A Convergent Approach to Aqueous Lead (Pb) Mitigation of a Supplemental Self-Supply Shallow Groundwater Source Accessed by Handpumps in Madagascar

Adaline Marie Buerck
University of South Florida

Follow this and additional works at: https://digitalcommons.usf.edu/etd

Part of the Environmental Engineering Commons, and the Public Health Commons

Scholar Commons Citation

This Dissertation is brought to you for free and open access by the USF Graduate Theses and Dissertations at Digital Commons @ University of South Florida. It has been accepted for inclusion in USF Tampa Graduate Theses and Dissertations by an authorized administrator of Digital Commons @ University of South Florida. For more information, please contact scholarcommons@usf.edu.
A Convergent Approach to Aqueous Lead (Pb) Mitigation of a Supplemental Self-Supply

Shallow Groundwater Source Accessed by Handpumps in Madagascar

by

Adaline Marie Buerck

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Co-Major Professor: James R. Mihelcic, Ph.D.
Co-Major Professor: Mahmooda Khaliq Pasha, Ph.D.
Jeffrey A. Cunningham, Ph.D.
Katherine Alfredo, Ph.D.
Norma Alcantar, Ph.D.

Date of Approval:
June 29, 2022

Keywords: Social Marketing, Sustainable Development Goals, Sub-Saharan Africa, Environmental Risk, Blood Lead Level

Copyright © 2022, Adaline Marie Buerck
Dedication

I dedicate this to God, for blessing me with grace and mercy. Your everlasting faith and love provided me with the strength, understanding, and perseverance to face life’s obstacles.

I dedicate this to my parents, for their continuous love and support and teaching me to dream big. I am grateful for everything you have done to support me in life and my education. I owe the person I am today to you.

I dedicate this to my brothers, for believing in me and encouraging me throughout my life. Thank you for teaching me how to be myself, take risk, and always get back up.

I dedicate this to my friends, for your constant encouragement and camaraderie.
Acknowledgments

To my advisors, Dr. James Mihelcic and Dr. Mahmooda Khaliq Pasha, thank you for your encouragement, patience, and advice during this journey. Your mentorship and passion for the work you do provided me with motivation to pursue this research and develop a unique skill set for which I am grateful to you both. Thank you to my committee members, Dr. Cunningham, Dr. Alfredo, and Dr. Alcantar, for your time, feedback, and guidance while completing this degree. I would also like to thank Drs. Zarger, Trotz, Zhang, and Prouty for providing additional support when needed and facilitating my growth as a professional.

I would like to thank Luke John Paul Barrett, Lova Rakotoarisoa, Rinah Rakotondrazaka, and Michal Usowicz for helping to organize and oversee this project in the field in Madagascar. To the staff of ONG Ranontsika, the animators (surveyors), medical personnel at clinics in Toamasina, Madagascar, pump technicians, and Ministries of Water and Health thank you for assisting and participating in the different phases of the research.

To my friends and colleagues thank you for being with me during this journey, continually renewing my confidence, and reminding me that I’m doing my best. You have all made this an enjoyable and life changing experience and I am forever grateful for each of you.

Finally, this work would not have been possible without the financial support provided by The University of South Florida – Strategic Investment Pool (SIP) Awards, the Oak Foundation through Pure Earth, Jammin’ 4 Water – Water Charities Fundraising, internal funding from the USF College of Public Health, Rotary District 5450 W.A.S.H. 2021 Student Award, The Graduate Assistance in Areas of National Need (GAANN) Fellowship (Project No.
P200A180047), the Florida Section of the American Water Works Association (FSAWWA) Roy Likins Scholarship, and the Richard Ian Stessel memorial Fellowship in Environmental Engineering.

This work has been supported by a grant from the National Science Foundation (1735320: Collaborative Research: NRT-INFEWS: Systems Training for Research ON Geography-based Coastal Food Energy Water Systems). 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 funder.
Table of Contents

List of Tables ........................................................................................................................................ iv

List of Figures ........................................................................................................................................ v

Abstract ................................................................................................................................................... vii

Chapter 1: Introduction .......................................................................................................................... 1
  1.1 Motivation ........................................................................................................................................ 1
  1.2 Project Background ......................................................................................................................... 5
    1.2.1 Study Location .......................................................................................................................... 5
    1.2.2 History of USF’s Work in Madagascar .................................................................................... 7
  1.3 Overall Goal and Study Objectives .............................................................................................. 8

Chapter 2: Health and Economic Consequences of Lead Exposure Associated with
Products and Services Provided by the Informal Economy .............................................................. 11
  2.1 Introduction ..................................................................................................................................... 11
  2.2 Materials and Methods ................................................................................................................ 16
    2.2.1 Project Site and Description of Intervention .............................................................................. 16
    2.2.2 Measurement of Lead (Pb) Concentrations in Pumped Water .................................................. 17
    2.2.3 Estimation of Blood Lead Levels (BLLs) .................................................................................. 18
    2.2.4 Estimation of IQ Loss and DALYs ......................................................................................... 20
    2.2.5 Estimation of Economic Impact ............................................................................................. 23
  2.3 Results and Discussion ................................................................................................................ 24
    2.3.1 Measurement of Lead (Pb) Concentrations in Pumped Water .................................................. 24
    2.3.2 Estimation of Blood Lead Levels (BLLs) .................................................................................. 26
    2.3.3 Estimation of IQ Loss and DALYs ......................................................................................... 27
    2.3.4 Estimation of Economic Impact ............................................................................................. 29

Chapter 3: Reductions in Children’s Blood Lead Levels from a Drinking Water
Intervention in Sub-Saharan Africa .................................................................................................... 31
  3.1 Introduction ..................................................................................................................................... 31
  3.2 Materials and Methods ................................................................................................................ 34
    3.2.1 Sample Selection and Distribution ......................................................................................... 34
    3.2.2 Data Collection Methods ....................................................................................................... 34
      3.2.2.1 Blood Lead Level (BLL) Measurements .......................................................................... 34
      3.2.2.2 Aqueous Lead Concentrations in Pumped Water ............................................................ 35
      3.2.2.3 Blood Lead Level (BLL) Estimations .............................................................................. 35
    3.2.3 Statistical Analysis .................................................................................................................. 36
Chapter 4: Convergence of Social Marketing and Engineering: A Lead Mitigation Study in Madagascar .......................................................... 50
  4.1 Introduction............................................................................. 50
  4.2 Materials and Methods........................................................... 53
    4.2.1 Study Location and Population ........................................ 54
  4.3 Results and Discussion........................................................... 55
    4.3.1 Step 1. Background, Purpose, and Situational Analysis ........ 55
    4.3.2 Step 2. Define Behavior Objectives and Select Target Audience ..... 56
    4.3.3 Step 3. Formative Research: Research to Understand Knowledge, Attitudes, Behavior, Barriers, and Benefits ............................ 60
    4.3.4 Step 4. Development of Creative Concepts and Strategic Marketing Mix ................................................................. 64
    4.3.5 Step 5. Testing and Revision of Materials with Target Audience ..... 68
    4.3.6 Step 6. Program Implementation ........................................ 70
    4.3.7 Step 7. Monitoring and Evaluation ........................................ 72
  4.4 Conclusions and Recommendations for Practice .................... 80

Chapter 5: Conclusion .................................................................. 83
  5.1 Objective 1: Estimate the Economic Costs Associated with the Use of Leaded Pump Components ........................................ 84
  5.2 Objective 2: Determine the Impact that the Pitcher Pump Remediation (Replacing the Leaded Piston and Foot Value Weights) Has on Measured BLLs of Children Associated with Those Pitcher Pumps .................. 85
  5.3 Objective 3: Determine Whether Social Marketing Influenced the Intention to Change Behavior for Pump Technicians in the Use of Non-leading Components ............................................................................. 86
  5.4 Discussion ............................................................................. 88
  5.5 Recommendations for Future Research ....................................... 88
    5.5.1 Field Methodology for Examination of Particulate Lead .......... 88
    5.5.2 Examination of IEUBK Model for Use in LMICs............... 89
    5.5.3 Further Examination of Sustainable Decision Change ........... 90

References .................................................................................. 92

Appendix A: Copyright Permissions .................................................. 112
  A.1 Copyright Permissions for Material in Chapter 2 ............................ 112

Appendix B: Supplemental Information for Chapter 2 ....................... 113
  B.1 Study Location ...................................................................... 113
B.2 Remediation Process ........................................................................................................114
B.3 Paired Pre- and Post-Remediation Data.........................................................................114

Appendix C: Supplemental Information for Chapter 3..............................................................116
C.1 Remediation Process ..........................................................................................................116
C.2 Model Inputs .....................................................................................................................116

Appendix D: Supplemental Information for Chapter 4 .............................................................118
D.1 Quantitative Survey/Questionnaire .....................................................................................118
D.2 Qualitative Interview Guide ...............................................................................................121
D.3 Creative Brief .....................................................................................................................127
D.4 Example of Campaign Branding and Materials .................................................................130
D.5 RE-AIM Dimensions Utilized for Evaluation ...................................................................132
D.6 Pre-Survey for Evaluation ...............................................................................................133
D.7 Post-Survey for Evaluation ..............................................................................................134
D.8 Skills Check Observational Checklist ...............................................................................135
D.9 Follow-up Interview Guide ................................................................................................136
D.10 Workshop Observation Sheet ..........................................................................................139
D.11 Pump Observation Sheet ..................................................................................................140

Appendix E: IRB Approvals .......................................................................................................141
E.1 IRB Study000143 Approval ...............................................................................................141
E.2 IRB Study003327 Not Human Subjects Research Determination .....................................143
E.3 Study Approval from the Biomedical Research Ethics Committee of the Ministry of Public Health of Madagascar .................................................................144
List of Tables

Table 1.1 Dissertation outline .................................................................................................................10

Table 2.1 Modeling blood lead levels in children; Categorized pump data &
Integrated Exposure Uptake Biokinetic (IEUBK) Model inputs .........................................................20

Table 2.2 Disability weights (DW) for severity levels of intellectual disability .........................22

Table 3.1 Modeling blood lead levels in children; Integrated Exposure Uptake
Biokinetic (IEUKB) Model inputs ........................................................................................................37

Table 3.2 Pearson correlation matrix for pre- and post-remediation comparison ..................43

Table 3.3 Sequential regression analysis predicting change in BLL .............................................45

Table 4.1 Summary table of stakeholder behavior change analysis ..............................................59

Table 4.2 Socio-demographic and knowledge variable breakdown of surveyed
 technician sample ............................................................................................................................63

Table 4.3 Summary of doer/non-doer analysis ..............................................................................64

Table 4.4 Materials utilized during the implementation of the campaign .................................71

Table 4.5 Evaluation examined through the dimensions of reach, effectiveness,
adoption, implementation, and maintenance (RE-AIM) ..........................................................74

Table C.1 Modeling blood lead levels in children; Integrated Exposure Uptake
Biokinetic (IEUBK) Model inputs ....................................................................................................117

Table D.1 Research questions presented through the dimensions of reach,
effectiveness, adoption, implementation, and maintenance (RE-AIM) .................................132
List of Figures

Figure 1.1 Schematic of conventional pitcher pump found in Madagascar ........................................6

Figure 2.1 Distributions of measured lead concentrations in pumped household water before and after pump retrofit with unleaded components ........................................25

Figure 2.2 Estimated cumulative distributions of blood lead levels (BLLs) in children using water from non-retrofitted pumps and from retrofitted pumps .....................................................27

Figure 2.3 Estimated IQ distributions without a pump intervention and with a pump intervention compared to a “baseline” IQ distribution with a mean of 100 and a standard deviation of 15 ........................................28

Figure 3.1 Age and gender of sample population (n=55 children) ..................................................38

Figure 3.2 Geographic distribution of the 48 pumps used by the children in the study across Toamasina, Madagascar .................................................................39

Figure 3.3 Box plots of BLL concentrations (µg/dL) of children aged six months to six years pre- and post-remediation of pumps (i.e., removal and subsequent replacement of leaded components) (n = 55) ........................................40

Figure 3.4 Box plots of the aqueous lead concentrations (µg/L) pre- and post-remediation of pumps (i.e., removal and subsequent replacement of leaded components) (n = 36) ........................................42

Figure 3.5 Plot of change BLL concentrations (µg/dL) of children aged six months to six years to decrease in aqueous Pb (n = 45), pre-Pb (n = 55), and post-Pb (n = 55) ........................................44

Figure 3.6 Cumulative distributions of modeled and measured blood lead levels (BLLs) in children using water from non-retrofitted pumps ........................................46

Figure 4.1 Steps in the social marketing process informed by review of existing social marketing and behavior change frameworks ........................................54

Figure 4.2 Stakeholders for pitcher pump production and usage ........................................57
Figure 4.3  Key steps and information in the study design and methods used for collection and analysis.................................................................61

Figure 4.4  The marketing mix (4P’s of Marketing) as applied to pitcher pump technicians in Toamasina, Madagascar.................................................................66

Figure 4.5  Campaign strategy including decision flow for mid-stream players (technicians) and the transmission of knowledge to aid in the technician’s progression through the stages of change (Raihan & Cogburn, 2021)........................................................................68

Figure 4.6  Concept testing outline for pre-testing of campaign branding and materials ......................................................................................70

Figure 4.7  Overall project implementation and key points in evaluation.................................73

Figure B.1  Map of Toamasina with arrondissements or districts indicated in green and study area where handpumps were retrofitted indicated in blue .................113

Figure D.1  Campaign branding: paompy tany tsisy firaka (PTTF) or pitcher pump without lead ..................................................................................130

Figure D.2  Example of signs used during information and training sessions .........................130

Figure D.3  Project branded handwashing station ..................................................................130

Figure D.4  Branded campaign materials (pamphlet and notebook) .....................................131
Abstract

The World Health Organization (WHO) has consistently listed lead (Pb) as one of the ten chemicals of major public health concern. Though the toxic nature of lead has been known since the 20th century it is still utilized in a wide variety of products due to its favorable properties. Exposure to lead still accounts for approximately 900,000 deaths annually and disproportionately impacts those in low- and middle-income countries (LMIC) due to a variety of reasons such as poverty, malnutrition, and lack of knowledge on the toxic nature of lead. Lead exposure routes include air, soil, dust, diet, and water. Though aqueous lead exposure is a primary exposure route examined in high income countries there is limited information about this exposure route in LMICs. In turn, the aim of this study is to demonstrate that improved health is possible by reducing exposure to lead contaminated water by way of a case study in Toamasina, Madagascar. Toamasina is a coastal city where centralized piped water is not always affordable or reliably available, creating a demand for a supplemental decentralized self-supply water system which frequently takes the form of a pitcher pump that serves an individual or small group of households. These pumps are traditionally manufactured with leaded components that pose a range of health risks to those using the water for drinking and cooking. Complexities arise from the unique market for hand-driven wells, cultural norms, and the lack of understanding of the health effects of lead on locals. An engineered solution to retrofit the pumps with non-leaded components was identified by previous researchers, but previous adoption of the engineered solution was limited.
In total, this research remediated over 1,000 pumps, tested aqueous lead levels in over 600 pumps, modeled blood lead levels (BLLs) and economic impact, tested BLLs in more than 300 children, and developed and implemented a social marketing campaign geared towards pump technicians. Statistically significant decreases in aqueous lead levels were observed in both the 2018 ($Z = -11, \ p < .0001$) and 2020 ($t(35) = 3.78, \ p < 0.001; \ 95\% \ CI[6.75,22.42]$) remediations. A return-on-investment (ROI) of greater than 1000-to-1 was estimated based on the 2018 remediation. However, comparison of measured and modeled BLLs showed the IEUBK model highly underpredicted BLLs, indicating that the projected ROI is likely a conservative estimate. With no correlation seen between aqueous lead and change in BLL it is likely there is a variable impacting BLLs that is not being accounted for. Nevertheless, measured BLLs were observed to have a statistically significant decrease ($t(54) = 6.15, \ p < 0.001; \ 95\% \ CI[2.81,5.52]$).

Evaluation from the social marketing campaign showed an increased adoption of lead-free practices. Findings also indicate a need for future research efforts focusing on increasing awareness among the Toamasina residents and pump owners.

Utilizing a convergent research approach, this dissertation integrates engineering, social marketing, and public health to demonstrate how improved global health can be achieved. This dissertation presents methodology that can be utilized in other geographic locations and adapted to examine other exposure routes/sources. Results presented indicate the importance that aqueous lead exposure can have in LMICs, the impact that small scale remediations can have on reducing exposure and protecting public health, and the need for interdisciplinary approaches to sustainably address global challenges.
Chapter 1: Introduction

1.1 Motivation

Multiple heavy metals consistently end up on the World Health Organizations (WHO) list of ten chemicals of major public health concern (World Health Organization, 2010b; World Health Organization Regional Office for Africa, 2014). Heavy metals are of concern because of the many adverse health implication that arise due to their toxic nature at increased doses. One of these metals is lead (Pb). Lead, a common naturally occurring element, was found in the 20th century to be toxic to humans (Pedersen, 2016; World Health Organization, 2019a). Effects of an elevated blood lead level (BLL) include IQ loss, irritability, forgetfulness, abdominal pain, high blood pressure, heart disease, and reduced fertility among others (World Health Organization, 2019a). However, due to its extremely malleable nature and resistance to corrosion, it has had widespread use in industries such as paints, cosmetics, batteries, gasoline, and pipelines. Since identification of its toxic nature, the use of lead has been gradually reduced as seen by the phaseout of leaded gasoline and lead paint in many parts of the world.

In the United States, many laws were implemented to protect individuals’ health from lead-contaminated water: the Toxic Substance Control Act, the Clean Water Act, the Lead Contamination Control Act, and the Lead and Copper Rule of the Safe Drinking Water Act (United States Environmental Protection Agency, 2020). Knowledge on the health impact at given levels of exposure and potential for protective actions are continuously being examined and revised. Recent notable revisions include the update of the Lead and Copper Rule (LCR), released in December 2021, with a compliance deadline of October 2024. The updated LCR (1)
implies a trigger level at 10 μg/L based on the 90th percentile of tap water samples where additional planning, monitoring, and treatment requirements go into place and (2) requires establishment of a lead service line (LSL) inventory and replacement plan (USEPA, 2019). Blood lead level reference values from the Centers for Disease Control and Prevention (CDC) were also updated in 2021 moving the reference value from 5 μg/dL to 3.5 μg/dL, though it is found that there is no safe level of lead exposure (ACCLPP, 2012; Health, 2016; National Center for Environmental Health, 2021; World Health Organization, 1993).

Even with multiple policies and large educational campaigns that have been implemented in the United States, it was still estimated that ~20,000 premature deaths occurred and ~350,000 disability-adjust life years (DALYs) were lost in 2019 due to lead exposure (Institute for Health Metrics and Evaluation, 2019). There have also been a growing number of lead-related public health crises from lead exposure in drinking water making headlines in the United States, including Washington, D.C. (Edwards, 2014; Edwards et al., 2009; Brown et al., 2011), Newark, NJ (Faherty, 2021), and Flint Michigan (Hanna-Attisha, 2019; Hanna-Attisha et al., 2016).

Lead exposure is not only a concern in the United States but is a global crisis. A recent study reports that approximately 800 million children globally (1 in 3 children) are at or above the 5 μg/dL BLL standard (Rees & Fuller, 2020). Worldwide, lead exposure accounts for approximately 900,000 premature deaths and ~21 million DALYs in 2019 (Institute for Health Metrics and Evaluation, 2019). Lead exposure disproportionately impacts those in low- and middle-income countries (LMIC) due to a variety of reasons including vulnerabilities (i.e. poverty and malnutrition) (Kordas et al., 2018; Mahaffey, 1995; United Nations, 2019) and high demand for lead-acid batteries (Kordas et al., 2018).
The Global Alliance on Health and Pollution (GAHP) started the Health and Pollution Action Plan (HPAP) program to assist governments in LMICs to develop and implement solutions to priority pollution challenges. Madagascar was one of the first GAHP members to request a HPAP. This document is not an exhaustive review of challenges facing Madagascar, but rather an identification, synthesis, plan, and recommendation to help protect public health and understand knowledge gaps better. Within this report, lead was identified as one of the primary chemicals posing risk in Madagascar (Global Alliance on Health and Pollution, 2018). According to the Institute for Health Metrics and Evaluation (IHME), it is estimated that lead exposure accounted for ~1,300 premature deaths and ~41,000 DALYs in 2019 (Institute for Health Metrics and Evaluation, 2019). With limited data available for the country on Pb exposure, and no known BLL measurements in country, it is understood that these estimates are likely to be low. Currently identified sources of Pb in Madagascar are particulate matter (PM), wastewater discharge from textile factories, mining, battery recycling, and locally manufactured products (e.g., cookware and handpumps) (Global Alliance on Health and Pollution, 2018; Rasoazanany et al., 2007; Weidenhamer et al., 2014). Still, there is the possibility of many other sources of exposure of which we are currently unaware.

Five exposure pathways for lead (water, diet, air, soil, and dust) account for the total uptake of lead into the body (SRC, 2021; The technical review workgroup for lead, 1994). In LMICs air, soil, and dust linked to lead-acid battery manufacturing and recycling, metal mining and processing, and electronic waste are prevalent sources and are often targeted for remediation efforts (Ericson et al., 2021). However, exposure from drinking and cooking water is starting to gain attention within LMICs. In Sub-Saharan Africa, studies are finding it commonplace for lead or lead-containing materials (i.e., brass) to be used in traditional water systems resulting in
elevated aqueous lead levels (Akers et al., 2020; Fisher et al., 2021). Furthermore, as aqueous lead concentrations increase, dietary intake also becomes a more important pathway, in some cases accounting for upwards of 50% of total lead uptake (Akers et al., 2020). However, there is limited examination of aqueous and dietary exposure to lead in LMICs.

Reduction in lead exposure from a given source can be accomplished in a myriad of ways including technology (Khalid et al., 2016; Kordas et al., 2018), policy (Kordas et al., 2018; UNEP Global Alliance to Eliminate Lead Paint, 2019), behavior change (Greene et al., 2015), and combinations of these methodologies once the source is identified. Common exposure control methods for aqueous lead include corrosion control (Lee et al., 1989), material replacement (i.e., LSL) (Sandvig et al., 2008), and point-of-use (POU) water filters (Bosscher et al., 2019). However, many of these methods are costly, not available, or not applicable in LMICs, and all will still need to be coupled with education and behavior-based interventions. For example, POU water filters have been found to be effective at reducing lead in drinking water if used and maintained properly (Bosscher et al., 2019), but evaluations show a lack of sustained POU adoption in LMICs (Evans et al., 2014; Fiebelkorn et al., 2012; Sobsey et al., 2008).

The need for integrating culture, perception, and behavior with technology advances for sustainable uptake has been noted (Mihelcic et al., 2017). One technique that can be used to enhance the uptake of technologies or other mitigation methods (e.g., policy) is social marketing. Social marketing applies commercial marketing tools to change behavior for positive social impact (Lee & Kotler, 2016). Social marketing has been applied to a variety of fields including health, environmental protection, and safety/injury prevention (French et al., 2010; Grier & Bryant, 2005; Lee & Kotler, 2016; Wakefield et al., 2010). Few studies exist within the WASH sector that explicitly use social marketing, but of 32 studies examining behaviors or products
related to improving water and sanitation, a high degree of successful behavior change was seen (Evans et al., 2014). In regard to lead exposure, social marketing has seen success. For example, one social marketing campaign carried out in New York City had positive impact on lead exposure reduction by encouraging parents to report peeling paint to building management to be properly maintained or fixed (Greene et al., 2015). However, to my knowledge, social marketing has not been used to reduce lead exposure within LMICs.

In this dissertation research, social marketing will be engrained as a method to complement technological innovations (i.e., non-leaded pump components) and will engage with the local population to address aqueous lead exposure from locally manufactured and installed supplemental water supply systems within Toamasina, Madagascar. The framework utilized within this dissertation is applicable to other geographic locations, informal sector economies, exposure routes, and contaminants to understand and protect public health.

1.2 Project Background

1.2.1 Study Location

The island nation of Madagascar is the fourth-largest island in the world and geographically unique due to its isolated location off the coast of Africa. A majority of the 27.5 million citizens living in Madagascar are located on the eastern half of the island. Madagascar has a young population with approximately 60% under the age of 25 (Central Intelligence Agency, 2022). Throughout Madagascar, approximately 56.1% of the population has access to an improved drinking water source (Central Intelligence Agency, 2022). An improved source is water that is piped into a dwelling, piped water into yard/plot, public tap or standpipe, tube well or borehole, protected dug well, protected spring, or rainwater (UNICEF & World Health Organization, 2012). This leaves 43.9% of the population without access to any such improved
systems (Central Intelligence Agency, 2022). One of the improved systems that is abundantly used within Toamasina, a coastal city in Madagascar of approximately 280,000 people (as indicated from census data collected from officials during 2019 field visit), as a primary and supplemental water source is the pitcher pump (i.e., handpump) (Figure 1.1). These decentralized self-supply water systems take the form of a manually driven well point with an attached locally manufactured pitcher pump that serves a household or a small group of households. Traditionally, these pumps have been manufactured with three lead components: piston valve, foot valve, and the soldering around the well screen. In addition, sometimes brass well screens are used, which likely contain a varying percentage of lead. These leded parts, in turn, can contaminate the water that is then used for cooking and drinking, putting individuals at risk for multiple negative health implications.

**Figure 1.1** Schematic of conventional pitcher pump found in Madagascar. The three labeled parts (piston valve, foot valve, well screen and solder) indicate areas where lead can be found. Source: Artwork by Linda Phillips. Reproduced from Mihelcic et al., (2009); with permission from ASCE.
1.2.2 History of USF’s Work in Madagascar

The University of South Florida (USF) identified potential lead exposure from a local water supply in Madagascar in 2010 when Dr. Trotz, Dr. Mihelcic, and graduate student Michael MacCarthy (MacCarthy, 2014) visited the country. Jonathan Annis (Annis, 2006) and Luke Barrett (Barrett, 2013) (former students of Dr. Mihelcic) were working at that time in Madagascar on water, sanitation, and hygiene (WASH) projects. The following year Brad Akers (Akers, 2014) and Meghan Wahlstrom-Ramler (Wahlstrom-Ramler, 2014), two students at USF, joined the USF Peace Corps Master’s International program (now known as the Engineering for International Development program) (Manser et al., 2015; Mihelcic, 2010; Trotz et al., 2009) and were placed in Madagascar for their two years of service. Michal Usowicz (Usowicz, 2018) joined the USF Peace Corps Master’s International Program in 2014 and served three years in Madagascar. Many of these students did research that examined the pitcher pump system from different perspectives, including identifying lead exposure from water used to cook and drink that was sourced from locally made handpumps (Akers, 2014; Akers et al., 2015, 2020; MacCarthy et al., 2013; Usowicz, 2018). Starting in 2016, USF began its partnership with ONG Ranontsika, a local water organization in Toamasina, to address issues with local water provision and exposure to lead. In 2017, the team was awarded a grant from Water Charities to perform an intervention that resulted in the remediation of lead components for over 500 pumps (as discussed subsequently in this dissertation). Continued work in 2020 resulted in the remediation of an additional 500 pumps. Since then, the USF team alongside ONG Ranontsika have worked on lead contamination and mitigation and other water-quality topics in Madagascar (Wilson, 2021).
1.3 Overall Goal and Study Objectives

The goal of this research is to demonstrate that lead mitigation efforts focused on the informal sector (i.e. pitcher pump technicians) can bring about improvements in public health and economic wellbeing for those living in Toamasina, Madagascar. To best achieve the goal of this research three primary objectives have been developed.

- Objective one is to estimate the economic costs associated with the use of leaded pump components. This will be examined by answering two questions in relation to the 2018 remediation efforts.
  - Question 1: What are the estimated BLLs associated with the water lead levels?
  - Question 2: What is the association between estimated BLLs and economic burden (i.e. lost opportunity costs)?

- Objective two is to determine the impact that the pitcher pump remediation (replacing the leaded piston and foot value weights) has on measured blood lead levels (BLLs) of children associated with those pitcher pumps. Three research questions will be examined in regard to the 2020 remediation work.
  - Question 1: Is there a statistically significant difference in children’s BLLs before and after pump remediation?
  - Question 2: How effective is the Integrated Exposure Uptake Biokinetic (IEUBK) Model, developed by the U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2010) at predicting the measured BLLs?
• Objective three is to determine whether social marketing influenced the intention to change behavior for pump technicians in the use of non-leaded components. To guide the implementation, monitoring, and evaluation the RE-AIM (Reach, Effectiveness, Adoption, Implementation, Maintenance) framework was utilized to develop the following two research questions.
  o Question 1: To what extent do technicians execute lead free practices?
  o Question 2: What, if any, impact have the marketing strategies had on increasing the use of lead-free practices?

This dissertation is divided into five chapters. Chapters 2, 3, and 4 are standalone manuscripts that each address one of the objectives above (Table 1.1). Chapter 2 examines the economic impact from the aqueous lead concentrations measured in pumps. Chapter 3 further investigates the importance of aqueous lead as an exposure route and the link between remediation efforts (i.e., removal and subsequent replacement of lead components) and impact on BLLs. Chapter 4 lays out the social marketing framework followed over the course of the study and evaluation of the campaign. Chapter 5 reviews the overall project conclusion and recommendations for future work.
Table 1.1 Dissertation outline

**Problem:** Globally Pb exposure is an ongoing issue with the greatest impact on low- and middle-income countries.

**Research Gap:** Informal sector, blood lead levels have never been examined in Madagascar, and the combination of social marketing.

**Overarching Research Goal:** To demonstrate that lead mitigation efforts focused on the informal sector (i.e., pitcher pump technicians) can bring about improvements in public health and economic wellbeing for those living in Toamasina, Madagascar.

**Objective 1:** Estimate the economic costs associated with leaded pump components

**Methods:** Remediation of pumps, Water quality (Palintest SA1100), BLL (IEUBK), IQ loss, DALY, Economic impact

**Objective 2:** Determine the impact that the pitcher pump remediation (replacing the leaded piston and foot valve weights) has on measured blood lead levels (BLLs) of children associated with those pitcher pumps

**Methods:** Remediation of pumps, BLL (LeadCare II), Water quality (Palintest SA1100), BLL (IEUBK)

**Objective 3:** Determine whether social marketing influenced the intention to change behavior for pump technicians in the use of non-leaded components

**Methods:** Observation, Field notes, Questionnaires, Structured interviews, Skills check
Chapter 2: Health and Economic Consequences of Lead Exposure Associated with Products and Services Provided by the Informal Economy

2.1 Introduction

Pollution disproportionately affects the health and well-being of those living in low- and middle-income countries (LMICs) (Landrigan et al., 2018). One chemical pollutant that poses multiple health risks is lead (Pb), which now accounts for 1.06 million annual premature deaths and 24.4 million disability-adjusted life years (DALYs) worldwide (World Health Organization, 2019a). Lead exposure also accounts for large percentages of idiopathic developmental intellectual disability (IQ loss), hypertensive heart disease, ischemic heart disease, and stroke (Rees & Fuller, 2020). For children, the World Health Organization (WHO) states that lead is associated with neurobehavioral damage at blood lead levels (BLLs) as low as 5 µg/dL, and that any lead exposure is associated with harm to the developing fetus (World Health Organization, 2010a). Unfortunately, a recent study reports approximately 800 million children globally (1 in 3 children) are at or above that 5 µg/dL BLL standard (Ericson et al., 2021; Rees & Fuller, 2020). In addition, children with nutritional deficiencies experience increased absorption of lead (Mahaffey, 1995). Worldwide, there are estimated to be 149 million such children under 5 years old, with ≥ 75% of the cases in LMICs (United Nations, 2019).

---

Lead has, however, been used for centuries for a variety of reasons. It has favorable material properties for use in manufacturing that include electrical conductivity, low melting point, workability, and a vibrant color. Accordingly, it has found its way into numerous occupational workplaces and household products (World Health Organization, 2015). Hence, although lead can be found naturally in the environment, most lead exposure is associated with anthropogenic activities related to extraction and use of the metal (Fewtrell et al., 2003; Kamenov & Gulson, 2014). In LMICs, adverse lead exposure has been identified with informal battery recycling (Rees & Fuller, 2020) and mining (Bello et al., 2016; Von Schirnding et al., 2003; Yabe et al., 2015). In addition, the presence of lead in locally sourced and manufactured pottery, seafood, fruits and vegetables, spices, and medicinal supplements likely contributes to high BLLs (Cherfi et al., 2014; Clark et al., 2009; Forsyth et al., 2019; Ismail et al., 2019; Okatch et al., 2012). Other identified uses of lead include subsistence fishing via the manufacturing of fishing sinkers (Mathee et al., 2013), cooking vessels (Weidenhamer et al., 2014), and household water pumps (MacCarthy et al., 2013). The continued use of lead in such a wide variety of products and industries is one of the reasons that millions of children worldwide continue to suffer from elevated BLLs (Rees & Fuller, 2020).

Lead products in commerce can, in principle, be regulated to protect public health; for example, leaded gasoline is reported to now be sold in just one country in Africa, Algeria (Rees & Fuller, 2020; United Nations Environment Programme, 2010). However, a daunting challenge is eliminating lead exposure associated with products manufactured, sold, and serviced by the informal sector in LMICs. The term informal sector commonly refers to small businesses and/or individuals (e.g., street vendors and artisans) who produce ordinary goods and services and operate at the fringes of the formal economy (Benjamin & Mbaye, 2012; De Soto, 1989; Perry et
In much of the world, this informal sector dominates the economy. For instance, in Sub-Saharan Africa, these small businesses can account for at least 80% of total nonagricultural employment, up to 60% of a country’s gross domestic product (GDP), and as much as 93% of new employment (Benjamin & Mbaye, 2012). Similar large percentages of informal sector employment are recorded in Asia (65%) and Latin America (51%) (International Labour Office, 2002).

The combination of lead’s useful properties and the importance of the informal economic sector have led to routes of increased lead exposure. For example, reverse supply chains, such as battery recycling that occur in informal market sectors of LMICs, have been examined with regard to environmental and health impacts of open burning of materials and the lack of regulations (Williams et al., 2008). Informal battery recycling is also an important route of lead exposure (Rees & Fuller, 2020). As just one example, in the suburbs of Dakar (Senegal) it was reported that child BLLs ranged from 39.8 to 613.9 µg/dL with 82% of the sample having life-threatening BLLs greater than 70 µg/dL resulting from informal recycling of used lead-acid batteries (Haefliger et al., 2009).

Another example of an informal market that uses leaded components, which will be used as a case study in this paper, is in the coastal city of Toamasina, Madagascar. Toamasina has experienced rapid urbanization over the past decades, especially in the expansion of informal urban/peri-urban settlements. Within the context of our study location, urban/peri-urban refers to an area within an administrative boundary where a significant majority of the population is not primarily engaged in agriculture (UNICEF, 2012). The municipal water provider is challenged by operational inefficiencies and lacks the capacity to upgrade aging infrastructure; thus, thousands of households either cannot afford or do not have access or continual service to piped
utility water. In response, a demand has emerged for manually driven well points affixed with a locally produced handpump (referred to as Pompe Tany). The Pompe Tany is a type of manually operated suction pump that traditionally have been manufactured with lead components by local artisans and technicians in small workshops. It is estimated that 9,000 of these water supply systems exist in Toamasina that serve 170,000 individuals (MacCarthy et al., 2013). Anthropogenic lead concentrations in the water from these systems were shown to frequently exceed the WHO guideline of 10 µg/L, and elevated BLLs are estimated to occur in some children from exposure to drinking water and eating rice and other starches cooked in the pump water (Akers et al., 2015, 2020). Consistent with these observations, a recent study estimated that Madagascar lost US$ 117–166 million in 2015 due to lost productivity from pollution, with lead pollution identified as one of the primary causes (Global Alliance on Health and Pollution, 2018).

In some respects, these informal activities represent sound waste management by prioritizing reuse of waste products over simple disposal, a key concept in the pollution prevention hierarchy (Kirch, 2008). In fact, approximately 50% of lead originates from recycled materials (Holm et al., 2002). However, it is essential to recognize the unintended health and economic consequences of this strategy. For example, the WHO (2015) reports that IQ loss from lead exposure results in US$134.7 billion lost to the African economy each year (World Health Organization, 2015). Thus, while supportive of the ingenuity of actors in the informal sector, we posit that there exists a vital need to partner with the informal sector through education, training, and external support, so this significant sector of the global economy can provide improved products that bring about health, economic, and environmental benefits. One strategy to provide such improved products is through the application of principles of green engineering. In
particular, we endorse the principle that all material and energy inputs and outputs of products endeavor to be as innately nonhazardous as possible (Anastas & Zimmerman, 2003).

Therefore, the overall objective of this paper is to demonstrate the local health and economic benefits that can be generated when an informal-sector industry modifies its practices to employ safer approaches (i.e., alternative materials). We use the Pompe Tany industry in Toamasina, Madagascar, as a case study that exemplifies broadly applicable principles. To achieve the overall objective, this study had the following specific goals: (1) measure concentrations of lead in pumped water before and after replacing leaded pump components in over 500 pumps; (2) estimate BLLs of children in households that use Pompe Tany with and without leaded components; (3) quantitatively estimate IQ loss and DALYs associated with lead exposure in Toamasina; and (4) estimate economic loss associated with lead exposure and economic benefits of the intervention (i.e., the retrofitting of pumps with unleaded components). Through these goals, our study provides a complete picture of the potential localized health and economic impacts of informal sectors.

This study is driven by multiple Sustainable Development Goals (SDGs) including goal three (good health and well-being), goal six (clean water and sanitation), goal eight (decent work and economic growth), goal twelve (responsible consumption and production), and goal seventeen (partnerships (that includes capacity building)) (United Nations Department of Economic and Social Affairs, n.d.). Furthermore, our study provides a more complete picture of the impact that informal sector practices can have on local health and economies or residents. This contrasts with previous studies focused on estimating country-wide and continental impacts of lead exposure in LMICs (Ericson et al., 2018; World Health Organization, 2015).
Importantly, the principles demonstrated in this paper can easily be replicated in other parts of the world to support the informal sector while also improving health and economic well-being.

2.2 Materials and Methods

2.2.1 Project Site and Description of Intervention

Toamasina is a city in eastern coastal Madagascar where many households access shallow groundwater using a manually driven well connected to a manually operated suction pump (MacCarthy et al., 2013). The pumps are manufactured locally by artisans and technicians, who historically have used recycled lead for weights to operate check valves (i.e., piston and foot valves) in the pumps. Water delivered by the pumps is used for both non-potable and potable uses, including drinking and cooking (Akers et al., 2020). In an initial study of 18 households using these pumps, it was observed that lead is detectable in the pumped water, frequently at concentrations above 10 μg/L, and occasionally at levels exceeding 40 μg/L (Akers et al., 2015). It was estimated that the presence of this lead in the water correlates to elevated BLLs in children (Akers et al., 2015, 2020).

In 2018, we worked with local pump technicians to replace the lead weights in both check valves with iron (Fe) weights in 504 of these household pump systems. During this retrofit of the piston and foot valve no plumbing (i.e. piping) below the pump is disturbed, and the only item removed is the pump head (Figure S.2). Pumps throughout the study area were selected based on (1) the ability to oversee adaptations, and (2) household willingness to participate in the project. Based on surveys completed by the owners of the pumps at the time of the retrofit, we estimate that 730 children between the ages of 1 and 5 years old were served by the 504 pumps.
2.2.2 Measurement of Lead (Pb) Concentrations in Pumped Water

Standard sampling for lead contamination in plumbing water requires an extended period of stagnation and collection of a “first-draw” water sample for lead concentration analysis (U.S. Environmental Protection Agency, 2019). The sample collection is typically conducted by the household resident, allowing for this initial sample collection prior to household water use. However, for a communal water source, this was not feasible. These water systems are typically the only water source for several households, and it was not practical to restrict access prior to sampling. Instead, the protocol for collecting water was adjusted to consistently sample fully flushed water samples. This approach has been used by a variety of previous studies that require sampling public sources (Akers, 2014; Alfredo et al., 2014). In the present study, a volume of 15 L (approximately one to five well volumes) was purged from the system and discarded. This was performed to ensure that all water collected subsequently represented a “flushed” sample of water. Following the 15 L purge, another 15 L were pumped into a bucket from which a 10 mL glass pipette was rinsed, and a 5-mL aliquot was immediately collected and analyzed on-site for the concentration of lead.

Analysis of lead in the water was performed with a Palintest Scanning Analyzer SA1100 (Erlanger, KY, USA). This method uses anodic stripping voltammetry and follows EPA Method 101 (Argent, 1999; Brezonik et al., 1976). This analysis does not account for particulate lead and no acidification was performed on samples. The Palintest SA1100 reports aqueous lead concentrations in the range 2–100 µg/L. ICP instrumentation was not available to quantify lower detection limits. Concentrations below 2 µg/L are reported by the SA100 as ‘< lower than limit of detection’ and concentrations above 100 µg/L are reported as ‘> higher than test range’. Water samples were collected from a subset of the 504 rehabilitated pump systems before and after the
check-valve replacement; specifically, 244 pumps prior to the intervention and 418 pumps following the intervention. Two hundred and twenty-five of the rehabilitated pumps had paired sample data, i.e., Pb concentrations were measured both before and after the retrofit in 225 of the wells.

2.2.3 Estimation of Blood Lead Levels (BLLs)

We used Windows version 11, Build 1.1, of the Integrated Exposure Uptake Biokinetic (IEUBK) Model, developed by the U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2010), to estimate BLLs in children aged one to five years. This model is able to predict distributions of BLLs in children based on known or assumed exposure to lead.

To perform the modeling, we sub-divided the population of children into four age groups: 1–2 years, 2–3 years, 3–4 years, and 4–5 years. For simplicity, we assumed that the overall population of children was split evenly among these four age groups. This assumption was chosen as no breakdown of a Malagasy population to the one-year level is available, and there is no known reason to expect any significant differences between the number of children in these age groups. These age groups were further divided into five sub-groups, corresponding to different concentrations of lead in the household water. The five concentration sub-groups were 0–2 μg/L (2 μg/L: the lower detection limit of testing equipment), 3–5 μg/L, 6–10 μg/L (10 μg/L: the WHO drinking water guideline), 11–20 μg/L, and >20 μg/L. These groupings allowed for a relatively uniform spread between groups with no group containing more than 30% of the wells tested prior to retrofitting. To decide the fraction of children in each of these five concentration categories, we used the measured concentrations of lead in the household pump systems, distinguishing between the pre-intervention lead measurements and the post-intervention lead
measurements. For instance, in the 244 pumps measured prior to check-valve replacement, 22.5% of the wells exhibited a lead concentration between 6–10 μg/L, so we assumed that 22.5% of “pre-intervention” children belonged to this category. However, in the 418 pumps measured after the check-valve replacement, only 2.4% of the wells exhibited a concentration between 6–10 μg/L, so we assumed that 2.4% of “post-intervention” children belonged to this category. Thus, overall, we considered 20 groups of children for the pre-intervention IEUBK modeling (four age groups, five concentration groups) and 20 groups of children for the post-intervention IEUBK modeling. After completing the IEUBK modeling for each sub-group individually, the results were re-combined, weighted according to the fraction of children in each sub-group. This produced a predicted distribution of BLLs for children using non-retrofitted (pre-intervention) wells, and a separate predicted distribution of BLLs for children using retrofitted (post-intervention) wells.

Within each modeling group, the IEUBK requires certain input data for exposure routes related to drinking water, diet, air, soil, and dust (The technical review workgroup for lead, 1994). We used default model values for air and for soil and dust as no local lead measurements for air or soil and dust are known for this region. For drinking water, we used the median measured lead concentration for each of the five concentration sub-groups; for instance, within the 6–10 μg/L sub-group, the median measured concentration was 8 μg/L in the pre-intervention wells and 7.5 μg/L in the post-intervention wells. Because the Palintest instrument has a lower measurement limit of 2 μg/L, we don’t know the median water concentration in the 0–2 μg/L sub-groups, and we therefore assumed a concentration of 2 μg/L for these groups to be conservative. For diet, we used the methods described by Akers et al., 2020 which adjusted the inputs to fit a Malagasy diet. Model inputs are summarized in Table 2.1.
Table 2.1 Modeling blood lead levels in children; Categorized pump data & Integrated Exposure Uptake Biokinetic (IEUBK) Model inputs

<table>
<thead>
<tr>
<th>Pb Range (µg/L)</th>
<th># of Pumps</th>
<th>Median Flushed Pb Concentrationa (µg/L)</th>
<th>Dietary Uptakeb (µg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1-2 yo&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pre-Intervention</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2</td>
<td>43&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2</td>
<td>1.17</td>
</tr>
<tr>
<td>3-5</td>
<td>66</td>
<td>4</td>
<td>2.34</td>
</tr>
<tr>
<td>6-10</td>
<td>55</td>
<td>8</td>
<td>4.69</td>
</tr>
<tr>
<td>11-20</td>
<td>42</td>
<td>14</td>
<td>8.20</td>
</tr>
<tr>
<td>21-100</td>
<td>38</td>
<td>28</td>
<td>16.41</td>
</tr>
<tr>
<td>Post-Intervention</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2</td>
<td>330&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2</td>
<td>1.17</td>
</tr>
<tr>
<td>3-5</td>
<td>68</td>
<td>3</td>
<td>1.76</td>
</tr>
<tr>
<td>6-10</td>
<td>10</td>
<td>7.5</td>
<td>4.39</td>
</tr>
<tr>
<td>11-20</td>
<td>4</td>
<td>12.5</td>
<td>7.32</td>
</tr>
<tr>
<td>21-100</td>
<td>6</td>
<td>44</td>
<td>25.78</td>
</tr>
</tbody>
</table>

(a) For the 0-2 category, we used 2 µg/L for modeling purposes; For all other categories, we used the median *measured* concentration within that category
(b) Dietary uptake for each category was estimated using the procedures of Akers et al. (2020)
(c) yo: years old
(d) In the pre-intervention measurements, the measured Pb concentration was 2 ug/L for 20 wells and was below the detection limit of 2 ug/L for 23 wells
(e) In the post-intervention measurements, the measured Pb concentration was 2 ug/L for 64 wells and was below the detection limit of 2 ug/L for 266 wells

2.2.4 Estimation of IQ Loss and DALYs

It is well known that exposure to lead can result in intellectual disability including loss of IQ (Bellinger, 2008; Needleman, 2004; J. Schwartz, 1994). Furthermore, childhood exposure to lead can result in decline of cognitive function and socioeconomic status in adulthood (Reuben et al., 2017). Therefore, to quantify the health impact of lead exposure to children in Toamasina, we estimated the IQ loss and the resultant disability adjusted life years (DALYs).

Different research groups have proposed different quantitative relationships between BLL and IQ loss, but most studies agree that a 10 µg/dL increase in BLL results in a loss of about 1–4 IQ points (Bellinger, 2008; J. Schwartz, 1994). Here, we used the following equation,
which is based on the results of Lanphear et al., 2005 and applies to children with BLL greater than 2.4 µg/dL (Lanphear et al., 2005). The paper of Lanphear et al., 2005 is a pooled analysis of seven studies: one from the United States, one from Mexico, and one from Yugoslavia. The findings of Lanphear et al., 2005 are widely cited and have been used in multiple studies examining LMICs (Attina & Trasande, 2013; Ericson, Dowling, et al., 2018).

\[
\text{IQ loss} = 6.2903 \log_{10}(\text{BLL}) - 2.3886 \quad \text{(eq. 1)}
\]

Using this equation, the estimated distributions of BLLs were used to estimate distributions of lost IQ points. This was done by subtracting the modeled IQ loss distribution from a “baseline” IQ distribution (mean of 100 and standard deviation of 15) to represent the estimated change seen in the local Malagasy child population. Thus, three different IQ distributions can be compared: a “baseline” IQ distribution for a population not exposed to lead, the IQ distribution of Toamasina children using water from non-retrofitted (pre-intervention) pumps, and the IQ distribution of Toamasina children using water from rehabilitated (post-intervention) pumps.

The IQ loss caused by lead exposure can then be used to estimate DALYs for children in Toamasina. A DALY is based on years of life lost (YLL) and years lost due to disability (YLD). Because mild intellectual disability should not result in death, YLL was assumed to be zero, and thus DALY was assumed to be equivalent to YLD. YLD is estimated as the number of prevalent cases times a disability weight. There are five possible disability weights for lead-related intellectual disability, varying with the severity of the disability, as shown in Table 2. The five categories represent borderline, mild, moderate, severe, and profound intellectual disability.

For each of these five categories, the number of prevalent cases (per 1,000 children) is determined simply from the estimated IQ distributions (previously described). Also, for each
category, two different disability weights have been estimated, the global burden of disease estimates (GBD) and the more comprehensive WHO endorsed global health estimates (GHE), as shown in Table 2.2 (Department of Information Evidence and Research, 2018). Here we estimated DALYs using both sets of disability weights, thereby estimating a range of DALYs. Also, the disability weights shown in Table 2 are multiplied by an adjustment factor of 2.05, which accounts for increased consequences of mental impairment in African regions with high child and adult mortality, a category in which Madagascar is included (Fewtrell et al., 2003). The adjustment factor was calculated by the WHO and uses the assumption that non-congenital causes of intellectual impairment (i.e. anemia, hookworm infection, etc.) are discrete and additive, but does not adjust for factors of malnutrition (Fewtrell et al., 2003). The overall calculation of DALYs is performed by multiplying the number of prevalent cases times the (adjusted) disability weight for each of the five categories, then summing to calculate the overall result. This yields an estimate of DALYs per 1,000 children.

Table 2.2 Disability weights (DW) for severity levels of intellectual disability

<table>
<thead>
<tr>
<th>IQ range</th>
<th>Severity of Intellectual Disability</th>
<th>Disability Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GBD 2016a*</td>
</tr>
<tr>
<td>70-85</td>
<td>Borderline</td>
<td>0.011</td>
</tr>
<tr>
<td>50-69</td>
<td>Mild</td>
<td>0.043</td>
</tr>
<tr>
<td>35-49</td>
<td>Moderate</td>
<td>0.100</td>
</tr>
<tr>
<td>20-34</td>
<td>Severe</td>
<td>0.160</td>
</tr>
<tr>
<td>&lt;20</td>
<td>Profound</td>
<td>0.200</td>
</tr>
</tbody>
</table>

(a) GBD 2016: Global Burden of Disease 2016 assessment  
(b) GHE 2016: Global Health Estimates  
*WHO (2018)52
2.2.5 Estimation of Economic Impact

It is known that intellectual impairment from environmental neurotoxins and neurotoxicants contribute to lost economic productivity, and that the economic cost of this lost productivity increases with the severity of the intellectual impairment (Attina & Trasande, 2013; Bierkens et al., 2012; Dórea, 2019; United Nations Environment Programme, 2010). These costs are sometimes referred to as a lost opportunity costs and do not consider other societal costs such as increases in crime rates or need for special education services. The attributable cost due to lead exposure from pump water was calculated following the method presented by Attina & Trasande, 2013.

\[
\text{Cost} = \sum_{i=1}^{N} EAF_i (\text{IQ loss})_i \left( \frac{\text{lost economic productivity}}{\text{IQ loss}} \right) \quad (\text{eq. 2})
\]

In this equation, the following definitions and estimations apply.

- \( N \) is the number of children aged one to five associated with the 504 pumps rehabilitated during the intervention. Because each child obtains some benefits from the decreased exposure to lead, \( N = 730 \).

- \( EAF_i \) indicates the environmentally attributable fraction of lead for the \( i^{th} \) child. For this study, \( EAF_i \) was assumed to be 1.0 for all children, based on an assumption that little lead exposure is due to natural processes (Attina & Trasande, 2013).

- \((\text{IQ loss})_i\) indicates the lead-related IQ loss for the \( i^{th} \) child. Although we do not know the BLL or the IQ loss for any individual child, we estimated the distribution of IQ loss, as described above. By randomly sampling this distribution \( N \) times, we are able to obtain the required \( N \) individual estimates of \((\text{IQ loss})_i\).

A lost economic productivity of US$16,500 per lost IQ point was used here, based on estimates of Attina & Trasande (2013) for lost economic productivity in Eastern Africa which
included Madagascar (Attina & Trasande, 2013). The value of US$16,500 per IQ point recommended by Attina & Trasande, 2013 is consistent with other estimates, which have ranged from ~US$12,00-26,000 per lost IQ point (Gould, 2009; Zhou & Grosse, 2019).

Equation (2) was applied to both the “pre-intervention” and “post-intervention” distributions of children, i.e., to children using non-rehabilitated wells and to children using rehabilitated wells. The difference between the costs of these two distributions represents the cost saved by performing the intervention.

The total cost of the intervention was also calculated. The rehabilitation of an individual pump costs approximately US$4 per pump for locally sourced materials and labor to replace the components of the pump’s foot valve and piston valve.

2.3 Results and Discussion

2.3.1 Measurement of Lead (Pb) Concentrations in Pumped Water

The concentrations of lead measured in the pumped water pre- and post-intervention are presented in Figure 2.1. Prior to the intervention, 33% of measured lead concentrations (n=244) exceeded the WHO (2014) provisional guideline of 10 µg/L, and some of the measured concentrations even exceeded 100 µg/L. After retrofitting the pumps with non-leaded components, the measured lead concentrations (n=418) were below 10 µg/L in 98% of samples.

A Wilcoxon Signed-Rank Test of the paired data showed that the retrofit of the pump significantly reduced the lead concentration in the pumped water (Z = -11, p < .001). More information about this analysis and the paired pre- and post-intervention data can be found in the Supporting Information.

Underestimation of lead concentration in water is likely, representing lower bounds, due to flushing of the system before sampling. For wells that are used frequently throughout the day,
“flushed” conditions are expected to prevail, and the measured Pb concentrations are likely representative of actual conditions; for wells that are used only sporadically, the concentrations reported here may underestimate the stagnant or “first-draw” conditions (Akers et al., 2015).

Figure 2.1 Distributions of measured lead concentrations in pumped household water before and after pump retrofit with unleaded components. Dark Gray: Pre-intervention concentrations ($n=244$). Light Gray: Post-intervention concentrations ($n=418$).

Leaded solder has been phased out in many parts of the world (Sandvig et al., 2008), but it is still used in Madagascar. The varying levels of lead seen in the pumped water post-intervention are potentially attributable to the age of the well-screen solder, as lead release from solder is reported to decrease over time (Sandvig et al., 2008). Examination of the well screen and leaching of lead from solder was beyond the scope of this paper but is an important aspect to be examined with future studies and efforts to engage with agents in the informal economic sectors, such as pump technicians.
2.3.2 Estimation of Blood Lead Levels (BLLs)

The estimated distributions of BLLs for children in Toamasina (aged one to five), accounting for modified water and dietary lead uptake and holding other variables constant (i.e. air, soil, and dust lead uptake values), are provided in Figure 2.2. Figure 2.2 presents estimated BLL distributions for children using water (associated with drinking and cooking) from non-retrofitted (pre-intervention) pumps and from retrofitted (post-intervention) pumps. The figure shows that approximately 34% of children using non-retrofitted pumps are estimated to have BLLs over 5 µg/dL. However, for children using retrofitted pumps, only 13% would have a BLL above 5 µg/dL.

The reference level of 5 µg/dL is a widely accepted threshold established by the US Centers for Disease Control and Prevention (CDC) and is recognized by the WHO to be associated with irreversible health impacts (ACCLPP, 2012; World Health Organization, 2010a, 2019a). However, several studies have shown health risks linked to levels below 5 µg/dL (Ekong et al., 2006; Navas-Acien et al., 2007), indicating that children with any BLL could experience some negative impact. The shift in the estimated BLL distributions (Figure 2.2) therefore indicates that the removal of lead components from the pumps not only lowers the concentration of lead in the pumped water but may also improve the health of those using the pumps. However, BLLs are not expected to decrease immediately upon removal of leaded components from the pump, because the half-life of lead in blood is one to two months (Centers for Disease Control and Prevention, 2017).
2.3.3 Estimation of IQ Loss and DALYs

Estimated BLL distributions were used to estimate distributions of IQ in children in Toamasina. Figure 3 shows three estimated IQ distributions. One is a “baseline” IQ distribution with a mean of 100 and a standard deviation of 15, which corresponds to a population of children with no significant lead exposure. The other two IQ distributions shown in this figure correspond to children using non-retrofitted wells (pre-intervention) and children using retrofitted wells (post-intervention); that is, the IQ distributions in Figure 2.3 correspond to the BLL distributions in Figure 2.2. Figure 2.3 shows that, if leaded components are not removed from the pumps, exposure to lead in household water is estimated to decrease the IQ distribution of children in Toamasina by about 2 points on average. That decrement is lowered to about one IQ point as a result of the intervention (Figure 2.3).
Figure 2.3 Estimated IQ distributions without a pump intervention and with a pump intervention compared to a “baseline” IQ distribution with a mean of 100 and a standard deviation of 15.

The results from the DALY calculations indicate 1.0 – 2.2 DALYs per 1000 children if no intervention were to take place, and only 0.5 – 1.1 DALYs per 1000 children once pumps were retrofitted (post-intervention). These DALY estimates are low, because they only account for IQ decrements and do not account for other health impacts that lead is known to cause (Regional Office for the Americas of the World Health Organization, n.d.).

Based on the ranges of DALYs given above, we estimate that the intervention we performed may save 0.4-1.0 DALYs for the 730 children using the 504 retrofitted pumps. If this number is extrapolated to consider all 9000 pumps that are estimated to be present in Toamasina (MacCarthy et al., 2013), it suggests that removing lead from household pumps may save 8.0-20.0 DALYs for children in Toamasina, based solely on prevention of IQ loss.
Estimates of ~21.7 million DALYs due to lead exposure globally have been reported with ~1.5 million DALYs in Sub-Saharan Africa (Institute for Health Metrics and Evaluation, 2019). Within Madagascar these estimates suggest ~1,000 DALYs attributable to lead exposure. These estimates include death attributable to lead exposure as well as adult DALYs (including other health concerns such as cardiovascular diseases) which our study did not consider.

2.3.4 Estimation of Economic Impact

For the 730 children aged one to five using the pumps treated in this study, the lost economic productivity pre-intervention was estimated to be US$18.7 million over the children’s lifetimes. Following the intervention (retrofitting of pumps), the lost economic productivity due to the continued presence of some lead in the environment was reduced to US$10.0 million. Therefore, the intervention performed here is estimated to have saved US$8.7 million in recovered productivity over the lifetime of the 730 children. This is equivalent to US$11,800 per child. For context, this is over seven times Madagascar’s 2019 GDP per capita of $1,647 (Central Intelligence Agency, 2022). As previously mentioned, this calculation is based only on IQ loss and does not consider other societal costs and benefits such as crime rates or special education services.

The total cost of the intervention if households would individually contract a pump technician (~US$ 2,000) includes the cost for locally sourced labor and materials for the 504 pump adaptations. This equates to ~US$2.76 per child. However, the estimated cost of US$2.76 per child accounts only for the 730 children aged one to five that are associated with the pumps, and it does not account for adults or older children that might also benefit from the retrofit. If all beneficiaries of the retrofit are considered, the per-person cost would be even lower.
These results indicate that for every dollar spent on this intervention, ~US$4,000 is saved in economic productivity. This return on investment is higher than what has been observed in most lead mitigation studies. For example, a return of US$17 – 221 for each dollar invested in lead hazard control in the United States has been reported by Gould (2009), also noted by WHO (2010) (Gould, 2009; World Health Organization, 2010a). Other water and sanitation improvements (i.e. chlorination, piped water, and provision of improved sanitation) in LMICs were estimated to have returns of US$5 – 46 (Hutton et al., 2007).

Economic losses due to lead exposure have also been estimated on a continental scale; for example, Attina & Trasande, 2013 estimate 98.2 million IQ points lost or US$134.7 billion in economic losses in Africa due to lead exposure (Attina & Trasande, 2013). On a global scale, the estimation of losses of lifetime earnings in LMICs attributable to lead exposure range from US$729.6 – 1,162 billion annually (Rees & Fuller, 2020). These large-scale estimates point towards the need to address lead exposure in LMICs. In this study, the estimated US$10.0 million saved and a return on investment of ~US$4,000 for every dollar spent on the intervention demonstrate the importance of not only further identifying sources of exposure to lead and other chemical pollutants but also potential mitigation strategies that engage with local agents in the informal economic sectors. Social/behavioral approaches can also be used to address needs, concerns and current behaviors of these local agents to support them in innovating improved products that maintain their function but also result in improved well-being (Khaliq et al., 2021). The results presented in this study also demonstrate how the formation of partnerships between public, private, and civil society entities, as suggested by UN Sustainable Development Goal 17 (United Nations Department of Economic and Social Affairs, n.d.), can realize important local economic and health benefits.
Chapter 3: Reductions in Children’s Blood Lead Levels from a Drinking Water Intervention in Sub-Saharan Africa

3.1 Introduction

The regulation of the use of lead (Pb) in society (e.g. phase-out of leaded gasoline, Lead and Copper Rule in U.S., E.U. drinking water directive) has resulted in substantial decreases in elevated blood lead levels (BLL) in high-income countries (HIC) (Hayes & Hoekstra, 2010; Mathee et al., 2020; United States Environmental Protection Agency, 2020). For example, the phase-out of leaded gasoline in the U.S. was associated with a decrease (37% or 5.4 µg/dL) in the average BLL in a cross-sectional survey representative of the U.S. civilian noninstitutionalized population (Annest et al., 1983). Unfortunately, lead is still a major global environmental pollutant estimated to account for over one million annual premature deaths (World Health Organization, 2019a).

Children are most at risk of elevated BLLs, with a recent study reporting approximately 800 million children globally (1 in 3) with BLLs at or above 5 µg/dL (Ericson et al., 2021; Rees & Fuller, 2020). Most of these children reside in low- and middle-income countries (LMICs) where there is a lack of regulations and understanding of the harmful effects of lead, as well as other comorbidities and malnutrition that can increase childhood lead absorption (Kordas et al., 2018; Mahaffey, 1995; United Nations, 2019). All ages have potential for negative health implications from lead exposure, but children are at highest risk. Examples of health implications include, but are not limited to, idiopathic developmental intellectual disability (IQ loss), gastrointestinal disturbances, delayed growth, and hematological effects (Rees & Fuller, 2020).
Because of advances in reducing non-water-related routes of exposure, a predominant source of childhood lead exposure in HICs is now piped drinking water, as noted with high-profile cases such as Flint, MI (Roy et al., 2019), Washington, DC (Edwards et al., 2009), and Glasgow, UK (Akoumanaki, 2017). Many studies have looked at the relationship between aqueous lead concentrations and BLLs in children within HICs (Edwards et al., 2009; Deshommes et al., 2013; Levallois et al., 2014; Hanna-Attisha et al., 2016). Remediation efforts such as corrosion control, service-line replacements, and point-of-use filters have been effective in reducing BLLs and in improving public-health outcomes (Bosscher et al., 2019; Pieper et al., 2019; World Health Organization, 2019b).

In LMICs, however, there is limited discussion, if any at all, on the importance of piped water in elevated BLLs. For example, a 2021 systematic review of 520 lead studies in LMICs identified zero studies classifying aqueous lead as a possible exposure route (Ericson et al., 2021). The major sources of lead exposure identified in that review included informal lead-acid battery manufacturing and recycling, metal mining and processing, and electronic waste (Ericson et al., 2021). However, a study by Fisher et al. (2021) reported that 9% (24/216) of rural community water system samples (collected from handpumps and community taps) in Mali, Ghana, and Niger had elevated lead concentrations in excess of the WHO drinking water guideline of 10 µg/L (World Health Organization Water, Sanitation, Hygiene, and Health Team, 2011). This suggests the need to evaluate and address the presence of lead in potable water in LMICs.

Consistent with these recent findings by Fisher et al. (2021), investigations into lead exposure in Madagascar identified a source of aqueous lead exposure in locally manufactured pitcher pumps (i.e., handpumps) (Akers et al., 2015, 2020). These pumps are a common primary
or supplemental water source in Madagascar accounting for around three quarters of water systems (Ryan, 2014; Ryan & Carter, 2016). Aqueous lead concentrations from these pump systems were observed to often exceed the WHO guideline of 10 µg/L, with some pump water samples reaching concentrations > 100 µg/L (Akers et al., 2015, 2020; MacCarthy et al., 2013). The major contributors to the aqueous lead were two leaded pump components (i.e., piston and foot valves) introduced during the manufacturing process. Using the aqueous lead measurement data, children’s BLLs were projected with the U.S. Environmental Protection Agency (EPA) Integrated Exposure Uptake Biokinetic (IEUBK) model, estimating that up to 90% of children could exhibit BLLs > 5µg/dL (Akers et al., 2020). Furthermore, IEUBK modeling outputs predicted that remediation of pumps (i.e. removal and replacement of lead components) would result in reduction in BLLs (Buerck et al., 2021). Given the fact existing comorbidities and malnutrition can increase childhood lead absorption in LMICs, it is unknown how reducing lead exposure through a source of water would effect measured BLLs. In addition, we were unable to identify a study, specific to Sub-Saharan Africa or other LMICs, measuring childhood BLLs before and after an intervention to replace a known source of lead in a water system to track the resulting decrease in measured childhood BLLs. Accordingly, this study seeks to quantify the reduction in children’s BLLs when leaded components are removed (i.e., remediated) from a water supply system.

This chapter examines aqueous lead exposure as an important pathway for increased BLLs in LMICs using Toamasina, Madagascar and the locally manufactured pitcher pumps as a case study. By examining pitcher pumps, we demonstrate the impact that aqueous lead exposure can have in LMICs from water supply systems. We utilize a methodology transferable to other
LMICs where similarly constructed handpumps or wells and distribution systems contain leaded components.

3.2 Materials and Methods

3.2.1 Sample Selection and Distribution

This observational pre/post remediation (i.e., replacement of lead pump components with non-leaded pump components) study evaluated aqueous lead concentrations of pumps and BLL measurements of children under six years of age in Toamasina, Madagascar. This assessment is part of a larger project that remediated 500 pumps and assessed the BLLs at baseline for over 300 children in Toamasina prior to remediation efforts (Champion et al., 2022). Recruitment for the larger project employed a cluster sampling approach and used nine local health clinics across five arrondissements (or city districts) in Toamasina. Families seeking care at the clinic were recruited based on willingness to participate and having a child between six months to six years old. All study protocols were approved by the Biomedical Research Ethics Committee of the Ministry of Public Health of Madagascar and the USF Institutional Review Board (STUDY000143).

3.2.2 Data Collection Methods

3.2.2.1 Blood Lead Level (BLL) Measurements

Following parental consent, a 50 µL blood sample was collected from the child’s finger by trained medical personal and analyzed using a Magellan LeadCare II device (North Billerica, MA). The LeadCare II testing instrument is a portable device for testing the amount of lead in whole blood using anodic stripping voltammetry. Our test kits were not affected by the 2021 FDA recall (U.S. Food and Drug Administration, 2021).
To limit contamination, the child washed their hands with soap and water and the finger was cleaned with alcohol prior to sampling. The LeadCare II system displayed measured BLL readings as either a value between 3.3 - 65 µg/dL, “Low” if below the lower detection limit of 3.3 µg/dL, or “High” if above the upper limit of 65 µg/dL. Values below the detection limit were replaced with 2.33 µg/dL in our analysis, calculated as the lower detection limit divided by √2, consistent with previous studies (Desai et al., 2021). No values above 65 µg/dL were seen in the study sample.

3.2.2.2 Aqueous Lead Concentrations in Pumped Water

Following the methodology outlined by Akers et al. (2015), samples were collected both prior to and following the remediation of the pump. The remediation process consisted of removing and replacing the lead-containing piston and foot valves with non-leaded components. The sampling procedure consisted of wasting 15 L from the pitcher pump system (~1-5 well volumes) and then collecting another 15 L sample for analysis. A 10 mL glass pipette was rinsed using the sample water and a 5 mL aliquot sample was collected to represent a flushed composite sample. Samples were analyzed using a Palintest Scanning Model 1100 Analyzer (SA1100) that measures dissolved lead by the process of anodic stripping voltammetry with a lower limit of detection of 2 µg/L of lead. Readings under the detection limit were put in as 1.41 µg/L for analysis (calculated as the lower detection limit divided by the square root of two (Desai et al., 2021)). Only dissolved lead was measured as part of this study.

3.2.2.3 Blood Lead Level (BLL) Estimations

Blood lead levels for children aged one to five years were modeled using Windows version 2, Build 1.66, of the Integrated Exposure Uptake Biokinetic (IEUBK) Model, developed by the U.S. Environmental Protection Agency (United States Environmental Protection Agency,
The model requires inputs for exposure routes related to water, diet, air, soil, and dust and outputs an estimated geometric mean BLL for specific age range of child with the given exposure. The IEUBK model is commonly used to estimate lead exposure effects throughout the world (Adeyi & Babalola, 2017; Rees & Fuller, 2020).

Default values were used for air (0.1 µg/m3), soil (200 µg/g), and dust (150 µg/g) exposure as there were no known local lead measurements at the time of the study. Measured aqueous Pb concentrations were used for the water inputs. Dietary uptake values were adjusted using the methodology of Akers et al. (2020) to acknowledge absorption of lead through commonly eaten starches (e.g., rice) representative of a Malagasy diet (Akers et al., 2020; Buerck et al., 2021). Table 3.1 presents the model inputs used for water and diet.

The outputs from IEUBK for each group were then weighted according to the percent of pumps with the given aqueous measurement and used to produce a distribution of predicted BLL values for a population of 1,000,000 children.

3.2.3 Statistical Analysis

Paired-sample t-test were conducted to determine if there were significant differences in measured aqueous lead levels and BLLs pre- to post-remediation. Further analysis of paired samples included examining correlations between the aqueous Pb and BLLs via Pearson correlations and regression analysis. Pre-remediation measured BLLs were also analyzed with respect to the modeled Pre-remediation BLLs.
Table 3.1 Modeling blood lead levels in children; Integrated Exposure Uptake Biokinetic (IEUKB) Model inputs

<table>
<thead>
<tr>
<th>Number of Pumps</th>
<th>Median Flushed Pb Concentrations (µg/L)</th>
<th>Dietary Uptake(^a) (µg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1-2 yo(^b)</td>
</tr>
<tr>
<td>18</td>
<td>1.41</td>
<td>0.83</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>1.17</td>
</tr>
<tr>
<td>1</td>
<td>2.8</td>
<td>1.64</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>1.76</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>2.05</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>2.35</td>
</tr>
<tr>
<td>1</td>
<td>4.7</td>
<td>2.76</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>2.93</td>
</tr>
<tr>
<td>1</td>
<td>5.8</td>
<td>3.40</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>3.52</td>
</tr>
<tr>
<td>1</td>
<td>6.3</td>
<td>3.69</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>4.10</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>4.69</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>5.28</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>5.86</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>6.45</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>7.62</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>8.21</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>8.79</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>9.38</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>9.97</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>10.55</td>
</tr>
<tr>
<td>1</td>
<td>19</td>
<td>11.14</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>12.31</td>
</tr>
<tr>
<td>1</td>
<td>27</td>
<td>15.83</td>
</tr>
<tr>
<td>1</td>
<td>28</td>
<td>16.42</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>23.45</td>
</tr>
<tr>
<td>1</td>
<td>42</td>
<td>24.62</td>
</tr>
<tr>
<td>2</td>
<td>43</td>
<td>25.21</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>28.73</td>
</tr>
<tr>
<td>2</td>
<td>51</td>
<td>29.90</td>
</tr>
<tr>
<td>1</td>
<td>52</td>
<td>30.49</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>38.11</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>58.63</td>
</tr>
</tbody>
</table>

\(^a\) Dietary uptake for each category was estimated using the procedures of Akers et al. (2020)

\(^b\) yo: Years old
3.3 Results and Discussion

3.3.1 Blood Lead Level (BLL) Measurements

For this study, a sample size of 34 paired samples was required, based on a medium effect size of 0.05, 80% power, and 95% confidence interval (Dhand & Khatkar, 2014). In total, this study collected and analyzed paired data (i.e., data collected pre- and post-remediation of the two pump check valves) for 55 children 6 months to 6 years (31 males and 24 females). Further breakdown of the sample population by age, gender, and distribution of the location within Toamasina can be seen in Figure 3.1 and 3.2. BLL readings were taken prior to the pump remediation, and at least 1 month (37-67 days) post pump remediation to allow for approximately one half-life of lead in the blood to occur (half-life of lead in blood is 1-2 months) (Centers for Disease Control and Prevention, 2017).

![Figure 3.1](image-url)  
**Figure 3.1** Age and gender of sample population (n=55 children).
Prior to the remediation, 96% of children (n = 53) had measured BLLs over 5 µg/dL (the BLL reference value). Following the remediation only 65% of children (n = 36) had measured BLL over 5 µg/dL. A paired-samples t-test conducted on the BLL values showed a significant decrease (t(54)= 6.15, p < 0.001; 95% CI[2.81,5.52]) in measured BLL concentrations (pre-remediation (mean= 10.85, SD= 6.30) and post-remediation levels (mean= 6.68, SD= 3.70). A graphical representation of pre- and post-remediation BLLs can be seen in Figure 3.3.

In total, the BLL of 48 children (87%) decreased, ranging in magnitude from decreases of 0.2 to 24.8 µg/dL (mean = 4.91 µg/dL), while six children had an increase of 0.9 µg/dL on average. With the half-life of BLL estimated to be 1-2 months, and an average of 45 days between the remediation and the post BLL test, it is likely that BLLs will further decrease in the future (Centers for Disease Control and Prevention, 2017).
Figure 3.3 Box plots of BLL concentrations (µg/dL) of children aged six months to six years pre- and post-remediation of pumps (i.e., removal and subsequent replacement of leaded components) (n = 55). Pre-remediation BLL concentrations (mean = 10.85, SD = 6.30) and post-remediation BLL concentrations (mean = 6.68, SD = 3.70). Box hinges represent first and third quartiles, and middle represents the median. Whiskers extend 1.5 times the inter-quartile range of the hinge. Points beyond the whiskers are outliers.

3.3.2 Aqueous Lead Concentrations in Pumped Water

In correspondence with the 55 children with paired BLL data, 48 pumps were examined pre- and post-remediation of the two pump check valves. Seven less pumps were examined as one pump had three children associated with it and five pumps had two children associated with it. Prior to the remediation, 27% (n = 13) of the pumps sampled using the flushed sampling protocol of this study contained aqueous lead concentrations that exceeded the WHO provisional guideline of 10 µg/L (World Health Organisation Water, Sanitation, Hygiene, 2011). This was higher than other studies examining aqueous lead in Sub-Saharan Africa, such as Fisher et al. (2021), where 9.2% (24/261) of samples exceeded the WHO provisional guideline. Fisher et al. (2021) sampled using a one-hour stagnation time, compared to our flushed sampling protocol. This difference in protocol further speaks to the levels of aqueous lead measured as it has been
found that aqueous lead concentrations follow a logarithmic growth pattern in relation to stagnation time (Lytle et al., 2021).

Following remediation, a small number of pumps continued to exceed the provisional guideline (2/48), which is similar to the 2018 campaign in which 3% exceeded the guideline post remediation (Chapter 2). However, the two pumps measuring greater than 10 µg/L did see a measurable decrease, with one pump seeing an aqueous lead concentration decrease of over 50%. The aqueous lead concentration of pump water prior to and following the removal of lead is shown in Figure 3.4.

Pumps with aqueous lead concentration at detection or under detection prior to the remediation were removed (n = 12). All pumps removed remained at or below detection. Of the 36 pumps remaining, all observed a decrease in aqueous lead concentration ranging from 1 to 97 µg/L. A paired sample t-test was performed to examine if the remediation resulted in a statistically significant difference in aqueous lead. A significant difference in the aqueous lead concentrations for pre-remediation levels (mean = 17.31, SD = 23.97) and post-remediation levels (mean = 2.47, SD = 2.98) was seen (t(35)= 3.78, p < 0.001; 95% CI[6.75,22.42]).

We hypothesize that the primary contribution to lead concentrations in the pitcher pumps was due to the leaded valves. However, the most likely reason for some pumps to still have elevated lead levels following remediation is other water system materials containing varying amounts of lead. For example, lead solder is still used in Madagascar, though phased out in many parts of the world (Sandvig et al., 2008). Leaded solder is used to attach the well screen in most groundwater supply systems. Many studies have found it common for leaded solder to leach into drinking water and in some cases be major contributors to the aqueous lead concentrations (Brown et al., 2011; Lee et al., 1989). However, it has also been found that lead release from
solder decreases over time, so the age and state of the pump could be indicators of the potential impact of aqueous lead from pump solder (Sandvig et al., 2008). Other materials used in pump and well screen manufacturing, such as galvanized steel, brass, and bronze, also have the potential to add to aqueous lead concentrations (Clark et al., 2015; Lee et al., 1989; Li et al., 2020; Mcfadden et al., 2011; Pieper et al., 2019). Studies have found brass components are particularly likely to contribute to aqueous lead levels in both HICs and LMICs (Fisher et al., 2021; Kimbrough, 2007). A study on West African water systems found systems with brass components were predicted to have 3.8 times the aqueous lead content as compared to systems without brass components (Fisher et al., 2021).

![Figure 3.4](image)

**Figure 3.4** Box plots of the aqueous lead concentrations (µg/L) pre- and post-remediation of pumps (i.e., removal and subsequent replacement of leaded components) (n = 36). Pre-remediation levels (mean = 17.31, SD = 23.97) and post-remediation levels (mean = 2.72, SD = 2.98). Box hinges represent first and third quartiles, and middle represents the median. Whiskers extend 1.5 times the inter-quartile range of the hinge. Points beyond the whiskers are outliers. Two outliers for the pre-remediation were over 50 µg/L and are not represented in the figure.
3.3.3 Statistical Analysis of Relationship Between Aqueous Lead and BLLs

Pearson correlations were examined for nine variables: age, height, weight, pre-BLL, post-BLL, pre-aqueous Pb, post-aqueous Pb, Δ BLL, and Δ aqueous Pb. Results can be seen in Table 3.2. Five variables prove to be highly correlated ($r \geq 0.6$) and statistically significant to the 0.001 level. Highest correlation was seen between age, height, and weight. These three variables were all highly positively correlated as expected for an average population. Pre-BLL was found to be correlated with both post-BLL ($r = 0.62$, $p < 0.001$) and the change in BLL ($r = 0.81$, $p < 0.001$). These correlations show that participants with a higher starting BLL tended to have a higher post-BLL and greater change in BLL. As there is greater potential for a BLL to decrease if the participant had a high starting BLL, these correlations do follow expected trends in BLL reduction.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Age</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Height</td>
<td>0.93***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Weight</td>
<td>0.83***</td>
<td>0.86***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Pre-BLL</td>
<td>0.13</td>
<td>0.17</td>
<td>0.22</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Pre-Aqueous Pb</td>
<td>-0.04</td>
<td>0.00</td>
<td>-0.15</td>
<td>-0.24</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Post-BLL</td>
<td>0.18</td>
<td>0.14</td>
<td>0.28</td>
<td>0.62***</td>
<td>-0.33*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Post-Aqueous Pb</td>
<td>-0.18</td>
<td>-0.2</td>
<td>-0.23</td>
<td>-0.23</td>
<td>0.31*</td>
<td>-0.29</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Δ BLL</td>
<td>0.03</td>
<td>0.12</td>
<td>0.07</td>
<td>0.81***</td>
<td>-0.06</td>
<td>0.04</td>
<td>-0.07</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9. Δ Aqueous Pb</td>
<td>-0.02</td>
<td>0.03</td>
<td>-0.13</td>
<td>-0.22</td>
<td>0.99*</td>
<td>-0.31*</td>
<td>0.2</td>
<td>-0.05</td>
<td>1</td>
</tr>
</tbody>
</table>

Notes: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; (N = 45)

The relationship between change in BLL and aqueous lead concentrations in corresponding pumps used for drinking and cooking were graphically examined for further comparison. Review of Figure 3.5 additionally demonstrates no relationship between changes in BLL and aqueous lead concentrations alone, suggesting the need to control for other variables in this analysis. To the author’s knowledge, the aqueous lead concentration was the only exposure
route directly changed during the study; therefore, regression analysis focused on controlling for demographic variables was performed.

**Figure 3.5** Plot of change BLL concentrations (µg/dL) of children aged six months to six years to decrease in aqueous Pb (n = 45), pre-Pb (n = 55), and post-Pb (n = 55). No statistically significant correlations were found.

In the first model of the sequential regression approach used here, the independent variable was only pre-aqueous Pb concentrations (Table 3.3, Model 1). This was chosen as the first variable as pre-aqueous Pb levels would be an easy parameter to measure throughout a community and assist in the prioritization of remediation efforts. Similar to the lack of correlation in Figure 3.5B, there was no statistical significance when pre-aqueous Pb levels was the only variable independent variable. Important to note, however, is that the direction of the coefficient is not logical: as the pre-Pb concentration increases, there is less (-) change in BLLs. As Pb contamination impacts younger individuals, the inclusion of either age, weight, or height was the next logical variable to include. The weight of the participants was entered in Model 2 to control for participant variability; however, once again, neither variable predicted BLL changes with any statistical significance. Again, the direction of the relationships is not logical in Model 2.
Finally, in Model 3 pre-BLL was entered and accounted for a significant amount of change in BLL \( [R^2=0.689, F(3,41)=30.29, p<0.001] \), yet still did not result in statistical significance for pre-remediation Pb levels (Table 3.2). However, in Model 3 the direction of the relationships was logical: a positive association with pre-remediation Pb, a negative association with weight (as weight decreases, changes in BLL increase), and a positive association with pre-remediation BLLs. While pre-remediation BLLs can assist in developing a Pb mitigation plan, it is more complex as it would rely on testing actual BLLs instead of simply measuring Pb concentrations at the pump.

The lack of correlation and prediction ability could be due to multiple factors including: the complexities of the blood lead relationship (i.e., pre-existing health conditions, calcium and iron intake, etc.), limit of only approximately one half-life before post-test, aqueous lead measurements not accounting for particulate lead, or small sample size. Further analysis should be performed to examine additional variables that could be impacting the change in BLL. Examples of variables to use include time between pre- and post-BLL test, parents’ occupation, and geographic location.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b</td>
<td>SE b</td>
<td>b</td>
</tr>
<tr>
<td>Pre-Aqueous Pb</td>
<td>-0.014</td>
<td>0.036</td>
<td>-0.012</td>
</tr>
<tr>
<td>Weight</td>
<td>0.094</td>
<td>0.229</td>
<td>-0.144</td>
</tr>
<tr>
<td>Pre-BLL</td>
<td>0.684***</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>4.578***</td>
<td>1.005</td>
<td>3.515</td>
</tr>
<tr>
<td>F</td>
<td>0.162</td>
<td>0.164</td>
<td>30.29***</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>43</td>
<td>42</td>
<td>41</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.004</td>
<td>0.008</td>
<td>0.689</td>
</tr>
<tr>
<td>N</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

*Note: ***p<0.001, **p<0.05, *p<0.1*
3.3.4 Blood Lead Level (BLL) Estimations

Children aged one to five with a measured BLL and aqueous Pb concentration pre-remediation were modeled using IEUBK. In total, 123 children aged one to five were examined. The estimated and measured distribution of BLLs is provided in Figure 3.6. The model estimated that 76% of children would have BLLs below 5 µg/dL reference value. However, only 23% of the measured BLLs were below the reference value indicating that the modeled values highly underpredict the measured BLLs.

![Cumulative distributions of modeled and measured blood lead levels (BLLs) in children using water from non-retrofitted pumps.](image)

**Figure 3.6** Cumulative distributions of modeled and measured blood lead levels (BLLs) in children using water from non-retrofitted pumps.

This underestimation of the model could be due to multiple factors including underestimating or missing important exposure routes of lead. Given the lack of statistically significant correlation between pre-remediation Pb concentration and changes in BLL, this alternative exposure route within the community is highly probable. In the model, default values were used for soil, dust, and air as no local lead measurements are known for this region. These
default values are based on peer-reviewed literature and represent U.S. national averages (SRC, 2021). Therefore, the use of these default values could result in underestimation of exposure from soil, dust, and air as regulations and phase-outs of leaded products (i.e., leaded gasoline (Mielke et al., 2019; Rees & Fuller, 2020)) in Madagascar started later than, and are not as stringent as, those in the U.S. (further discussion can be found in Champion et al. (2022)). However, with no soil, dust, or air lead readings locally in Toamasina, and many measurements in LMICs being at known contaminated sites (i.e., mining, battery recycling, etc.), verification of the effect from the exposure is limited.

Within Madagascar, the lack of regulations and understanding of the harmful effects of lead on health also pose a risk due to exposure through products (i.e., cookware), parents’ occupation (i.e., mechanic/technician), and diet (i.e., beans and rice) (Champion et al., 2022). Chronic malnutrition and anemia are also prevalent in Madagascar, particularly within young children (Central Intelligence Agency, 2020; USAID, 2014, 2021). These health conditions reduce the calcium and iron in the body, both competitors to lead uptake, allowing for increased lead uptake (Mushak, 1991; The technical review workgroup for lead, 1994). The increased prevalence of chronic malnutrition seen in Madagascar could indicate a need to adjust the bioavailability and uptake potential values in the model to accurately depict the BLLs of children in Madagascar and other LMICs. However, given the poor output of regression model 2, weight is not the only controlling factor we need to consider.

Stanek et al. (2020) showed water can be an important pathway for lead, similar to this study. It should be noted our study did not account for particulate lead. Accounting for particulate lead would be expected to increase the aqueous lead levels measured, in turn increasing the importance of water and diet pathways (Triantafyllidou, 2011; Wilson, 2021).
The IEUBK model has been used to estimate lead exposure impacts from various sources throughout the world (Adeyi & Babalola, 2017; Chantian et al., 2020; Debebe et al., 2020; Zhang et al., 2017). Results have been used to prioritize programs/funding and to develop and implement policy (Delgado-Caballero et al., 2018; Utembe & Gulumian, 2021; Wang et al., 2018). The IEUBK model is a valuable resource in instances with limited funding or ability to measure children’s BLLs. However, the current IEUBK model should be used with caution for estimating BLLs in LMICs as it is likely a miss representation due to unique aspects of exposure experienced in these regions.

3.4 Conclusion

This study highlights the importance of aqueous lead exposure in LMICs through measured blood and water lead concentrations. Measurements showed only 4% of pumps had aqueous lead concentrations over the WHO guideline of 10 µg/L at the completion of the pump remediation, similar to those recorded on a much larger pump sample size in previous studies (Chapter 2). Subsequently, measured BLLs showed a statistically significant decrease after the removal of leaded components ($t(54)= 6.15$, $p < 0.001$). However, no statistically significant correlations were seen between BLL and aqueous-lead concentrations. Examination of modeled BLLs and measured BLLs indicated that the IEUBK model underpredicts BLLs. Discrepancies between measured and modeled BLLs shows a need for model updates to account for the unique factors seen in LMICs. Small-scale remediation can play an important role in decreasing exposure to lead, especially through water in LMICs. Furthermore, remediation efforts similar to this study have shown a return on investment of approximately $4000 for every dollar spent (Buerck et al., 2021). Though not a common lead source addressed in LMICs, aqueous lead
exposure holds the ability to generate positive health benefits through small-scale and economically feasible remediation efforts.
Chapter 4: Convergence of Social Marketing and Engineering: A Lead Mitigation Study in Madagascar

4.1 Introduction

The importance of water, sanitation, and hygiene (WASH) for the protection of health is embedded in the Sustainable Development Goals (SDGs) (World Health Organization, 2002). However, the WASH section has struggled with long-term sustainability of projects with approximately 30-50% reported to fail within two to five years of implementation (UNDP Water Governance Facility/ UNICEF, 2015). This finding is clearly visible when examining handpumps in rural sub-Saharan Africa, where on average 36% of handpumps are non-operational at any given time, with some estimates showing upwards of 60% as non-operational (Chumbula & Massawe, 2018). Access to water plays a fundamental role in overall health and to achieve the ambitious SDGs an increased emphasis is needed on sustainable approaches and strategies (UNICEF, 2012; Waddington & Snilstviet, 2009; World Health Organization Water, Sanitation, Hygiene, 2011). Furthermore, studies have shown that to achieve long-term project sustainability it is crucial to integrate community engagement and end-user benefit into the project (Dvir et al., 2003; Lipovetsky et al., 1997; Sindall et al., 2021).

---

2 This Chapter is published and or in preparation in part or in full in the following papers:
Recently a shift to project learning and community integration has been seen within organizations such as United States Agency for International Development (USAID) and United Nations Environment Program (UNEP). These shifts involve the engagement of the community in designing and implementing interventions, reviewing previous efforts, looking to lessons learned, and conducting gap analysis to build on weaknesses. Some initiatives include the “project learning approach” used in the Applying Science to Strengthen and Improve Systems (ASSIST) project and the UNEP “Lessons Learned Framework” (Massoud & Kimble, 2018; USAID, 2019). Many of these frameworks utilize human-centered design or design thinking, however, a formal shift towards making these integrated approaches standard has yet to be seen and is still an ongoing discussion dating back to the mid-1970s (Burton et al., 2021; Hulme, 1989).

Building further off these frameworks is the integration of community-based and participatory approaches. These frameworks focus on co-creation, or an integration of local community stakeholders in the design process. Some of these approaches have shown initial success for ongoing WASH projects, as measured by community acceptance and ownership (Douthwaite et al., 2008; Tsekleves et al., 2022; Ward et al., 2018). While community ownership and acceptance is tantamount to project success, there are multiple causes for project failure; this understanding has recently shifted to the integration of systems thinking in WASH projects (Cannon et al., 2022; Liddle & Fenner, 2017; McAlister et al., 2022; Valcourt, Javernick-will, et al., 2020; Valcourt, Walters, et al., 2020). Systems thinking looks at the interactions between dynamic quantitative and qualitative factors to identify leverage points, that can strengthen the system as a whole (Valcourt, Walters, et al., 2020). However, once a leverage
point is identified, the need to integrate behavior change is often needed to create a systemic or sustainable change (Kaufman et al., 2021; Slattery & Kaufman, 2022; Williams et al., 2017).

One approach to behavior change that incorporates the user experience rather than implementing a top-down approach is Social Marketing (Lee & Kotler, 2016). Social marketing adopts commercial marketing tools to change behavior for positive social impact, and it has been applied to a variety of fields including health, environmental protection, and safety/injury prevention. Social marketing espouses that in order to market an innovation successfully, the product must provide a solution or benefit that users consider more valuable than the competition (what they are currently doing or using) (Bryant et al., 2003). Social marketing works on the assumption that traditional information, education, and communication tactics (i.e., the information deficit model (Marteau et al., 1998)) are not enough to change individuals’ behavior and that the complexities of the human experiences and barriers need to be understood and placed at the center of program development to achieve long-lasting change (McKenzie-Mohr & Schultz, 2014).

In recent years, social marketing has been applied across the globe on a range of behaviors. One illustrative campaign in New York City sought to utilize social marketing to prevent childhood Pb poisoning. The campaign was able to achieve an increase in individuals checking for peeling paint in their homes (48% of respondents at the start of the campaign and 60% by the end) and achieved a rate of 82% reporting when people found a problem with the paint in their homes (Greene et al., 2015). Though few studies exist in the WASH sector that explicitly use social marketing, Evans et al., (2014) reviewed the use of social marketing within the context of water and sanitation products, showing a high degree of successful behavior change within safe water systems programs.
This paper aims to shed light on the benefits of using social marketing within the WASH sector through examination of how social marketing was used to plan, develop, implement, and evaluate a behavior change initiative for pitcher pump (i.e., handpump) technicians in Madagascar. Using a case study design, we will share the social marketing steps used, our experiences with implementing the steps and finally lessons learned.

4.2 Materials and Methods

There are multiple frameworks that can be employed and encompass themes common in social marketing, including human-centered design, Community-Based Social Marketing (CBSM), Community Based Prevention Marketing (CBPM), stages of change theoretical framework, and Social Behavior Change Communication framework (SBCC) (Bryant et al., 2014; Burton et al., 2021; Grier & Bryant, 2005; Lee & Kotler, 2016; Mckee et al., 2014). These various frameworks share common steps and procedures, and the review of their structure informed the development of a new study specific framework (refer to Figure 4.1) used to guide the design, implementation, and evaluation of this study. The framework used consists of seven steps: 1.) Situational analysis, background, and purpose, 2.) Define behavior objectives and select target audience, 3.) Formative research: research to understand knowledge, behavior, barriers, and benefits, 4.) Development of creative concepts and strategic marketing mix, 5.) Testing and revision of materials with target audience, 6.) Program implementation, and 7.) Monitoring and evaluation. Though the framework is depicted as a series of linear steps (Figure 4.1) it is an iterative process with changes or updates made based on research and participant feedback.
**Figure 4.1** Steps in the social marketing process informed by review of existing social marketing and behavior change frameworks.

4.2.1 Study Location and Population

Toamasina, Madagascar, is an urbanizing coastal city of over 300,000 people where centralized piped water is not always affordable or reliable, creating a demand for supplemental decentralized self-supply water systems, commonly used in low-income countries. In Toamasina, these systems often consist of a manually driven well point and locally manufactured pitcher pump that serve a household or a small group of households. These systems have traditionally been manufactured with leaded components (MacCarthy et al., 2013). These leaded components contaminate water above WHO guidelines and pose a range of health risks to those using the water for household purposes. Further complexities for this system include the unique market for these hand-driven wells, other potential chemical and microbial water contaminants, and the lack of local understanding of health effects of these contaminants (Akers et al., 2020; MacCarthy et al., 2013).

Prior studies in Toamasina have found that approximately one third of the pitcher pumps with leaded components exhibit lead concentrations above the WHO provisional drinking water
guideline of 10μg/L (Buerck et al., 2021). In turn, exposure from cooking and drinking this water results in around 34% of children aged one to five with blood lead level (BLLs) concentrations of over 5µg/dL, a level at which point irreversible health impacts occur (ACCLPP, 2012; Buerck et al., 2021; World Health Organization, 2010a, 2019a).

4.3 Results and Discussion

4.3.1 Step 1. Background, Purpose, and Situational Analysis

In this initial step, the objective is to define the problem, identify the assets and barriers, and to get a better understanding of what is known and not known about the topic. Having identified the social issue or topic of concern (ex. lead exposure in Madagascar) the goal is to gain further understanding of the players involved (i.e., organizations, community leaders, etc.) and the extent of the issue. This can include epidemiological data, scientific articles, research reports, or other credible sources of information (Lee & Kotler, 2020).

From ongoing research in the region, the research team was familiar with Toamasina, a port city in Madagascar where piped water is not always readily available resulting in the need for a supplemental water system, including locally manufactured pitcher pump and a shallow ground well (MacCarthy et al., 2013). The research team was familiar with the health risks posed by the pitcher pumps, that are historically manufactured with leaded components. Previous work had identified an alternative to leaded components that required minimal changes to the traditional pump design (Akers et al., 2015). However, attempts to solve this issue and implement the technology innovation in Toamasina was met with skepticism by local pump technicians and users. These efforts designed for the local community and pump technicians, focused on increasing awareness and knowledge of the adverse effects of lead. While designed with good intention, the “top-down” approach, lack of an established community partner and
trust (potentially due to an ongoing election around the time of the work in 2018) created uncertainty within the community. This ultimately led to reimplementation of lead into previously remediated pumps (i.e., pumps that had leaded components replaced with non-leaded components) thus highlighting the need for a more holistic approach to address the lead in the pumps to protect the health of the community.

In applying step one, we learned that the established history enjoyed by our university in the field, allowed the team to build-up connections and trust with community partners, such as ONG Ranontsika (locally established non-profit agency), the Ministry of Water, and the Ministry of Health; which in the end enhanced our understanding of the local context and background and put the overall initiative in a positive light.

4.3.2 Step 2. Define Behavior Objectives and Select Target Audience

This step builds on the understanding gained in step one and hones in on identifying affected population segments, whose behavior needs to change to achieve better health outcomes. Segmentation can use geographic, demographic, psychographic, behavioral, health, or lifestyle factors to create small segments from the larger population based on shared characteristics. Following the identification of broad segments, each is evaluated from the perspective of likelihood of adopting the behavior and the impact of this behavior on the larger health concern. Existing research provides data pertaining to segment size, reachability, responsiveness, incremental costs, and responsiveness to marketing mix (Lee & Kotler, 2020). The segment with the greatest opportunity (i.e. greatest need, most ready for action, easiest to reach, good match for organization) is then chosen as the target audience (Siegel & Doner, 2007).
In this step, the study team conducted literature reviews to better understand the mechanics of the pumps, Pb leaching, informal sector economies, and insights on the local culture. Further discussions were held with key informants including, ONG Ranontsika and other local partners who had spent time in the area and worked with the pitcher pumps. Using an iterative information gathering process a stakeholder map was developed and segments of interest were identified (Figure 4.2).

![Stakeholders for pitcher pump production and usage. Rectangles = primary decision makers; Ovals = influencers to the decision.](image)

Primary stakeholders identified included pump owners, pump users, and pump manufacturers. Pump owners and users were classified into different segments as it is common to have multiple families or houses that share use of a single pump. These segments were then examined by performing a return on investment (ROI) analysis. An ROI is often defined as the quantifiable benefit received as a result of an investment (Dietrich et al., 2017). For context within this study, it is the potential level of impact a segment could create vs. the expected adoptability of the target behavior change (Table 4.1).
Along with this traditional social marketing technique, mathematical modeling of the potential phaseout of leaded components was examined to assist in audience selection. This modeling examined different decision change rates (i.e., percent of audience that changes to lead-free pump components) and in turn the impact that those individuals can create with the overall pump remediation efforts over time (i.e., how many pumps they encounter and would remediate without the need for continued support from our project). The coupling of these traditional social marketing strategies with mathematical modeling resulted in the selection of the primary target audience of pitcher pump technicians and a behavioral focus of use of lead-free valve components in the installation or repair of pitcher pumps. The pump technicians were selected due to an understanding that they hold most of the decision power in what materials are used in the manufacturing and repair of pumps, they are a small and clear group (approximately 50 technicians expected in the area), there is ability to reach the audience, and potential for sustainable decision change with minimal need for continued long-term support (Khaliq et al., 2021).

In this stage it became apparent that the long history of the team and local partnerships were a benefit to the project. This allowed for a clear picture of the behavioral objectives surrounding the pump and the various segments. The interdisciplinary makeup of the team offered multiple perspectives on the mitigation efforts. For example, to reach 100% removal of lead a new method for the well screen would need to be adopted. However, from a behavior change perspective, focusing on multiple behavior adjustments (i.e., using new materials and methods for valves and well screen) can result in limited outcomes and sustainability of any behavior change (Schwartz & Ward, 2004). This led to a team discussion, initiated by the social
marketing team members, resulting in a decision to focus just on the valve replacement of the pump, versus a focus on valve and well screen.

Table 4.1 Summary table of stakeholder behavior change analysis

<table>
<thead>
<tr>
<th>Primary Stakeholders</th>
<th>Potential Targeted Behavior Change</th>
<th>Notes</th>
<th>Return on Investment (ROI) Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pump Owners:</strong></td>
<td>Without adapted pumps</td>
<td>• Protect their families/community from negative health effects. • Don't always use the pump so could be less invested</td>
<td>High</td>
</tr>
<tr>
<td>Individuals that have made the decision and monetary contribution to purchase and upkeep a pump</td>
<td>Advocate for/adapt to and maintain a leadless pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With adapted pumps</td>
<td>Share knowledge on leadless components and why they switched. Maintain leadless pump</td>
<td>• Protect their families/community from negative health effects.</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Pump Users:</strong></td>
<td>Adults</td>
<td>• Protect their children and themselves from long-term effects. • Don't interact with the pump repairing much.</td>
<td>Moderate</td>
</tr>
<tr>
<td>Individuals that utilize the pumps for basic water needs (i.e. drinking, cooking, cleaning, etc.)</td>
<td>Advocate for leadless pumps to protect themselves and their families</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Children</strong></td>
<td>Share information with parents</td>
<td>• Most at risk population.</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Pump Manufacturers:</strong></td>
<td>Material Providers</td>
<td>• Potential increase in earnings. • Don't have much say in what is used in manufacturing. • Sells what they have access to.</td>
<td>Moderate</td>
</tr>
<tr>
<td>Provide materials for or utilize materials in the making of pitcher pumps</td>
<td>Help manufacture leadless parts and advocate for their use.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Skilled Laborer (Technician)</strong></td>
<td>Use leadless parts when making</td>
<td>• Protect themselves and their communities from negative health effects.</td>
<td>High</td>
</tr>
</tbody>
</table>

The convergence approach of engineers and social marketers working together brought forward its own set of advantages and disadvantages. In a general sense, within engineering, definitive decisions or solutions corroborated by mathematical modeling are commonly utilized; Though there have been efforts to integrate greater contextual understanding into engineering practices (Roldan-Hernandez et al., 2020; American Society of Civil Engineers, 2007). Whereas,
social marketing relies more heavily on environmental and social context coupled with community input to arrive at culturally informed decisions or solutions. In this project, this difference or “limitation” was used to enhance the project and blend the strengths of both disciplines. The mathematical modeling of phaseout enhanced and assisted the audience segmentation phase and the decision to choose the pump technicians as the priority population.

4.3.3 Step 3. Formative Research: Research to Understand Knowledge, Attitudes, Behavior, Barriers and Benefits

Formative research, is both quantitative and qualitative, consists of both primary and secondary research, and aids in understanding the target audience (Lee & Kotler, 2016). Primary research is original research conducted with the target audience and can be qualitative or quantitative or employ mix-methods. This is coupled with secondary research, or previously conducted research, to assist in filling in any knowledge gaps and provide a holistic view of the target audience (Evans, 2016).

Primary data for this study took the form of quantitative surveys/questionnaires and qualitative semi-structured in-depth interviews. Figure 4.3 summarizes the study design and methods utilized for formative research. The questionnaire and interview guide were developed using the social marketing mix and the theory of planned behavior (TPB) with the objective of understanding the barriers, benefits, motivators, influencers, and communication channels used by technicians. The TPB was utilized based on its constructs and strength in providing a framework to predict intentions to change behavior (Ajzen, 1991). Secondary data, in the form of reports, survey responses from prior efforts, and dissertation and thesis writeups, were used to assist in the creation of the questionnaires and to supplement the findings from the primary data findings (Akers et al., 2015; MacCarthy et al., 2013; Usowicz, 2018). The interviews covered
the following domains: occupational training source; installation/repair work practices; types of materials used, preferences for types of materials, and availability/accessibility to materials; techniques associated with installation and repair; knowledge of water safety and water quality; channels through which they receive training or information; knowledge of the health effects of Pb; and barriers and facilitators to the use of Pb free components (questionnaire and interview guide can be found in Appendix D.1 and D.2). The guide was pretested with two technicians who the team had worked with in the past. Pretesting consisted of in-country staff or animators (i.e., those who would be carrying out the interviews in the field) running through a mock recruitment/interview and gaining feedback on the clarity of questions. This allowed for the animators to becoming familiar with the materials and for materials to be revised, based on feedback, prior to recruitment.

Figure 4.3 Key steps and information in the study design and methods used for collection and analysis.

Technicians were identified using purposive sampling (Bernard & Bernard, 2013) by means of an initial list of technicians from the prior remediation work in 2018. Technicians were then asked to participate in a quantitative survey in which they were asked to refer other
technicians. Using a snowball sampling approach (Goodman, 1961), the referred technician would then be contacted and asked to participate in the quantitative survey (Appendix D.1). This process was repeated until no new technicians were referred, indicative that all technicians within Toamasina had been reached. In total, 49 technicians operating in Toamasina were identified.

The 49 technicians were further segmented excluding those with prior contact with previous remediation efforts. The 24 technicians remaining were asked to participate in a semi-structured in-depth interview. In total, 18 interviews were conducted. The 18 technicians interviewed were generally trained informally (i.e., transferring skills from another profession and/or learning from family and friends) and were based within 11 fokontany/neighborhoods and two arrondissements/administrative districts, Ankirihiry and Tanambao V. Additional information on the sample is reported in Table 4.2.

Interviews were recorded, transcribed in Malagasy, translated to English, and then sent to the University of South Florida (USF) study team for analysis. To ensure accuracy, a subset of English transcripts were back-translated to Malagasy. English transcripts were coded by three team members in MaxQDA 2020 (Software, 2019) using a codebook developed with a priori and emerging codes (Elliott, 2018) To ensure that codes had been applied consistently by all three coders, intercoder reliability was assessed by calculating Cohen’s kappa coefficient, which is read on a scale of -1 to 1 where 0.61-0.80 is substantial and 0.81-1 is almost a perfect agreement (McHugh, 2012). Kappa was found > 0.80 for all pairs of coders. Thematic analysis was conducted on coded transcripts to identify key patterns. A “doer/non-doer” lens was adopted for analysis of the coded transcripts (Khaliq et al., 2021). Findings from the analysis are summarized in Table 4.3. Key insights from the formative research revealed the importance of peers (those
considered experts or “market mavens”), the need for information on the dangers of lead, and the understanding that use of lead was an outdated practice.

Table 4.2 Socio-demographic and knowledge variable breakdown of surveyed technician sample

<table>
<thead>
<tr>
<th>Socio-demographic and knowledge variable</th>
<th>Percentage (%) of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary language</strong></td>
<td></td>
</tr>
<tr>
<td>Malagasy</td>
<td>71%</td>
</tr>
<tr>
<td>French</td>
<td>29%</td>
</tr>
<tr>
<td><strong>Status</strong></td>
<td></td>
</tr>
<tr>
<td>Married or in a domestic partnership</td>
<td>82%</td>
</tr>
<tr>
<td>Single</td>
<td>18%</td>
</tr>
<tr>
<td><strong>Household size</strong></td>
<td></td>
</tr>
<tr>
<td>1-2 people</td>
<td>18%</td>
</tr>
<tr>
<td>3-4 people</td>
<td>47%</td>
</tr>
<tr>
<td>5-6 people</td>
<td>18%</td>
</tr>
<tr>
<td>7+ people</td>
<td>18%</td>
</tr>
<tr>
<td>Previously heard information about water quality issues and water contamination</td>
<td>65%</td>
</tr>
<tr>
<td><strong>Training received</strong></td>
<td></td>
</tr>
<tr>
<td>Apprenticeship</td>
<td>6%</td>
</tr>
<tr>
<td>Transferred skills from another profession (i.e. welding)</td>
<td>82%</td>
</tr>
<tr>
<td>Formal technician training</td>
<td>6%</td>
</tr>
<tr>
<td>More than one source of training</td>
<td>6%</td>
</tr>
<tr>
<td>Presence of another technician in the family</td>
<td>65%</td>
</tr>
<tr>
<td>Average number of new pumps installed each month</td>
<td>3</td>
</tr>
<tr>
<td>Average number of pumps repaired each month</td>
<td>3.5</td>
</tr>
</tbody>
</table>

* Demographic data from 1 participant is missing

In this step of the project, the team found the mixed-method approach of using quantitative and qualitative approaches beneficial (Dawadi et al., 2021). The quantitative survey offered a clear idea of the audience size, reachability, and makeup. Within our work we found the segment to be quite small. Though a small segment can be limiting in a research study it allows for greater reach and customizability for the audience. Based on the findings from the quantitative survey the qualitative semi-structured interviews were able to be further tailored to gain deeper insights into the target audience.
### Table 4.3 Summary of doer/non-doer analysis

<table>
<thead>
<tr>
<th>Reported motivators for their current behavioral choice</th>
<th>Doers</th>
<th>Non-doers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• excessive cost of Pb (n=4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lack of availability of Pb (n=2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• desire to avoid negative health effects (n=6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• physical properties of Pb (e.g., density, malleability, and it does not rust) (n=7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benefits of lead-free components</th>
<th>Doers</th>
<th>Non-doers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• cost savings from using cheaper metals (n=4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• wider availability/lack of supply issues with other metals (n=2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• health benefits (n=2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• health benefits (n=7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• cost savings (n=1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barriers to lead-free components</th>
<th>Doers</th>
<th>Non-doers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lack of knowledge of how to use other metals and lack of willingness to learn (n=4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lack of knowledge of health effects of Pb (n=2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• metals such as iron are more difficult to use for manufacturing of pump components (n=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants mentioned:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lack of knowledge of how to use other metals (n=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• metals such as iron are more difficult to use for manufacturing of pump components (n=4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• concern that the quality of pump manufacturing will worsen with switch to non-lead (n=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lack of awareness of the adverse effects of Pb (n=2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Perceived motivators for change to lead-free components</th>
<th>Doers</th>
<th>Non-doers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants perceived that technicians would feel motivated to change:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• were told they can easily use iron (n=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• were aware of the adverse effects of Pb on health (n=4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• were told that other metals are easier to find (n=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants perceived that technicians would feel motivated to change:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• if they were told they would protect public health (n=6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• if they were shown how to easily switch to other metals (n=3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.3.4 Step 4. Development of Creative Concepts and Strategic Marketing Mix

This step consists of designing a social marketing strategy through development of the marketing mix (product, price, place, promotion) and creative concepts. To stay centered and focused, a positioning statement or key promise is often utilized. This consists of a statement highlighting the key benefit the desired behavior would have for the target audience. Along with the positioning statement other audience insights (i.e., identified barriers, communication channels, tone, creative considerations, etc.) gleaned from formative research are shared via a
creative brief (Lee & Kotler, 2016; Rossiter et al., 2018). The creative brief is for internal use only and is shared with all those that are helping to design the social marketing strategy.

The creative brief highlighted what the intended goal was for the target audience to know, feel, or do after interacting with the campaign. For example, as a result of the campaign the pump technician should

- know the health consequences of lead and that using non-leaded components is the only way to prevent lead contamination,
- feel that they are problem solvers and are producing a product they can be confident in attaching their name to, and
- they will use non-leaded components for the manufacturing and repair of pumps.

The positioning statement for this study there for was: “I want to be innovative and respected in my community, as a result, I will create and maintain lead-free pitcher pumps.” Other insights such as: they do not trust all technicians but well known, innovative, and respected technicians are looked to for inspiration or advice at times therefore those technicians could be good spokespeople and that hardware shops, specifically metal shops, are commonly visited by technicians so could be an opening for communication. The complete creative brief can be found in Appendix D.3.

The marketing mix, often referred to as the 4P’s (product, price, place, promotion), is then developed (Figure 4.4). The product does not have to be a physical item but can consist of an event/service, behavior/experience, or information. The product often focuses on something that will benefit the target audience, something you are promoting to your target audience, or something that will assist the target audience in performing the desired behavior (N. R. Lee & Kotler, 2020). The price can be monetary or non-monetary (i.e. peace of mind). The perceived
benefits need to outweigh the required price of the desired behavior and alternative choices for the desired behavior to be seen as favorable and adoptable (Thackeray & McCormack Brown, 2010). Place refers to where and when the target audience will perform the desired behavior, receive services, or obtain any materials (Edgar et al., 2015; Lee & Kotler, 2016). The final part of the mix is promotion, the key message of the campaign, the messengers for the campaign, and the communication channels (i.e. brochures, t-shirts, radio ads, etc.) that will be used.

<table>
<thead>
<tr>
<th>The Marketing Mix (4P’s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product</strong></td>
</tr>
<tr>
<td>The target behavior and associated benefits</td>
</tr>
<tr>
<td>Behavior change to switch to non-leaded components for usage in pitcher pumps</td>
</tr>
<tr>
<td>• Core product:</td>
</tr>
<tr>
<td>• Sense of belonging</td>
</tr>
<tr>
<td>• Being considered an innovator and expert</td>
</tr>
<tr>
<td>• Augmented product:</td>
</tr>
<tr>
<td>• Promotional materials</td>
</tr>
</tbody>
</table>

*Figure 4.4* The marketing mix (4P’s of Marketing) as applied to pitcher pump technicians in Toamasina, Madagascar.

The design process was guided by the transtheoretical model of health, and consisted of many iterations based on conversations about cultural fit and feasibility (Figure 4.5) (Howard, 2014; Raihan & Cogburn, 2021). Development of this strategic marketing mix was justified by the formative research and discussions with the local marketing agency, ONG Ranontsika, and local government (Ministries of Water and Health). This was an iterative process between development, pretesting, and campaign updates (discussed below in *Step 5: Testing and revision of materials with target audience*).
Following multiple iterations (refer below to Step 5), the campaign brand of PTTF (Paompy Tany Tsisy Firaka = Pitcher Pump Without Lead) was selected. PTTF was then integrated into the campaign strategy consisting of three main components (1) an information session, (2) technical training, and (3) in-field practice that was integrated into a larger remediation project (i.e., removing and replacing lead components with non-leaded components in over 500 pitcher pumps). The campaign strategy allowed for the transmission of knowledge which aided in stepping the technicians through the stages of change (i.e., precontemplation, contemplation, preparation, action, and maintenance) (Raihan & Cogburn, 2021). For example, during the information session the technician likely moves from precontemplation to contemplation as they are informed of the risk of lead usage. A graphical depiction of the campaign strategy and where the technician may be in the stages of change during the campaign can be seen in Figure 4.5.

A creative agency was introduced to the project team after completion of step 3. A challenge associated with this introduction was in sharing information about the project that was written down, but also of the environmental context with this new partner so that they could engage in the design process. Further enhancing this need for communication between all project partners was the global covid-19 pandemic which prohibited the creative agency from performing any field visits. This challenge illustrated an important lesson for social marketing, in that project partners (community, research, creative, evaluation, etc.), especially creative, should be introduced to the project as early as possible to start building clear lines of communication and shared understanding of project goals.
4.3.5 Step 5. Testing and Revision of Materials with Target Audience

Pretesting is conducted to evaluate messages and strategies, identify deficiencies, and fine-tune approaches and materials so that they speak to the target audience effectively (Brown et al., 2008). Pretesting is generally qualitative in nature, taking the form of focus groups or interviews, to gain insights into how different aspects of the campaign speak to the target audience. Using these insights, the approaches and materials are revised. This is an iterative process and can go through multiple rounds depending on time constraints and the size of the target audience (Lee & Kotler, 2020). This is a key component of the development process as it provides further insights into your target population and allows one to understand whether the
developed campaign will have the desired impact. This data is also helpful for any future campaigns that might be done in the area as it offers a starting point (Cook et al., 2020).

The pre-testing process in this work, guided by the concept testing outline seen in Figure 4.6, consisted of individual interviews conducted by in-country staff in Malagasy with three technicians. These interviews assessed comprehension, acceptance, relevance, ability to persuade, and improvements. During the interview, materials were presented, and the technician was asked to reflect out loud on the design, color, form, and message of a given tool (i.e., flyer, t-shirt, message, branding). Probing questions, such as those in Figure 4.6, were asked to check the technician’s reaction and understanding of the different concepts. In-country personal recorded response notes during the interview. Following the interview further notes and observations were recorded and then shared in a written document and verbally during a meeting with the University research team and creative agency. Examples of feedback received from technicians during the interviews included recommendations such as:

- Adjustments to wording to make messaging clearer in the Malagasy language.
- To avoid white for shirts or other wearable items as they would get dirty very quickly in their line of work.
- The branding option preferred (i.e., PTTF) evokes water, spoke to them, and captured the essence of the project.

Feedback from pretesting guided the selection and revision of campaign messaging, materials, and strategy. Images of some of the final messaging and materials can be found in Appendix D.4. This was an important step in meeting the needs of the end-user. If the team had not tested the products, such as the t-shirts and the log notebooks, and gotten feedback, the target audience would be provided with resources not useful for them. Additionally, it was important to
tailor the messaging, the look and feel according to the target audience needs as it increased the likelihood of engaging and persuading them.

<table>
<thead>
<tr>
<th>Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Interviewer/moderator introduces themselves, ask participant(s) to introduce themselves, and the goal of the interview/focus group</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Campaign overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Interviewer/moderator presents the background for the project and the goal of the campaign</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Display of concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Interviewer/Moderator introduces the concepts, explaining they are preliminary ideas and participants are asked to given their honest opinion regarding them</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compare concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Display concepts again side-by-side and ask to compare/rank</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional info</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Which channels to convey these concepts?</td>
</tr>
<tr>
<td>• If logos are included in the concepts, what do they think of them? does it change the way information is perceived?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction to materials (example questions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• What do you think the main idea behind this concept is?</td>
</tr>
<tr>
<td>• What do you think/feel when reading those words or seeing those images?</td>
</tr>
<tr>
<td>• Is there anything that confuses you about this material?</td>
</tr>
<tr>
<td>• What would you change?</td>
</tr>
</tbody>
</table>

**Figure 4.6** Concept testing outline for pre-testing of campaign branding and materials.

4.3.6 Step 6. Program Implementation

Step six delves into the implementation of the designed initiative, with the understanding that it could be revised and updated based on audience feedback. In this case, implementation took place over a four-month period by local Malagasy staff. Materials utilized and/or disseminated during the campaign are listed in Table 4.4.
Table 4.4 Materials utilized during the implementation of the campaign

<table>
<thead>
<tr>
<th>Material</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyers</td>
<td>Used for recruitment of technicians as well as recruitment of families for pump remediations during the field practice</td>
</tr>
<tr>
<td>Rollups and whiteboard posters with tripod</td>
<td>Used to reinforce messaging during the information session and technical training</td>
</tr>
<tr>
<td>Large-branded step and repeat banner</td>
<td>Used for pictures of technicians, specifically when given certificate of completion, to provide a feeling of honor and respect as well as to reinforce PTTF branding</td>
</tr>
<tr>
<td>Branded handwashing station and branded potable water station</td>
<td>Reinforced branding and messaging through materials added for compliance of enhanced COVID protocols for participant protection</td>
</tr>
<tr>
<td>Technician maintenance logs (customer card/technician books)</td>
<td>Logs were used for multiple purposes: 1.) professionalism of technicians in keeping track of customers and repairs, 2.) allow for the project to check which repairs had been made during the field practice, and 3.) aid in evaluation of the campaign by providing a list of pumps remediated following the completion of the field practice</td>
</tr>
<tr>
<td>PTTF t-shirts, PTTF work overalls, PTTF tool bags, keychains with messages, PTTF notebooks</td>
<td>Aid in enhancing campaign recognition and making technicians feel professional and recognized in the community</td>
</tr>
<tr>
<td>Certificate of completion (Signed by the Ministry of Water and Ministry of Health)</td>
<td>Aid in making technicians feel professional</td>
</tr>
</tbody>
</table>

Technicians were invited to attend a two-hour information session in October 2020. Recruitment was conducted through door-to-door contact by a respected member of the research team who informed the technicians of the session and provided them with a flyer to remind them of the date and time. In total, 20 technicians attended the information session. Others in attendance included project staff, members from the local community partner, the regional director for the Ministry of Water, and the regional medical inspector of Toamasina. The session consisted of a presentation composed of five main parts (1) about the project, (2) about lead, (3) the benefits of lead-free pitcher pumps, (4) lead in the pitcher pumps, and (5) the manufacture of the lead-free pitcher pump. Following the presentation testimonials were provided by two highly
respected technicians, who had made a change in their behavior and were long time users of lead-free components.

Approximately a month later, November 2020, a two-day technical training session took place with 16 technicians in attendance. The training session was designed to increase the skill set of the technicians in using non-leaded components and consisted of a mix of presentations, discussion, and hands on practice making lead-free pumps. Those that completed the training were presented with a certificate of completion (signed by the Ministries of Water and Health), overalls, and other branded materials.

Following the training, technicians gained in field practice using the new technical skills, by assisting in ongoing remediation (i.e., removal of leaded components and simultaneous replacement with non-leaded components) of 500 pumps. Field practice took place over the course of three months (December 2020 to February 2021) with oversight and skills checks performed by the in-country NGO.

This step of the project was possible due to our collaborative in-country partner and our partnerships with important entities, such as Ministry of Water and Ministry of Health. This collaboration was essential as implementation occurred during the global pandemic, increasing the need for additional health consideration during information and training sessions (i.e., larger and/or outdoor spaces for the events, mask, hand washing stations, and meeting approvals). Furthermore, the global pandemic and local restrictions did hamper efforts to continue refresher courses and follow-ups with technicians.

4.3.7 Step 7. Monitoring and Evaluation

Monitoring and evaluation is carried out throughout the campaign to establish baselines, relative benchmarks, and assess campaign impact. A variety of study designs and techniques can
be utilized including the use of quantitative or qualitative surveys, pre/post-tests, and review of program reports and records (Program Performance and Evaluation Office of the Centers for Disease Control and Prevention, 2021). These techniques are incorporated along with the ongoing implementation (step 6) to assure accurate execution, determine if shifts in campaign strategy are needed and whether the campaign is achieving its intended outcomes.

This research project focused on formative and summative evaluation and integrated pre/post surveys, participant observation, semi-structured interviews, and skills checks to assess the campaign (Figure 4.7).

Figure 4.7 Overall project implementation and key points in evaluation.

Evaluation design was guided by the RE-AIM (reach, effectiveness, adoption, implementation, and maintenance) framework and developed using the theory of planned behavior (TPB). The RE-AIM framework was selected as it was originally designed to aid in the translation of scientific advances (i.e., engineered solutions) into practice (Glasgow et al., 2019); a goal of the research presented in this dissertation. All five dimensions of the framework were reviewed during the development of the campaign and evaluation. Table 4.5 displays the evaluation components that were implemented for each dimension (further information in Appendix D.5).
Table 4.5 Evaluation examined through the dimensions of reach, effectiveness, adoption, implementation, and maintenance (RE-AIM)

<table>
<thead>
<tr>
<th>RE-AIM Dimensions</th>
<th>Definition/Description (re-aim.org)</th>
<th>Method of Collection</th>
</tr>
</thead>
</table>
| Reach             | The absolute number, proportion, and representativeness of individuals who are willing to participate in a given initiative, intervention, or program, and reasons why or why not. | • Field notes and surveys completed  
• Project reports (from each phase) |
| Effectiveness     | The impact of an intervention on important individual outcomes, including potential negative effects, and broader impact including quality of life and economic outcomes; and variability across subgroups (generalizability or heterogeneity of effects) | • Pre/post questionnaire  
• Observations  
• Skills check  
• Follow-up calls with pump owners |
| Adoption          | The absolute number, proportion, and representativeness of settings and intervention agents (people who deliver the program) who are willing to initiate a program, and why. | Six months following remediation:  
• Visit to technician shop  
• Check of logbook  
• Survey/Interview  
• Review of field logbooks |
| Implementation    | The intervention agents’ fidelity to the various elements of an intervention’s key functions or components, including consistency of delivery as intended and the time and cost of the intervention. Importantly, it also includes adaptations made to interventions and implementation strategies. | • Project schedule  
• Project reports (from each phase)  
• Project team discussion/reflection  
• Project budget |
| Maintenance       | At the setting level, the extent to which a program or policy becomes institutionalized or part of the routine organizational practices and policies. At the individual level, the long-term effects of a program on outcomes after a program is completed. | • Pre/post questionnaire  
• Observations  
• Skills check  
• Follow-up with pump owners  
• Review of field logbooks  
• Project team discussion/reflection |

The TPB was embedded into the evaluation to provide specific constructs (i.e., behavioral control, attitudes, norms, intention to change behavior, and behavior change) to assess for impact and adoption of the desired behavior (Ajzen, 1991, 2020; Kessler et al., 2012). The
TPB has been used to explain and predict a wide variety of behaviors such as healthy eating (Conner et al., 2002), oral health (Dumitrescu et al., 2011), and understanding hand hygiene (O’Boyle et al., 2001).

The pre- and post-surveys were based on the TPB and a validated questionnaire (Ajzen, 2006) adapted for project and cultural context. Questions consisted of a mixture of seven-point likert-scales and four-point ordinal scales. Similar likert-scale questionnaires have been used within LMICs. For example, Agampodi et al. (2015) examined peer-reviewed studies looking at social capital in relation to health within LMICs, many of which used likert-scales.

Questions within this study examined how important technicians felt reducing lead was, how they viewed their ability to identify lead and use non-leaded components, and what their intent around lead usage was. The post-training survey contained a set of retrospective questions to gain further understanding of the reliability of the assessments. For example, technicians were asked both, “Before the training, I intended to switch to lead free components” and “Now, I intend to switch to lead free components” to see if they felt there was a change. This verification was added to help identify and/or avoid a social desirability bias which based on local customs were a possibility (Dietrich et al., 2017). The complete pre- and post-surveys can be found in Appendix D.6 and D.7 respectively.

During the field practice, in-country personnel performed two skills checks. The skills checks consisted of an observation of technicians retrofitting a pump (i.e., removing and replacing lead components). An observational checklist (or skills check) for making lead-free pumps was developed with support from past researchers, in-country personnel, and a technician to identify key elements for making lead-free pumps. Elements include checking that the pump retains water and has a good flow rate/adequate quantity, proper weight size was used, leather
was properly cut in a half-moon at an inline, leather is fixed with the rough side up, and weights are sturdily attached (full checklist can be found in Appendix D.8). Follow-up calls with households whose pumps were remediated were also carried out by in-country personnel to verify pumps were working properly and they were pleased with the job that had been completed. Notes from these calls were added to the skills check sheets and shared with the research team. Technicians that had a complaint made during follow-up calls (i.e., family indicated an issue with or that pump did not work after the remediation and pump had to be re-examined/ fixed) received an individual feedback session to answer questions and provide further training if needed.

All technicians who completed the technical training (n=16) were contacted for follow-up approximately six months following the completion of field practice. Initial contact was done via phone to verify that the technicians were still located in Toamasina, still working as a technician, and were open to meeting with the team. Follow-ups were done by a team consisting of one in-country personnel and one highly regarded technician, who had been trained in interview and participant observation techniques, and were carried out in the field at the technicians workshop or at a job site. The interview guide (Appendix D.9) was developed using the TPB and asked questions from the pre/post surveys in an open-ended fashion to gain further insights. For example, the pre/post survey asked to indicate on a scale from one (definitely false) to seven (definitely true) how the following statement represented them “I feel confident in my ability to manufacture/repair a pump without the use of lead”. During the interview, the statement from the survey was asked as a question, “How comfortable do you feel making a pump without lead?,” with probes to encourage technicians to expand on why they felt they were or were not comfortable.
During the interview notes were also taken recording items seen in the technician’s shop that could indicate the continued use of lead (ex., lead, batteries, tools, etc.) (reference guide to aid in observation of workshop can be found in Appendix D.10). If the technician had their logbook, images were taken to examine work completed since the field practice portion of the campaign (i.e., check pumps for use of lead components). If they no longer had a logbook they were asked to show us some recent pumps they had done work on. If the technician had a job during the week of follow-ups, a skills check was also performed using the same checklist used during the field practice. The semi-structured interviews were recorded, transcribed, translated, and then shared with the research team. All other notes from the follow-ups were also translated and shared.

Overall, 21 pump technicians completed the pre-survey at baseline and 16 pump technicians completed the post-training survey. Paired-samples t-tests were used to evaluate if a shift in behavioral control, attitudes, norms, intention to change behavior, and behavior change was present from pre- to post-responses including retrospective questions. The analysis of perceived ability to manufacture and repair pumps without lead between the retrospective and current responses on the post-training survey showed the only statistically significant difference in response (t(14) = -2.955, p < 0.05). This increase in perceived ability was also seen when grouping responses as very confident (5 to 7), confident (4), and not confident (1 to 3) where there was a 13% increase in the proportion of technicians who felt very confident in their ability to manufacture a pump without lead from the pre- to post-survey. On pre-survey, or at baseline, 14% of technicians reported they ‘never’ use lead or do not intend to use lead moving forward in the manufacturing or repair of pitcher pumps. When assessed at the first check point (i.e., post-survey) this action/intent was indicated by 60% of technicians. Discussions with the
implementation team provided additional indication that technicians were engaged with and accepting of the proposed engineered solution. However, evaluation methods were updated moving forward as initial analysis indicated traces of disirability bias or confusion of the seven point likert scale.

During the field practice over 500 pumps were remediated by the technicians. Five of the 16 technicians received additional training and support, due to customer feedback on the installation and repair of pumps. Overall technicians understood all required steps and techniques for making or repairing pumps to be lead-free.

Follow-ups meetings were conducted with 11 of the 16 technicians who completed the technical training. These visits showed that technicians felt confident in identifying lead (n = 11) and were comfortable in making lead free pumps (n = 10). Seven of the 11 technicians indicated that they are using all iron/steel since the training in November 2020. However, some technicians used words like “try” which may speak to the use of lead at times. Of the four technicians that indicated still using lead, all mentioned customer request as the reason for selecting lead, but do not use lead all the time. For example, one technician said,

“If it is about the valves, I always use iron, I don’t use lead anymore, only sometimes the clients don’t want to remove the lead in their pump and I am obliged to put it back in, especially on the repair, but if I am installing a new pump then I never use lead anymore.” (Male technician, age 31)

This speaks to a need for a campaign focused on education and behavior change for the Toamasina public (i.e., pump owners and users) to achieve complete phaseout.

No technicians had continued use of their logbooks following the completion of the field work done during the campaign. Multiple reasons were given for why the logbook was no longer used including: the book was lost, it gets too dirty in the field (as the book was white), the book was to big.
Twenty-five pumps were examined, during the follow-ups, of which six had lead. This matched what technicians mentioned about sometimes using lead if the family requested it. However, further evaluation to check if the family had requested lead is need and will be performed during the summer of 2022. Follow-up will include remediation of pumps if family/pump owner agree.

Planning for monitoring and evaluation during the strategy development phase, rather than leaving it as an afterthought, was an important lesson learned. Thinking through the evaluation at the design point allowed us to be more thoughtful and systematic in our approach. The TPB was used as the theoretical underpinning for our evaluation, but it also guided the design of the initiative in addressing knowledge gaps, attitudes and norms, and behavioral control.

Desirability bias, the desire to be seen in accordance with societal expectations (Dietrich et al., 2017), was found to likely be present at times in survey and interview responses. For example, in the pre-survey participants the median response on all likert-scale questions was seven, indicating they found reducing lead to be extremely important and had high intent and ability to not use lead in pumps. However, this was in contradiction with previous responses during the formative research phase. For this reason, the survey was adjusted to be a semi-structured interview for the follow-ups to attempt to overcome bias or confusion in survey questions. Along with the shift to an interview structure technicians were asked to show us recent pumps they installed or repaired for visual confirmation of methods used (i.e., was there lead used or not). The multistage evaluation allowed for continual feedback granting the ability to update evaluation materials and was essential for overcoming bias.
Implementation of this project during the middle of the global covid-19 pandemic presented some logistical issues with the evaluation and follow-ups. Establishing our team early in the process and ensuring that the community, researchers, evaluators, and creative professionals were sitting together at various stages of the project, sharing their respective skills, and working together ensured project success. However, due to travel limitations and other health protocols in place rapid adjustments had to be made in the field and inhibited evaluation activities. This has led to a need for further follow-up and evaluation and highlighted the benefits of having members of the study team present for all phases of a project.

4.4 Conclusions and Recommendations for Practice

Preliminary findings from our study show a shift towards behavior change, the use of non-leaded components in the manufacturing of pitcher pumps, and more importantly, the imbedding of the practices within the mid-stream players (i.e., pump technicians). This change was possible due to the consumer orientation, espoused by social marketing and its focus on audience segmentation, selection of a specific behavior, focus on research, and understanding the concept of exchange to design an integrated marketing strategy. An additional feature of social marketing is the reliance on theory to guide the design of interventions, which was an important step in the design of the PTTF initiative. Using the TPB not only assisted our research team in developing a project that was responsive to the needs of the end-user, but it also allowed us to unpack the mechanism of behavior change and incrementally put in place the building blocks to achieve behavior change. Using this theory coupled with the research, we designed an intervention that spoke to the target audience and also used it to evaluate the work to show a sustainable change.
The social marketing framework guiding this study was developed based on a review of multiple commonly used frameworks (i.e., Social Marketing 10 steps, CBSM, CBPM, SBCC). The review highlighted key steps shared amongst all the frameworks and the overlap that existed. Using these frameworks as the basis for our work, we combined them into a framework (Figure 1) that fit the study context. The framework utilized enhanced project flow, communication amongst diverse audiences, brought together engineers and social marketers, and facilitated a healthy dialogue throughout the study. This framework, our utilization, and lessons learned can be integrated into other WASH projects to achieve behavior change that is sustainable.

This paper addresses weaknesses expressed in the development engineering and social marketing literature. Within engineering, there is an expressed need for new approaches that understand and address the needs of end-user and builds local capacity thereby decreasing program failure (Roldan-Hernandez et al., 2020); Within social marketing, the paucity of practice orientated literature that explicates the application of social marketing and the outcomes associated with the implementation. We implemented extant social marketing frameworks and utilized primary and secondary research early on to inform the planning and development of this intervention; In doing so, we preliminarily demonstrate that implementing these changes early in the process of program design can assist in reducing program failure. This is a recommendation similar to that of Akbar et al., 2021 and Cook et al., 2020 who both identified formative research at the early stages is vital to project success. Additionally, by sharing the process that we used and the lessons learned, we hope to fill a research gap identified in Mlinaric et al., 2017 by adding to the practice-based literature which is often lacking and biased towards positive outcomes. Finally, this paper demonstrates the convergence of engineers and social marketers
working collaboratively on an interdisciplinary team and how this served to enhance project understanding, aid in building local partnerships, and help with long-term sustainability.
Chapter 5: Conclusion

This dissertation aims to demonstrate that lead mitigation efforts focused on the informal sector (i.e. pitcher pump technicians) can bring about improvements in public health and economic wellbeing. To assess the goal of this dissertation three objectives were formulated each with specific research questions to address (Objective 1: Estimate the economic costs associated with the use of leaded pump components; Objective 2: Determine the impact that the pitcher pump remediation (replacing the leaded piston and foot value weights) has on measured blood BLLs of children associated with those pitcher pumps; Objective 3: Determine whether social marketing influenced the intention to change behavior for pump technicians in the use of non-leaded components.) This study uses a case study approach to examine locally manufactured, installed, and repaired pitcher pumps in Toamasina, Madagascar.

A major contribution of this work includes support for utilizing convergent research methods to examine complex problems such as chemical contamination. To the authors knowledge no BLLs had previously been measured in LMICs for relations to aqueous lead exposure. Our analysis of water and blood lead levels shows the significance of aqueous lead exposure in LMICs. Furthermore, to the authors knowledge social marketing has not been used to reduce lead exposure within LMICs. This research shows sustainable uptake of engineered solutions is possible by behavior change of midstream players facilitated by social marketing. The methods used are adaptable and applicable for other geographic areas and toxins.

In addressing the research objectives, questions, and gaps it is found that we can reject null hypothesis for this research. That is to say, lead mitigation efforts focused on the informal
sector (i.e., pump technicians) did bring about improvements in public health, as shown by a decrease in aqueous lead concentrations, decreases in the concentration of lead found in blood of children under six, and protected overall economic wellbeing, as seen by saved IQ points and an estimated return on investment of greater that 1000-to-1.

5.1 Objective 1: Estimate the Economic Costs Associated with the Use of Leaded Pump Components

The presence of leaded components and elevated aqueous lead concentrations in pitcher pumps in Toamasina, Madagascar was known. However, the impact the engineered solution (i.e., removal and subsequent replacement of leaded components in pumps) would have on aqueous lead concentrations, BLLs, and economic cost was unknown. Research questions were developed to gain an understanding of the impact of the engineered solution (i.e., remediation). Remediation efforts took place in the summer and fall of 2018 and the data collected was examined to answer the research questions.

What are the estimated BLLs associated with the water lead levels? Water quality data collected in the field prior to \( n = 244 \) and following the retrofit \( n = 418 \) of the pumps with non-leaded components showed a statistically significant reduction in aqueous lead concentrations (Wilcoxon signed-rank test \( Z = -11, p < .001 \)). The water quality data was then examined to estimate the BLLs expected for children aged 1 to 5 years in the community by way of the Integrated Exposure Uptake Biokinetic (IEUBK) model. Results show that 34% of children using pumps with lead would have BLLs greater than 5 µg/dL. However, following the removal of lead from the pumps only 13% of children would present with BLLs greater than 5 µg/dL.
What is the association between estimated BLLs and economic burden (i.e. lost opportunity cost)? Using the modeled BLL distributions, disability-adjusted life years (DALYs) due to IQ loss were estimated. The remediation of the pumps was estimated to save 0.5 – 1.1 DALYs per 1000 children based solely on the prevention of IQ loss. Furthermore, the reduction in BLLs and saved IQ points were estimated to provide an average economic benefit of US$11,800 per child based on predicted increases in lifetime productivity. Representing a return on investment of greater than 1000-to-1, a return markedly greater than the US$17 – 221 seen for lead hazard control investment in the United States (Gould, 2009; World Health Organization, 2010a). It should be noted that the ROI estimation is likely a conservative estimate as it was found in Chapter 3 that the model under predicted the BLLs.

These findings indicate that remediation efforts improve health outcomes and negate local lost opportunity costs from exposure to chemical pollutants such as lead (Pb). These promising findings laid the basis for continuation of the work and verification of findings with phase two, where an additional 500 pumps were remediated in 2020.

5.2 Objective 2: Determine the Impact that the Pitcher Pump Remediation (Replacing the Leaded Piston and Foot Value Weights) Has on Measured BLLs of Children Associated with Those Pitcher Pumps

In 2020, an additional 500 pumps were remediated to help in verifying the modeled findings. During this remediation, we collected water quality data and BLL readings for children associated with the pumps before and after lead removal. Utilizing the collected data two research questions were examined.

Is there a statistically significant difference in children’s BLLs before and after pump remediation? A measurable decrease in BLLs was seen in 87% (n = 48) of the 55 children who’s
BLL was tested prior to and following the retrofit of their associated pump. Paired-samples t-test (t(54)= 6.15, p < 0.001; 95% CI[2.81,5.52]) indicated a statistically significant difference in the paired BLLs. Statistically significant differences in aqueous lead levels of pumps were also seen in the pumps associated with the children (t(35)= 3.78, p < 0.001; 95% CI[6.75,22.42]). Further analysis controlling for additional variables that could be impacted BLLs should be examined.

*How effective was the IEUBK model at predicting the measured BLLs?* The modeled BLL values highly underpredicted the measured BLLs. The model estimated that 76% of children would have BLLs below 5 µg/dL reference value. Whereas only 23% of the measured BLLs were below the reference value. This underestimation of the model could be due to multiple factors including underestimating or missing important exposure routes of lead (i.e., particulate lead, increased air, soil, or dust exposure, etc.). This is highly probable given the lack of statistically significant correlation between pre-remediation Pb concentration and changes in BLL.

5.3 Objective 3: Determine Whether Social Marketing Influenced the Intention to Change Behavior for Pump Technicians in the Use of Non-leaded Components

Using social marketing, a behavioral focus was selected (use of non-leaded components), priority audience identified (handpump technicians), and formative research was conducted, which led to a communication/skill-based intervention targeting knowledge, attitudes, and practices of technicians, who manufacture and repair pumps. The sought-after behavior change was to replace and no longer use Pb components in the pump by way of an engineered substitute (i.e., non-leaded components). Evaluation of the campaign examined both process and outcome measures to assess the campaigns effectiveness. The following research questions were derived from the RE-AIM framework.
What strategies were used, and how and when were they implemented? The social marketing campaign consisted of three main components (information session, technical training, and field practice) coupled with messaging and materials. The campaign evaluations consisted of surveys, semi-structured interviews, skills checks, and participant observations. A baseline survey to assess attitudes, norms, and intention to change behavior, developed using the theory of planned behavior, was given prior to the information session and then readministered following the technical training. Participant observations and skills checks were conducted during the field practice and again approximately six months later along with semi-structured interviews.

What, if any, impact has the strategies had on increasing the use of lead-free practices? From baseline to the first check point, following the technical training, increases in both intent to ‘never’ use lead and ability to make the switch to lead-free components was seen. Follow-up meetings approximately six months following the completion of field practice indicated that technicians feel comfortable in identifying lead, confident in using lead-free components, and capable of sharing information on the harmful effects of lead. These responses indicate a behavior shift leading to increased use of lead-free practices.

To what extent do technicians execute lead free practices? Interviews with technicians, skill checks, and observing technicians while working showed that most of the technicians utilized lead free practices in their manufacturing and repair of pumps. It was found that lead is still used when requested by customers to not lose business. This shows that future research efforts should focus on increasing awareness among the Toamasina residents and pump owners.
5.4 Discussion

This dissertation lays out a framework that can be utilized in other geographic locations and examination of a variety of informal sector economies, exposure routes (i.e., piping, food, air, etc.), contaminants (i.e., chemical, biological, or microbial), and WASH projects to increase sustainable decision change and encourage project success. For those interested in following similar frameworks it is recommended adequate time is spent building local partnerships and learning about the local culture and project context. The knowledge gained from our partnerships was vital to the progression and success of the project. It is the authors belief that local partnerships are key in enhancing project success as it provides direction for the study or project and forces one to start with the people and not the solution (i.e., aids in reducing cookie cutter approaches seen when starting with the solution and reduces parchute engineering as discussed in Roldan-Hernandez et al., 2020).

5.5 Recommendations for Future Research

Recommendations for future research include field methodology for examination of particulate lead, examination of IEUBK model for use in LMICs, and further examination of sustainable decision change. Each of these are discussed in more detail below.

5.5.1 Field Methodology for Examination of Particulate Lead

This work utilized the Palintest Scanning Analyzer SA1100, a common field instrument used for testing dissolved aqueous lead. However, recent findings suggest that there is likely notable levels of particulate lead present (Shah, 2021; Wilson, 2021). These findings on the importance of particulate lead are echoed in studies in HICs where particulate lead has been found to be the dominate form of lead in drinking water (Triantafyllidou, 2011). To fully examine the impact of aqueous lead exposure in Toamasina particulate lead concentrations
should be measured in water samples obtained from pumps with leaded components. However, it is also noted that particulate lead is difficult to predict due to the erratic nature, so best practices for field collection should be examined prior to field testing (Deshommes et al., 2010; Schock, 1990).

5.5.2 Examination of IEUBK Model for Use in LMICs

This work utilized the IEUBK model to estimate BLLs in LMICs. Though this method is a valuable tool for estimating the likelihood of elevated BLLs the modeled estimates did not match the measured values seen in the community. This discrepancy could be due to differences in health status between HICs and LMICs or under accounting for background exposure levels or other exposure routes. Three recommendations for future research to enhance the capacity for IEUBK to predict BLLs in LMICs are discussed below.

First, there are background inputs in the IEUBK model that are not representative of health situations in LMICs. For example, the model assumes the body weight of a 12-month-old to be 12.3 kg. However, stunting, wasting, and underweight prevalence in children remain common place in LMICs and need to be accounted for. Examination of the impact that the weight assumption has on model outputs would be beneficial.

Second, the IEUBK model is based on U.S. national averages (SRC, 2021) with the ability to enter collected field data for lead concentrations from air, soil, dust, diet, and water. This dissertation discusses methods for updating diet and water for representing local exposure within LMICs. However, as mentioned in most cases exposure data, equipment, and funds are limited making it difficult to get field readings for all exposure sources in LMICs. To assist in making the model more applicable for usage in LMICs creation of default reference tables should be considered. For example, examining the various exposure values from soil in the
United States, a default exposure table based on years since leaded gasoline phase out (an event known to impact exposure from soil) could be developed to aid model usage in LMICs.

Third, findings presented in Champion et al., (2022) indicate other exposure routes present in the community that where likely not fully accounted for in the model. It is recommended to examine other exposure sources, starting with those identified in Champion et al., (2022), to gain a more holistic view of the exposure experienced in Toamasina. Using collected data, the IEUBK model should be examined for potential updates required for use in LMICs.

5.5.3 Further Examination of Sustainable Decision Change

This dissertation presented an examination of technicians’ decision change to using lead free components for the piston and foot valves. Current evaluation indicates a positive shift in behavior in the technicians. However, it is recommended that further follow-up with technicians be done. This is recommended as studies have indicated repeated doses of messaging are required for increased maintained decision changed (Shi, J. & Smith, S.W., 2015). Furthermore, based on review of the follow-up interviews it was indicated that some materials could be updated to be more useful for technicians and aid in sharing the messaging. It is recommended that follow-ups provide technicians with updated materials (i.e., a laminated informational handout) and are carried out approximately six months to a year down the line. This will also allow for further examination on whether long-term sustainable decision change occurred.

This study did not address the prevalence of lead in the well screen/solder. Similar methods could be utilized to focus a training specifically on the use of non-leaded well screens in the area. It is recommended that researchers work with the technicians to identify a culturally
appropriate and structurally stable alternative for the well screen and solder before development of the campaign and/or training.

Furthermore, the findings indicated that a subset of pump owners are requesting lead be used in their pumps speaking to a need for community level awareness of lead and its health consequences. Findings also indicated that there are likely other important sources of lead exposure in the community. These findings enhance the need for community education to achieve greater health protection. The use of convergent methods, as used in this dissertation, are recommended for identifying lead sources and developing an intervention to create decision change, mitigate lead exposure sources, and cease lead usage within products. One audience that could be utilized for the next phase of the project is first time parents using the clinics. This audience is recommended as they go to the clinics multiple times for child checkups and vaccines allowing for frequent messaging and the team has an established history of working with the local clinics.
References


American Society of Civil Engineers. (2007). The vision for civil engineering in 2025. American Society of Civil Engineers.


World Health Organization. (2010b). *Preventing disease through healthy environments: Action is needed on chemicals of major public health concern.*


Appendix A: Copyright Permissions

A.1 Copyright Permissions for Material in Chapter 2
Appendix B: Supplemental Information for Chapter 2

B.1 Study Location

As indicated within the main text, this study took place in Toamasina, Madagascar. Toamasina is located on the east coast of Madagascar. Toamasina consists of five arrondissements or districts (Ankirihiry, Tanamvao V, Ambodimanga, Anjoma, and Morarano). Figure B.1 outlines the five districts within Toamasina in green. The work discussed within this paper was based in Ankirihiry located in the north to southwest region of Toamasina. The retrofitting of the handpumps occurred within the neighborhoods of Andranomadio, Mangarivotra, Ankirihiry, and Mangarano within the Ankirihiry district. The specific parcels within these neighborhoods where the retrofitting took place are indicated in Figure B.1 by the blue outline.

Figure B.1 Map of Toamasina with arrondissements or districts indicated in green and study area where handpumps were retrofitted indicated in blue.
B.2 Remediation Process

As indicated within the manuscript, pitcher pumps are locally manufactured and installed in Toamasina. Historically, recycled lead has been used for the weights within the piston and foot valve. Leaded solder is commonly found within the well screen as nonleaded solder is not available in Toamasina. Figure 1.1 provides an illustration of where these leaded components can be found within a conventional pitcher pump in Toamasina. During remediation, the pump head is detached, the piston and foot valves are removed and replaced, and the pump head and valves are reattached. During this process the piping below the pump is not disturbed.

B.3 Paired Pre- and Post-Remediation Data

This section examines the presented data in a paired pre- and post-retrofit context. In total, 244 pre-retrofit aqueous Pb concentrations were obtained, of which 225 had an associated paired post-retrofit aqueous Pb concentration. Of the 225 pumps with both pre- and post-intervention concentration measurements, two (0.9%) indicated levels above the upper detection limit (> 100 µg/L) in the initial pre-retrofit conditions. For one of those two pumps, the measured Pb concentration dropped to below the lower detection limit (< 2 µg/L) following the retrofit while the second stayed above the upper detection limit. Of all 225 pumps, only seven (3.1%) saw an increase in lead concentration from pre- to post-retrofit. Twenty-four pumps (10.6%) saw no measurable change in lead concentration; however, 19 of the 24 measured below the lower detection limit both pre- and post-retrofit. The remaining 194 pumps (86.3%) exhibited a measurable decrease in Pb concentration following the pump remediation.

A check for normality of the pre- and post-intervention data indicated that the measured Pb concentrations were not normally distributed. For this reason, a Wilcoxon Signed-Rank Test was performed. This analysis was conducted in three different ways to account for samples that
measured below the detection limit (DL) (2 µg/L) of the Palintest scanning analyzer. In Model 1, the concentrations of samples under the detection level of 2 µg/L were assumed to be equal to 0 µg/L; in Model 2, concentrations of these samples were assumed to be 1 µg/L (0.5*DL); in Model 3, concentrations of these samples were assumed to be 2 µg/L, equal to the DL. All three models indicated a statistically significant change in aqueous Pb concentrations between pre-retrofit and post-retrofit conditions (Model 1: Z = -11.679, p < 0.001. Model 2: Z = -11.648, p < 0.001. Model 3: Z = -11.091, p < 0.001.)
Appendix C: Supplemental Information for Chapter 3

C.1 Remediation Process

Historically, pitcher pumps (locally known as pompe tany) have been manufactured with leaded components including the piston valve, foot valve, and well screen or soldering. Figure 1.1 presents a schematic of the pitcher pump and where the leaded components are found. The leaded valves are commonly made from recycled lead which is melted down and formed into the desired shape using the sand as a mold. The lead found in the well screen is commonly from the soldering. To our knowledge there is no lead-free soldering available within Toamasina. Therefore, the remediation efforts focused on only the piston and foot valves. The remediation consisted of detaching the pump head, removing and replacing the leaded piston and foot valves with iron components, and reattaching the pump head. The piping below the pump was not disturbed during this process.

C.2 Model Inputs

The Integrated Exposure Uptake Biokinetic (IEUBK) Model requires input data for air, water, diet, soil, and dust to predict a geometric mean blood lead level (BLL) for specific age range of child with the given exposure. Default values were used for air, soil, and dust exposure. Measured aqueous Pb concentrations associated with each child were used as the water exposure input. Dietary uptake values were adjusted to account for a Malagasy diet using the methodology of Akers et al., 2020. A summary of model inputs for the 46 children examined can be seen in Table C.1.
### Table C.1 Modeling blood lead levels in children; Integrated Exposure Uptake Biokinetic (IEUBK) Model inputs

<table>
<thead>
<tr>
<th>ID</th>
<th>Age (years)</th>
<th>Pre-Remediation</th>
<th></th>
<th></th>
<th>Post-Remediation</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flushed Aqueous Pb Concentration (µg/L)</td>
<td>Pb Dietary Uptake (µg/day)</td>
<td>Flushed Aqueous Pb Concentration (µg/L)</td>
<td>Pb Dietary Uptake (µg/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.1</td>
<td>65</td>
<td>46.87</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>65</td>
<td>46.87</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1.44</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.3</td>
<td>1</td>
<td>0.72</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1</td>
<td>0.86</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.6</td>
<td>2</td>
<td>1.44</td>
<td>2</td>
<td>1.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3.5</td>
<td>4</td>
<td>3.16</td>
<td>1</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1.58</td>
<td>1</td>
<td>1.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.6</td>
<td>4</td>
<td>2.88</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.6</td>
<td>4</td>
<td>3.16</td>
<td>1</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.9</td>
<td>6</td>
<td>3.52</td>
<td>1</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4.9</td>
<td>27</td>
<td>23.13</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>10</td>
<td>8.57</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>5</td>
<td>2</td>
<td>1.71</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>1</td>
<td>0.72</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.6</td>
<td>10</td>
<td>5.86</td>
<td>1</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.6</td>
<td>2</td>
<td>1.17</td>
<td>2</td>
<td>1.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1.2</td>
<td>6</td>
<td>3.52</td>
<td>3</td>
<td>1.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>16</td>
<td>13.71</td>
<td>3</td>
<td>2.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>10</td>
<td>7.91</td>
<td>1</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>14</td>
<td>8.21</td>
<td>1</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>5</td>
<td>14</td>
<td>12.00</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>5</td>
<td>6</td>
<td>5.14</td>
<td>3</td>
<td>2.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1.2</td>
<td>10</td>
<td>5.86</td>
<td>4</td>
<td>2.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>6</td>
<td>5.14</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>2.6</td>
<td>4</td>
<td>2.88</td>
<td>1</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>4</td>
<td>4</td>
<td>3.43</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>3</td>
<td>7</td>
<td>5.54</td>
<td>1</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>2</td>
<td>11</td>
<td>7.93</td>
<td>2</td>
<td>1.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>7</td>
<td>5.54</td>
<td>1</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>4</td>
<td>7</td>
<td>6.00</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>3.5</td>
<td>100</td>
<td>79.11</td>
<td>7</td>
<td>5.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>2.6</td>
<td>100</td>
<td>72.11</td>
<td>3</td>
<td>2.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>3.5</td>
<td>1</td>
<td>0.79</td>
<td>2</td>
<td>1.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>4</td>
<td>13</td>
<td>11.14</td>
<td>6</td>
<td>5.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>4</td>
<td>4</td>
<td>3.43</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>5</td>
<td>2.93</td>
<td>1</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>3</td>
<td>3</td>
<td>2.37</td>
<td>2</td>
<td>1.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>1.4</td>
<td>14</td>
<td>8.21</td>
<td>12</td>
<td>7.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>1</td>
<td>0.86</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>1.5</td>
<td>6</td>
<td>3.52</td>
<td>1</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>4</td>
<td>8</td>
<td>6.85</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>5</td>
<td>1</td>
<td>0.86</td>
<td>1</td>
<td>0.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>2</td>
<td>5</td>
<td>3.61</td>
<td>2</td>
<td>1.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>4</td>
<td>2</td>
<td>1.71</td>
<td>2</td>
<td>1.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>3</td>
<td>21</td>
<td>16.61</td>
<td>2</td>
<td>1.58</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D: Supplemental Information for Chapter 4

D.1 Quantitative Survey/Questionnaire

Hello,

I am Rinah and I am working with the University of South Florida. We are gathering information to help understand the culture around pitcher pumps and repairs. To do so, we are trying to find and conduct quantitative interviews with pitcher pump technicians in the region.

I realize your time is very valuable and want to thank you for meeting with me to share your ideas. They will be used to design a creative campaign to help the region with adopting lead-free replacements for pitcher pumps.

I have prepared some questions. There are no right or wrong answers. I want both positive and negative comments.

This interview should take approximately 10-20 minutes. Your participation is voluntary. If you do not wish to participate, you may stop or skip any questions at any time. We will not use your name in our report but are gathering contact information for phase two of the project.

Interview ID

Demographic Survey

1. Name: ____________________________

2. Lot: ______________________________
   Parcelle: ___________________________
   Fokotany: __________________________
   Near-by Landmarks: ________________

3. GPS: ______________________________

4. Contact Number: ___________________

5. What is your primary language?
   a. English
   b. French
   c. Malagasy

6. Do you have knowledge of any of the other languages? If so which ones? ______________

7. Gender:
   a. Male
   b. Female
   c. Other (please specify) ______________
   d. Prefer not to say

8. Age: _____________________________

9. Marital Status:
   a. Single, never married
   b. Married or domestic partnership
   c. Widowed
   d. Divorced
   e. Separated
10. Family size:
   a. 1-2
   b. 3-4
   c. 5-6
   d. 7+

11. How many family members are 0-6 years old? __________

12. Religion:
   a. Catholic
   b. Protestant
   c. Jewish
   d. Muslim
   e. Hindu
   f. Other

13. Monthly Income
   a. Under 50,000Ar
   b. 50,000-100,000Ar
   c. 100,000-150,000Ar
   d. 150,000-200,000Ar
   e. 200,000 or more Ar

14. What is your profession? _________________

15. Have you had contact with this project? ____________ Yes ____________ No
   a. What type of contact? ________________
      i. Participated in a training
      ii. Completed surveyed
      iii. Heard the message by word of mouth
      iv. Other _______________________
      v. No response

16. How long have you been a technician? _______________________

17. Who taught you how to make/repair pumps?
   a. Apprenticeship (Please specify)
   b. Transferred skills from another profession to make pumps
   c. Formal technical training
   d. Other (please specify)

18. Are there any other technicians in your family? Yes________ No_________
    a. If yes who? (relationship) _______________________

19. In the last two weeks what neighborhoods have you worked in? (List of neighborhoods)

20. Do you work primarily with landlords or private pump owners? (Scale 1-5)

21. How many repairs do you do on average in a two-week period? _____________________
22. What type of repairs?
   a. Piston valve (#___________)
   b. Foot valve (#___________)
   c. Both piston and foot valve (#___________)
   d. Well screen (#___________)

23. How frequently does a foot valve wear out?
24. How frequently does a piston valve wear out?

25. How many new pumps do you install on average in a one-month period? ________________

26. What do you use as weights for the foot and piston in the pumps you work on?
   a. Lead
   b. Iron
   c. Steel
   d. Other (Please specify)

27. Where do you get your materials to make a new pump? __________________________

28. Where do you get your materials to repair a pump? ___________________________

29. What is the general cost of each type of repair (in Ar):
   a. Piston valve ________
   b. Foot valve ________
   c. Both piston and foot valves ________
   d. Well screen ________
   e. New well and pump head ________

30. Would you be willing to participate in an hour-long interview at a later date? Yes___ No___

31. Do you know of any other technicians? If so, could you provide their name, contact information, or location with us?

32. Is there any further comments or information you wish to provide?
D.2 Qualitative Interview Guide

Participant ID:
Date:
Interviewer’s name:

Madagascar Pb
Individual Interview Guide

Introduction to the project
Hi, I am [YOUR NAME AND INTRODUCE YOURSELF/NOTE TAKER]. I am with Ran and we are working in collaboration of a university conducting this research. They are most interested in the improvement of the quality of water and improvement of public health. The work is being focused on the pitcher pumps which is why we are wanting to talk to you today.

Thank you for agreeing to talk to me today. We are meeting with a few different pump technicians to gain a better understanding of who you are, how you manufacture your pumps, and your concerns regarding water quality, and public health.

I realize your time is very valuable and want to thank you for meeting with me once again to share your ideas. We will use your opinions to design a program to help improve the installation and maintenance of your pitcher pumps. We currently don’t have any plans to distribute tools or materials.

I have prepared some questions to get our conversation started. Please remember that there are no right or wrong answers, and you should feel free to talk about whatever you think is important. This interview should take approximately 1 hour. Your participation is voluntary. If you do not wish to participate, you may stop at any time. We will not use your name in our reports so please feel free to tell us whatever you think would be helpful. I am going to audio record our conversation so that I don’t miss any of your ideas. If you want me to turn it off at any time, just let me know.

Do you have any questions or concerns before we get started?

Do I have your permission to record this conversation?

- NO ➔ Would you still like to continue with the interview without the recording?
  - NO ➔ STOP (thank them for their time)
  - YES ➔ Go to question 1 and conduct the interview taking detailed notes
- YES ➔ Go to question 1

To begin, I would like to get to know you a little better.
1. Could you share with me a little bit about yourself?

   Probe: What do you do when you are not working?

2. What do you like most about your living in Toamasina?

   Probe: To better understand if they are here due to family, work, the city, etc.

Thinking about your profession as a technician repairing/installing pitcher pumps...

3. What helped you to choose to be a technician?

   Specify what we mean by technician: repairing/installing pitcher pumps

4. What do you like about working as a technician?

   Probe: What is something that you do not like about being a technician?

5. Thinking about your work as a technician, what do you think is your contribution to the community?

   Probe: What do you think is the value of repairing/installing pumps in the community?

In our first visit with you, you mentioned that you learned about being a technician from [PULL FROM QUANTITATIVE SURVEY].

6. Can you tell us more about how you first learned to make/repair pitcher pumps?

   Probes: approximate training date, type/approach, provider (person/institute/vocational school, etc.)

Now I would like to shift our discussion on your daily work routine and the process that you take to install or repair a pitcher pump.

7. Say a landlord calls you to install a new pump. What are some of the key steps that you take in installing the pitcher pump?

   Probe: suggest they could draw the pitcher pump if that helps them explain the process
   Probe: What do you need to be in place prior to installing pump?
   Probe: Is there someone else who assists you? – If yes: Who is this person that assists you? How do they assist you (get materials, etc.)?
   Probe: What equipment do you use?
8. Which material(s) do you use to repair/make the pumps?

Probe: piston, foot, well screen, solder, pump head, well shaft, etc.

If they use one material, ask question 10. If they use more than one material, ask question 10 using one material (i.e. lead) then repeat question 10 with next material (i.e. iron) and so on.

9. How does [MATERIAL THEY USE FOR PISTON AND FOOT VALVE (use one material at a time)] compare to the other materials?

   Probe: What do you like about this material?
   Probe: Which qualities in this material do you value? (e.g. it last long, it is not expensive)
   Probe: How does [MATERIAL THEY USE] influence your work with the pitcher pump?
   Probe: Does it help with better long-term results? (e.g. more durable) Please explain why.
   Probe: Does it make repairing/installing easier? How?

Repeat 10 if they used multiple materials.
If single material is used or all materials have been asked about, continue to question 11.

10. Over the course of your career as a technician, have you changed your technique for repairing/making pitcher pumps?

   Probe: If no, what influenced them to make that choice?
   Probe: If yes, how?
   Probe: Where/How did you learn the new technique? (i.e. on the job, technical training, etc.)
   Probe: What influenced you to change to the new technique?

11. What do you find most difficult about repairing/installing pumps?

   Probe: Is there something that would make it easier for you to repair/install pumps?

Now, let’s talk specifically about the clients for which you repair or install pitcher pumps.

12. What are some common questions or concerns that you hear from your customers?

13. What do you think of the health safety of the water from Pompe Tany in Toamasina?

   Probe: (if they express concern) what concerns do you have?
   Probe: If they are talking about physical attributes, what does that indicate to them? (i.e. weird taste could indicate chemicals or pathogens in the water...)
   Probe: (if they express concern) Do you think that others in the community share these concerns?
Probes: What are some steps you take if you think there are safety concerns with the water?

15. In your view, what makes water of “high quality”?
   Probe: safety, how it looks, tastes, feels

16. Where have you learned about water safety and water quality?

17. Do technicians in your area generally provide any water safety or quality information to clients?
   Probe: If so, which type of information?
   Probe: If not, do you think they should?
   Probe: what type of information should they provide?

18. Do technicians in your area generally give recommendations to clients to treat the water? Please explain.

Thinking about what you’ve heard on the metal lead (Pb)...

19. When I say the word lead, what comes to mind?

20. Can you share what you have heard or know about lead?

Information for the interview to share: Lead is a naturally occurring heavy metal and has been used widely. You can find lead in common household items such as car batteries, paint, pipes, and even makeup. Because lead is harmful to a person’s health, it is no longer used in household items that are in close contact with adults and children (for example: the shift to unleaded gasoline). The health effects of lead generally occur after long-term exposure and are particularly more harmful to children under the age of six. Some of the components in pitcher pumps (well screen, piston, foot valve) can contain lead.

Note for Interviewers:
Lead (Pb) can be found in the piston and foot valves as well as the well screen. The check valves are often solid lead, while the well screen has Pb incorporated into the components. For example: the solder is typically composed of lead-tin and brass (what makes the screen itself) can also have small amounts of lead incorporated into it to enhance properties such as helping lower the melting temp to make more workable.
Thinking of the services you offer to your clients...

(IF THEY SAID THEY DON'T USE LEAD in question 9, ask question 22(a) and then go to 25]

21. (a) How does knowing this information affect your work and role as a pump manufacturer?

(IF THEY SAID THEY USE LEAD in question 9, question 22(b) onwards]

21. (b) Does knowing this information motivate you to make any changes to the materials you use for pitcher pumps, meaning switching to lead free components? Please explain.

If knowing this information motivates to change to non-leded components:

22. How would you go about replacing the leaded parts?

Probe: Foot valve or piston valve

23. What are some barriers for you to switch to non-leaded components?

Probe: Foot valve or piston valve

24. What benefits, if any, do you see in making lead-free pitcher pumps?

25. Which of these benefits that you mention would motivate another technician the most to stop using lead?

26. Are there specific words, images or concepts that you must show or explain that would motivate technicians to remove lead?

27. Are there specific activities or events that we could do to help encourage you or your colleagues to stop using lead?

Probe: Should each pump that is installed have a certificate of quality or certificate from the government certifying that components are lead free?
   a.

28. What are some reasons for why technicians would not switch to lead free components?

Probe: Of the challenges that you have shared, which one plays the biggest role in not switching?

---

1 This means a pump that has no lead in the foot valve and/or piston
Probe: How difficult is it be to switch to a lead-free foot valve?

Probe: How difficult is it be to switch to a lead-free piston?

Now, let’s talk about where you get information.

30. Which channels/information sources do you look to for information on pitcher pumps?

31. Who do you trust the most to provide you with information on pitcher pumps? Why?

Probe: talking about information on new techniques, how to make or repair the pumps

Probe: would you be interested in receiving one-on-one training from another technician on repairing pumps?

32. Where do you look to learn more about water safety? (water suppliers, organizations, TV, newspaper, radio, Facebook, WhatsApp, flyers at clinics, etc.)

33. Who do you trust the most to provide you with information about water safety in Toamasina? Why?

Probe: would you trust another technician to provide you with information about water safety?

Probe: would you trust a trained technician from the Ministry of Water to provide you with information on water safety?

34. Are there any sources of information you don’t trust? Why?

35. Are there any issues related to pitcher pumps you would like to receive more information on?

Probe: From which channels/sources?

36. Would you find it helpful to receive information on water safety from a local association of technicians, if one were to exist?

This concludes our interview. Before we conclude, is there anything that you would like to add? Anything that I haven’t asked you about that you would like to share?

Do you have any questions for me?

Thank you again for your time and for sharing your experience with me.
## D.3 Creative Brief

### Creative Brief for the project: Increasing demand for lead-free valves in pitcher pumps through the use of social marketing

1. **Target Audience(s)**  
   *Describe the person that you want to reach with your communication. Include a primary & secondary (influencers) audience as well as any relevant audience research.*

   **PRIMARY:** Technicians of pitcher pumps in Toamasina, Madagascar  
   **SECONDARY:**  
   - Technicians held in high regard who train other technicians  
   - Head technician in a workshop/Pump workshop owner  
   - Welders who supply, train or work in collaboration with technicians  
   - Health officials / ambassadors  
   **POSSIBLE TERTIARY:**  
   - Manufacturers of pump components  
   - Landlords/clients/general population

2. **Objective(s)**  
   *What do you want your target audiences to know, feel, or do after experiencing the communication?*

   **KNOWLEDGE** (Think)  
   *As a result of the communication, technicians will know:*
   - The health consequences of lead (Pb)  
   - That lead is harmful to women, children, and families  
   - That water quality/safety is compromised by lead, among other factors  
   - That they have the ability to create non-lead pumps that are durable and long-lasting  
   - Using unleaded components is the only way to prevent lead contamination. They do not believe that lead can be removed with treatment like boiling or chlorination (surer)  

   **BELIEF** (Feel)  
   *As a result of the communication, technicians will believe:*
   - They are problem-solvers/innovators/forward thinkers in the community who are in a position to provide a vital service and introduce positive change  
   - They are developing a lead-free product that they feel proud of and confident in attaching their name to it  
   - That changing their technique will result in more business and work considered professional  

   **BEHAVIORAL** (Do)  
   *They will:*
   - Use non-lead components for the construction and repair of pitcher pumps

3. **Obstacles**  
   *What beliefs, cultural practices, pressure, misinformation, etc. stand between your audience and the desired behavior?*
   - No knowledge or lack of knowledge of lead and its impact on health. (Explain using Malagasy and local terminology)  
   - Lack of knowledge of which materials they could use as a substitute to lead  
   - Lack of knowledge of the safety of other materials  
   - The weight of lead weighs makes for a better seal compared to lighter metals  
   - Lead is easy to work with, easy to melt and mold  
   - Habit - that’s what they have learned from the people who trained them. It’s ingrained in their way of working [Quote: “The Malagasy way is to use lead”]  
   - Materials are not readily available so they use what they can find  
   - Cost of the materials plays a role  
   - Belief that someone else is profiting from saved lead (Not from current research but shared from anecdotal evidence)  
   - Pump owner do not approve of lead-free pump
4. **Key Promise**

Select one single benefit that will outweigh the obstacles in the mind of your target audience. Suggest format: if (desired behavior), then (immediate benefit).

I want to be innovative and respected in my community, as a result, I will create and maintain a lead-free pitcher pump.

5. **Support Statements**

*This is the substantiation for the key promise, i.e., the reasons why the promise is true. Oftentimes, this will begin with a “because.”*

- Changing to lead-free components will still allow them to provide for themselves and their families and could potentially be good for their business.
- Changing to lead-free components will improve the safety of their products for clients and their client’s children.
- Switching to lead-free components is possible
  - Show easy and inexpensive strategies
  - Leverage the fact that in most cases they are already doing it when lead is not available
- Switching to other metals may not require them to buy additional instruments or work tools
- Other technicians in the community are already going lead-free and they have a successful business.
- Positives of the job mentioned by participants include satisfaction for the client (1), standing in the community/contributing to the community (5), financial support for one’s family (3), enjoyment or pride in the job (job is interesting (4). [Quotes: “Giving life to people through the water” (participant 13); “Water is life” (participant 17).]

6. **Tone**

*What feeling should the communication have? Should it be authoritative, humorous, emotional, etc.?*

- Informational / matter of fact
- Authoritative
- Casual language / humorous

7. **Communication Channels**


Preferred channels of communication include:

- Word of mouth, other technicians they trust
  - They don’t trust all technicians though, need to identify respected ones and underline that are not “followers” but rather they can get inspiration and adapt/test the technique and figure it out on their own
  - A few specific people are mentioned by name in the interviews (potential spokespersons)
  - Well known technicians or one’s others go to for advice (e.g., ambassadors)
- Rumors/mentioned by some participants as a trusted source of information on water quality
- Text messages
- Radio/TV only mentioned by few participants, some trust them some say they do not
- Although not mentioned in the interviews, when asked about some potential interventions (we provided them with 3 options), many participants mentioned wanting to hear from the Ministry:
  - Establishment of a pitcher pump technician association 7/18
  - Training and one-on-one support by well-established and respected technicians 9/18
  - Training by the MinWASH for technicians on pitcher pump techniques and water quality 13/18
8. **Openings**

*What opportunities (times and places) exist for reaching the audience? When is the audience most open to getting your message? Examples: World AIDS Day, Mother’s Day, etc....*

- Fairs (world water day, toilet day, women’s day, etc.)
- Hardware shops (metal specifically)
- Junk yard
- Ramotsuka kiosk
- Health centers

9. **Creative Considerations**

*Any other critical information for creative partners? Will communication be in more than one language? Should it be tailored to a low-literate audience? Are there any political considerations? Any words or visuals to stay away from? Should time or space be available on materials for local contact information?*

- Preference for guerrilla marketing rather than conventional
- Nuance around tying lead work to Ramotsuka
- Tailored to DIY technicians
- Empower DIY Maker spirit while stressing professionalism
- Leadless pumps do not necessarily = potable water pumps
- Refocus attention on quantity water over quality and hygiene/sanitation over drinking water
- Empowering entrepreneurial spirit by developing leadless pump business model
D.4 Example of Campaign Branding and Materials

Figure D.1 Campaign branding: paompy tany tsisy firaka (PTTF) or pitcher pump without lead.

Figure D.2 Example of signs used during information and training sessions.

Figure D.3 Project branded handwashing station.
Figure D.4 Branded campaign materials (pamphlet and notebook).
D.5 RE-AIM Dimensions Utilized for Evaluation

<table>
<thead>
<tr>
<th>RE-AIM Dimensions</th>
<th>Definition/Description (re-aim.org)</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach</td>
<td>The absolute number, proportion, and representativeness of individuals who are willing to participate in a given initiative, intervention, or program, and reasons why or why not.</td>
<td>• Who was the target audience? Who/how many individuals actually participated in each phase? Is the audience sample representative? • What were the steps of the campaign? What approvals were needed for each? • Who other than the target audience were reached (i.e., those participating in the remediation)?</td>
</tr>
<tr>
<td>Effectiveness</td>
<td>The impact of an intervention on important individual outcomes, including potential negative effects, and broader impact including quality of life and economic outcomes; and variability across subgroups (generalizability or heterogeneity of effects)</td>
<td>• Is there a statistically significant change in technician’s intent to use lead-free components? • Is there a statistically significant change in technician’s knowledge on how to make/use lead-free components? • Is there a statistically significant change in technician’s behavior (i.e., do they use lead-free components)? • Is there a statistically significant change in technician’s beliefs about Pb and Pd-free components?</td>
</tr>
<tr>
<td>Adoption</td>
<td>The absolute number, proportion, and representativeness of settings and intervention agents (people who deliver the program) who are willing to initiate a program, and why.</td>
<td>For this project adoption will be examined regarding technician’s adoption/continued use of provided materials (i.e., field logbook, customer logbook, promotional items). • Are technicians logging customers and work done? • Do technicians provide customers with logbook? • Are technicians displaying certificate or wearing project apparel?</td>
</tr>
<tr>
<td>Implementation</td>
<td>The intervention agents’ fidelity to the various elements of an intervention’s key functions or components, including consistency of delivery as intended and the time and cost of the intervention. Importantly, it also includes adaptations made to interventions and implementation strategies.</td>
<td>• What was the time frame of the campaign? • What adaptations were made to the campaign during implementation? Were they documented? • What obstacles arose during implementation? • What were the cost (money, time, burden, etc.) of implementation?</td>
</tr>
<tr>
<td>Maintenance</td>
<td>At the setting level, the extent to which a program or policy becomes institutionalized or part of the routine organizational practices and policies. At the individual level, the long-term effects of a program on outcomes after a program is completed.</td>
<td>• Assessment of outcomes 6 months after implementation (refer to effectiveness questions). • Are follow-up activities needed? • If the program was to be redone or integrated into the ministry or other institution, what modification would be needed?</td>
</tr>
</tbody>
</table>
D.6 Pre-Survey for Evaluation

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reducing lead in water for me is:</td>
<td>extremely unimportant 1 2 3 4 5 6 7 extremely important</td>
</tr>
<tr>
<td>2. Most technicians I know believe it is beneficial to switch to lead free components:</td>
<td>definitely false 1 2 3 4 5 6 7 definitely true</td>
</tr>
<tr>
<td>3. Switching to lead free components when I repair or install a new pump is:</td>
<td>extremely difficult 1 2 3 4 5 6 7 extremely easy</td>
</tr>
<tr>
<td>4. I intend to switch to lead free components:</td>
<td>strongly disagree 1 2 3 4 5 6 7 strongly agree</td>
</tr>
<tr>
<td>5. I use lead when I manufacture/repair water pumps:</td>
<td>always sometimes rarely never</td>
</tr>
<tr>
<td>6. I feel confident in my ability to identify lead within an existing pump:</td>
<td>definitely false 1 2 3 4 5 6 7 definitely true</td>
</tr>
<tr>
<td>7. I feel confident in my ability to manufacture/repair a pump without the use of lead:</td>
<td>definitely false 1 2 3 4 5 6 7 definitely true</td>
</tr>
</tbody>
</table>
D.7 Post-Survey for Evaluation

<table>
<thead>
<tr>
<th>Name</th>
<th>Address (Lot, Parcel, Fokontany)</th>
<th>Contact Number</th>
</tr>
</thead>
</table>

Thank you for taking the time to participate. Please answer the following questions truthfully and to the best of your ability.

1. Before the training, reducing lead in water for me was:  
   extremely unimportant 1 2 3 4 5 6 7 extremely important  
   Now, reducing lead in water for me is:  
   extremely unimportant 1 2 3 4 5 6 7 extremely important

2. Most technicians I know have stopped using lead in pump repair and manufacturing:  
   definitely false 1 2 3 4 5 6 7 definitely true

3. Most technicians I know believe it is beneficial to switch to lead free components:  
   definitely false 1 2 3 4 5 6 7 definitely true

4. Before the training, switching to lead free components when I repair or install a new pump was:  
   extremely difficult 1 2 3 4 5 6 7 extremely easy  
   Now, switching to lead free components when I repair or install a new pump is:  
   extremely difficult 1 2 3 4 5 6 7 extremely easy

5. Before the training, I intended to switch to lead free components:  
   strongly disagree 1 2 3 4 5 6 7 strongly agree  
   Now, I intend to switch to lead free components:  
   strongly disagree 1 2 3 4 5 6 7 strongly agree

6. Before the training, I used lead when I manufactured/repaird water pumps:  
   always sometimes rarely never  
   Now, I use lead when I manufacture/repair water pumps:  
   always sometimes rarely never

7. Before the training, I felt confident in my ability to identify lead within an existing pump:  
   definitely false 1 2 3 4 5 6 7 definitely true  
   Now, I feel confident in my ability to identify lead within an existing pump:  
   definitely false 1 2 3 4 5 6 7 definitely true

8. Before the training, I felt confident in my ability to manufacture/repair a pump without the use of lead:
### Observational checklist for making lead-free pumps

<table>
<thead>
<tr>
<th>Task</th>
<th>Check</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before proceeding with pump remediation:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked that the pump head retained water (proper seal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Check the flow rate (adequate quantity and good flow rate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked if the leather valve of the pump required frequent change (Pump head in bad/old condition uses up leather quickly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Repairing the upper valve:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked for lead (Pb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removed old leather and weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used a weight that was proportional to the size of the piston</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used weights to mark correct spots to cut on the leather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cut the leather in a half-moon at an inclined style</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed the leather with the rough side up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked to make sure there was no wrinkle or roughness in the leather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked to make sure the piston can move up and down but in an airtight fashion</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Repairing the lower valve</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Checked for lead (Pb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ensured pump plates and “bride” are smooth and level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used a weight that was proportional to the size of the “bride” and diameter of the pipe extremity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight was sturdily attached to the leather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The cut was made at an angle so that the part that open up can rest on the part that is permanently fixed on the “bride”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed leather, placed the head and tightened bolts to lock pump head on pipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ensured pump retains water</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
D.9 Follow-up Interview Guide

**Participant ID:**

**Date:**

**Interviewer’s name:**

---

### Madagascar Technician Evaluation

#### Interview Guide

**Introduction to the project**

Hi, I am [YOUR NAME AND INTRODUCE YOURSELF/NOTE TAKER]. I am working in collaboration with Ranontsika and the University of South Florida in conducting this short interview. We are interested in improving the quality of water and public health. The work is being focused on the pitcher pumps which is why we are wanting to talk to you today.

Thank you for agreeing to talk to me today. We are meeting with a few different pump technicians to gain a better understanding of how you manufacture your pumps.

I realize your time is very valuable and want to thank you for meeting with me once again to share your ideas. We will use your opinions to evaluate a program that took place in 2020. I have prepared some questions to get our conversation started. Please remember that there are no right or wrong answers, and you should feel free to share.

This interview should take approximately 1 hour. Your participation is voluntary. If you do not wish to participate, you may stop at any time. We will not use your name in our reports so please feel free to tell us whatever you think would be helpful. I am going to audio record our conversation so that I don’t miss any of your ideas. If you want me to turn it off at any time, just let me know.

**Do you have any questions or concerns before we get started?**

**Do I have your permission to record this conversation?**

- **NO →** Would you still like to continue with the interview without the recording?
  - **NO →** STOP (thank them for their time)
  - **YES →** Go to question 1 and conduct the interview taking detailed notes
- **YES →** Go to question 1

**I would like to discuss your daily work routine and the process that you take to install or repair a pitcher pump.**

Out of the last ten pumps you manufactured, installed, or repaired what materials did you use for the piston and foot valves?

**Do you feel you will continue to use ____ in the manufacturing, installation, or repair of pumps?**

**Probe:** Can you elaborate why or why not?

How many of the last ten pumps did you use lead in?

**You indicated that you use lead in ____ pumps out of your last ten that you manufactured, installed, or repaired. Do you feel most Technicians in Toamasina do the same as you?**

**Probe:** Why do you think ____ Technicians use or don’t use lead?

**Do you feel confident in your ability to identify lead?**

**How comfortable do you feel making a pump without lead?**

**Probe:** Can you elaborate on why you feel that way?
Now, let’s talk specifically about the clients for which you repair or install pitcher pumps.

How do you feel your clients view your work? For example, in regards to the capacity, efficiency, or quality of your work.

Probe: What do you think it is about your work/business that led your clients to select you for the work?

Probe: Are there characteristics about you or your business that they value? [Go past geography and previous work history].

You mentioned previously that you use lead _ (Sometime, Never, All the time)_.

Have you had any clients ask you about the use/lack of use of lead in the pitcher pump?

Probe: If so, what did they ask?

If your client asked you for information about lead (Pb), what would you tell them?

**With regards to the training that you participated in about a year ago**

Could you share what points you remember from the training?

Probe: What information about lead, the methods on making lead free components, materials, etc.?

What are some questions you still have or you would like information on from that training?

How were the trainings helpful with developing your business and interacting with your clients?

Probe: How were the trainings NOT helpful with developing your business and interacting with your clients?

**We are going to go through some of the different materials you received during the training.**

Of the materials you received as part of the training, which did you find most and least helpful?

Flyers
- t-shirt
- coveralls
- backpack
- notebook
- logbook
- certificate

Probe: Can you give us your general opinion on the materials and if/how they have impacted your business? (Probe if not getting response: have people commented on the materials, do you display the certificate, etc.)

Flyers
- t-shirt
- coveralls
- backpack
- notebook
- logbook
- certificate
Specifically, for the logbook, have you continued use of your logbook?

Yes____________________
No____________________

No:
Were there any reasons you stopped use of the logbook?
What did you like about the logbook?
What didn’t you like about the logbook?

Yes:
Can we please see your logbook?
Can we take pictures of the logbook?
Yes________
   i. code: _______________________
No_______

Does this material help you in your daily work?
Is it easy to use?
Do you think it is necessary to have one?
Is there anything that could enhance the logbook?
Do you feel that you will be able to make your own logbook once this is filled?

Is there any other information with regards to lead or water quality that would be helpful to you or that you could use a refresher on?

One last question
As you have completed these trainings and are now very professional technicians we would like to ask if you know of any new technicians (i.e. technicians that have started in the last two years)? We are hoping to compare your work and professionalism to that of newer technicians that have not been through the trainings.

This concludes our interview. Before we conclude, is there anything that you would like to add? Anything that I haven’t asked you about that you would like to share?

Do you have any questions for me?

Thank you again for your time and for sharing your experience with me.
D.10 Workshop Observation Sheet

<table>
<thead>
<tr>
<th>Fanaraha-maso atao ao amin'ny atelier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technician ID ________________________</td>
</tr>
<tr>
<td>Pump GPS ____________________________</td>
</tr>
</tbody>
</table>

**English:** Is there any lead visible in the shop? The kind?

**French:** Y a-i-l du plomb visible dans l’atelier ? les quels ?

**Malagasy:** Misy fitovana misy Firaka na hampiasana firaka hit aoe ao anaty atelier ? [oh: fatana misy charbon, fer soudage, vilany kely fandrendrehana Firaka]
- Raha misy irona avy izany?

**English:** Is there any lead intended to be used as weights for the valves visible in the workshop?

**French:** Est ce qu’il y a du plomb destiné a être utilisé comme poids pour les clapets visibles dans l’atelier ?

**Malagasy:** Misy firaka izay efa vita voafoa hita fa hampiasaina ho lanja amin’ny paompy ve hita ao amin’ny atelier ?

**English:** Is there a hole in the sand which is used to shape molten lead around/ in the workshop?

**French:** Ya-t-il un trou dans le sable qui est utilisé pour façonner le plomb fondu autour/ dans l’atelier ?

**Malagasy:** Misy lavaka kely boribory amin’ny fasika izay ampiasaina mba hamaritana lay Firaka voandreka ve hita manodidina ny atelier ?

**English:** Do you see fishing line or elastic in the workshop?

**French:** Voyez-vous du fil de pêche ou de l’élastique dans l’atelier ?

**Malagasy:** Misy fitovana toy ny elastique sy tadim pitana hita ve ao amin’ny atelier ? [Mety ho ampiasaina amin’ny fanamboarana tamis tsy misy Firaka]

**English:** Is there a lead found in the workshop, has the lead already been used or an old one already used that may have been removed from a pump?

**French:** Si y a du plomb trouvé dans l’atelier, le plomb a-t-il déjà été utilisée ou un ancien déjà usee qui a peut-être été enlever d’une pompe ?

**Malagasy:** Raha toa ka mahita firaka ao amin’ny atelier, firaka vaovao ve izany sa firaka efa nisana izay mety avy amin’ny paompy nesorina ?

**English:** Do you see batteries around or in the workshop?

**French:** Voyez-vous de la batterie autour ou dans l’atelier ?

**Malagasy:** Misy bateri mpetrapetra amin’ny manodidina na ao anaty atelier?

**English:** Is the store located in a house ? Are there children around ?

**French:** Le magasin est-il situé dans une maison ? Y a-t-il des enfants dans les environs ?

**Malagasy:** Ao aty tany hany ve ny atelier sa misaraka amin’ny toeram-ponenana ? Misy zaza mila-hao ve manodidina eo?

**English:** Are individual protective materials visible?

**French:** Des matériaux de protection individuelle sont-ils visibles ?

**Malagasy:** Misy fitovana fiarovana rehetra misa a ve hita manodidina eo? [gant tanana, solomaso, kiraro, sus]
D.11 Pump Observation Sheet

Pump Check Observation Sheet

Technician ID ______________________
Pump GPS _______________________

English: What type of materials is the pump made of?
Français: De quel type de matériaux la pompe est-elle faite ?
Malagasy: Inona ny fitaovanana/materiel ampiasain’ilay tekaisianina?

English: Which components are made of what type of metal or plastic?
Français : Quels composants sont constitués de quel type de métal ou de plastique ?
Malagasy: Inona amin’ilay pompe no ampiasaina hanaovana inona ary inona ilay karazana vy/plastika ampiasain’ilay tekaisianina?

English: Is the pump working properly?
Francais: La pompe fonctionne-t-elle correctement ?
Malagasy : Manideha tsara ve ilay pompe?

English: General condition of the pump?
Francais: État général de la pompe ?
Malagasy: Toetra ilay Pompy amin’ny kapobeny? [tontà/vaovao/simba/mande kely ny ranoh, etc]
Appendix E: IRB Approvals

E.1 IRB Study000143 Approval

Dear Dr. James Mihelec:

On 3/31/2020, the IRB reviewed and approved the following protocol:

<table>
<thead>
<tr>
<th>Application Type</th>
<th>Initial Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRB ID</td>
<td>STUDY000143</td>
</tr>
<tr>
<td>Review Type</td>
<td>Expedited</td>
</tr>
<tr>
<td>Title</td>
<td>&quot;REDUCING CHILDHOOD LEAD EXPOSURE IN TOAMASINA, MADAGASCAR BY REMEDIATION OF LEAD CONTAINING HAND PUMP COMPONENTS&quot;</td>
</tr>
<tr>
<td>Funding</td>
<td>Pure Earth Blacksmith Institute</td>
</tr>
<tr>
<td>Approved Protocol and Consent(s)/Assent(s):</td>
<td>IRA_BILL, Consent</td>
</tr>
</tbody>
</table>

Attached are stamped approved consent documents. Use copies of these documents to document consent.

Within 30 days of the anniversary date of study approval, confirm your research is ongoing by clicking Confirm Ongoing Research in BullIRB, or if your research is complete, submit a study closure request in BullIRB by clicking Create Modification/CR.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Your study qualifies for a waiver of the requirements for the informed consent process for the local research team only as outlined in the federal regulations at 45 CFR 46.116(f). Consent will be obtained from the study team in Madagascar.

A PREEMINENT RESEARCH UNIVERSITY

Institutional Review Boards / Research Integrity & Compliance
FWA No. 00001669
University of South Florida / 3702 Spectrum Blvd, Suite 165 / Tampa, FL 33612 / 813-974-5638
This research involving children as participants was approved under 45 CFR 46.404:
Research not involving greater than minimal risk to children is presented.

Parental permission and assent are waived.

Sincerely,

Shanitra Butler
IRB Research Compliance Administrator
NOT HUMAN SUBJECTS RESEARCH DETERMINATION

October 4, 2021

Dear Adaline Buerck:

On 10/1/2021, the IRB reviewed the following protocol:

<table>
<thead>
<tr>
<th>IRB ID</th>
<th>STUDY003327</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Evaluation of Pitcher Pump Technicians Response to Social Marketing Campaign</td>
</tr>
</tbody>
</table>

The IRB determined that the proposed activity does not constitute research involving human subjects as defined by DHHS and FDA regulations.

IRB review and approval is not required. This determination applies only to the activities described in the IRB submission. If changes are made and there are questions about whether these activities constitute human subjects research, please submit a new application to the IRB for a determination.

While not requiring IRB approval and oversight, your project activities should be conducted in a manner that is consistent with the ethical principles of your profession. If this project is program evaluation or quality improvement, do not refer to the project as research and do not include the assigned IRB ID or IRB contact information in the consent document or any resulting publications or presentations.

Sincerely,

Jennifer Walker
IRB Research Compliance Administrator
E.3 Study Approval from the Biomedical Research Ethics Committee of the Ministry of Public Health of Madagascar

<table>
<thead>
<tr>
<th>DESIGNATION DES PIECES</th>
<th>NOMBRE</th>
<th>OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettre N° 051 MSANP/SG/AGMED/CNPVCERBM du 12/03/2020 relative à l’autorisation de recherche intitulée : « Réduction de l’exposition des enfants à Toamasina /Madagascar par la réhabilitation des compostes des puits à pétrole contenant du plomb (Pb), financé par PURÉ EARTH Blacksmith Institute et Université du Sud de la Floride. »</td>
<td>01</td>
<td>« Pour attribution »</td>
</tr>
</tbody>
</table>

Copie à : « à titre de compte-rendu »
- Monsieur le Ministre de la Santé Publique
- Monsieur le Secrétaire Général du Ministère de la Santé Publique
Ministère de la Santé Publique

Secrétariat Général

AGENCE DU MÉDICAMENT DE MADAGASCAR

REPUBLIKAN’I MADAGASIKARA
Finavaza- Tanindrazana-Fandrosana

---------

Le Président du Comité d’Éthique de la Recherche Biomédicale

à

Monsieur le Docteur James Mihelic, Phd,
Professeur en Génie Civil et Environnementale
Université du Sud de la Floride

N°: 254 MSANP/SG/AGMED/CERBM

OBJET : Autorisation de la recherche biomédicale.


Monsieur,

Suite à la délibération du Comité d’Éthique de la Recherche Biomédicale auprès du Ministère de la Santé Publique lors de la réunion extraordinaire du 05 Mars 2020, vous êtes autorisé à réaliser la recherche intitulée : « Réduire l’exposition des enfants à Toamasina /Madagascar par la remédiation des composantes des pompes à pichet contenant du plomb (Pb) », financé par PURE EARTH Blacksmith Institute et Université du Sud de la Floride.