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Evaluation Of Point Of Use Drinking Water Treatment Systems For Colonias In The Southwest United States

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Dedication

To my Father the first and greatest engineer
To my father who was an engineer in every respect except for the degree
To my wife who does the impossible: love me back
To my mother who gives herself away to serve others
To my advisor who taught me to learn
To my friends in whom I can always depend

EVALUATION OF POINT OF USE DRINKING WATER TREATMENT SYSTEMS FOR COLONIAS IN THE SOUTHWEST UNITED STATES

by

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Abstract

Clean drinking water is often taken for granted in first world countries, such as the United States. However, thousands of *colonias* residents (settlements in the Southwest US that lack access to basic infrastructure) still lack access to clean drinking water. Such is the case in the Paso Del Norte Region. In Doña Ana County, NM, and El Paso County, TX, *colonia* residents typically rely on shallow domestic wells and hauled water, respectively. However, both water sources can pose health concerns from elevated total dissolved solids and microbiological contamination. With connection to centralized water treatment and distribution still years away, *colonias* require a more immediate and effective solution for their current situation. This research proposed that such a solution could be achieved with a point-of-use (POU) water treatment system. The goal of this project was to provide *colonia* residents with an economically, socially, and environmentally sustainable water treatment system. The objectives of this study were to: (1) assess user preferences and actual water quality data in order to design a household-level water treatment system; (2) develop a holistic point-of-use technology evaluation system that can be used by residents to screen and select a POU drinking water system for their home; and (3) evaluate methods for preserving water quality in drinking water storage tanks. First, focus group studies were conducted in colonias to discuss possible water treatment options and record residents' perceptions and preferences. Water samples were collected from willing participants and analyzed for basic drinking water quality parameters. Second, many types of commercially available water treatment technologies were reviewed and analyzed, and a five-component evaluation and ranking system was developed to facilitate selection and implementation in *colonias*. Third, experiments were performed to evaluate the efficacy and feasibility of using copper and/or hypochlorite treatment to control algae and preserve water quality in storage tanks. The research performed in this study showed that *colonias* that rely on groundwater face more challenges, in the form of microbiological contamination and high salinity, than *colonias* that rely on hauled water. A treatment train of basic cartridge filtration and point-of-use desalination was proposed to address the water quality issues in *colonias* relying on well water or hauled water. It was also determined that the most economically, socially, and environmentally sustainable system was an under-the-sink reverse osmosis (RO) unit. This research also yielded a system of preserving water quality in drinking water tanks, which includes chlorine monitoring and dosing, periodic tank cleaning, and the possible use of copper as an algaecide.

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Chapter 1: Introduction

BACKGROUND

Access to basic water infrastructure is generally taken for granted in the United States. However, throughout the United States, it is still possible to find communities that have either less than adequate or non-existent water infrastructure. More than 12.3 million people live in these *colonias* (a name given to unincorporated communities in the Southwest with minimal infrastructure), along the US-Mexico border (Donelson, 2004). The exact cause of lack of access to basic infrastructure is site-specific, but analysts believe that these reasons, in general, include high infrastructure costs and weak political influence (Olmstead, 2004).

The lack of basic services is more than an inconvenience for the *colonias* residents; because of the conditions that *colonia* residents experience, such as unclean water, health problems are common (Davidhizar and Bechtel, 1999). While it is possible for *colonia* residents to purchase bottled water for drinking, some must drive up to 30 miles to be able to do so (Davidhizar and Bechtel, 1999), and bottled water is not a practical source of water for general hygiene such as bathing and domestic washing.

While legislation aimed at improving conditions in *colonias* has been approved (Mier et al, 2008), and programs improving water services have been created (Wescoat, 2006), *colonias* still face daunting challenges of implementation. Some *colonias* are being connected to centralized water treatment and distribution systems, but there are some communities where the economical and political conditions are such that a connection to the public water supply will take many years, if ever realized. Several of these *colonias* can be found in Doña Ana County

(southern New Mexico, northwest of the City of El Paso) and El Paso County (Far West Texas, east of the City of El Paso), as shown in Figure 1.1.

Figure 1.1: Research study area – *colonias* in the Paso del Norte region

PROBLEM STATEMENT

Colonias in eastern El Paso County rely predominately on certified water haulers for water supply. These water haulers are legally required to be certified by the Texas Commission on Environmental Quality (TCEQ) and provide water that comes only from sources approved by TCEQ (TCEQ, 2013). While the water sources may be good quality, water at the point-of-use may suffer from re-contamination due to the storage of water for several weeks. Indeed, post-collection microbial contamination has been recognized as a problem for households who collect water from other sources and later transport to their homes (Gundry, 2004). Beyond microbiological contamination, research has also shown that algae inside water storage tanks are a problem for *colonia* residents of eastern El Paso County (Campos et al, 2013). For example, Figure 1.2 shows the inside of a water tank, which has been contaminated by algae in the Hueco Tanks area.

Figure 1.2: Algae contamination inside of a household water storage tank in Hueco Tanks

The main water source for colonias in Doña Ana County, NM is shallow groundwater wells, and groundwater in this area is known to be contaminated with high total dissolved solids (salinity). While well water is generally assumed to be less prone to pathogenic contamination (*e.g.*, parasites, bacteria, and virus), it is still possible for the water to become contaminated at the point-of-use because of the lack of residual disinfectant.

Goals and Objectives

In light of the water quality problems faced by *colonias*, the goal of this research is to address concerns caused by inadequate quality of drinking water through a point-of-use (POU) and/or point-of-entry (POE) water treatment system. To accomplish this goal, the objectives of this research are to:

1) Assess user preferences and actual water quality conditions in order to construct a conceptual design for a household-level water treatment system.
2) Develop a holistic point-of-use technology evaluation system that can be used by household residents to screen and select a POU drinking water system for their home.
3) Evaluate the efficacy and feasibility of using copper and/or hypochlorite treatment for preserving water quality in household water storage tanks in *colonias*.

Chapter 2: Determining the Technical and Social Requirements for a Water Treatment System for *Colonias* in the Southwest United States

INTRODUCTION TO *COLONIAS* AND THEIR INFRASTRUCTURE NEEDS

More than 12.3 million individuals live in *colonias* (Spanish word for "settlement"), which are communities with minimal infrastructure along the US-Mexico border (Donelson 2004) that have minimal governance (Colonias Development Council 2009). A group of *colonias* can be found in the Paso Del Norte Region, particularly of Dona Ana County, NM and El Paso County, TX (Figure 2.1). Although the story varies as to how these *colonias* arrived at their current state, the general reasons include high costs of developing infrastructure and little to no political influence (Olmstead 2010). Colonia residents in Doña Ana County (northwest of the City of El Paso) rely primarily on domestic well water, while most households in *colonias* in El Paso County (east of the City of El Paso) obtain their water through certified water haulers (25 TAC §229.83 2006).

When there is a lack of water infrastructure, health problems are common (Davidhizar and Bechtel 1999). Indeed, *colonias* residents have previously had issue with stomach and skin illnesses, which in some *colonias* have been attributed to microbiological contamination and/or algae. Other *colonias* residents have had problems with clogged pipes and broken appliances (Campos, Walker, Walton, et al. 2013).

Whereas legislation aimed at improving *colonias* has been approved in some parts (Mier et al. 2008), as well as programs that focus on improving the water service (Wescoat, Headington, and Theobald 2007), some *colonias* are still far from obtaining clean drinking water. A more immediate solution could come in the form of point of entry water treatment devices.

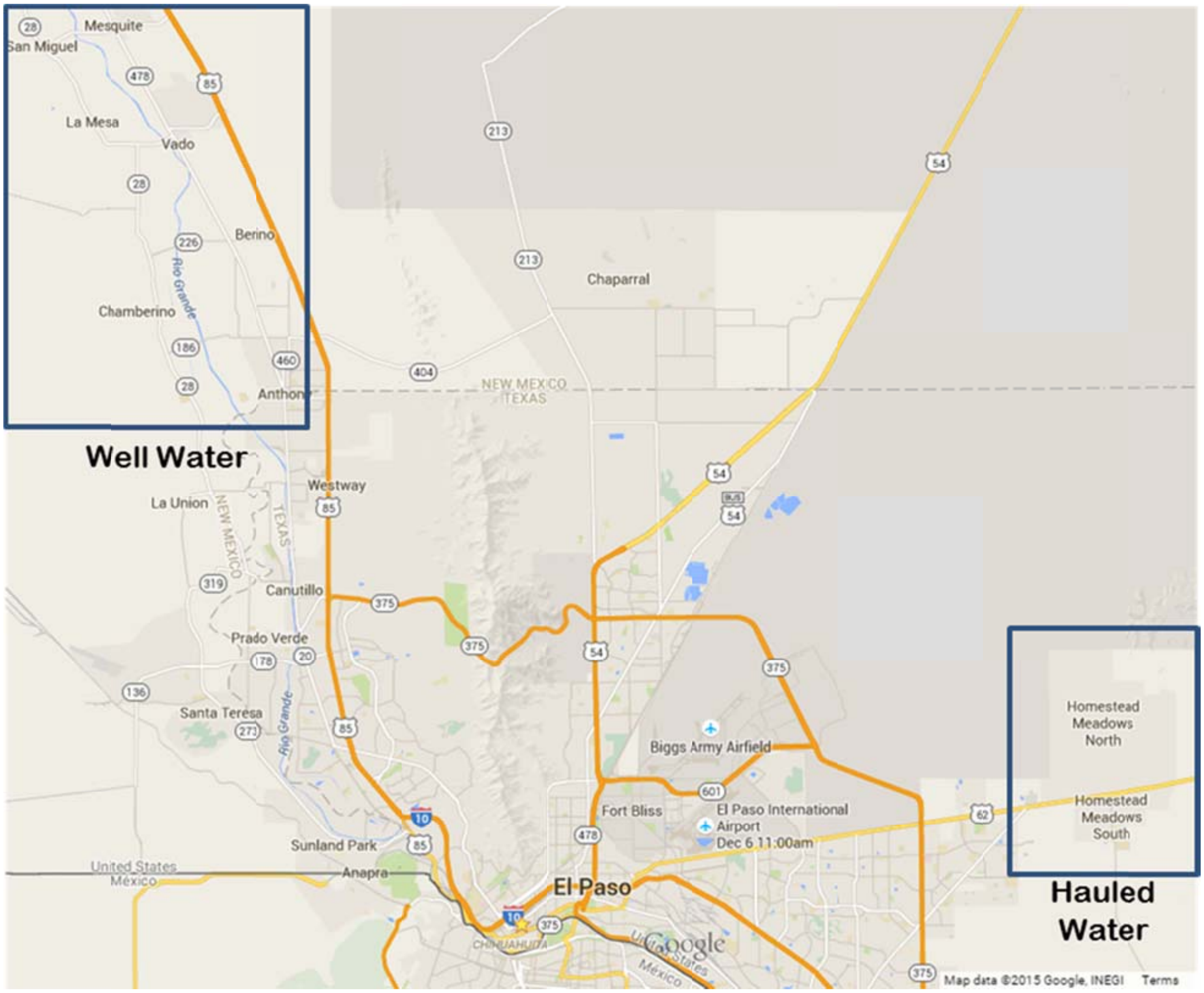

Figure 2.1: Locations of the Paso Del Norte *colonias* engaged in this research

With regards to POE or POU implementation, *colonias* pose a conundrum as they do not meet the EPA definition of a public water system – that is, they do not have at least 15 connections or regularly serves an average of at least 25 individuals daily for at least 60 days of the year (40 CFR §141.2 1996) Furthermore *colonias* are also composed of people who, unlike their counterparts in the developing world, have other options to obtain drinking water and are reluctant or unaware to use the less expensive but more traditional POU devices such as gravity powered filters (Campos, Walker, Santiago, et al. 2013), which are popular in developing countries. *Colonias* have, what can be referred to as, an "expectation problem", as they believe

that the water that reaches their house should be as good, in terms of quality, quantity, and pressure, as the water provided by a public utility. Many things can be said about the problem in itself, but the reality still remains that residents are very likely to forego using a water filtration system if it does not provide them with what they perceive to be “clean drinking water”.

The ideal solution for the *colonias* could be a POE system, as it would provide good clean water for the entire household. However, POE systems pose another problem in the form of capital cost. The high cost of POE filtration can be attributed to providing drinking water quality to all fixtures within a home, which may not all require drinking water quality. Whole house devices often feature a cartridge filter followed by a large microfiltration (MF), ultra filtration (UF), or reverse osmosis (RO) membrane. Utilizing an all-membrane system has the advantage of requiring less maintenance by the residents, but it also greatly increases the capital and operational costs. An alternative to membrane filtration is chemical disinfection. Chemical treatments have the advantage of usually costing much less than a membrane. However, if not properly designed and implemented, chemical treatment could prove to be ineffective or altogether more damaging (e.g. DBPs).

Goals and Objectives

There is a need to determine the technical and social sustainability requirements to provide a water treatment system for residents of the Paso Del Norte *colonias*, which may also represent the general requirements needs The goal of this study was to develop a conceptual design for a household-level water treatment system. The first objective was to engage the heads of households through focus groups and determine the social sustainability requirements for a water treatment system. The second objective was to sample and analyze the *colonias’* water supply so as to understand the water quality issues they face. The third objective of this research was to

develop a conceptual design for a water treatment system for the *colonias* and to create a set of educational materials that would help them improve their water quality, even if no system was provided for them.

METHODOLOGY

Focus Groups

A research protocol was developed and approved by the institutional review boards (IRBs) of the University of Texas at El Paso (UTEP), New Mexico State University (NMSU), and the Environmental Protection Agency (EPA) to engage human subjects. The approved IRB protocol for the focus groups allowed researchers to recruit participants, provide them with an informed consent, administer a questionnaire for participants, engage with participants in an open-group discussion, and provide them with a meal and a $30 incentive for participating in the project.

The sampling method for recruiting participants for the focus groups was convenience sampling. The participants in the focus groups were recruited by *promotoras* (Spanish for female "promoters"), who were contacted through the Southern New Mexico Promotora Committee and through El Paso Health and Human Services office. Promotoras and promotores (Spanish for male "promoters") are community health workers who, with or without compensation serve as liaisons between health services, social services, and the community (Texas Department of State Health Services 2015). The focus groups ranged in size from about 5-15 households per focus group. Participants consisted of *colonias* residents in Doña Ana County, NM and El Paso County, TX. A total of five focus groups were conducted; three were conducted in Doña Ana County, NM on Jan 25, 2013, Feb 1, 2013, and March 1, 2013 and two were conducted in El Paso County on Dec 3, 2012 and March 8, 2013. Focus groups consisted of two parts: the first

part consisted of completing a written survey while the second part consisted of a presentation and group discussion. The moderators guide was written by Dr. Rebecca Palacios, and the evaluation team (Dr. Palacios, Dr. Tomaka, and Alma Torres), developed the evaluation survey. The focus groups were conducted by Dr. Palacios, Dr. Tomaka, and Alma Torres from NMSU, and Dr. Ivonne Santiago, Isaac Campos Flores (author of this dissertation), and Lydia Garcia from UTEP.

A demonstration system was assembled with three different types of point-of-use treatment units for display during the focus group presentations, as shown in Figure 2.2. The first type was a pitcher unit, shown in part (a) of Figure 2.2. The second type (shown in part (b) of Figure 2.2) consisted of a five-gallon bucket, a hose, and an in-line gravity-driven filter attached at the end of the hose. The third type (shown in part (c) of Figure 2.2) consisted of a kitchen sink and cabinet with a standard cartridge filter housing and an in-line membrane filter inside the cabinet. The three types of treatment units in the demonstration system were selected to gauge the participants' willingness to use a particular type of filter. The results of this part of the study were qualitative, as they were performed during an open group discussion.

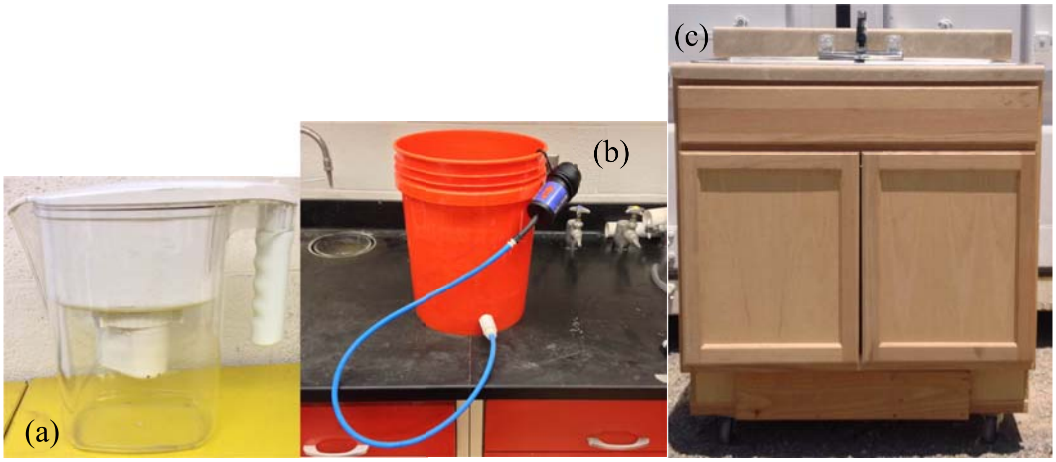

Figure 2.2: Types of point-of-use water treatment units demonstrated during focus group studies: (a) pitcher, (b), gravity driven, and (c), in-line water treatment system presented during the focus groups

Water Sample Collection

After the focus group studies, 22 water samples (eight from households in El Paso County and 14 from Doña Ana County) were collected from the homes of willing participants. The specific *colonias* that were sampled for water were Chamberino, Anthony, and La Mesa in New Mexico (shown in Figure 2.3), and Hillcrest and Buena Suerte Estates in Texas (shown in Figure 2.4). Two separate water samples were collected from the kitchen faucet in each household that was visited. Both sample sets were collected according to Standard Method (SM) 9060 A (AWWA 2012). The first sample set was collected in an IDEXX sterile bottle (with sodium thiosulfate) for estimating the concentration of the pathogenic indicators, total coliforms and E. Coli. The first sample was placed in a cooler with ice while it was transported to the laboratory where it would be analyzed. If the analysis did not take place immediately, samples were stored inside a refrigerator at approximately (±2) 4° C; all microbiological samples were analyzed within 24 hours after collection. The second set of samples were collected in either a

low-density polyethylene (LDPE) or polypropylene (PP) bottle. These samples were not transported in a cooler so as to prevent precipitation of sparingly soluble inorgranic constituents.

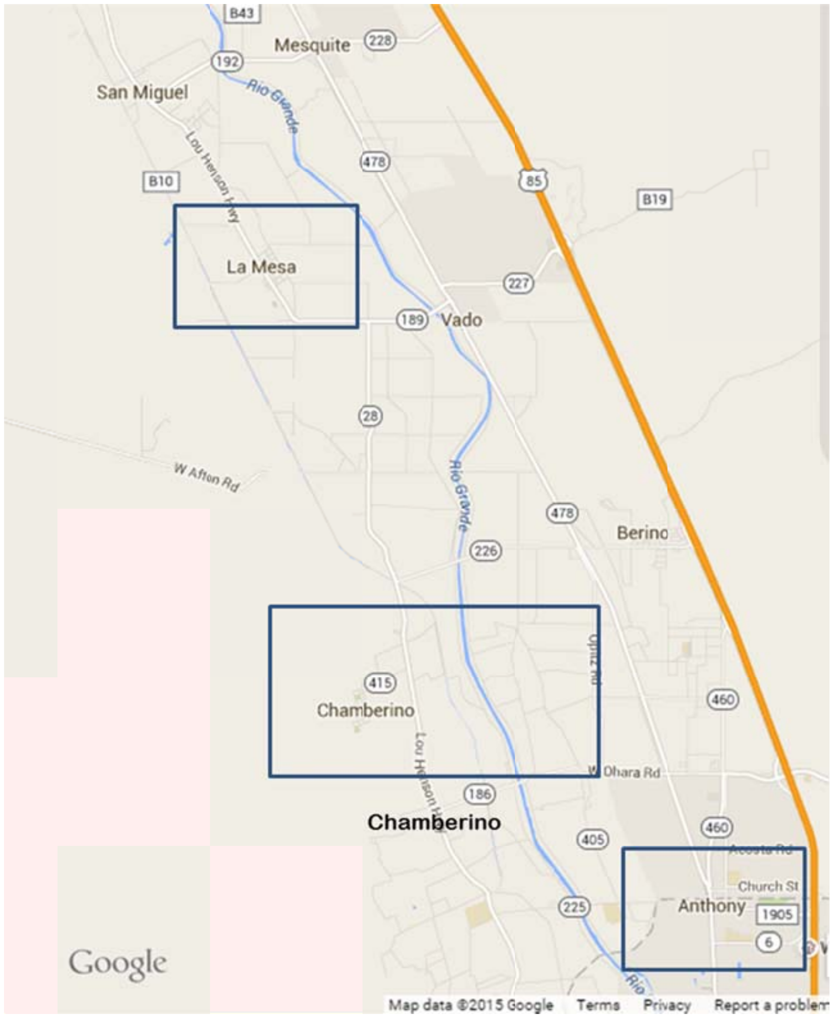

Figure 2.3: Location of *colonias* in Doña Ana County where water was sampled

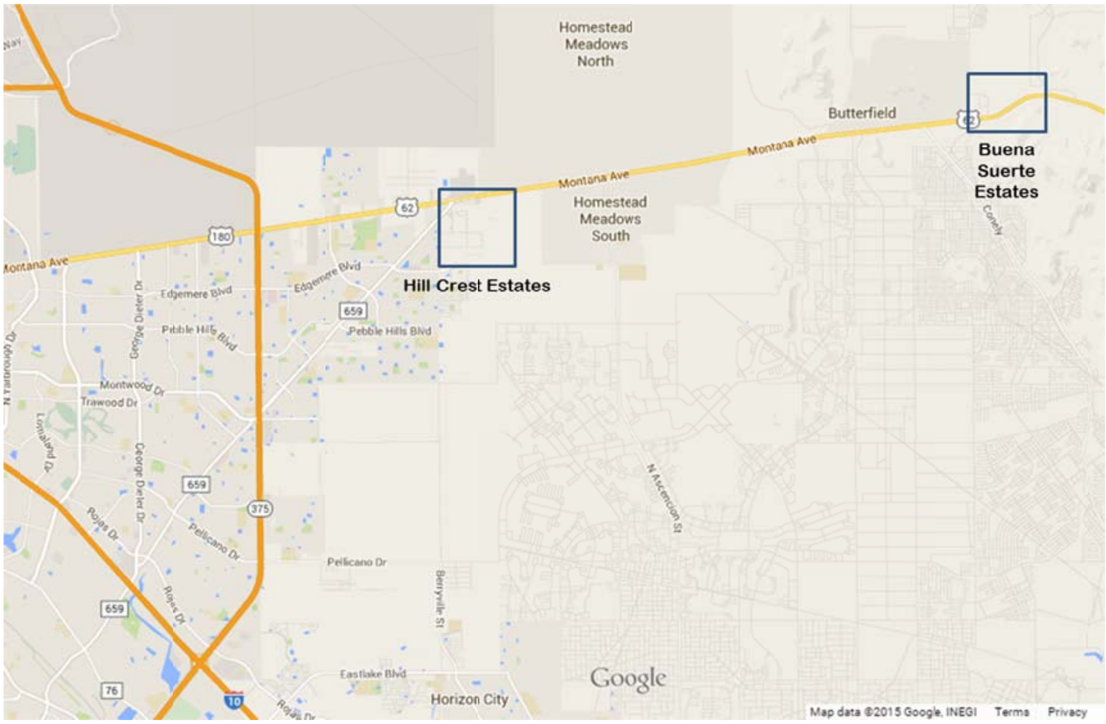

Figure 2.4: Location of *colonias* in El Paso County where water was sampled

Water Quality Analysis

Fourteen households who rely on wells were sampled, as well as seven households who have their water hauled to them. Total dissolved solids were measured according to SM 2540C. Anions and cations were analyzed using a Dionex simultaneous system consisting of an ICS-1100 unit with an IonPack™ CS16 column for cations and an ICS-2100 with an IonPack™ AS18 for anions (SM 4110B). Dissolved arsenic, iron, and manganese were measured by spectrophotometry with a Perkin Elmer Optima 7300 DV (SM 3120B). Arsenic has been reported to be present in wells throughout the southwest United States (Camacho et al. 2011) and, according to the focus groups that were conducted in this study, iron and manganese can precipitate within a house's plumbing or appliances. All samples introduced to the ICP were filtered and acidified with 2% nitric acid (v/v). Conductivity (SM 2510B), pH (SM 4500-H^+B,) temperature (SM 2550B), and oxidation reduction potential (SM 2580B) were measured in the

field using a Myron L Ultrameter II™ as soon as the samples were collected. Alkalinity was measured using a MicroLab automatic titrator and sulfuric acid. Free chlorine was also measured in the field following (SM 4500-ClG). Total coliforms and E. Coli were analyzed using IDEXX's Colilert®-18 method and reagents (SM 9221C). Water quality results were analyzed using Minitab 17 (Minitab Inc 2013).

RESULTS AND DISCUSSION

Focus Groups

The survey results, which had a sample size of 22 for residents relying in well water and 24 for residents relying on hauled water, revealed the demographics of the *colonias* in the study. Fifty-seven percent of the residents in the surveyed Doña Ana County and El Paso County *colonias* were female, with each subset (relying on well water and relying on hauled water, respectively) having a similar distribution (Garcia Cobos 2014). Fifty four percent of the surveyed residents that rely on well water were under the poverty level, while only 35% of the surveyed residents that rely on hauled water were under the poverty level (Garcia Cobos 2014). Approximately two-thirds of the surveyed residents in both subsets had at least some high school education (Garcia Cobos 2014). Lastly, the average household size was four residents for both well water and hauled water *colonias* (Garcia Cobos 2014).

The first step in determining the proper water treatment system for residents of the *colonias* was to fully understand the issues that they are facing. The conducted focus groups revealed that 67% of the surveyed *colonia* residents think that their water is not safe to drink and 73% are concerned with chemicals in their water (Garcia Cobos 2014). This lack of confidence could imply that the solution provided to the *colonia* residents would have to involve educational materials in an addition to a water treatment system.

Colonia residents prefer the under-sink system over the pitcher or gravity options presented in the focus groups. The reason for their preference lies in both the convenience of having an in-line system and on the direct competition of proposed point-of-use units: bottled water. During the group discussion, residents often compared the units, not with the lack of potable water, but with bottled water that they purchased in convenience stores or supermarkets.

During group discussions among *colonia* residents of Doña Ana County (west of El Paso), several residents of households which rely on well water mentioned that their water often turned black or brown after it was allowed to rest. During the group discussions among *colonia* residents of El Paso County, participants explained that the majority of their issues with their household water were with cutaneous conditions, such as rashes. On the other hand, residents of the El Paso County *colonias* mentioned that they sometimes encountered black/dark green matter inside of their potable water tanks. Furthermore, the residents also reported a variety of methodologies for chlorinating their water and cleaning their storage tank. Some reported that they did not chlorinate their water or clean their tank because they did not know how to do so properly.

The concerns expressed by the residents allowed the team to better understand the nature of the problem that these *colonias* face. First, it was determined that, while providing potable water is of the utmost importance, residents were also concerned with the water they used for bathing and washing, thus calling for a point-of-entry system for some households in combination with a point-of-use system. Secondly, several residents of Doña Ana County appear to have issues with iron and manganese. Third, some *colonia* residents in El Paso County have problems with algae in clear or painted tanks, and with the methodologies they utilize to chlorinate their water and clean their water storage tanks.

Water Quality Analysis

The statistical distributions of the measured total dissolved solids (TDS) concentrations are summarized in box and whisker plots[1] in Figure 2.5. High concentrations of TDS can increase mortality from all categories of ischaemic heart disease and acute myocardial infarction (World Health Organization 2003). For households relying on well water, 79% of the samples exceeded EPA's secondary limit of 500 mg/L TDS (40 CFR §143.3), and 50% of the samples exceeded the secondary limit of 1,000 mg/L TDS recommended by New Mexico Environment Department (NMED) and Texas Commission on Environmental Quality (TCEQ) (NMAC 20.6.2.3103 2002)(30 TAC §290.105). In households with hauled water, 50% of houses had TDS exceeding EPA's secondary limit of 500 mg/L, and none of the samples exceeded the states' secondary limit of 1000 mg/L. These results indicate that desalination treatment would be necessary in most *colonia* households to reduce TDS concentrations to comply with the EPA secondary limit.

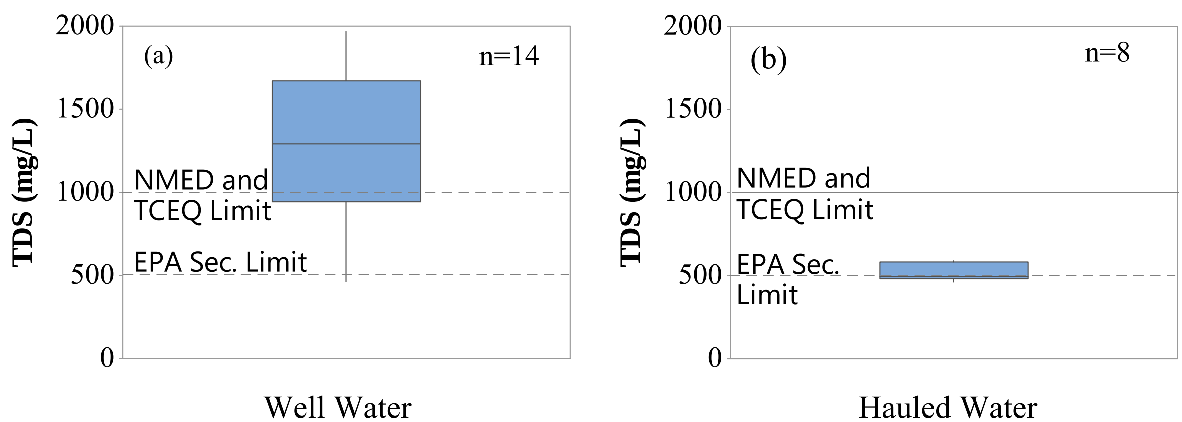

Figure 2.5: TDS concentrations of households relying on (a) well water and (b) hauled water

[1] The boxes and whiskers each represent a statistical quartile. The end of the whiskers show maximum and minimum values, and the line between the two boxes shows the median value (50th percentile).

With similarity to the analysis of TDS, the distribution of sample concentrations of hardness and sulfate are shown in Figure 2.6. In all instances, it is possible to see that residents relying on well water are more prone to be outside of the limits set forth by EPA, NMED, and TCEQ. Residents relying on well water seem to have very hard water (more than 150 mg/L as $CaCO_3$), whereas the water sampled from residents relying in hauled can be classified as simply hard, ranging from 100 to <150 mg/L $CaCO_3$ (MWH 2012). Hard water can cause scale deposition and increased soap consumption (World Health Organization 2011). With respect to sulfate, more than 75% percent of samples from wells were above EPA's and TCEQ's secondary limits, while none of the samples from hauled water were above EPA's secondary limit. Ingestion of large quantities of sulfate can cause purgation (World Health Organization 2004a). Hard water and sulfates can decrease the useful life of some appliances and boilers.

A summary of the ORP and pH measurements is shown in Figure 2.7. Based on ORP measurements in the field, the ORP of well water was significantly lower than the ORP of hauled water. At low ORPs it is possible for reduced form transition metals (e.g. Fe^{2+} and Mn^{+}) to remain soluble in water. However, when water is pumped from the well and is exposed to air, the oxygen can oxidize metals and form precipitates (typically hydroxides). Although high concentrations of iron were not detected by ICP-OES (most samples were below the calculated detection limit of 0.5 µg/L), several samples developed an orange tint, suggesting the presence of excess iron in the water. With respect to pH, *colonias* in Doña Ana County and El Paso County are within all three agencies' limits.

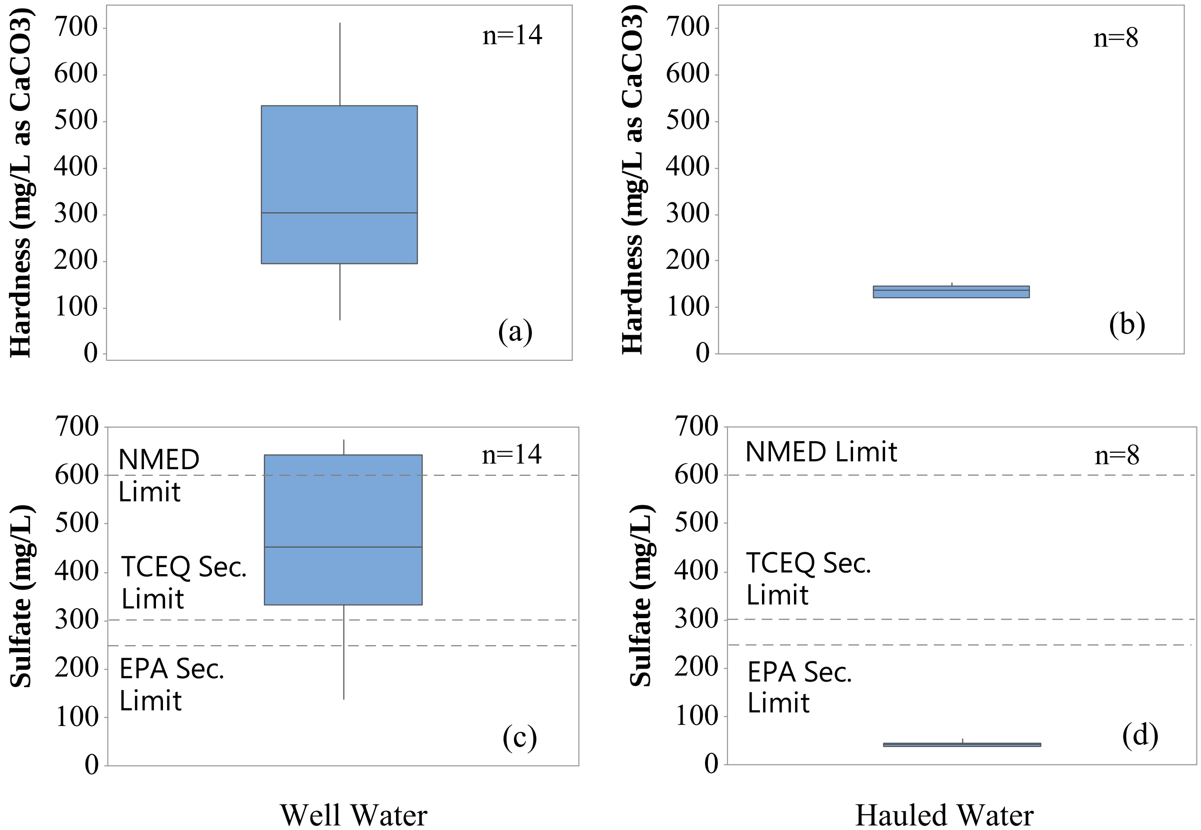

Figure 2.6: Hardness concentrations in *colonias* relying on (a) well water and (b) hauled water. Sulfate concentrations in (c) well water and (d) hauled water.

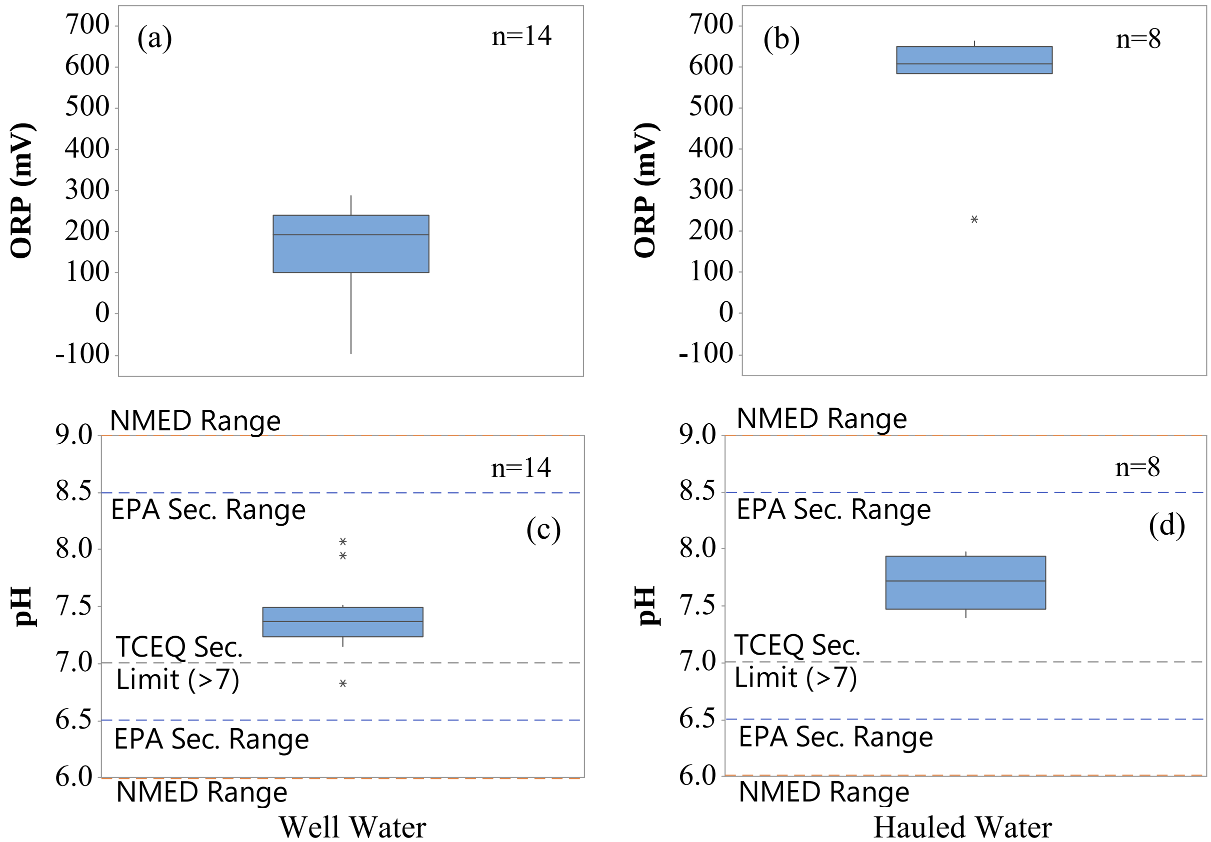

Figure 2.7: Measured ORP in households relying on (a) well water and (b) hauled water. Measured pH values for *colonias* that utilize (c) well water and (d) haulued water.

Figure 2.8 summarizes the free chlorine concentrations of all the measured drinking water tank samples. None of the households relying on well water added chlorine to their water supply. On the other hand, six of the seven households who rely on hauled water had at least 0.2 mg/L of free chlorine (chlorine residual is required when the hauled water is delivered). Five of 14 samples from well-water households tested positive for total coliforms; of these five, two samples exceeded the maximum detection of 200.5 MPN/100mL, and the other three samples had concentrations of 129.9, 8.7, and 2 MPN/100mL. Of the five samples that tested positive for total coliforms, only one tested positive for *E Coli* with a concentration of 53.1 MPN/100mL. However, none of the households relying on hauled water tested positive for total coliforms.

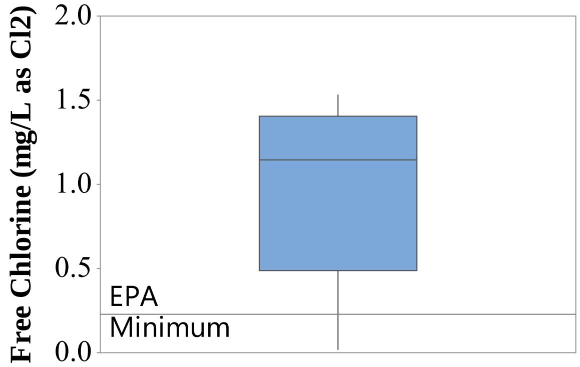

Figure 2.8: Free chlorine concentration in households relying on hauled water

CONCEPTUAL DESIGN

The issue of high TDS concentrations requires a physical-chemical treatment process; a schematic of the proposed water treatment system for *colonia* residents is shown in Figure 2.9. A point-of-entry (POE) one micron (1 µm) cartridge filter can mitigate solids and larger microbes, and a point-of-use (POU) reverse osmosis (RO) was selected as the main treatment process because it is capable of removing dissolved solids (*e.g.*, chloride, sulfate, hardness, TDS) as well as microbes. For households with high concentrations of iron and/or manganese, a point-of-entry (POE) greensand filter could be installed after the cartridge filter. For households with hauled water, chlorine can be added into the storage tank to preserve water quality, and copper sulfate could be added to mitigate algae growth.

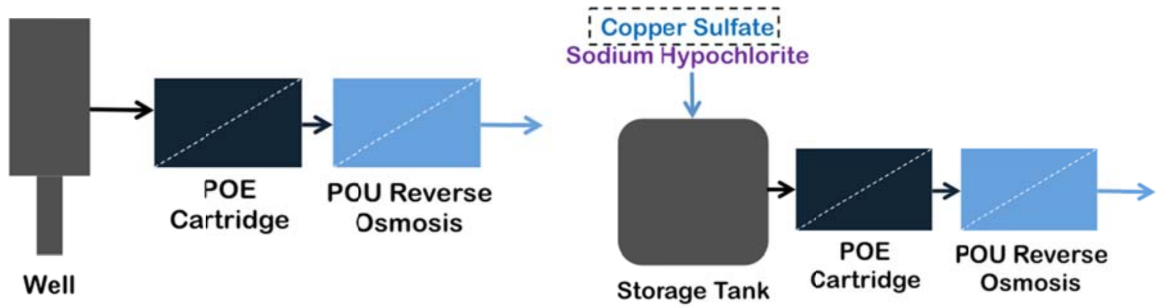

Figure 2.9: Schematic for proposed water treatment system for households relying on well water or hauled water

CONCLUSION

The goal of this study was develop a conceptual design for a household level water treatment system. The first objective was to engage the heads of household through focus groups and determine the social sustainability requirements. The second objective was to sample and analyze the two different water supplies, wells and hauled water, to determine the issues faced by *colonia* residents. The third and last objective was to develop a conceptual design for a water treatment system.

Observations from the first objective allowed the research team to understand that *colonia* residents are more likely to use in-line water treatment systems, as opposed to pitchers or gravity driven devices. Results from the second objective showed that residents relying in well water face issues with high TDS concentrations and microbiological contamination, while the issues faced by residents relying in hauled seem to be related to preserving the water quality in the drinking water tanks (e.g. free chlorine). Lastly, a conceptual design for a water treatment system was developed based on the lessons learned on the focus groups and the results from the water quality analyses.

Chapter 3: Sustainability of Point of Use Water Treatment Devices for Households in Developed Countries with Wells or Drinking Water Storage Tanks

INTRODUCTION TO POINT-OF-USE DRINKING WATER SYSTEMS

Water is essential for the development of society (Clasen 2010), and in order to answer the global need for clean drinking water, many studies and interventions have been performed with point of use (POU) and point of entry (POE) water treatment systems (Sobsey et al. 2008). Studies have determined that interventions through improvements in drinking water and sanitation make a positive impact on societies (Fewtrell et al. 2005). However, most of these studies and interventions with POUs and POEs have focused on developing nations (Parker Fiebelkorn et al. 2012; Sobsey et al. 2008; Peter-Varbanets et al. 2009).

Some developed nations, such as the United States, do not provide regulated, treated drinking water to all of its residents. As of 2010, approximately 264 million residents (about 86% at the time the study was conducted) were connected to a public water system (USGS 2010). Out of those 264 million, some residents are actually served through hauled water (trucks that bring water from a public water system). The rest of the population, about 44 million, were self-served by groundwater (USGS 2010). Some of these private water supplies are contaminated with pathogens (Sobsey et al. 2008; Gurian et al. 2006) or chemicals, or they could suffer from undesirably high salinity. POUs could represent a rapid solution of drinking water for residents who rely on either hauled water or groundwater.

A review of the literature reveals some gaps in the area of POUs for developed countries. The greatest of these gaps can be found in the area of social sustainability where the end user's culture and idiosyncrasies are not considered. This lack of focus on social sustainability

sometimes leads to recommending products that may be environmentally and economically sustainable, but are ultimately not used by residents because the products do not align with the residents' ideas of what POUs should accomplish. Gurian et al (2006) studied the preference of people for tank chlorination, batch chlorination, and UV in households in the *Paso Del Norte Region* (El Paso, TX and Juarez, Mexico) and concluded that UV disinfection was preferred over chlorinating the water when it was still in the tank or in smaller five-gallon batches. Gurian et al (2006), however, did not list any filtration devices or different brands and/or model numbers of their study. Corella-Barud et al (2009) performed an observational study with two UV systems installed in clinics with the intent of providing households in the study with free clean drinking water, if they could transport the water back to their house in their own containers. Water treated at the clinics was compared against store-bought water, water from a tap reported to be the source of drinking water, and a tap located inside of their residential property, but outside of the house. Corella-Barud et al (2009) observed that residents' willingness to travel to the clinic to obtain water dropped by a third over the course of their study (the study expanded from the spring of 2013 to the summer of the same year) and that outdoor faucets had a lesser concentration of total coliforms when compared to other sources. The authors also commented that leaving drinking water disinfection to non-professionals could lead to inconsistent and inaccurate disinfectant dosing.

POU systems have also been reviewed with respect to disaster relief. Lantagne et al (2014) reviewed the efficacy of small-scale chlorine disinfection for disaster relief, where they concluded that a dose of 4-7 mg/L was an effective treatment method, whether the water was cleared, colored, murky, or muddy. Loo et al (2012) researched a variety of water treatment technologies and estimated an approximate cost of employing them. Loo et al's (2012) review

covered most technologies and processes in the POU market including biosand filters, boiling, ceramic filters, chlorination tablets, flocculation/sedimentation, solar heaters, silver nanoparticles, ultrafiltration (UF), nanofiltration (NF), forward osmosis (FO) and reverse osmosis (RO) membranes, and ultraviolet (UV) lamps; the price of the units reviewed ranged from $4-$10,000 and $0.001/L-$4/L (the study used multiple ways to express cost, presumably because of missing data). Silverstain (2006) recommended to the U.S. Environmental Protection Agency (EPA) that POU devices could be employed as an interim solution in disaster relief. These studies provide excellent reviews of POU technologies, but because their primary focus was disaster response, they feature certain omissions: (1) end-user perspectives, (2) application to non-emergency/non-disaster domestic life, (3) under-the-sink technologies, or (4) an objective method of comparing or ranking the suitability of POUs.

Goals and objectives

Thus, there is a need to develop a method for evaluating the overall sustainability of POU technologies for households relying on private groundwater wells or hauled water, especially including criteria for social sustainability. The goal of this study was to develop a simple ranking system that can be used by household residents to screen and select a POU drinking water system for their home. The first objective was to develop a general sustainability scoring and ranking system for comparing POUs in light of two common approaches of POU implementation: (a) adoption of POUs by individual households and (b) systematic deployment of POUs by a governing agency. The second objective was to assign scoring values to each category of the ranking system for comparing POUs. The third objective was to apply this scoring methodology to a review of commercially available technologies and produce a shortlist of top-performing POUs.

METHODOLOGY

Ranking system for POU/POE implementation

POUs have previously been shown to improve drinking water quality (Clasen and Cairncross 2004; Sobsey 2002; Parker Fiebelkorn et al. 2012). POUs can be employed by voluntary household adoption (micro-level) or systematic governmental deployment (macro-level). An example of the micro-level approach is in the household adoption of POUs for drinking water in developing countries (Butler et al. 2013). Since electricity and water distribution may not be present in developing countries, many POU devices employed utilize elevation head (Batch) to provide the pressure to drive water through a treatment unit. Trial and error by humanitarian organizations has shown that POUs are used optimally when the residents are involved as partners in the distribution effort (Mansuri and Rao 2004). When the community is not involved in the water treatment effort, treatment units are often operated with poor maintenance and, once they malfunction, they may be abandoned. A drawback of the micro-level approach is that the water quality might be inconsistent from household to household due to variations in operation or maintenance. Poor maintenance or operation of the treatment unit could lead to contamination of the product water.

Alternatively, an example of the macro-level approach is found in the U.S. where the Environmental Protection Agency (EPA) has approved the use of POUs/POEs for public water systems (PWSs) to comply with Maximum Contaminant Level (MCL) regulations for inorganic contaminants (40 CFR §141.100). However, point of use devices may not be employed to meet microbiological MCLs (40 CFR §141.100). POUs and POEs may be employed by public water systems to comply with the revised arsenic regulation. While humanitarian organizations may have more flexibility with respect to employing treatment units in developing countries (*e.g.*,

prototype products or unconventional processes), the EPA requires that all water treatment units used by PWSs to comply with drinking water regulations must be certified by NSF International or by the World Quality Association (EPA 2002). Furthermore, units must be operated entirely by the PWS, not by the household owner. Utility-operated POUs and POEs are required by law to meet the same primary MCLs as water treatment plants (EPA 2002). Thus, the quality of the water is expected to be consistent from household to household in a given system. Furthermore, POU and POE technologies may be perceived to be a conciliatory solution by residents who believe that universal clean drinking water is a basic right.

Thus, a ranking system for POUs and POEs must consider the following aspects: (1) the technical performance of the unit with respect to removing contaminants and providing adequate drinking water quality; (2) the verification of reliable performance; (3) user preferences for unit operation; (4) the economic costs of the unit; (5) and the environmental impacts (pollution) of the unit.

There are a plethora of methods in which the five aforementioned aspects could be aggregated to determine an overall score. Considering Occam's razor and a quote attributed to Albert Einstein, "a scientific theory should be as simple as possible, but no simpler", the simplest form of aggregation, a summation without weights, was employed to compute the total score for each water treatment unit, shown in Equation 3.1.

$$\text{(Eq. 3.1)} \quad \textit{Overall Score} = \textit{Performance} + \textit{Verification} + \textit{Preference} + \textit{Affordability} + \textit{Environmental}$$

A summary of the ranking criteria for all categories is provided in Table 3.1, and a discussion of the rational for each category is provided in subsequent sections.

Table 3.1: Summary of Ranking Criteria for POU Drinking Water Treatment Systems

	Score		
Category	**1**	**2**	**3**
Technical/treatment Performance	Removes aesthetic contaminants, helminths, and protozoa (parasites)	Removes bacterial and pathogens and contaminants in bin 1	Removes dissolved solids and contaminants in bin 2
Verification and Certification	Internal testing	Independently tested	NSF International certified
User Preference	Small batch (<5 L)	Large batch (≥5 L)	In-line (on demand)
Economic Affordability	Initial Cost ≥ $200	$20 < Initial Cost < $200	Initial Cost ≤ $20
Environmental Sustainability	Produces regular solid waste	Produces liquid waste stream (r < 90%) and minimal solid waste	Produces minimal liquid waste and minimal solid waste

As each unit was assigned a score, additional policies, beyond the criteria listed in the methodology section, were developed to adjust to the findings. The review for commercial units encompassed a period of approximately three years. Over the three-year time frame, some of the units became seemingly discontinued, such as Whirlpool's WHER25 which was sold at Lowe's Home Improvement store but is currently unavailable for purchase on *Lowe's* website. Another unit that was seemingly discontinued was Sunbelt's *Smart All Purpose Bleach*, which was sold at The Home Depot and is of note because it was commercially available at a national retailer, and it was certified according to NSF International 60. Discontinued units were noted on the table as such. The type of technology was also listed in the table, but whenever the technology was not readily identifiable, the assumed technology (based on the contaminants it removes and the standards it follows) was included in parentheses.

Whenever there were multiple products that shared the same technology from the same company, only one product as included in the list. Thus, although there are several variations of

DOW Chemical's UF membranes, only one was included in the list. It was also the policy of this review that if the manufacturer/vendor did not make a certification obvious, it was assumed that the manufacturer/vendor only performed internal testing. Furthermore, if a product claimed to be NSF International certified, its certification was cross-checked with NSF International's website to ensure that the certification was still current.

Additional methods were developed in the area of comparing flowrate; when multiple conflicting values for the flowrate of a unit were available, only the lowest flowrate was recorded, for the sake of being conservative. A treatment unit was classified as a POE unit (instead of POU) if the unit is capable of treating a flow rate greater than one gallon per minute (gpm). When it came to cost, if the price of a unit was not listed on the webpage and a price quote was required, it was assumed that the unit would have been too costly for this study. Model numbers for each unit were also included in the list and, when no model number was seemingly available, the product name was used instead.

Treatment Performance

There are several technologies available depending on the main contaminant of concern. A list of the types of technologies that were reviewed is provided in Table 3.2. Treatment systems with infused nanoparticles (*e.g.* silver) were not included in this review. Although many studies have been performed to prove the nanoparticles' ability to inactivate pathogens, its effect on humans is still being studied (Rogers et al. 2012). Technical performance of POUs can be divided into three levels: aesthetics and suspended particles, bacterial and viral pathogens, and dissolved solids.

Table 3.2: List of POU technologies and typical contaminants removed

Technology	Contaminant(s)
Activated Alumina	Arsenic, fluoride, chlorine, *etc*.
Carbon block and granular activated carbon	Chlorine, volatile organic compounds, heavy metals, *etc*.
Cartridge Filter	Particles
Ceramic Filter	Sediment, rust, sand
Chlorine (hypochlorite)	Bacteria, viruses
Copper (II) Sulfate	Algae
Greensand	Iron, manganese
Iodinated Resin	Bacteria, viruses
Ion Exchange	Nitrate, arsenate, etc.
Microfiltration	Sediment, bacteria
Nanofiltration	Dissolved organics, hardness
Ozone	Protozoa, bacteria, viruses, organic compounds
Reverse Osmosis	Dissolved solids, ions
Ultrafiltration	Sediment, bacteria, and viruses
Ultraviolet-Light	Bacteria, viruses, and protozoa

Many of the devices bear NSF International's certification seal by meeting the requirements for aesthetic effects (NSF 42). When a device is tested under NSF 42, its primary purpose is to polish the water with respect to taste and odor (e.g., by filtration through granular activated carbon). Based on initial water sampling near El Paso, TX, approximately 26% of samples tested positive for total coliforms and 5% of the total samples also tested positive for *E Coli*. Approximately 57% of samples exceeded the EPA secondary standard of 500 mg/L total dissolved solids (Campos et al. 2014). Thus, microbiological contaminant removal is required, and dissolved solids removal is preferred.

POU water treatment systems may remove or inactivate pathogens (helminths, protozoa, bacteria, and viruses), such as with ultraviolet (UV) light or bleaching/chlorination (although chlorine is not generally considered effective against *Cryptosporidium*). Other effective technologies include microfiltration (MF) and ultrafiltration (UF). Microfiltration membranes

with a pore size of 0.1 µm (microns) can remove bacteria, and ultrafiltration membranes, with pore sizes in the range of 0.01 µm can remove viruses, as well.

Technologies commonly used to remove dissolved solids are reverse osmosis (RO), nanofiltration (NF), and ion exchange. Systems in this category are capable of removing dissolved solids and thus address concerns with specific elements or ions such as arsenic. The use of POUs to comply with EPA's 10µg/L arsenic rule has been previously been considered in a handbook developed by the EPA (2003). Also note that, while RO and NF membranes are mainly used to remove dissolved solids, they can also be effective at removing bacterial and viral pathogens (Madaeni, Fane, and Grohmann 1995).

Thus, a score will be assigned to each treatment system, depending on the contaminants that they can remove. A score of one (1) was given if the treatment unit only addresses gross filtration and/or water quality aesthetics and suspended particles, including helminths and protozoa. A score of two (2) was assigned if a system can remove or inactivate bacteria. Lastly, a score of three (3) was awarded to a system that can remove dissolved solids.

Performance Verification and Certification

Challenge testing may be grouped into two categories: manufacturer's internal testing and third party independent testing. Manufacturers often perform their own internal testing, and some use the results of their internal testing as part of their product marketing. However, these internal testing results may be perceived to be biased, so independent testing is required for performance verification.

The two most popular entities that certify products in the water industry in the U.S. are NSF International and the U.S. Pharmacopeia (USP). Both of these organizations are independent, but they work closely with the U.S. Food and Drug Administration (FDA) and the

U.S. EPA, respectively. USP has standards related to water treatment device materials, as well as filtration of particles, such as USP Chapter 88 (USP-NF 2015). However, its primary focus is not for residential potable water production, but with pharmaceutical manufacturing. It is possible to argue, however, that even if a product is only certified by USP for its material of making, that such information is still valuable for household POU water treatment. Nonetheless, most of the standards that USP has for water treatment devices are mirrored by an NSF International standard. Therefore, this research paper will focus on NSF International certification.

American National Standards Institute (ANSI) is specifically named in the Safe Drinking Water Act (SDWA) as being in charge of developing standards for POUs or POEs that are to be implemented by a PWS to meet EPA's drinking water limits (EPA 2002). However, ANSI's role is not to create standards, but to accredit agencies, such as NSF International, which do develop standards (ANSI 2015). NSF International certification is not required for a water treatment product to be sold in the U.S.; nor does NSF International certification guarantee the performance of the filters, but it does provide "extensive range of services for the water industry to help ensure the quality and safety of products in the marketplace" (NSF International 2015). From the perspective of ranking POU products, one could simply require NSF International certification, but this may not be necessary. While NSF International certification may benefit the consumer, NSF International certification may not be necessary in every circumstance.

Furthermore, there is room for improvement in some aspects of NSF International certification. One of the areas for improvement is found in the way its standards are organized and presented. There are at least seven standards that cover POUs and POEs, listed in Table 3.3. Except for the sophisticated consumer, it is relatively easy to confuse one standard for another. Some manufacturers are clearly display the NSF International logo, but some are not clear about

which standards their product meets. Moreover, selecting a product through the NSF International website can be challenging to navigate for most users, as product information is communicated inefficiently and without effective filtering tools. Lastly, not all of NSF International's testing methodology is immediately available to the public, which make it difficult to determine if a treatment device will be able to address the contaminants of a particular water. For example, if a homeowner wanted to determine if a particular water treatment unit would be useful for his/her situation, the homeowner would have to first characterize his/her water, then determine which NSF standards are pertinent to his/her situation by browsing NSF International's website, then proceed to acquire copies of NSF International's standards (some standards are more than $150), and, finally, verify whether his/her water quality falls within the scope of the standard.

Table 3.3: List of NSF International Standards Applicable to Water POUs and POEs

NSF International Standard Number	Standard Name	Focus of Standard
42	Drinking Water Treatment Units-Aesthetic Effects	Reduction of constituents that make water aesthetically unpleasing (e.g. chlorine reduction, taste and odor reduction)
44	Cation Exchange Water Softeners	Minimum requirements for materials, design, construction, and performance of the system.
53	Drinking Water Treatment Units-Health Effects	Health-related contaminant reduction performance claims (e.g. cyst reduction, chromium reduction, radon reduction)
55	Ultraviolet Microbiological Water Treatment Systems	Reduction of microorganism using ultraviolet radiation. Separated in class A for microbiologically contaminated water and class B for microbiologically safe water
58	Reverse Osmosis Drinking Water Treatment System	Total dissolved solids reduction with an option to certify for other claims such as cysts, arsenic, cadmium, chromium, lead, nitrate, and nitrite
60	Drinking Water Treatment Chemicals	Requirements for content and purity of chemicals added to drinking water.
61	Drinking Water System Components	Evaluation of contaminants and impurities in materials or products in contact with drinking water or drinking water treatment chemicals.
401	Drinking Water Treatment Units - Emerging Compounds/Incidental Contaminants	Reduction of emerging contaminants (e.g. carbamazepine, linuron, Estrone, and Bisphenol A)

(Thomson Reuters 2015; NSF International 2015)

Thus, grading for the testing and certification category was based on a scale of 1-3 depending on the level of certification. A score of one (1) was assigned if the manufacturer of the water treatment unit performed internal testing but does not show evidence of independent testing. A score of two (2) was assigned if the unit was independently tested by a third party and is not NSF certified. Lastly, a score of three (3) was assigned to the water treatment system that has been certified by an NSF International standard that is listed in Table 3.3.

Social Sustainability (User Preferences)

Social sustainability can encompass many areas, but, in this study, it will refer primarily to an individual's willingness to utilize a certain product. The specific factors that determine whether an individual will use a certain product are tied to his/her culture and preferences. Nonetheless, it is still possible to focus on two specific factors as social sustainability is considered: quantity of produced water per batch and time required for the batch to be completed.

It has been previously reported that *colonias* residents, unincorporated settlements that lack basic infrastructure in the southwest US, residents demonstrated reluctance to adopting filtration devices that excelled at economical and environmental sustainability, but performed poorly in the area of social sustainability (Campos et al. 2014). Out of the three water treatment configurations that were shown to the residents in focus groups (pitcher filtration, Batch filtration with a bucket, and in-line filtration under the kitchen sink), a large majority of the residents preferred the in-line sink filtration. One significant factor for this preference is the main competition that POUs and POEs face: bottled water purchased at supermarkets. Water treatment systems in the US are not competing against lack of water, but against bottled water. Because bottled water (whether it is bottled by a company or by the end user) is ubiquitous in the developed world, water treatment devices are not likely to be used unless they score higher than bottled water in the area of user preference, which is a significant component of overall social sustainability for POUs and POEs.

Based on results from the focus group studies, the social sustainability (user preference) score was assigned based on the configuration of the treatment units. A score of one (1) was assigned to a small batch treatment system that was limited by its own design/shape (*i.e.,* pitchers

with a volume less than 5 L). A score of two (2) was assigned to a treatment system that is not limited by its design in the amount of water it can treat (*e.g.*, Batch filters, though there is a practical limit to tank/bucket volume). Lastly, a score of three (3) was awarded to a treatment unit that is plumbed inline to a faucet (*e.g.*, under the sink filters).

Economic Affordability

For a system to be adopted by a household, it must be able to treat water at a cost that its users can afford. Some of the most technologically and socially sound units that were reviewed were POE UV systems that are able to continuously treat large quantities of microbiologically contaminated water with little to no waste. However, these same systems are also some of the most expensive.

Thus, although it is obvious that systems must be priced adequately to be economically sustainable, the real question in this criterion is how to define "adequately priced". Considering that, for most POU systems, the initial capital cost is significantly greater than the operating and maintenance costs, and considering that the capital cost is often the greatest barrier to implementation in low-income households, the capital cost was selected as the principal indicator for cost. Since the capital cost of reviewed POUs ranged over several orders of magnitude, a logarithmic-bin approach was applied: treatment units with an initial cost greater than $200 were assigned a score of one (1); units with an initial cost between $20 and $200 were assigned a score of two, and units less than $20 were given a score of three.

Environmental Impacts

Environmental sustainability has been the focus of many studies across multiple disciplines, and many complex methodologies have been developed to attempt to determine the impact that a process or product will have on the environment. For this study, a simplified, two-

step approach was employed. The first step involved analyzing the type of the waste produced by each water treatment system, along with the public's perception of waste to create simple ranking criteria.

The scoring scheme for the first step is as follows: A score of one (1) was given a unit that produces regular solid waste (*e.g.*, cartridge filtration disposal to landfill). A score of two (2) was assigned to a system that produces no regular solid waste but does produce a liquid waste stream from a relatively low-recovery process (*i.e.*, less than 90% recovery; *e.g.*, reverse osmosis). Finally, a score of three (3) was awarded for a system that produces no regular solid waste and only a small liquid/residual waste from a relatively high-recovery process (*i.e.*, greater than or equal to 90% recovery; *e.g.*, backwashable microfiltration or ultrafiltration units).

RESULTS AND DISCUSSION

A list of 38 point of use (POU) water treatment units reviewed in this research and the sustainability scores of each unit are provided in Table 3.4.

Table 3.4: List of Reviewed POU and POE Units

Rank	Overall Score	Company and Model #	Configuration	Type of Treatment	Technical Perform.	Verif. and Certif.	User Preference	Economic Sustain.	Env. Sustain.
1	13	GE-GXRM10RBL	POU In-Line Filtration	Reverse Osmosis (RO)	3	3	3	2	2
1	13	Pentair-RO-2550	POU In-Line-Filtration	RO	3	3	3	2	2
1	13	Whirlpool-WHER25	POU In-Line-Filtration	RO	3	3	3	2	2
1	13	Sunblelt-210 HD	POU/POE Batch Disinfection	Sodium Hypochlorite	2	3	2	3	3
2	12	Multipure-MP750PlusRO	POU In-Line Filtration	RO	3	3	3	1	2
2	12	Aclarus-AOWT-4	POE In-Line Disinfection	Ozone	2	3	3	1	3
2	12	Hydranautics-HYDRAcap40	POE In-Line Filtration	Ultrafiltration (UF)	2	3	3	1	3
2	12	DOW-SFD-2860	POE In-Line Filtration	UF	2	3	3	1	3
2	12	DOW-IntegraFlo 1100	POE In-Line Filtration	UF	2	3	3	1	3
2	12	Sawyer-SP211	POU Batch Batch	Microfiltration (MF)	2	2	2	3	3
2	12	EarthTec-EarthTec	POU/POE Batch Disinfection	Copper	2	3	2	2	3

Rank	Overall Score	Company and Model #	Configuration	Type of Treatment	Technical Perform.	Verif. and Certif.	User Preference	Economic Sustain.	Env. Sustain.
3	11	AMI-M-U2540PES	POE In-Line Filtration	UF	3	1	3	1	3
3	11	Sawyer-SP202*	POE In-Line Filtration	Microfiltration (MF)	2	2	3	1	3
3	11	Filtrete-4US-MAXL-S01	POU In-Line Filtration	Cartridge/Carbon†	2	3	3	2	1
3	11	Clorox-4460030799	POU/POE Batch Disinfection	Sodium Hypochlorite	2	1	2	3	3
3	11	Basic Water Needs-Tulip-Siphon	POU Batch Filtration	Ceramic Filter	2	2	2	2	3
3	11	Sawyer-SP293	POU Batch Filtration	UF	2	2	2	2	3
3	11	UV Pure-Hallet 15xs	POE In-Line Disinfection	Ultraviolet (UV)	2	3	2	1	3
4	10	Toray-HFU-1020	POE In-Line Filtration	UF	2	1	3	1	3
4	10	Toray-HFS-1020	POE In-Line Filtration	UF	2	1	3	1	3
4	10	Philips-UV-2GPM-220-CE*	POU In-Line Disinfection	UV	2	1	3	2	3
4	10	Pure-Ozone Faucet Tap Water System	POU In-Line Disinfection	Ozone	2	1	3	2	3
4	10	Viqua-SC1	POU In-Line Disinfection	UV	2	1	3	2	3
4	10	OEM-QY-HFUF 10	POU In-Line Filtration	UF	2	1	3	3	1

Rank	Overall Score	Company and Model #	Configuration	Type of Treatment	Technical Perform.	Verif. and Certif.	User Preference	Economic Sustain.	Env. Sustain.
4	10	Everpure-ViruPure	POU In-Line Filtration	UF'	2	3	3	1	1
4	10	Filtrete-3US-PS01	POU In-Line Filtration	Cartridge/Carbon†	1	3	3	2	1
4	10	GE-GXSV65R	POU In-Line Filtration	Carbon Block	1	3	3	2	1
5	9	Multipure-MP880SC	POU In-Line Filtration	Cartridge/Carbon†	1	3	3	1	1
5	9	Seychelle-1-10300-FC-K	POU Batch Filtration	Ionic Adsorption Micron Filtration System	2	2	2	2	1
5	9	Seychelle-1-40101-W	POU Batch Filtration	Cartridge/Carbon†	3	2	1	2	1
5	9	Cascade Designs-Platypus Filter	POU Batch Filtration	MF	2	1	1	2	3
5	9	Steripen-SteriPEN Classic 3	POU Batch Disinfection	UV	2	2	1	2	3
5	9	Steripen-SteriPEN Sidewinder	POU Batch Disinfection	UV	2	2	1	2	3
6	8	Perfect Water Technologies-CFF25-10	POE In-Line Adsorption	Activated Alumina and Coconutshell Carbon	1	1	3	2	1
6	8	Fairey-HIP-Supercarb	POU In-Line Filtration	MF	1	3	2	1	1
6	8	Fairey-HIP-Ultracarb	POU In-Line Filtration	MF	1	3	2	1	1

Rank	Overall Score	Company and Model #	Configuration	Type of Treatment	Technical Perform.	Verif. and Certif.	User Preference	Economic Sustain.	Env. Sustain .
6	8	Pure Hydration-Aquapure Traveller	POU Batch Filtration	2-micron Electrostatic Filter with powdered activated carbon	2	2	1	2	1
7	7	US Water Systems-089-FSF	POE In-Line Oxidizer	Greensand	1	1	3	1	1
8	6	Shaklee-Get Clean Water Pitcher	POU-Batch	Cartridge/Carbon†	1	1	1	2	1
6	8	Pure Hydration-Aquapure Traveller	POU Batch Filtration	2-micron Electrostatic Filter with powdered activated carbon	2	2	1	2	1

† The precise technology employed by the treatment system is unknown; based on the contaminants that are being removed, the most probable technology was assumed

After each unit had been assigned the appropriate score, several units were found to have similar scores. In order to differentiate between units, the list was arranged by overall scores, then by user preference, treatment performance, verification and certification, economic sustainability, and environmental sustainability. The arrangement methodology is based on the results of the focus groups by Campos et al (2014), where *colonia* residents appeared to be influenced first by how convenient the it was to use the filter, then by which contaminants it could remove (this would include treatment performance and verification and certification), followed by its cost and its environmental impact.

The top ranking units were under-the-sink reverse osmosis systems. While many of these RO systems are not NSF certified to remove pathogens, removal of dissolved solids would suggest a relatively high removal of bacterial and viral pathogens. While some water supplies may not required dissolved solids removal, the virus removal provided by RO units may benefit the user. The capacity cost (capital cost normalized by flowrate) of these RO units was calculated to range from $7 to $15 per gallon per day (gpd).

A cost comparison analysis between the top three RO and bottled water was performed and is shown in Figure 3.1. The cost comparison was developed by determining the present value of each alternative, assuming a 20-year life of the hardware, regular expenses for filter replacement according to manufacturers' recommendations, and an inflation rate of 2.4%/year, which is the average of inflation over the last 10 years (Coinnews Media Group (Coin News) 2015). Average water consumption was calculated based on the average water consumption per household in the *colonias,* utilizing survey results from a previous study for household size (Garcia Cobos 2014), and an EPA study on the ingestion of water (EPA 2004). The conservative assumption was made that units will only produce drinking water. Figure 3.1 reveals that

purchasing bottled water can be as much as 10 times more expensive than utilizing a POU RO unit.

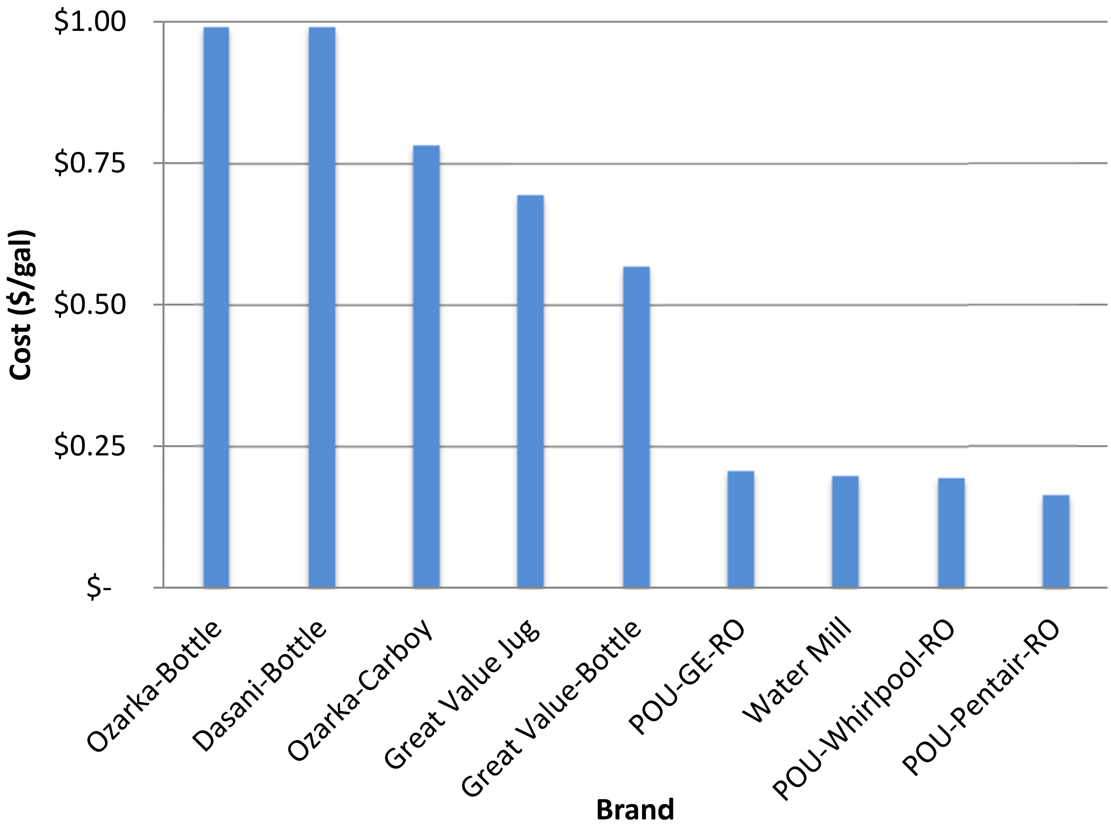

Figure 3.1: Cost comparison among some of the leading brands of bottle water and the top three POU systems.

In light of top-ranked POU units being RO systems, an educational pamphlet (shown in Appendix B) was created for residents to help facilitate the technological aspect of purchasing a water treatment system for themselves. Although the brochure is specific to the Paso Del Norte region, its contents is generalizable.

The next highest ranking units were two disinfection technologies: an in-line ozone generator and batch-dosing of sodium hypochlorite. However, at a price of $3,000, the ozone generator by Aclarus may not be financially affordable for most households. On the other hand,

the bleach by Sunbelt has presumably been discontinued. The next set of units are POE UF filters, with costs of thousands of dollars. Thus, the next three feasible technologies are actually copper, bleach by Clorox, and a POE MF unit by Sawyer.

Several other units also made claims with regards to NSF International certification, but their claims could not be cross-checked with NSF International's website. As previously stated, the NSF-International website can prove to be challenging at times, so it may that the certification has been awarded, but it is not observable through their webpage.

The road towards determining which water treatment unit is the most adequate one for a particular water can be challenging, as it may be seen by the many caveats in the results section. The purpose of the text, tables, and ranking criteria produced in this research is to provide a clearer path towards accomplishing that goal.

CONCLUSIONS

The goal of this study was to develop a simple ranking system that can be used by household residents to screen and select a POU drinking water system for their home. This goal was accomplished by developing a set of ranking criteria and applying those criteria to commercially available water treatment units. The top-ranking POUs were reverse osmosis water treatment units, which suggests that POU RO units could be a solution to improving drinking water for households relying on groundwater or hauled water.

More research is needed to develop another set of ranking criteria that are substantiated by surveys or other research mechanism. If survey results that specified which ranking criteria were most important for people, it would have been possible to confidently add weights to each of the criteria. Furthermore, more research is also needed in the area of environmental sustainability. The environmental sustainability aspect of the ranking criteria used in this study

does not fully convey the impact that a particular unit will have on the environment from cradle-to-grave.

Chapter 4: Preserving Water Quality in Drinking Water Storage Tanks

INTRODUCTION TO CHLORINE, ALGAE, AND COPPER

Disinfection has been considered the most important step in preventing diseases transmitted through water (Bowden et al. 2006). The most widely used disinfectant is chlorine (Milot, Rodriguez, and Serodes 2002), in part because it provides a residual concentration. Current common practice in the US involves providing residual concentration of chlorine to prevent recontamination of water in the distribution system (MWH 2005). The effectiveness of chlorine residuals in the distribution system has been reviewed and confirmed in a study submitted to EPA (HDR Engineering, Cadmus Group 2006). For surface waters, the EPA established a minimum of 0.2 mg/L of free chlorine (40 CFR §141.72) and a goal of less than 4.0 mg/L to avoid DBPs (40 CFR §141.65 2007). Although the 0.2 mg/L concentration may be enough to prevent recontamination from viruses and bacteria, such a low concentration may sometimes be insufficient to remove algae (Davis 1985).

Green algae are eukaryotic organisms that contain chlorophyll *a*, much like plants, (Maier, Pepper, and Gerba 2009). Algae are usually the dominant species in waters with pH less than 4 and they are found in a variety of places in both fresh and salty water (Maier, Pepper, and Gerba 2009). Although they are a fundamental part of aquatic life (Maloney 1966), they can become a nuisance in a water body if their growth is not controlled. Some algae can harm humans either by facilitating the conditions for other pathogenic microorganisms to thrive or by directly poisoning humans (Paerl 1988).

Traditionally, the methods employed in water treatment to remove algae are shock-chlorination and the addition of copper sulfate. Shock-chlorination involves the application of a dose of approximately 10 mg/L of free chlorine and has been used in public swimming pools to

control chloramines and to control algae (Davis 1985). However, with respect to drinking water, chlorination may produce disinfection byproducts (DBPs) such trihalomethanes (THMs) or halo-acetic acids (HAAs), which are known to be carcinogenic (Boorman et al. 1999).

On the other hand, copper sulfate has been reported to be an effective treatment method for various kinds of algae (Moss et al. 1977; Netien, Boiron, and Marin 1966; Haughey et al. 2000). Copper is known to inhibit growth, photosynthesis, enzyme activity, and pigment synthesis (Franklin et al. 2000; Stauber and Florence 1987). Effective treatment doses have been reported to range from 25 to 1,000 μg/L (Hullebusch et al. 2002).

However, although copper's effectiveness has been well documented, this treatment method is not as commonly employed as shock chlorination. Among the reasons behind the reluctance to use copper sulfate in drinking water basins and storage tanks are: (1) health concerns (Dietrich et al, 2004; Brewer, 2012; WHO, 2004) and EPA's primary limit of 1.3 mg/L (40 CFR §141.80 2007); (2) the reported faster decay of chlorine in the presence of copper (Gordon, Adam, and Bubnis 1995; Lister 1956a; Lister 1953); and (3) copper pipe corrosion (Dietrich et al. 2004; Olivares et al. 2014; Pizarro et al. 2014). Different as they may seem, these three concerns are all related to the concentration of copper in the water. If the concentration of copper can be kept safely under the EPA's MCL, then concerns number one and three can be fully addressed. The reported faster decay of free chlorine in the presence of copper, cannot be as easily addressed.

In addressing the second issue of chlorine decay in the presence of copper, much research has been performed with high concentration sodium hypochlorite stock solutions. Studies such as Gordon et al's classical study (Gordon, Adam, and Bubnis 1995) and Lister's (Lister 1956b) studied the effects of copper in chlorine concentrations that might be commonly found in stock

solutions of sodium hypochlorite (e.g., 59,000 to 191,000 mg/L). However, more research is needed in determining the effects that copper has on chlorine decay at concentrations found in drinking water (*i.e.*, < 4 mg/L). If the detrimental effects that copper has on chlorine could be proven to be insignificant at the US Environmental Protection Agency (EPA) approved concentrations of 0.2-4 mg/L for chlorine (40 CFR §141.65 2007; 40 CFR §141.72)and 0-1.3 mg/L for copper (40 CFR §141.80 2007), the second main concern with copper could be resolved. This could save a significant amount of maintenance time and effort for treatment plant operators who are otherwise required to regularly remove algae by manually scrubbing or pressure washing.

Another research gap regarding algal growth in drinking water treatment plants and storage tanks is nutrients. Whereas many studies have been performed to prove that algal growth could be inhibited by dissolved copper (Moss et al. 1977; Netien, Boiron, and Marin 1966; Haughey et al. 2000), these studies often feature carefully controlled growth media (*e.g.*, nutrients) that favor algal growth and may not be representative of conditions seen in treatment plants and storage tanks. Thus, a study of algal growth inhibition by copper with a perspective in drinking water treatment and storage is necessary.

Goals and objectives

The goal of this study was to preserve the quality of water in drinking water tanks. The first objective was to determine the most technically, economically, and socially sound commercially-available chlorine test strips, to empower residents with the ability to monitor their own water quality. The second objective was to quantitatively determine the decay rate of chlorine in the presence of copper and to qualitatively test the efficacy of chlorine and copper for controlling growth of algae-containing-biomass collected from a local *colonia* residential storage

tank. The third objective of this study to create a set of educational materials that would help *colonia* residents to improve their water quality, even if no system was provided for them.

MATERIALS AND METHODS

Determining the most precise, accurate and economical locally available chlorine test strips

The first and most important factor in preserving the water quality in drinking water tank is to accurately measure the free chlorine concentration. Although there are several methods to measure the free chlorine concentration, the most inexpensive method are chlorine test strips, which are widely used in recreational swimming pools.

Twenty nine different chlorine test strips (full list found in Appendix C), were reviewed. Of those 29, five locally available chlorine test strip brands, listed in Table 4.1, were tested against the DPD free chlorine method (SM 4500-ClG) using a Hach DR 890. (Although it could have been possible to order some of the chlorine test strips available online, only locally available products were selected because it is unclear whether *colonia* residents have the means to order items online.) Each sample was analyzed three times by each test strip brand and by the DPD method. Free chlorine solutions were prepared using sodium hypochlorite from Across Organics and laboratory deionized (DI) water (conductivity < 1 μS/cm) was produced by reverse osmosis and mixed-bed ion exchange.

Brand	Price ($)	Number of Strips	Price/Strip ($)
AquaCheck	8.48	50	0.17
Chlorine Pro	14.95	100	0.15
HTH	13.97	50	0.28
Kemtek	14.98	25	0.60
Leslies	11.99	50	0.24

Table 4.1: Chlorine strips brands tested against the DPD free chlorine method

CATALYTIC EFFECTS OF COPPER ON THE DECAY OF FREE CHLORINE

Chlorine decays in the presence of light (Cooper et al. 2007). It has also been suggested that the rate of chlorine decay in the presence of copper could be altered by UV-light (Gordon et al, 1995). Drinking water storage tanks used in municipal drinking water treatment plants and distribution systems are typically opaque materials, but some residential water storage tanks in colonias are transparent plastic. Thus, this study used both translucent and amber HDPE bottles to compare the chlorine decay in the presence of copper and light, as summarized Table 4.2 and Table 4.3. A full-factorial design was employed with three replicates, which required 72 bottles for the first experiment in DI and 48 bottles for the second experiment in tap water. Amber bottles were US Pharmacopeia 661 certified. New bottles were used for this experiment, which were washed with phosphate- and residue-free soap (*Liqui-Nox*).

Table 4.2: List of constants for testing catalytic decay of chlorine

Constant	Experiment #1	Experiment #2
Water Chemistry	DI Water with $NaHCO_3$	Tap Water
Test Volume	500 mL	100 mL
Temperature	Room Temperature	Room Temperature
Initial Free Chlorine Concentration (mg/L as Cl2)	4.0 mg/L	4.0 mg/L
Amount of KH_2PO_4 (mg/L)	7.31	NA
Amount of Na_2HPO_4 (mg/L)	14.95	NA

Table 4.3: List of variables for testing catalytic decay of chlorine

Variable Name	Experiment #1	Experiment #2
Bottle Opacity	Translucent or Amber	Translucent or Amber
pH Buffers (phosphate and/or carbonate)	6.5, 7.5, 8.5	6.5, 8.5
Cu^{2+} Concentration (mg/L)	0.0, 0.1, 0.5, 1.0	0.0, 0.1, 0.5, 1.0

Several regulations and health guidelines were considered for determining the concentrations for the copper (II) ion in controlling algae in water treatment plants and storage tanks. First, U.S. EPA Primary Drinking Water Standards require public water systems to have no more than 1.3 mg/L of copper in 10% of the sampled tap water sources (40 CFR §141.80 2007). Copper is also included in the National Secondary Drinking Water Regulation List with a maximum concentration of 1.0 mg/L (40 CFR §143.3). Also, the World Health Organization (WHO) published a comprehensive review of copper and its health risks (World Health Organization 2004b), which provides guideline maximum concentration of 2 mg/L. Finally, more recent studies have suggested a link between dietary copper, a high fat diet, and

Alzheimer's Disease[2] (Brewer 2012). In light of both regulations and health concerns, the most conservative limit for copper is the EPA's secondary drinking level at 1.0 mg/L. Thus, the specific concentrations evaluated in this study were: 0, 0.1, 0.5, and 1.0 mg/L. (For houses with copper plumbing, a lower dose may be required to achieve copper concentrations less than 1.3 mg/L in tap water.)

While both hypochlorous acid (HOCl, pKa 7.5) and the hypochlorite ion (OCl^-) are considered to be "free chlorine", HOCl has faster disinfection kinetics, and is therefore more desirable in water treatment than its conjugate base (MWH 2005). In seeking to understand the effect of copper to both HOCl and OCl^-, the three pH values to be studied will be 6.5, 7.5, and 8.5, which correspond to HOCl speciation fractions of approximately 90%, 50%, and 10%, respectively. These pH values are also within or close to the range of pH in drinking water (40 CFR §143.3). In order to maintain the pH at the listed values, a 0.16 mmol/L phosphate buffer was prepared with the appropriate buffering.

The free chlorine concentration was measured with a Hach DR 890 Colorimeter and Hach Method 8021 (SM 4500-ClG). Temperature, pH, and the oxidation-reduction potential (ORP), were also measured using an Orion A325 Star pH/Cond meter or an Orion 5 Star pH/Cond meter/DO Portable.

The chemicals used were ACS grade cupric sulfate from *Fisher Scientific* and sodium hypochlorite from *Across Organics*. Potassium phosphate monobasic (KH_2PO_4), sodium phosphate dibasic (Na_2HPO_4), and sodium bicarbonate ($NaHCO_3$) from *Fisher Scientific* were used to buffer the pH. The hydrochloric acid used to adjust the pH of the samples was TraceMetal™ grade from *Fisher,* and sodium hydroxide was ACS grade from *Fisher,* as well.

[2] Brewer also conceded that blaming copper, alone, would be unfair, as a high fat diet, low zinc concentration in the blood, and, most importantly, age are also factors (Brewer 2012)

The nitric acid used was reagent grade from *Fisher Scientific*. The containers used were 500 mL HDPE translucent and amber bottles. Laboratory deionized (DI) water (conductivity < 1 µS/cm) was produced by reverse osmosis and mixed-bed ion exchange. Tap water for the second experiment came from El Paso Water Utilities (EPWU) public water supply. Typical concentrations of major ions in sample water from EPWU are listed in Table 4.4.

Table 4.4: Typical concentrations of major ions in EPWU tap water

Parameter	Conc (mg/L)
[ψ]TDS	630
[ψ]Total Alk as $CaCO_3$	121
[γ]Cl^-	67
[γ]SO_4^{2-}	148
[γ]F^-	0.27
[ψ]SiO_2	36
[γ]NO_3^-	0.26
[ψ]NO_2^-	<0.05
[ψ]PO_4^{3-}	<0.05
Ca^{2+}	18
Mg^{2+}	4.8
Na^+	48
K^+	79
[γ]pH	8.1 (no units)

[γ]Results are from separate tap water sample
[ψ]Typical concentrations according to EPWU water quality (EPWU 2014)

The first experiment analyzed the effect that the presence of copper has on the rate of decay of chlorine in DI water. Sodium hypochlorite was added such that the initial concentration was 4.0 ± 0.1 mg/L (as Cl_2). An initial concentration of 4.0 mg/L was selected because it is the maximum residual disinfection level (MRDL) set by EPA for chlorine (EPA 1998). The second experiment analyzed the effect that copper has on the decay of chlorine in tap water. All solutions were maintained at room temperature (20-25 °C).

Each bottle was kept closed throughout the duration of the experiment, except when a reading was taken. In order to maintain constant illumination, fluorescent lighting in the

laboratory was kept on throughout the experiment. Once experiments had been started, temperature, pH, ORP, and free chlorine concentration were measured daily. The endpoint of the experiment occurred after 60 days for the first experiment and 28 days for the second experiment.

Synergistic Effects of Copper (II) and Free Chlorine for Preventing Algal Growth

The second objective of this experiment was to qualitatively evaluate the efficacy of copper and chlorine in controlling indigenous algae-containing-biomass in residential water storage near El Paso, TX. Experimental constants and variables are summarized in Table 4.4 and Table 4.5, respectively. A full-factorial design was employed with three replicates, which required 54 bottles. The water to be used in all sample bottles of this experiment was tap water from EPWU's public water supply. Sodium thiosulfate from the *Hach Company* was added to the samples when it was required.

The algae-containing-biomass for the second experiment was collected from a 2500 gallon translucent plastic water storage tank in a colonia on the east side of El Paso. A sample of algae-containing-biomass was scraped off the walls of the water storage tank, and a sample of approximately 3.5 gallons of water was also collected from the water storage tank for culturing the biomass in the laboratory. The culture media was spiked with 0.75 mg/L of phosphorus with *Fisher Scientific* ACS-grade Na_2HPO_4 to encourage the algae to grow. A 0.75 mg/L phosphorus concentration was calculated based on the Redfield N:P ratio of 16:1 (Redfield 1934) and an estimated maximum nitrogen concentration of 11 mg/L, from EPA's primary standards of 10 mg/L of nitrate, as nitrogen, and 1 mg/L of nitrite as nitrogen (40 CFR §141.62).

Each sample bottle was seeded with 0.25g±0.025g of surface blot-dried algae. The algae was added to a 100 mL bottle, which provided an extreme case of algae to water ratio.

The copper concentrations evaluated were 0, 0.1, and 1.0 mg/L. The pH in this section of experiments was periodically adjusted to remain at 6.5 and 8.5. The initial free chlorine concentrations employed in this experiment were 0, 1, and 2 mg/L. Each solution bottle was kept open throughout the duration of the experiment to allow for carbon dioxide for the algae. The duration of the experiment was 10 days.

Table 4.4: Experimental constants for testing efficacy of copper and chlorine for controlling biomass growth

Constant Name	Value
Water Chemistry	Tap Water
Volume (mL)	100
Temperature	Room Temperature
Algae-containing-biomass (g)	0.25±0.025
Phosphate (mg/L)	5
Nitrate (mg/L)	100
pH	6.5 and 8.5

Table 4.5: Experimental variables for testing efficacy of copper and chlorine for controlling biomass growth

Variable Name	Values
Cu^{2+} Concentration (mg/L)	0.0, 0.1, 1.0
Free Cl_2 Concentration (mg/L)	0, 1, 2
pH	6.5 8.5

RESULTS AND DISCUSSION

Determination of the most suitable chlorine test strips

Linear regressions and R^2 of each the tested chlorine test strips, as well as the control values from the Hach DR 890, are shown in Figure 4.1. Based on the R^2, it possible to see that the best performing pH test strips are the Leslie's and Chlorine Pro. The price/strip comparison revealed that AquaChek and Chlorine Pro are the least expensive test strips. HTH strips seemed to have performed the most poorly. It is not known whether the box that was purchased was altogether defective or if HTH test strips are just not very accurate or precise at measuring free chlorine. Although it could have been possible to purchase another box of HTH test strips to determine if the previously purchased box was defective, it was ultimately decided that purchasing another box would require to perform all the measurements for all brands anew since the stock solutions of chlorine would have decayed by then.

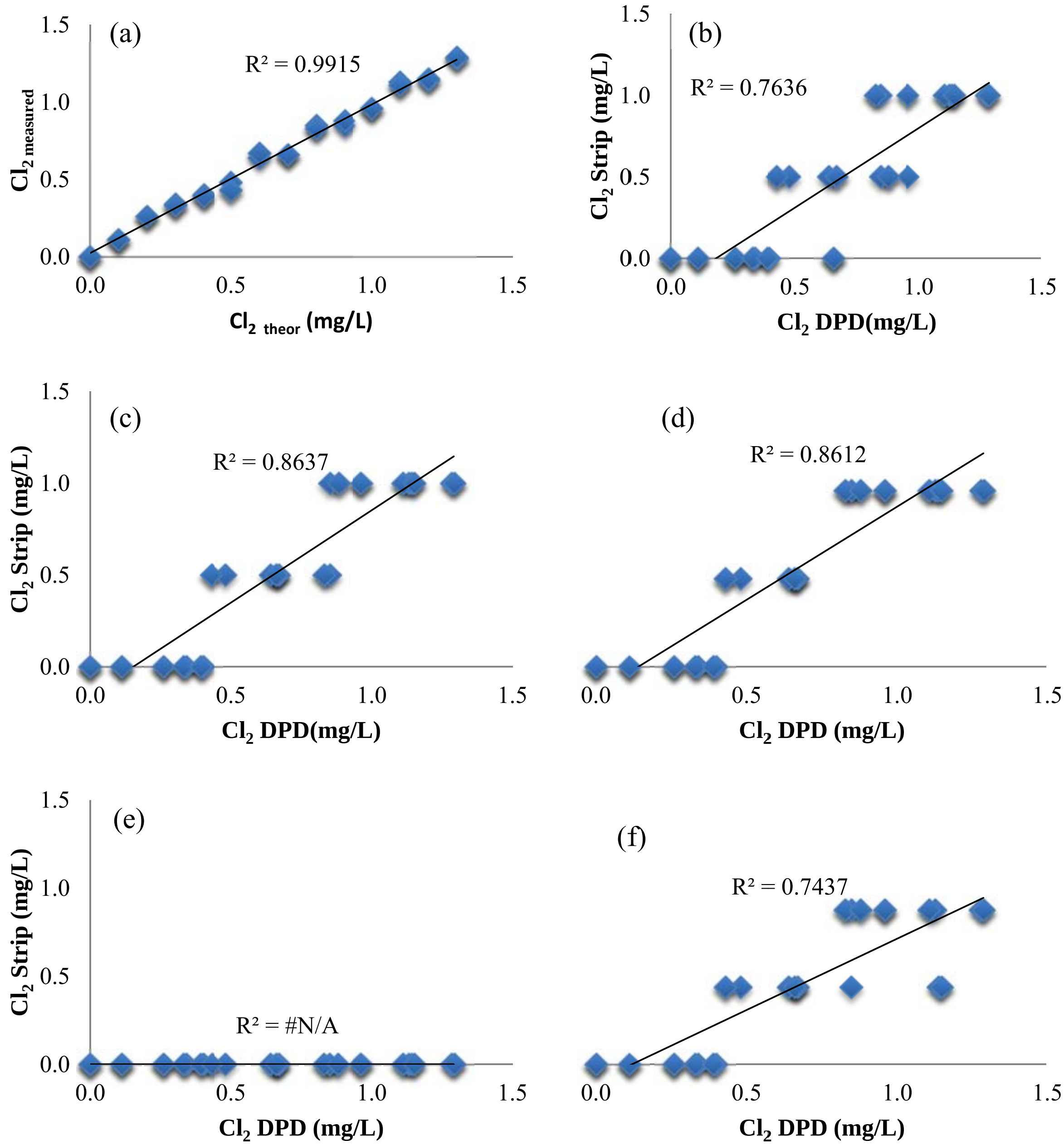

Figure 4.1: Linear regressions of theoretical vs measured values of free chlorine for (a) DPD free chlorine method, (b) Aquachek, (c) Chlorine Pro, (d) Leslie's, (e) HTH, and (f) KemTek

Catalytic effect of copper on free chlorine decay

Experiment 1 – Deionized water

During the 60-day experiment, chlorine was measured 18 times and the measured decay was fitted with first and second order trend lines (the latter shown in Figures 4.2 and 4.3). Upon visual inspection of the data, three permutations of Experiment 1 had an outlier replicate. The outliers were omitted from the following calculations after they were confirmed to be outliers based on the sum of square errors: if the sum of square errors decreased more than ten-fold by removing the presumed outlier, the replicate was removed from the rest of the calculations. One permutation (amber bottle, pH=8.5, $[Cu^{2+}]$=0.1 mg/L) was also omitted because none of the three replicates matched, which yielded a very poor R^2 of 0.59.

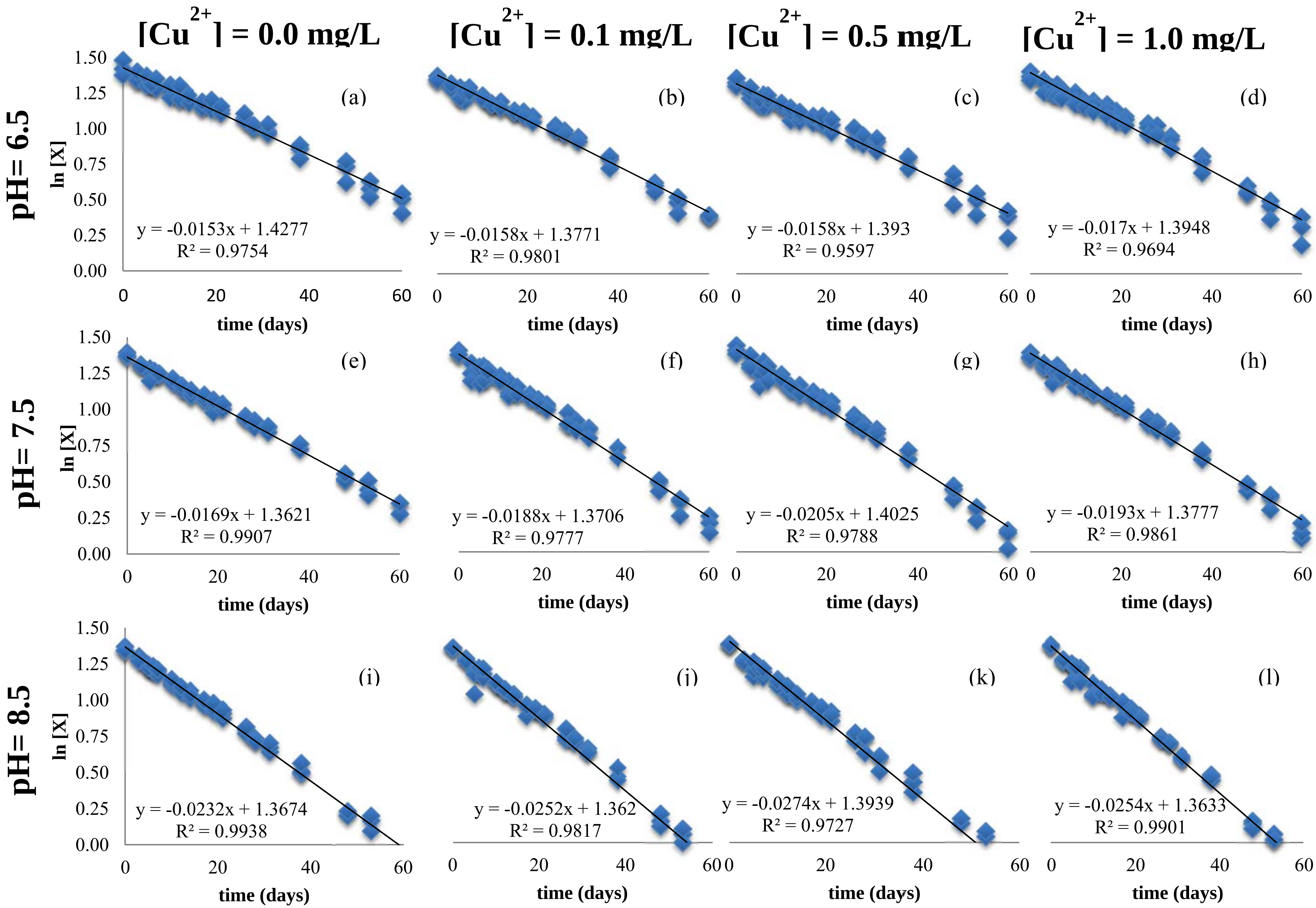

Figure 4.2: Experiment 1 Chlorine decay with copper in DI water in clear bottles (pH 6.5, 7.5, and 8.5)

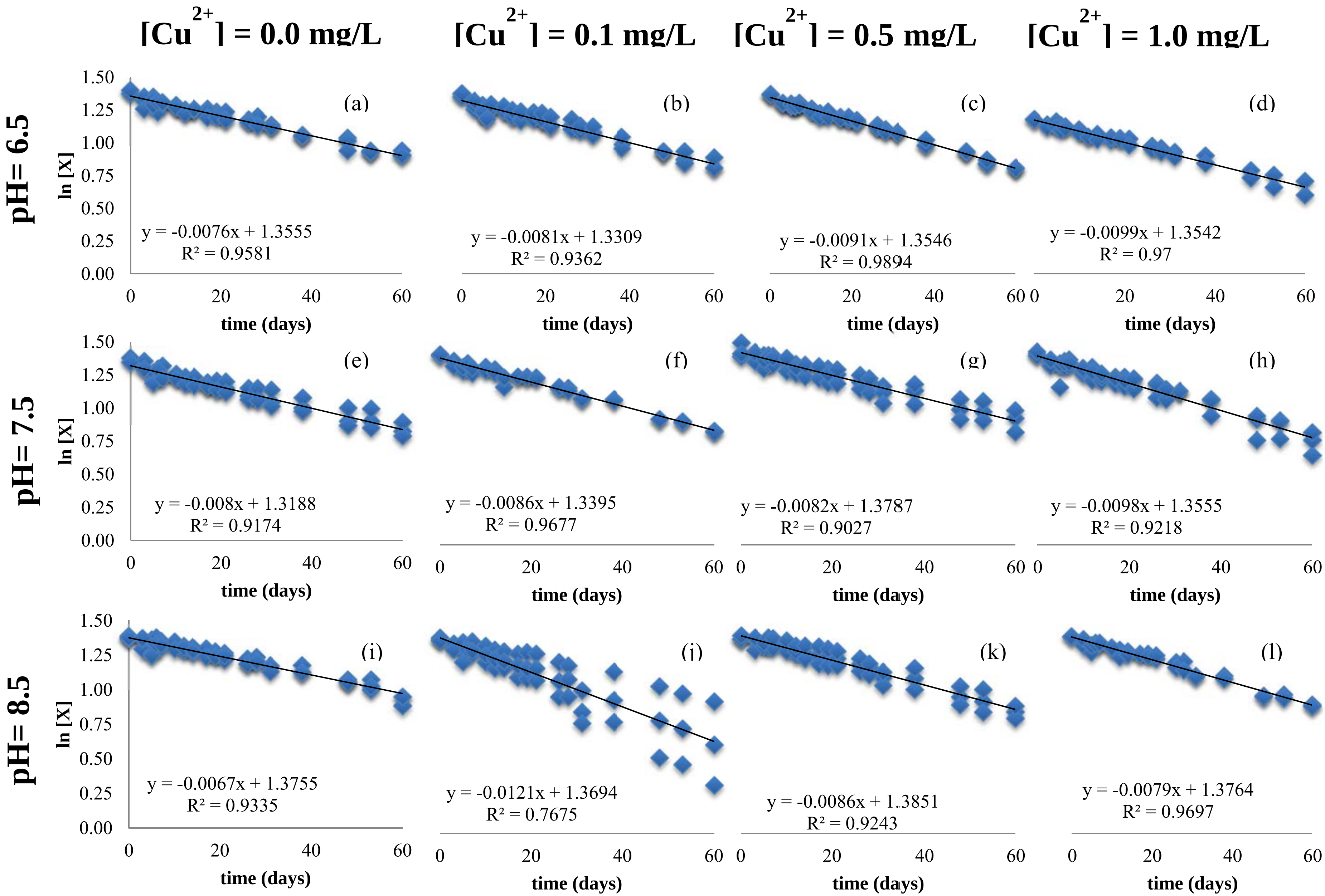

Figure 4.3: Experiment 1 Chlorine decay with copper in DI water in amber bottles (pH 6.5, 7.5, and 8.5)

In order to determine which of the equations provided the best fit, the data was first tested for goodness-of-fit using an F-test using *Microsoft* Excel (calculated manually). The goodness-of-fit F-test test was passed by both regressions (*i.e.*, R^2 results can be used for comparison) so the average R^2 values of each fit were employed to determine which reaction order provided the best fit. The average R^2 values of the first and second order regressions were also tested using Minitab 16 (Minitab Inc 2013), with a paired t-test to determine if there was a statistically significant difference in between them (*i.e.* the means don't just appear different because of deviation in data, but are, in fact, the same). The t-test revealed that there is evidence to believe that both means are in fact different with a confidence level 99%. Based on the R^2 values, a first order decay model best-fit the observed trend the best for the experiment performed with DI water.

The results from Experiment 1, shown in Figure 4.4, revealed that free chlorine decayed 2.1 to 3.4 times faster in translucent bottles (part a) than in amber bottles (part b). Chlorine decay in transparent bottles was well correlated with increasing pH, but chlorine decay was relatively insensitive to pH in amber bottles. Overall, exposure to light significantly increases the rate of decay of free chlorine, much more than addition of copper. Furthermore, it can also be inferred that the most effective way to minimize chlorine decay is to avoid exposure to light.

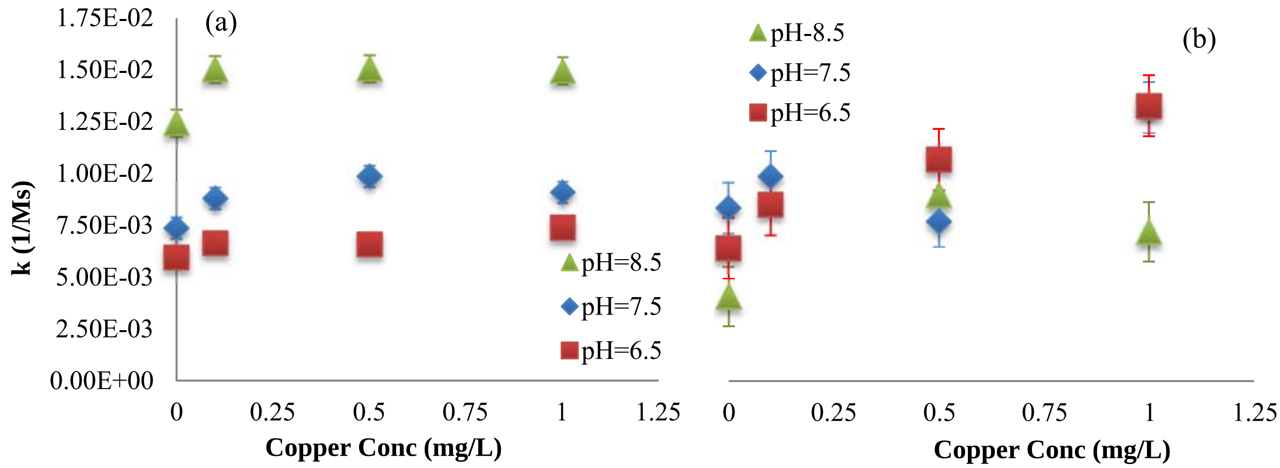

Figure 4.4: Experiment #1 Chlorine decay rate constants with copper (II) in DI for (a) translucent bottles and (b) amber bottles

With respect to pH sensitivity in Figure 4.4, *Visual Minteq* 3.0 (Gustafsson and EPA 2014) was used to simulate copper speciation. For experiments performed in DI water and with a phosphate buffer, approximately 68% percent of the total copper was available as free Cu^{2+} ion at pH 6.5, while only 3% of the free cupric copper remained at a pH of 8.5, as shown in Figure 4.5. At pH 6.5, approximately 25% of the total copper was complexed with phosphate, and 6.5% of the total copper was complexed with hydroxide. At pH 8.5, approximately 10% of the total copper was complexed with phosphate, and approximately 81% of the total copper was complexed with hydroxide. Thus, it can be seen that pH plays a greater role in determining the amount of free copper available than phosphate as the copper (II) ion has a greater affinity for hydroxide than for phosphate.

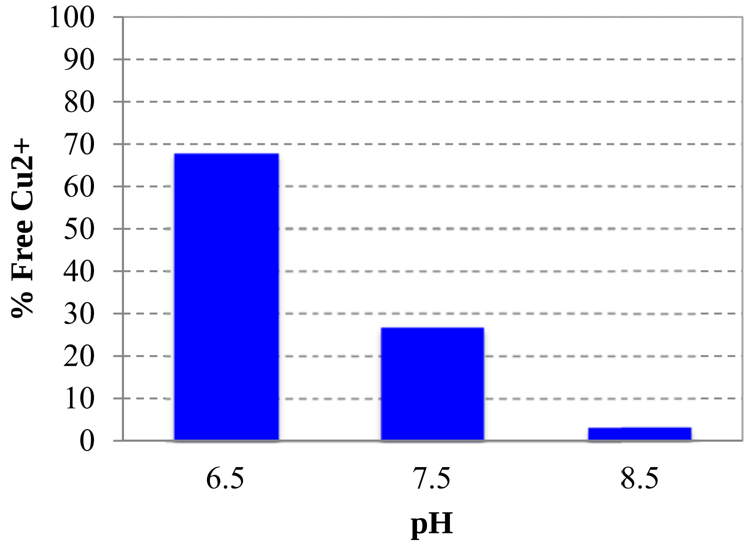

Figure 4.5: Free Cu^{2+} in Experiment 1 by pH

Experiment 2 – Tap water

The results for the second experiment showed that free chlorine decay was 1.1 to 2.3 times faster in translucent bottles as opposed to amber bottles, as shown in Figure 4.6. Figure 4.7 shows the percentage of free copper (II) at different pHs. A statistically significant trendline was added to the decay constants at pH 6.5, the value for the coefficient of determination can be seen in Figure 4.6. A statistically significant trendline could not be added to the decay rates at a pH of 8.5 because solutions with 0.1 mg/l of copper seemed to decay at a faster than what the observed trend would suggest. There seemed to be a correlation between the faster decay rates and the concentration of copper as solutions with 1 mg/L decaying as much as 1.9 times faster (pH=8.5, translucent) than a solution at the same pH, but without any additional copper. Overall, the single greatest catalyst for the decay of free chlorine appears to be an increase in pH, causing decay rates at a pH of 8.5 that were as much as 6 times faster then the corresponding decay rate at a pH of 6.5; decay rates were from 1.5-6.1 times faster when solutions with corresponding pHs were considered. As seen in Figure 4.6 and based on a simulation with Visual Minteq, approximately

80% of the total copper was available as free Cu^{2+} ion at a pH of 6.5, while only 4% of the total copper was free cupric copper at pH of 8.5. At a pH of 8.5, most of the copper is complexed with hydroxide ions.

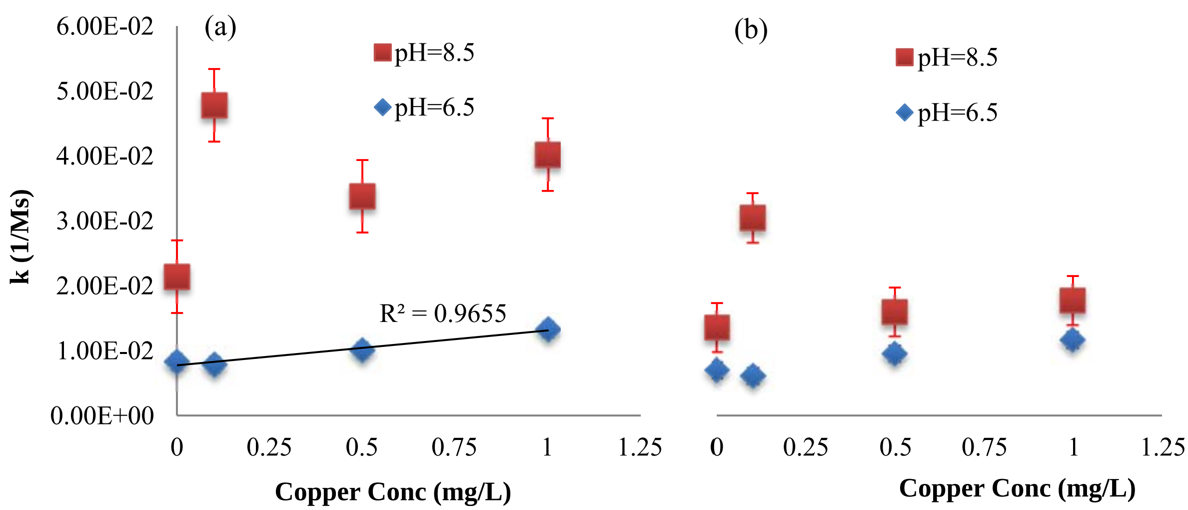

Figure 4.6: Experiment 2 Chlorine decay rate constants with copper (II) in tap water for (a) translucent bottles and (b) amber bottles

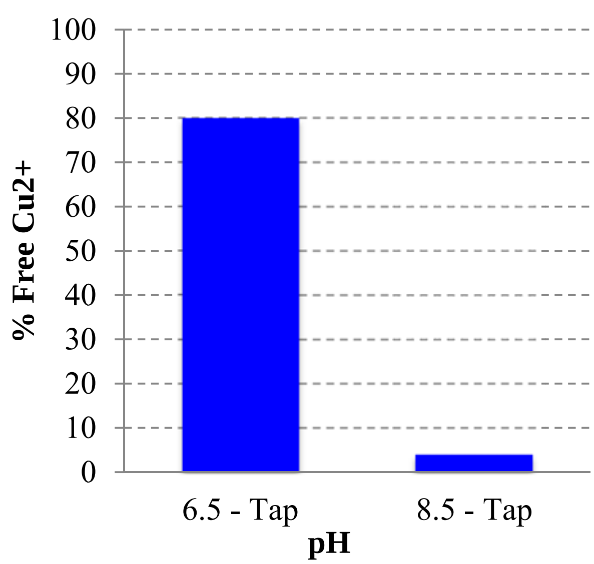

Figure 4.7: Free Cu^{2+} in Tap Water Experiments by pH

Synergistic Effects of Free Chlorine and Copper (II)

Maintaining the free chlorine concentration constant presented a problem in this experiment the initial demand was never met (presumably because of the large algae to solution ratio) although sodium hypochlorite was added at least twice per week. Although it could have been possible to increase the free chlorine concentration in the solutions to appoint where the initial demand was met, doing so would have probably shifted the dominant algae control mechanism from copper addition to shock chlorination.

Initial and final weights of algae were measured in an effort to quantify the loss in biomass Experiment #3. A paired t-test revealed a monotonic trend of increasing magnitude of biomass attrition with increasing copper concentration, as shown in Table 4.6. If "statistical significance" is defined by $p < \alpha$ and $\alpha = 0.05$, then the difference in mass-loss between copper concentrations of 0 mg/L and 1 mg/L are statistically significant, as shown in Table 4.7. This statistically significant difference in mass-loss indicates that copper is an effective biocide of the organism(s) present in the ecosystem.

Table 4.6: Average biomass loss at various copper concentrations

Copper Conc. (mg/L)	Average biomass loss (g)	Standard Deviation (g)
0.0	0.058	0.050
0.1	0.075	0.040
1.0	0.092	0.040

Table 4.7: Comparison of the Impact of Copper in Algae Biomass

Comparison	p-Value of Paired t-Test
0 mg/L Cu vs 0.1 mg/L Cu	0.173
0 mg/L Cu vs 1 mg/L Cu	0.018
0.1 mg/L Cu vs 1 mg/L Cu	0.053

Photographs, shown in Figure 4.8 and Figure 4.9, were taken throughout the duration of the experiment to provide a visual representation of the effect copper has on algae. Perhaps counter-intuitively, the biomass exposed to copper acquired a more vibrant green as compared to the initial samples and the final control. Vibrant greens are associated with the amount of chlorophyll a in the biomass. Therefore, the pictures revealed that the algae appeared to be thriving in the presence of copper. One explanation for this is that the biomass that was removed from the tank was actually a full ecosystem of organism and that the addition of copper aided the algae to become the dominant species by killing other species (perhaps mold).

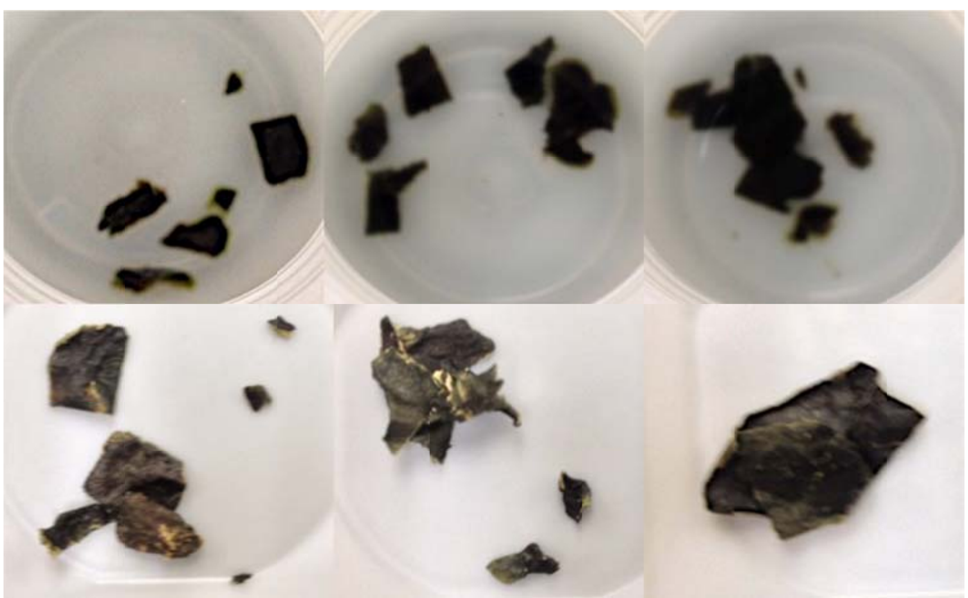

Figure 4.8: Initial (top row) and final (bottom row) pictures of algae samples with 0 mg/L of copper at a pH of 6.5

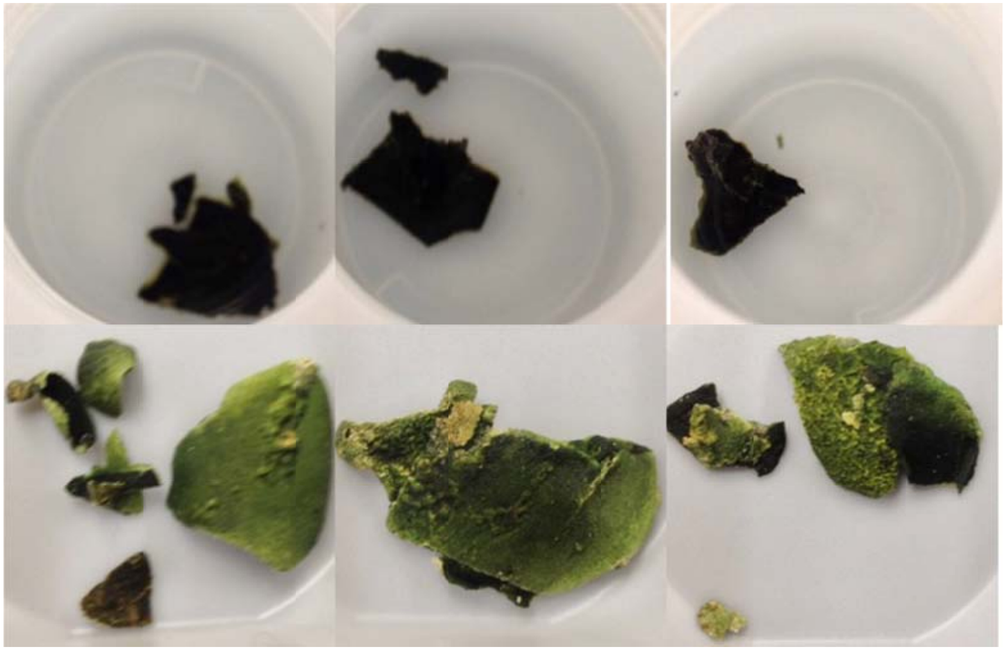

Figure 4.9: Initial (top row) and final (bottom row) pictures of triplicate algae samples with 1.0 mg/L of copper at a pH of 6.5

CONCLUSIONS

The experiment performed in this study provided evidence that the copper (II) ion does not significantly increase the rate of decay of free chlorine at drinking water concentrations when compared to other factors such as pH and organic mass. Furthermore, this research can also be understood to conclude that a second order decay model is appropriate for the decay of free chlorine in the presence of copper a drinking water concentrations. More experimentation is required understand the effects that temperature has on copper and chlorine decay reaction.

In the area of the susceptibility of utilizing cupric copper to control algae indigenous to El Paso, TX, it necessary to consider the effect copper has on a community of organisms, as opposed to a single organism if copper is to be employed to control biomass growth in tanks. More research is needed to fully comprehend the effect that copper has on multiple organisms in

the same ecosystem. This research is needed as, in the great majority of instances, a particular species of algae will not be the sole species on particular ecosystem.

Chapter 5: Conclusions

General

The goal of this research was to provide a rapidly deployable solution for the drinking water issues faced by *colonias* in the Paso Del Norte region with a point-of-use and/or point-of-entry water treatment system. The goal was addressed through several phases of research. First, focus groups were conducted to assess the preferences of *colonia* residents, and a conceptual design for a household-level water treatment system was developed. This design included a point-of-entry cartridge filter and a point-of-use reverse osmosis filter. Second, a point-of-use technology evaluation system was developed that could be used by residents to determine the best water treatment system for their specific needs. Third, experiments were conducted to evaluate the use of copper as an algaecide in water storage tanks.

To address the first objective, this study showed that it was residents who rely on well water who faced more challenges than those who rely on hauled water. *Colonias* that use groundwater have issues with both microbiological contamination and high salinity, while residents who use hauled water seem to be at risk of developing algae in their tanks (if the tanks are not opaque). The water quality results also enabled the conceptual design of a water treatment process that would address the needs of the *colonias*. Furthermore, educational materials were also developed for the residents in an effort to improve their water quality without a significant capital cost.

The second objective was by advancing the body of knowledge and practice of point-of-use water treatment by developing a simple, yet robust, ranking system for commercially available POU water treatment systems. The research revealed that determining which filtration

unit to purchase is a process that, without any assistance from professionals or professionally developed tools, can prove to be extremely difficult. Another conclusion of this research was that RO systems offer the most economically, socially, and environmentally sustainable solution for *colonias*.

The third and last objective of this research was completed by determining which locally available chlorine test strips were the most accurate, precise, and economical at measuring free chlorine. Experiments showed that a second order decay is a suitable model for the kinetics of the copper and free chlorine decay reaction. The experiments performed also suggest that the copper (II) ion does not significantly increase the rate of decay of free chlorine when compared to pH and organic matter. However, experiments also revealed that the effectiveness of copper as an algaecide is also contingent on the complexity of the ecosystem of organisms encountered. Lastly, educational materials that detailed a methodology to preserve the water quality in drinking water storage tanks.

FUTURE WORK

More research is needed to determine the seasonal variability of the water quality in the Paso Del Norte *colonias*. This could be particularly important during irrigation season and during the summer, which could cause significant changes in the water quality of well water and hauled, respectively. Furthermore, more research is needed to determine the source of microbiological contamination in well water.

Further research may also be required to improve the ranking system for commercially available water treatment systems. Namely, more research is needed to determine which of the three types of sustainability considered in this study (economical, social, and environmental) are

more important for the residents. More research could also be performed to determine the carbon footprint of the recommended RO system.

Lastly, it is also necessary to collect and characterize more water samples of algae growing inside of water storage tanks. More experiments may also be performed to further explore effective algaecides for water storage tanks.

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Appendix A: Water quality results

Sample		Microbiological		Aggregate					
Code	Type	T. Coliform	E. Coli	Temp	pH	Cond.	ORP	TDS	TS_{calc}
		MPN	MPN	(°C)	-	(μS/cm)	mV	(mg/L)	(mg/L)
1017-1	Tank	< 1.0	<1.0	21.5	7.87	883	650	485	693
1017-2	Tank	< 1.0	<1.0	22.0	7.96	829	603	462	673
1017-3	Tank	< 1.0	<1.0	23.1	7.97	835	590	580	704
1022-3	Tank	< 1.0	<1.0	22.1	7.65	909	616	495	729
1120-1	Tank	< 1.0	< 1.0	21.3	7.41	1,089	231	590	787
1120-3	Tank	NA	NA	19.4	7.69	843	664	480	632
1120-4	Tank	NA	NA	20	7.75	838	647	1,295	632
0403-2	Tank	< 1.0	< 1.0	19.70	7.40	833	584	#N/A	546
1022-1	Well	> 200.5	53.1	21.1	7.95	1,956	254	1,225	1483
1022-2	Well	129.80	< 1.0	22.6	8.07	2,602	254	470	2057
1029-1	Well	< 1.0	<1.0	21.7	7.36	1,966	-56	1,175	1719
1029-2	Well	8.7	<1.0	21.4	7.37	1,965	-95	980	1683
1029-3	Well	< 1.0	<1.0	20.2	7.30	1,555	130	900	1249
1029-4	Well	< 1.0	<1.0	20.7	7.15	3,101	167	1,970	2840
1029-5	Well	2	<1.0	23.4	7.25	2,665	235	1,550	2352
1029-6	Well	< 1.0	<1.0	21.9	7.42	2,796	199	1,815	2827
1107-1	Well	> 200.5	< 1.0	18.7	7.39	1,732	60	955	1583
1107-2	Well	< 1.0	< 1.0	18.2	7.33	2,518	186	1,635	1918
1107-3	Well	< 1.0	< 1.0	15.4	7.18	2,317	117	1,537	2269
1107-4	Well	< 1.0	< 1.0	18.8	7.51	748	212	480	762
1107-5	Well	< 1.0	< 1.0	17	7.49	747	231	460	794
1120-2	Well	NA	NA	19.8	6.83	2,078	287	430	1534

Sample		Hach			
Code	Type	Free Chlorine (mg/L)	Iron (mg//L)	Manganese (mg//L)	Silica (as SiO2) (mg/L)
1017-1	Tank	1.12	0.02	1.50	21
1017-2	Tank	0.44	0.01	0.90	25
1017-3	Tank	1.33	0.02	1.20	25
1022-3	Tank	0.64	0.2	0.90	12
1120-1	Tank	1.43	0.02	0.90	25
1120-3	Tank	1.53	0.02	1.00	28
1120-4	Tank	1.17	0.02	0.90	26
0403-2	Tank	0.02	0.06	-	-
1022-1	Well	0.05	0.16	0.30	27
1022-2	Well	0.03	0.20	1.40	26
1029-1	Well	0.04	2.76	2.10	24
1029-2	Well	0.02	0.31	0.90	25
1029-3	Well	0.03	0.09	1.10	38
1029-4	Well	0.01	0.21	0.90	35
1029-5	Well	0.01	1.01	2.60	24
1029-6	Well	0.03	0.89	2.60	32
1107-1	Well	0.13	0.63	2.30	29
1107-2	Well	0.09	0.03	1.20	34
1107-3	Well	NA	0.29	1.30	30
1107-4	Well	NA	0.01	1.20	24
1107-5	Well	NA	0.01	0.80	24
1120-2	Well	0.1	0.01	1.10	36

Sample		Cations by IC				Hardness	Anions by IC				Anions by Titration	
Code	Type	Ca2+	K+	Mg2+	Na+	Ca^{2+} & Mg^{2+}	Cl-	F-	NO3-	SO42-	ALK	ALK
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L as CaCO3)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L as $CaCO_3$)	(mg/L as HCO_3^-)
1017-1	Tank	35	7	10	127	127	198	0.477	5.25	37	117	147
1017-2	Tank	37	8	10	115	135	176	0.569	5.62	38	118	149
1017-3	Tank	43	8	12	114	154	180	0.567	6.13	44	114	144
1022-3	Tank	38	7	11	127	139	203	0.492	4.97	39	127	160
1120-1	Tank	37	8	12	167	140	266	0.492	4.27	53	79	100
1120-3	Tank	32	8	10	120	119	177	0.634	5.67	44	93	117
1120-4	Tank	31	7	10	120	119	177	0.582	5.62	45	92	116
0403-2	Tank	42	7	11	113	149	179	0.563	6.89	38		0
1022-1	Well	44	7	17	357	180	281	1.076	7.26	402	148	186
1022-2	Well	74	8	24	473	285	351	0.856	6.52	667	132	166
1029-1	Well	74	7	33	244	321	157	0.479	0.80	458	336	423
1029-2	Well	120	8	47	119	493	171	0.137	0.61	417	244	307
1029-3	Well	54	31	20	191	218	228	1.77	0.65	208	236	297
1029-4	Well	161	8	75	376	710	490	0.172	1.25	656	289	364
1029-5	Well	78	13	60	388	441	269	0.617	1.29	637	368	464
1029-6	Well	168	10	60	293	669	338	0.269	1.35	674	486	612
1107-1	Well	82	7	28	205	319	169	0.434	0.70	374	316	398
1107-2	Well	27	28	2	567	74	267	0.318	1.22	456	393	495
1107-3	Well	160	13	61	183	651	315	0.176	1.19	495	309	389
1107-4	Well	56	4	14	61	197	71	0.287	1.19	154	162	204
1107-5	Well	72	4	15	55	240	64	0.288	0.30	137	164	207
1120-2	Well	41	7	17	388	174	299	1.273	8.68	449	118	149

Sample		Metals by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES)						
Code	Type	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	As (µg/L)	Fe (µg/L)	Mn (µg/L)
1017-1	Tank	31.81	7.443	9.129	129.7	<MDL	<MDL	<MDL
1017-2	Tank	33.9	7.84	9.521	106.4	<MDL	<MDL	1.22
1017-3	Tank	42.35	9.336	11.64	112.9	<MDL	<MDL	1.864
1022-3	Tank	35.09	8.037	10.1	129.6	<MDL	<MDL	0.84
1120-1	Tank	40.59	10.19	11.63	173.6	<MDL	<MDL	<MDL
1120-3	Tank	35.42	9.132	10.16	121.2	<MDL	<MDL	1.303
1120-4	Tank	36.1	8.615	10.55	117.9	<MDL	<MDL	<MDL
1022-1	Well	39.97	8.858	15.23	>MDL	<MDL	<MDL	1.256
1022-2	Well	66.89	10.51	24.87	>MDL	<MDL	<MDL	10.78
1029-1	Well	149.1	8.42	34.5	239.4	<MDL	<MDL	123.4
1029-2	Well	238.7	8.722	53.44	118.8	<MDL	<MDL	0.849
1029-3	Well	89.74	32.2	21.27	189.4	<MDL	<MDL	5.036
1029-4	Well	277	10.57	117.6	>MDL	<MDL	<MDL	0.881
1029-5	Well	175.6	16.88	78.26	>MDL	<MDL	<MDL	241.5
1029-6	Well	243.3	12.99	76.6	>MDL	<MDL	19.27	2.794
1107-1	Well	109.6	8.687	30.4	213.1	<MDL	<MDL	4.29
1107-2	Well	8.487	34.51	1.593	>MDL	<MDL	<MDL	34.26
1107-3	Well	318.7	15.37	103.9	163.3	<MDL	<MDL	115.9
1107-4	Well	92.78	4.499	16.12	56.16	<MDL	<MDL	0.838
1107-5	Well	90.12	4.251	15.92	53.37	<MDL	<MDL	1.061
1120-2	Well	43.53	9.647	17.56	>MDL	2.35	<MDL	1.469

Appendix B: Educational materials

Taking Care of Your Filters is Simple

A properly maintained filter is extremely important to having a good water quality and spending less money. Just follow these quick tips to help your filters last longer.

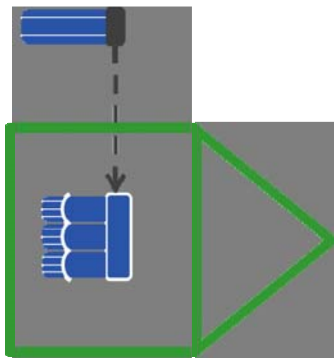
Quick Tips:

-Keep all filters protected from direct sunlight

-If you expect a freeze, don't forget to open and empty your point of entry filter

-Check the filter outside of your house once a month.

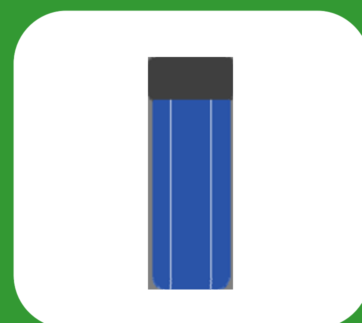
-Check the water pressure in your kitchen faucet each month. If the water pressure seems low, it might be time to change the filters inside of your house.



POU Water Treatment

Water Treatment

Filter Maintenance



Study by:

University of Texas at El Paso

New Mexico State University

Water Quality Lab: 915-747-6926

Point of Entry (Whole House)

-The outside filter will remove particles to all of the water entering your house. However, you should **ONLY** drink the water from your kitchen faucet.

-Depending on your system, you might have one or two whole house filters. If you get water from a well, you'll have a "greensand" filter that will remove the excess iron and manganese.

-Check your filter every month. If the color of your filter is mostly orange or black, it's time to change it.

-The filters that are installed are some of the most reliable and inexpensive in the market, but they are not sold locally. You can buy these filters online:

wateranywhere.com

Housing: $16

Particle Filter: $6

Greensand Filter: $80

You can find similar particle filters locally also in hardware stores. Here is a list of some of the ones you can buy (next page):

Brand	Store	Housing Model #	Housing Price	Filter Model #	Filter Price
GE	The Home Depot	GXWH04F	$20	FXWSC	$10
GE	The Home Depot	GXWH35F	$54	FXHSC	$17
Whirlpool	Lowe's	WHKF-DWH	$22	WHKF-WHSW	$8
Whirlpool	Lowe's	WHKF-DWHBB(221159)	$66	WHKF-WHPLBB	$17

Point of Use Filter (Kitchen Faucet)

-The water coming out from the kitchen filter is safe to drink and cook.

Here is where to buy the kitchen filters:

Home Depot

Replacement Filters

GE reverse osmosis filter (Part # 184534) for $50

GE carbon and particle filters (Part # 456451) for $45

Complete Unit

GE Reverse Osmosis Filtration System (Part # GXRM10RBL) for $175

Lowe's

Replacement Filters

Whirlpool reverse osmosis filter (Part # 129801) for $50

Particle and carbon filters (Part #129793) for $45

Complete Unit

Whirlpool Reverse Osmosis Filtration System (Part # 129808) for $150

Taking Care of Your Filters is Simple

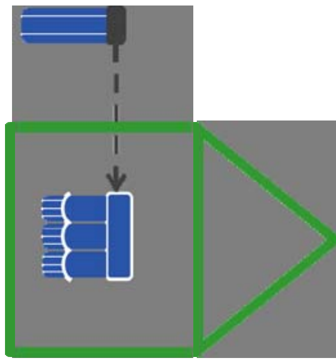
Un buen mantenimiento a su filtro es indispensable para tener una buena calidad de agua y ahorrar dinero. Solo sigue los siguientes pasos para hacer que su filtro dure mas tiempo sin tener que remplazarlo.

-Mantenga todos los filtros protegidos del sol

-Si espera que se congele en la noche, abra sus filtros y vacíelos de toda el agua que tengan

-Revise el filtro que esta afuera de su casa una vez al mes

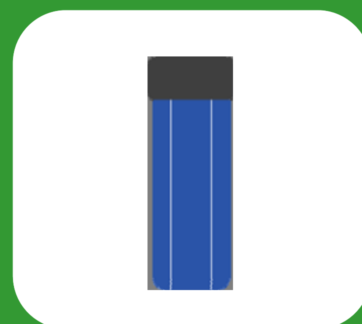
-Revise la presión del agua en el sink de la cocina una vez al mes. Si la presión esta baja, quizá sea tiempo de remplazar sus filtros.



Tratamiento de Agua PDE (POU)

Tratamiento de Aguas

Mantenimiento de Filtro



Estudio Organizado por:

Universidad de Texas en El Paso

Universidad Estatal de Nuevo Mexico

Laboratorio de Calidad de Agua : 915-747-6926

Punto de Entrada (Todo el Hogar)

-El filtro de afuera remueve partículas de toda el agua que entra a la casa, pero recuerde **SOLO** tome agua del sink de la cocina.

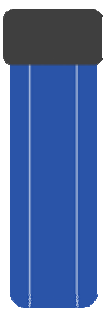
-Dependiendo de su sistema, quizá usted tenga uno o dos filtros. Si usted tiene un filtro de manganeso, este filtro remueve el hierro y el manganeso de su agua.

-Revise el filtro que esta afuera de su casa una vez al mes. Si su filtro esta casi completamente naranja o café, es tiempo de remplazarlo.

-Los filtros que le instalamos son confiables y baratos, pero no se venden localmente. Usted los puede comprar por internet en:

wateranywhere.com

<u>Envase de filtro (housing):</u> $16

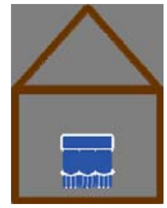


<u>Filtro de Partículas:</u> $6

<u>Filtro de Manganeso:</u> $80

Usted puede encontrar filtros de partículas en las ferreterías locales. En la siguiente pagina esta una lista de estos filtros.

Marca	**Tienda**	**Modelo del Envase #**	**Precio del Envase**	**Modelo del Filtro**	**Precio del Filtro**
GE	The Home Depot	GXWH04F	$20	FXWSC	$10
GE	The Home Depot	GXWH35F	$54	FXHSC	$17
Whirlpool	Lowe's	WHKF-DWH	$22	WHKF-WHSW	$8
Whirlpool	Lowe's	WHKF-DWHBB(221159)	$66	WHKF-WHPLBB	$17



Punto de Entrada (Sink de la Concina)

-El agua del sink de la concina es segura para tomar y cocinar.

Aquí es donde puede comprar filtros nuevos:

Home Depot

<u>Filtros De Remplazo</u>

Filtro de osmosis inversa (numero de Parte 184534) por $50

Filtros de carbón y partículas (numero de parte 456451) por $45

<u>Unidad Completa</u>

Sistema de filtración de osmosis inversa GE (numero de parte GXRM10RBL) por $175

Lowe's

<u>Filtros De Remplazo</u>

Filtro de osmosis inversa (numero de Parte 129801) por $50

Filtros de partículas y carbón (numero de parte 129793) por $45

<u>Unidad Completa</u>

Sistema de filtración de osmosis inversa Whirlpool (numero de parte 129808) por $150

You can Improve Your Water Quality

Improving your water quality is simple! By keeping your water tank clean and replacing your filters at the right time, you can enjoy a healthier glass of water every day.

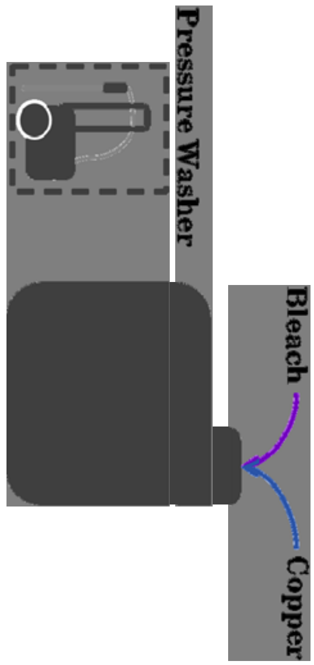
Quick Tips:

-Clean you tank after every summer, preferably during the winter.

-If your tank is opaque or has been painted, check for algae at least once a month.

-Measure chlorine levels at least once a week

-Add chlorine if you measure 0.5 mg/L or less.



Water Treatment

Water Treatment

Cleaning and Chemicals

Study by:

University of Texas at El Paso

New Mexico State University

Water Quality Lab: 915-747-6926

Cleaning the Tank

Pressure Washer
-The hardest part of cleaning a water storage tank is climbing inside to clean it. A pressure washer allows you to clean the tank without having to climb in the tank.
Note: Always remember to wash you tank with clean water.

-Pressure washers are expensive to purchase, but you can rent them at your local Home Depot:

The Home Depot
12221 Montwood Drive (only location with rentals)
El Paso, TX 79936
(915) 856-3082

Deposit:	$15
4 hour rental:	$52
24 hour rental:	$72

Test Strips and Bleach

Test Strips
-Bleach or chlorine keeps your water free of bacteria and viruses. Use chlorine test strips to know when to add bleach. Chlorine test strips can be purchased from the following vendors:

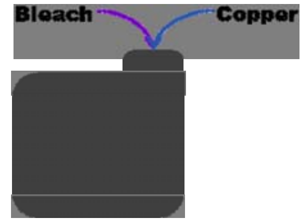
Chlorine Test Strips

Brand	Price	Local Store
Chlorine Pro	$15	Lowe's
Aqua Chek	$8	Lowe's
Leslie's	$12	Leslie's Pool Supply

Bleach
-To use the chlorine test strips, simply fill a cup with water from the bathroom sink (any sink that does not have a filter under it would work) and introduce the test strip. The test strip will change color depending on the chlorine concentration. Follow the instructions on the bottle to determine the concentration.
-If you measure **0.5 mg/L of free chlorine** or less then add bleach in the following amounts:

Bleach Dose

Water in Tank (gal)	Amount to be Added (mL)	Which is About…
500	38	3 tablespoons
1500	114	1/2 of a cup (4 oz)
2500	189	3/4 cup (6 oz)



Copper

-Drinking water tanks sold today should be black to prevent algae from growing. However if your tank was painted or is opaque, you might consider adding copper.

-If you see algae (black-greenish stuff on the walls), clean the tank and add copper to a newly filled tank.

Here is how to get the copper:

EarthTec
www.cleanwaterfortheplanet.com
Or www.suntropic.com
Price: $40
Add: 33 mL or about 2 tablespoons

Usted Puede Mejorar la Calidad de su Agua

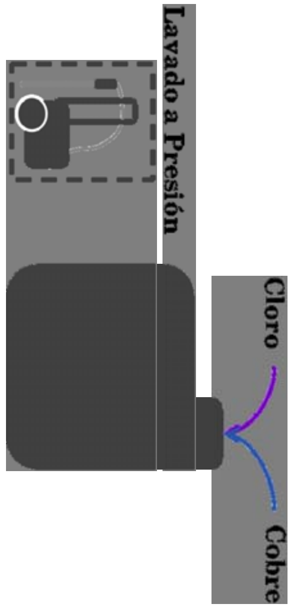
Mejorar la calidad de su agua es simple! Manteniendo su tanque limpio y remplazando sus filtros al tiempo correcto, usted puede disfrutar vaso de agua mas saludable todos los días.

-Limpie su tanque después de cada verano, de preferencia en el invierno

-Si su tanque no es de plástico negro, revise su tanque una vez al mes para asegurarse que no haiga algas.

-Mide el nivel de cloro una vez a la semana

-Añada cloro si la concentración es 0.5 mg/L o menos.



Tratamiento de Agua PDE (POU)

Tratamiento de Agua

Limpieza del Tanque y Químicos

Estudio Organizado por:
Universidad de Texas en El Paso (UTEP)
Universidad Estatal de Nuevo Mexico (NMSU)

Laboratorio de Calidad de Agua : 915-747-6926

Limpieza del tanque

Lavador a presión

-La parte mas difícil de limpiar su tanque de agua es entrar dentro del tanque. Un lavador a presión le ayudara a poder limpiar el tanque desde afuera.

Recuerde: Siempre limpie su tanque con agua limpia.

-Los lavadores a presión son caros, pero usted lo puede rentar en Home Depot:

The Home Depot
12221 Montwood Drive (only location with rentals)
El Paso, TX 79936
(915) 856-3082

<u>Deposito:</u> $15
<u>Renta por 4 horas:</u> $52
<u>Renta por 24 horas:</u> $72

Prueba de Cloro y Cloro

Prueba de Cloro

-El cloro mantiene su agua libre de bacterias y virus. Use su prueba de cloro para saber cuando añadir cloro. Las pruebas de cloro se pueden conseguir en las siguientes tiendas:

Pruebas de Cloro

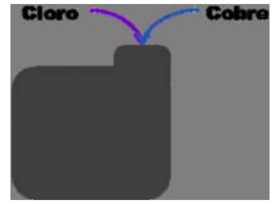
Marca	Precio	Tienda Local
Chlorine Pro	$15	Lowe's
Aqua Chek	$8	Lowe's
Leslie's Pool	$12	Leslie's Pool Supply

Cloro

-Para usar su prueba de cloro, simplemente llene un vaso con agua del sink del baño, o cualquier otro sink que no tenga filtros de carbón, y introduzca la prueba (una tira) en el vaso con agua. La prueba de agua cambiara de color si el agua tiene cloro. Siga las instrucciones en el envase para determinar la concentración.
-Si mide 0.5 mg/L de cloro libre (free chlorine) o menos entonces usted necesita añadir cloro según la siguiente tabla:

Bleach Dose

Agua en el Tanque (gal)	Cantidad a Añadir (mL)	Que es mas o menos…
500	38	3 tablespoons
1500	114	1/2 of a cup (4 oz)
2500	189	3/4 cup (6 oz)



Cobre

-Los tanques para agua potable en venta el día de hoy deben de ser negros para prevenir que algas crezcan dentro del tanque. Sin embargo, si el plástico de su tanque no es negro, quizá tenga que añadir cobre.

-Si ve algas (cosas negras o verdes en las paredes del tanque), limpie el tanque y añada cobre.

Consiga el cobre en:

EarthTec
www.cleanwaterfortheplanet.com
O www.suntropic.com
Precio: $40
Añada: 33 mL o <u>2 tablespoons</u>

Appendix C: Chlorine test strips

Manufacturer	Brand	Product Number	Vendor	Price	Price Per Strip	Availability
BioGuard	BioGuard	N/A	Able Pool and Spa	$10.99 for Complete Test Kit	Complete Test Kit	All Year
AquaChek	AquaChek	18709	Leslie's Swimming Pool Supplies	$11.49 for 50 Test Strips	$0.23	All Year
N/A	Leslie's	18721	Leslie's Swimming Pool Supplies	$12.49 for 50 Test Strips	$0.25	All Year
N/A	Taylor Technologies	18571	Leslie's Swimming Pool Supplies	$13.79 for Basic Test Kit	Basic Test Kit	All Year
Aqua EZ	Chlorine Pro	178148	Lowe's	$14.95 for 100 Test Strips	$0.15	All Year
Kem-Tek	Kem-Tek	450720	Lowe's	$14.98 for 25 Test Strips	$0.60	All Year
Aqua Chem	Aqua Chem	450726	Lowe's	$14.98 for 25 Test Strips	$0.60	All Year
Aqua EZ	Aqua Chek	2429	Lowe's	$8.48 for 50 Test Strips	$0.17	All Year
HTH	HTH	30507	The Home Depot	$15.98 for 50 Test Strips	$0.32	All Year
AquaChek	Aqua Chek Free Chlorine Pool and Spa Test Strip	WPZ1001	Walmart	$21.51 for 50 Test Strips per Bottle ($4.99 shipping) [Set of 2]	$0.27 (w/ shipping) $0.22	Spring & Summer
AquaChek	TruTest Strips	NP208	Walmart	$9.79 for 50 Test Strips	$0.30 (w/ shipping) $0.20	Spring & Summer
Poolmaster	Smart Test	PHM1017	Walmart	$18.50 for 50 Test Strips	$0.47 (w/ shipping) $0.37	Spring & Summer
Jed Pool Tools Inc	Jed Pool Tools	00-490	Walmart	$11.55 for 50 Test Strips	$0.33 (w/ shipping) $0.23	Spring & Summer
Poolmaster	Smart Test	PHM1138	Walmart	$14.10 for 50 Test Strips	$0.38 (w/ shipping) $0.28	Spring & Summer
HTH	HTH	30507	Walmart	$13.97 for 50 Test Strips	$0.28	Spring & Summer

Manufacturer	Brand	Product Number	Vendor	Price	Price Per Strip	Availability
HTH	Salt Pool Care	4084	Walmart	$18.47 for 50 Test Strips	$0.37	Spring & Summer
AquaChek	AquaChek Yellow	TB1003	SpaDepot	$6.95 for 50 Test Strips	$0.14	N/A
WaterWorks 5	WaterWorks 5	WU-99531-20	Cole-Parmer	$21.20 for 30 Test Strips	$0.71	N/A
WaterWorks 5	WaterWorks 5	WU-99531-15	Cole-Parmer	$29.95 for 30 Test Strips	$1.00	N/A
Insta-Test	LaMotte	UX-99532-66	Cole-Parmer	$7.75 for 50 Test Strips ($11.54 Shipping)	$0.39 (w/ Shipping) $0.16	N/A
Insta-Test	LaMotte	4EVZ5	Grainger	$8.95 for 25 Test Strips	$0.36	N/A
Insta-Test	LaMotte	4EVX4	Grainger	$27.15 for 25 Test Strips	$0.54	N/A
Industrial Test Systems	SenSafe	3VEV1	Grainger	$22.38 for 50 Test Strips	$0.45	N/A
Industrial Test Systems	WaterWorks	480024	Amazon	$11.50 for 50 Test Strips	$0.23	N/A
Industrial Test Systems	SenSafe	481026	Amazon	$19.98 for 50 Test Strips	$0.40	N/A
AquaChek	AquaChek Yellow	N/A	Amazon	$8.07 for 50 Test Strips	$0.16	N/A
Insta-Test	LaMotte	3031	Amazon	$17.10 for 50 Test Strips	$0.34	N/A
Industrial Test Systems	Industrial Test Systems	N/A	Amazon	$12.99 for 50 Test Strips	$0.26	N/A
Omega	Omega	HHWT-486637	Omega Engineering	$13.00 for 100 Test Strips ($10.00 Shipping)	$0.23 (w/ Shipping) $0.13	N/A

Vita

Isaac Campos Flores earned his Bachelor of Science in Civil Engineering from The University of Texas at El Paso in 2011. In 2012, he joined the doctoral program in Civil Engineering at The University of Texas at El Paso.

While pursuing his degree, Dr. Campos Flores worked as a research assistant for the Department of Civil Engineering. During his final semester he also worked as a full time Water Resources Specialist at ARCADIS-US.

Dr. Campos Flores is the author of a chapter in the book Handbook of Arsenic Toxicology and has also presented his research at national and international conferences including the 2014 American Water Works Association (AWWA) Annual Conference and Exposition.

Dr. Campos Flores's dissertation entitled, "A Holistic and Sustainable Water Treatment System for Colonias in the Southwest United States" was supervised by Dr. W. Shane Walker.

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This thesis/dissertation was typed by Isaac Campos Flores.