May 2014

Lead (Pb) Contamination of Water Drawn from Pitcher Pumps in Eastern Madagascar

David Bradlee Akers
University of South Florida, d.bradakers@gmail.com

Scholar Commons Citation

Akers, David Bradlee, "Lead (Pb) Contamination of Water Drawn from Pitcher Pumps in Eastern Madagascar" (2014). *Graduate Theses and Dissertations.*
http://scholarcommons.usf.edu/etd/4975

Lead (Pb) Contamination of Water
Drawn from Pitcher Pumps in Eastern Madagascar

by

D. Brad Akers

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: Jeffrey A. Cunningham, Ph.D.
James R. Mihelcic, Ph.D.
Raymond D. Harbison, Ph.D.

Date of Approval:
March 25, 2014

Keywords: Heavy Metal Leaching, Developing World, Self-Supply Water,
Anodic Stripping Voltammetry (ASV), Sub-Saharan Africa

DEDICATION

I want to dedicate this thesis to Tricia Wilbur. Tricia, without you, I couldn’t have done any of this. In no way can I overstate your influence in not only keeping me sane, but encouraging me to be at my best under (sometimes) the most non-ideal circumstances. We were over 9,000 miles apart during our Peace Corps services, but somehow we managed to communicate and stay together. Our time apart was important, and I am happy to be able to share in two unique cultures as a result. Now I am ready to wrap this up, and I cannot wait to move on from this and start the rest of my life with you.

Beyond this, I dedicate this work to my family and friends who supported the decision to not only spend time in graduate school pursuing a degree and refining skills, but time abroad in the Peace Corps, pursuing a direction for my life, a way to better myself, and a service outlet for my professional skills. Thank you for being supportive in ways you cannot fully understand.

ACKNOWLEDGMENTS

I want to first thank my thesis advisory committee: Dr. Jeffrey A. Cunningham, my major professor, for his help in completing work that I am proud of; Dr. James R. Mihelcic, director of the USF Peace Corps Master's International (MI) program, for training and this wonderful opportunity; and Dr. Raymond D. Harbison for his perspective in developing my thesis.

Thanks to those who provided mentoring and technical support: Ghislain Ravelonjatovo, my program's Associate Peace Corps Director; Jonathan Annis, professional colleague in Madagascar and former MI; USF PhD candidate Michael F. MacCarthy; MI student Meghan Wahlstrom-Ramler; Malagasy research assistant Onnie Razafikalo; local pump artisan Fabrice Koesaka; and USF undergraduate Austin Atkins.

I have to send an immeasurable thanks "*ny fisaorana be dia be*" to the countless Malagasy who welcomed me into their country, communities and households. I am changed for the better because of my time spent in your country and am very lucky to have worked with you.

This study was conducted as part of a partnership between the University of South Florida (Tampa) (USF) and RANO HamPivoatra (Water for Progress), a USAID-funded project in Madagascar implemented by a consortium led by the NGOs CRS and CARE.

This material is based upon work supported by the National Science Foundation under Grant Nos. DUE 0965743 and DUE 1200682. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Access to safe water supply—a major determinant of public health—is less than 50% in Madagascar, and access to piped, treated water remains out of reach financially for many in the urban and peri-urban areas where available. The Self-supply option of the Pitcher Pump has been meeting the need for household water in coastal areas of Madagascar since the early 1960s and has proven a sustainable option for many. These pumps make use of leaded components in the construction, however, which may pose a health risk for heavy metal intoxication and therefore cause the water to be unsafe for drinking and cooking. This study assesses the potential for lead (Pb) leaching from Pitcher Pump systems into water at levels of health concern. The objectives of this study are to assess Pb concentrations in water drawn from Pitcher Pumps, to determine the relationship between various factors and the Pb levels, to make a preliminary assessment of public health implications of Pb contamination, and to offer informed recommendations to reduce the likelihood of consuming contaminated water.

A field study was undertaken to measure concentrations of dissolved Pb in water from Pitcher Pumps under recently flushed and first-draw pumping conditions at 18 households in the city of Tamatave, Madagascar. Variables potentially affecting Pb leaching were determined including pump age, depth to the well screen, pump manufacturer, season of sample collection, and basic water quality indicators. Sampling campaigns were conducted three times over the course of eight months. Time-release case studies were also carried out at two households to determine the time scale over which the Pb concentration in stationary water reaches equilibrium with the Pb-containing system components. Pilot studies of iron (Fe)-for-Pb substitution of select pump system components were carried out at the same two households to attribute the major contribution of Pb leaching to one set of parts and to assess one strategy for decreasing dissolved Pb concentrations. Finally, the Internal Exposure Uptake Biokinetic Model for Lead in Children (IEUBK Model) of the US Environmental Protection Agency (EPA) was employed to estimate realistic blood lead levels (BLLs) in children under five years of age, based on Pb concentrations measured in the water.

Of the 18 pumps sampled, 15 produced at least one sample exceeding the World Health Organization (WHO) provisional guideline of 10 μg/L dissolved Pb in water. Specifically, 67% of all samples showed concentrations above 10 μg/L under first-draw pumping conditions. Flushing the pumps prior to use decreased the Pb levels significantly ($p < 0.0001$), with only 35% of samples exceeding the provisional guideline. Under flushed conditions, the median Pb concentration in pumped water was 9 μg/L, down from 13 μg/L at one hour of inactivity. No statistically significant correlations were observed between measured Pb concentrations and factors like the season of sample collection, pump age, manufacturer, or water quality indicators like pH or temperature. Under first-draw conditions, the concentration of Pb in water increased with increasing duration of pump inactivity, until equilibrium was reached with the leaded pump components. For two pumps, substitution of Fe valves for Pb greatly decreased Pb concentrations in the water, from 37–100 μg/L and 7–24 μg/L down to 3–4 μg/L and 2–8 μg/L, respectively. Model-predicted geometric mean BLLs in children range from about 2–8 μg/dL, in some instances exceeding the Centers for Disease Control and Prevention (CDC) guideline for an elevated BLL (5 μg/dL), depending on the exposure concentrations.

This study finds that water provided by Pitcher Pump systems in Madagascar frequently exceeds the WHO provisional guideline value for safe consumption under first-draw conditions, and may do so even after flushing the pumps. The Pb concentrations measured in the field have the potential to elevate BLLs in children under five to levels implicated in serious health issues. Leaching of Pb into the water is therefore an issue of concern for users of the Pitcher Pump systems in Tamatave, and likely for other areas served by this technology. Flushing the pumps before water collection generally reduces Pb levels in the water. These results suggest that most of the Pb leaches from pure Pb check valve weights at the mouth of the pump, and consequently, a substitution of Fe weights on the valves greatly reduces Pb concentrations and the probability for exceeding the WHO provisional guideline. Relatively simple operational changes on the part of the pump manufacturers and the pump users might, therefore, help to ensure the continued sustainability of Pitcher Pumps in eastern Madagascar.

CHAPTER 1: INTRODUCTION

The United Nations (UN) introduced the Millennium Development Goals (MDGs) to address all of the recognized issues in quality of life for the World's nations. MDG number 7, target c is "to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation" from 1990 by 2015 (UN, 2008). In 2010, The UN General Assembly reinforced the importance that safe water and sanitation have in human development by declaring both to be "a human right that is essential for the full enjoyment of life and all [other] human rights" (UN, 2010; UN et al., 2010). Despite these declarations, as of 2012 an estimated 783 million people still lack access to an improved water source, threatening public health in countries around the world (WHO and UNICEF, 2012). In Madagascar, access to improved water is at 46% as of 2010, and is predicted to fall well short of the country's MDG of 64.5% (WHO and UNICEF, 2012). Piped, treated water to public stands and private residences exists in some more urban and peri-urban areas, but is prohibitively expensive for many citizens. Furthermore, the utilities' capacity to increase the number of public and private connections is limited and water supply is sometimes inconsistent. Therefore, many people in Madagascar make use of decentralized, household-level water supply, i.e., Self-supply.

Digging wells or driving wells for hand pumps is very feasible in coastal Madagascar due to a combination of the high water tables and sandy soils (MacCarthy et al., 2013; WaterAid, 2013). Many households in coastal areas of Madagascar, particularly in the Eastern region of Toamasina (Tamatave), have installed a locally produced hand pump on the premises for some or all of their water needs. In particular, the local population has adopted the simple, inexpensive technology of the Pitcher Pump, locally named the *Pompe Tany* (the French word for pump and the Malagasy word for ground). This technology was introduced to Madagascar in the early 1960s, and has spread from the Tamatave region to other primarily coastal areas (MacCarthy et al., 2013). Pump manufacturers receive training locally, either from senior manufacturers or technical schools, and they make use of locally available materials for construction and maintenance. Approximately 170,000 people within 28,000 households currently use the *Pompe Tany* in Tamatave (MacCarthy et al., 2013).

However, the *Pompe Tany* system poses a potential for chemical contamination from its components. The Pitcher Pump system consists of a suction pump with two check valves, which work to lift water from a shallow well attached to the pump (see Figure 1). Some of the components of *Pompe Tany* systems contain lead (Pb), and therefore present the risk of leaching into pumped water. In particular, local artisans in Tamatave typically fabricate check valves using leather flaps and Pb weights, formed using lead extracted from old batteries. Additionally, well screens are often made of brass, which may contain Pb, and screens are joined to the well pipe using lead-tin (Pb-Sn) solder. As water comes into contact with these components, Pb may contaminate the supply via "electrochemical, geochemical, and hydraulic [physical] mechanisms" (Triantafyllidou and Edwards, 2012). Water contaminated with either soluble or particulate Pb becomes a contributing exposure route of this toxin to consumers. The negative health effects of Pb exposure are far-reaching and difficult to quantify, and threaten long-term health even at very low concentrations and exposure levels (Rossi, 2008; Triantafyllidou and Edwards, 2012). In water, there is no lower guideline or limit for the safe consumption of Pb (WHO, 2011a).

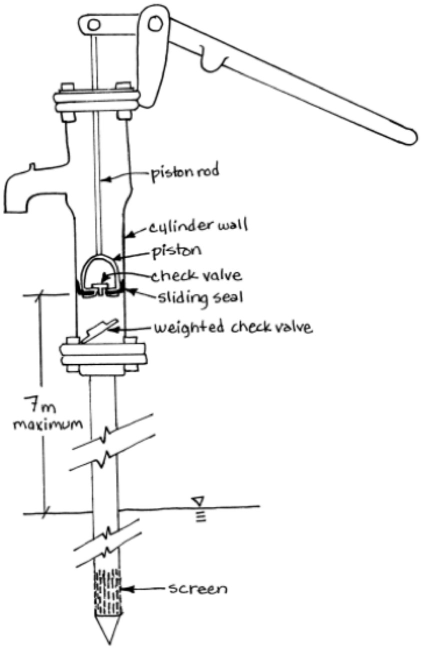


Figure 1. Diagram of a typical suction pump and components (reproduced from Mihelcic et al., 2009 with permission from Linda Phillips [Appendix I]).

To the best of my knowledge, there has only been one published study of Pb concentrations in household water accessed by Pitcher Pumps in eastern Madagascar (from our research group), and this study, completed in one sampling campaign, showed four of 10 pumps to be above the WHO provisional guideline of 10 µg/L (MacCarthy et al., 2013). Therefore, it is not yet known if Pb contamination from pump components represents a significant threat to public health. However, based on the number of people who rely on Pitcher Pump systems as their primary water source, there is potential for a significant public health crisis if Pb concentrations prove to be dangerously high. This risk justifies further assessment of the magnitude of this threat. Furthermore, if measurements reveal that pumped water contains unacceptable concentrations of Pb, it would be beneficial to determine if Pb concentrations can be reduced through relatively simple changes in operation (e.g., flushing the well before drawing water) or infrastructure (e.g., replacing lead weights in check valves with an alternative metal such as iron).

Therefore, the objectives of this thesis research are:

(1) to conduct a preliminary survey of Pb concentrations in water drawn from Pitcher Pumps at several households in Tamatave, Madagascar;

(2) to determine if Pb concentrations in pumped water decrease after flushing the pumps;

(3) to perform a preliminary analysis of the correlation between Pb concentrations and pump characteristics such as age, depth to water table, manufacturer, season and/or water quality;

(4) to assess whether replacing Pb in check valves with iron decreases Pb concentrations;

(5) to make a preliminary assessment of the public health implications of Pb exposure from Pitcher Pump systems; and,

(6) to make culturally, economically, and socially appropriate recommendations for dealing with possible Pb contamination of the water.

Taken together, these six objectives will help form an understanding of the public health risk posed by using Pb components to manufacture Pitcher Pump systems in Tamatave and will investigate the effectiveness of minor modifications to current practice directed at reducing this risk. Ultimately, this research aims to protect the health of thousands of households in Madagascar who rely on Pitcher Pump systems for a sustainable supply of domestic water.

CHAPTER 2: LITERATURE REVIEW AND MOTIVATION

2.1 Water and the Developing World

Water and health are intrinsically linked. Simply put, water is life, and beyond the necessity of approximately 2.5–5 liters per person per day for direct consumption, and a higher 7.5 liters per day for a breastfeeding mother, this natural resource is needed for personal and house hygiene, food preparation, and clothes washing, and an optimal amount of 50–100 liters per person per day should be provided to the public (Gleick, 1996; Howard and Bartram, 2003). The provision of some ideal quantity of water is not enough to ensure a healthy life, however, as the water may be unsafe for consumption and hygienic purposes. Unsafe water is involved in many life-threatening or debilitating illnesses: diarrheal diseases like cholera and giardiasis can be transmitted through the consumption of water contaminated with pathogens, while some parasites like schistosomiasis (Bilharzia) are spread through skin contact with water, and water may act indirectly as a breeding ground for mosquitoes, which transmit infectious diseases such as malaria or lymphatic filariasis (Prüss-Üstün et al., 2008). The effects of these water-, sanitation- and hygiene-related (WASH-related) illnesses can range from dehydration and malnutrition to severe disability and loss of life (Prüss-Üstün et al., 2008).

The Disability-Adjusted Life Year (DALY) is a metric for the global disease burden (WHO, 2013a). WASH-related diseases are responsible for 10% of all of the world's DALYs, or disease burden (Prüss-Üstün et al., 2008). Another powerful indicator of public health for a country is the number of deaths of children under the age of five. Infectious diseases accounted for 68% of the under-five child mortality worldwide in 2008, with approximately 15% of the total mortality owed to diarrheal disease (Black et al., 2010). These numbers become more extreme in developing regions: for the sub-Saharan African region, malaria (a water-related disease) and diarrhea combined to give about 20% of DALYs in 2010, and 19% of the under-five mortality was due to diarrheal disease in 2008 (Black et al., 2010; IHME, 2013). Most of the WASH-related diseases are transmitted through the fecal-oral route, and are considered easily preventable through access to safe water and basic sanitation, combined with proper hygiene practices (Mihelcic et al., 2009).

These facts have led to a focus in international development and aid on WASH. The Millennium Development Goals (MDGs) were introduced to address all of the recognized issues in quality of life for the World's nations, and MDG number 7, target c of this initiative is "to halve…the proportion of people without sustainable access to safe drinking water and basic sanitation" from 1990 by 2015 (UN, 2008). The UN General Assembly recently declared access to safe and clean drinking water and basic sanitation "a human right that is essential for the full enjoyment of life and all [other] human rights" (UN, 2010; UN et al., 2010). As a result, this development goal officially enters into public policy initiatives in the Word's nations, and becomes a social responsibility for developing and developed countries.

2.2 Madagascar and Self-Supply Water

Madagascar is a sub-Saharan African country, the 4th largest island in the world with an estimated population of 22.6 million as of July 2013 (CIA, 2013). In 2012, Madagascar was 151 of 186 countries ranked (the lowest 20%) for the Human Development Index (HDI)—which provides a measure of human development based on life expectancy, education and income—in the United Nations Development Programme's (UNDP) Human Development Report (UNDP, 2013). Madagascar was, until very recently, considered politically unstable following a coup in 2009, which left the country without an officially recognized democratic government for nearly five years, though elections have finally proceeded in December 2013 (UNRIC, 2012; Iloniaina and Lough, 2014). The political situation has undermined previous progress made in development and exacerbated extremes in poverty and inequality (World Bank, 2013a). This is the current status for a country that was already one of the poorest in the world, and which has shown negative economic growth in terms of real gross domestic product (GDP) in each of the decades following independence from France in 1960 (World Bank, 2013b). The country's main health issues are suspected pneumonia (respiratory infections) and diarrheal disease, the latter contributing to 33% of the under-five mortality in 2008 (Black et al., 2010).

This health information brings MDG 7 to the forefront of development issues in the country. Access to safe water and improved sanitation were recorded at 46% and 15%, respectively as of 2010 (WHO and UNICEF, 2012). Both indicators will fall short of the respective MDG targets in 2015. Interestingly, the world as a whole met its goal for safe water access in 2010 (WHO and UNICEF, 2012), yet disparities in coverage between urban and rural populations exist throughout world, leaving over 780 million still without this access (WHO and UNICEF, 2012). For example, 74% of urban and only 34% of rural Malagasy (the people of Madagascar) had access to improved water in 2010 (WHO and UNICEF, 2012). This situation is largely attributable to the existence of piped networks operated and managed by a parastatal utility. Where available, securing permanent access to water from these systems remains out of reach for many families because of a combination of high tariffs and underinvestment to increase the number of private and public connections serving the marginalized neighborhoods (ADF, 2005; WaterAid, 2005; USAID, 2010; Annis and Razafinjato, 2012).

Madagascar's utility is called *Jiro sy Rano Malagasy* (or JIRAMA), meaning "Malagasy electricity and water." In Tamatave, the utility-owned source of piped, treated water is over 1,000 times cheaper than the local bottled water in Madagascar, and is relatively affordable when compared to US utility rates: tariffs are about 1,000 Ariary/m^3 (US\$0.45/m^3) for a private connection to a residence, a fraction of the US\$1.29/m^3 for water in the US (GWI, 2013; JIRAMA, 2013). Yet in a country where over 92% of the population lives on less than US\$2 per day, this regulated water source remains financially out of reach for many (World Bank, 2013a). High capital costs—up to 602,273 Ariary (US\$273) for a private connection in Tamatave to the dwelling or plot capable of serving up to 10 people—keep many from investing in those household or shared connections (Ranaritsara, personal communication, 2013). At public taps, the cost of water increases, at about 50 Ariary per 20-liter Jerry can, 2500 Ariary/m^3 (US\$1.14/m^3) and even higher if purchased by the 10-liter bucket (30 Ariary per 10 liters = US\$1.36/m^3), actually above the average US utility rate (GWI, 2013; JIRAMA, 2013; Ranaritsara, personal communication, 2013). Furthermore, JIRAMA lacks the capability to sustainably increase water supply capacity to meet the great demand in sprawling Tamatave with consistent service (ADF, 2005; WaterAid, 2005; USAID, 2010).

Table 1 lists improved and unimproved water sources as defined by the World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Program (JMP) for monitoring progress on the world's access to improved water and sanitation. A variety of sources are considered improved, and the particular availability and cost of a source in an area will largely determine the type of source utilized by people. Those without physical or financial access to piped water must therefore search for more decentralized, affordable "improved" sources of water or else be relegated to one of the "unimproved" sources.

Table 1. Water Supply Sources as Defined by WHO and UNICEF (2012).

"Improved" sources of drinking water	"Unimproved" sources of drinking water
• Piped water into dwelling • Piped water into yard/plot • Public tap or standpipe • Tubewell or borehole • Protected dug well • Protected spring • Rainwater	• Unprotected spring • Unprotected dug well • Cart with small tank/drum • Tanker truck • Surface water • Bottled water

Self-supply is defined as the development of household or small-scale water supply technologies through self-investment with low-cost technologies (Sutton, 2004a; MacCarthy et al., 2013). One type of "Self-supply" option is that of a hand pump. The use of groundwater generally reduces the likelihood of exposure to pathogens due to mechanical and biological attenuation of contaminants, and groundwater represents about 99% of the world's available freshwater resources (Pedley et al., 2006; Delleur, 2007; EPA, 2009a). Consequently, many in developing countries use hand pumps, with 18% of the world's population—over 1 billion people—served by boreholes or tube wells in 2010 (Carter et al., 2010; WHO and UNICEF, 2012; WaterAid, 2013). Many people in coastal areas of Madagascar, particularly in the Eastern region of Toamasina (Tamatave), have invested in a hand pump on the premises for some or all household water needs. Some models of community hand pumps marketed internationally, such as the India Mark III and Vergnet pumps have been successfully installed in southern Madagascar, and the Canzee pump has been introduced in other areas (UNICEF and RWSN, 2004; MacCarthy et al., 2013). However, nongovernmental organizations (NGOs) typically provide the majority of the financial investment for projects related to the construction and installation of these pumps, and proper operation and maintenance training and supply chains for parts have limited the introduction of these technologies (UNICEF and RWSN, 2004; MacCarthy et al., 2013). Accordingly, the local population has adopted the simpler, smaller-scale, lower-cost technology of the Pitcher Pump, locally named the *Pompe Tany*. This technology consists of a suction pump with a manually driven tube well (see Figure 1 in Chapter 1 and Figure 2 in this chapter), which is quite common in coastal Madagascar, partly due to the shallow water tables and sandy soils found there (MacCarthy et al., 2013; WaterAid, 2013).

Generally, community-scale hand pumps have shown issues with sustainability. For example, for the continent of Africa, 30 percent of community pumps were estimated to be non-functional in 2004, and 2009 data confirmed that only 60–65% of hand pumps were functional at the time surveyed (Sutton, 2004b; Carter et al., 2010). Potential reasons for this low functionality include structural issues in the pump or borehole, lack of technical knowledge for normal maintenance, poor supply chain for parts, and depletion or overestimation of the groundwater source (Harvey, 2004; Carter et al., 2010). Essentially, many of the issues for other community-scale water supply are also issues for hand pumps. The *Pompe Tany*, however, generally serves 1–10 households as opposed to entire communities. In contrast to community pumps, this technology was introduced to Madagascar over 50 years ago, and has proven to be a sustainable and growing technology since then, spreading from the city of Tamatave to other primarily coastal areas (MacCarthy et al., 2013). Pump manufacturers are trained locally by current manufacturers and/or technical schools, and they make use of locally available materials for construction and maintenance (see Figures 2–5 in Chapter 2; Appendix II). Complete installation of a Pitcher Pump system is more affordable than a JIRAMA tap stand serving the same number of households (approximately US$35–100 vs. ~$273) and pump repair services are available to customers from manufacturers (Appendix II; MacCarthy et al., 2013; Ranaritsara, personal communication, 2013). Approximately 9,000 Pitcher Pump systems are currently in use with 170,000 people served in the city of Tamatave, and survey responses from local manufacturers indicate that the number is growing at about 200–800 households served per month in Tamatave and surrounding areas (MacCarthy et al., 2013; Appendix II). Significantly, pump owners in the area have indicated that pumps were purchased and installed without subsidies or financial assistance of any kind (MacCarthy et al., 2013).

Figure 2. Typical installation of a *Pompe Tany*: a) percussion augering of soil; b) removed soil; c) percussion drilling of tube well/casing; d) finished pump.

This type of water supply does not necessarily indicate sustainable access to safe water, however. Preliminary research shows that water drawn from Pitcher Pumps in Tamatave, Madagascar may or may not be clean due to the lack of a sanitary seal, the shallow water table, and proximity to pit latrines and septic tanks. These circumstances put the water at risk for contamination through rainwater infiltration and microbial leaching and transport through soil and groundwater. Research has shown that water from Pitcher Pumps generally does not fit within the WHO microbial standard of 0 colony forming units (cfu) per 100 mL, or the less stringent goal of 1–10 cfu/100 mL for “low risk” quality for household systems (WHO, 1997; MacCarthy et al., 2013; Wahlstrom-Ramler, 2014). Water drawn from these pumps therefore needs treatment before consumption via point-of-use treatment methods. Common point-of-use treatment methods in Madagascar include boiling or chlorine disinfection (WHO, 1997). Survey respondents indicated treating pumped water 43% of the time, while 39% of those who reported exclusively using Pitcher Pump systems for drinking water supply believed the water to be clean upon pumping (Appendix III).

Additionally, pathogens are not the only threat to a safe water supply and therefore public health. Safe water, by definition, does not pose a significant health risk to consumers over a lifetime (WHO, 2011a). Safe water is therefore classified as water with “microbial, chemical and physical characteristics that meet WHO guidelines or national guidelines on drinking water quality” (WHO, 2013b). Chemical contamination of water may result from leaching or point-source contamination from natural reserves, and/or from anthropogenic sources such as agricultural activities, industry, human dwellings, and even water treatment methods (WHO, 2011a). These forms of contamination are not typically a focus in developing countries, as the most basic kinds of water-related illnesses—e.g., from pathogenic contamination—pose the most immediate threat to public health and safety. Furthermore, to some degree, water quantity can be more important than water quality for human health because of the lifestyle that greater access to water facilitates. Examples include more water available for consumption and hygienic (e.g., washing) and productive purposes, and increased time for productive activities (i.e., school and work) (Mihelcic et al., 2009). Yet when a health risk becomes apparent, it warrants an investigation into the implications for the affected population. The *Pompe Tany* poses the potential for chemical contamination in the form of Pb leaching from its components, as is described in detail later in this chapter (Section 2.4.2).

2.3 Pb Exposure and Public Health

Incidences of harmful exposure to Pb and Pb poisoning have been recorded for 6,000 years (Lessler, 1988). This toxic heavy metal has even been associated with the Fall of Rome, owing to known exposure routes with heavily concentrated Pb due to its use in wine preparation and food flavoring, in cookware, coinage, and its heavy use in aqueducts (open-flow water systems), and is suspected to have caused a pandemic of Pb poisoning, typically manifesting as a colic with associated symptoms like seizures (Waldron, 1973; Lessler, 1988). Later, Pb poisoning became well documented during the Industrial Age for workers with lead-based paints, ceramics glazes and other products (Hernberg, 2000; Tong et al., 2000). More recently, Pb was used as an additive in gasoline as an anti-knock agent and was thereby greatly distributed in the atmosphere through combustion exhaust from automobiles and in soils via atmospheric deposition (Hernberg, 2000). Pb is currently used in lead-acid batteries and is still used in components of water conduction systems (WHO, 2011a; Triantafyllidou and Edwards, 2012). Thus, exposure to this toxic metal has continued to be problematic over time, and it remains a contemporary public health issue.

The WHO estimates that about 1% of the total global disease burden—about 13 billion DALYs—is related to Pb exposure due to its myriad health effects (Fewtrell et al., 2003). Acute exposures to Pb can cause encephalopathy (swelling of the brain), colic (gastrointestinal disturbance and pain), renal failure and death, though these more extreme exposure scenarios were not included in the calculation of the disease burden above (Fewtrell et al., 2003; ATSDR, 2007). More common is chronic, low-level exposure, either occupationally or environmentally

(Tong et al., 2000; ATSDR, 2007). Pb has no known purpose in the human body, and is detrimental to public health even at low exposures. In children, chronic exposure is known to cause problems such as mild mental retardation and loss of IQ, anemia, and gastrointestinal effects. In adults, Pb exposure can cause increased blood pressure and hypertension, both of which can lead to cardiovascular disease; reproductive issues have also been observed (Fewtrell et al., 2003; White et al., 2007; WHO, 2011b). Renal impairment is possible at higher blood lead levels (BLLs) above 40 µg/dL, and though Pb has not been proven to cause cancer in humans, it is considered by some researchers to be a likely carcinogen (Silberberg et al., 2000; Silberberg, 2003; Needleman, 2004; WHO, 2011b). Current studies link Pb exposure to issues like breast cancer and Alzheimer's disease (Needleman, 2004; ATSDR, 2007; White et al., 2007; Alatise and Schrauzer, 2010; Bakulski et al., 2012; Liu et al., 2013).

Young children comprise the most vulnerable group to detrimental effects from Pb exposure due to greater susceptibility and a longer lifetime of exposure (ATSDR, 2007; WHO, 2011a). Impacts to the central nervous system, generally resulting in cognitive effects in children, have been investigated most comprehensively in academia and public health, and an extensive literature database exists, which demonstrates general cognitive effects including loss in IQ, incidence of mild mental retardation, various behavioral issues and other cognitive deficits like impaired motor skills (Fewtrell et al., 2003; ATSDR, 2007). However, a wider range of effects has also been seen in children. Increased blood Pb has been associated with significant abnormal autonomic and cardiovascular responses to stress in children, which is a known predictor of future hypertension and heart disease, and remarkably, "these effects were significant at Pb levels considered to be very low and notably well below 10 µg/dL, the [former] Centers for Disease Control and Prevention (CDC) definition of an elevated blood Pb level"

(Gump et al., 2011). Actually, there is a wealth of evidence in the literature to show that negative health effects are present below 10 µg/dL in the blood, especially with respect to the central nervous system in children, though an increased mortality in adults has also been demonstrated by some researchers (Bellinger et al., 1989; Canfield et al., 2003; Needleman, 2004; Rossi, 2008). There is even some evidence of negative effects below 5 µg/dL (Lanphear et al., 2000; Fewtrell et al., 2003; Lanphear et al., 2005; Rossi, 2008; WHO, 2011b). Accordingly, the current CDC definition of an elevated BLL is 5 µg/dL (CDC, 2012).

The aforementioned array of evident and suspected health effects demonstrates the need to limit exposure to Pb, particularly in young children, who are still developing and can absorb 4–5 times the amount of Pb per unit body mass as adults (WHO, 2011a). This information makes it clear that Pb exposure must be prevented where possible and limited in all other instances. As much of Pb exposure is most damaging in developing children, and the most detrimental effects to the central nervous system appear to be irreversible, the disease burden attributable to Pb can only be alleviated with better characterization, regulation, and mitigation of all relevant exposure routes (Tong et al., 2000; Fewtrell et al., 2003; CDC, 2012).

2.4 Pb Leaching and Water Supply

2.4.1 Water as a Contributing Exposure Route

As public policy changes eliminate some of the most prominent exposure routes for Pb, other routes become more important (Triantafyllidou and Edwards, 2012). As of January 2008, most developed and developing countries, including Madagascar, have phased out the sale of leaded gasoline, thereby greatly diminishing exposure from the air and eliminating a source of Pb contamination of soil (UNEP, 2008). In developed countries, lead paints have also been phased out, though safe removal and replacement continues to be a challenge that can contribute to the daily intake of Pb, and lead paint supplies remain available in many developing countries (ATSDR, 2007; EPA, 2013; WHO, 2011b; WHO, 2013c). Nevertheless, as these drastic changes in the exposure profile of Pb are realized, new emphasis should be placed on the remaining sources. As the ability to detect and measure heavy metals improves with technological innovation, researchers are able to link Pb with a wider array of health issues and at much lower exposures than previously believed (Lanphear et al., 2000; Needleman, 2004; Triantafyllidou and Edwards, 2012).

Water can be an important exposure route for Pb for those who drink contaminated water or use it for cooking (Triantafyllidou and Edwards, 2012). In recent history, water has made up a relatively low contribution of the overall Pb intake, with food, dirt and dust adding up to over 80% of daily ingested Pb (WHO, 2011b). Sometimes exposure through water is overlooked entirely in characterizing exposure routes and attributing incidence of elevated BLL to those exposures (Tong et al., 2000; Triantafyllidou and Edwards, 2012). However, Pb in water has been linked to elevated BLLs, and as stated above, as some pathways are mitigated or eliminated, others like water become more important, especially as evidence of health effects become apparent at decreasing exposure (Fewtrell et al., 2003; Riddell et al., 2007; Brown et al., 2011).

Unlike most other drinking water contaminants, the source of Pb is typically the conduction system itself. Lead in water generally does not come from natural sources, but rather from corrosion of components in water systems (WHO, 2011a). The amount of Pb in a given water sample depends on many factors, including “the presence of chloride and dissolved oxygen, pH, temperature, water softness”, and the amount of Pb contained in components in contact with the water (WHO, 2011b). Though water conduction systems are meant to contain unleaded parts now, Pb leaching continues through sources like Pb conductive piping that has yet to be replaced, lead-tin (Pb-Sn) soldering, and brass fittings (Crittenden et al., 2005; WHO, 2011b; Triantafyllidou and Edwards, 2012).

The United States Environmental Protection Agency (EPA) maximum contaminant level goal (MCLG) for Pb in water at the point of consumption is zero (Triantafyllidou and Edwards, 2012). The EPA rule related to Pb in water is the Lead and Copper Rule, which stipulates an Action Level (AL) of 15 µg/L. Once 10% of households in an area test over the AL, utilities will be forced to take action to change corrosion control schemes or even change critical infrastructure and inform people of the health risk associated with the elevated Pb concentrations (EPA, 2004). Thus, the AL regulates costly, large-scale changes made to infrastructure and centralized water treatment, and should not be viewed as a threshold for safe public health exposure (Maas et al., 2005; Triantafyllidou and Edwards, 2012). The WHO provisional guideline for dissolved Pb in water (10 µg/L), based on public health impacts at low levels of Pb consumption, is lower than the EPA AL (WHO, 2011a,b). The guideline was initially set by the Food and Agriculture Organization of the United Nations (FAO) and the WHO in the Joint FAO/WHO Expert Committee on Food Additives (JECFA), and was based on a provisional tolerable weekly intake (PTWI) of 25 µg/kg per week in infants. In 2010, this guideline was reevaluated as this previously accepted exposure was shown to affect cognitive function in children and increase blood pressure in adults (FAO and WHO, 2011; WHO, 2011b). Accordingly, there is no evident lower threshold for safe BLL, and therefore, safe levels of Pb exposure (Lanphear et al., 2000; Canfield et al., 2003; Triantafyllidou and Edwards, 2012). Based on the absence of a safe level of consumption, the JECFA was unable to determine a new, "safe" PTWI, and has consequently designated a "provisional guideline" for Pb in water at 10 µg/L—a value rooted in the practical difficulties in keeping Pb below this level in centralized water treatment schemes and in quantifying Pb concentrations at low levels (WHO, 2011a,b).

2.4.2 Madagascar Context and the Pitcher Pump

Pb exposure in developing countries has increased in recent years due to rapid industrialization (Tong et al., 2000). In fact, presently, most exposure to Pb occurs in the developing world, and "AfrD", a subset group of countries in Africa including Madagascar, showed an average BLL of above 11 µg/dL in children and adults (Fewtrell et al., 2003). Consequently, incidences of mental retardation in children and increased blood pressure in adults can be estimated (Fewtrell et al., 2003; WHO, 2004). Calculations like these must take into account the relative weight of the disease burden (e.g., environmental Pb) and the regional adjustment ratio for diseases (e.g., mild mental retardation) because certain developing regions are predisposed to a higher risk of disease burden from a number of other factors that contribute to the relative quality of life (Fewtrell et al., 2003; WHO, 2004). From this, we can see that Pb exposure is not likely a problem isolated to developed or "industrialized" nations, and the resulting Pb exposure could be more important for the poor populations of developing countries.

Literature shows that more Pb can be absorbed in malnourished children, which makes children in developing countries more susceptible to its toxic effects (Mahaffey, 1974; Mahaffey, 1998; Tong et al., 2000; Fewtrell et al., 2003; WHO, 2011b). In addition to known Pb-interference with nutrient pathways in the body, it has been demonstrated that proper dietary intake of nutrients (e.g., iron, calcium, zinc, vitamin C, etc.) is needed to abate toxic effects of Pb (Ahamed and Siddiqui, 2007). Lead has been shown to both be absorbed more efficiently in individuals with low iron, and to outcompete iron in heme synthesis, actually contributing to anemia (Patrick, 2006; ATSDR, 2007; Hegazy et al., 2010). Malnutrition, in turn, is a common problem in developing countries. In Madagascar in 2004, 36.80% of children under five were malnourished by metric of weight, and 49.20% of children under five were determined to be malnourished by metric of height in 2009 (Index Mundi, 2013). Madagascar is one of the top 10 countries in the world with highest rate of chronic malnutrition (UNICEF, 2013). Consequently, the Malagasy are at an increased risk for the toxic effects of Pb when compared to an average population in a developed country, making Pb exposure from all sources a more important issue.

In developed countries, Pb exposure through water is regulated (WHO 2011a). Regulation of Pb primarily consists of centralized control of water treatment additives and corrosion control strategies (Dodrill and Edwards, 1995; Triantafyllidou and Edwards, 2012). Additionally, determination of Pb concentrations in water is carried out by external agencies and laboratories. Yet in developing countries, where people have developed Self-supply technologies due to the unmet demand for affordable, reliable water supply, the problem of monitoring and controlling Pb-release is not centralized. Instead, many decentralized small-scale systems each serve one to several households. In Tamatave, I considered Pitcher Pump systems, in production since 1960 and used present-day by some 170,000 of the city’s 280,000 residents (MacCarthy et al, 2013). I believe this to be a unique system of possible Pb sources potentially resulting in great levels of exposure throughout the city of Tamatave.

The Pitcher Pump is a suction pump with two check valves, which work to lift water from a shallow borehole (generally 0–7 meters below ground level) and through the casing attached to the pump. Figure 1 in Chapter 1 provided a full technical diagram of a Pitcher Pump and Figures 3–5 diagram the components of the Pitcher Pump, some of which contain Pb, and therefore present the risk of leaching into the water. The pipe is made from galvanized iron, which poses no health risks of its own. The well screen is made of brass, which has historically contained Pb to increase workability and reduce wear (EPA, 1996). Joining the screen to the galvanized pipe is lead-tin (Pb-Sn) soldering, which melts at low temperatures and is workable, therefore making it ideal for binding metals (Crittenden et al., 2005; Schock and Lemieux, 2010). Screens are mounted on either side of the bottom portion of the pump and stretch about 4 cm × 12 cm. The well screen is attached via Pb-Sn soldering, which is still widely available in hardware stores even in the US (Triantafyllidou and Edwards, 2012). The pump head is stainless or mild steel, depending on the manufacturer and customer preferences, and the check valves (piston and foot valves) in Madagascar are made from leather flaps with connected metal (Pb) weights to ensure a seal. Figure 6 shows a typical processing of Pb plates from lead acid batteries (approximately 94% lead according to Patnaik (2003)) into materials for sale to pump artisans.

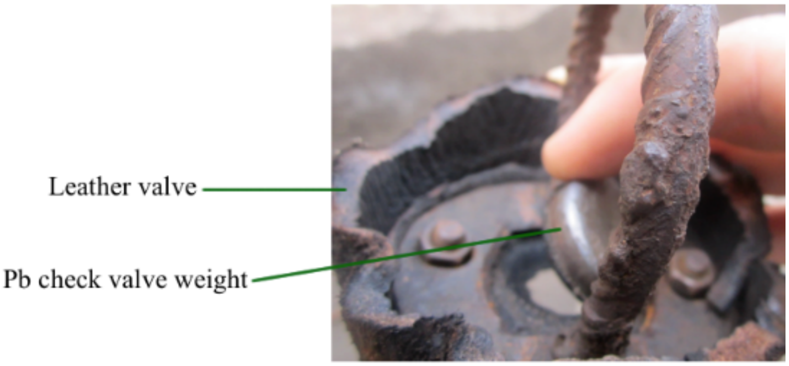


Figure 3. Upper check valve of Pitcher Pump with pure Pb valve weight (open).

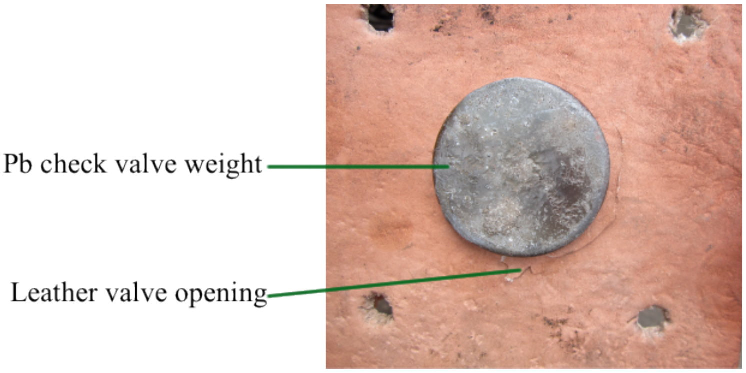


Figure 4. Lower check valve of Pitcher Pump with pure Pb valve weight (closed).

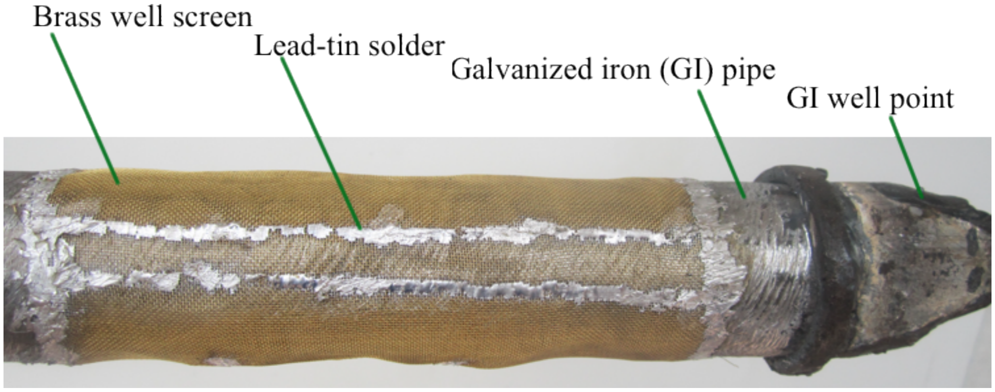


Figure 5. Lower portion of pump well with well screen and driving point.

Figure 6. Lead harvesting from batteries for repurposing: a) an artisan works to remove lead-antimony plates and melt them into small pieces for resale; b) close-up view of lead-antimony plates; c) stick of Pb heated over a charcoal stove.

There is an analogy between Pb pipes (lead service lines) and Pb check valves. Both are nominally pure conduction system components and vulnerable to corrosion as water passes through and/or over their surfaces. An easier comparison to familiar systems in the US is the brass well screen and Pb-Sn soldering around the screen where the water enters the well. As water comes into contact with all of these components, Pb may contaminate the supply via "electrochemical, geochemical, and hydraulic [physical] mechanisms" (Triantafyllidou and Edwards, 2012). The water, which then contains soluble and particulate Pb, becomes a direct contributing exposure route of this toxin for consumers of the water.

There is relatively little literature published on the topic of Pb leaching from submersible groundwater pumps (EPA, 1995; Maas et al., 1998; Sidle and Li, 2007). The few available publications generally show that Pb leaches from leaded components mostly in the first weeks and months after installation, sometimes at levels well above the WHO provisional guideline, then later drop in concentrations down to levels below concern. Contact time with water in the system and water quality factors like pH also affect leaching (EPA, 1995; Maas et al., 1998; Sidle and Li, 2007). However, pumps analyzed by previous investigators do not have a component analogous to that of the pure Pb check valve weights. Furthermore, one study was identified that mentions Pb leaching from Pitcher Pump systems in Madagascar and provides some evidence of potential Pb contamination, but only includes data from 10 sample locations (MacCarthy et al., 2013). All of this information about the population at risk to potential negative health impacts and the absence of a full study on the topic of Pb leaching in Madagascar's pumps inspired this investigation into the chemical and physical quality of water drawn from the Pitcher Pumps.

CHAPTER 3: MATERIALS AND METHODS

3.1 Sampling Campaigns

3.1.1 Household Selection and Interviews

To address Objective (1), I selected a number of household pumps to participate in sampling and analysis for Pb concentrations. The primary selection criterion was the total number of pumps, 18, the maximum number of pumps I was able to regularly sample due to limited time available to run samples and testing materials costs. Next, Objective (3) was considered when selecting households for participation: I wanted to test pumps of various ages and well depths, fabricated by different manufacturers and located in different neighborhoods. In this way, each pump had a distinct set of variables that could be used to compare for factors affecting Pb leaching. I selected all households for the study in a systematic way.

Before I spoke with any households and pump users, Malagasy culture dictated that I find the *Chef du Fokontany*, or town president, for each town/neighborhood and speak with him directly. I presented myself in Malagasy and explained my background, my reason for working in Tamatave, and my presence as a student and a Peace Corps Volunteer. Before completing any fieldwork, I asked for the permission of the town president to work in the local area. Additionally, I completed all of the survey and sampling work with a Malagasy field research assistant, Onnie Razafikalo. The local population seemed to have a cautious mistrust of foreigners. Consequently, the Malagasy people are much more comfortable talking about their water and sanitation practices and issues with a local person rather than foreigners. The field research assistant is also part of the same general ethnic group, the *Betsimisaraka*, as the general population of Tamatave, which helped people relate to her. Partnering with a local Malagasy person also helped greatly in any work completed with pump manufacturers.

I executed a modified snowball method for selection of participating households (Everitt and Skrondal, 2010). Initially, I observed a *Pompe Tany* from the road and visited the first household. Household members would then either participate in the survey and sampling campaign, only the survey without sampling, or neither. In all cases, the current household would mention other households or areas with Pitcher Pumps, which would set the next destination. The method is modified from the original process of snowball sampling, however, in that some of the sites referred by previous households were skipped in order to meet the strict selection criteria (i.e., differences in pump age, well depth, manufacturer, and/or neighborhood) mentioned above (Everitt and Skrondal, 2010).

A broader range of households was included for interviews than for Pb concentration measurements as this research was carried out with another Master's International student, who was collecting more samples than I for testing water quality with respect to microbial contamination (Wahlstrom-Ramler, 2014). Consequently, interviews were conducted at 53 households (see Appendix III) in seven neighborhoods to characterize basic water and sanitation practices including water usage and drinking water sources. This established that many people use Pitcher Pump water for drinking and cooking, e.g., direct consumption. Another smaller set of interviews were also completed with nine pump manufacturers in the area to determine normal materials of construction and to estimate the population served by Pitcher Pump systems (Appendix II). All interviews were formally conducted by the Malagasy research assistant introduced above.

The Institutional Review Board (IRB) administered by the Human Research Protection Program (HRPP) at the University of South Florida was not originally involved in the development of the survey. The decision to exclude the IRB was based on the fact that the initial research in Madagascar concerning the Pitcher Pump systems by Michael F. MacCarthy was submitted to IRB and was ultimately deemed acceptable (i.e., not research that treated respondents as human subjects) and therefore did not require formal IRB approval. Upon corresponding with the IRB retroactively, concerns were raised that some of the questions regarding water usage and treatment could be interpreted as data collected on human subjects rather than as an evaluation of the Pitcher Pump systems themselves. Upon further clarification, it was determined that most of the data collected did not constitute human-subject research, and was therefore appropriate for reporting by our research group (Wahlstrom-Ramler, 2014; Appendix IV). Any survey questions deemed questionable by the IRB were stricken from record and excluded from the thesis.

Figures 7 and 8 show the locations of the five *fokontany* (neighborhoods) selected for the study of potential Pb contamination of water in Pitcher Pump systems and the general geography of the area. The five neighborhoods included in the study are shown to spread through a good part of residential Tamatave. Each of the neighborhoods was the general location for at least three of the 18 pumps included in the study. Four of the neighborhoods are located near the central river of Tamatave, and all of the sampling locations are within a 1.25 km radius of their farthest neighbor (e.g., a 2.5 km diameter circle). The distance between pumping locations is unintentionally small, but is a byproduct, in a sense, of the modified snowball method approach to sampling, and the restrictive criteria that I followed in making final decisions on whether to include households in the sampling campaign.

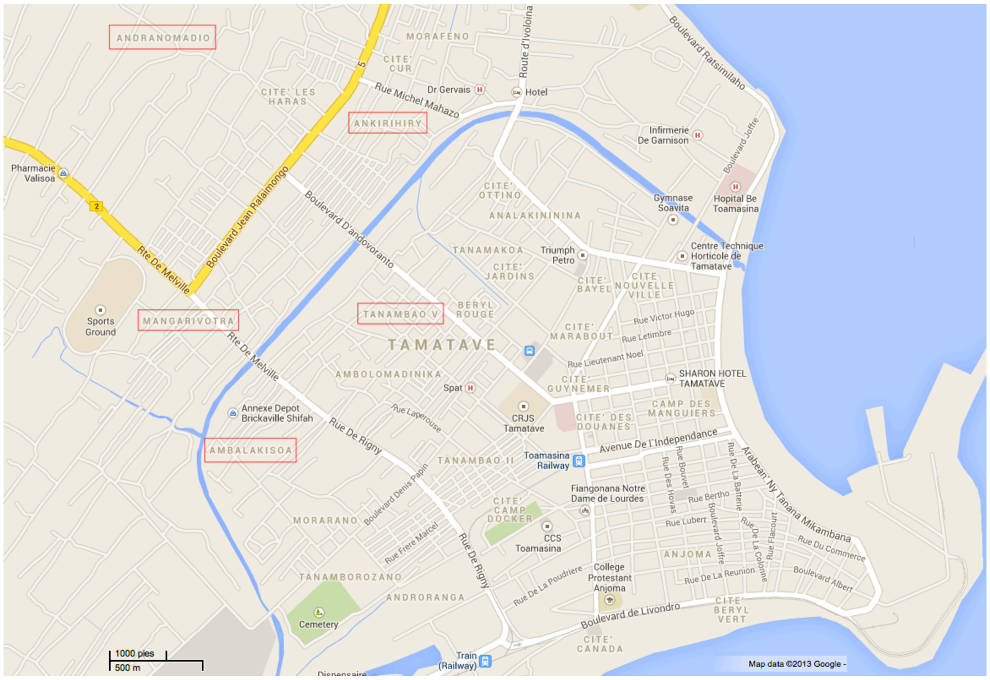


Figure 7. Map of Tamatave obtained from Google© 2013 information. The image has been modified only in that the neighborhoods (*fokontany*) included in the study are designated with a red box around the corresponding name: Ambalakisoa; Andranomadio; Ankirihiry; Mangarivotra Avaratra; and Tanambao V.

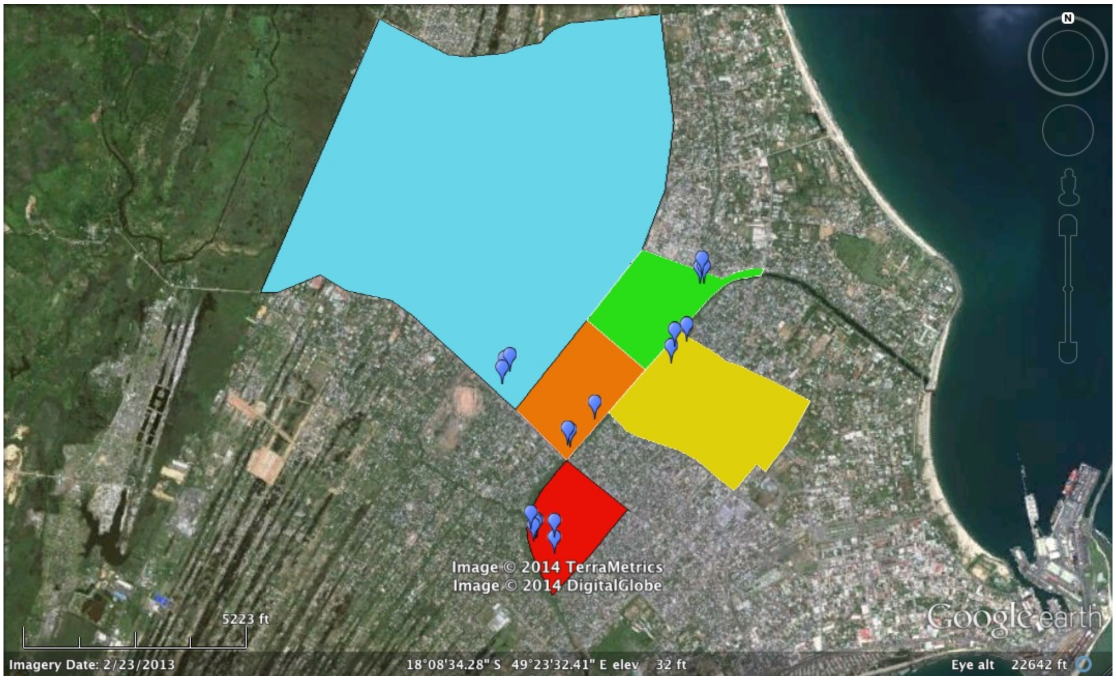


Figure 8. Map of Tamatave obtained from Google Earth (Version 7.1) with DigitalGlobe© 2014 and Terrametrics© 2014 information. Neighborhoods sampled (listed in Figure 7) are shaded and Pitcher Pump GPS locations indicated with a pin.

3.1.2 Flushed and First-Draw Sample Collection

To execute Objectives (1)–(3), I developed a field sampling protocol for the quantification of Pb concentrations in the city of Tamatave. From preliminary observations I made during a field trip to Tamatave in September 2012, and later confirmed with field observations at 53 households, the most commonly identified receptacle for water collection was a bucket. Buckets used for collection are either 10 or 15 liters in size (Appendix III). A first 250 mL sample is sometimes analyzed and taken as the possible first glass of water poured for consumption in the US (Triantafyllidou and Edwards, 2012). Under the Lead and Copper Rule, samples for Pb analysis are generally taken in a 1-liter container (Triantafyllidou and Edwards, 2012). The 250-mL volume, which would supposedly show a higher concentration for first-draw samples, was not used in this research in an effort to make realistic conclusions that are relevant to the context of domestic use in Tamatave. Because a family will typically fill up a 10-liter or 15-liter bucket for first-draw at the pump, I used the 10-liter volume as a guide for sample collection. Though 15-liter buckets were reported more frequently in the December 2012 interviews (57%) as compared to 10-liter buckets (42%), I did not want to overly dilute the sample (Appendix III). Essentially, I believe that a 10-liter bucket is adequately representative of a feasible first-draw sample after a pump has been inactive for some amount of time.

To obtain flushed samples, I first measured the circumference of the well casing and used it along with reported well depths to calculate the volume of the Pitcher Pump system. Then, I flushed approximately 2.5 well volumes from each pump. After the pumps were adequately flushed, I filled a calibrated 15-liter bucket to 10 liters. I then rinsed a 25 mL pipette in a representative sample from the pump, mixed the contents of the 10-liter bucket, and drew a 5 mL sample for analysis (see Section 3.2.1). After a pump was flushed, it would be effectively closed for the next hour, as agreed to by the participating household, and thereby held inactive. To close a pump, it was either taken apart or covered with a piece of tape and/or a plastic bag to signify to the pump users/owners that it was not ready for use (Figure 9). After I analyzed the flushed sample, I dumped the collection bucket and rinsed it with more flushed water, to attempt to dislodge any particulate Pb that might have clung to the walls. Once an hour had passed, the pump was reopened, and I collected the first 10 liters of water drawn from the pump—the first-draw sample—and subsequently prepared it for analysis. Though longer contact time between the water and Pitcher Pump components would have been more representative of a "first-draw" after a period of nonuse, I was forced to limit the period of inactivity to an hour for practical reasons. Therefore, flushed samples were said to have 2.5 times the well volume removed from the pumps, and first-draw samples were collected after one hour of pump inactivity.

Figure 9. Sample collection and preparation: a) flushing of the pump by Meghan Wahlstrom-Ramler; b) "closed" pump during the 1-hour waiting period after flushed sample collection; c) preparation of a drawn sample with a pipette.

I collected and analyzed samples from each pump at three times during the year (December 2012, March-April 2013, July 2013) to include the season as a possible variable for

Pb leaching in Objective (3). Presumably, changes in the season make a corresponding change in the local microenvironment for Pitcher Pump systems via changes in water chemistry (e.g., temperature, rainfall, organic compounds in solution) (Triantafyllidou and Edwards, 2012; Deshommes et al., 2013). During the final sampling campaign in July 2013, three pumps were removed from consideration. Those three pumps had consistently shown Pb levels below 10 μg/L in the first two sampling campaigns. Omitting those three pumps enabled me to have enough materials to run a second time-release/component-replacement study (Section 3.1.3).

3.1.3 Time-Release and Material Component Substitution Studies

I conducted case studies at two selected households with observed elevated Pb measurements to satisfy Objective (4). These studies were multi-purpose. First, I wanted to conduct a time-release study and measure Pb concentrations under more realistic first-draw scenarios (i.e., with periods of inactivity longer than one hour), and thereby make general observations about whether concentrations continue to increase over time. It is noteworthy that some pumps had poor seals, and the water would fall back down below ground level during periods of pump inactivity. The pumps selected for time-release studies had good seals and retained water in the pump head throughout the period of inactivity (see Figure 10). The second aspect of the case study was a pilot study for the replacement of Pb components with Fe components. I hypothesized that replacing Pb components with Fe in existing systems would decrease Pb in the water drawn from the pump. I aimed to test this hypothesis and to determine if resultant Pb concentrations would decrease to levels below the WHO provisional guideline under any/all periods of pump inactivity.

The method for sample collection during time-release studies was similar to that of flushed and (one-hour) first-draw samples. In fact, the "flushed" and "first-draw" samples were included as data points in the time-release studies (corresponding to equilibration times of 0 and 1 hour, respectively). The difference between procedures for time-release studies and the normal sampling campaigns (Section 3.1.2) was the draw times: I collected samples under pumping conditions of flushed, one-hour, two-hour, four-hour, six-hour, and greater than 11-hour periods of inactivity.

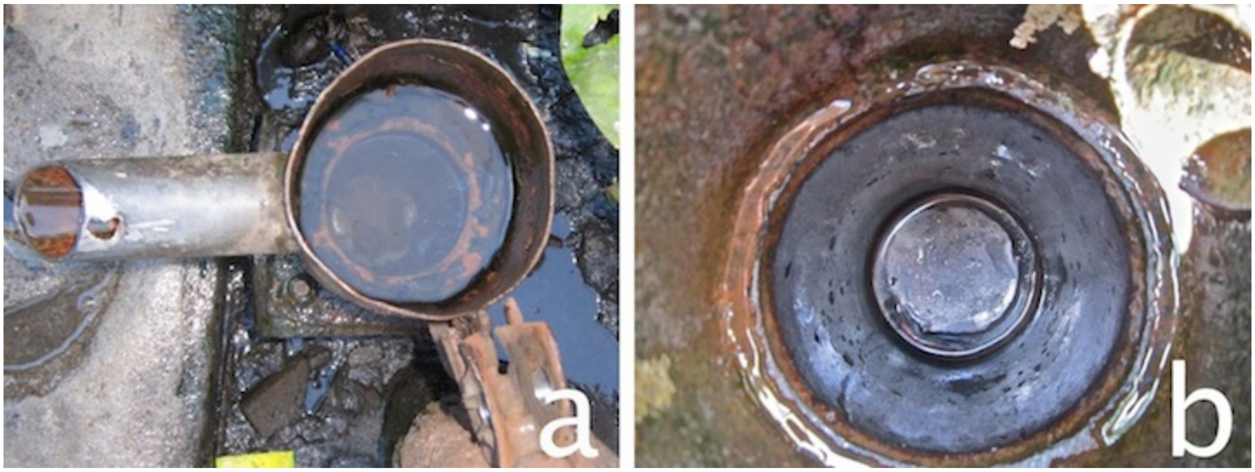


Figure 10. Examples of proper and poor seals in Pitcher Pumps: a) a good seal retaining water after 1 hour of inactivity; b) a poor seal failing to retain water for longer than two minutes.

Then, I commissioned a local pump manufacturer to fabricate Fe valve weights and install them in place of Pb valve weights (Figures 11–13). Once new Fe valve weights were ready, the entire pump head was replaced for the studied pump. Entire pump head replacement was unnecessary to make my desired observations. However, for both selected pumps, the pump heads were not in good shape, and the new pump heads were presented as gifts to the families that were so inconvenienced by the study as to have long periods without access to their pumps. For Pump #8, the second time-release study (i.e., with Fe components) was initiated 24 hours after installation. The second time-release study for Pump #18 was delayed from sampling campaign #1 to campaign #2 in April 2014 due to limited time and materials in December 2012.


Figure 11. Finished retrofitted pump with pump manufacturer (pumping) and owner (behind).

Figure 12. Typical fabrication of Pb valve weights: a) sand-casting of molten Pb; b) removal of sand-casted Pb valve weight seconds after pouring; c) installation of Pb into piston valve.

Figure 13. Fabrication of Fe valve weights: a) use of an old galvanized wrench; b) use of nut and bolt; c) representation of a finished foot valve with Fe weight.

Figure 14. Alternative Fe scrap materials used in valve fabrication: a) lower (foot) valve; b) upper (piston) valve.

3.2 Characterization of Water Drawn from Pitcher Pumps

3.2.1 Anodic Stripping Voltammetry (ASV) for Pb Measurement

Quantification of dissolved Pb in water was completed by the process of Anodic Stripping Voltammetry (ASV). This physical-chemical process makes use of an amalgamating electrode—in our case, mercury—to rapidly plate all metal ions in solution via reduction (Brezonik et al., 1967; Palintest, 2009). Next the current is reversed and metals are oxidized back into solution, desorbing at characteristic potentials. The energy needed to move beyond a potential is then related to concentration (Brezonik, 1967; Palintest, 2009). The Palintest® SA1100 Scanning Analyzer comes pre-calibrated, with several available calibration curves readily programmed for corresponding testing strips, and the range of detection is 2–100 µg/L Pb in water over a practical temperature range of 15–30°C (Palintest, 2009). The general description of methods is paraphrased below, and can be found in the product manual (Palintest, 2009). First, the instrument was calibrated via data chip containing the calibration curve corresponding to the particular type of electrode. Next, samples prepared by the process outlined in Section 3.1.2 were loaded into a 5 mL sample vial via pipette. A solution preparation tablet was then added to the sample and crushed and stirred until completely dissolved. The ASV was subsequently closed and locked and the analysis (e.g., plating and stripping) would begin. The measured Pb concentration was displayed after approximately three minutes of processing. Figure 15 provides a picture of the ASV and the process of field measurement.

Figure 15. ASV process: a) the ASV unit with electrode in place and sample prepared; b) sample processing; c) corresponding measurement of dissolved Pb concentration.

3.2.2 Water Quality Parameters

To contribute to Objective (3), I attempted to monitor water quality parameters to then relate certain aspects of water quality to Pb leaching. The basic indicator that I attempted to calculate is the Langelier Saturation Index (LSI), which provides a measure of corrosivity (Roberge, 2008). The LSI shows the theoretical saturation of a water with respect to carbonate species, and is therefore an indicator of the potential for carbonate to scale, dissolve, or neither (Roberge, 2008). I hypothesized that a measure of corrosivity could indicate the relative extent of Pb leaching in waters in contact with Pb-containing components, as it is sometimes used in industry to determine the behavior of water distribution systems (Roberge, 2008; Crittenden et al., 2005). Factors that affect corrosivity include pH, temperature, hardness, alkalinity, and the ionic strength of a solution (Roberge, 2008). Therefore I attempted to collect data for these and other parameters.

Measurements of pH, temperature, total dissolved solids and dissolved oxygen were obtained with a Hydrolab® Quanta® Water Quality Monitoring System, capable of making multiple instantaneous *in situ* measurements (Hydrolab, 2002). To supplement and in some cases verify these measurements, testing strips were used: Fisher Scientific, LLC Whatman™ pH Indicator Papers for pH range 6.0–8.1; Fisher Scientific, LLC Insta-Test™ Alkal Test Strips for alkalinity as carbonate for range 0–180 mg/L; Fisher Scientific, LLC Insta-Test™ Hard Test Strips for calcium hardness for low range of 0–180 mg/L. It should be noted that the hardness test strips might have been inappropriate for the setting, as the hardness detection range was classified as low. Test strips for alkalinity and hardness provided ranges of those parameters, but not precise numbers. Therefore, when calculating the corrosivity of a water sample, I included a low range estimate (meaning the combination of all measurements and ranges that provided the least corrosive water) and a high range (meaning the combination of all measurements and ranges that provided the most corrosive water) (Appendix V; Roberge, 2008).

Figure 16. Use of the Hydrolab® Quanta® probe in the field to determine water quality parameters. Shown with pump manufacturer Fabrice Koesaka (left), myself (middle) and Master's student Meghan Wahlstrom-Ramler (right).

Issues with equipment in the field prevented a thorough analysis of these parameters, except in the July 2013 sampling campaign (Appendix V). Maintenance issues with the Quanta® probing instrument left data incomplete in the December 2012 sampling campaign, and the instrument was sent back to the US from Madagascar for repairs (Appendix V). After repairs, the instrument provided questionable data (e.g., pH measured above 10 initially, and above 8 and 9 after a further calibration) as compared to the Whatman™ pH papers (Appendix V). Therefore, when conducting calculations for LSI, I ignored the pH readings from the Quanta® instrument, and instead used the more reasonable, though less precise, pH measurements completed with test strips. In sum, the water quality parameter measurements were tenuous, and the resultant LSI calculations should be viewed as strictly preliminary.

3.2.3 Analysis of Data

To make statements about levels of Pb in Tamatave and satisfy Objective (1), I calculated descriptive statistics, including mean, median, and standard deviation of Pb concentration measurements. I plotted histograms of the data and concluded that the frequency distribution was not normal, but skewed. To make an appropriate comparison between flushed and first-draw samples, I compared medians rather than mean values due to a non-normal distribution of data. To test for a significant difference between these measured values, which relates to Objective (2), I employed the paired sample Wilcoxon signed-rank test, a nonparametric assessment for related non-normal distributions (Gibbons and Chakraborti, 1992).

In completing Objective (3), I calculated descriptive statistics again of Pb concentrations measured in the field for small groups of Pb measurement corresponding to most variables encountered with the sampling procedure (see Appendix VI). For the major analysis of different field variables (defined in Section 3.1.1), I completed a multivariable analysis. The most complete data that I obtained in the field were on the measurements of Pb concentration, the pump age, pump manufacturer, depth to the well screen, the season of sample collection, and a measure of contact time. Taking these six variables, I created a dataset with 84 total observations for 14 pumps, which I entered into a matrix. I assigned discrete values for variables without a natural measured value like season and manufacturer. In the case of the manufacturers, no natural value from 1–6 exists, so I assigned numbers to individual manufacturers in the order their pumps were encountered in the field. From the data matrix, I calculated the correlation matrix and corresponding matrix of p-values (statistical significance values) via MatLab® to determine which variables, if any, had strong, statistically significant relationships (Basilevsky, 1994; Quinn and Keough, 2002). I chose the correlation matrix over the covariance matrix due to dissimilar units and scales of different variables in the original dataset (Dunteman, 1989; Basilevsky, 1994; Quinn and Keough, 2002). Correlations with Pb concentration were of particular interest. Subsequently, the correlation matrix was entered into MatLab® for principal component analysis (PCA), which may tell of underlying components in the overall variance of the data (Dunteman, 1989).

Water quality data collected in the field were incomplete in the December 2012 and April 2013 sampling campaigns due to equipment issues. Namely, the Hydrolab® Quanta® Water Quality Monitoring System was undergoing repairs. Therefore, the water quality data called out in Section 3.2.2 as requisite for calculation of the LSI were available only for the July 2013 sampling campaign. Consequently, I conducted a second, separate multivariate analysis including a correlation matrix and subsequent PCA for the July 2013 dataset. The methods are the same as those listed above, except that I substituted LSI values in place of the variable for seasonality, as the samples were all drawn in one campaign and therefore one season.

3.3 Preliminary Assessment of Public Health Implications

To adequately address Objective (5), some information about the blood concentrations of Pb (Blood Lead Levels [BLLs]) is necessary. Because I had no available database with documented BLLs in the population of interest in Tamatave, I used a model to predict potential outcomes in BLLs due to exposures set by concentrations of Pb in water that I measured in the field. Thus, I was able to make a preliminary assessment of possible health consequences as predicted BLLs through a review of the literature.

The EPA Internal Exposure Uptake Biokinetic Model for Lead in Children (IEUBK Model) is designed to take all of the possible exposure pathways for Pb in children and estimate blood Pb concentrations, or blood lead levels (BLLs) based on biokinetic information (EPA, 2007). The model requires inputs for exposure routes other than water, including soil and dust, diet, and air (EPA, 2007). With a complete exposure scenario in place, the model is capable of predicting BLLs in children up to seven years of age. To the best of my knowledge, this information does not exist for Madagascar in the literature. Lacking this data, I used the WHO guide for the assessment of disease burden attributable to Pb to supplement and verify reasonable estimates of these values (Fewtrell et al., 2003; EPA, 2007; Appendix VII). Fewtrell et al. (2003) also inform or qualify several constants for the IEUBK Model, including certain exposure concentrations and the amount of water consumed by different age groups. The set of parameters for "contaminated water, low other exposures" was used, except for the actual water concentrations (Appendix VII). As children under five years of age are typically recognized as the most vulnerable group to harmful chemical and/or pathogen exposure, I completed calculations for children aged 0–59 months (ATSDR, 2007; WHO, 2011a). Scenarios for the IEUBK Model are summarized in Table 2 and explained in Appendix VII.

Table 2. Selected Scenarios and Input Parameters for the EPA Internal Exposure Uptake Biokinetic Model for Lead in Children (IEUBK Model)

	Concentration of Pb in Water			
Scenario ID	Description of Water Concentrations	First-Draw Concentration (μg/L)	Flushed Concentration (μg/L)	Other Exposure Routes[a]
1a	Mean – σ [b]	4.9	2.3	Low[c]
1b	Mean – σ	4.9	2.3	Moderately Low[c]
2a	Median	13.0	9.0	Low
2b	Median	13.0	9.0	Moderately Low
3a	Mean	13.8	10.5	Low
3b	Mean	13.8	10.5	Moderately Low
4a	Mean + σ	22.7	18.6	Low
4b	Mean + σ	22.7	18.6	Moderately Low
5a	Mean + 2σ	31.7	26.8	Low
5b	Mean + 2σ	31.7	26.8	Moderately Low
6a	Moderate Inactivity[d]	51.0	9.0	Low
6b	Moderate Inactivity	51.0	9.0	Moderately Low
7a	Long Inactivity[d]	102	9.0	Low
7b	Long Inactivity	102	9.0	Moderately Low

[a] Other exposure routes are soil and dust, diet, and air.

[b] σ denotes standard deviation in observed concentrations. Some scenario concentrations were obtained either by subtraction of a standard deviation from the mean, or addition of a standard deviation to mean concentrations.

[c] Low/Moderately Low concentrations for air and dust were determined from ranges set by WHO (2003) for low exposures. For a thorough list of exposures and constants used in the model, see Appendix VII.

[d] Moderate and Long Inactivity refers to pump inactivity. Corresponding concentrations simulate plausible concentrations after longer contact time for water in the pump wells. The median value concentration was used for the flushed column values (Table 3).

Each scenario for possible Pb exposures is broken into two, with "a" corresponding to the lowest ranges and combinations of exposure routes other than water, and "b" corresponding to the upper limit of these other exposure routes, considered moderately low in concentration. Each set of water Pb concentrations is informed by field measurements. In Scenarios 2 and 3, for example, median and mean Pb concentrations measured in the field are used as inputs, respectively for both flushed and first-draw water. Other water concentrations were obtained by adding or subtracting standard deviations of the sample concentrations from the mean values. It should be noted here that the model assumes 0.2 liters per day of water consumed when aged 0–11 months, 0.5 liters per day when aged 12–23 months, and increases stepwise to 5.5 liters per day for children aged 48–59 months, all based on US averages (EPA, 2007). The model also includes concentrations for flushed and first-draw water, and assumes 50% of water consumption is first-draw (EPA, 2007). The remainder is split between flushed water (in the household) and fountains. Because no water fountains are present in Tamatave, I attributed the other 50% of water consumption to flushed water (EPA, 2007). It should also be noted that the model does not account for water used in food preparation. All scenario parameters were entered into the IEUBK Model (*Windows® version 1.1, build 11*), and the software then computed corresponding BLL distributions in the population.

With respect to potential public health implications in adults, the EPA has developed a draft version of an All Ages Lead Model (AALM), and the Adult Lead Methodology (ALM) is used for dealing with Pb in soil as the sole exposure route, treating the soil site as a work site and the adult as a non-resident (EPA, 2003a; EPA, 2005). Accordingly, there is no citable model for estimating adult BLLs that is similarly rigorous to the IEUBK. The best estimate available for urban adults in Madagascar comes from a regional estimate, where Madagascar was not directly sampled, but grouped regionally according to WHO regions and mortality strata. The "AfrD" group including Madagascar was comprised of 26 countries, including Algeria, Burkina Faso, Cameroon, Ghana, Nigeria (the only country with recent data on population BLL), and several others (Fewtrell et al., 2003). From this source, urban adults were estimated to have geometric mean BLL of 11.6 μg/dL in the year 2000. This value was used as an input in the IEUBK Model for consideration of mother-infant transfer of Pb at birth (Appendix VII). Therefore, Objective (5) was restricted to an assessment of child BLLs, which gives an assessment of the most vulnerable group of people exposed to Pb in water drawn from Pitcher Pumps.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Summary of Results for Pb Concentrations in Pitcher Pump Systems

The first objective of this thesis research is to conduct a preliminary survey of Pb concentrations in water drawn from Pitcher Pumps at several households in Tamatave, Madagascar. To that end, Pb concentration measurements were collected in five different neighborhoods in the city of Tamatave at 18 households with Pitcher Pumps. The second objective is to determine if Pb concentrations in pumped water decrease after flushing the pumps. Accordingly, samples collected and analyzed were taken both after pumps were flushed and after a period of pump inactivity with the pumps closed. Summarized data on Pb concentrations measured in collected samples are presented in Table 3.

To address Objective (1), I measured the Pb concentration at 18 different households that used the *Pompe Tany*. Table 3 shows that in all three sampling campaigns, I observed Pb concentrations above the WHO provisional guideline for Pb in drinking water (WHO, 2011a). For all the sampling campaigns, the lowest number of pumps exceeding this level of Pb was four of the 18 included in the study. Thus, at any given time, there could be 22% or more of pumps producing water with elevated concentrations of Pb. Of all of the samples collected, 51% exceeded the guideline with a median value of 11 μg/L. In fact, of the 18 households surveyed, 15 produced at least one sample with a measured Pb concentration of greater than 10 μg/L. Table 3 shows that pumped water from these systems frequently exceeded 10 μg/L of Pb in water, presenting a preliminary profile of Pb concentrations in Tamatave, and providing evidence that people in the area may be consuming contaminated water.

Table 3. Summary of Results on Pb Leaching from December 2012, April 2013, and July 2013 Sampling Campaigns

Sampling Campaign	Median Pb Concentration Measured (μg/L)	Maximum Pb Concentration Measured (μg/L)	Middle 67% of Measured Pb Concentrations (μg/L)	% of Samples Exceeding WHO Provisional Guideline
December 2012				
Flushed Samples	9.5	44	5-16	44 %
First-Draw Samples	13	37	6-19	61 %
April 2013				
Flushed Samples	7.0	35	5-11	24 %
First-Draw Samples	12	39	9-23	69 %
July 2013				
Flushed Samples	10	30	7-15	36 %
First-Draw Samples	13	42	10-18	71 %
Totals				
Flushed Samples	9.0	44	5-15	35%
First-Draw Samples	13	42	6-19	67%

However, it does appear that flushing the pumps prior to drawing a sample for analysis can decrease the Pb concentration in the water. For each subset of data in Table 3, the median Pb concentrations in first-draw waters are higher than those in flushed waters. In all three sampling campaigns, the number of households exceeding 10 μg/L was > 60% for first-draw water samples, but < 50% for flushed water samples. Considering all flushed and first-draw samples, the totals come to 35% and 67%, respectively, exceeding 10 μg/L. According to the Wilcoxon signed-rank test (Gibbons and Chakraborti, 1992), the median of 13 μg/L for first-draw samples is significantly greater than the value of 9.0 μg/L for flushed samples, with the probability of measuring the same median value under both conditions only $p < 0.0001$. Therefore, it is evident that the number of pumps exceeding the guideline increases after just one hour of stagnation. In other words, flushing a pump before the first draw reduces the probability of pumping and using water contaminated beyond the provisional guideline.

4.2 Factors Affecting Dissolved Pb Concentrations in Water

Objective (3) of this thesis is to perform a preliminary analysis on factors that may affect Pb leaching, both in pump characteristics and the local environment. The main six variables hypothesized to affect leaching behavior are summarized in Table 4. Analyses of each variable listed in Table 4 and the corresponding Pb concentrations are included in Appendix II.

Table 4. Factors Hypothesized to Influence Dissolved Pb in Water

Variable	Possible Influence on Pb Concentration
Pump Age	Decreasing source of Pb over time or scaling in older tube wells inhibits leaching in older pumps.
Manufacturer	Differences in finished product, including materials of construction, provide different leaching behaviors.
Depth to Well Screen	Changes in the water chemistry profile at different depths affect leaching behavior.
Season	Changing temperature and rainfall affect water chemistry, and subsequently, the overall leaching behavior in the area.
Contact Time	Leaded pump components leach into sitting water over time, increasing Pb concentration until equilibrium is reached.
Corrosivity	The theoretical potential to dissolve metals is a function of the local microenvironment and will change in different locations, thereby affecting Pb dissolution from leaded components.

The most important recorded variables were used in a principal component analysis (PCA) to confirm the more simplified observations drawn from descriptive statistics (Dunteman, 1989). The first five variables, selected by the criteria of completeness in data collection (see

Appendix V), were compared and analyzed initially. Taking the measured Pb concentration as another variable, there are six in total. These variables are defined in Table 5. For a more complete understanding of which variables may strongly affect the process of Pb leaching, a 6-dimensional space is then constructed. Sidle and Li (2007) performed a similar analysis on Pb leaching data, and in so doing, were able to attribute the variance in measured Pb to just a few key variables.

Table 5. Variables for Multivariate Analysis

Variable	Symbol	Units
Pb Concentration	x_1	µg/L
Pump Age	x_2	years
Manufacturer	x_3	discrete (1–6)
Depth to Well Screen	x_4	meters
Season	x_5	discrete (1–3)
Contact Time	x_6	discrete (1–2)

First, the 14 pumps sampled during all three sampling campaigns were used to form a dataset, contributing 84 observations for the six variables of interest. Qualitative variables, or discrete variables, were assigned whole numbers to enable comparison with the numerical observations from other variables. Contact time, x_6, refers to whether the sample was recorded under "flushed" or "first draw" conditions, the two states of water in the system. Next, linear algebra was used to compile the data into an ordered matrix, and then to compare variable sets in a correlation matrix (see Chapter 3). All of the recorded observations were used to compute the normalized covariance matrix, or the correlation matrix, of the six variables along with p-values for significance in the corresponding correlation calculation (Dunteman, 1989; Basilevsky, 1994;

Quinn and Keough, 2002). The correlation matrix is used to describe how variables change together in pairs.

Table 6. Correlation Matrix for Multivariate Analysis of Variables Affecting Pb Leaching from Pump Components

	x_1	x_2	x_3	x_4	x_5	x_6
x_1	1.00					
x_2	0.16	1.00				
x_3	-0.11	-0.16	1.00			
x_4	0.10	**-0.63**[b]	0.05	1.00		
x_5	0.00	0.00	0.00	0.00	1.00	
x_6	**0.24**[a]	0.00	0.00	0.00	0.00	1.00

[a] Value is significant at $p < 0.05$
[b] Value is significant at $p < 0.001$

The diagonals of Table 6 are equal to unity because each variable relates as one with itself. Looking at column 1, the Pb concentration, it appears that the seasonality (x_5) has no influence on this variable. The highest variability in Pb concentrations is attributed to the contact time of water in the system (x_6), which is expected. The value for *C [6,1]* is 0.24, and the corresponding probability of obtaining that correlation by chance is $p < 0.05$, meaning the observation is statistically significant at a 95% confidence level. From column two, it might be concluded that newer pumps are generally installed deeper, as depth to well screen (x_4) varies inversely with the pump age, and a plot of these variables returns an R^2 value of 0.40. According to the correlation analysis, only contact time ($p < 0.05$) correlates significantly to the Pb concentration; and the only other meaningful correlation is between pump age and depth ($p < 0.001$, or significant at a 99.9% confidence interval).

After the correlation matrix was set up, it was entered into MatLab® to compute the contribution of variance in Pb concentrations for each variable, recorded in eigenvectors and eigenvalues, and to look for underlying structural influences on the data distribution (Dunteman, 1989). Results are compiled in Table 7.

Table 7. Principal Component Analysis of Variables Affecting Pb Leaching from Pump Components

Variables	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6
Pb Concentration	0.12	0.71	0.00	-0.04	-0.63	-0.28
Pump Age	0.70	-0.01	0.00	0.06	-0.18	0.69
Manufacturer	-0.24	-0.23	0.00	0.86	-0.38	0.07
Depth to Well Screen	-0.66	0.25	0.00	-0.23	-0.13	0.66
Season	0.00	0.00	1.00	0.00	0.00	0.00
Contact Time	0.04	0.62	0.00	0.45	0.63	0.10
Standard Deviation	0.45	0.38	0.41	0.40	0.43	0.39
Eigenvalues	1.67	1.28	1.00	0.98	0.76	0.31
Contribution to Variance	27.9%	21.3%	16.7%	16.4%	12.7%	5.2%
Cumulative Variance	27.9%	49.1%	65.8%	82.2%	94.8	100%

From Table 7, the first two principal components (PCs) have the largest eigenvalues, and accordingly, contribute the most to the overall variance of the data, at 27.9% and 21.3%, respectively (Dunteman, 1989). However, only 49.1% of variance is explained by these two components, and the next three eigenvalues are all similar in scale. Looking at PC_1, the pump age and depth to well screen contribute the largest loadings and shape the PC the most, suggesting the importance of these factors in explaining data variance. However, for PC_2, the Pb concentration and the contact time provide the largest loadings. PC_2, then, gives evidence that contact time is an important influence on Pb concentrations. Once PC_3—apparently completely explained by seasonality—is taken into account, all of the original variables have played a significant role in shaping the PCs and explaining data variance. Different variables contribute to the overall variance in data collected. Only after PC_5 is more than 90% of variance explained. Accordingly, there is no overall reduction in dimensionality or a simplified pattern in overall data variance, meaning no new relationships are elucidated with this multivariate analysis. However, several observations from the correlation matrix and the simplified two-dimensional analysis of variables (included in Appendix VI) are confirmed: namely, the only variable that significantly affects Pb concentrations is contact time, which is demonstrated with large loadings contributed to the same PCs; the Pb concentrations measured—much like other system variables—are definitively independent of season; and other contributions to variability in Pb concentrations are small.

One of the only studies on Self-supply water systems and Pb leaching—commissioned by the EPA and carried out in academia—suggests that after a period of initial use, approximately between 9–23 weeks, Pb leaching should not continue to be an issue under low to moderate corrosivity conditions (Maas et al., 1998). Another reference from the EPA (1995) says that generally submersible pumps should stop leaching Pb at levels of concern (e.g., even those above 5 µg/L) after an initial period of use of four to six weeks. However, for the *Pompe Tany* systems in Madagascar, only a relatively weak correlation ($C_{1,2} = 0.16$ in Table 6) was seen between Pb levels and the pump's age. In fact, some of the oldest pumps (Pumps 1, 10 and 18) leached the most Pb in some instances, meaning that generally, the leaded components continued to leach into the water even after an initial "breaking in" period. This is further supported by the fact that pumps of all ages showed some proportion of samples with Pb concentrations above the WHO guideline (Appendix VI). This observation was also noted by Sidle and Li (2007), who concluded that new pumps differed little from decades-old pumps in terms of leaching into the water, though it was suspected that geological and/or atmospheric sources probably contributed to the bulk of trace Pb measured.

The particular manufacturer appears to have little effect ($C[3,1] = -0.11$; $p > 0.3$) on Pb concentration measured in pumped water. However, the possibility exists that some manufacturers in the area produce pumps differently, but that because of the selection procedure in the field—e.g., the modified snowball method for participant selection—these unique manufacturers and their products were not encountered in the 18 household pumps I sampled. For example, Appendix II provides results from interviews with nine area manufacturers, including all of those that produced pumps incorporated in this study, as well as a few others. One of these technicians solely uses iron as a valve weight (see Figures 3 and 4 in Chapter 2), as opposed to the nominally pure Pb used by the majority of others. This manufacturer had been using iron for over two years, and switched to this material for economic reasons. I believe, based on personal interviews in the field, and supported by another study from the University of South Florida (MacCarthy et al., 2013), that over 50 different small businesses that manufacture and repair Pitcher Pump systems work in the city of Tamatave. Therefore, it is feasible that there are some other manufacturers like the one mentioned above, with unique materials or procedures that differ from the majority, and would provide different measurements for Pb concentration. This has not been determined, and so can only be hypothesized at present. However, it is also important to recognize that the first *Pompe Tany* manufacturer in the country, Mr. Masy, trained many of the earlier manufacturers, who then trained newer, current manufacturers, and this original process and materials list is the one generally followed as a consequence. It is likely, then, that most of the pumps and manufacturers in Tamatave will give data similar to those recorded. It is also noteworthy that Mr. Masy is still in operation, and four of his pumps were included in my study.

The depth to the well screen does not appear to be a major determinant of Pb concentrations, according to the PCA. It may be that because all of the pumps are relatively shallow—none greater than 10 meters into the ground—and/or because each pump is located in the same city, the water chemistry does not differ enough at the various depths to show a clear relationship with Pb leaching.

The collective results presented in Tables 6 and 7 suggest that the season, or time of year, will not affect Pb concentrations in water drawn from the pumps. The reason for this observation may be that the coastal groundwater in Madagascar does not change much with the seasons, or that a complex system of variables like groundwater constituents actually offset the potential for increased corrosion due to elevated temperatures. The December campaign took place just before summer begins in Madagascar with moderately dry, hot weather; next, the April campaign started in late March and went through early April, still in the middle of summer, and in the midst of the heavy rainy season; finally, the July campaign took place during winter, with lower temperatures and only light rains. However, results were similar in each campaign (Table 3), and the correlation matrix and PCA confirm this basic observation (Tables 6 and 7).

The contact time of water in the system, the variable with a supposed strong influence on Pb concentration (see Table 3), exhibits significant influence on Pb in multivariate analysis. In fact, the contact time gives the only statistically significant correlation with Pb concentrations (Table 6). Additionally, this variable contributes large loadings to the same PCs as Pb concentrations in Table 7. Thus, the PCA analysis, particularly the correlation matrix, strengthens the observations made in Section 4.1.

Next, this multivariate analysis was repeated for the dataset from the July 2013 sampling campaign. This sampling campaign has complete enough data to calculate a new variable, the corrosivity of the water in the form of the Langelier Saturation Index (LSI) (see Appendix V). For each sample, the low end of the estimated LSI range (see Appendix V) is used in place of seasonality, as the campaign dataset was collected in one season only, thereby maintaining a six-dimensional space of interrelated variables to evaluate. It should be noted that the high end of estimated LSI values was used in an identical analysis, but the results are generally very similar to those obtained with lower-end LSI values. Accordingly, only this first analysis is included in the text. Variables for analysis are defined in Table 8 below, followed by the corresponding correlation matrix (n = 28 measurements) in Table 9.

Table 8. Variables for Multivariate Analysis in July 2013

Variable	Symbol	Units
Pb concentration	z_1	µg/L
Pump Age	z_2	years
Manufacturer	z_3	discrete (1–6)
Depth to Well Screen	z_4	meters
Corrosivity (LSI)	z_5	dimensionless
Contact Time	z_6	discrete (1–2)

Table 9. Correlation Matrix for Multivariate Analysis of Variables in July 2013 Affecting Pb Leaching from Pump Components

	z_1	z_2	z_3	z_4	z_5	z_6
z_1	1.00					
z_2	0.12	1.00				
z_3	0.07	-0.16	1.00			
z_4	0.17	**-0.63**[a]	0.05	1.00		
z_5	0.16	**0.44**[b]	0.23	-0.17	1.00	
z_6	0.21	0.00	0.00	0.00	0.00	1.00

[a] Value is significant at $p < 0.001$

[b] Value is significant at $p < 0.05$

In column 1, the corrosivity (z_5) varies with the Pb concentration on a similar scale as the depth to the well screen, while the contact time (z_6) varies the most with Pb concentration. Unexpectedly, though, the more positive LSI values (i.e., less corrosive waters) are said to contribute to higher Pb concentrations. Unlike the first correlation matrix, no variable is said to have a significant ($p < 0.05$) correlation with Pb concentration. It is possible that the number of observations for this second analysis was insufficient to make meaningful contributions to the Pb concentrations ($n = 28$ as compared to $n = 84$). Another possible explanation for the unclear relationship between LSI and Pb concentration is that the LSI has historically shown varying, sometimes poor, correlation with measured corrosion rates (Crittenden et al., 2005). The LSI, based on theoretical pH, may be insufficient as a representative calculation of the corrosivity of water. Crittenden et al. (2005) demonstrate a relationship between the LSI and the Gibbs free energy driving force for carbonate precipitation, showing the parameter to be more useful when other aspects of carbonate chemistry are considered, namely calcium carbonate precipitation potential and the calcium carbonate saturation buffer intensity.

Column 2 indicates again that the depth to well screen varies the most with pump age at a statistically significant correlation ($p < 0.001$). Interestingly, while the corrosivity is shown to have only a moderate influence on Pb leaching, it correlates strongly with pump age ($C[5,2] = 0.44$; $p < 0.05$). The LSI is a measure of the tendency for carbonate to scale, not an indication of how much scale has formed (Section 3.2.2). Therefore, the only plausible interpretation of this correlation with pump age is that older pumps are generally installed in areas with more corrosive waters according to the LSI, i.e., lower pH/ higher alkalinity/ lower hardness (Appendix V). However, this interpretation is tenuous. I have no reason to believe that newer pumps are installed in less corrosive waters, especially with all locations within a 1.25 km radius of farthest neighbors.

Table 10. Principal Component Analysis of Variables Affecting Pb Leaching from Pump Components

Variables	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6
Pb Concentration	0.07	0.64	-0.32	-0.47	-0.47	-0.20
Pump Age	0.67	-0.06	-0.13	-0.13	-0.07	0.71
Manufacturer	-0.03	0.45	0.65	0.43	-0.36	0.23
Depth to the Well Screen	-0.57	0.30	0.03	-0.34	0.41	0.55
Corrosivity (LSI)	0.46	0.38	0.33	-0.16	0.64	-0.31
Contact Time	0.02	0.39	-0.59	0.66	0.25	0.06
Standard Deviation	0.43	0.23	0.45	0.45	0.44	0.41
Eigenvalues	1.86	1.34	1.11	0.85	0.60	0.24
Contribution to Variance	31.0%	22.4%	18.5%	14.2%	10.0%	3.9%
Cumulative Variance	31.0%	53.4%	71.9%	86.1%	96.1%	100%

The first PC in Table 10 gives a larger eigenvalue (1.86) than in Table 7, the next PC much lower at 1.34. PCs 1 and 2 contribute to over 53% of the variance as opposed to 49.1% in the previous PCA. However, it still takes until the inclusion of PC_5 to net > 90% of the cumulative variance. Furthermore, in PC_1, variables z_2, z_4, and z_5 all lend significant loadings, and variables z_1, z_3, z_4, z_5 and z_6 contribute substantial loadings to PC_2. So within two PCs, each of the original variables is said to contribute significantly to the overall variance. Based on the outcomes of the matrix in Table 10, the final PC could be dropped, but all of the original variables would still be included in explaining overall variance. Therefore, much like the first PCA in Table 7, no new patterns or relationships are made apparent in PCA. Furthermore, Table 10 is more ambiguous than Table 7, with several variables contributing sizeable loadings to the same components as Pb concentration, whereas in Table 7, contact time clearly showed the most defined relationship to Pb in PC loading distributions. However, contact time does still contribute several of the larger loadings to Pb-related PCs, as expected.

4.3 Time-Release Characterization of Pb Leaching and Pilot Studies for Material Component Substitution

Objective (2) concerns whether flushing the pumps will decrease Pb concentrations to levels below the WHO provisional guideline consistently. An auxiliary component of this objective is to characterize the equilibration of Pb-containing components with the water. Accordingly, two households were selected to participate in a time-release study for pumping times ranging from 0 to over 12 hours of contact time—or pump inactivity. Objective (4) for research on Pb leaching in Tamatave is to assess whether replacing Pb in check valve weights with iron (Fe) decreases Pb concentrations for pumped water. The same households participating in the time-release experiment, therefore, received pump renovations after participation in the time-release study, including new Fe check valve weights in place of the former Pb weights. After valve replacement, the time-release experiment was repeated entirely for these household pumps to evaluate Objective (4).

Figures 17 and 18 show results for Pb leaching over various periods of pump inactivity and with different valve components at the two participating households below. Data were collected at flushed, or time = 0 hours, then at time = 2, 4, 6, and 11.5–13 hours of contact time between the groundwater and the pump components. Each of the four time-release studies was conducted over a two-day period to allow time for the household residents to continue to make use of the pumps in between run times for experimental procedures. For Pump #18 (Figure 17), the second phase of data collection (e.g., after valve component replacement) was delayed until a few months after valve replacement to Sampling Campaign #2 in April 2013 due to limited time and materials in December 2012. Figures 17 and 18 present plots of both time-release studies along with the WHO provisional guideline for perspective.

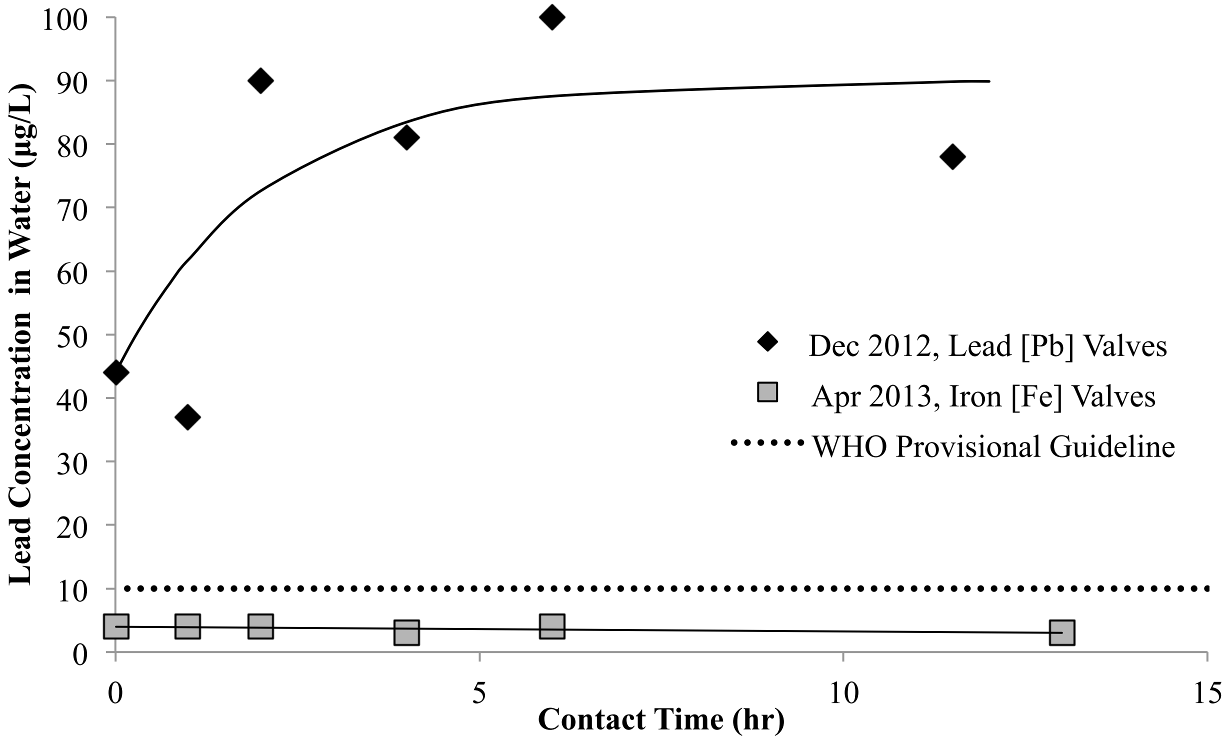


Figure 17. Pb concentration measured in water over time periods of nonuse for “Pump #18” with lead check valves weights, then repeated after replacement with iron valve weights.

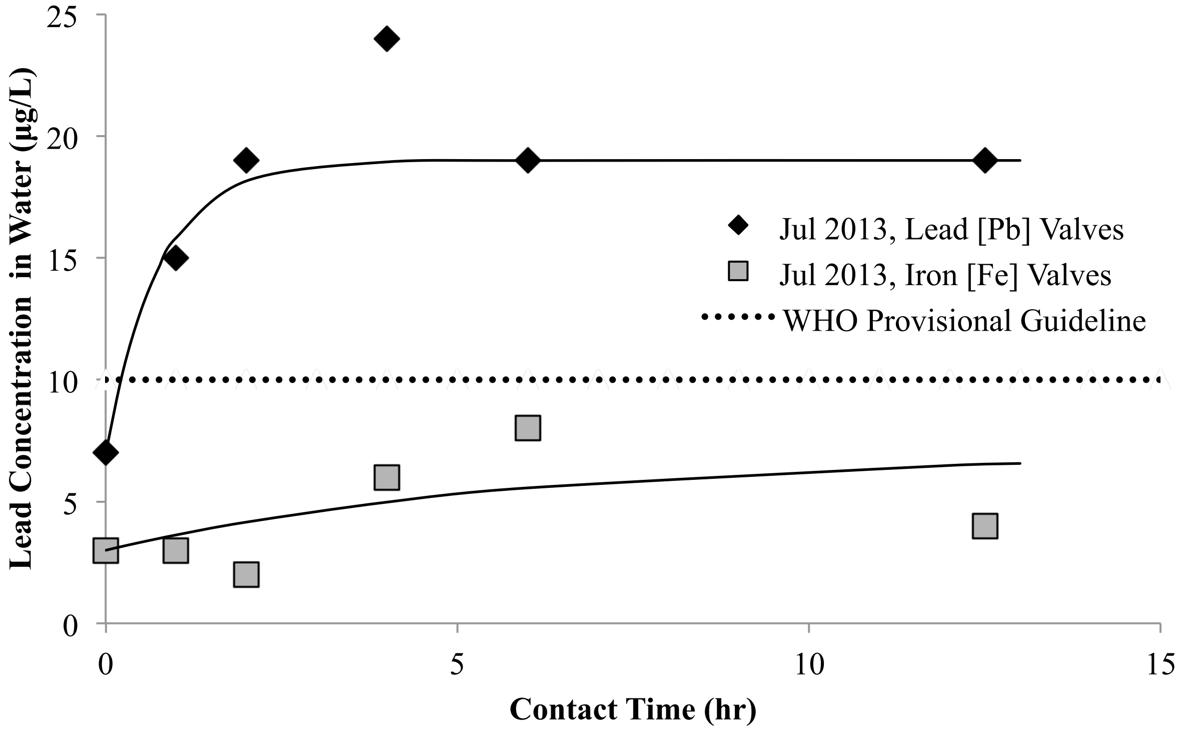


Figure 18. Pb concentration measured in water over time periods of nonuse for “Pump #8” with lead check valve weights, then repeated after replacement with iron valve weights.

Based on Figures 17 and 18, when a well is not in use, the concentration of Pb in the water generally increases over time as the leaded pump components equilibrate with water. This observation strengthens observations made in Sections 4.1 and 4.2 regarding Objective (2) of the thesis, and provides additional evidence for the need to flush the pumps prior to use, especially because longer periods of inactivity are realistic for residential use of the pumps. A preliminary estimate of equilibration time is approximately 4–30 hours, based on estimates of an apparent first-order rate coefficient, k_i, describing the equilibration of the water with the pump. Curve fits approximating this equilibration process with all Pb-containing components were obtained with a modified first order kinetic reaction equation and plotted along with the data (Figures 17 and 18).

Table 11. First Order Pb Equilibration Fits for Time-Release Studies

Sampling Campaign	Computed k_i Value for Equilibration Process	Estimate of Equilibration Time ($5/k_i$)
December 2012[a]		
Lead Valves	0.49/h	10 h
July 2013		
Lead Valves	1.3/h	3.8 h
Iron Valves	0.17/h	29 h

[a] The data obtained from iron components evaluated for Pump #18 in the April 2013 campaign are not included because the data are fairly linear and seem to have already reached equilibrium at the earliest sampling time.

In both pilot studies, replacing leaded pump components with iron components decreased the concentration of Pb in the water. The first pump showed a drastic decrease, ranging initially from 37–100 μg/L with Pb components, and decreasing to 3–4 μg/L with the iron replacements. The second pump decreased in measured concentrations from 7–24 μg/L down to 2–8 μg/L. Both retrofitted pumps showed concentrations below the WHO provisional guideline after valve replacement, even after exceeding 12 hours of contact time. This suggests that retrofitting existing pumps could be a reasonable strategy for decreasing the likelihood of high Pb exposure in Pitcher Pump users. This observation confirms that the replacement of pure Pb valve weights with Fe weights reduces Pb concentrations in water drawn from the same pump. Also noteworthy is that Pump #18, whose valves were replaced in December 2012 following the first sampling campaign, continued to show low levels of Pb in the final sampling campaign (July 2013), with 2 μg/L under both flushed and first-draw pumping conditions.

A third conclusion from Figures 17 and 18 is that amongst all the leaded components used in *Pompe Tany* systems, the Pb valve weights might contribute the most to the dissolved Pb in pumped waters. The remaining components, the solder and well screen, still leach into the water, or the lower plots in Figures 17 and 18 would always show results below 2 μg/L (the lower detection limit of the ASV instrument). However, it appears that the contribution from the solder and the well screen is low compared to the contribution from the valve weights for the two wells considered here. One reason for this difference could be that Pb valve weights are nominally pure, while the brass screen and solder are only alloys with Pb (EPA, 1996; Patnaik, 2003; Crittenden et al., 2005). Though with a smaller overall surface area than the fittings, the Pb valve weights have much more Pb at the surface exposed to water, and therefore provide a more plentiful source of leachable Pb. The effects of alloyed Pb content and surface area are likely important; one study saw that fittings in household plumbing accounted for 0.7–2.6% of total Pb in water, while onsite lead piping accounted for a greater 21–37% (Sandvig et al., 2008).

If the pumps were truly flushed, then theoretically no Pb would be leaching into the water at time = 0 hours. In both figures, the flushed condition does not provide the expected Pb concentration of zero; the concentrations in the flushed sample varied from 3–43 μg/L in the samples indicated in Figures 17 and 18. Also evident in both figures is that the flushed condition does not provide the same Pb measurement after valve replacement. These observations suggest two possibilities. First, perhaps a rapid equilibration takes place as the water passes through the pump, due to increased rates of mass transfer with high driving force, which might explain the jump in concentration for the flushed conditions from the zero value. Furthermore, pumps with the Pb valves force pumped water into contact with more leaded components, which could explain the drop in Pb concentrations post-renovation. Another possibility is that the volume removed from the pumps during flushing was not enough to completely remove previously dissolved Pb from the local environment, both in the pump well and immediately surrounding the well screen, possibly due to complex flow conditions that create vortices in the well casing and pump head. This prevents the total amount of leached Pb from being removed during flushing so initial Pb concentrations are greater than zero. However, this contribution to the Pb concentration should be low. According to reactor theory, the concentration of a conservative chemical in a plug flow reactor (PFR) changes directly with the incoming stream (Mihelcic and Zimmerman, 2014). For a completely mixed flow reactor (CMFR), however, the change in concentration within the system is dictated by exponential decay (Mihelcic and Zimmerman, 2014). Therefore, one entire volume flushed through a system should remove all of the Pb if the Pitcher Pump system can be treated as a PFR, or about 92% should be removed after 2.5 volumes of flushing if the system can be treated as a CMFR. Assuming the Pitcher Pump acts as a mixture between these two idealized reactors, it is reasonable to assume that most of the original Pb in solution would be removed after 2.5 volumes are flushed. Thus, the first scenario of rapid dissolution seems more likely to explain flushed concentrations above zero.

Iron may present practical issues in implementation as the material for Pb-component substitution. The Fe valve weights might rust and could thereby introduce particles into the water. It is feasible, though not likely, that valve repairs might increase in frequency due to rust weakening the system. More importantly, iron may cause water quality issues. Iron is not expected to pose a health risk for users, as 2–50 mg/L are typical iron concentrations found in natural fresh waters (WHO, 2011a). In fact, there is no WHO guideline for this element naturally found in water (WHO, 2011a). The true concern with Fe in drinking water is that it may affect user acceptability—even at levels below 2 mg/L—due to color and taste issues (WHO, 2011a). Essentially, ferric iron (iron oxidized by exposure to the air or iron-dependent bacteria) can create ferric hydroxide particles and cause a reddish color to be present in the water, and can stain clothing at around 0.3 mg/L (WHO, 2011a). This latter point could be of concern because the Pitcher Pump is a culturally accepted water supply technology at present. Visible changes in water quality could cause barriers to retrofitting current systems, and for the acceptability of new systems (WHO, 2011a). However, the valve weight is a small contribution to the overall Fe in the system (Section 2.4.2) and observations in the field did not show high levels of rust or reddish water produced from Pitcher Pumps currently in use. Thus, Fe valve weights are not expected to contribute major practical issues for domestic use or acceptability.

4.4 Preliminary Assessment of Potential Public Health Implications

Objective (5) of this thesis is to make a preliminary assessment of the public health implications of Pb exposure from Pitcher Pump systems. The most vulnerable population to Pb exposure is young, developing children (ATSDR, 2007; WHO, 2011a). In absence of accurate measurements of BLLs in Tamatave for this group, the EPA IEUBK Model, described in Chapter 3, was used to estimate theoretical distributions of BLLs in this target population. The model uses common Pb exposure routes, biokinetics and constants derived from the literature to inform the model's prediction of BLLs (EPA, 2007; Appendix VII). The results included in this section are not actual data, then, but model estimates of what could be occurring, included simply to give an indication of possible health-related outcomes from consuming water from Pitcher Pump systems.

Table 12. Output Projections from the EPA IEUBK Model for Selected Scenarios for Children Aged 0–59 Months

Scenario ID	Geometric Mean BLL[a,b] (μg/dL)	Population Above BLL = 5 μg/dL	Population Above BLL = 10 μg/dL
1a	1.9	1.8%	0.02%
1b	4.4	40%	4.2%
2a	2.4	6.4%	0.1%
2b	5.0	49%	6.7%
3a	2.5	7.4%	0.2%
3b	5.0	51%	7.2%
4a	3.2	17%	0.7%
4b	5.6	60%	11%
5a	3.8	28%	2.0%
5b	6.2	67%	15%
6a	3.9	29%	2.2%
6b	6.2	68%	16%
7a	5.7	60%	11%
7b	7.8	83%	30%

[a] Model outputs include a geometric mean Blood Lead Level (BLL) for a log-normal distribution in a population ag
choice, here 0–59 months (children < 5 years).

[b] The standard deviation is an assumed value of 1.6, taken from EPA (2007) and is based on the documented variability of Pb uptake in populations with similar exposures.

The output projections presented in Table 12 show the geometric mean BLLs for children under five years of age, the most vulnerable age group to Pb exposure. Also included are the percentages of the theoretical population above 5 and 10 μg/dL BLL in each scenario. The “b” scenarios (i.e., scenarios with upper limits of the exposure routes other than water) generally increase the BLLs strongly as compared to the “a” scenarios (i.e., scenarios with lower limits of pathways other than water). This observation demonstrates the need for accurate measurements and characterization of these other exposure routes. Also apparent in the table is that significant portions of the population could be at risk for elevated BLLs based on concentrations of Pb in water measured in the field. This is more clearly evident in Figures 19 and 20.

Figures 19 and 20 show the probability density function and the cumulative distribution, respectively, plotted with the former and current CDC definitions of elevated BLLs (10 and 5 μg/dL, respectively) for perspective (CDC, 2012). Scenario 2a, the lowest exposure scenario included in these figures, has water concentrations equal to the median overall values measured for flushed and first-draw samples. According to these estimates, 6.4% of the population is above a BLL of 5 μg/dL. This may indicate that there is little risk of significant Pb exposure. The next scenario included (Scenario 4b) uses the mean measurements of Pb concentrations plus one standard deviation and changes "other exposures" to moderately low concentrations. The population sees in increase in 3.2 μg/dL for the resulting geometric mean BLL, and Figure 20 shows that over half of the population would be classified as having an elevated BLL under scenario 4b. Scenario 7b is considered the most extreme scenario that can find a basis in my field measurements. One household actually registered a concentration greater than 100 μg/L at six hours of pump inactivity (Figure 17; Appendix V). It is feasible then, that this concentration could be characteristic of the first draw for a pump in Tamatave, particularly after a night without pump use.

Note that the IEUBK model assumes that the children are eating a healthy diet, and it cannot take into account such common problems in developing nations as iron deficiency. The additional physical strains that malnourished children in developing countries face make them likely to absorb more of the Pb to which they are exposed (Tong et al., 2000; Fewtrell et al., 2003; Ahamed and Siddiqui, 2007). The IEUBK Model would need a literature-based change of parameters to better predict likely BLL distributions. These results, then, could be underestimates of actual distributions of BLLs in children in Madagascar, and this possibility provides additional weight to the preceding table and figures.

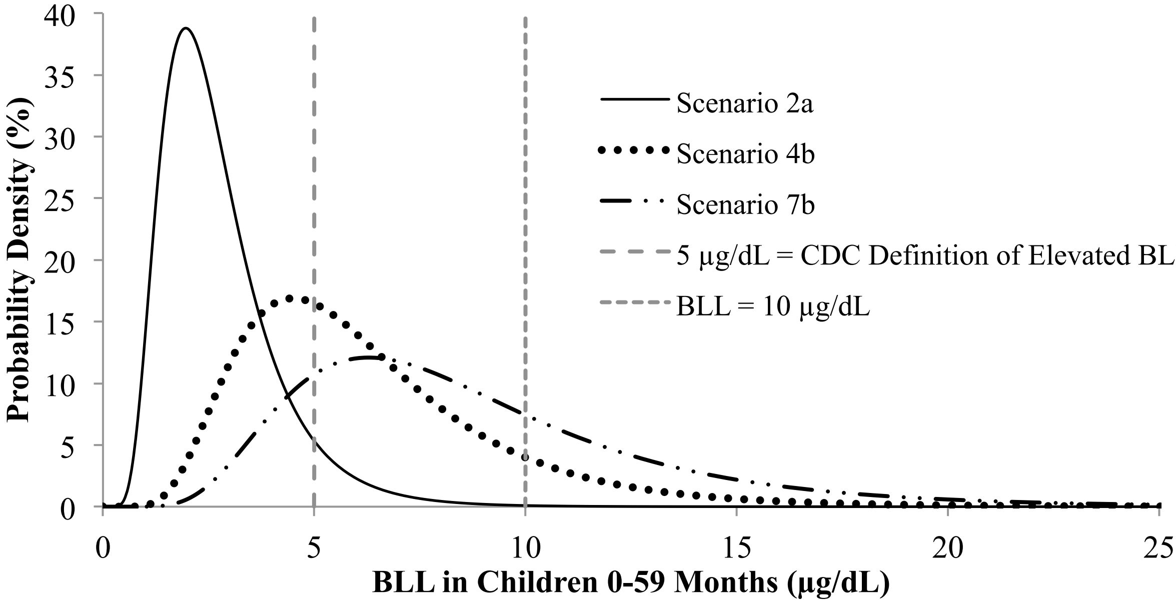


Figure 19. Probability density function plot of IEUBK-predicted BLL for children under 5 years of age under exposure conditions set by Scenarios 2a, 4b, and 7b. These scenarios are thought to represent low-, medium-, and high-risk realistic scenarios related to possible concentrations of Pb in water drawn from Pitcher Pumps. Current and former CDC definitions of elevated BLL are included for perspective (CDC, 2012).

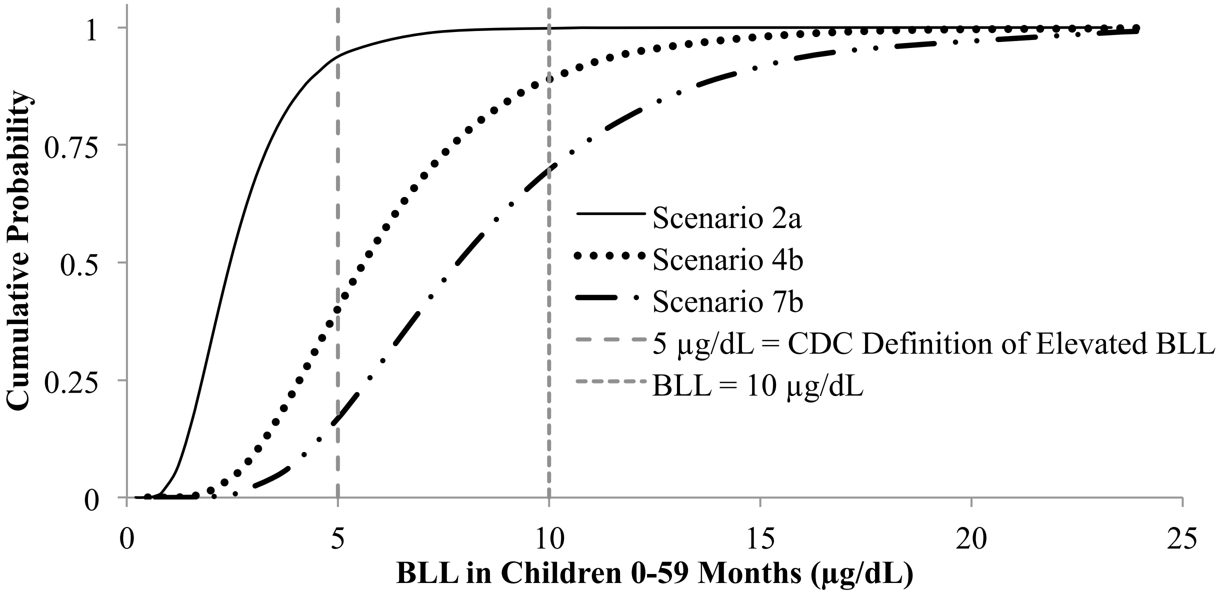


Figure 20. Cumulative distribution function plot of IEUBK-predicted BLL for children under 5 years of age under exposure conditions set by Scenarios 2a, 4b, and 7b. As with Figure 19, the current and former CDC definitions for elevated BLL are plotted for perspective.

The literature provides plenty of evidence for negative health impacts at BLLs in the ranges presented in this chapter, including a loss of IQ and increased incidence of mild mental retardation, behavioral effects and increased blood pressure in small children (Lanphear et al., 2000; Fewtrell et al., 2003; WHO, 2011b). Any health-related damage done, particularly to the central nervous system, is generally irreversible (Fewtrell et al., 2003; Rossi, 2008). All IEUBK Model simulations were based on water Pb concentrations measured in the field and reasonable estimates of concentrations of Pb for other exposure routes. Furthermore, Pb in water that would ultimately enter the diet via food preparation is presently unaccounted for, and would potentially increase total exposure (EPA, 2007; Appendix VII). Thus, these model projections serve to show that consumption of water drawn from Pitcher Pump systems in Madagascar could lead to BLLs in small children that exceed the CDC guideline for an elevated BLL, and thereby put children at risk for potential health issues.

4.5 Limitations in Field Sampling Protocol and Detection of Pb

A common problem in characterizing Pb in water is the inaccuracy that can present itself as a result of deficiencies in the sampling protocol and execution. Because Pb has important health implications even when present at low concentrations (10 μg/L), a method for quantification capable of precise and accurate measurements at low concentrations is required. To achieve accurate measures of Pb in water, thorough protocols should be followed and measurements performed with rigorous instruments. However, sometimes there are practical restrictions on the field procedure, especially in the field. Therefore, our results should be viewed and interpreted with those restrictions in perspective. Listed in Table 13 are the summarized methods approved by the EPA and commonly accepted in the literature (Triantafyllidou et al., 2013). The WHO does not subscribe to one method in particular (WHO, 2011b).

As can be seen in Table 13, only a few instruments and protocols are approved. Also notable is that some level of sample pretreatment is required for all methods. A lack of pretreatment of samples can cause all Pb not readily soluble (e.g., particulate, complexed, and colloidal) to go undetected, and organic surfactants and ligands may go beyond complexing with Pb to actually foul the electrode and decrease sensitivity (Nimmo and Fones, 1997; Bonfil and Kirowa-Eisner, 2002; Triantafyllidou et al., 2013). Particulate Pb, depending on its specific bioavailability, can prove a significant contribution to overall uptake (Deshommes and Prévost, 2012). Therefore, the impact of these limitations on data is a possible underestimate of Pb.

Table 13. EPA-Approved Analytical Methods for LCR Compliance Monitoring of Total Lead in Drinking Water Samples in the USA as Listed in the Federal Register (US EPA, 2009), and Specific Sample Pre-Treatment Requirements for Each Method (US EPA, 1994a, b, 2003; Palintest, 1999; APHA et al., 1998)[a]

Method approved for lead compliance monitoring under the lead and copper rule[b]	Instrumentation[c]	Sample pre-treatment requirement: Standard preservation	Sample pre-treatment requirement: Aliquot digestion
EPA 200.8 Rev 5.4	ICP-MS	Yes	Not unless turbidity (>1 ntu)
EPA 200.9 Rev 2.2	STGFAA	Yes	Not unless turbidity (>1 ntu)
Palintest Ltd. or Hach Co. Method 1001	DPASV[d]	Yes	Yes
Standard Method 3113 B	EAA	Yes	Not unless turbidity (>1 ntu)
EPA 200.5 Rev 4.2	AVICP-AES	Yes	Yes

[a] This table is reproduced from Traintafyllidou et al. 2013 with permission from Springer (Appendix I). For particular definitions of technologies and a more in-depth explanation of methods listed and approved, see the original paper and listed references (Triantafyllidou et al., 2013)

[b] Either an original EPA method or a third-party method approved by the EPA

[c] ICP-MS (inductively coupled plasma-mass spectrometry); STGFAA (stabilized temperature graphite furnace atomic absorption); DPASV (differential pulse anodic stripping voltammetry); EAA (electrothermal atomic absorption); AVICP-AES (axially viewed inductively coupled plasma-atomic emission spectroscopy)

[d] DPASV is used in my thesis for Pb measurement (Chapter 3)

The most basic process for sample preparation includes standard preservation, defined by the addition of 0.15% nitric acid and subsequent storage for a minimum of 16 hours to allow for the dissolution of Pb particles in the acidified water (Triantafyllidou et al., 2009). In relatively turbid waters, further digestion is required; for differential pulse anodic stripping voltammetry (DPASV), further digestion is always required (Triantafyllidou et al., 2013). Another motivation for including a digestion step is a documented limitation of the Palintest® SA1100 instrument—used in this thesis research—to measure particulate Pb in solution (Cartier et al., 2012). Because the instrument cannot read particulate Pb, presumably a shortcoming in all instruments, an acid digestion step is necessary for accurate readings of the total Pb concentration (Triantafyllidou et al., 2013).

Regarding particulate Pb, most of these particles would be present as small pieces of leaded components due to physical or chemical corrosion. In a water distribution system, possible sources could include tap aerators, solder, pure Pb piping in the distribution system, or Pb adsorbed onto iron deposits in the distribution system and household plumbing (Triantafyllidou et al., 2009; Deshommes et al., 2010; Cartier et al., 2011; Triantafyllidou et al., 2013). Unfortunately, the presence or quantities of these particulate forms of Pb in water are difficult to predict due to their random nature of leaching, depending on household usage patterns and disturbances like system component replacement (Sandvig et al., 2008; Deshommes et al., 2010; Cartier et al., 2011). One study showed that fittings in household plumbing contributed less to total Pb than Pb piping, but that both introduced Pb particles to the system (Sandvig et al., 2008). Furthermore, EPA-approved sampling protocols have been shown to miss up to 80% of total Pb as particulate Pb (Triantafyllidou et al., 2009). Another study showed that particulate Pb from household plumbing contributed from < 3 μg/L up to 4–12 μg/L in some cases, which were not accounted for with EPA-approved testing (Deshommes et al., 2010). The literature highlights the sporadic nature of Pb particulates and emphasizes the importance of careful procedures to quantify total Pb in water samples.

Based on this information, one might worry that the sampling protocol employed in this study (detailed in Section 3.2.1) potentially missed great portions of the total Pb. However, the water sampled in the US- and Canada-based studies referenced above passed through many more Pb-bearing fittings and piping as compared to the Pitcher Pump systems. This means that water in those studies was exposed to much more surface area Pb and had much greater opportunity to wear or slough particles from the system. Pitcher Pump systems include two small Pb valves (~23 cm^2 surface area each), approximately 96 cm^2 area of brass screen, and approximately 64 cm in length of Pb-Sn soldering (~16 cm^2), compared to the miles of piping and fittings present in the West. Furthermore, the water I analyzed in this study appeared visually clear, whereas other studies typically show particles that are visible to the human eye (Triantafyllidou et al., 2009; Deshommes et al., 2010; Cartier et al., 2011; Triantafyllidou et al., 2013). Therefore, the importance of particulate Pb in Pitcher Pump systems is hypothesized to be moderate. Yet, it remains pertinent to classify the contribution of particulate Pb in at least some samples.

However, I encountered practical limitations to the work I could carry out in the field. First, I could not spend excessive amounts of time away from my assigned Peace Corps site, a community which is located about 150 km away from Tamatave. Travel to and lodging in Tamatave could be relatively expensive, and a minimum of one full day (train schedules were irregular) of travel was necessary just to arrive. Therefore, my time in the field was extremely limited. Next, there were no laboratories available for collaboration. Accordingly, I could not use readily available acids and bases or store samples before analysis. Finally, the cost to ship items to Madagascar, particularly large quantities of strong acids and bases, was prohibitive. In light of these problems, I was forced to carry out my sampling and analysis all in the field, under a strict timeframe. Due to these practical limitations, I could not complete an acid digestion step in my analysis of Pb concentrations in pumped water. The Pb concentrations I recorded, therefore, could be underestimates of the total Pb in waters drawn from Pitcher Pump systems.

In addressing some shortcomings in sample pretreatment, there is reason to believe that any complexed Pb could be accounted for by the instrument. The Palintest® SA1100 underwent a limited field trial at the University of South Florida before being shipped to Madagascar for application in the field. Appendix VIII shows summarized experimental conditions and measurements of spiked Pb concentrations. The instrument was evaluated using known concentrations and levels of dissolved oxygen and pH, simple criteria determined to be important for possible variables in the field (Bonfil et al., 2002; Baldrianova et al., 2011). Consistent instrument performance in this trial shows that realistic variations in pH and dissolved oxygen have little effect, if any, on measurements of Pb. Additionally, a field evaluation of the Palintest® SA1100 by Cartier et al. (2012) shows that the method is accurate over the range of 2–50 µg/L ($R^2 = 0.991$) when measurements are checked against inductively coupled plasma-mass spectroscopy.

Under non-ideal circumstances, and with the support of this information for the ASV unit, I carried out the field sampling in the best way possible. However, I acknowledge that deficiencies in the protocol may have led to a general underestimation of Pb concentrations in water. Nevertheless, an underestimate of the median Pb concentration, or of the number of pumps exceeding the WHO provisional guideline for Pb in water does not discredit the findings in Table 3; rather, it strengthens those findings and suggests that the problem of Pb leaching may be more severe than indicated by the sampling procedure.

4.6 Chapter 4 Synopsis

To review the results and discussion presented here, I will reiterate important results and how they satisfy research objectives. Table 3, in answer to Objective (1), presents a survey of Pb concentrations in water drawn from Pitcher Pumps in Tamatave, Madagascar. The resulting profile suggests that pumps produce water with dissolved Pb, often above the WHO guideline of 10 μg/L. Regarding Objective (2), Table 3 gives evidence that flushing pumps can reduce the frequency with which pumps in the area exceed that guideline, from 67% after just an hour of inactivity, down to 35% after flushing. Section 4.2, particularly Tables 7 and 10, give the analysis of Pb-leaching behavior and external factors called out in Objective (3). Section 4.2 concludes that contact time is the only variable found to affect Pb concentration at a statistically significant level with 95% confidence. Corrosivity could be important, but cannot be shown to affect Pb concentration significantly with a 95% confidence interval. Objective (4) is satisfied in the pilot studies for Pb component replacement presented in Figures 17 and 18, which indicate that valve replacement effectively lowered the pumped Pb concentrations in both cases to below the level of concern of 10 μg/L, even over long periods of pump inactivity. Figures 17 and 18 also lend evidence to fulfill Objective (2), showing that waters equilibrate with leaded pump components over time, and suggesting that flushing pumps prior to use will reduce Pb concentrations.

Section 4.4 addresses Objective (5) by using field data for Pb concentrations in water to inform model predictions of resulting child BLLs, which shows that elevated BLLs resulting from consuming Pitcher Pump water is possible. Table 12 presents the estimated outputs for different exposure scenarios, and the resulting populations above the CDC definition of an elevated BLL of 5 μg/dL. The table, accompanied by Figures 19 and 20, serves to show that it is possible that large percentages of the under-five population in Tamatave—as much as 83%—could have elevated BLLs as a result of consuming water from the Pitcher Pumps. These results are qualified in that exposure pathways other than water are not characterized, and the basis for subsequent evaluation is only a model prediction. However, the assessment called out in the objective is only preliminary, and therefore Section 4.4 achieves this goal. Furthermore, there is reason to believe that Pb field measurements are lower-end estimates of actual total Pb. Therefore actual BLLs could be higher than the estimates included in my thesis.

CHAPTER 5: CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

5.1 Conclusions and Main Findings

The Pitcher Pump has been proven to be a sustainable option for water supply in Tamatave. Many of those who lack access to other methods of water supply have invested in improving their livelihoods with this technology. The resulting market is providing an invaluable service which should be protected and promoted by government and NGOs alike. However, as over half of households in Tamatave report using water from the *Pompe Tany* for drinking and cooking, it is important that, to the extent possible, Pitcher Pump systems provide water that is of reasonable quality and do not introduce users to any contaminants that are not naturally found in the local environment. Therefore, to guarantee the future sustainability of this technology, safe water quality should be ensured in addition to the realized benefits of quantity. Consistent with this aim, the first five objectives of this research are:

(1) to conduct a preliminary survey of Pb concentrations in water drawn from Pitcher Pumps at several households in Tamatave, Madagascar;

(2) to determine if Pb concentrations in pumped water decrease after flushing the pumps;

(3) to perform a preliminary analysis of the correlation between Pb concentrations and pump characteristics such as age, depth to water table, manufacturer, season and/or water quality;

(4) to assess whether replacing Pb in check valves with iron decreases Pb concentrations; and

(5) to make a preliminary assessment of the public health implications of Pb exposure from Pitcher Pump systems.

Conclusions and findings are listed below in a manner corresponding to the research objectives outlined above. Thus, this study finds:

(1) Water drawn from Pitcher Pump systems is frequently contaminated above the WHO provisional guideline of 10 μg/L Pb, especially under first-draw pumping conditions.

   a. Approximately 67% of samples were measured at levels above the guideline under first-draw conditions.
   b. Of 18 Pitcher Pump systems included in the study, 15 showed contamination above 10 μg/L for at least one sampling event during three sampling campaigns.

(2) The process of flushing Pitcher Pump systems before collection significantly decreases the probability of drawing water above the WHO provisional guideline.

   a. Flushing Pitcher Pump systems approximately 2.5 times the respective well volumes produced samples that exceeded the guideline 35% of the time vs. 67% of samples exceeding the guideline under first-draw conditions.
   b. In all three sampling campaigns, < 40% of flushed samples exceeded the guideline, compared to > 50% of first-draw samples exceeding the guideline.
   c. There is a statistically significant increase in Pb concentrations of first-draw samples ($p < 0.0001$) as compared to flushed samples.
   d. Contact time (i.e., whether water is drawn under flushed or first-draw conditions) has a statistically significant positive correlation with Pb concentrations in water ($p < 0.05$).

    e. As water sits in contact with leaded pump components, Pb tends to leach from those components until soluble Pb comes into equilibrium with the water, reaching apparent equilibrium in a time scale of a few hours to several hours.

(3) Of the variables evaluated in this study, only contact time showed a statistically significant correlation with Pb concentrations in water.

    a. Principal Component Analysis (PCA) confirmed observations made in the correlation matrix that variables such as pump age, manufacturer, and depth to the well screen do not generally affect Pb leaching, or do not contribute to the same principal components in data variance.
    b. Seasonality showed no correlation with Pb leaching in the correlation matrix or the PCA matrix.

(4) Replacement of Pb valve weights in Pitcher Pump systems decreases the concentration of soluble Pb to below the WHO guideline consistently, and therefore, most of the soluble Pb likely leaches from the Pb valve weights included in most Pitcher Pump systems.

    a. In one pilot study, first-draw samples after 6–11.5 hours of pump inactivity in a system with Pb valve weights showed levels 9 to 10 times the WHO provisional guideline; after valve weight replacement with Fe, the same pump produced waters around 3–4 µg/L, even following 13 hours of pump inactivity. Pb concentrations remained around 2 µg/L several months later in the final sampling campaign.
    b. In the other pilot study, first-draw samples after 6–12.5 hours of pump inactivity showed levels approximately twice the WHO provisional guideline; after valve weight replacement with Fe, the same pump produced waters around 2–8 µg/L, even after 12.5 hours of pump inactivity.

(5) Pb concentrations observed in the field have the potential to result in children under five having mean BLLs above 5 μg/dL, which is considered an elevated BLL by the CDC. Important health implications have been associated with BLLs above 5 and 10 μg/dL (Lanphear et al., 2000; Lanphear et al., 2005; WHO, 2011a; CDC, 2012).

   a. The EPA IEUBK Model predicted the geometric mean BLL of children under five years of age to be between 1.9 and 7.8 μg/dL, depending on the model exposure scenario. Of the 14 scenarios considered, 36% predicted a geometric mean BLL above 5 μg/dL.
   b. An exposure scenario including median-measured Pb concentrations in both flushed and first-draw samples provided a geometric mean BLL approximately equal to the CDC guideline, with 49% of the population of children under five above this level (Table 2; Table 12).
   c. An exposure scenario including a high first-draw concentration and a low flushed concentration projected that >80% of children under five would have BLLs exceeding the current CDC guideline, and furthermore, 30% of the population would exceed the former CDC guideline of 10 μg/dL (Table 2; Table 12).

In summary, Pitcher Pump systems tend to leach Pb at concentrations that might be of concern for children under 5 years of age whose households use Pitcher Pumps for drinking and/or cooking water in Tamatave, Madagascar. Though the contribution of Pb exposure from cooking water is not directly considered in this work, its inclusion would only increase the overall Pb exposure and uptake. Pitcher Pump systems produced waters with Pb at levels of concern, largely independent of factors other than contact time of water with Pb-containing components. The Pb water concentrations measured in the field provide scenarios of concern for

EPA modeling of Pb exposures in children. However, flushing Pitcher Pump systems before drawing water significantly decreased the likelihood of consuming water with Pb contamination above the WHO provisional guideline. Furthermore, Fe-for-Pb substitution of check valve weights reduces the concentrations of Pb consistently below 10 μg/L. These simple modifications in pump use and fabrication offer simple strategies to substantially reduce risk from exposure to Pb in water drawn from Pitcher Pumps.

5.2 Recommendations for Action

Objective (6), the final objective of this research, is to make culturally, economically, and environmentally appropriate recommendations for dealing with possible contamination of water drawn from Pitcher Pump systems. Therefore, based on field observations, interviews with pump users and manufacturers, the conclusions made in Section 5.1, the successful history of the Pitcher Pump as a sustainable Self-supply water technology, and the need to ensure its future success and sustainability in coastal Madagascar, I recommend the following:

(1) Pump users should be taught to flush pumps before collection for direct consumption, especially after long periods of pump inactivity such as first-draw times in mornings. A reasonable amount to flush might be 2.5–3 times the well volume, which will vary in total volume pumped (i.e., buckets) depending on well depth.

(2) Pump users should be educated that flushed water remains suitable for household water needs other than cooking and drinking such as washing clothes, cleaning, and hygienic behaviors, and should not be "wasted."

(3) Pump manufacturers should receive training on the ability to use Fe components to fabricate valves in lieu of Pb components, and on the public health considerations that

establish this need. Graduates of this training should be eligible to train other manufacturers locally and in other coastal areas of Madagascar.

(4) Pump manufacturers should be taught that the use of Fe in place of Pb has the potential to make the manufacturing process more profitable through use of less expensive materials, and that the service of retrofitting existing pumps for valve replacement can be advertised as an improvement to water quality, perhaps creating business. Along these lines, pump manufacturers should be trained at a basic level in marketing to support new business practices and promote pump retrofitting.

Taken together, these recommendations can be part of a holistic intervention to promote the most effective use of the Pitcher Pump by improving water quality. Recommendations made to pump users and manufacturers should fit within the context of urban Tamatave, and the means of the parties involved. These water points are not centrally managed, nor is water quality monitored by a government entity. These circumstances are not likely to change in the near future. As such, guidance for improving water quality and mitigating the potential threat from elevated Pb exposure must be affordable and appropriate for a household or an independent manufacturer and small business owner to implement.

Accordingly, Recommendations (1) and (2) aimed at pump users do not seek to drastically change the existing behaviors of the public, hopefully only the order in which water is drawn for certain purposes. The Pitcher Pump has proven to be a culturally acceptable technology, in large part due to its convenience. If the general process of flushing pumps before use is promoted—without the auxiliary message of continuing to make use of that flushed water—not only might the public refuse to change behaviors (e.g., adopting longer pumping times and exerting more work), significant amounts of water could be wasted. The repurposing of first-draw water to household activities, rather than merely flushing the pumps and disposing of flushed water, attempts to address the potentially negative environmental trade-off of flushing pumps. However, personal behavior change in any form is notoriously difficult to achieve; often education is not enough to sustainably influence to adoption of new behaviors (Abrahamse et al., 2005; Panter-Brick et al., 2006; Mihelcic et al., 2009; Greenwell et al., 2013). Therefore, interventions to limit Pb exposure might be most effective at the manufacturing level.

Recommendations (3) and (4) seek to change the manufacturing process as simply as possible (e.g., changing out the predominant material for valve weights and thereby eliminating the largest contributor to soluble Pb). These recommendations attempt to facilitate this change with an emphasis on the economic benefit, which is naturally occurring in material costs. In fact, as noted previously in Section 4.2, one manufacturer encountered in Tamatave—outside of the sampling campaign—had altered his fabrication process to utilize Fe in place of Pb two years prior (Appendix II). The manufacturer claimed to have changed his practices purely for economic reasons, as he was unaware of any health problems associated with Pb. This anecdotal evidence provides a positive sign that Recommendations (3) and (4) have the potential for adoption. Additionally, replacement of Pb materials in Pitcher Pump systems decreases the spread of Pb to the local environment and exposure to users. These recommendations can also protect the health of the manufacturers and other artisans who work with Pb on a regular basis. Some artisans spend significant amounts of time harvesting Pb from plating in old car batteries, melting it down for repurpose and resale. Pump manufacturers melt the Pb to cast it for valves, which could lead to airborne Pb exposure.

Another consideration for these recommendations is the existing market for Pitcher Pumps in Tamatave. This technology has successfully supplied water to thousands of families for over half a century, organically growing in scale over time. Any interventions taken by the government, by NGOs, or by other entities must be mindful of the potential to damage the existing market for must be mindful of the potential to damage the existing market for Self-supply water in Tamatave. Steps should be taken to frame messages in a way that encourage the use of pitcher pumps while stressing the importance of flushing before drawing water for drinking and cooking and valve replacement. Any intervention should benefit both users and manufacturers, and current users should be encouraged to demand improvements to Pitcher Pump systems (e.g., new materials and services) from the local manufacturers.

5.3 Areas for Future Work

An *ideal* recommendation, not included in Section 5.2, is the formal regulation of *Pompe Tany* manufacturing and the effective barring of Pb in valve construction. However, this would be difficult, if not impossible, to implement. From informal discussions with manufacturers, some do not have the necessary license to be recognized by the local government as a small-business provider of this technology. Additionally, no monitoring in product quality is present aside from the licensing fee, which concerns operating a small business, not specifically water supply. In summary, there are no mechanisms presently in place to evaluate compliance with a regulated change in accepted manufacturing processes.

Furthermore, formal recommendations made to the government, locally and nationally, must meet certain criteria when taking into consideration budget allocations and legal necessities. Essentially, then, very detailed and definitive information about the potential health risks should be documented before specific regulations are proposed. The WHO suggests a process for informing public policy change with respect to Pb exposure and public health (Fewtrell et al., 2003). Specifically, WHO proposes that population BLLs be properly evaluated and weighted, particularly for children, that environmental exposure routes be accurately characterized, and that estimates of disease burden (i.e., DALYs) be considered carefully in policy formations.

Therefore, areas for future work, some of which are designed to follow WHO guidelines for informing public policy related to Pb exposure, include the following.

(1) Another round of Pb-testing of water should be carried out in Tamatave, perhaps spanning more neighborhoods and manufacturers, or extending to other coastal areas in Madagascar with Pitcher Pumps, but with a more rigorous experimental procedure to account for total Pb rather than only soluble Pb.

(2) Samples of Pb in dust and soil, air, and food should be analyzed to characterize Pb pathways other than water and to present a more complete exposure scenario for residents in Tamatave. At a minimum, specific cooking and eating habits should be recorded in the field to estimate and account for the transference of water Pb into prepared food, which would likely increase the overall estimated environmental Pb exposure.

(3) At least one representative study for BLL measurements should be carried out in Tamatave to gauge the incidence of elevated BLL and make connections to the exposure pathways, particularly water, and, ideally, to estimate the environmental disease burden attributable to Pb.

(4) Water quality testing should be carried out in Tamatave, particularly in the neighborhoods included in the study, to understand the effects certain water quality parameters have on Pb leaching and to explain variance in Pb concentrations initially measured in the field. Several of the parameters that I attempted to measure should be included along with some others for completeness. In particular, pH, temperature,

conductance, alkalinity, hardness, chloride concentration, and sulfate concentration should be included. The first five measures would be used in calculating saturation index values (Roberge, 2008). The latter two parameters would be used to estimate an effective indicator of Pb-leaching behavior (Edwards and Triantafyllidou, 2007; Willison and Boyer, 2012).

Areas (1)–(3) for future work are designed to follow guidelines set out by the WHO for informing public policy related to Pb exposure. These areas for future work call for more water sampling to represent other neighborhoods in the Tamatave area and to account for potentially undetected Pb in particulate form, to quantify other potential Pb sources like dust, air and soil for a more complete picture of environmental Pb exposure, and finally to test for BLLs in the specific area of interest. Once these data have been compiled and evaluated, they should be used to calculate potential disease burden for the local area, which can then be reported formally to the government with the expectation of policy action to address the problem of Pb in a legal manner. In an ideal case, the requisite steps for informing and enacting government intervention should be followed. With the information provided by studies proposed in Areas (1)–(3), a better understanding of Pb exposure will be possible. Moreover, concrete links to public health will be demonstrated in this way. It should also be noted that Area (2) for future work can be used to make more reliable predictions with the EPA IEUBK Model if the BLL measurements in Area (3) are unlikely to be available for the direct calculations in the WHO spreadsheets.

Without some of this key information, the most practical recommendations that can be made are ones that do not require legislation or changes in infrastructure (i.e., those recommended in Section 5.2). Because the *Pompe Tany* is a Self-supply option with exclusively private sector provision, counsel may be most effective anyway if targeted at the actual users and manufacturers, though the government can and should be involved in getting pertinent information across to these parties.

Area (4) for future work is targeted to provide further insight into existing Pb-leaching data. Water quality analysis in the field was incomplete due to the lack of a laboratory for proper sampling, the prohibitive cost of shipping materials to Madagascar or samples back to the US, and equipment issues in the field. A more complete water quality analysis in the areas included in the study is hypothesized to explain some of the variance in soluble Pb measured. Presumably, pump system components of roughly the same materials and manufacturing process should leach Pb into water at similar rates and therefore result in similar concentrations, unless changes in the local microenvironment are sufficient to influence the process of Pb leaching.

REFERENCES

Abrahamse, W., Steg, L., Vlek, C. and Rothengatter, T., (2005). A review of intervention studies aimed at household energy conservation. Journal of Environmental Psychology, 25, 273-291.

African Development Fund (ADF), (2005). Madagascar: Rural Drinking Water Supply and Sanitation Programme, Appraisal Report. African Development Bank Group, Tunis, Tunisia.

Agency for Toxic Substances and Disease Registry (ATSDR), (2007). Toxicological profile for lead. Centers for Disease Control and Prevention (CDC). Atlanta, CAS# 7439-92-1.

Ahamed, M. and Siddiqui, M.K.J., (2007). Environmental lead toxicity and nutritional factors. Clinical Nutrition, 26, 400-408.

Alatise, O.I. and Schrauzer, G.N., (2010). Lead exposure: A contributing cause of the current breast cancer epidemic in Nigerian women. Biological Trace Element Research, 136, 127-139.

American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF), (1998). Standard Methods for the Examination of Water and Wastewater, 20ed. American Public Health Association, Washington, D.C.

Annis, J. and Razafinjato, G., (2012). Public-private partnerships in Madagascar: Increasing the sustainability of piped water-supply systems in rural towns. Waterlines, 31(3), 184-196.

Bakulski, K.M., Rozek, L.S., Dolinoy, D.C., Paulson, H.L., and Hu, H., (2012). Alzheimer's disease and environmental exposure to lead: The epidemiological evidence and potential role of epigenetics. Current Alzheimer Research, 9(5), 563-573.

Baldrianova, L., Agrafiotou, P., Svancara, I., Jannakoudakis, A.D., and Sotiropoulos, S., (2011). The effect of acetate concentration, solution pH and conductivity on the anodic stripping voltammetry of lead and cadmium ions at in situ bismuth-plated carbon microelectrodes. Journal of Electroanalytical Chemistry, 660, 31-36.

Basilevsky, A.T., (1994). Statistical Factor Analysis and Related Methods: Theory and Applications. John Wiley and Sons, New York, NY.

Bellinger, D., Leviton, A., Waternaux, C., Needleman, H., and Rabinowitz, M., (1989). Low-level lead exposure, social class, and infant development. Neurotoxicology and Teratology, 10, 497-503.

Black R.E., Cousens S., Johnson H.L., Lawn, J.E., Rudan, I., Bassani, D.G., Jha, P., Campbell, H., Walker, C.F., Cibulskis, R., Eisele, T., Liu, L., and Mathers, C., (2010). Global, regional, and national causes of child mortality in 2008: A systematic analysis. The Lancet, 375 (9730), 1969-1987.

Bonfil, Y. and Kirowa-Eisner, E., (2002). Determination of nanomolar concentrations of lead and cadmium by anodic-stripping voltammetry at the silver electrode. Analytica Chimica Acta, 457, 285-296.

Bonfil, Y., Brand, M., and Kirowa-Eisner, E., (2002). Characteristics of subtractive anodic stripping voltammetry of Pb and Cd at silver and gold electrodes. Analytica Chimica Acta, 464, 99-114.

Brezonik, P.L., Brauner, P.A., and Stumm, W., (1967). Trace metal analysis by anodic stripping voltammetry: Effect of sorption by natural and model organic compounds. Water Research, 10, 605-612.

Brown, M.J., Raymond, J., Homa, D., Kennedy, C., and Sinks, T., (2011). Association between children's blood lead levels, lead service lines, and water disinfection, Washington, DC, 1998–2006. Environmental Research, 111, 67-74.

Canfield, R.L., Henderson, C.L., Cory-Sletcha, D.A., Cox, C., Jusko, T.A., and Lanphear, B.P., (2003). Intellectual impairment in children with blood lead concentrations below 10 micrograms per deciliter. New England Journal of Medicine, 348(16), 1517-1526.

Carter, R.C., Harvey, E., Casey, V., (2010). User financing of rural handpump water services. The IRC Symposium 2010, Pumps, Pipes and Promises: Costs, Finances and Accountability for Sustainable WASH Services' addressed the intersecting issues of costing, financing and accountability in WASH service delivery. IRC International Water and Sanitation Centre, The Hague, Netherlands.

Cartier, C., Laroche, L., Deshommes, E., Nour, S., Richard, G., Edwards, M. and Prévost, M., (2011). Investigating dissolved lead at the tap using various sampling protocols. Journal of American Water Works Association, 103(3), 55-67.

Cartier, C., Bannier, A., Pirog, M.J., Nour, S., and Prévost, M., (2012). A rapid method for lead service line detection. Journal of American Water Works Association, 104(11), 35-36.

Centers for Disease Control and Prevention (CDC), (2012). CDC response to advisory committee on childhood lead poisoning prevention recommendations in "Low level lead exposure harms children: A renewed call of primary prevention". Atlanta, GA: US Department of Health and Human Services, CDC.

Central Intelligence Agency (CIA), (2013). The world factbook. Accessed December 10, 2013 from: https://www.cia.gov/library/publications/the-world-factbook/geos/ma.html

Crittenden, J.C., Trussel, R.R., Hand, D.W., Howe, K.J. and Tchobanoglous, G., (2005). MWH's Water Treatment: Principles and Design, 2ed. John Wiley & Sons, Hoboken, N.J.

Delleur, J.W., (2007). The Handbook of Groundwater Engineering, 2nd. Ed. CRC Press, Boca Ratan, FL.

Deshommes, E., Laroche, L., Nour, S., Cartier, C. and Prévost, M., (2010). Source and occurrence of particulate lead in tap water. Water Research, 44, 3734-3744.

Deshommes, E. and Prévost, M., (2012). Pb particles from tapwater: Bioaccessibility and contribution to child exposure. Environmental Science and Technology, 46, 6269-6277.

Deshommes, E., Prévost, M., Levallois, P., Lemieux, F., and Nour, S., (2013). Application of lead monitoring results to predict 0–7 year old children's exposure at the tap. Water Research, 47, 2409-2420.

Dodrill, D.M. and Edwards, M., (1995) Corrosion control on the basis of utility experience. Journal of American Water Works Association, 87(7), 74-85.

Dunteman, G.H., (1989). Principal Components Analysis. Paper no. 69 in Sage University Paper series on Quantitative Applications in the Social Science. Newbury Park, CA.

Edwards, M. and Trintafyllidou, S., (2007). Chloride-to-sulfate mass ratio and lead leaching into water. Journal of American Water Works Association, 99(7), 96-109.

Environmental Protection Agency (EPA), (1994a). Method 200.8. Determination of trace elements in waters and wastes by inductively coupled plasma - mass spectrometry, Rev 5.4. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH 45268.

Environmental Protection Agency (EPA), (1994b). Determination of trace elements by stabilized temperature graphite furnace atomic absorption, Rev 2.2. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH 45268.

Environmental Protection Agency (EPA), (1994c). Guidance manual for the integrated exposure uptake biokinetic model for lead in children. Washington, D.C., EPA/540/R-93/081.

Environmental Protection Agency (EPA), (1995). Update on lead leaching from submersible well pumps and private drinking water systems. Washington, D.C., EPA-812-F-95-002.

Environmental Protection Agency (EPA), (1996). Stagnation Time, Composition, pH, and Orthophosphate Effects on Metal Leaching from Brass. Washington, D.C., EPA/600/R-96/103.

Environmental Protection Agency (EPA), (2003a). Recommendations of the Technical Review Workgroup for lead for an approach to assessing risks associated with adult exposures to lead in soils. Washington, D.C., EPA-540-R-03-001.

Environmental Protection Agency (EPA), (2003b). Method 200.5. Determination of trace elements by axially viewed inductively coupled plasma atomic emission spectrometry, Rev 4.2, Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH 45268.

Environmental Protection Agency (EPA), (2004). Lead and copper rule: A quick reference guide. Washington, D.C., EPA-816-F-04-009.

Environmental Protection Agency (EPA), (2005). Guidance Manual for the All Ages Lead Model: Draft version 1.05. Washington, D.C., EPA/600/R-05/102.

Environmental Protection Agency (EPA), (2007). User's Guide for the Integrated Exposure Uptake Biokinetic Model for Lead in Children (IEUBK) for Windows®. EPA-540-K-01-005.

Environmental Protection Agency (EPA), (2009a). Drinking Water Treatment. Washington, D.C., EPA 816-F-04-034.

Environmental Protection Agency (EPA), (2009b). Analytical methods approved for drinking water compliance monitoring of inorganic contaminants and other organic constituents. Accessed February 20, 2014 from http://www.epa.gov/safewater/methods/pdfs/methods/methods_inorganic.pdf.

Environmental Protection Agency (EPA), (2013). Toxic substances control act (TSCA). Accessed January 10, 2014 from: http://www.epa.gov/oecaagct/lsca.html

Everitt, B.S. and Skrondal, A., (2010). The Cambridge Dictionary of Statistics, 4th ed., Cambridge University Press, New York, NY.

Fewtrell, L., Kaufmann, F., and Prüss-Üstün, A. (2003). Lead: Assessing the environmental burden of disease at national and local levels. Environmental Burden of Disease, Series No. 2. The World Health Organization, Geneva, Switzerland.

Food and Agriculture Organization of the United Nations and World Health Organization (FAO and WHO), (2011). Evaluation of certain food additives and contaminants. Seventy-third report of the Joint FAO/WHO Expert Committee on Food Additives. WHO Technical Report Series, No. 960. Geneva: World Health Organization.

Gibbons, J.D. and Chakraborti, S., (1992). Nonparametric Statistical Inference, 3ed. Marcel Dekker, New York, NY.

Gleick, P.H., (1996). Basic water requirements for human activities: Meeting basic needs. Water International, 21(2), 83-92.

Global Water Intelligence (GWI), (2013). Global water tariffs continue upward trend. Accessed September 15, 2013 from: http://www.globalwaterintel.com/archive/12/9/market-profile/global-water-tariffs-continue-upward-trend.html

Greenwell, J., McCool, J., Kool, J. and Salusalu, M., (2013). Typhoid fever: Hurdles to adequate hand washing for disease prevention among the population of a peri-urban informal settlement in Fiji. Western Pacific Surveillance and Response Journal, 4(1), 41-45.

Gump, B.B., MacKenzie, J.A., Bendenskas, K., Morgan, R., Dumas, A., Palmer, C.D., and Parsons, P.J., (2011). Low-level Pb and cardiovascular responses to acute stress in children: The role of cardiac autonomic regulation. Neurotoxicology and Teratology. 33(2), 212-219.

Hardenbergh, S.H.B., (1997). Why are boys so small? Child growth, diet and gender near Ranomafana, Madagascar. Social Science and Medicine, 44(11), 1725-1738.

Harvey, P.A, (2004). Borehole sustainability in rural Africa: An analysis of routine field data. The 30th Water Engineering Development Centre (WEDC) Conference 2004, People-Centred Approaches to Water and Environmental Sanitation, Vientiane, Lao People's Democratic Republic (PDR).

Hegazy, A.A., Zaher, M.M., Abd El-Hafez, M.A., Morsy, A.A., and Saleh, R.A., (2010). Relation between anemia and blood levels of lead, copper, zinc and iron among children. BioMed Central Research Notes, 133, 1-9.

Hernberg, S., (2000). Lead poisoning in a historical perspective. American Journal of Industrial Medicine, 38, 244-254.

Howard, G. and Bartram, J., (2003) Domestic water quantity, service level and health. The World Health Organization. Geneva, Switzerland.

Hydrolab, (2002). Quanta Water Quality Monitoring System: Operating Manual, Rev. 2. Hydrolab Corporation, Austin, TX. Retrieved from: http://www.aqualab.com.au/files/24/manual.pdf

Iloniaina, A., and Lough, R. Court confirms Madagascar election result; loser rejects it. Reuters [Online]. January 7, 2014. Accessed January 20, 2014 from http://www.reuters.com/article/2014/01/17/us-madagascar-election-idUSBREA0G16B20140117

Index Mundi, (2013). Madagascar: Malnutrition prevalence. Retrieved from: http://www.indexmundi.com/facts/madagascar/malnutrition-prevalence

Institute for Health Metrics and Evaluation (IHME), Human Development Network, The World Bank, (2013). The Global Burden of Disease: Generating Evidence, Guiding Policy — Sub-Saharan Africa Regional Edition. Seattle, WA: IHME.

Jiro sy Rano Malagasy (JIRAMA), (2013). Eau tarification. Retrieved September 15, 2013 from: http://www.jirama.mg/index.php?w=scripts&f=Jirama-page.php&act=tarifeau

Lanphear, B.P., Dietrich, K., Auinger, P., and Cox, C., (2000). Cognitive deficits associated with blood lead concentrations <10 µg/dL in US children and adolescents. Public Health Reports, 115, 521-529.

Lanphear, B.P., Hornung, R., Koury, J., Yolton, K., Baghurst, P., Bellinger, D.C., Canfield, R.L., Dietrich, K.N., Bornschein, R., Greene, T., Rothenberg, S.J., Needleman, H.L., Schnaas, L., Wasserman, G., Graziano, J., and Roberts, R., (2005). Low-level environmental lead exposure and children's intellectual function: An international pooled analysis. Environmental Health Perspectives, 113(7), 894-899.

Lessler, M.A., (1988). Lead and lead poisoning from antiquity to modern times. Ohio Journal of Science, 88(3), 78-84.

Liu, K., Hao, J., Zeng, Y., Dai, F., and Gu, P., (2013). Neurotoxicity and biomarkers for lead exposure: A review. Chinese Medical Sciences Journal, 28(3), 178-188.

Maas, R.P., Patch, S.C., Pope, J., and Thornton, L., (1998) Lead-leaching characteristics of submersible residential water pumps. Journal of Environmental Health, 60, 8-13.

Maas, R.P., Patch, S.C., Morgan, D.M., and Pandolfo, T.J., (2005). Reducing lead exposure from drinking water: Recent history and current status. Public Health Reports, 120, 316-321.

MacCarthy, M.F., Annis, J.E., and Mihelcic, J.R., (2013). Unsubsidized Self-supply in eastern Madagascar. Water Alternatives, 6(3), 424-438.

Mahaffey, K.R., (1974). Nutritional factors and susceptibility to lead toxicity. Environmental Health Perspectives, 7, 107-112.

Mahaffey, K.R., (1998). Predicting blood lead concentrations from lead in environmental media. Environmental Health Perspectives, 106(6), 1485-1493.

Mihelcic, J.R., Myre, E.A., Fry, L.M., Phillips, L.D., and Barkdoll, B.D., (2009). Field Guide to Environmental Engineering for Development Workers: Water, Sanitation, Indoor Air, American Society of Civil Engineers (ASCE) Press, Reston, VA.

Mihelcic, J.R. and Zimmerman, J.B., (2014). Environmental Engineering: Fundamentals, Sustainability, Design, 2ed. John Wiley & Sons, Hoboken, NJ.

Needleman, H., (2004). Lead poisoning. Annual Review of Medicine, 55, 209-222.

Nimmo, M. and Fones, G.R., (1997). The potential pool of Co, Ni, Cu, Pb and Cd organic complexing ligands in coastal and urban rain waters. Atmospheric Environment, 31(5), 693-702.

Palintest Ltd., (1999). Method 1001: Lead in drinking water by differential pulse anodic stripping voltammetry. Palintest Ltd., Erlanger, KY 41018.

Palintest Ltd., (2009). Palintest® SA1100 Scanning Analyzer Manual. Retrieved from: www.hach.com/asset-get.download.jsa?id=15666830903.

Panter-Brick, C., Clarke, S.E., Lomas, H., Pinder, M. and Lindsay, S.W., (2006). Culturally compelling strategies for behaviour change: A social ecology model and case study in malaria prevention. Social Science and Medicine, 62, 2810-2825.

Patnaik, P., (2003). Handbook of Inorganic Chemicals. McGraw-Hill, New York, NY.

Patrick, L., (2006). Lead toxicity, a review of the literature, Part I: Exposure, evaluation, and treatment. Alternative Medicine Review, 11(1), 2-22.

Pedley, S., Yates, M., Schijven, J.F., West, J., Howard, G. and Barrett, M., (2006). Chapter 3: Pathogens: Health relevance, transport and attenuation. In Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources ed., Schmoll, O., Howard, G., Chilton, J. and Chorus, I., 49-80. IWA Publishing, London, UK.

Prüss-Üstün, A., Bos R., Gore F., and Bartram J. (2008). Safer water, better health: costs, benefits and sustainability of interventions to protect and promote health. The World Health Organization, Geneva, Switzerland.

Quinn, G.P. and Keough, M.J., (2002). Experimental Design and Data Analysis for Biologists. Cambridge University Press, New York, NY.

Ranaritsara, J. B. G., Jiro sy Rano Malagasy (JIRAMA), Toamasina, Madagascar. Personal communication, 2013.

Riddell, T.J., Solon, O., Quimbo, S.A., Tan, C.M.C., Butrick, E., and Peabody, J.W., (2007). Elevated blood-lead levels among children living in the rural Philippines. Bulletin of the World Health Organization, 85(9), 674-680.

Roberge, P.R., (2008). Corrosion Engineering: Principles and Practice. McGraw-Hill, New York, NY.

Rossi, E. (2008). Low level environmental lead exposure: A continuing challenge. The Clinical Biochemist Reviews, 29, 63-70.

Ryan, T.P., (2007). Modern Engineering Statistics. John Wiley & Sons, Hoboken, NJ.

Sandvig, A., Kwan, P., Kirmeyer, G., Maynard, B., Mast, D., Trussell, R.R., Trussell, S., Cantor, A. and Prescott, A., (2008). Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues. Technical report prepared for American Water Works Association Research Foundation (AWWARF) and US Environmental Protection Agency (EPA), Denver, CO.

Schock, M.R. and Lemieux, F.G. (2010). Challenges in addressing variability of lead in domestic plumbing. Water Science and Technology, 10(5), 793-799.

Sidle, W. C. and Li, P., (2007). Impact of submersible pumps on Pb constituents in residential wells. Environmental and Geochemical Health, 30(1), 1-9.

Silberberg, E.K., Waalkes, M., and Rice, J.M., (2000). Lead as a carcinogen: Experimental evidence and mechanisms of action. American Medicine of Industrial Medicine, 38, 316-323.

Silberberg, E.K., (2003). Facilitative mechanisms of lead as a carcinogen. Mutation Research, 533, 121-133.

Sutton, S., (2004a). Self-supply: A fresh approach to water for rural populations. Rural Water Supply Network (RWSN), Water and Sanitation Program (WSP) and Department for International Development (DFID), St. Gallen, Switzerland.

Sutton, S., (2004b). Preliminary desk study for potential self supply in sub-Saharan Africa. WaterAid and the Rural Water Supply Network (RWSN), London, UK.

Tong, S., von Shirnding, Y.E., and Prapamontol, T., (2000). Environmental lead exposure: a public health problem of global dimensions. Bulletin of the World Health Organization, 78(9), 1068-1077. The World Health Organization, Geneva, Switzerland.

Triantafyllidou, S., Lambrinidou, Y., and Edwards, M., (2009). Lead (Pb) exposure through drinking water: Lessons to be learned from recent U.S. experience. Global NEST Journal, 11(3), 341-348.

Triantafyllidou, S. and Edwards, M. (2012). Lead (Pb) in tap water and in blood: Implications for lead exposure in the United States. Critical Reviews in Environmental Science and Technology, 42, 1297-1352.

Triantafyllidou, S., Nguyen, C.K., Zhang, Y., and Edwards, M., (2013). Lead (Pb) quantification in potable water samples: Implications for regulatory compliance and assessment of human exposure. Environmental Monitoring and Assessment. 185, 1355-1365.

United Nations (UN), (2008). The millennium development goals report 2008: Statistical annex. The United Nations, New York, NY, USA.

United Nations (UN), (2010). A/Res/64/292: The human right to water and sanitation. Sixty-fourth session, Agenda item 48.

United Nations (UN), Office of the United Nations High Commissioner for Human Rights (OHCHR), United Nations Human Settlement Programme (UN-HABITAT), and World Health Organization (WHO), (2010). Right to Water, Fact Sheet No. 35. Office of the United Nations High Commissioner for Human Rights, Geneva, Switzerland. Accessed October 9, 2013 from: http://www.ohchr.org/Documents/Publications/FactSheet35en.pdf

United Nations Development Programme (UNDP), (2013), The rise of the south: Human progress in a diverse world. Human Development Report. United Nations Development Programme. New York, NY, USA.

United Nations Environment Programme (UNEP), (2008). Leaded petrol phase-out: Global status January 2008. United Nations Environmental Programme, Geneva, Switzerland.

United Nations Children's Fund (UNICEF) and Rural Water Supply Network (RWSN), (2004). Manually operated pumps for drinking water supply in Madagascar. Technical report for the Swiss Centre for Appropriate Technology (SKAT), St. Gallen, Switzerland.

United Nations Children's Fund (UNICEF), (2013). Madagascar Health and nutrition: The issue. Accessed October 1, 2013 from: http://www.unicef.org/madagascar/5557.html

United Nations Regional Information Centre (UNRIC), (2012). Madagascar: the untold crisis. Retrieved from: http://www.unric.org/en/madagascar/27072-madagascar-the-untold-crisis

U.S. Agency for International Development (USAID), (2010). Madagascar water and sanitation profile. Accessed March 10, 2014 from: http://www.washplus.org/sites/default/files/madagascar2010.pdf

Wahlstrom-Ramler, M., (2014). Drinking Water in the Developing World: Sources of Fecal Contamination in Pitcher Pump Systems and Measurement Alternatives. M.S. Thesis, University of South Florida, Tampa, FL.

Waldron, H.A., (1973). Lead poisoning and the ancient world. Medical History, 17(4), 391-399.

WaterAid, (2005). Madagascar: Where local Commune administrations urgently need more staff and resources to deliver increases in sustainable access to water and sanitation. National Water Sector Assessment for WaterAid, London, UK.

WaterAid, (2013). Technical brief: Handpumps. WaterAid, London, UK. Retrieved from: http://www.wateraid.org/~/media/Publications/Handpumps.ashx

White, L.D., Cory-Slechta, D.A., Gilbert, M.E., Tiffany-Castiglioni, E., Zawia, N.H., Virgolini, M., Rossi-George, A., Lasley, S.M., Qian, Y.C., and Riyaz Basha, M., (2007). New and evolving concepts in the neurotoxicology of lead. Toxicology and Applied Pharmacology, 225, 1-27.

Willison, H. and Boyer, T.H., (2012). Secondary effects of anion exchange on chloride, sulfate, and lead release: Systems approach to corrosion control. Water Research, 46. 2385-2394.

World Bank, (2013a). Madagascar: Measuring the impact of the political crisis. Accessed June 10, 2013 from: http://reliefweb.int/report/madagascar/measuring-impact-political-crisis

World Bank, (2013b). GDP per capita growth (annual %). The World Bank: Working for a World Free of Poverty. Accessed July 10, 2013 from http://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG/countries/

World Health Organization (WHO), (1997). Guidelines for drinking-water quality, Second Ed. The World Health Organization, Geneva, Switzerland.

World Health Organization (WHO), (2004). Global burden of disease 2004 update: Disability weights for diseases and conditions. The World Health Organization, Geneva, Switzerland.

World Health Organization (WHO), (2011a). Guidelines for drinking-water quality, Fourth Ed. The World Health Organization, Geneva, Switzerland.

World Health Organization (WHO), (2011b). Lead in drinking-water: Background document for development of Guidelines for drinking-water quality Rev/1. Geneva, Switzerland.

World Health Organization (WHO), (2011c). Safety evaluation of certain food additives and contaminants. WHO Food Additives Series, No. 64. Geneva, Switzerland.

World Health Organization (WHO), (2013a). Metrics: Disability-Adjusted Life Year (DALY). Retrieved from: http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/

World Health Organization (WHO), (2013b). Health through safe drinking water and basic sanitation. Retrieved from: http://www.who.int/water_sanitation_health/mdg1/en/

World Health Organization (WHO), (2013c). Stop lead poisoning in children. Accessed October 2, 2013 from: http://www.who.int/mediacentre/news/notes/2013/lead-20131018/en/

World Health Organization and United Nations Children’s Fund (WHO and UNICEF), (2012). WHO / UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation. New York, NY, USA.

APPENDICES

Appendix I Copyright Permissions for Figures and Tables and Other Supporting Information

This Appendix provides official documentation for the reproduction and/or reuse of published figures, tables and other supporting information. Correspondences and/or licenses are included in the following pages.

AI.1 Permission to Reproduce Figure 1

Brad Akers <akers@mail.usf.edu> Sat, Jan 25, 2014 at 10:19 AM
To: lindap133@hotmail.com

Hi Linda,

My name is Brad Akers. I am a Master's International student at the University of South Florida, and a recently returned Peace Corps Volunteer from Madagascar. I am writing to ask permission to use your diagram of a Pitcher Pump for both my thesis and a future paper publication. I worked extensively with Pitcher Pumps in my research.

The diagram is Figure 16-15 located on page 308 of the Field Guide to Environmental Engineering for Development Workers: Water, Sanitation, and Indoor Air. ASCE Press, Reston, VA.

Thanks,
Brad Akers
Master's International Student
Department of Civil and Environmental Engineering
University of South Florida
Tampa, FL
(864) 593-9395
akers@mail.usf.edu

Linda Phillips <lindap133@hotmail.com> Sat, Jan 25, 2014 at 1:56 PM
To: Brad Akers <akers@mail.usf.edu>

Good afternoon, Brad! Welcome back. Yes, you have my permission to use the Pitcher Pump diagram form the Field Guide. Good luck with your thesis...and make sure to tell Meghan WR "hi" from me when you see her! Linda

AI.2 Permission to Reproduce Table 13, Content from Springer

SPRINGER LICENSE
TERMS AND CONDITIONS

Jan 27, 2014

This is a License Agreement between David B Akers ("You") and Springer ("Springer") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Springer, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.

License Number	3316821492511
License date	Jan 26, 2014
Licensed content publisher	Springer
Licensed content publication	Environmental Monitoring and Assessment
Licensed content title	Lead (Pb) quantification in potable water samples: implications for regulatory compliance and assessment of human exposure
Licensed content author	Simoni Triantafyllidou
Licensed content date	Jan 1, 2012
Volume number	185
Issue number	2
Type of Use	Thesis/Dissertation
Portion	Excerpts
Author of this Springer article	No
Order reference number	
Title of your thesis / dissertation	Lead (Pb) Contamination of Water Drawn from Pitcher Pumps in Eastern Madagascar
Expected completion date	Apr 2014
Estimated size(pages)	100
Total	0.00 USD
Terms and Conditions	

Introduction
The publisher for this copyrighted material is Springer Science + Business Media. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at http://myaccount.copyright.com).

Limited License
With reference to your request to reprint in your thesis material on which Springer Science and Business Media control the copyright, permission is granted, free of charge, for the use indicated in your enquiry.

Licenses are for one-time use only with a maximum distribution equal to the number that you identified in the licensing process.

This License includes use in an electronic form, provided its password protected or on the university's intranet or repository, including UMI (according to the definition at the Sherpa website: http://www.sherpa.ac.uk/romeo/). For any other electronic use, please contact Springer at (permissions.dordrecht@springer.com or permissions.heidelberg@springer.com).

The material can only be used for the purpose of defending your thesis, and with a maximum of 100 extra copies in paper.

Although Springer holds copyright to the material and is entitled to negotiate on rights, this license is only valid, subject to a courtesy information to the author (address is given with the article/chapter) and provided it concerns original material which does not carry references to other sources (if material in question appears with credit to another source, authorization from that source is required as well).

Permission free of charge on this occasion does not prejudice any rights we might have to charge for reproduction of our copyrighted material in the future.

Altering/Modifying Material: Not Permitted
You may not alter or modify the material in any manner. Abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of the author(s) and/or Springer Science + Business Media. (Please contact Springer at (permissions.dordrecht@springer.com or permissions.heidelberg@springer.com)

Reservation of Rights
Springer Science + Business Media reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

Copyright Notice:Disclaimer
You must include the following copyright and permission notice in connection with any reproduction of the licensed material: "Springer and the original publisher /journal title, volume, year of publication, page, chapter/article title, name(s) of author(s), figure number(s), original copyright notice) is given to the publication in which the material was originally published, by adding; with kind permission from Springer Science and Business Media"

Warranties: None

Example 1: Springer Science + Business Media makes no representations or warranties with respect to the licensed material.

Example 2: Springer Science + Business Media makes no representations or warranties with respect to the licensed material and adopts on its own behalf the limitations and disclaimers established by CCC on its behalf in its Billing and Payment terms and conditions for this licensing transaction.

Indemnity
You hereby indemnify and agree to hold harmless Springer Science + Business Media and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

No Transfer of License
This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without Springer Science + Business Media's written permission.

No Amendment Except in Writing
This license may not be amended except in a writing signed by both parties (or, in the case of Springer Science + Business Media, by CCC on Springer Science + Business Media's behalf).

Objection to Contrary Terms
Springer Science + Business Media hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and Springer Science + Business Media (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

Jurisdiction
All disputes that may arise in connection with this present License, or the breach thereof, shall be settled exclusively by arbitration, to be held in The Netherlands, in accordance with Dutch law, and to be conducted under the Rules of the 'Netherlands Arbitrage Instituut' (Netherlands Institute of Arbitration).***OR:***

All disputes that may arise in connection with this present License, or the breach thereof, shall be settled exclusively by arbitration, to be held in the Federal Republic of Germany, in accordance with German law.

Other terms and conditions:

v1.3

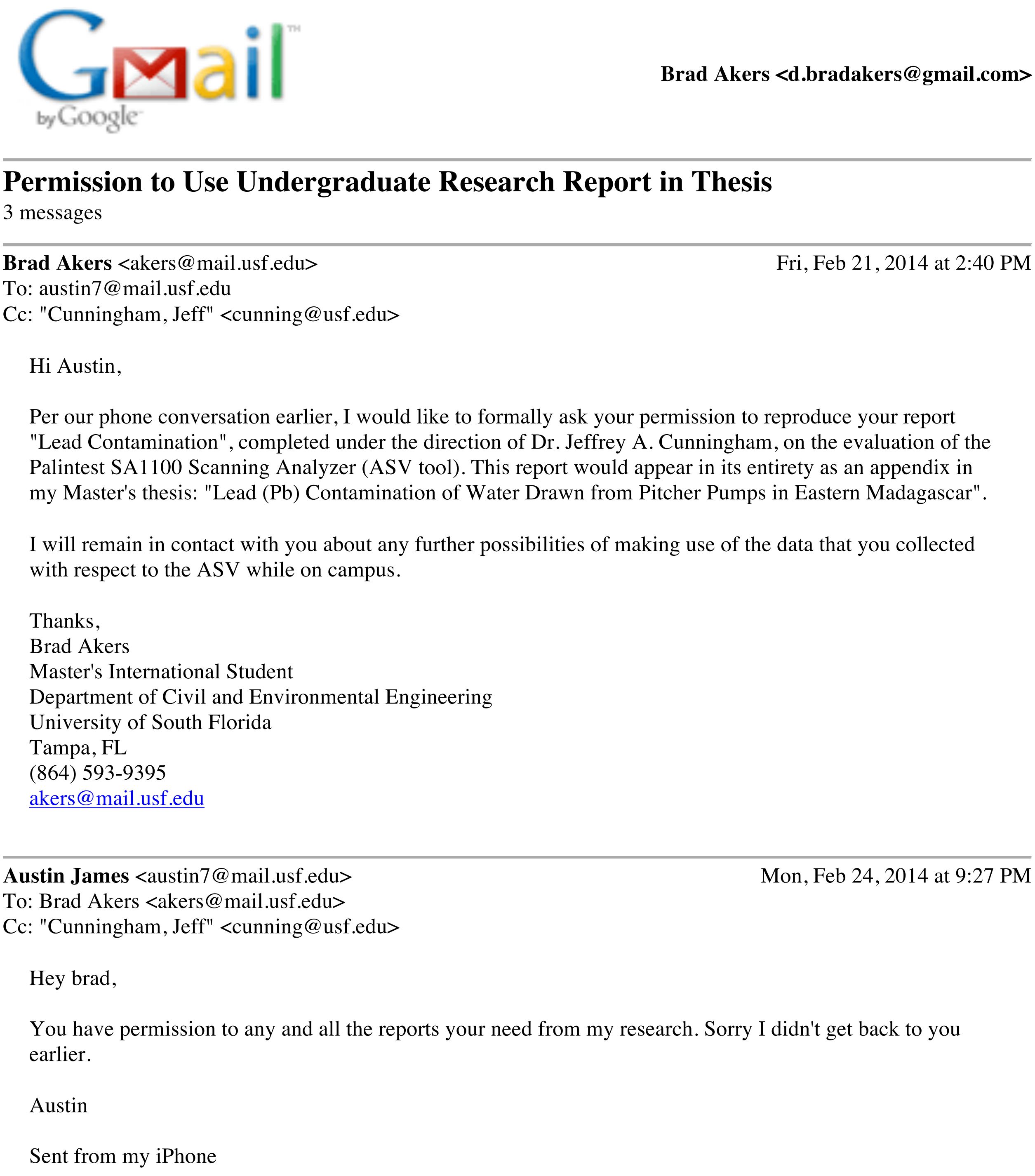
If you would like to pay for this license now, please remit this license along with your payment made payable to "COPYRIGHT CLEARANCE CENTER" otherwise you will be invoiced within 48 hours of the license date. Payment should be in the form of a check or money order referencing your account number and this invoice number RLNK501211183.
Once you receive your invoice for this order, you may pay your invoice by credit card. Please follow instructions provided at that time.

Make Payment To:
Copyright Clearance Center
Dept 001
P.O. Box 843006
Boston, MA 02284-3006

For suggestions or comments regarding this order, contact RightsLink Customer Support: customercare@copyright.com or +1-877-622-5543 (toll free in the US) or +1-978-646-2777.

Gratis licenses (referencing $0 in the Total field) are free. Please retain this printable license for your reference. No payment is required.

AI.3 Permission for Appendix VIII, Content from Austin Atkins



Brad Akers <d.bradakers@gmail.com>

Permission to Use Undergraduate Research Report in Thesis

3 messages

Brad Akers <akers@mail.usf.edu> Fri, Feb 21, 2014 at 2:40 PM
To: austin7@mail.usf.edu
Cc: "Cunningham, Jeff" <cunning@usf.edu>

Hi Austin,

Per our phone conversation earlier, I would like to formally ask your permission to reproduce your report "Lead Contamination", completed under the direction of Dr. Jeffrey A. Cunningham, on the evaluation of the Palintest SA1100 Scanning Analyzer (ASV tool). This report would appear in its entirety as an appendix in my Master's thesis: "Lead (Pb) Contamination of Water Drawn from Pitcher Pumps in Eastern Madagascar".

I will remain in contact with you about any further possibilities of making use of the data that you collected with respect to the ASV while on campus.

Thanks,
Brad Akers
Master's International Student
Department of Civil and Environmental Engineering
University of South Florida
Tampa, FL
(864) 593-9395
akers@mail.usf.edu

Austin James <austin7@mail.usf.edu> Mon, Feb 24, 2014 at 9:27 PM
To: Brad Akers <akers@mail.usf.edu>
Cc: "Cunningham, Jeff" <cunning@usf.edu>

Hey brad,

You have permission to any and all the reports your need from my research. Sorry I didn't get back to you earlier.

Austin

Sent from my iPhone

Appendix II Interviews with Pump Manufacturers in Tamatave

This Appendix documents the total survey/questionnaire results collected from local pump manufacturers in the city of Tamatave, Madagascar in April 2012. No neighborhood locations are indicated in responses, nor the names of individual manufacturers in order to protect the anonymity of respondents. Questions are general, combined with observations made at each household. The informal survey aimed to evaluate the scale of private Pitcher Pump-related industry in Tamatave and to make observations about commonly used materials and practices. No questions included in the short survey collect personal data on subjects, nor do they intend to study respondents or their behaviors as human subjects. As such, the Institutional Review Board (IRB) administered by the Human Research Protection Program (HRPP) at the University of South Florida was not involved in the development of the survey. Results are included in the following pages.

Table AII.1. Interviews with Pump Manufacturers.

Pump Manufacturer	Primary Town of Employment	Business Starting Date	Source of Training	Time of Apprenticeship	Pump Fabrication Rate	Recipient Locations of Pumps
1	Ankirihiry	2006	Manufacturer	6 years	4/week	Toamasina; Mahanoro; Vatomandry; Fenoarivo-Atsinanana; Antananarivo
2	Mangarivotra-Avaratra	2000	Manufacturer	1 year	6/week	Toamasina; Fenoarivo-Atsinanana; Ambatondrazaka; Antsiranana; Antananarivo
3	Andranomadio	2001	Father	4 years	2/month	Toamasina; Antananambo
4	Mangarivotra-Avaratra	1974	Father & technical school	10 years	2/week	Toamasina; Antananarivo; Fianarantsoa; Toliara; Mahajanga; Antsiranana
5	Tanambao V	1960	La Marine Diego (Société Française)	7 years	3/week	Toamasina; Fenoarivo-Atsinanana; Vavatenina; St. Marie; Antalaha; Manakara; Toliara; Antananarivo
6	Tanambao V	1992	Manufacturer	10 years	2/week	Toamasina; Soanierana Ivongo; St. Marie; Toliara; Fenoarivo-Atsinanana
7	Mangarivotra-Atsimo	2012	Manufacturer	4 years	1/week	Mahavelona; Ambodiatafana; Sarimasina
8	Analankinina Morarano	1982	Manufacturer	4 years	3/month	Fenoarivo-Atsinanana; Farafangana; Manakara; Tolagnaro; Antalaha
9	Morafeno	1998	Father	5 years	2/week	Toamasina; Ampasimbe; Antananarivo

Table AII.1 – Cont.

Pump Manufacturer	People Trained			Well Screens		Check Valves		Materials Always Consistent?	Repairs	
	Number	Location	Date	Type	Vendor	Type	Vendor		Most Common	Average Cost (Ar)
1	5	Mangarano	2006	Etain	Hardware store	Lead	AFA (Mangarano)/small business	Yes	Valves (lead)	4000
2	2	Mangarano	2000	Etain; acide	Market	Lead	Boutique/small business	Yes	Leather	16000
3	-	-	-	Etain	Hardware store	Iron	Hardware store; boutique (small business)	Yes	Leather; screen	5000; 25000
4	Not sure	Toamasina	1980/ongoing	Etain	Market; hardware store	Lead	From batteries	Yes	Leather; screen	4000; 35000
5	~45	Toamasina; Toliara	Many; (~10 years ago since Toliara training)	Etain	Hardware store	Lead	From batteries	Yes	Leather; screen	15000; 25000
6	~25	Toamasina	1992/ongoing	Etain; acide; zinc	Hardware store	Lead	From batteries	Yes	Leather	12000
7	-	-	-	Etain	Hardware store	Lead	From batteries	Yes	Leather; screen	2000; 30000
8	Not sure	Toamasina	Does not remember	Etain	Hardware store	Lead	Hardware store	Yes	Leather; screen	3000; 25000
9	-	-	-	Etain legere; etain	Hardware store	Lead	Hardware store; boutique	Has tried iron check valves	Leather; screen	5000; 30000

Appendix III Interviews with Pump Users in Tamatave

This Appendix documents the total survey/questionnaire results collected at households in the city of Tamatave, Madagascar in December 2012. Neighborhood locations are indicated in responses, but names are left out of the survey responses to protect the anonymity of respondents. Questions are general, combined with observations made at each household. The survey aimed to document the general purpose of water drawn from Pitcher Pump systems and basic water, sanitation and hygiene (WASH) practices of people in Tamatave. The survey served as a basic evaluation of local WASH programs and the service(s) available from local private industry. As such, the Institutional Review Board (IRB) administered by the Human Research Protection Program (HRPP) at the University of South Florida was not involved in the development of the survey. An informal look at the survey determined that the questions included in this appendix serve as an evaluation of a system and do not treat respondents as human subjects (Appendix IV). Results are included in the following pages.

Table AIII.1. Household Interviews of Pump Users in Tamatave, Madagascar.

Location	# of households served by the pump
Mangarivotra N.1	1
Mangarivotra N.2	8
Mangarivotra N.3	1
Mangarivotra N.4	2
Mangarivotra N.5	4
Mangarivotra N.6	3
Mangarivotra N.7	3
Mangarivotra N.8	2
Mangarivotra N.9	3
Ankirhiry.1	2
Ankirhiry.2	2
Ankirhiry.3	8
Ankirhiry.4	10
Ankirhiry.5	2
Ambalakisoa.1	10
Ambalakisoa.2	3
Ambalakisoa.3	5
Ambalakisoa.4	6
Ambalakisoa.5	9
Ambalakisoa.6	16
Ambalakisoa.7	2
Ambalakisoa.8	6
Ambalakisoa.9	4
Ambalakisoa.10	10
Ambalakisoa.11	11
Ambalakisoa.12	5

Table AIII.1. – Cont.

Location	Cooking/Drinking Water Sources					Pitcher Pump water use							What water do you treat?			
	Pump	JIRAMA	River	Spring	Rainwater	Drinking	Cooking	Hand washing	Hygiene/ bathing	Household maintenance	Washing clothes	Other	Drinking	Cooking/ kitchen	Other	Do not Treat
Mangarivotra N.1	X	X				X	X	X	X	X	X		X			
Mangarivotra N.2		X						X	X	X	X					X
Mangarivotra N.3	X					X	X	X	X	X	X		X			
Mangarivotra N.4	X					X	X	X	X	X	X					X
Mangarivotra N.5	X					X	X	X	X	X	X					X
Mangarivotra N.6	X	X					X	X	X	X	X					X
Mangarivotra N.7	X					X	X	X	X	X	X		X			
Mangarivotra N.8	X					X	X	X	X	X	X		X			
Mangarivotra N.9	X	X				X	X	X	X	X	X					X
Ankirhiry.1	X	X					X	X	X	X	X					X
Ankirhiry.2	X	X						X	X	X	X					X
Ankirhiry.3	X					X	X	X	X	X	X					X
Ankirhiry.4	X					X	X	X	X	X	X		X			
Ankirhiry.5	X	X					X	X	X	X	X					X
Ambalakisoa.1	X	X				X	X	X	X	X	X		X			
Ambalakisoa.2	X	X				X	X	X	X	X	X		X	X		
Ambalakisoa.3	X					X	X	X	X	X	X		X			
Ambalakisoa.4	X	X				X	X	X	X	X	X		X			
Ambalakisoa.5	X	X					X	X	X	X	X					X
Ambalakisoa.6	X					X	X	X	X	X	X		X			
Ambalakisoa.7	X	X						X	X	X	X					X
Ambalakisoa.8	X					X	X	X	X	X	X					X
Ambalakisoa.9	X					X	X	X	X	X	X		X			
Ambalakisoa.10	X					X	X	X	X	X	X					X
Ambalakisoa.11	X					X	X	X	X	X	X					X
Ambalakisoa.12	X	X					X	X	X	X	X					X

Table AIII.1. – Cont.

Location	Water Treatment and Usage							
		Water Treatment Method					# of water collections from all sources	# of water collections from Pitcher Pumps
	Why do you not treat the water	None	Boiling	Chlorine	SODIS	Other		
Mangarivotra N.1					X		20	18
Mangarivotra N.2	JIRAMA connection is already clean	X					24	21
Mangarivotra N.3			X				13	13
Mangarivotra N.4	The water from the pump is already clean	X					8	8
Mangarivotra N.5	The water from the pump is already clean	X					20	18
Mangarivotra N.6	JIRAMA connection is already clean	X					4	3
Mangarivotra N.7			X				26	26
Mangarivotra N.8			X				7	7
Mangarivotra N.9	JIRAMA is already clean	X					10	8
Ankirhiry.1	JIRAMA water is already clean	X					30	25
Ankirhiry.2	JIRAMA water is already clean	X					12	10
Ankirhiry.3	Water from pump is clean	X					10	10
Ankirhiry.4			X				8	8
Ankirhiry.5	Using JIRAMA					JIRAMA	4	3
Ambalakisoa.1			X				13	11
Ambalakisoa.2			X				17	15
Ambalakisoa.3			X				25	25
Ambalakisoa.4			X				10	8
Ambalakisoa.5	JIRAMA water already clean	X					17	14
Ambalakisoa.6			X	X			17	17
Ambalakisoa.7	JIRAMA water already clean	X					8	6
Ambalakisoa.8	Water from pump is clean	X					10	10
Ambalakisoa.9			X				8	8
Ambalakisoa.10	Water from the pump is clean and has been cared for	X					30	30
Ambalakisoa.11	Water from pump is already clean	X					15	15
Ambalakisoa.12	Water from JIRAMA is already clean	X					19	16

Table AIII.1 – Cont.

	Water Collection						
		Size of receptacle					
Location	How many receptacles for collection	Bucket 5L	Bucket 10L	Bucket 15L	Jerry 15L	Jerry 20L	Jerry 25L
Mangarivotra N.1	1		X				
Mangarivotra N.2	1			X			
Mangarivotra N.3	1		X				
Mangarivotra N.4	2			X			
Mangarivotra N.5	2			X			
Mangarivotra N.6	1			X			
Mangarivotra N.7	1			X			
Mangarivotra N.8	1			X			
Mangarivotra N.9	1		X				
Ankirhiry.1	2		X				
Ankirhiry.2	1			X			
Ankirhiry.3	2		X				
Ankirhiry.4	1			X			
Ankirhiry.5	1		X				
Ambalakisoa.1	2		X				
Ambalakisoa.2	2			X			
Ambalakisoa.3	1			X			
Ambalakisoa.4	2		X				
Ambalakisoa.5	2		X				
Ambalakisoa.6	2			X			
Ambalakisoa.7	2		X				
Ambalakisoa.8	2		X				
Ambalakisoa.9	1			X			
Ambalakisoa.10	1			X			
Ambalakisoa.11	2		X				
Ambalakisoa.12	2			X			

Table AIII.1. – Cont.

Location	Sanitation		
	Latrine	Depth of pit (m)	Notes
Mangarivotra N.1	Y	4	Concrete floor; clean structure
Mangarivotra N.2	Y	2	concrete structure, foot rests are plastic; plastic drum with holes
Mangarivotra N.3	Y	1	simple pit; no real superstructure; close to pit
Mangarivotra N.4	Y	1.5	Plastic drum with holes in the bottom; downhill from pump
Mangarivotra N.5	Y	3	Downhill of pump; pit; ok superstructure
Mangarivotra N.6	Y	2	Poor condition, but w/a roof; simple pit
Mangarivotra N.7	Y	4	Poor condition, but w/a roof; simple pit
Mangarivotra N.8	N	NA	Defecate in coffee fields
Mangarivotra N.9	Y	Don't know	Pit; no cover; superstructure
Ankirhiry.1	Y	3	
Ankirhiry.2	Y	2	Concrete platform; good structure
Ankirhiry.3	Y	1	Pit; no cover; superstructure
Ankirhiry.4	Y	2	No roof/door; close to pump
Ankirhiry.5	Y	2	Concrete; clean; pit; structure
Ambalakisoa.1	Y	3	pit; full; poor condition
Ambalakisoa.2	Y	2	pit; concrete slab; shower close
Ambalakisoa.3	N		Defecate near canal
Ambalakisoa.4	Y	2	
Ambalakisoa.5	N		Down by the canal
Ambalakisoa.6	Y	2	
Ambalakisoa.7	Y	1.5	Shared latrine w/Ambalakisoa.6
Ambalakisoa.8	Y	2	Pour flush; septic; clean
Ambalakisoa.9	N		Shared with another compound
Ambalakisoa.10	Y	2	Pit; good cover; ok structure
Ambalakisoa.11	N		
Ambalakisoa.12	Y	3	Pit; concrete slab; tin structure

Table AIII.1 – Cont.

Location	Pump Information			
	Date of pump installation	Age of well (yr)	Cost of pump and installation	How is the water quality?
Mangarivotra N.1	2008	4	Don't remember	Clear and clean
Mangarivotra N.2	2009	3	50,000	Clean
Mangarivotra N.3	2009	3	20,000	Clean
Mangarivotra N.4	2002	10	Don't remember	Clean
Mangarivotra N.5	2001	11	Don't remember	Clean
Mangarivotra N.6	1992	20	Don't remember	Clean
Mangarivotra N.7	1982	30	Don't remember	Clean
Mangarivotra N.8	2007	5		Clean
Mangarivotra N.9	2011	1	120,000	Clean
Ankirhiry.1	1992;2012 significant work	20	30,000	Clear and clean
Ankirhiry.2	2007	5	70,000	Clean
Ankirhiry.3	2005	7	50,000	Clean
Ankirhiry.4	2008	4	20,000	Clean
Ankirhiry.5	Over 10 yrs ago	10	Don't remember	Clean
Ambalakisoa.1	1995	17	60,000	Clean
Ambalakisoa.2	2003	9	Don't remember	Clean
Ambalakisoa.3	1997	15	50,000	Clean
Ambalakisoa.4	Over 20 yrs ago	20	40,000	Clean
Ambalakisoa.5	2000	12	50,000	Clean
Ambalakisoa.6	2002	10	80,000	Clean
Ambalakisoa.7	2012	0	200,000	Clean
Ambalakisoa.8	1995	17	40,000	Clean
Ambalakisoa.9	2010	2	160,000	Clean
Ambalakisoa.10	1986	26	50,000	Clean
Ambalakisoa.11	2010	2	100,000	Clean
Ambalakisoa.12	2002	10	200,000	Clean

Table AIII.1 – Cont.

Location	Pump Information			
	How deep to the water table?	Depth of Pipe (m)	Constant water supply?	If no, why not?
Mangarivotra N.1	5	6	Y	
Mangarivotra N.2	5.3	6	Y	
Mangarivotra N.3	6	7	Y	
Mangarivotra N.4	7	8	Y	
Mangarivotra N.5	6	7	Y	
Mangarivotra N.6	2.5	6	Y	
Mangarivotra N.7	6	6	Y	
Mangarivotra N.8	6	7	Y	
Mangarivotra N.9	6	7	Y	
Ankirhiry.1	5.3	5.5	Y	
Ankirhiry.2	8.5	8	Y	
Ankirhiry.3	2	4	Y	
Ankirhiry.4	3	6	Y	
Ankirhiry.5	5.4	6	Y	
Ambalakisoa.1	3	4	Y	
Ambalakisoa.2	4	5	Y	
Ambalakisoa.3	10	10	Y	
Ambalakisoa.4	7	8	Y	
Ambalakisoa.5	7	8	Y	
Ambalakisoa.6	8	10	Y	
Ambalakisoa.7	6	6.5	Y	
Ambalakisoa.8	5	6	Y	
Ambalakisoa.9	8	8.5	Y	
Ambalakisoa.10	7	7	Y	
Ambalakisoa.11	8	8.5	Y	
Ambalakisoa.12	7	8	Y	

Table AIII.1. – Cont.

	Pump Repairs							
	Most recent repair							
Location	Leather check valves	Pipe	Well screen	Lever	Cost	Date	Frequency of repair	Priming necessary?
Mangarivotra N.1	X				2600	12-sep	every 6 mo	Y
Mangarivotra N.2	X				5000	12-nov	1-2 times per month	Y
Mangarivotra N.3	X				5000	12-nov	1-2 times per month	N
Mangarivotra N.4		X			40000	12-dic	Every 3 years	Y
Mangarivotra N.5	X	X			6000;40000	Nov. 12;Oct. 12	Every month; do not know	N
Mangarivotra N.6	X				6000	12-nov	Every 4 mo	N
Mangarivotra N.7	X				1300	12-jun	Once a year	N
Mangarivotra N.8								N
Mangarivotra N.9				X	2500	12-sep	Once until now	N
Ankirhiry.1			X		10000	12-nov	Every 2 years	Y
Ankirhiry.2	X				6000	12-nov	Every 6 wks	Y
Ankirhiry.3	X				5000	12-oct	Every 3 months	N
Ankirhiry.4	X				6000	12-nov	Every month	Y
Ankirhiry.5	X				12000	12-oct	Every 6 month	N
Ambalakisoa.1	X				7500	12-nov	Every 6 mo	N
Ambalakisoa.2	X				12000	12-may	Every 6-7 mo	N
Ambalakisoa.3	X				5000	12-ago	Every 6 mo	N
Ambalakisoa.4	X				15000	12-oct	Once a year	N
Ambalakisoa.5	X				8000	12-nov	Every 2 mo	N
Ambalakisoa.6	X				40000	12-jun	Every 8 mo	
Ambalakisoa.7					NA	NA		
Ambalakisoa.8	X		X		10000;30000	12-oct	Every 6 mo; every 15 yrs	N
Ambalakisoa.9	X				10000	12-sep	Every 5 mo	N
Ambalakisoa.10	X				9000	12-nov	Every 4 mo	N
Ambalakisoa.11	X				6000	12-dic	Every mo	N
Ambalakisoa.12	X				4000	12-dic	Every mo	N

Table AIII.1. – Cont.

Location	# of households served by the pump
Antanambao Veriery.1	5
Antanambao Veriery.2	2
Andranomadio.1	3
Andranomadio.2	5
Andranomadio.3	5
Andranomadio.4	2
Andranomadio.5	3
Andranomadio.6	2
Andranomadio.7	10
Andranomadio.8	4
Mangarivotra S.1	5
Mangarivotra S.2	15
Mangarivotra S.3	6
Mangarivotra S.4	8
Mangarivotra S.5	3
Mangarivotra S.6	1
Mangarivotra S.7	7
Mangarivotra S.8	1
Mangarivotra S.9	10
Mangarivotra S.10	3
Mangarivotra S.11	12
Mangarivotra S.12	1
Mangarivotra S.13	2
Mangarivotra S.14	1
Tanambao V.1	4
Tanambao V.2	3
Tanambao V.3	2

Table AIII.1. – Cont.

Location	Cooking/Drinking Water Sources					Pitcher Pump water use							What water do you treat?			
	Pump	JIRAMA	River	Spring	Rainwater	Drinking	Cooking	Hand washing	Hygiene/ bathing	Household maintenance	Washing clothes	Other	Drinking	Cooking/ kitchen	Other	Do not Treat
Antanambao Veriery.1	X					X	X	X	X	X	X					X
Antanambao Veriery.2	X					X	X	X	X	X	X		X			
Andranomadio.1	X	X						X	X	X	X					X
Andranomadio.2	X	X						X	X	X	X					X
Andranomadio.3	X	X						X	X	X	X					X
Andranomadio.4	X	X						X	X	X	X					X
Andranomadio.5	X	X						X	X	X	X					X
Andranomadio.6	X	X						X	X	X	X					X
Andranomadio.7	X	X						X	X	X	X					X
Andranomadio.8	X	X						X	X	X	X					X
Mangarivotra S.1	X					X	X	X	X	X	X		X			
Mangarivotra S.2	X					X	X	X	X	X	X		X			
Mangarivotra S.3	X	X						X	X	X	X					X
Mangarivotra S.4	X	X				X	X	X	X	X	X		X			
Mangarivotra S.5	X					X	X	X	X	X	X		X			
Mangarivotra S.6	X	X						X	X	X	X					X
Mangarivotra S.7	X					X	X	X	X	X	X					X
Mangarivotra S.8	X					X	X	X	X	X	X					X
Mangarivotra S.9	X					X	X	X	X	X	X		X			
Mangarivotra S.10	X	X						X	X	X	X					X
Mangarivotra S.11	X	X						X	X	X	X					X
Mangarivotra S.12	X	X				X	X	X	X	X	X		X			
Mangarivotra S.13	X					X	X	X	X	X	X		X			
Mangarivotra S.14	X	X						X	X	X	X					X
Tanambao V.1	X					X	X	X	X	X	X		X			
Tanambao V.2	X	X						X	X	x	X					X
Tanambao V.3	X	X				X	X	X	X	X	X		X			

Table AIII.1. – Cont.

Location	Water Treatment and Usage							
		Water Treatment Method					# of water collections from all sources	# of water collections from Pitcher Pumps
	Why do you not treat the water	None	Boiling	Chlorine	SODIS	Other		
Antanambao Veriery.1	Water is clean and dependable	X					10	10
Antanambao Veriery.2			X				8	8
Andranomadio.1	JIRAMA water is already clean	X					2	1
Andranomadio.2	JIRAMA water is already clean	X					10	8
Andranomadio.3	JIRAMA water is already clean	X					11	9
Andranomadio.4	JIRAMA water is already clean	X					30	25
Andranomadio.5	JIRAMA water is already clean	X					20	17
Andranomadio.6	JIRAMA water is already clean	X					25	20
Andranomadio.7	JIRAMA water is already clean	X					16	14
Andranomadio.8	JIRAMA water is already clean	X					35	30
Mangarivotra S.1			X				8	8
Mangarivotra S.2			X				13	13
Mangarivotra S.3	JIRAMA water is already clean	X					30	25
Mangarivotra S.4			X				40	30
Mangarivotra S.5			X				10	10
Mangarivotra S.6	JIRAMA water is already clean	X					10	8
Mangarivotra S.7	Water from the pump is already clean	X					26	26
Mangarivotra S.8	Water from the pump is already clean	X					5	5
Mangarivotra S.9			X				4	4
Mangarivotra S.10	JIRAMA water is already clean	X					24	20
Mangarivotra S.11	JIRAMA water is already clean	X					20	18
Mangarivotra S.12			X				15	13
Mangarivotra S.13			X				10	10
Mangarivotra S.14	JIRAMA water is already clean	X					20	18
Tanambao V.1			X				10	10
Tanambao V.2	JIRAMA water is already clean	X					13	10
Tanambao V.3			X				9	7

Table AIII.1 – Cont.

Location	Water Collection						
	How many receptacles for collection	Size of receptacle					
		Bucket 5L	Bucket 10L	Bucket 15L	Jerry 15L	Jerry 20L	Jerry 25L
Antanambao Veriery.1				X			
Antanambao Veriery.2				X			
Andranomadio.1						X	
Andranomadio.2				X			
Andranomadio.3				X			
Andranomadio.4			X				
Andranomadio.5				X			
Andranomadio.6			X				
Andranomadio.7				X			
Andranomadio.8				X			
Mangarivotra S.1			X				
Mangarivotra S.2			X				
Mangarivotra S.3				X			
Mangarivotra S.4				X			
Mangarivotra S.5				X			
Mangarivotra S.6			X				
Mangarivotra S.7			X				
Mangarivotra S.8				X			
Mangarivotra S.9				X			
Mangarivotra S.10				X			
Mangarivotra S.11				X			
Mangarivotra S.12			X				
Mangarivotra S.13				X			
Mangarivotra S.14			X				
Tanambao V.1			X				
Tanambao V.2				X			
Tanambao V.3			X				

Table AIII.1. – Cont.

Location	Sanitation		
	Latrine	Depth of pit (m)	Notes
Antanambao Veriery.1	Y	2	Pour flush; clean
Antanambao Veriery.2	Y	1.5	
Andranomadio.1	Y	3	Pit; no cover; superstructure
Andranomadio.2	Y	2	Pour flush; concrete; close
Andranomadio.3	Y	2.5	Pit; hole in water table
Andranomadio.4	Y	2	Pour flush; clean
Andranomadio.5	Y	1	
Andranomadio.6	Y	Don't know	Inside house; septic; pour flush
Andranomadio.7	Y	1.5	Pit; hole in water table
Andranomadio.8	Y	2.5	Pour flush; septic tank
Mangarivotra S.1	Y	3	Pit; no door; downhill of pump
Mangarivotra S.2	N	N/A	Defecate in Canal
Mangarivotra S.3	Y	1.5	Pit; concrete slab; clean
Mangarivotra S.4	Y	2	Pit; concrete slab; metal structure
Mangarivotra S.5	Y	2	pit; concrete slab
Mangarivotra S.6	Y	3	Pit; concrete slab; structure
Mangarivotra S.7	Y	2	Pit; concrete slab; structure
Mangarivotra S.8	N	N/A	Did not indicate where family defecates
Mangarivotra S.9	Y	3	Poor; barrel; structure
Mangarivotra S.10	Y	2	Pit; concrete slab; metal structure
Mangarivotra S.11	Y	2	Pit; concrete slab; metal structure
Mangarivotra S.12	Y	2	Pour flush; septic; clean
Mangarivotra S.13	Y	1.5	Pit; dirty; metal structure
Mangarivotra S.14	Y	1.5	Pit; no cover; metal structure
Tanambao V.1	Y	Don't know	No latrine; use canal
Tanambao V.2	Y	1.5	Poor; no roof; tarp walls; downhill of pump
Tanambao V.3	Y	2	Pit; concrete slab; metal structure; clean

Table AIII.1 – Cont.

	Pump Information			
	Date of pump installation	Age of well (yr)	Cost of pump and installation	How is the water quality?
Location	2012	0	305,000	Clean
Antanambao Veriery.1	2012	0	300,000	Clean
Antanambao Veriery.2	2006	6	Self-built	Dirty
Andranomadio.1	2012	0	90,000	Dirty
Andranomadio.2	2007	5	100,000	Clean
Andranomadio.3	2002	10	50,000	A little dirty
Andranomadio.4	2002	10	40,000	A little dirty
Andranomadio.5	2000	12	Don't remember	Clean
Andranomadio.6	2010	2	100,000	A little dirty
Andranomadio.7	2000	12	50,000	Clean
Andranomadio.8	2012	0	130,000	Clean
Mangarivotra S.1	2007	5	120,000	Clean
Mangarivotra S.2	1994	18	60,000	Clean
Mangarivotra S.3	1988	24	Don't remember	Clean
Mangarivotra S.4	1994	18	50,000	Clean
Mangarivotra S.5	2012	0	120,000	Clean
Mangarivotra S.6	Over 30 yrs ago	30	Don't remember	Clean
Mangarivotra S.7	2012	0	150,000	Clean
Mangarivotra S.8	1992	20	Don't remember	Clean
Mangarivotra S.9	2003	9	80,000	Clean
Mangarivotra S.10	1998	14	100,000	Clean
Mangarivotra S.11	2002	10	60,000	Clean
Mangarivotra S.12	2004	8	160,000	Clean
Mangarivotra S.13	2005	7	140,000	Clean
Mangarivotra S.14	2008	4	190,000	Clean
Tanambao V.1	2012	0	100,000	Clean
Tanambao V.2	1980	32	Don’t remember	Clean
Tanambao V.3	2012	0	305,000	Clean

Table AIII.1 – Cont.

Location	Pump Information			
	How deep to the water table?	Depth of Pipe (m)	Constant water supply?	If no, why not?
Antanambao Veriery.1	12	13	Y	
Antanambao Veriery.2	12	13	y	
Andranomadio.1	5	6	Y	
Andranomadio.2	2	3.5	N	Some months the water is very dirty
Andranomadio.3	3	5	N	Some months the water is very dirty
Andranomadio.4	2	4	Y	
Andranomadio.5	3	4	N	Some months the water is dirty
Andranomadio.6	4	5	Y	Some months the water is dirty
Andranomadio.7	2	3	N	Some months the water is dirty
Andranomadio.8	3	5	N	Some months the water is dirty
Mangarivotra S.1	10	10	Y	
Mangarivotra S.2	9	9	Y	
Mangarivotra S.3	13	13	Y	
Mangarivotra S.4	6	7	Y	
Mangarivotra S.5	4	5	Y	
Mangarivotra S.6	4	5	Y	
Mangarivotra S.7	6	7	Y	
Mangarivotra S.8	5	6	Y	
Mangarivotra S.9	6	7	Y	
Mangarivotra S.10	6	7	Y	
Mangarivotra S.11	5.5	6	N	Some months the water is dirty
Mangarivotra S.12	5	5 or 6	Y	
Mangarivotra S.13	3.5	4	Y	
Mangarivotra S.14	5	6	Y	
Tanambao V.1	8	8.5	Y	
Tanambao V.2	9	10	Y	
Tanambao V.3	6	7	Y	

Table AIII.1. – Cont.

Location	Pump Repairs							
	Most recent repair				Cost	Date	Frequency of repair	Priming necessary?
	Leather check valves	Pipe	Well screen	Lever				
Antanambao Veriery.1								N
Antanambao Veriery.2								Y
Andranomadio.1	X				8000	11-dic	Twice a year	Y
Andranomadio.2								N
Andranomadio.3	X				14000	12-nov	Every 5 mo	Y
Andranomadio.4	X				5000	12-nov	Every month	N
Andranomadio.5	X				20000	12-oct	Every 2 mo	Y
Andranomadio.6	X				21000	12-nov	Every 6 mo	N
Andranomadio.7	X				4500	12-oct	Every 4 mo	N
Andranomadio.8	X				8000	12-jun	Every month	N
Mangarivotra S.1								N
Mangarivotra S.2	X				9000	12-dic	Every 2 mo	N
Mangarivotra S.3	X				5000	12-oct	Every 3 mo	N
Mangarivotra S.4	X				5000	12-oct	Every 4 mo	N
Mangarivotra S.5	X				8000	12-nov	Every month	N
Mangarivotra S.6								Y
Mangarivotra S.7	X				6000	12-jun	Once a year	N
Mangarivotra S.8								N
Mangarivotra S.9	X				3500	12-nov	Every 2 mo	N
Mangarivotra S.10	X	X			4000;20000	Dec 12/Jun 12	Every 2 mo/ every 10 yrs	Y
Mangarivotra S.11	X				3000	12-jun	Once a year	Y
Mangarivotra S.12	X				10000	12-nov	Every 6 mo	N
Mangarivotra S.13	X				10000	12-sep	Every 3 mo	N
Mangarivotra S.14	X			X	8000/10000	Oct 12/June 12	Every 6 mo; once until now	Y
Tanambao V.1	X				10000	12-nov	Every 6 mo	N
Tanambao V.2					NA			N
Tanambao V.3	X				10000	41802	Every 6 mo	Y

Table AIII.2. Cost Assessment of Pumps Constructed Since the Year 2000.

Number	Cost (1,000 Ar)	Year of Construction
1	50	2000
2	50	2000
3	80	2002
4	200	2002
5	50	2002
6	40	2002
7	60	2002
8	80	2003
9	160	2004
10	50	2005
11	140	2005
12	70	2007
13	100	2007
14	120	2007
15	20	2008
16	190	2008
17	50	2009
18	20	2009
19	160	2010
20	100	2010
21	100	2010
22	70	2011
23	200	2012
24	305	2012
25	300	2012
26	90	2012
27	100	2012
28	130	2012
29	120	2012
30	150	2012
Summary Statistics		
Calculation	MGA (1,000 Ar)	US$
Mean	112	50.80
Standard Deviation (σ)	71	32.40
Median	100	45.50
Price + σ	183	83.20
Price – σ	41	18.50

Appendix IV Permission to Include a Correspondence with the Institutional Review Board Regarding an Informal Evaluation of Interviews with Pump Users

This Appendix documents a correspondence between a research colleague of mine and the Institutional Review Board (IRB) at the University of South Florida. According to the informal review of a survey developed to assess Pitcher Pump systems initially, some of the questions were deemed to treat the respondents as human subjects. Any and all questions considered to be treating respondents as human subjects were stricken from record and were not included anywhere in this thesis or its appendices. Most of the original questions were deemed to serve their purpose as an evaluation of the water supply technologies themselves, however, and were therefore considered appropriate to include in this thesis.

Brad Akers <d.bradakers@gmail.com>

Fwd: IRB Question
5 messages

Meghan Wahlstrom <mawahlstr@gmail.com> Thu, Mar 20, 2014 at 1:28 PM
To: Brad Akers <d.bradakers@gmail.com>

Brad,

Here is my e-mail correspondence with the IRB board. You have my permission to use it in your thesis.

Meghan
---------- Forwarded message ----------
From: **Byers, Cheryl** <cbyers1@usf.edu>
Date: Wed, Feb 19, 2014 at 4:02 PM
Subject: RE: IRB Question
To: Meghan Wahlstrom <mawahlstr@gmail.com>

That should all be fine Meghan. Good luck with your research!

Cheryl

Cheryl L. Byers, MHA, CIP
Assistant Vice President for Research Compliance
Research Integrity Officer
University of South Florida

From: Meghan Wahlstrom [mailto:mawahlstr@gmail.com]
Sent: Wednesday, February 19, 2014 1:56 PM

To: Byers, Cheryl
Subject: Re: IRB Question

Thanks so much. I'm I ok to assume that the information gathered about frequency that the pumps were repaired and the amount they paid are ok? Those are about the pumps themselves.

Is a GoogleMap showing color coded sample locations fine to put in my thesis? I would not be presenting the name of the household nor typing out the coordinate anywhere in the paper. If you would like I can send a copy of the map to show you what I would like to use.

Sorry for all the questions.

Meghan

On Wed, Feb 19, 2014 at 1:49 PM, Byers, Cheryl <cbyers1@usf.edu> wrote:
Hi Meghan,
It was the questions you sent:
- how they used the water collected from the Pitcher Pumps (i.e cooking, washing, drinking, etc.),
- the method they used (if any) to treat their water,
- the number of families who used the pump, and finally,
- the number of times they collected water throughout the day

Just keep your data to these points and you'll be fine.
Cheryl

Cheryl L. Byers, MHA, CIP
Assistant Vice President for Research Compliance
Research Integrity Officer
University of South Florida

From: Meghan Wahlstrom [mailto:mawahlstr@gmail.com]
Sent: Wednesday, February 19, 2014 1:48 PM
To: Byers, Cheryl
Subject: Re: IRB Question

Cheryl,

Thank you for your response. I was not able to see the highlighted section. Would you be able to resend it?

Meghan

On Wed, Feb 19, 2014 at 1:44 PM, Byers, Cheryl <cbyers1@usf.edu> wrote:
Hi Meghan,
Thank you for your email. I vaguely remember the work Mike was doing and remember it being specific to the pump and not to individuals which is why we determined he did not require IRB review/oversight. However, in reviewing your questionnaire, it appears that you were asking questions specific to the individual (i.e., how often does your family see an incident of diarrhea) and recording identifiable data (names and GPS coordinates) and therefore, this is human subjects research that required IRB review/oversight. The IRB does not conduct retrospective review of research; however, upon speaking with the IRB Chairperson, we have determined that if you only use data from the questions below (see highlighted section), this is not human subjects research.

Please note that in the future, you should always confirm whether IRB approval is needed PRIOR to conducting the research. Let me know if you have any additional questions.
Cheryl

Cheryl L. Byers, MHA, CIP
Assistant Vice President for Research Compliance
Research Integrity Officer
University of South Florida

From: Meghan Wahlstrom [mailto:mawahlstr@gmail.com]
Sent: Wednesday, February 19, 2014 9:08 AM
To: Byers, Cheryl
Subject: IRB Question

Dear Cheryl,

I have a question for you regarding IRB.

In 2012 and 2013 I served as a Peace Corps volunteer in Madagascar as part of the Master's International Program. My research is a continuation of work done in Madagascar by Mike MacCarthy, who was in contact with you in 2011 regarding his studies (which were determined not to need IRB approval)

Whereas Mike's research objective was to evaluate the effectiveness of a project in a developing community context in which low-cost household groundwater supply systems have proven to be sustainable, mine was to evaluate the possibility of improving the quality of water produced by those systems by increasing the depth of the well screen.

Here is a summary of main field research tasks:
- Water quality testing of existing Pitcher Pumps
- Visual observation and inspection of water and sanitation systems at those properties where water samples were collected.
- Interviews with well owners focusing on water usage, treatment, and collection practices
- Installation of four monitoring wells at one of the site
- Water quality testing from the installed monitoring well.

Much of the interview data was collected for general background knowledge, and only a limited amount was to be used in my master's thesis. I was planning mainly to use the information on the well itself (i.e. depth, age, distance from pollution source, condition). However, now that I am writing my thesis, I'm finding that my discussions and conclusions could be strengthened a bit by using some additional data.

I am writing to find out if some of the questions asked could be considered questions on human subjects. I've attached a copy of the full questionnaire for your review but examples of the some of the questions of concern are questions regarding:
- how they used the water collected from the Pitcher Pumps (i.e cooking, washing, drinking, etc.),
- the method they used (if any) to treat their water,
- the number of families who used the pump, and finally,
- the number of times they collected water throughout the day

I'm using the data from the questions above to determine the risk, if any, associated with the water provided by the pumps. For example, if the water is found to be contaminated with bacteria but the owners are not using that water for drinking, then the risk is minimal. Or, if the water is contaminated but the owners treat the water prior to drinking, then the risk is minimal.

Please note that we did collect names and GPS coordinates of the households we interviewed; however, this was for our use only. Nowhere in the report or appendix will the names or coordinates be written out. I do plan on using a map from GoogleEarth showing sample locations with the colors of the markers corresponding to water quality data; however, nowhere on the map will the coordinates be listed nor will there be any label identifying the owner's name nor the arbitrary ID number we gave the houses.

Thank you,

Meghan

Appendix V Total Collected Field Data

This Appendix documents the total data measured and documented for fieldwork during the project. Data are included from sampling campaigns carried out in December 2012, late March/early April 2013, and July 2013. Sampling campaigns were based around seasonal changes in Madagascar and my limited travel availability as a Peace Corps Volunteer. Methods outlined in Chapter 3 were employed to collect and compile data. Irregularities in procedure are noted in each table below.

Table AV.1. Total Collected Field Data for December 2012 Sampling Campaign

Sample ID	Manufacturer ID	Depth to Well Screen[a]	Age	pH	Temperature	Total Dissolved Solids	Dissolved Oxygen	Flushed Pb	First-Draw Pb
		m	yr		°C	g/L	mg/L	µg/L	µg/L
Pump 1	M1	6	20	7.02	27.75	0.179	2.39	6	4
Pump 2	M1	7	5	6.83	27.77	0.161	2.66	16	16
Pump 3	M1	7	1	<6.8[b]	–[c]	–[c]	–[c]	12	13
Pump 4	M2	5.5	0	7.39	28	0.192	2.04	2[e]	2
Pump 5	M2	8	5	7.32	–[c]	0.296	2.19	20	19
Pump 6	M2	6	4	7.62	27.09	0.159	1.87	3	9
Pump 7	M3	4	17	7.14	26.89	0.468	3.27	9	5
Pump 8	M3	5	9	6.4	25.84	0.186	4.94	15	14
Pump 9	M3	8	21	6.7	27.54	0.283	3.23	2	4
Pump 10	M4	8	12	<6.8[b]	27.34	0.179	2.39	18	27
Pump 11	M4	8.5	2	<6.8[b]	–[c]	–[c]	–[c]	11	13
Pump 12	M4	8	10	<6.8[b]	–[c]	–[c]	–[c]	8	13
Pump 13	M6	4	10	<6.8[b]	–[c]	–[c]	–[c]	5	6
Pump 14	M5	4	10	<6.8[b]	27[d]	–[c]	–[c]	9	18
Pump 15	M5	5	12	<6.8[b]	29[d]	–[c]	–[c]	9	22
Pump 16	M6	8.5	4	<6.8[b]	26[d]	–[c]	–[c]	14	13
Pump 17	M6	10	0	<6.8[b]	–[c]	–[c]	–[c]	10	6
Pump 18	M6	7	32	<6.8[b]	–[c]	–[c]	–[c]	44	37

[a] Generally, well depths were taken as values reported for pipe length by pump users. Few values were confirmed by measurement in the field.

[b] The Oxfam-DelAgua Water Testing Kit was used for pH due to equipment malfunction in the Hydrolab® Quanta® probe; lower limit of pH was "<6.8".

[c] The Hydrolab® Quanta® instrument malfunctioned on 12/3/2012 and was inoperable for the remainder of data collection.

[d] Temperature was recorded via glass alcohol thermometer readable to 2 significant digits.

[e] Lower limit of detection by ASV was 2 µg/L. The actual reading displayed was exactly 2 µg/L, not "<2 µg/L"

Table AV.2. Total Collected Field Data for April 2013 Sampling Campaign.

Sample ID	pH[a]	Temperature[b]	Calcium Hardness[c]	Alkalinity[d]	Flushed Pb	First-Draw Pb
		°C	mg/L Ca	mg/L $CaCO_3$	µg/L	µg/L
Pump 1	6.6	27.5	120-180	40-80	35	39
Pump 2	6.3	27.5	120-180	0-40	6	9
Pump 3	6.7	27	120-180	40-80	11	15
Pump 4	6.5	28.5	120-180	40-80	3	9
Pump 5	6.6	28	120-180	40-80	4	12
Pump 6	6.3	28.5	60-120	40-80	9	–[e]
Pump 7	6.3	27.5	120-180	0-40	5	11
Pump 8	6.1	28.5	60-120	0-40	7	29
Pump 9	6.4	28	60-120	0-40	3	6
Pump 10	6.4	28	120-180	0-40	17	23
Pump 11	6.4	27	120-180	0-40	15	14
Pump 12	6.1	27.5	30-60	0-40	7	16
Pump 13	6.6	26.5	120-180	80-120	10	18
Pump 14	6.9	27.5	120-180	80-120	6	11
Pump 15	6.9	26	120-180	120-180	9	9
Pump 16	6.6	27.5	120-180	40-80	9	10
Pump 17	6.7	27	120-180	80-120	7	12
Pump 18	6.3	26	120-180	0-40	4	4

[a] pH was determined by Fisher Scientific, LLC Whatman™ pH Indicator Papers for pH range 6.0–8.1 (Fisher, 2014a)

[b] Temperature was measured via glass alcohol thermometer.

[c] Hardness was measured via Fisher Scientific, LLC Insta-Test™ Hard Test Strips for calcium hardness for low range of 0–180 mg/L (Fisher, 2014c)

[d] Alkalinity was measured via Fisher Scientific, LLC Insta-Test™ Alkal Test Strips for alkalinity as carbonate for range 0–180 mg/L (Fisher, 2014b).

[e] One of the 10 ASV test strips typically included in a box was missing. This particular house did not heed the agreement to wait for a 1-hour period before drawing water and was therefore excluded from the 1-hour sampling pool to make up for the missing test strip.

Table AV.3. Total Collected Field Data for July 2013 Sampling Campaign.

Sample ID	pH via Quanta Probe[a]	pH via Test Strips	Temperature	Total Dissolved Solids	Dissolved Oxygen	Calcium Hardness	Alkalinity	Flushed Pb	First-Draw Pb
			°C	g/L	mg/L	mg/L $CaCO_3$	mg/L $CaCO_3$	µg/L	µg/L
Pump 1	8.84	6.8	25.96	0.23	6.98	120-180	40-80	11	13
Pump 2	8.41	6.3	26.26	0.18	3.3	30-60	0-40	6	6
Pump 3	8.66	6.6	26.56	0.30	3.34	120-180	40-80	10	19
Pump 5	8.49	6.8	24.82	0.22	7.29	120-180	40-80	10	14
Pump 7	7.95	7.2	24.7	0.40	3.97	120-180	40-80	3	5
Pump 8	7.87	6.3	25.7	0.44	4.4	120-180	0-40	7	15
Pump 10	8.55	7	24.4	0.21	5.56	120-180	40-80	30	42
Pump 11	7.7	6	24.71	0.37	5.29	120-180	0-40	11	13
Pump 12	8.4	6.8	25.7	0.26	6.54	120-180	40-80	7	15
Pump 13	8.67	6.5	24.02	0.43	2.61	120-180	80-120	10	10
Pump 14	9	6.8	24.26	0.23	3.77	120-180	80-120	9	11
Pump 15	9.15	6.3	24.63	0.39	5.19	120-180	120-180	15	17
Pump 16	8.75	6.6	24.69	0.52	5.56	120-180	40-80	21	18
Pump 17	9.17	6.8	24.9	0.17	5.25	60-120	80-120	2	2
Pump 18	8.82	6.3	25.18	0.24	5.11	120-180	0-40	2	2

[a] The service record for the Quanta probe certifies that pH was calibrated. However, some readings were over >10. I performed another calibration, and thereby achieved lower pH readings at the same households the next day, though readings remain much higher than those of the Fisher Scientific pH paper strips (calibrated numbers are included in the Table above).

Table AV.4. Example Calculation of Langelier Saturation Index (LSI) for a Measure of Corrosivity.

Sample ID	Dimensionless TDS[a]	Dimensionless Temperature[a]	Dimensionless Hardness[a]		Dimensionless Alkalinity[a]		Theretical pH (*pHs*)[a]				Langelier Saturation Index[a]	
			Low	High	Low	High	Low Ca, low CO_3	Low Ca, high CO_3	High Ca, low CO_3	High Ca, high CO_3	Low	High
Pump 1	0.14	2.07	1.68	1.86	1.60	1.90	8.22	7.92	8.05	7.74	-0.94	-1.42
Pump 2	0.13	2.06	1.08	1.38	0.00	1.60	10.41	8.81	10.11	8.51	-2.21	-4.11
Pump 3	0.15	2.06	1.68	1.86	1.60	1.90	8.22	7.92	8.05	7.74	-1.14	-1.62
Pump 5	0.13	2.09	1.68	1.86	1.60	1.90	8.24	7.94	8.07	7.76	-0.96	-1.44
Pump 7	0.16	2.09	1.68	1.86	1.60	1.90	8.27	7.97	8.09	7.79	-0.59	-1.07
Pump 8	0.16	2.07	1.68	1.86	0.00	1.60	9.86	8.25	9.68	8.08	-1.78	-3.56
Pump 10	0.13	2.10	1.68	1.86	1.60	1.90	8.25	7.95	8.07	7.77	-0.77	-1.25
Pump 11	0.16	2.09	1.68	1.86	0.00	1.60	9.87	8.27	9.69	8.09	-2.09	-3.87
Pump 12	0.14	2.07	1.68	1.86	1.60	1.90	8.23	7.93	8.06	7.76	-0.96	-1.43
Pump 13	0.16	2.10	1.68	1.86	1.90	2.08	7.99	7.81	7.81	7.63	-1.13	-1.49
Pump 14	0.14	2.10	1.68	1.86	1.90	2.08	7.95	7.78	7.78	7.60	-0.80	-1.15
Pump 15	0.16	2.09	1.68	1.86	2.08	2.26	7.79	7.62	7.62	7.44	-1.14	-1.49
Pump 16	0.17	2.09	1.68	1.86	1.60	1.90	8.28	7.98	8.11	7.80	-1.20	-1.68
Pump 17	0.12	2.09	1.38	1.68	1.90	2.08	8.23	8.05	7.93	7.75	-0.95	-1.43
Pump 18	0.14	2.08	1.68	1.86	0.00	1.60	9.84	8.24	9.66	8.06	-1.76	-3.54

[a] Calculations with this notation are based on Roberge (2008) calculations and generalized LSI equations.

[c] Values obtained via this method were deemed more conservative and more rigorously calculated, and were therefore used in other analyses.

Appendix VI Supplemental Analysis on Potential Factors Affecting Pb Leaching

Tables AVI.1–AVI.5 included below provide supplemental statistical analysis of relationships between Pb-leaching behavior and variables measured in the field. Descriptive statistics are used to develop and present simple comparisons between ranges of selected variables.

Table AVI.1. Pb Concentrations Measured in Pumps Installed by Each Manufacturer

Manufacturer ID	Mean Concentration (μg/L)	Median Concentration (μg/L)	Standard Deviation (μg/L)
Manufacturer 1 [*3 pumps*]			
Flushed Samples	12.6	11.0	9.1
First-Draw Samples	14.9	13.0	10.2
Manufacturer 2 [*3 pumps*]			
Flushed Samples	7.3	4.0	6.4
First-Draw Samples	10.8	10.5	5.7
Manufacturer 3 [*3 pumps*]			
Flushed Samples	6.4	6.0	4.2
First-Draw Samples	11.1	8.5	8.4
Manufacturer 4 [*3 pumps*]			
Flushed Samples	13.8	11.0	7.4
First-Draw Samples	19.6	15.0	9.8
Manufacturer 5 [*2 pumps*]			
Flushed Samples	9.5	9.0	2.9
First-Draw Samples	14.7	14.0	5.1
Manufacturer 6 [*4 pumps*]			
Flushed Samples	11.5	9.5	11.5
First-Draw Samples	11.5	10.0	9.7

Table AVI.2. Pb Concentrations in Pumps with Various Well Screen Depths

Depth Range	Mean Concentration (µg/L)	Median Concentration (µg/L)	Standard Deviation (µg/L)
4–5.9 meters [*6 pumps*]			
Flushed Samples	7.8	9.0	3.7
First-Draw Samples	12.5	11.0	6.9
6–7.9 meters [*5 pumps*]			
Flushed Samples	14.5	11.0	13.0
First-Draw Samples	16.4	13.0	11.6
8–10 meters [*7 pumps*]			
Flushed Samples	11.3	10.0	7.2
First-Draw Samples	14.6	13.0	8.8

Table AVI.3. Pb Concentrations in Pumps of Various Ages

Pump Age Range	Mean Concentration (µg/L)	Median Concentration (µg/L)	Standard Deviation (µg/L)
0–4 years [*6 pumps*]			
Flushed Samples	9.4	10.0	5.3
First-Draw Samples	11.2	13.0	5.0
5–9 years [*3 pumps*]			
Flushed Samples	10.1	7.0	5.6
First-Draw Samples	14.9	14.0	6.5
10–19 years [*6 pumps*]			
Flushed Samples	10.3	9.0	6.3
First-Draw Samples	15.5	14.0	9.1
20+ years [*3 pumps*]			
Flushed Samples	16.8	8.5	18.1
First-Draw Samples	17.2	9.5	16.5

Table AVI.4. Pb Concentrations in Pumps in Participating Neighborhoods

Neighborhood ID	Mean Concentration (µg/L)	Median Concentration (µg/L)	Standard Deviation (µg/L)
Neighborhood 1 [*3 pumps*]			
Flushed Samples	12.6	11.0	9.1
First-Draw Samples	14.9	13.0	10.2
Neighborhood 2 [*3 pumps*]			
Flushed Samples	7.0	3.5	7.0
First-Draw Samples	10.8	10.5	5.7
Neighborhood 3 [*6 pumps*]			
Flushed Samples	10.3	8.0	7.0
First-Draw Samples	15.6	14.0	9.9
Neighborhood 4 [*3 pumps*]			
Flushed Samples	9.1	9.0	2.8
First-Draw Samples	13.6	11.0	5.3
Neighborhood 5 [*3 pumps*]			
Flushed Samples	15.3	10.0	12.9
First-Draw Samples	14.0	12.0	10.5

Table AVI.5. Pb Concentrations in Pumps with Various Water pH[a]

Depth Range	Mean Concentration (µg/L)	Median Concentration (µg/L)	Standard Deviation (µg/L)
pH = 6.0–6.3 [*8 samples*]			
Flushed Samples	8.0	7.0	3.3
First-Draw Samples	14.5	14.0	6.9
pH = 6.4–6.7 [*13 samples*]			
Flushed Samples	11.9	10.0	8.7
First-Draw Samples	15.8	14.0	8.4
pH = 6.8–7.2 [*9 samples*]			
Flushed Samples	9.7	9.0	8.2
First-Draw Samples	13.6	11.0	11.5

[a] pH data were generally incomplete. Measurements made via test strips in April and July 2013 sampling campaigns were used to make the table.

Overall, it is difficult to determine relationships between the variables selected and the relative amount or rate of Pb leaching. The most accurate way to interpret the data tables is to say that no strong relationships are evident between any single variable and Pb leaching. Starting with Table AVI.1, the individual pump manufacturers are compared by mean, median, and standard deviations of measured Pb in sample waters drawn from pumps finished by each manufacturer. Tables AVI.2 and AVI.3 are less intuitively prepared. Ranges for different reported depths to the well screens and different pump ages were grouped so that a similar number of samples could be analyzed and compared. Table AVI.4 is more like Table AVI.1 in that pumps and samples are broken up according to location, which is not a subjective measure. Finally, Table AVI.5 is split up into three common ranges of pH measured in the sample waters in the field.

Though in some tables the means of flushed and first-draw samples can appear to be fairly different from one category of a variable to the next, the median values are usually much more similar. In this type of analysis with a very limited number of samples ($n = 3–5$), usually a normal distribution cannot be established, and in fact, might not exist (Ryan, 2007). Therefore, the median is a better measure of the range of Pb concentrations measured. Furthermore, the standard deviations of corresponding Pb concentrations will usually offset the small differences in calculated mean values. In fact, in some cases like pump age in Table AVI.3, the standard deviations are actually greater in magnitude than the calculated mean. Thus, the conclusion drawn from data analysis in these tables is that no strong relationships between variables and Pb-leaching behavior present themselves when viewed with descriptive statistics.

Appendix VII Supplemental Information on the Use of the EPA Integrated Exposure Uptake Biokinetic Model for Lead in Children

This Appendix documents the supplemental information necessary to reproduce model simulations in the IEUBK Model. Information includes numbers not covered in the body of the thesis for the specific inputs of each of the scenarios included in the thesis. Other constants are explained. Furthermore, the relative contribution of Pb exposures from water consumption are compared those of other common environmental exposures in each of the three selected scenarios included in Figures 19 and 20.

The WHO document for calculating disease burden attributable to Pb exposure was used to inform concentrations for air and dust (Fewtrell et al., 2003). EPA default concentrations for these two exposure routes are constant for a given scenario of exposure and subsequent simulation (Fewtrell et al., 2003; EPA, 2007). Substitution of the WHO ranges listed under the scenario "contaminated water, low other exposures" allows for an upper and lower range of these environmental exposures, which I believe better characterizes the wide margins of uncertainty about these exposures in Madagascar (Fewtrell et al., 2003).

Table AVII.1. Supplemental Information for Air and Dust Inputs in the IEUBK Model

Media	Low Exposure	Moderately Low Exposure
Air (µg/m^3)	0.05	0.5
Dust (mg/kg)	50	200

The indoor air concentration is assumed to be 30% of the outdoor air concentration, based on US data. It should be noted that the indoor air concentration in Tamatave would likely be equal to that of the outdoor concentration due to a lack of ventilation and the hot climate, which means that houses are open—all windows and doors, typically—all day. However, in the interest of minimizing exposure from this uncharacterized exposure route, I left the default relationship between indoor and outdoor air from the IEUBK Model in place (EPA, 2007). The "low exposure" value of 0.05 $\mu g/m^3$ is half of the default value set by the IEUBK Model, while value assumed for the "moderately low exposure" is greater than the default value by a factor of five (Fewtrell et al., 2003; EPA, 2007). I label this exposure as "moderately low" because it is included in the WHO scenario for "contaminated water, low other exposures" and remains at a lower magnitude than would be for leaded gasoline, for example (Fewtrell et al., 2003).

Dust concentrations are based on US values, and are assumed to relate to soil concentrations. The EPA IEUBK Model does not assume greater dust Pb exposure from things like lead paint chips, which I judge to be an appropriate assumption in Tamatave, where houses are made from local materials like wood or bamboo, and are typically not painted (EPA, 2007). I assumed the dust concentration to be equal to that of the soil concentration due to the open nature of the houses in Tamatave (e.g., no thresholds or seals, open doors and windows). The dust concentration, at its maximum value of 200 mg/kg (µg/g), is equal to that set as the default value in the IEUBK model (Fewtrell et al., 2003; EPA, 2007).

Table AVII.2. Estimated Dietary Intake of Rice for Small Children in Madagascar

Child Age (months)	Estimated Uncooked Rice Consumed per Meal (cups)
6–11	0.1
12–23	0.2
24–35	0.3
36–47	0.4
48–59	0.5

Table AVII.3. Supplemental Information for Default Dietary Pb Intake for Use in the IEUBK Model

Child Age (months)	Default Dietary Pb Intake (µg/day)
6–11	2.26
12–23	1.96
24–35	2.13
36–47	2.04
48–59	1.95

The model does not take into account that Pb-contaminated water is used to prepare food. The WHO document does not give a "low exposure" number for food Pb concentrations because the data are very site-specific (Fewtrell et al., 2003). In Madagascar, meals generally consist of "a large portion of rice with *loaka*, a side dish of meat or vegetables, three times a [sic] day" (Hardenbergh, 1997). Based on informal observations I made during my time as a Peace Corps volunteer, Table AVII.2 shows the quantity of rice typically consumed by young children. If two cups of water are used to prepare each cup of uncooked rice, and a child eats a 1/2 cup of (uncooked) rice for a meal, then 0.24 liters of water goes into a meal. Because Pb is conservative, the 0.24 liters of water can be multiplied by a measured concentration (10 µg/L for example). This calculation finds that approximately 2.4 µg are consumed in one meal. The same exposure for three meals would indicate that approximately 7.2 µg/day are consumed by children approximately 48–59 months. However, I did not actually measure food Pb concentrations, nor did I measure the amount of water used to cook rice or the amount of rice consumed by children in Tamatave. Therefore, because of the speculative nature of this calculation, a significantly lower value was assumed for dietary concentrations, based on data from the US, to make as conservative an estimate as possible (EPA, 2007; Table AVII.3).

Maternal data is the next category of input data for the IEUBK Model. The maternal data consists of an input BLL for the mother at the time of birth, and is designed to estimate initial organ Pb concentrations in newborn infants (EPA, 2007). In Section 3.3, I established that the best possible estimate for this value in urban Madagascar comes from a study with limited data that grouped 26 African countries together (Fewtrell et al., 2003). Accordingly, the only concentration used for this input in all scenarios was 11.6 µg/dL (Fewtrell et al., 2003).

The next input for the IEUBK Model consists of gastrointestinal absorption coefficients, which determine the bioavailability of Pb from a particular environmental exposure route (EPA, 2007). The default constants are based on studies in the US (EPA, 1994c; EPA, 2007). Without more rigorous data available for the urban population in Tamatave, I left these parameters at default values.

The final input is the geometric standard deviation (GSD), a measure of the variability of Pb uptake in a given population with identical exposures (EPA, 1994c; EPA, 2007). I used the default value of 1.6 for the GSD, developed from studies in the US.

After the inputs are finalized, the program calculates the geometric mean BLL for children of specified ages, the percentage of a distribution of children that would be above a user-specified BLL of concern, and media-specific intakes and uptakes (e.g., effective doses absorbed) (EPA, 2007). Table AVII.4 provides the media-specific percentage of exposures for the three scenarios used in Chapter 4 to communicate the link between environmental Pb concentrations and public health (Table 12; Figures 19 and 20).

Table AVII.4. IEUBK Model-Estimated Media-Specific Contributions to Absorbed Environmental Exposure

	Child Age (months)	Water (% of total)	Soil/Dust (% of total)	Air (% of total)	Diet (% of total)
Scenario 2a	6–11	27.9	43.1	0.3	28.7
	12–23	42.6	41.9	0.3	15.2
	24–35	43.0	40.5	0.5	16.0
	36–47	43.7	40.5	0.5	15.3
	48–59	50.1	33.1	0.6	16.2
Scenario 4b	6–11	20.4	67.2	1.2	11.2
	12–23	30.1	63.0	1.1	5.7
	24–35	30.5	61.4	2.0	6.1
	36–47	31.0	61.1	2.1	5.8
	48–59	37.8	53.3	2.4	6.5
Scenario 7b	6–11	40.8	50.0	0.9	8.3
	12–23	53.6	41.8	0.8	3.8
	24–35	54.1	40.5	1.4	4.0
	36–47	54.6	40.1	1.4	3.8
	48–59	62.0	32.5	1.5	4.0

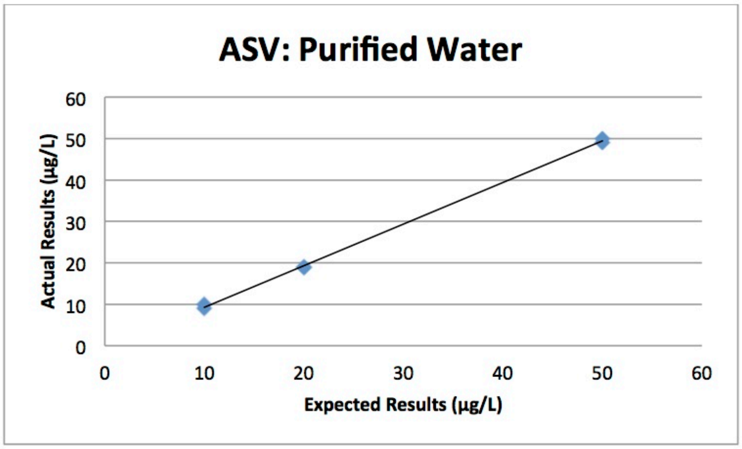
Appendix VIII Supplemental Information for the Evaluation of Pb-Detection Equipment

This appendix includes a research report completed by an undergraduate researcher at the University of South Florida in Tampa, FL. The student's report is included with permission (Appendix I) in total, with each page inserted as an image, and is based on the evaluation of the Palintest® SA1100 Scanning Analyzer for measurements of Pb in water. Pure and natural waters were spiked with known concentrations before measurements. Samples were analyzed in the SA1100 via Anodic Stripping Voltammetry (ASV) to make comparisons between known concentrations and measured concentrations to evaluate the accuracy and precision of the SA1100, and ultimately the appropriateness of ASV for field measurements in Madagascar. The report is included in the following pages.

Lead Contamination

By: Austin James Michael Atkins

Lead by: Professor Jeff Cunningham



Conclusion:

The results of this test suggest that the ASV is capable of accurately measure the amount of lead in purified water at multiple concentrations. This can be seen in the illustration where a linear relationship is present.

ASV: Groundwater

Objective:

To test the ASV's accuracy in its ability to measure lead concentrations in groundwater.

Procedure:

1.) From a local well, collect 500 mL of groundwater.

2.) Using the formula C1V1=C2V2, make each lead sample that will be used in this test. (Example: Given a 10 mg/L stock solution of lead nitrate, you will need to mix in 10 µL of the stock solution with groundwater to obtain a 50 mL sample of 10 µg/L concentration.) Concentrations: 10 µg/L and 50 µg/L

3.) Following the ASV's owner's manual, test each sample twice for the amount of lead present in each sample and record your findings.

ASV: Purified Water

Objective:

To test the ASV's accuracy in its ability to measure lead concentrations in purified water.

Procedure:

1.) Using the formula C1V1=C2V2, make each lead sample that will be used in this test. (Example: Given a 10 mg/L stock solution of lead nitrate, you will need to mix in 10 µL of the stock solution with purified water to obtain a 50 mL sample of 10 µg/L concentration.)
Concentrations: 10 µg/L, 20 µg/L, and 50 µg/L

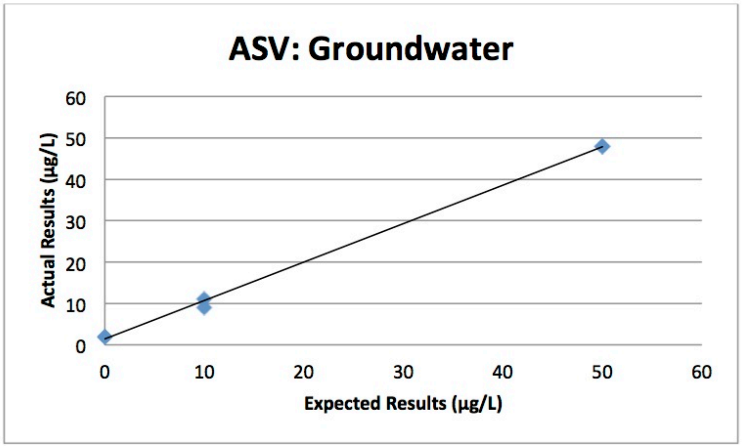
2.) Following the ASV's owner's manual, test each sample twice for the amount of lead present in each sample and record your findings.

Results:

Expected Results		Actual Results	
10	µg/L	10	µg/L
10	µg/L	9	µg/L
20	µg/L	19	µg/L
20	µg/L	19	µg/L
50	µg/L	50	µg/L
50	µg/L	49	µg/L

Results:

Expected Results		Actual Results	
0	µg/L	2	µg/L
0	µg/L	2	µg/L
10	µg/L	11	µg/L
10	µg/L	9	µg/L
50	µg/L	48	µg/L
50	µg/L	48	µg/L



Conclusion:

The results of this test suggest that the ASV is capable of accurately measure the amount of lead in groundwater at multiple concentrations. This can be seen in the illustration where a linear relationship is present.

ASV: Groundwater With pH Adjustment

Objective:

This test was meant to test the accuracy of the ASV using groundwater whose pH had been altered from 7.1 to both 5.95 and 7.95.

Procedure:

1.) From a local well, collect at least 500 mL of groundwater.

2.) Record the initial pH of the collected sample.

3.) Take 200 mL of the collected sample and titrate in nitric acid until the pH reaches a value relatively close to 6.

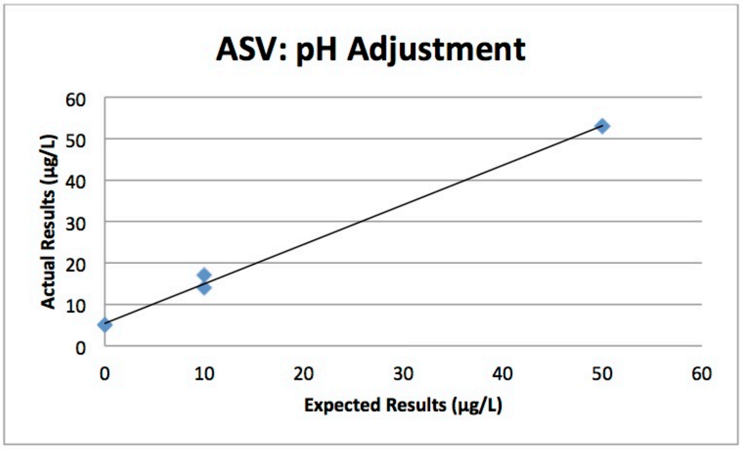
4.) Using the formula C1V1=C2V2, make each lead sample that will be used in this test. (Example: Given a 10 mg/L stock solution of lead nitrate, you will need to mix in 10 µL of the stock solution with groundwater to obtain a 50 mL sample of 10 µg/L concentration.) Concentrations: 10 µg/L and 50 µg/L

5.) Following the ASV's owner's manual, test each sample twice for the amount of lead present in each sample and record your findings.

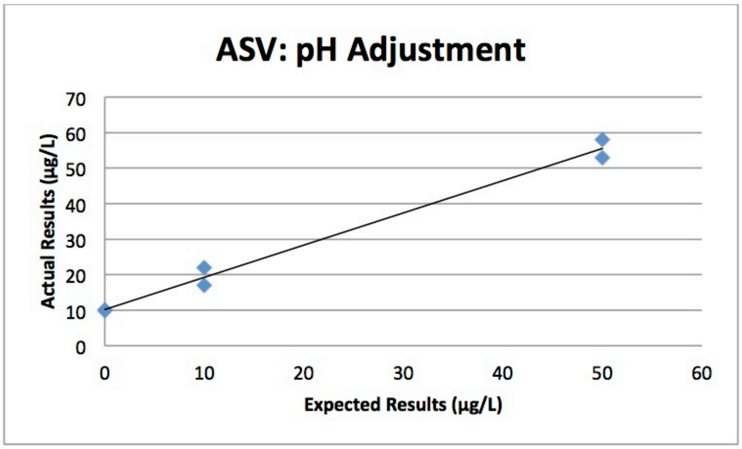
6.) Repeat steps 3-5 but instead titrate in sodium hydroxide until a pH relatively close to 8 is achieved.

Results:

7.95 pH			
Expected Results		Actual Results	
0	µg/L	5	µg/L
0	µg/L	5	µg/L
10	µg/L	14	µg/L
10	µg/L	17	µg/L
50	µg/L	53	µg/L
50	µg/L	53	µg/L



5.95 pH			
Expected Results		Actual Results	
0	µg/L	10	µg/L
0	µg/L	10	µg/L
10	µg/L	22	µg/L
10	µg/L	17	µg/L
50	µg/L	58	µg/L
50	µg/L	53	µg/L



Conclusion:

Based on the result of these test it is clear that the ASV is capable of accurately measuring various concentrations of lead in groundwater between the pH ranges of 6-8. This is illustrated on both graphs where a linear relationship is present.

ASV: Dissolved Oxygen Adjustment

Objective:

This test was meant to test the accuracy of the ASV using groundwater whose DO had been adjusted from 4.67 mg/l to both 1 mg/l and 9 mg/l

Procedure:

1.) From a local well, collect 500 mL of groundwater.

2.) Record the initial Dissolved Oxygen of the collected sample.

3.) Take 200 ml of the collected sample and bubble in nitrogen until the Dissolved Oxygen concentration reaches 1mg/L. Once this is accomplished store the sample with a nitrogen atmosphere so the Dissolved Oxygen concentrations remains at 1mg/L.

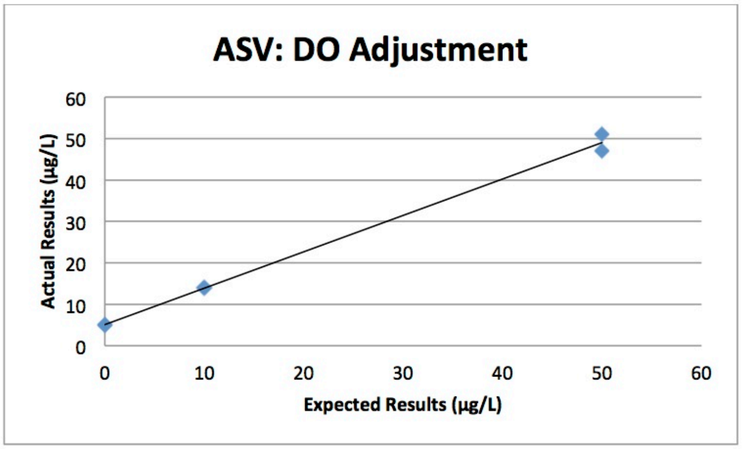
4.) Using the formula C1V1=C2V2, make each lead sample that will be used in this test. (Example: Given a 10 mg/L stock solution of lead nitrate, you will need to mix in 10 µL of the stock solution with groundwater to obtain a 50 mL sample of 10 µg/L concentration.) Concentrations: 10 µg/L and 50 µg/L

5.) Following the ASV's owner's manual, test each sample twice for the amount of lead present in each sample and record your findings.

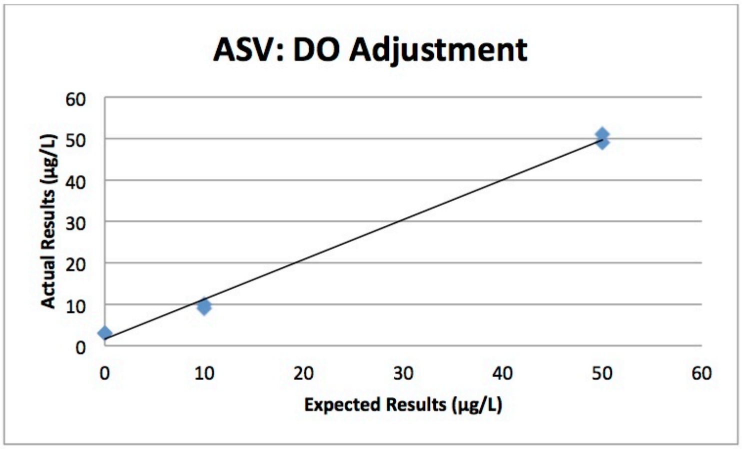
6.) Repeat steps 3-5 but instead bubble in air to raise the Dissolved oxygen in the sample to 9 mg/L.

Results:

DO 1 mg/L			
Expected Results		Actual Results	
0	µg/L	5	µg/L
0	µg/L	5	µg/L
10	µg/L	14	µg/L
10	µg/L	14	µg/L
50	µg/L	47	µg/L
50	µg/L	51	µg/L



DO 9 mg/L			
Expected Results		Actual Results	
0	µg/L	3	µg/L
0	µg/L	3	µg/L
10	µg/L	10	µg/L
10	µg/L	9	µg/L
50	µg/L	49	µg/L
50	µg/L	51	µg/L



Conclusion: From the results, it is clear that the ASV is capable of accurately testing for concentrations of lead in groundwater with Dissolved Oxygen concentrations ranging from 1mg/L to 9 mg/L. This is illustrated on both graphs where a linear relationship is present.