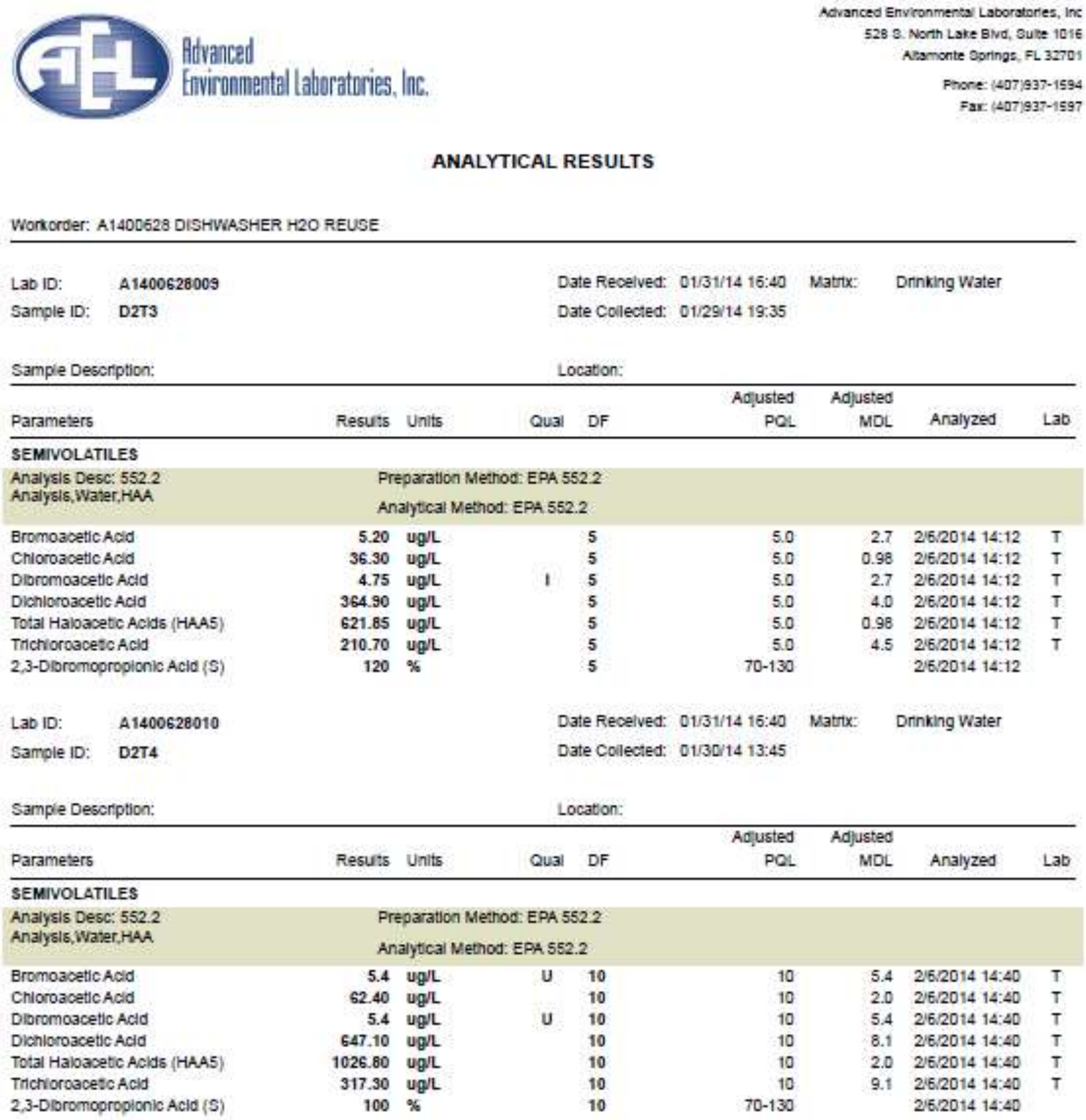
Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**4.65**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 12:48	T
Chloroacetic Acid	**22.25**	**ug/L**		**5**	5.0	0.98	2/6/2014 12:48	T
Dibromoacetic Acid	**2.80**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 12:48	T
Dichloroacetic Acid	**223.10**	**ug/L**		**5**	5.0	4.0	2/6/2014 12:48	T
Total Haloacetic Acids (HAA5)	**358.95**	**ug/L**		**5**	5.0	0.98	2/6/2014 12:48	T
Trichloroacetic Acid	**106.15**	**ug/L**		**5**	5.0	4.5	2/6/2014 12:48	T
2,3-Dibromopropionic Acid (S)	**99**	**%**		**5**	70-130		2/6/2014 12:48	

Lab ID: **A1400628008** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D2T2** Date Collected: 01/29/14 17:50

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.35**	**ug/L**		**5**	5.0	2.7	2/6/2014 13:16	T
Chloroacetic Acid	**31.15**	**ug/L**		**5**	5.0	0.98	2/6/2014 13:16	T
Dibromoacetic Acid	**5.00**	**ug/L**		**5**	5.0	2.7	2/6/2014 13:16	T
Dichloroacetic Acid	**334.50**	**ug/L**		**5**	5.0	4.0	2/6/2014 13:16	T
Total Haloacetic Acids (HAA5)	**575.05**	**ug/L**		**5**	5.0	0.98	2/6/2014 13:16	T
Trichloroacetic Acid	**199.05**	**ug/L**		**5**	5.0	4.5	2/6/2014 13:16	T
2,3-Dibromopropionic Acid (S)	**110**	**%**		**5**	70-130		2/6/2014 13:16	



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ANALYTICAL RESULTS

Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID: **A1400628009** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D2T3** Date Collected: 01/29/14 19:35

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.20**	**ug/L**		**5**	5.0	2.7	2/6/2014 14:12	T
Chloroacetic Acid	**36.30**	**ug/L**		**5**	5.0	0.98	2/6/2014 14:12	T
Dibromoacetic Acid	**4.75**	**ug/L**	I	**5**	5.0	2.7	2/6/2014 14:12	T
Dichloroacetic Acid	**364.90**	**ug/L**		**5**	5.0	4.0	2/6/2014 14:12	T
Total Haloacetic Acids (HAA5)	**621.85**	**ug/L**		**5**	5.0	0.98	2/6/2014 14:12	T
Trichloroacetic Acid	**210.70**	**ug/L**		**5**	5.0	4.5	2/6/2014 14:12	T
2,3-Dibromopropionic Acid (S)	**120**	**%**		**5**	70-130		2/6/2014 14:12	

Lab ID: **A1400628010** Date Received: 01/31/14 16:40 Matrix: Drinking Water
Sample ID: **D2T4** Date Collected: 01/30/14 13:45

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/6/2014 14:40	T
Chloroacetic Acid	**62.40**	**ug/L**		**10**	10	2.0	2/6/2014 14:40	T
Dibromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/6/2014 14:40	T
Dichloroacetic Acid	**647.10**	**ug/L**		**10**	10	8.1	2/6/2014 14:40	T
Total Haloacetic Acids (HAA5)	**1026.80**	**ug/L**		**10**	10	2.0	2/6/2014 14:40	T
Trichloroacetic Acid	**317.30**	**ug/L**		**10**	10	9.1	2/6/2014 14:40	T
2,3-Dibromopropionic Acid (S)	**100**	**%**		**10**	70-130		2/6/2014 14:40	

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ANALYTICAL RESULTS

Workorder: A1400628 DISHWASHER H2O REUSE

Lab ID:	**A1400628011**	Date Received:	01/31/14 16:40	Matrix:	Drinking Water
Sample ID:	**D2T5**	Date Collected:	01/31/14 13:10		

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/11/2014 18:28	T
Chloroacetic Acid	**71.30**	**ug/L**		**10**	10	2.0	2/11/2014 18:28	T
Dibromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/11/2014 18:28	T
Dichloroacetic Acid	**718.60**	**ug/L**		**10**	10	8.1	2/11/2014 18:28	T
Total Haloacetic Acids (HAA5)	**1127.00**	**ug/L**		**10**	10	2.0	2/11/2014 18:28	T
Trichloroacetic Acid	**337.10**	**ug/L**		**10**	10	9.1	2/11/2014 18:28	T
2,3-Dibromopropionic Acid (S)	**127**	**%**		**10**	70-130		2/11/2014 18:28	

Lab ID:	**A1400628012**	Date Received:	01/31/14 16:40	Matrix:	Drinking Water
Sample ID:	**D2T6**	Date Collected:	01/30/14 16:00		

Sample Description: Location:

Parameters	Results	Units	Qual	DF	Adjusted PQL	Adjusted MDL	Analyzed	Lab
SEMIVOLATILES								
Analysis Desc: 552.2 Analysis,Water,HAA	Preparation Method: EPA 552.2 Analytical Method: EPA 552.2							
Bromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/6/2014 15:36	T
Chloroacetic Acid	**57.20**	**ug/L**		**10**	10	2.0	2/6/2014 15:36	T
Dibromoacetic Acid	**5.4**	**ug/L**	U	**10**	10	5.4	2/6/2014 15:36	T
Dichloroacetic Acid	**632.70**	**ug/L**		**10**	10	8.1	2/6/2014 15:36	T
Total Haloacetic Acids (HAA5)	**971.40**	**ug/L**		**10**	10	2.0	2/6/2014 15:36	T
Trichloroacetic Acid	**281.50**	**ug/L**		**10**	10	9.1	2/6/2014 15:36	T
2,3-Dibromopropionic Acid (S)	**76**	**%**		**10**	70-130		2/6/2014 15:36	

APPENDIX E: DBP VOLATILIZATION MODEL

Disinfection by-product (DBP) vaporization

To evaluate potential health concerns associated with volatile DBP, dynamic modeling software was used to predict concentrations of free chlorine residuals, DBP production and DBP vaporization.

Chlorine consumption

Chlorine consumption was modeled based on data from an experiment that measured chlorine residuals over time in UF/EC treated dishwater. The treated dishwashing water (pH 9.6±0.1, TOC=95 mg/L) was dosed with chlorine and incubated at 32° C for different times (2, 4, 6, 24, and 48 hrs) at different sodium hypochlorite (NaOCl) doses (60, 70, and 75 mg Cl_2/L). Frequently, chlorine decay in the bulk phase is characterized by a first-order kinetic model as follows:

$$dc/dt = -kc \qquad \text{(E1)}$$

where c= chlorine concentration; k= first-order decay constant and t= time (Biswas et al. 1993).

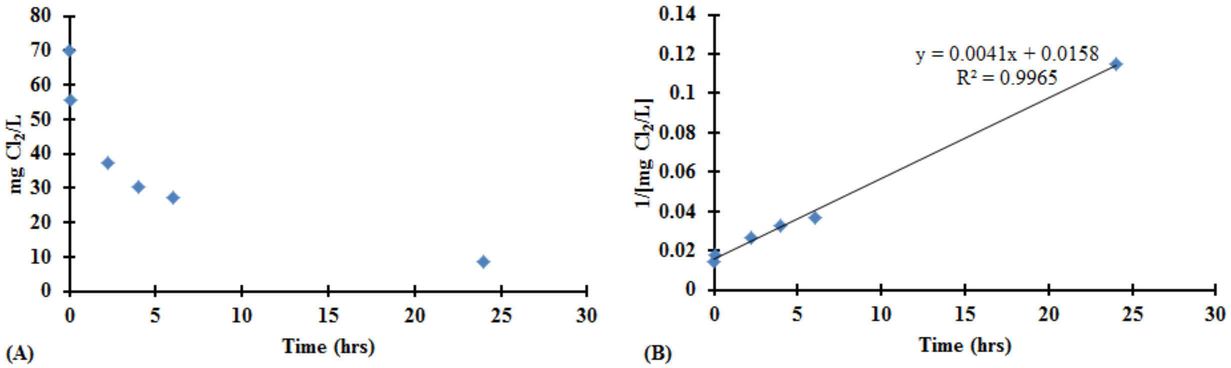


Figure E1. A) Shows the decay of chlorine consumption (70 mg/L) in treated greywater over 24 hours. B) Plots the inverse concentrations against time to get a k= .0041 mg/L^{-1} hr^{-1}

The results from the UF/EC greywater experiment, however; shows a second order decomposition reaction. This is likely explained by the chlorine reacting with organic material rather than with the surface of pipes, therefore,

$$HOCl + TOC \rightarrow \text{products} \tag{E2}$$

A paper looking at chlorine demand and TTHM formation kinetics supports this concept (Clark 1998). The kinetic model developed in study is summarized below.

$$r_{Cl_2} = -k(Cl_2)(\text{TOC}) \tag{E3}$$

Where r_{Cl_2}= chlorine decay in mg/L per hour, k= rate constant (mg/L^{-1} hr^{-1}), (Cl_2)= chlorine concentration (Cl_2 mg/L), and TOC= total organic carbon. Since the organic contaminants are so much more abundant in the water than the chlorine, their concentration is nearly constant and can be lumped into an effective first order rate constant (k_{eff}).

$$r_{Cl_2} = -k_{eff}(Cl_2) \tag{E4}$$

K_{eff} was found assuming the TOC in the experiment was much greater than Cl_2 concentrations (K_{eff} =0.0041) and effective first order reaction was integrated to model chlorine concentration with time.

$$Cl_2(t) = Cl_2(t,0)e^{-k_{eff}\times t} \tag{E5}$$

Chloroform Production

Disinfection by-production formation has been extensively studied since the early 1970’s. Among all the chlorinated by-products, chloroform certainly attracts a large amount of attention. Many studies have shown the influence of parameters like dose of chlorine, pH, temperature, content of organic matter and concentration of bromide or ammonia on chloroform production kinetics (Gallard and von Gunten 2002, Liang and Singer 2003, Trussell and Umphres 1978). This means predicting or modeling chloroform production is specific to the water being disinfected. Unfortunately, in the case of the treated dishwater, no literature contains kinetic information in very high organic, pH, and temperature environments (TOC=95mg/L, 9.5 and

55°C). Therefore a combination of literature and experimental data was used to model chloroform production. Experimental data was developed by treated dishwashing water (pH 9.6±0.1, TOC=95 mg/L) dosed with chlorine (70 mg/L) and incubated at 32^{o} C for different times (2, 4, 6, 24, and 48 hrs) and analyzing DBP production.

A study published in 2002 evaluated the kinetics of chlorination and THM formation (Gallard and von Gunten 2002). They found that THM precursors can be described as initial THM formation potential (THMFPi) that corresponds to fast reacting THM precursors (with 3 hours) and THMFP that responds to slowly reacting THM precursors (3 weeks). The kinetic model used for this volatile chloroform production model is based on the kinetics described in this paper. Several studies, including Gallard and Guntens (2002) paper, show second order kinetics, first order in chlorine and first order in reacting substances (THMFP). Therefor the rate of THM formation is given as:

$$\frac{d[THM]}{dt} = k \times [Cl_2] \times [THMFP] \qquad \text{(E6)}$$

Where [THMFP] is the concentration of the slowly reacting THM (THM after 48 hours in this case), [Cl_2] is the concentration of chlorine at time t, and k is the second order rate constant. Integrating the above equations yields,

$$\frac{1}{([Cl_2]_i - [THMFP])} \times \ln\left(\frac{([Cl_2] \times [THMFP])}{[Cl_2]_i([THMFP] - [THM])}\right) = kt \qquad \text{(E7)}$$

Where $[Cl_2]_i$ is the concentration of chlorine after the initial chlorine consumption (t=2.25 and [THM]= [0.43 ppm]) and [THMFP] is the total concentration of slowly reacting THM precursors. Unfortunately, the experimental DBP production data over time is with HAAs, however, there are 24 and 48 hour data for THMs. Figure 3a shows that the experimental data for HAAs follows the kinetics of Gallards and Guntens (2002) study. This kinetic model was then applied to the 24 and 48 hour data for chloroform (Figure E2b) to obtain a k value (0.0079 mg $L^{-1}hr^{-1}$) for modeling chloroform production.

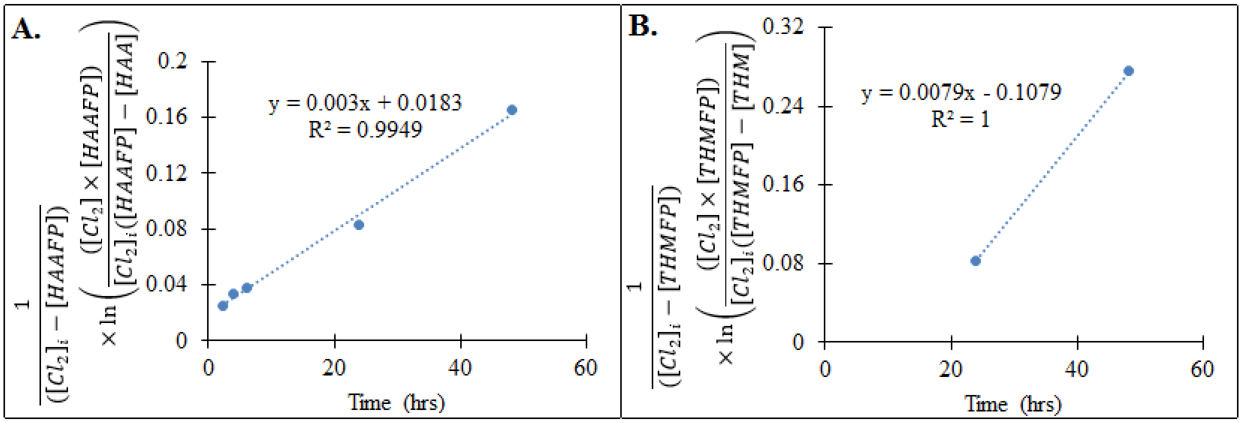


Figure E2. A) experimental data for HAA production. B) experimental data for THM production

Chloroform Vaporization

The kinetics for chloroform vaporization had to be fully assumed based on literature data because no experimental data was taken. Based on literature, many parameters can influence chloroform vaporization, including flow rate, temperature, ventilation, and pH. A chloroform vaporization model was developed from two publications. The first is a study by Howard and Corsi (1996) that looked at chloroform vaporization from kitchen sinks and the second is a paper by the same authors that look at chloroform vaporization from dishwashers.

Simplifying mass transfer to only volatilization can be expressed as:

$$\frac{dCV}{dt} = -K_L(C - \frac{C_g}{H_c})A \qquad \text{(E8)}$$

Where C= chloroform concentration in water mg, V= local volume of water in m^3 t=time in hours, K_l mass transfer coefficient, C_g= contaminant in air adjacent to water mg/m^3, H_c= Henry's law coefficient and A= interfacial surface area between water and air.

The paper modeling kitchen sink vaporization kinetics continues to develop the following equation.

$$C_g = C_l \left(\frac{Q_l}{Q_v}\right) f\{1 - e^{\frac{-t}{\emptyset_a}}\} \tag{E9}$$

Where C_g is the contaminant concentration in room air (mg/m^3), C_l is the contaminant concentration in water (mg/m^3), Q_l= water flow rate in m^3/hr, Q_l= room ventilation rater in m^3/hr, f is contaminant stripping efficiency, t=time in hours, $\emptyset_a$ is average residence time for air in room (hrs) and V is room volume in m^3.

The stripping efficiency was taken from the paper discussing chemical vaporization in dishwashers. The stripping efficiency of 97% was selected because of the high temperature (55°C) and presence of dishes used during the experiment. The stripping efficiency is given for toluene, but the author states the factor could be used for chloroform as well at high temperatures.

Stella model

Assumptions

Dynamic programing software (STELLA, isee systems, Lebanon, NH, USA) was used to predict the accumulation of volatile chloroform within the tent of the dishwashing unit. The dynamic model used k values and equations from experimental data and literature. All assumptions are listed below.

- Organics in holding tank: 92.5 mg L^{-1} TOC
- Chlorine in holding tank: 70 mg Cl_2 L^{-1} dose once every 24 hours
- Chlorine consumption in holding tank: 0.0041 mg Cl_2 L^{-1} hr^{-1} × Cl_2 in holding tank (mg Cl_2 L^{-1}) × TOC in holding tank (mg L^{-1})
- Chloroform production: 0.0079 mg L^{-1} hr^{-1} × Cl_2 in holding tank (mg Cl_2 L^{-1}) × TOC in holding tank (mg L^{-1})

- Chloroform removed to waste: chloroform in holding tank (chloroform production) × 1/3 pulsed twice a day (dilution factor)
- Chloroform vaporization: 0.97 × chloroform in holding tank (chloroform production)
- Chloroform vapor loss to ventilation: air exchanges (0.2) × chloroform vapor (ppm)
- Tent volume: 70 m^3
- Temperature for chlorine consumption and chloroform production k values were 32°C while temperature for vaporization was 55°C (worst case scenario).
- Air temperature: 25°C

Configuration

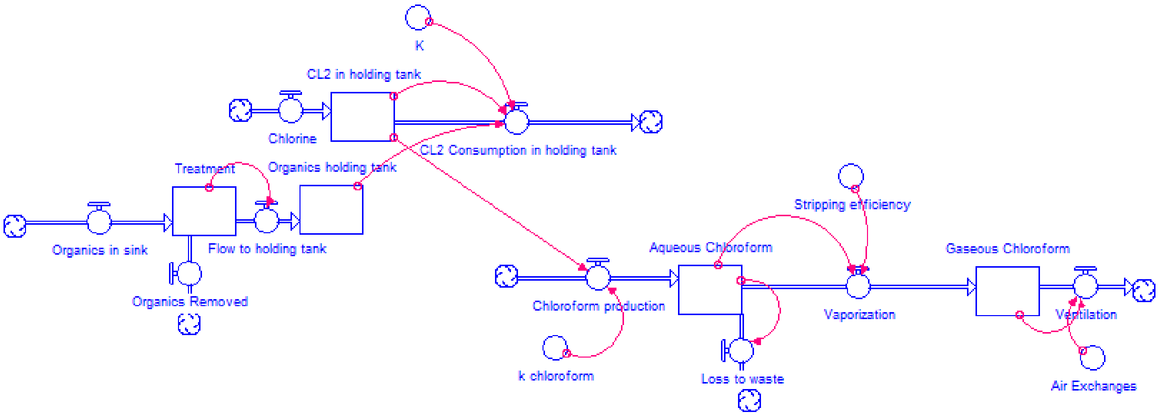
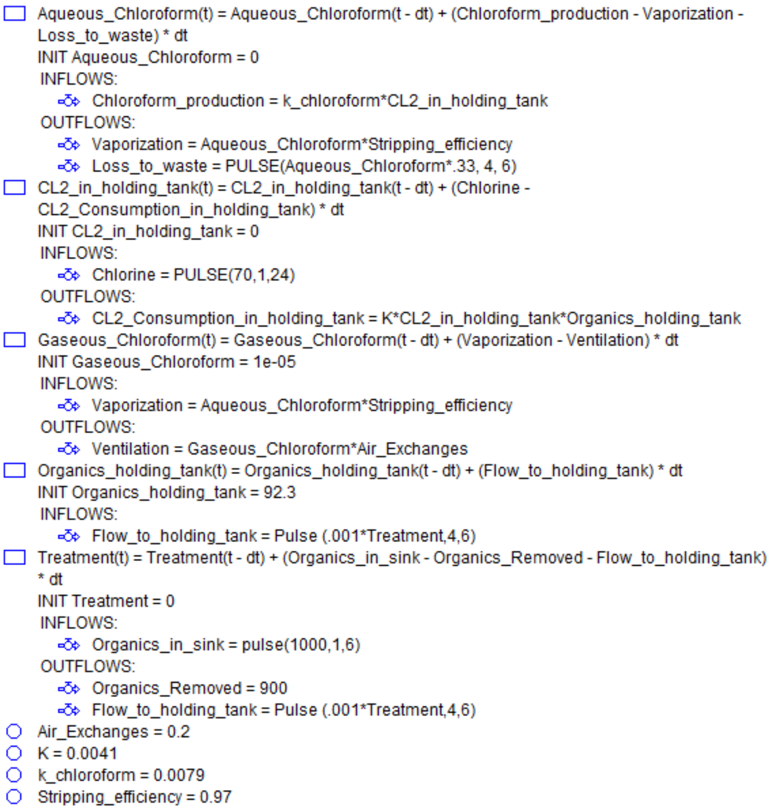


Figure E3. Stella model configuration.



```
☐ Aqueous_Chloroform(t) = Aqueous_Chloroform(t - dt) + (Chloroform_production - Vaporization -
  Loss_to_waste) * dt
  INIT Aqueous_Chloroform = 0
  INFLOWS:
    ⇨ Chloroform_production = k_chloroform*CL2_in_holding_tank
  OUTFLOWS:
    ⇨ Vaporization = Aqueous_Chloroform*Stripping_efficiency
    ⇨ Loss_to_waste = PULSE(Aqueous_Chloroform*.33, 4, 6)
☐ CL2_in_holding_tank(t) = CL2_in_holding_tank(t - dt) + (Chlorine -
  CL2_Consumption_in_holding_tank) * dt
  INIT CL2_in_holding_tank = 0
  INFLOWS:
    ⇨ Chlorine = PULSE(70,1,24)
  OUTFLOWS:
    ⇨ CL2_Consumption_in_holding_tank = K*CL2_in_holding_tank*Organics_holding_tank
☐ Gaseous_Chloroform(t) = Gaseous_Chloroform(t - dt) + (Vaporization - Ventilation) * dt
  INIT Gaseous_Chloroform = 1e-05
  INFLOWS:
    ⇨ Vaporization = Aqueous_Chloroform*Stripping_efficiency
  OUTFLOWS:
    ⇨ Ventilation = Gaseous_Chloroform*Air_Exchanges
☐ Organics_holding_tank(t) = Organics_holding_tank(t - dt) + (Flow_to_holding_tank) * dt
  INIT Organics_holding_tank = 92.3
  INFLOWS:
    ⇨ Flow_to_holding_tank = Pulse (.001*Treatment,4,6)
☐ Treatment(t) = Treatment(t - dt) + (Organics_in_sink - Organics_Removed - Flow_to_holding_tank)
  * dt
  INIT Treatment = 0
  INFLOWS:
    ⇨ Organics_in_sink = pulse(1000,1,6)
  OUTFLOWS:
    ⇨ Organics_Removed = 900
    ⇨ Flow_to_holding_tank = Pulse (.001*Treatment,4,6)
○ Air_Exchanges = 0.2
○ K = 0.0041
○ k_chloroform = 0.0079
○ Stripping_efficiency = 0.97
```

Figure E4. Stella model equations.

Results

The developed model predicts that if dosed with 70 mg Cl_2/L, the chlorine residual will be reduced to 8.79 mg Cl_2/L after 24 hours. This residual is higher than what is recommended by most greywater reuse standards, but represents a worst case scenario for chloroform production. Figure E5 shows Cl_2 concentrations over 72 hours.

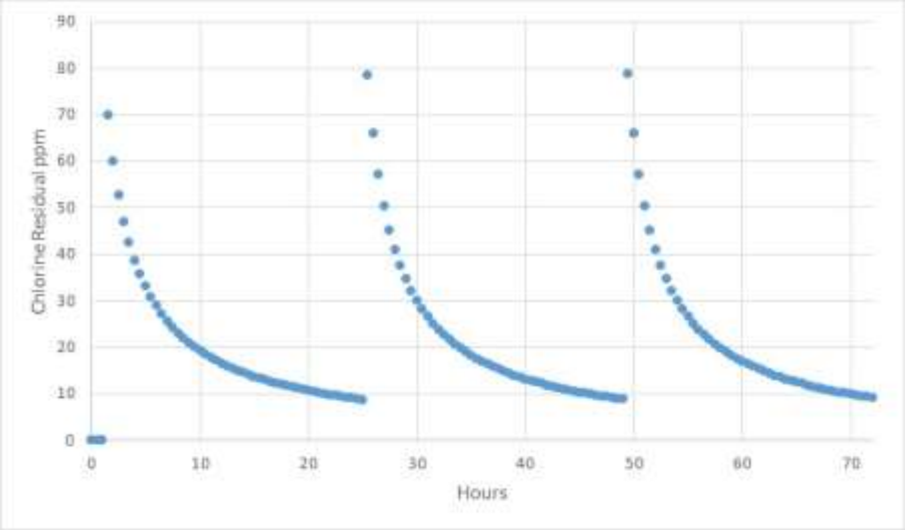


Figure E5. Chlorine Residual (mg Cl_2/L) in the holding tank over 72 hours.

Aqueous chloroform concentrations showed a spike of 0.45 ppm soon after chlorination followed by a series of gradual and sharp decreases, likely due to vaporization and a dilution effect from the sanitizing water, respectively. The aqueous chloroform concentrations fall to 0.072 ppm right before the holding tank is dosed on the following day. Figure E6 shows aqueous chloroform concentrations over 72 hours.

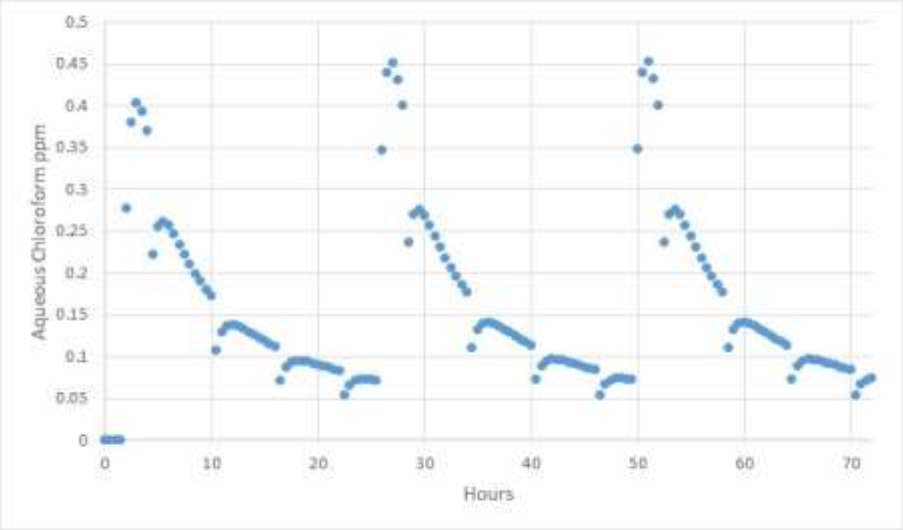


Figure E6. Aqueous Chloroform (mg/L) in the holding tank over 72 hours.

Gaseous chloroform showed a spike at 1.16 ppm soon after chlorination and a decrease to 0.47 ppm over the remainder of the day. Figure E7 shows gaseous chloroform concentrations in a 70 cubic meter tent with an air exchange rate of 0.2/hour. It is important to note that these concentrations will vary greatly depending on tent size, temperature and ventilation rates. The model is meant to display a worst case situation with minimal ventilation and a small tent, therefore the gaseous chloroform is likely to be much lower. In any case, proper ventilation, especially after chlorinating, will ensure the safety of the dishwashing personnel.

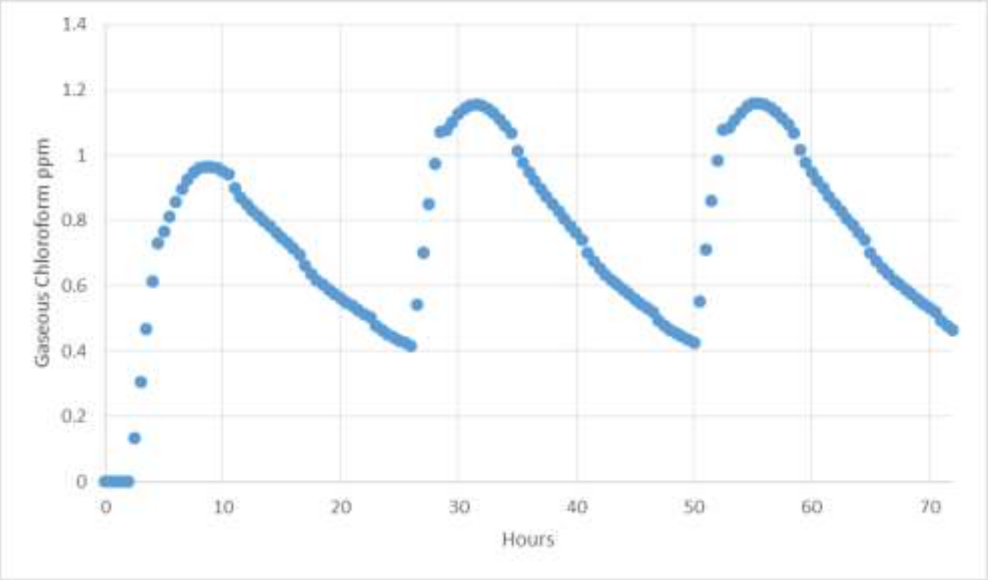


Figure E7. Gaseous Chloroform (ppm) in the military dishwashing tent over 24 hours.

Conclusion

The dynamic model developed on rate constants derived from experimental data shows a maximum gas chloroform of 1.16 ppm. The U.S. Occupational Safety & Health Administration (OSHA) requires chloroform concentrations to be below 50 ppm, but recommend that the permissible exposure limit be reduced to 2 ppm within an hour. Although the model predicts chloroform concentrations will not exceed the OSHA standards, proper ventilation (especially after adding chlorine) will ensure the safety of the dishwashing personnel. The developed model is based off several assumptions, to fully understand the risk of chloroform to health, full scale studies need to be performed.

APPENDIX F: QMRA REPORT

Estimation of the ratio of *E. coli* O157:H7 to total *E. coli* in dishwashing water

Ground beef has been implicated in the majority of food-related *E. coli* O157:H7 outbreaks in the U.S. (FSIS, 2001), therefore the ratio of *E. coli* O157:H7 to total *E. coli* in ground beef may be the closest approximation to the ratio in dishwashing water. Eisel et al. (1997) reported ranges of 10 to 100 cfu g^{-1} of *E. coli* in ground beef. The *E. coli* O157:H7 strain is found in 0.2% to 0.5% of ground beef samples, in concentrations ranging from 1 to 3 bacteria per gram typical serving size of 87 g (UFSaIS, 2001). Based on this information, the ratio of *E. coli* O157:H7 to total *E. coli* in ground beef (and the assumed ratio in dishwashing water) can be calculated as follows:

Lower estimate:

- Assumed concentration of *E. coli* O157:H7: 1 bacteria / 87 g of ground beef
- Assumed concentration of total *E. coli*: 100 cfu / g of ground beef
- Assumed fraction of ground beef servings with *E. coli* O157:H7: 0.2%
- Calculation: Ratio = $(1/87)/100*0.002 = 2.3\times10^{-7}$

Upper estimate:

- Assumed concentration of *E. coli* O157:H7: 3 bacteria / 87 g of ground beef
- Assumed concentration of total *E. coli*: 10 cfu / g of ground beef
- Assumed fraction of ground beef servings with *E. coli* O157:H7: 0.5%
- Calculation: Ratio = $(3/87)/10*0.005 = 1.7\times10^{-5}$

For the purposes of this study, it is assumed that the ratio of *E. coli* O157:H7 to total *E. coli* in dishwashing water is between 2.3×10^{-7} and 1.7×10^{-5}, and the higher of the two ratios was chosen as a conservative approach.

Quantitative Microbial Risk Assessment (QMRA) Model

Dose-Response Curves

The QMRA model was ran by a collaborator, Matt Verbyla, at the University of South Florida. The following is the model he developed.

The Pfaff transformation of the hypergeometric dose-response model for norovirus (Eq. (F1)) was used with previously-published best-fit values for model parameters α, β, and a, without making any assumptions about virus aggregation (using the best-fit values from the combined inocula (8fIIa + 8fIIb) used by (Teunis et al., 2008). The Pfaff transformation, which is a close approximation to the original model (assuming all doses ≤33,323) is necessary here since the best-fit value for parameter a provided by Teunis et al. (2008) exceeds one of the constraints of the Gauss hypergeometric function (Fiona Barker et al., 2013; Mok et al., 2014).

$$p_{\text{inf}} = 1 - \left({}_2F_1\left(\beta, \frac{\lambda(1-a)}{a}, \alpha - \beta; a\right) \left(\frac{1}{1-a}\right)^{-\left(\frac{\lambda(1-a)}{a}\right)} \right) \tag{F1}$$

The approximate Beta-Poisson dose-response model (Eq. (2)) was used for both *Salmonella* spp. and pathogenic *E. coli* O157:H7 (Soller et al., 2010). The use of this approximate model (instead of the exact model) is valid for *Salmonella* and *E. coli* O157:H7 since β » 1 and α « β (Teunis and Havelaar, 2000).

$$p_{\text{inf}} = 1 - \left(1 + \frac{\lambda}{\beta}\right)^{-\alpha} \tag{F2}$$

Maximum tolerable probability of illness

In order to establish maximum limits for the concentration of pathogenic microorganisms in reclaimed greywater, it is necessary to first establish a maximum tolerable probability of illness resulting from microbial infections. Maximum contaminant levels established by the U.S. EPA for chemicals and radionuclides have been determined based on a tolerable lifetime risk which is two orders of magnitude lower than the overall incidence of cancer in the U.S. (Munro and Travis, 1986; Mara et al., 2010). The U.S. EPA has previously recommended a maximum annual waterborne-disease infection risk of 10^{-4} (Macler and Regli, 1992), but this recommendation was based on background waterborne disease prevalence in the U.S. Individuals in military field settings already experience a high incidence of diarrheal disease, with average estimates ranging from 6 to 29 cases per 100 person-months in the field (Riddle et al., 2006). Using Equation F4, where n = 30 days per month, assuming that the monthly risk of illness per person (P_{ill}) is equal to 6 cases per 100 person-months (6.0%), the daily incidence of diarrheal disease for individuals in military field settings (p_{ill}) would be equivalent to approximately 0.2%.

$$P_{\text{ill}} = 1 - (1 - p_{\text{ill}})^n \qquad \text{(F3)}$$

A maximum tolerable daily probability of illness 0.002% (2×10^{-5}) was chosen for this study, since this risk is two orders of magnitude lower than the current incidence of diarrheal disease for people in military field settings. In other settings, where the existing incidence of disease is lower, this level of risk may be considered to be too high by local stakeholders. Water reuse guidelines should be set with consideration for the local context and the existing health burden affecting the population.

Code used in ‘R’

```
library(hypergeo)
#Tolerable probability of illness and number of Monte Carlo trials
      pill_max <- 0.00002
      iter <- 10000

#Norovirus dose-response model Pfaff Transformation (Teunis et al. 2008)
      a_NoV <- 0.9997
      a1_NoV <- (1-a_NoV)/a_NoV
      alpha_NoV <- 0.04
      beta_NoV <- 0.055
      eta_NoV <- 0.00255
      r_NoV <- 0.086
      Sf_NoV <- 1
      pinf_NoV <- function(d_NoV){Re(1-
(hypergeo(beta_NoV,d_NoV*a1_NoV,alpha_NoV+beta_NoV,a_NoV)*((1/a1_NoV)^(-
d_NoV*a1_NoV))))}
      pillinf_NoV <- function(d_NoV){(1-(1+eta_NoV*d_NoV)^(-r_NoV))}
#Lower and upper guesses for NoV
      LG_NoV <- 0
      UG_NoV <- 100
      step_NoV <- (UG_NoV - LG_NoV) / iter
#Non-typhi Salmonella dose-response model (Ahmed et al. 2010; McBride et al.
2013)
      alpha_Sal <- 0.3126
      beta_Sal <- 2884
      pillinf_Sal <- 0.2
#E. coli dose-response model parameters (Huertas et al. 2008)
      alpha_EC <- 0.4
      beta_EC <- 45.9
      pillinf_EC <- 0.28   #Soller et al. 2010

#NOROVIRUS
d_NoV <- LG_NoV
for(i in 1:iter){
      pill_NoV <- pinf_NoV(d_NoV) * pillinf_NoV(d_NoV) * Sf_NoV
      ifelse(pill_NoV < pill_max, d_NoV <- d_NoV + step_NoV, d_NoV <- d_NoV)
      }
      dt_NoV <- d_NoV - step_NoV
      test_NoV <- ((iter * step_NoV) - (d_NoV - LG_NoV))/step_NoV

#SALMONELLA
      dt_Sal <- beta_Sal * (exp(-log(1-pill_max/pillinf_Sal)/alpha_Sal) - 1)

#E COLI
      dt_EC <- beta_EC * (exp(-log(1-pill_max/(pillinf_EC))/alpha_EC) - 1)

#CHECK FOR APPROPRIATE RANGE OF GUESSES FOR NoV DOSE
print(test_NoV) # test_NoV should be lower than the number of iterations
"iter"
print(step_NoV) # the tolerable dose dt_NoV should be greater than the LG_NoV
```

```
#TOLERABLE DOSES
print(dt_NoV) #NOROVIRUS tolerable dose
print(dt_Sal) #SALMONELLA tolerable dose
print(dt_EC) #E. COLI O157:H7 tolerable dose
```

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