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Field Testing of Affordable Well Head Protection for Locally Manufactured, Self-Supply Pitcher Pumps on Manually Driven Tubewells in Madagascar

Michal Usowicz
University of South Florida, usowicz@mail.usf.edu

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Field Testing of Affordable Well Head Protection for Locally Manufactured, Self-Supply Pitcher Pumps on Manually Driven Tubewells in Madagascar

by

Michal Usowicz

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

Major Professor: James R. Mihelcic, Ph.D.
Amy L. Stuart, Ph.D.
Michael F. MacCarthy, Ph.D.
Valerie J. Harwood, Ph.D.

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DEDICATION

To my father.

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ABSTRACT

Lack of water access is an issue of global importance. The WHO and UNICEF's Joint Monitoring Program estimated that in 2015 71% of the world's population used a safely managed drinking water source and 89% of the world's population used an improved water source within a 30-minute round trip of home. Madagascar's national statistics lags far behind these global statistics with 54% of the population using improved water sources, 31% using unimproved water sources, and 16% with no service at all.

This research studied water access in Madagascar with self-supply Pitcher Pumps attached on hand-driven tubewells. The term self-supply in this context refers to privately owned and constructed water sources that are not financially subsidized by governments or non-governmental organizations. Self-supply is typically seen in the form of private wells in rural areas of developed countries like the United States or in developing countries in the form of shallow wells or rain water harvesting. Self-supply Pitcher Pumps are common along the coast in Madagascar in areas where the first aquifer is shallow and in sandy soil. They are ubiquitous at the site of this study, the port city of Tamatave. People in Madagascar have benefited from increased access to affordable water because of Pitcher Pumps for decades, however, there are health risks associated with consuming the water due to lead and microbial contamination of the water.

This study sought to improve microbial water quality of Malagasy Pitcher Pumps by testing two different types of well head protection: 1) a partially buried short 100-mm diameter PVC pipe collar placed around the rising main, and 2) a 50-cm diameter, circular concrete apron. The study was a mixed design experiment that allowed for *between* subject comparisons of wells over the same time period and for *within* subject comparisons of the same well sites with different types of well head protection. Wells were selected for the study that had a high risk of localized pathways of contamination and low risks of aquifer contamination relative to other wells in the area. Membrane filtration was used for microbial water quality measurements and detected a wide spectrum of bacteria grown at 37° C. In this study, data from 690 water samples of 44 wells (with and without well protection added) over a 9 months period was analyzed.

Weak but statistically significant ($p \le 0.05$) and marginally statistically significant ($0.05 < p \le 0.10$) correlations were found between bacteria concentrations and antecedent rainfall depth for wells with aprons but not for wells with a pipe collar or no protection. No statistically significant relationship was found between bacteria concentrations in wells and type of well head protection. The lack of reduction in bacteria concentrations with well head protection is likely due to the high density of on-site sanitation near the wells and the relatively shallow water table.

Generally, study results indicate that there is a wide variation of bacteria concentrations both from the same well across many months and between wells that are near each other. The second observation is consistent with other studies of wells in the area. It appears as if the best solution for improving water quality from Malagasy Pitcher Pumps to a potable level is point-of-use treatment of the water.

CHAPTER 1 INTRODUCTION

1.1 The Global Issue of Water Access

Lack of water access is a global issue. The WHO and UNICEF Joint Monitoring Program estimated that in 2015 71% of the world's population used *safely managed* drinking water sources (World Health Organization and UNICEF 2017). Safely managed sources were defined as water that is available on the premises, is available when needed, and is free of contamination. Furthermore, it estimated that approximately 89% of the world's population used at least an improved, sufficiently protected source of water within a 30 minutes round trip of their home. It should be noted that improved sources does not necessarily mean the water source is free from contamination. Additionally, the Joint Monitoring Program (World Health Organization and UNICEF 2017) estimated that 884 million people do not have access to *basic* drinking[1] water services; of this population about 423 million use unimproved, insufficiently protected sources of water, 159 million lack any sort of water services (e.g. use surface water such as rivers), and 262 million need to spend over 30 minutes round trip to collect water.

Figure 1.1 provides statistics for improved, unimproved, and no service levels for water access across different country groupings and demographics. Note how Madagascar (the location of this study) is performing worse for improved water access nationally and in rural and urban areas, compared to global, sub-Saharan Africa, and other developing country averages.

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[1] Basic water services are defined by the Joint Monitoring Program as improved (i.e. protected) water sources that are no more than a 30 minute round trip for the user's home (World Health Organization and UNICEF 2017).

Figure 1.1 Data from the WHO and UNICEF (2017) Joint Monitoring Program comparing coverage for water access from different regions and Madagascar. Percentage values are rounded so the graph is more readable and therefore do not always add up to 100.

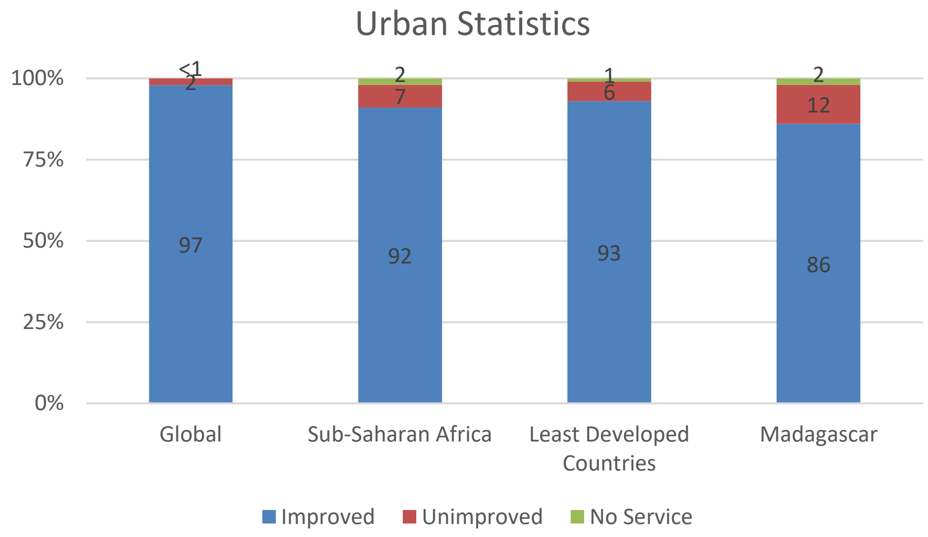

Figure 1.1 (Continued)

Water, sanitation, and hygiene related problems cause an estimated 1.5 million deaths per year and is the source of about 6.3% of all deaths globally (Prüss-Üstün et al. 2008). In Madagascar, roughly 22% of deaths of children under 5 years old are related to diarrhea (Black et al. 2010). Accordingly, improving water, sanitation, and hygiene is estimated to reduce at least 9.1% of the global disease burden as measured in disability adjusted life years (Prüss-Üstün et al. 2008).

1.2 Self-Supply

"Self-supply" refers to households constructing and developing their own private sources of water separate from municipal or natural sources (such as rivers) either by their own means or paying a local technician at their own expense (i.e. unsubsidized). Examples of self-supply include low-cost methods to access shallow groundwater (MacCarthy 2014) or implementation of rainwater harvesting systems (Blanchard 2012). Generally, self-supply in a developing world context is only feasible with rainwater collection or in areas with easily accessible, shallow groundwater because it needs to be extremely affordable to construct. In practice, being extremely affordable to construct means that it needs to be constructible with a minimal amount of hand or manual power tools and inexpensive materials (e.g. scrap metal). Additionally, a self-supply water system can be made more affordable if it is improvable incrementally so the owner does not need to pay the whole upfront cost at first.

All over the world, individuals and private households construct and maintain their own private water systems and therefore use “self-supply”. This is true regardless of if it is a developed or less developed country. In the United States for example, 22% of the rural population receives their water from a private household supply (Sutton 2009). Self-supply is also common in the developing world in both rural and urban areas. Grönwall et al. (2010) did an analysis of United States Agency for International Development Demographic Health Survey data for 43 countries in south and south-east Asia, Latin America, and sub-Saharan Africa and found that 268 million urban dwellers used near-by self-supply wells for water. The population-weighted percentages of people in urban areas using wells in each region surveyed was not the same. For example, in sub-Saharan Africa and south-east Asia about one third of urban dwellers were using wells and in Latin America it was only 3%. The percentages were much different in rural areas with sub-Saharan Africa reporting use of self-supply wells for a water supply at 45%, south-east Asia at 52%, and Latin America at 20%. The actual number of people relying on self-supply wells is likely to be much higher since the surveyed countries constitute less than half of the total number of people living in urban areas in developing countries.

Self-supply is ubiquitous globally but this thesis will only focus on self-supply in a developing world context. However, given that it is so ubiquitous, it is important to understand its advantages and limitations for improving access to water in developing countries.

1.2.1 Advantages and Disadvantages of Self-Supply

Self-supply in developing countries has a number of advantages over municipal systems managed by governments or subsidized community managed systems funded by non-governmental organizations (NGOs). One advantage is that self-supplied water services can be more reliable than other services. For example, a 2006 study in Zimbabwe found that 88% of private wells were operating as opposed to 72% of community managed wells (Smits and Sutton 2012). Another study conducted in Kaoma District in Zambia found that 94% of the 3,640 private wells surveyed were operating as opposed to 49% of 321 community wells (Smits and Sutton 2012). In addition to higher functionality, self-supply water points are available at all hours to the owners, as opposed to municipal public taps which commonly have limited hours of operation.

The literature on self-supply commonly emphasizes that self-supply is not intended to compete with municipal systems or community managed systems but instead can supplement these water systems (Sutton 2009). Self-supply may also increase water coverage in areas where larger systems are not cost-effective and technically feasible. For example, water coverage in rural Nicaragua increased by 24% over seven years due to investment in private, self-supply wells with rope pumps (Smits and Sutton 2012). Furthermore, due to government and NGO efforts in Zimbabwe since the 1990s over 120,000 private wells have been upgraded, making protected private wells the largest in number of any protected water point in the country (Sutton 2009). Self-supply can also supplement existing services, for example in Thailand most rural households supplement their water service with rainwater harvesting (Smits and Sutton 2012).

Sutton (*Self-Supply Reloaded: Overview and Update* 2016) also makes the argument that self-supply is a strategy to decrease the per capita cost of obtaining access to improved water sources for the entire population in low density, rural areas. It is generally recommended that a well connected to a hand-pump optimally services 250 people and an individual should not make more than a 30 minute round trip to obtain water (Sphere Project 2011). However, in low density rural areas to achieve a smaller travel time it becomes necessary to decrease the number of people being serviced by a water point, which, in turn, raises the per capita cost of each water point.

Enhanced water access can also improve health outcomes associated with having sufficient water for hygiene. For example, implementing rainwater harvesting was found to reduce DALYs by 9%

for urban dwellers in 37 West African cities, and if combined with point-of-use water treatment, the reduction was estimated to increase to 16% (Fry et al. 2010). Other studies have also shown that increases in quantity of water used and improvements in disposal of fecal matter can have a greater impact on health than increased water quality at the point of collection (Esrey, Feachem, and Hughes 1985; Howard and Bartram 2003).

Regarding economics, self-supply is unsubsidized but that does not necessarily mean that it does not support the poorest consumer that may not be able to afford a low cost well or rain water harvesting system in the first place. Sutton (*Self-Supply Reloaded: Overview and Update* 2016) stated that it is common for self-supply water wells to be shared with neighbors who may not have purchased the well. The author of this thesis commonly observed neighbors using well pumps in Tamatave, Madagascar when their pump was out of operation or when the municipal water system was not operating. Additionally, water pumps were always shared between renters and the landlords who owned the pumps; if there was a municipal water tap on the property sometimes the landlord's family would be the only people to use it.

One possible disadvantage of self-supply is low water quality; however, Sutton (2012) stated that this has not been extensively studied. One example is the case of the Malagasy Pitcher Pump market with many pumps surveyed producing water that is not safe microbiologically and in term of lead contamination levels (MacCarthy 2014; MacCarthy et al. 2013; Wahlstrom-Ramler 2014; Akers 2014; Akers et al. 2015). In contrast, there is some evidence that the water quality associated with self-supply water points may not be high risk. For example, Dean and Hunter (2012) reviewed epidemiological studies of the risks from rainwater harvesting and found that rainwater is safer than unimproved water sources and that there is no significant difference in the risks of rainwater harvesting when compared to improved water sources.

Self-supply is also not feasible in challenging hydrological conditions such as locations without shallow water tables or with low precipitation to support rainwater harvesting which limits its applicability globally. Additionally, a self-supply water point may not meet the common definitions of *improved* water sources because they are constructed cheaply since self-supply, by definition, is affordable to users.

1.3 Self-Supply from Pitcher Pumps in Madagascar

Throughout Madagascar since the 1960s, individual families have invested in a Pitcher Pumps installed on driven wells (MacCarthy et al. 2013; MacCarthy 2014). Figure 1.2 shows what a typical Pitcher Pump looks like. Many of the coastal areas of Madagascar have shallow, unconfined aquifers in sandy soils which makes the construction of shallow manually-driven wells feasible. From the author's experiences working in Madagascar and from reading the literature about Pitcher Pumps in Madagascar (MacCarthy 2014; MacCarthy et al. 2013; Wahlstrom-Ramler 2014; Akers 2014; Akers et al. 2015), it appears that Pitcher Pumps are constructed in the same general manner in different parts of Madagascar with only some variations in design of pump head, material used for valves, and design of well points and screens.

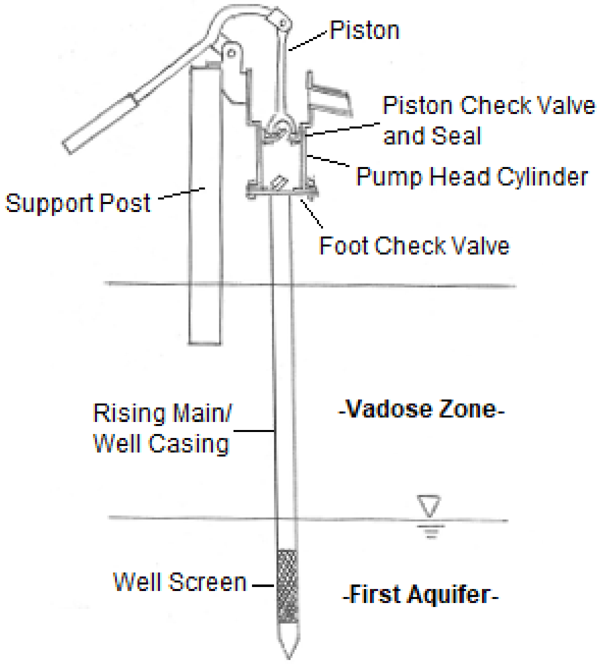

Figure 1.2 Diagram of Malagasy-style Pitcher Pump. Not to scale. (Diagram created by the author.)

Pitcher Pumps in Madagascar are fabricated locally in small metal workshops from scrap materials with basic metal and welding techniques. The pump head (Figure 1.3) is assembled by hammering, cutting, and welding scrap pieces of sheet metal and pipes together. The two check valves are made from leather (in Tamatave) or rubber (in other parts of the country) and commonly has lead weights installed that are scavenged from old automobile batteries, although the author observed iron weights or other scrap metal being used (also reported by Akers 2014). Furthermore, in another case a manufacturer in the Sava region of Madagascar reported to have a method of using PVC for check valves; however, the author was not able to examine that pump to learn the specifics of using PVC.

Figure 1.3 Pitcher Pump assembly from a Morondava workshop (excluding both check valves). (Photo from the author.)

The rising main/well casing[2] is fabricated by making a pipe with a point at the end and holes at the bottom. In Tamatave, a brass or stainless steel screen is soldered onto the pipe to make a well screen to prevent infiltration of sand into the well (Figure 1.4) (the solder is a source of lead contamination as discussed in Section *2.5 Past Research on Pitcher Pumps in Madagascar*). In Morondava (Menabe region) the author observed drillers using plastic mesh secured with tie wire or synthetic cloth secured with tie wire and long, thin pieces of rubber cut from a tire inner tube instead of a soldered brass screen. The author also developed a leadless well point design useable in Tamatave for this research project but it is not detailed in this paper since it was not within the objectives of the research project.

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[2] The rising main and well casing are the same in Malagasy Pitcher Pumps in this study.

Figure 1.4 Well point and well screen made from a brass mesh soldered on with a leaded solder. (Photo by the author.)

To install a well, a pilot hole is dug into the ground with an auger (a pipe with a bell end that is rammed into the ground to collect soil inside of it so the soil can be removed from the hole) to above the water table (since the pilot hole will collapse below the water table) and then the pipe is hammered approximately 1-2 meters into the shallowest (first) aquifer[3]. The pump head is then attached, priming water is added, and the well is pumped until the water is clear from fine materials disturbed in the well during drilling (approximately 100 to 200 liters needs to be pumped out).

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[3] There is a practical limit of 2 to 3 meters of depth into the water table because the pilot hole cannot be dug into the aquifer. This fact causes the flange at the top of the rising main to be approximately the height that it will be driven into the aquifer when it is placed into the pilot hole. If it is more than 2 to 3 meters tall it would require a ladder to hammer into the aquifer which would be more logistically challenging than the normal practice of standing on another technician's shoulders to get to a height that one can hammer the rising main into the aquifer (see Figure 1.5).

[redacted] [redacted]

Figure 1.5 Malagasy Pitcher Pump technicians hammering a rising main into the aquifer. Right: Example of a case where the pilot hole collapsed before installation and the top flange was too high to be easily hammered in without standing on another technician's shoulders. This also shows the construction challenge when a well screen is being placed deeper than about 1.5 meters into the aquifer because any pilot hole dug below the water table will collapse in the same fashion. Left: Example of the normal case where a rising main is not being placed very deeply into an aquifer and is also being placed into a pilot hole that has not collapsed. (Photographs by the author.)

Figure 1.6 shows locations of areas in Madagascar with Pitcher Pumps known to this thesis's author (however, this is not an exhaustive list). The largest market appears to be in Tamatave with much of the surrounding coast around Tamatave having Pitcher Pumps. MacCarthy (2014) estimated that approximately 9,000 Pitcher Pumps are used in this city. Brad Akers (a researcher who also studied Malagasy Pitcher Pumps) through a personal communication stated there are Pitcher Pumps also available in Diego and Meghan Wahlstrom (another researcher who also studied Malagasy Pitcher Pumps) stated that there were Pitcher Pumps in Manakara. This thesis author has also seen Pitcher Pumps in Vohemar and Sambava in the Sava region which reportedly had a handful of manufacturers in the region. Tulear also has a large Pitcher Pump market. Manufacturers in Morondava also reported to the author that there are towns along the coast between Tulear and Morondava that have Pitcher Pumps.

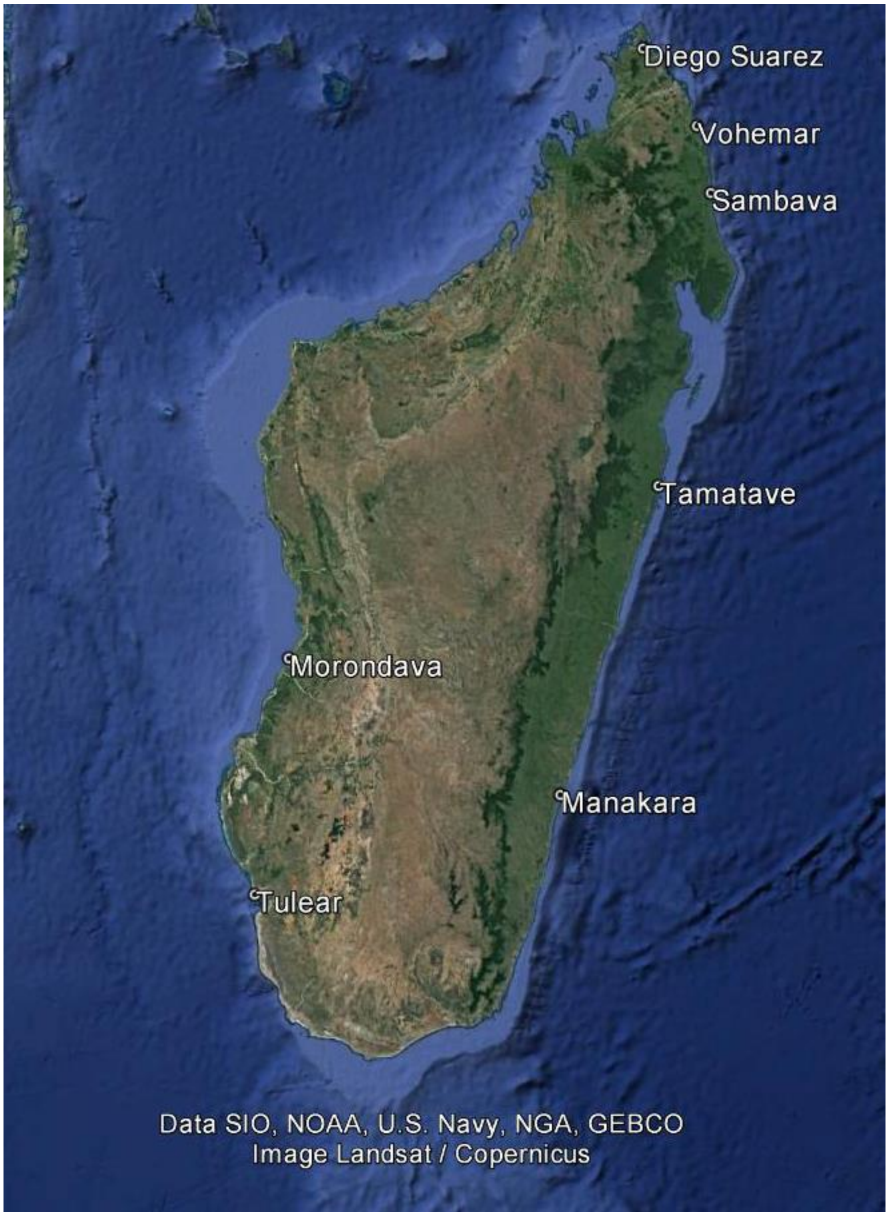

Figure 1.6 Locations of major cities in Madagascar with Pitcher Pumps. Pitcher Pumps are also common along the coasts around these towns. This is not an exhaustive list. Map obtained from Google Earth (Version 7.1.5.1557) with information from SIO, NOAA, U.S. Navy, NGA, GEBCO and Landsat/Copernicus.

There are other examples of self-supply wells in Madagascar too. Hand-dug wells lined with bricks or sheet metal from 55-gallon oil drums are also commonly seen in the central highlands and along the coasts. There are some individuals that produce other types of pumps for private individuals such as rope pumps or a type of reciprocating hand pump but their production numbers are negligible in comparison to all the Pitcher Pumps produced by Malagasy manufacturers.

1.4 Research Motivation and Objectives

It is known from past research that Malagasy Pitcher Pumps produce water of poor microbiological quality (Wahlstrom-Ramler 2014; MacCarthy et al. 2013; MacCarthy 2014). Accordingly, the motivation for this thesis research is to improve the water quality supplied by private tubewells that are operating under simple hydrological conditions (i.e. shallow aquifers and sandy soils) in developing countries, particularly Pitcher Pump systems located in Madagascar. As mentioned previously, MacCarthy (2014) estimated that approximately 9,000 Pitcher Pumps are used in the Malagasy coastal city of Tamatave. As stated in Section *1.3 Self-Supply from Pitcher Pumps in Madagascar*, many other locations in the country also have Pitcher Pump markets that are presumably smaller in sheer numbers because they are located in smaller urban centers. However, Pitcher Pumps still likely play an important role in water access in those areas. Needless to say, these pumps are important for water access in Madagascar and can complement existing municipal system or replace them when they are not operating or in areas where they have not extended to.

There has already been extensive research into technical improvements that can be made to Pitcher Pump systems in Madagascar. Akers et al. (2014; 2015), Wahlstrom-Ramler (2014), and MacCarthy (2014) all performed research into the Pitcher Pump market in Tamatave and provided recommendations on what changes to well designs could improve or have no effect on water quality. The research presented in this thesis seeks to further advance their recommendations to improve water quality from Pitcher Pumps in Madagascar, or other self-supply tubewells installed in other developing countries, by developing recommendations on low-cost well head protection for tubewells. There are currently no known recommendations for sizing or design of well head protection for private or community tubewells in developing countries identified in this research that are based on controlled laboratory testing, field testing, or engineering analysis. Accordingly, the primary goal of this research thesis is to develop practical recommendations based on field testing on what is the appropriate level of affordable well head protection that could be integrated with the Malagasy self-supply Pitcher Pump market that correspond to a specific level of reduction in contamination of water from microorganisms sourced from those pumps. The main study goal will be met by the following two objectives:

1. Test the effect of two appropriate well head protection designs at different protective diameters surrounding a well on bacteria concentrations grown at 37° C in the water.
2. Develop design requirements of an appropriate well head protection design based on testing and user interest and preferences.

CHAPTER 2 LITERATURE REVIEW

2.1 Principles of Groundwater Contamination and Measuring Microbial Risk

Fecal matter is the cause of most of the dangerous microbial contamination of drinking water; feces contains large quantities of pathogens, such as viruses, bacteria, protozoa, and helminths, that can infect humans (ARGOSS 2001). Helminths and protozoa are too big to flow easily through the subsurface and thus do not tend to be a concern in well contamination unless there has been direct contamination of the well via a localized pathway (ARGOSS 2001). Human feces are a danger to human health because they have the most pathogens that are adapted to living in the human body, however, there are still pathogenic organisms that can originate from animal feces.

Contamination of well water by microorganisms can happen via two pathways (Figure 2.1). The microorganisms can either be transported from a contamination source via flow in the groundwater in the aquifer, called an aquifer pathway, or microorganisms can flow directly into the well water through opening in the well construction and completely bypass the aquifer, called a local pathway.

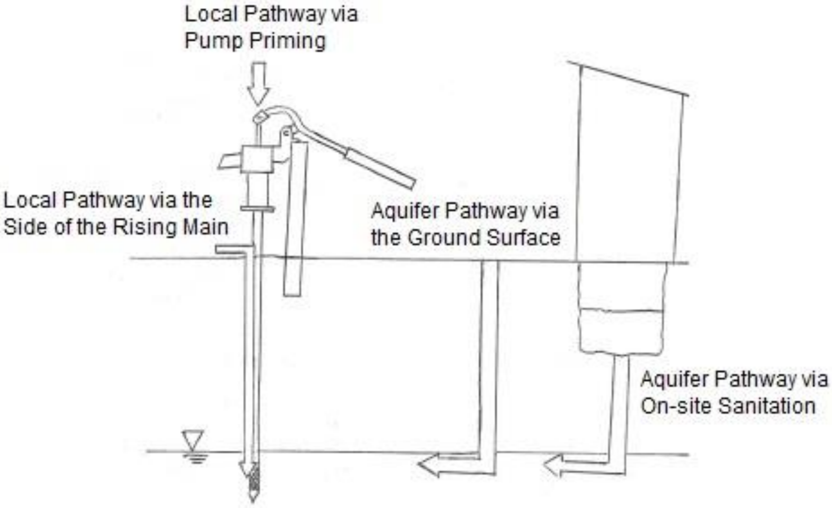

Figure 2.1 Diagram of local and aquifer pathways on a Malagasy Pitcher Pump.

2.1.1 Localized Pathways

Localized pathways (Figure 2.1) for contamination are paths through which a well is directly contaminated with run-off from the ground surface that *does not* travel through the soil into the aquifer but rather through direct paths. It is a *well-specific* pathway and is due to construction of the well. Generic examples of localized pathways for contamination is rain water flowing into a well through cracks in the well lining, running through a poorly constructed sanitary seal along the side of a borehole well casing, or flowing through cracks in a well apron. Section *2.4 Risks from Poor On-Site Sanitation and Well Head Protection* provides further explanation and evidence that localized pathways are important for well water quality.

There are some unique ways for localized pathways to form in Malagasy Pitcher Pumps. No operating Malagasy Pitcher Pump can have a localized pathway go through holes in the rising main/well casing[4] because any hole in the rising main would make the Pitcher Pump inoperable due to loss of pressure for the suction; all contaminated water must run all the way along the side of the rising main to the well screen. The annular gap next to the rising main might be enlarged due to shaking and deflection of the rising main during pumping if the pump is not secured strongly enough to a support post (which is the case much of the time). Priming water is another pathway for well contamination and Wahlstrom-Ramler (2014) found it to be a statistically significant source of contamination (p=0.03). However, in the context of this thesis research, a Pitcher Pump would only need regular priming if there is an issue with the bottom check valve not being able to hold pressure.

Accordingly, in this study the primary concerns for localized pathways is water flowing along the side of the rising main and from priming water for pumps with check valves failing to seal well. The way to prevent localized pathways of contamination is to build structures such as sanitary seals or concrete well aprons to prevent the flow of contaminated water (see Section *2.2 Typical Recommendations for*

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[4] The rising main and well casing are the same in Malagasy Pitcher Pumps, as shown in Figure 1.2.

Well Head Protection for more information). Additionally, well maintained check valves should require no priming.

2.1.2 Aquifer Pathways

Contamination can also flow into a well via the aquifer (Figure 2.1). Unlike local pathways, contamination through the aquifer pathway can affect multiple wells in an area. Water that contaminates wells through the aquifer pathway can enter the aquifer directly from the ground surface or from places with high quantities of water and contamination such as soak pits or on-site sanitation like pit latrines or pour-flush latrines (see Section *3.4.3 Well Preparation and Characteristic Measurements* for further description of the on-site sanitation in the study). The water first flows vertically through the unsaturated vadose zone and upon entering the aquifer can flow into the well during pumping. Pour-flush latrines are considered more hazardous for well contamination than pit latrines because of higher quantity of water flowing into them that can then carry contamination into the aquifer (MacDonald et al. 2005).

Microorganisms that are in groundwater are removed by different mechanisms. Microorganisms can be removed by physical filtration of the soil or adsorption on to the clay or sand granules in the soil. The removal efficiency for microorganisms can vary based on the pore spaces between the soil granules relative to the microorganisms with smaller pore sizes relative to the size of the microorganism being better for removal. If microorganisms are not removed by filtration they may die off naturally in the aquifer. Groundwater moves extremely slowly and the low velocities allow for microorganisms to die off naturally before reaching a well.

One cannot directly build protection for aquifer pathway contamination but can locate a well a long distance from a potential contamination source. Generally, there is a recommendation to place on-site sanitation 30 meters away from a well to allow for ample space for microorganisms to be filtered out and die-off in the groundwater (Action Contre la Faim 2005). More details on the process for filtration and attenuation of microorganisms in the subsurface is provided by Wahlstrom-Rambler (2014).

2.1.3 Measuring Health Risks from Drinking Water

A wide range of microorganisms in drinking water can cause illness in humans. They include viruses, bacteria, protozoa, and helminths. It is not practically possible to test for *all* the different pathogens in water that can cause illness so in practice the number of certain indicator organisms per unit volume are measured instead. Indicator organisms are types of organisms that are associated with fecal contamination of water (and therefore need to be found in feces) and do not naturally occur or multiply in the environment (World Health Organization 2011). The most widely used fecal indicator bacteria is *Escherichia coli* (*E. coli*) (World Health Organization 2011). Thermotolerant coliform can also be used as an indicator and are mostly comprised of *E.coli*. However, thermotolerant coliforms are not as good of an indicator of fecal contamination as *E.coli* (World Health Organization 2011). Total coliform can also be used to assess the general sanitary condition of water and includes *E.coli*. However, it also is not considered a good indicator of fecal contamination because they can multiply in water (World Health Organization 2011). Water absent of fecal bacteria should not be considered absolutely zero risk because some pathogens in water are not associated with fecal indicators (e.g. guinea worms) (Action Contre la Faim 2005) and there is a possibility that indicator bacteria may be present but not detected.

2.2 Typical Recommendations for Well Head Protection

Well head protection for a well such as a Pitcher Pump is constructed to block water on the surface of the ground from going directly into a well and contaminating it. It is ubiquitously recommended in textbooks on well construction in developing countries and consists of installing sanitary seals below the ground surface and a concrete well apron on the ground surface. Well head protection is considered to be an important part of the construction of wells for the protection of water quality, however, the current recommendations available to development practitioners are made for community wells and are inappropriate for self-supply wells.

Before discussing specific recommendations it is important to understand the differences in well designs. Well design in developing countries comes in two basic forms: 1) boreholes/tubewells or 2) hand-dug wells. Both types of wells are relevant to this study. Hand-dug wells are dug manually with shovels and as such can only practically access the first aquifer (for an example of their construction see Watt and Wood 1976). They are wide in diameter (frequently approximately 1.5 meters in diameter) because a worker needs to fit inside them to dig. In many cases hand-dug wells use buckets as lifting devices, although, they are frequently fitted with pumps (Watt and Wood 1976; Action Contre la Faim 2005). Hand-dug wells are frequently lined with concrete or other masonry materials but the author has also observed self-supply hand dug-wells lined with scrap 55-gallon drums. They can also be completely unlined if the well is being dug in an area with clay soils that does not collapse.

Boreholes/tubewells are smaller in diameter (frequently 100-150 millimeters in diameter for community supplies) and are frequently machined drilled but can be manually drilled also (MacDonald et al. 2005). They are frequently lined with PVC, steel, or stainless steel pipe. Since they are drilled, they can go very deep into the water table and can access water below the first aquifer.

The manually driven wells examined in this study are similar to hand-dug wells in that they can only practically access 2 to 3 meters into the water table and are therefore subject to many of the same aquifer pathways for contamination (See Section *1.3 Self-Supply from Pitcher Pumps in Madagascar* for more details on manual drilling). Manually driven wells should be classified as tube wells because of their thin diameter. Since manually driven wells are tube wells their surface works could be designed similarly or identically to a machined drilled borehole. Because of these similarities between the manually drilled wells in this study and other types of wells, things can be learned from studying the construction and contamination of both hand-dug wells and boreholes.

Well head protection recommendations are slightly different for boreholes and hand-dug wells. For boreholes, it is recommended that a sanitary seal of clay or grout[5] extending 3 to 6 meters below the ground surface to prevent water from flowing directly along the side of the well casing down to the well screen should be installed (Davis and Lambert 2002; MacDonald et al. 2005; Action Contre la Faim 2005) and for hand-dug wells it is recommended that the caissons have a water tight seal for at least 3 meters to prevent local pathways of contamination (Watt and Wood 1976).

For well head protection surface works, the same recommendations are found for both hand-dug wells and boreholes. A 2-meter diameter reinforced concrete well apron is typically recommended for well head protection for community wells. Common recommendations also include that drainage should be directed to a soak pit many meters away from the well. Additionally, well aprons are recommended to have a lip around the side and should be graded so that water flows to the soak pit. Typically, fencing is also recommended to keep animals away from the well (See Davis and Lambert 2002; MacDonald et al. 2005; Action Contre la Faim 2005; Watt and Wood 1976 for examples).

Figure 2.2 Left: A newly completed well apron for a community water supply with a hand pump being installed on a borehole in rural Madagascar. The apron is designed to drain spilled water away from the well pump and to a soak pit in the lower left of the image. Right: Damaged and cracked well apron on a hand-dug well. The well has been opened because the pump is not operating. (Pictures taken by the author.)

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[5] Generally recommended as a mixture of cement and sand, cement and bentonite, or just cement with water.

Well head protection is considered to be an important part of the engineering design of a well water point in developing countries, in fact, part of the *definition* of whether a well is considered *improved* or *unimproved* includes whether or not the well is protected (World Health Organization and UNICEF 2017). An example of how well head protection is considered important for water point design are the questions used for sanitary risk scoring of water points. Sanitary risk scoring for wells is a system to grade risks of water contamination with a series of 10 yes or no questions related to things that can be visually inspected at and around the surface works of a well (see Action Contre la Faim 2005; MacDonald et al. 2005; Davis and Lambert 2002; Cronin et al. 2006 for examples). While there are variations in the exact questions used, generally around half or more of the 10 questions are directly related to asking about the condition of the well apron and sanitary seals, the remaining questions are either about sanitary conditions beyond the apron (e.g. fencing) or latrine locations.

Engineering is an applied field and as such the advice of professionals in the field of water supply in developing countries was sought out for this research. Technical inquiries asking for justification for minimal sizes, depths, and other design parameters of sanitary aprons or sanitary seals on tube-wells in any context were sent to topical mailing lists, a technical inquiry service, and online forums for water supply professionals working in developing countries. Specifically, RedR's Knowledge Point online forum (www.knowledgepoint.org/), the WaterAid technical advisory service, the Accord WASH Alliance LinkedIn group (Accord WASH Alliance on LinkedIn 2015), and multiple mailing lists for the Rural Water Supply Network Dgroups (www.rural-water-supply.net/) were contacted[6]. The main reasons provided by professionals in these forums for well apron sizing were to prevent erosion of the ground due to spilled water, providing a platform for pump users, anchoring the pump and well casing, and designing a surface to channel water away from the pump; these are solely reasons related to common sense design

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[6] There is no vetting process for people who answer questions on these topical mailing lists and online forums, however, these networks are specifically set up for professionals working with water access in developing countries.

issues of community water points. No professional that responded to the posts gave any justification from grey or scientific literature or engineering design principles to prevent runoff or water intrusion from entering the well to justify the size of well aprons as needing to be 2 meters in diameter.

The common recommendations for community wells are not appropriate for private, self-supply wells for a number of reasons. The most obvious difference is that community wells service more people than private, self-supply wells. According to Sphere Project standards (2011) community wells are recommended to service up to 250 people. MacCarthy (2013; 2014) estimated that Tamatave Pitcher Pumps service an average of 19 people per pump; this is a factor of 10 difference than the recommended standard for community wells.

Many of the design issues with community wells dissolve with fewer people using a water point. Fewer people means less water will be spilled and that there will be less traffic in general. Small quantities of water being spilled at any one time can eliminate the need for a concrete pad to evacuate the water and a soak pit to collect it. Less foot traffic around the well also could eliminate the need for a large apron due to there being less mud since there is less water being spilled.

Community wells are also generally heavily subsidized. Cost is not as extreme of an issue with community wells due to their subsidies so there is not as much pressure for an extremely low cost solution. However, when a private person in a developing country wants to purchase an apron for their own well, cost is much more likely to be an issue. The most effective way to reduce this cost is by reducing material costs and making the apron smaller.

Engineering literature for developing countries addresses well head protection for community supplies but no literature was found with recommendations for well head protection of private, self-supply wells in developing countries. There is no evidence to show that the recommended well apron diameter of 2 meters or any other of the recommended features of a well apron are due to anything but engineering judgement and common sense decisions on the part of the designer. It makes sense given the context that the 2-meter diameter community well apron size would not be questions since there are many design reasons to make it large and a lack of extreme financial pressure to make it smaller. In a self-supply context, where cost is a major issue for private households and the number of people being served is much smaller, a smaller apron may be more appropriate to protect water quality.

2.3 Risks from Rain Run-off on Wells in Developing Countries

Many studies have found a relationship between precipitation and groundwater quality for both boreholes and hand-dug wells. As explained in Section *2.1 Principles of Groundwater Contamination and Measuring Microbial Risk* contamination can enter a well through either a direct, localized pathway or an indirect, aquifer pathway. Rain can carry micro-organisms and flow into wells or soak into the ground and into an aquifer. This effect on water quality can been seen in a worsening of water quality through the rainy season and shortly after raining.

Wells have been found to have lower water quality during the rainy season than the dry season in multiple studies. This effect of seasonality has been observed in terms of diarrheal disease reported at clinics (Cronin et al. 2006) and in terms of elevated levels of indicator bacteria such as thermotolerant coliform, *E. coli*, or enterococcus (Potgieter, Mudau, and Maluleke 2006; Godfrey, Timo, and Smith 2006; Leber et al. 2011; Knappett et al. 2012; Engström et al. 2015).

A review of 22 studies of improved water sources in developing countries performed by Kostyla et al. (2015) showed that boreholes had statistically significantly (p<0.001) greater fecal contamination in the rainy season and found that the relationship was consistent for both *E. coli* and thermotolerant coliforms in both rural and urban settings across different climate zones. They had an insufficient number of protected wells (presumably hand-dug wells) in the review to do any seasonal analysis of their water quality. They were unable to determine from their review if seasonal differences in water quality of improved sources was due to a large spike in contamination from rains at the start of rainy season from the “first flush” of contamination or because of a longer-term trend for higher contamination levels through the whole rainy season.

Potgieter et al. (2006) examined communal and private boreholes in South Africa for a wide variety of bacteria. Their results for private boreholes will just be discussed here because they are the most relevant to this study. Potgieter et al. (2006) provided no depths for the private boreholes and they were also mostly unprotected. It was found that there was a statistically significant difference in the contamination between the rainy and dry season for private boreholes, however, the differences in means were not large in magnitude and the range of contamination measured was similar. For example, total coliform in the rainy season (mean and standard deviation) was 85.6 ± 215.6 CFU/100 mL and in the dry season was 29.1 ± 114.3 CFU/100 mL ($p<0.0001$). For fecal coliform in the rainy season (mean and standard deviation) was 19.0 ± 84.8 CFU/100 mL and in the dry season was 7.8 ± 48.2 CFU/100 mL ($p=0.0011$). In this study, even though the seasonal differences in contamination are statistically significant, the ranges of the data sets for both seasons overlap. This indicates that there are some wells that are more contaminated in the dry season than some wells in the rainy season.

Leber et al. (2011) examined boreholes in Bangladesh but only results from shallow wells (<20 meters) are discussed here. Statistically significant ($p<0.05$) differences in *E. coli* detection in the rainy season verses the dry season were found with 61% of wells being positive for *E. coli* in the rainy season and 9% being positive in the dry season. Despite the differences in *E. coli* detection the median differences were small. One site studied had median values of 1.8 CFU/100 mL in the rainy season and 0.5 CFU/100 mL in the dry season while another site had of 0.8 CFU/100 mL in the rainy season and 0.5 CFU/100 mL in the dry season. There was also a wide distribution of values overlapping in the rainy and dry seasons with some of the largest values for *E. coli* detection taking place in the dry season. See Section *2.4 Risks from Poor On-Site Sanitation and Well Head Protection* for more discussion of this study and the pathways found for contamination.

Engström et al. (2015) studied both boreholes and hand-dug wells in South Sudan. It was found that there was a statistically significant relationship ($p<0.05$) between thermotolerant coliform and the long-term, cumulative precipitation depth (i.e. the rainfall depth over the preceding 5 days and the preceding month), however, no link was found between contamination and short-term precipitation (from the previous 24 and 48 hours). The authors stated that it is possible that this lack of association with short-term precipitation was due to the lack of importance of localized pathways due to well head protection of the wells and therefore rapid contamination was not possible. There were also large uncertainties in short-term precipitation depth due to the method of estimating the rainfall depth from satellite data. This study shows the importance of different pathways for aquifer contamination and how their signal will be different in fluctuations of well water quality. See Section *2.4 Risks from Poor On-Site Sanitation and Well Head Protection* for further discussion on the reasons.

Cronin et al. (2006) studied springs and shallow hand-dug wells in Mozambique. They found that levels of thermotolerant coliform in the well water was associated with rainfall and sanitary risk, and the aquifer was not highly contaminated to begin with. This is reflected also in the fact that diarrhea reported at health clinics was associated with rainfall during the rainy season ($R^2=0.55$) but not the dry season. They did not separate their analysis of springs and wells but found over all that the average thermotolerant coliform levels in the dry season were 39.1 CFU/100 mL and during the rainy season were 121.2 CFU/100 mL. The median levels during the dry season were 2 CFU/100 mL and during the rainy season 13 CFU/100 mL. These are significant differences in concentrations, however, they do not exclusively include well sources.

Rainfall is associated with increases in contamination of groundwater between the rainy and the dry season. In different studies discussed here, the difference in median or mean values is not always important from a contamination point of view and the distribution of contamination levels overlap. This suggests that while there are seasonal differences in contamination levels they may not always be great enough to make a large difference in the risk of water.

2.4 Risks from Poor On-Site Sanitation and Well Head Protection

Studies of well head protection in developing countries have found that it is important for protecting water quality, except in some cases where aquifer contamination was already very high. Studies are mostly vague on the details of construction of the well head protection, details of the problems with the well aprons, and sometimes even vague on whether the well is a borehole or hand-dug well. For example, the extent of the description of well head protection for many studies is simply stating if the apron is cracked but they do not have details on how the apron is cracking, the size or shape, if there is a curb on the edge of the apron, or any other descriptions. Some studies that use sanitary risk scores are better at describing the nature of the problems at the well head (since sanitary risk score surveys include questions like if the pump head is loose, if the apron is less than 2 meters in diameter, etc.) but these are still general in nature (see Section *2.2 Typical Recommendations for Well Head Protection* for more discussion of sanitary risk scores). Bain et al. (2014) also found the same issue with vagueness on design of well head protection when they did their meta-analysis of studies examining fecal contamination of water in low- and middle-income countries. This lack of details on the state and design of well head protection is a limitation of the current literature on the topic.

A number of different studies have reported that well head protection is important for water quality of a well. Studies have shown that contaminated groundwater can be due to damaged well head protection that might have openings in the well casing, cracking in the apron, or stagnant water on the apron (Godfrey, Timo, and Smith 2006; Cronin et al. 2006; Potgieter, Mudau, and Maluleke 2006; Escamilla et al. 2013). Studies that did not find that well head protection was effective may have had confounding variables affecting the study such as well priming (Knappett et al. 2012), contamination from dense population or flooding (Luby et al. 2008), or a shallow, vulnerable water table (Leber et al. 2011).

Bain et al. (2014) performed a meta-analysis of 319 different studies of fecal contamination from many different types of water sources in low- and middle-income countries. They found that protected groundwater sources are less contaminated than unprotected groundwater sources but high levels of contamination can still be found in protected wells. Their comparison of protected versus unprotected groundwater sources had an odds ratio of 0.26 (95% CI[7] 0.11-0.60, *p*=0.002) for detecting fecal indicator bacteria >1 per 100 mL and an odds ratio of 0.37 (95% CI 0.09-1.52, *p*=0.16) for detecting fecal indicator bacteria >100 per 100 mL. This meta-analysis shows that, in general, protecting groundwater lowers the probability of contamination but does not provide a lot of details on when well head protection is not effective or what design features of well head protection make it effective.

Water quality in wells can have a lot of variation even if they are protected. In a literature review, Bain et al. (2014) found that protected hand-dug wells were contaminated with fecal bacteria much of the time and high levels of contamination could also be seen in boreholes. Additionally, studies that evaluated wells with sanitary risk scores frequently found that wells still had fecal bacteria even with low sanitary risk scores. Figure 2.3 is modified from Bain et al. (2014) and shows important information about the ranges of contamination found in boreholes, protected hand-dug wells, and unprotected (i.e. open to the environment) hand-dug wells. In the meta-analysis, unprotected dug wells did not have low levels of contamination and protected dug wells could have a range of contamination from low to very high. Boreholes generally do not get as contaminated as unprotected dug wells but protected dug wells can be as clean as a borehole. These graphs demonstratin that protection of wells generally does improve water quality but it is not a guarantee of water free of indicator bacteria.

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[7] CI, confidence interval

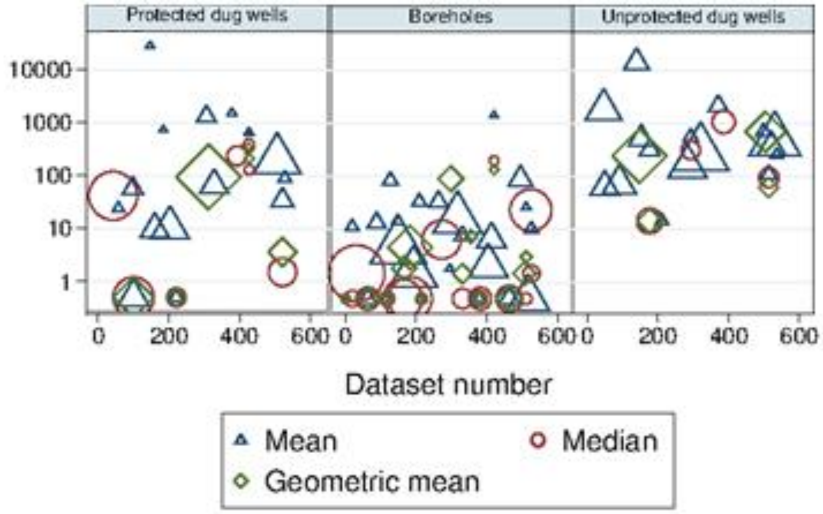

Figure 2.3 A modified figure from Bain et al. (2014) of data for mean, median, and geometric mean contamination of boreholes, protected dug wells, and unprotected wells from studies included in the review. The size of the data point is proportional to the number of water samples in the study. Unprotected dug wells did not have low levels of contamination and protected dug wells could have a range of contamination from low to very high. Boreholes generally do not get as contaminated as unprotected dug wells but protected dug wells can be as clean as a borehole. (See Appendix B for a note about permission to use this figure.)

A number of studies have investigated tubewells in Bangladesh (Escamilla et al. 2013; Knappett et al. 2012; Leber et al. 2011; Luby et al. 2008). While none of the studies explicitly state what type of pumps are being used except for making references to them being suction pumps, it is likely that the pumps involved are No. 6 pumps that are installed in large numbers in Bangladesh (Baumann 2011). No. 6 pumps are suction pumps that are commonly installed on thin tubewells using a manual hand-sludging technique and are identical in most aspects important to this study to Malagasy Pitcher Pumps except for the manual drilling method used to install them. This difference in the drilling method means that the well screen for the pumps in Bangladesh could potentially be placed deeper into the water table than is feasible in Madagascar. Potentially the learnings from these studies in Bangladesh might be applicable to understanding Malagasy Pitcher Pumps.

Escamilla et al. (2013) studied tubewells in rural Bangladesh. They found that concrete aprons reduced *E. coli* detection during the early and post monsoon season (p<0.1) but did not decrease contamination during the monsoon season when flooding occurred or during the non-monsoon season (no concentrations of *E.coli* were given in the paper). This indicates that concrete aprons can protect water quality of tubewells from rain but in some cases, such as when there is flooding, they are insufficient.

Knappett et al. (2012) studied tubewells in Bangladesh and compared annularly unsealed private wells with annularly sealed and unsealed monitoring wells. None of the 35 private wells studied had any annular sealing but 11 of them had intact concrete platforms and 19 either had a broken platform or no platform. Private wells with and without aprons were more frequently contaminated than sealed monitoring wells in the rainy season and all year round ($p<0.05$) but not during the dry season. Analysis on fecal indicator bacteria DNA also showed that private wells and sealed monitoring wells had similar levels of DNA except for a spike in private wells in the rainy season. An intact concrete platform on a private well did not have any effect on the water quality for both the rainy and dry season. This would seem to suggest that annular sealing is necessary for well head protection from rainfall and concrete aprons may not make a difference, however, there are some limitations to the analysis in this study that make this a tougher conclusion to come to. No comparison was reported that separated the private wells with and without aprons into two groups and compared them to sealed monitoring wells. The lack of controlling for priming of hand pumps in the study is of great importance and probably confounded the results since other studies have found that priming water is an important source of contamination (Wahlstrom-Ramler 2014). Additionally, the monitoring wells were not being used as water points by people and therefore cannot be a perfect control for a comparison with private wells that are being used by people.

In a study of wells in an urban area in South Sudan, Engström (2015) found that poor well water quality was associated with the depth of long-term, cumulative rainfall but no association was found with damaged well head protection (see Section *2.3 Risks from Rain Run-off on Wells in Developing*

Countries for further discussion of the results related to rainfall for this study). The study also found no correlation between water contamination and latrine presence within 30 meters. The authors suggested that this result was probably due to surface water infiltrating through an aquifer pathway and therefore the groundwater quality was such that well head protection did not make a difference.

Luby et al. (2008) studied tubewells in flood prone areas in Bangladesh. They found that the overall sanitary inspection score and any individual item in the sanitary risk score was not associated with microbial contamination. None of the physical characteristics on the sanitary inspection score of the borehole head works was associated with differences in microbial water quality. Factors such as lack of apron, apron ≤2.3 square-meters, cracked apron, apron undercut by erosion, drainage channel broken, poor drainage, and tubewell loose all had 95% confidence interval odds ratios that spanned 1.0 for both thermotolerant coliform and *E.coli* concentrations and therefore were unassociated with contamination. The authors speculated that this might be due to the population density of the study area or because some of the study wells have a history of inundation, which was significantly associated with borehole contamination. This is another case that well head protection was not able to protect water quality because the water was already of poor quality. As previously discussed, Escamilla et al. (2013) also found that well aprons provide little protection when the area is inundated with a flood.

Leber et al. (2011) also studied boreholes in Bangladesh (see Section *2.3 Risks from Rain Run-off on Wells in Developing Countries* for further discussion of the results related to rainfall for this study). They did not find a correlation between contamination and condition, or even existence, of approximately 4 square-meter concrete well aprons. The authors thought that this was likely due to shallow water tables that did not have enough attenuation of micro-organisms to clean the groundwater.

Overall, the evidence from studies and meta-analysis points to the fact that well head protection is protective of water quality from wells. It should be noted that a protected groundwater source does not *necessarily* mean that water will not be contaminated and in fact this review found that protected sources were frequently contaminated. Unfortunately, there is not great detail on the need for different design features in well head protection such as size, curbs, or drainage design. One can also conclude from the above studies that in many situations well head protection is helpful for protection from rainfall but in situations that there are confounding variables, such as pump priming or large amounts of contamination flowing through the aquifer pathway, well head protection may not be as protective of water quality.

2.5 Past Research on Pitcher Pumps in Madagascar

The University of South Florida (Tampa, FL, U.S.A.) has performed extensive research into the Pitcher Pump market in Tamatave, Madagascar (MacCarthy 2014; MacCarthy et al. 2013; Wahlstrom-Ramler 2014; Akers 2014; Akers et al. 2015; MacCarthy et al. 2016). The Malagasy Pitcher Pump market is reported to be the largest example of an unsubsidized well pump market in sub-Saharan Africa (MacCarthy et al. 2013). In fact, MacCarthy et al. (2013) estimated that 60% of Tamatave uses Pitcher Pumps as a source of water.

MacCarthy (2014) conducted interviews with Pitcher Pump owners in Tamatave. It was found that they were commonly shared among neighbors with 4.6 households on average using each pump, even if they did not pay for the pump. This is important because it shows that each pump has a benefit not only for the family that purchased it but also for neighboring families. MacCarthy (2014) also found that most of the pump owners in Tamatave would prefer to have a connection from the municipal system but did not because of the connection costs and the cost of water tariffs.

A majority of owners (75%, 40 of 53 surveyed households) reported drinking water from their pumps. Not all of these households treated their water before consumption; only 6 out of 40 reported using chlorine and 23 out of 40 reported boiling their drinking water (MacCarthy 2014). This indicates that these can be a significant source of drinking water for users. It also demonstrates that the pumps are still valued as only a source of water for non-potable uses because 25% of users surveyed had Pitcher Pumps but did not obtain drinking water from them.

MacCarthy (2014) also identified approximately 50 small businesses in Tamatave that manufactured Pitcher Pumps. These businesses ranged from having Pitcher Pumps as their primary business (selling between 12-30 pumps per month), a secondary business (selling between 4-12 pumps per month), or technicians who purchase pumps from other shops and perform the installation (1-16 pumps per month).

2.5.1 Water Quality

Both MacCarthy (2014) and Wahlstrom-Ramler (2014) tested levels of thermotolerant coliforms in Pitcher Pumps in Tamatave. MacCarthy (2014) determined that 37 of the 51 Pitcher Pumps tested had detectable levels of thermotolerant coliforms and 23 of the 51 Pitcher Pumps tested had >10 CFU/100 mL. Wahlstrom-Ramler (2014) determined that 26 of 59 pumps sampled had >10 CFU/100 mL. These results suggest that a large number of Pitcher Pumps in Tamatave are producing water that has intermediate to high risk to the users. Wahlstrom-Ramler (2014) also investigated the possible reasons for the microbiological contamination of Pitcher Pump water and how it may be reduced. She examined whether depth, neighborhood, priming, frequency of system repairs, distance from on-site sanitation, and number of users at a pump had an effect on the microbial contamination. The only one of these factors to be statistically significantly associated with thermotolerant coliform contamination was pump priming (p=0.03). Wells that needed priming had a median thermotolerant coliform concentration of 41.3 CFU/100 mL while wells that did not need priming had a median concentration of 3.5 CFU/100 mL.

Results showed that the thermotolerant coliform concentration increased in monitoring wells after a heavy rain but there was not enough data to draw definitive conclusions. It should be noted that Wahlstrom-Ramler's (2014) monitoring wells did not have any protective apron around them to prevent local pathways of contamination.

Akers (2014) and Akers et al. (2015) investigated the lead (Pb) contamination in the Pitcher Pump water in Tamatave due to lead components in the check valve weights and solder for well screens. He found that there were issues of concern with Pb leaching into water. In this study, the researchers performed three sampling campaigns on 18 different pumps in Tamatave and found that 15 of 18 produced samples that where above the World Health Organization (WHO) Pb guideline at some point over the three sampling campaigns. That study determined that flushing the Pitcher Pumps produced a statistically significant reduction in median Pb concentrations ($p<0.0001$) with 67% of first draw samples after 1 hour of pump inactivity produced Pb concentrations above the WHO guidelines and 35% produced Pb concentrations above WHO guidelines after flushing 2.5 well volumes of water out of the pump. After examining the importance of pump age, manufacturer, depth to well screen, season, contact time, and corrosivity to Pb concentrations, the researchers found that contact time with lead components was the only statistically significantly important variable. The study also replaced lead weights on check valves with iron weights on two pumps and found that that the iron weights consistently produced Pb concentrations below the WHO guideline even after periods of 11-13 hours of no use. This suggests that simply replacing the lead check valves with iron or another material could be a practical solution for reducing Pb concentrations in Pitcher Pump systems.

2.6 Morondava, Menabe Survey of Well Aprons

An informal, unstructured survey was conducted in the town of Morondava, Menabe region to learn about well aprons already being constructed in Madagascar before designing the well apron for this study. The town of Morondava is located on the western coast of Madagascar and has significantly less coverage with Pitcher Pumps than Tamatave. Informal visits were made to households that owned Pitcher Pumps to see if there were commonalities to designs, user preferences, or design issues for well aprons already constructed. The structures built around Pitcher Pumps in Morondava fell into three categories: bucket pads, half well aprons, and full well aprons.

Figure 2.4 Examples of bucket pads in front of Malagasy Pitcher Pumps. (Pictures taken by the author.)

Bucket pads are anything that is placed in front of the pump to put a bucket on while pumping to prevent putting the bucket on wet sand or mud. Almost all Pitcher Pumps had some sort of bucket pad. They can be made from a variety of materials but most commonly were free materials such as planks of wood or flat rocks, although some owners did construct concrete pads.

Figure 2.5 Examples of half well aprons around Malagasy Pitcher Pumps. (Pictures taken by the author.)

Some pumps had *half well aprons* that did not symmetrically extend to all sides around the pump. A half well apron is differentiated from a bucket pad by having concrete directly along the side of the rising main which *might* prevent localized pathways of contamination. It is differentiated from a full apron by not having concrete extend symmetrically around the rising main but rather having it extend in front of the pump to make a place for a bucket.

Figure 2.6 Examples of a full well apron around a Malagasy Pitcher Pump. (Picture taken by the author.)

A very small minority of pumps had *full well aprons* that were roughly 2 meters in diameter or more. These large aprons were only observed at households that were very likely wealthier than average given the structure of the house or at pumps in Morondava that were subsidized by a non-governmental organization.

In all these cases, when the pump owners were asked why the bucket pad or apron was constructed the only answer replied was to keep buckets from getting dirty with mud or sand. There was absolutely no indication that there was any other motivation than this. This is worth noting since any well head protection designed needs to include a place to put a bucket or accommodate a bucket pad.

Figure 2.7 Example of the gap formed on a concrete well apron from deflection of the rising main during pumping. The rising main is the pipe on the left of the photograph. (Picture taken by the author.)

An important design flaw was observed in well aprons already constructed. Figure 2.7 shows a close-up of one of the pumps observed with a well apron. Due to the deflection of the rising main during manual pumping the concrete around the rising main has worn down and there is a gap between the rising main and the apron. This gap could allow for contamination to travel into the well via a local pathway. This is the most significant piece of information gathered during the survey that informed the well apron design used in this study. See Section *3.2.3 Circular Concrete Apron* for more details on the well apron design used in this study and how this issue was avoided.

CHAPTER 3 METHODS

3.1 Study Site

This study took place in the city of Tamatave, Madagascar during 2016 and 2017. Data collection took place 19 July 2016 to 30 April 2017. Tamatave is a large port in Madagascar and is located on the eastern coast of the country. The population is estimated to be about 280,000 (MacCarthy et al. 2016).

The study area within Tamatave was selected because it overlapped with the study area for Wahlstrom-Ramler (2014). That particular study found that there was not a statistically significant difference in groundwater quality by neighborhood and pump technicians stated that the water table was deeper in the area (see Section *3.4.1 Criteria for Selection of Wells for Study* for additional justification for the groundwater depth). The 45 Pitcher Pumps in this study were located in seven *fokontany* (i.e., neighborhoods) (Table 3.1). The study covered an area about 1 ½ kilometers by ½ kilometers. Figure 3.1 shows a map of the study area with the locations of the 45 pumps.

Table 3.1 Number of pumps used in study in a particular fokontany (neighborhood).

Fokontany	**Number of pumps**
Morafeno	6
Ankirihiry Nord	18
Ankirihiry Sud	1
Tanambao 5	11
Antanamakoa	7
Analakinina Hopitaly Be	1
Mangarivotra	1

Figure 3.1 Map of the study area with the approximate locations of the 45 Pitcher Pumps used in the study categorized by their respective study groups. Map obtained from Google Earth (Version 7.1.5.1557) with information from DigitalGlobe ©2018.

The hydrology at this study site consists of an unconsolidated, coarse-grained, sandy, shallow aquifer. Wahlstrom-Ramler (2014) categorized the soil in the area as a coarse-grained with fines and specifically as medium grained, sub angular sand (Unified Soil Classification System [USCS]=SM) to 4.2 meters below the ground surface. This was consistent with the cuttings from drilling operations observed during the study, although some wells in the study appeared to have some small amounts of clay attached to the well screens when they were removed from the ground. The depth of the water table measured in the study ranged from 217 ± 5 cm to 655 ± 5 cm with a median depth of 402 ± 5 cm in June, July, or beginning of September 2016 at the start of the study (see Appendix C for data). This was consistent with Wahlstrom-Ramler (2014) who measured depths of water tables ranging from 3.2 to 9.0

meters and a median depth of 4.1 meters. All wells in this study were located at least approximately 50 meters away from a canal.

The east coast of Madagascar, where the study site was located, has rainfall all year round with wetter months and drier months but no distinct dry and rainy seasons; this study started during the drier months (July) and ended during the wetter months (April).

From observation, almost all of the people in the neighborhood in this study were meeting a significant portion of their daily water needs from Pitcher Pumps. Essentially every housing lot in the neighborhoods that this study was conducted in had a Pitcher Pump on the property. The only exceptions were a few very wealthy households that had a municipal water connection from JIRAMA (the municipal water service). Even if a household had a municipal water connection they frequently reported using Pitcher Pumps for non-potable uses like washing clothes or watering plants.

Property was divided into housing lots in the study neighborhoods. Multiple single-story houses were on the property lots with the owner living in one and with multiple renters living in others (in some cases the landlord lived off the property). The land on the housing lots was generally bare soil with some trees or small plants. Furthermore, there was generally no concrete on the land aside from the foundations of houses. The lots were approximately 30 to 50 meters wide by 40 to 60 meters deep; they were not a standard size and were roughly rectangular. The number of people per housing lot, and therefore the number of people that used the pumps, varied from 4 to 30 adults and children but neighbors would use a pump if theirs was broken; it should be noted that the number of people living on each housing lot fluctuated through the study. Most housing lots had one pit latrine or pour-flush latrine shared among all the residents (see Section *3.4.3 Well Preparation and Characteristic Measurements* for more discussion of on-site sanitation design). Most of the time houses were located in the center of the property with the on-site sanitation and pumps located near the edges of the property. In practice this means that it is very difficult to find a location for a pump that is both convenient for the user and also meets the 30-meter horizontal distance from on-site sanitation that is recommended by many sources for siting wells (Action Contre la Faim 2005).

3.2 Types of Well Head Protection Being Tested

3.2.1 No Well Head Protection

A vast majority of the wells in the study area did not have any concrete around the well or any other type of well head protection (Figure 3.2). If there was concrete surrounding the well it was associated with some other construction. Some pumps were observed to have short plants growing directly around the rising main called *Songno* in Malagasy and a few people claimed to the author that they helped to clean the water in the well.

Figure 3.2 Example of Pitcher Pump in Tamatave without well head protection. (Photo taken by the author.)

3.2.2 Pipe Collar

The most basic type of well head protection used in this study is a pipe collar that is buried shallow around the rising main. The pipes used for well head protection in this study were made from a pressure-rated (i.e. thick walled) PVC pipe. However, in principle any material can be used as long as the walls do not have holes in them. A 100-millimeter diameter pipe 25-centimeters long was used with 10 centimeters buried below grade and 15 centimeters above grade (Figure 3.3).

Figure 3.3 Example of a Pitcher Pump with pipe collar installed. (Photo taken by the author.)

The pipe collars were installed on driven wells by putting the rising main through the pipe collar before hammering the rising main into the aquifer. Pipe collars cannot be placed on after drilling because of a flange at the top of the rising main for the attachment of the Pitcher Pump's head. To install the pipe collar on an in-use Pitcher Pump the rising main needs to be removed from the ground and then placed through the pipe collar before reinstalling the well. Removing the rising main pipe from the ground is a common procedure done on Pitcher Pumps in Madagascar to make repairs to the rising main or well screen so it is not unreasonable to think that a person could upgrade to this well head protection if they wanted to during normal pump repairs.

In this study the pipe collar was designed to prevent water from flowing directly along the side of the rising main. Surface run-off should flow to the edge of the pipe collar and then down 10 cm to the bottom of the pipe. At that point the water should percolate through the vadose zone like any other water. There should be some lateral movement of the water through the vadose zone but if the soil is homogeneous the direction that the water moves horizontally is equally probable in all directions, therefore, there is a probability that it may still travel to the rising main and flow down the side as a localized contamination pathway. The pipe collar was reasonably sturdy when installed but there were some cases where it was knocked crooked (and then straightened again); it is not believed that being crooked would greatly affect its ability to protect against a local pathway of contamination.

3.2.3 Circular Concrete Apron

The largest well head protection used in this study was a 50-cm diameter circular apron, 9-cm thick built around a pipe collar with the top outer edge of the apron being on grade with the surrounding soil and the top of the apron being graded so that water flows away from the rising main (Figure 3.4). The apron was constructed of poured concrete with a standard 1:2:2 concrete mix (ratio of cement:sand:gravel by volume).

Figure 3.4 Concrete well apron constructed in this study. (Photo taken by the author.)

The apron was installed around the pipe collar because it was found during the survey in Morondava that vibration of the rising main during pumping damaged concrete well aprons (See Section *2.6 Morondava, Menabe Survey of Well Aprons*). Building an apron around the pipe collar avoids this issue completely. Additionally, it allows for the removal and re-installation of the rising main for repairs without breaking the well apron.

The top of the apron needed to be on grade with the surrounding soil because buckets used to gather water from the pumps are placed approximately 25 cm away from the pump. If the apron is not on grade with the surrounding soil, this would cause the bucket to teeter awkwardly on the side of the apron.

The apron diameter of 50 cm was chosen because it was of a moderate size and was much smaller than the recommended diameter of 2 meters for community pump well aprons (see Section *2.2 Typical Recommendations for Well Head Protection*). The circular shape was selected so that the protection would be symmetrical around the pump. The final apron thickness of 9 cm was determined by the concrete form that was used. The upper portion of a plastic tub was used for the apron form. This was chosen as a form because it happened to be the dimensions of the apron and also provided a chamfer on the upper edge of the apron, which is consistent with standard masonry practices to avoid chipping of the edge of concrete slabs.

This apron should work with the same principle as described above for the pipe collar. The difference is that the probability is smaller that the run-off will horizontally travel in the vadose zone, intersect with the rising main, and then run down to the groundwater since the diameter of the apron is 5 times bigger than the pipe collar, however, it is unknown to the author how much smaller the probability is.

3.3 Study Phases

The study was a mixed within-subjects, between-subjects design and involved a semi-parallel, semi-serial sampling of wells. The 45 study wells were randomly divided with an online random number generator (www.random.org/) into three groups of 15 wells each: 1) a control with no well head protection, 2) an experimental group with a pipe collar, and 3) an experimental group with a concrete well apron. During Phase 1 of the study, baseline values for water quality were measured for all wells before adding any well head protection. This phase lasted 18 weeks. In Phase 2 a pipe collar was installed in both experimental groups and water quality was measured for all wells for 8 weeks. In Phase 3 a concrete apron was added to one of the experimental groups and water quality was measured for all wells for 8 weeks (Table 3.2).

Table 3.2 Study phases for the control and experimental groups. The pipe collar was tied above the ground for Phase 1 of the pipe collar and concrete apron groups so that they were identical to a pump without well head protection.

	Control Group	**Pipe Collar Group**	**Apron Group**
Phase 1	No Well Head Protection	No Well Head Protection	No Well Head Protection
Phase 2	No Well Head Protection	Pipe Collar	Pipe Collar
Phase 3	No Well Head Protection	Pipe Collar	Concrete Apron

The purpose of this study design was to control for both rainfall and local conditions around the well. Serial sampling of the same well with increasing the well head protection around each experimental well allowed for the comparison of each well to itself without well head protection. This allowed for the control of site-specific conditions around the well such as contamination from on-site sanitation. Having three phases for the study with control and experimental wells being sampled in parallel allowed for rainfall to be controlled for, assuming that rainfall was similar throughout the study area.

The timing of the phases with respect to the rainy season is also important. The first phase that gathered control baseline data was started during the drier season in Tamatave and the experimental phases took place during the wetter season. This in theory would allow a large signal from rainfall to be seen during the wetter season and allowed us to compare it to a “background” signal for the bacteria normally found in the well water and then see if well head protection helped.

3.4 Site Preparation

3.4.1 Criteria for Selection of Wells for Study

To test the effect of well head protection this study specifically selected wells that would have a high probability of being contaminated from surface run-off via a localized pathway and a lower probability of being contaminated via an aquifer pathway and via pump priming. It was hoped that this way it would be possible to resolve the signal in the data from contamination via localized pathways by lowering the interference from water contamination from aquifer pathways or contamination from pump priming.

The main criteria for well selection was: 1) depth of the well screen ≥ 4 meters, 2) horizontal on-site sanitation distance ≥ 5 meters from the well, 3) the well was located in an area with a risk of contamination from rainfall runoff (e.g. land was not elevated, pump was not under a roof), 4) area around the pump did not have a reported history from the owner of being flooded during the rainy season, and 5) the pump was not located within 40 centimeters of a building, fence or wall to allow for concrete apron construction. The depth of the well and distance of the on-site sanitation was mainly limited by practical reasons. On-site sanitation located farther away and deeper wells could not be located because of the population density and aquifer geology. The well also needed to be located in a location that had a risk of contamination from rainfall runoff. Sometimes wells were located on land slightly elevated from its surroundings or were under an eave of a roof and were excluded for that reason. The low-cost well head protection in this study could not be designed to deal with flooding so no area that would regularly flood during the rainy season was chosen (however, some pumps were flooded during a cyclone and lots might briefly have several centimeters of water covering them during a very heavy rainfall event). As will be described in Section *3.4.3 Well Preparation and Characteristic Measurements* pump check valves were replaced before the start of the study so that they would be fully operational and not need priming.

3.4.2 Selection Process

Researchers located wells for the study by stopping door-to-door to see if the pump on the property fit the criteria listed in Section *3.4.1 Criteria for Selection of Wells for Study*. Researchers then returned to the property of the pumps selected for the study to discuss the study details with the pump owner and obtain approval for use of their pump in the study. The Institutional Review Board at University of South Florida stated that the study was not human subjects research and thus did not need special approval (see Appendix A).

3.4.3 Well Preparation and Characteristic Measurements

Wells were prepared for the study by removing leaded components from the pumps (Akers 2014), measuring lengths of removed pipes, making proactive repairs if needed, installing pipe collars on experimental group wells, and measuring the water table in the wells.

Well screens and check valves were replaced to remove lead components from pumps. After removing the well rising mains from the ground, well points and screens were sawed off and a new, unleaded well point was welded on. While above ground, well rising mains were measured for length and the diameter was identified by an experienced well technician[8]. Proactive repairs were made to a pump if it was thought that the rising main or top flange might be damaged upon reinstallation of the pump. Pump heads were also repaired if it was thought that manufacturing errors or corrosion on the inside of the pump head cylinder would lead to the need to repair the piston leather more frequently and therefore add an additional variable to the experiment.

After reinstalling the well's rising main, the water table was measured with a water-level dipper made from a fishing line and weight. The pump was then primed with less than a liter of municipal tap water with every liter treated with about 3 drops of 1.64% Sodium Hypochlorite solution (taken from a

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[8] The inner diameter could not always be directly measured because most rising mains were made of pipes of multiple diameters.

point-of-use chlorination product marketed in Madagascar as *Sûr'Eau*) added to disinfect the priming water but not to shock chlorinate the well.

The horizontal distance of on-site sanitation from well pumps was measured with a measuring tape. The distance to the closest latrine on four sides was measured except in cases were the latrine was very far away in comparison to other latrines (in most cases, this was > 25 meters from the pump) or the latrine was far down a very steep hill and was believed to probably not impact the well. Distance of on-site sanitation could not be measured in a straight line in most cases due to buildings so a path at right angles was measured instead and the Pythagorean Theorem was used to calculate the distance (Figure 3.5). All latrine distances are available in Appendix C.

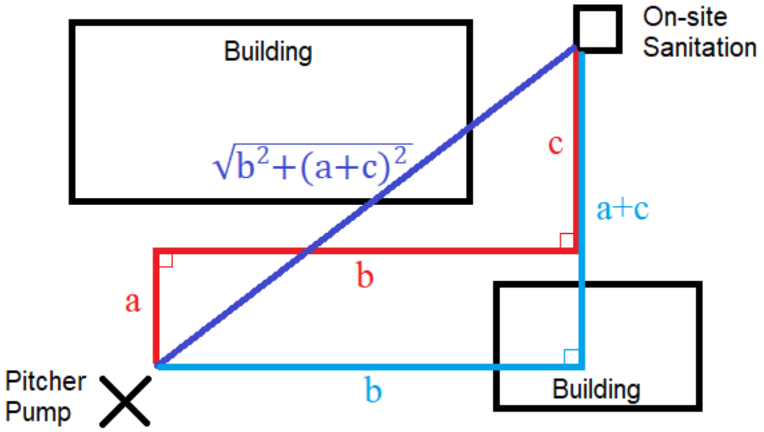

Figure 3.5 Example of how the distance of on-site sanitation was measured if a straight line measurement was impossible. The measurements were taken with a tape measure at right angles (red lines) and the calculation of the horizontal distance (dark and light blue lines) was made with the Pythagorean Theorem.

Two basic types of on-site sanitation was found in the study site[9]: 1) pit latrines and 2) pour-flush latrines. Pit latrines consisted generally of an unlined hole in the ground with a simple floor and privacy-structure and will certainly be directly contaminating the groundwater near them. Pour-flush latrines are constructed in different ways in Tamatave but the typical form is that there is one toilet bowl that leads via a short pipe to a sewage collection tank and they are flushed with a bucket. The

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[9] There were no municipal sewers in the study site.

design of the sewage collection tank is relevant to this study because those would be the potential points of groundwater contamination. The sewage collection tanks can either be a single chamber without a floor to allow for water infiltration or multiple, separate chambers with a floor for collection of solids and without a floor for infiltration of water. It was impossible to ascertain if the chambers were well sealed so during measurement the conservative assumption was made that the edge of the tank closest to the pump was the point that contaminated water might be infiltrating into the aquifer. Previously, Section *2.1.2 Aquifer Pathways* provided a brief discussion of the differences in risks to groundwater for pit latrines and pour-flush latrines.

3.5 Sample Collection

Pumps were sampled in duplicate with the exception of the first samples of some of the pumps being sampled in triplicate. If there was a repair to a pump then the pump would not be sampled for at least 5 days to ensure the washing out of any contamination. A majority of the sampling was perform by a Malagasy research assistant Isilore Andrinjafy. Before taking the sample the owner or other people on the premises were asked if there were any problems with the pumps that required repairs or priming; the research assistant estimated that in approximately 1 in 10 samples there was no one on the premises to ask. Pumps were always in use throughout the day.

Before sampling approximately 1 well volume of the water was purged out of the well so that the sample contained water from the bottom of the well. Commonly 3 to 5 well volumes should be purged if aquifer water quality is to be sampled (Vail 2013) but 1 well volume was chosen for this study so that water at the bottom of the well would be sampled. The purged water was collected in a bucket and discarded away from the pump so that spilled water did not affect the water sample. The wells were not purged if the sampler observed a pump user just collect water from the pump; instead the purge volume taken by the pump user was estimated. No effort was made to ask *everyone* on the housing lot if they had just taken water from the pump since it would take too much time. After sampling the samples were identified by writing the site designation and time of sampling.

The outlet of the pump was not sterilized with alcohol or a lighter flame as is commonly recommended (Delmas and Courvallet 1994; Action Contre la Faim 2005). The reason for this was because the pump heads were open to the air and it was believed it would be impossible to meaningfully sterilize the open surfaces without brushing the inner surfaces with one's hand and possibly contaminating them.

Sterilized bottles were used for sampling that were either glass or polypropylene and had volumes of approximately 125 mL, 350 mL, and 500 mL. Each bottle was sterilized in a laboratory of the non-governmental organization *Ranontsika* with an autoclave at 15 psi for 15 minutes or more. Immediately after collection, the water samples were placed in thermally insulated bags with ice packs and transported to the laboratory where they were placed in a refrigerator until processing.

3.6 Laboratory Sample Processing

3.6.1 Media Preparation

The media used in this study was RAPID'*E.coli* 2 (Bio-Rad, Hercules, CA, USA) which is a chromogenic medium meant for the detection of Total Coliform and *E. coli* via the detection of two enzymes, β-D-glucuronidase and β-D-galatosidase (Bio-Rad 2015). The chromogenic feature of the media was not utilized in this study.

Preparation of the media was according to the manufacturer's specifications except for the addition of a proprietary supplement which was not added due to a mistake. Normally the proprietary, selective supplement is added to suppress the growth of interfering flora normally found in water and with it added the RAPID'*E.coli* 2 is an Association Française de Normalisation (AFNOR)[10] certified

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[10] AFNOR is the national organization for standardization in France.

alternative method for the EN ISO 9308-1. Section *3.7 Gram Staining* provides additional discussion on how not using a supplement impacts the interpretation of the study results.

Powdered RAPID' *E.coli* 2 was measured with a scale (American Weigh Scale AWS-100 Digital Pocket Scale, 0.01 gram resolution) and mixed with distilled water and then autoclaved for 15 minutes at 15 psi. Distilled water was made in the laboratory with a distiller. After autoclaving the agar was aseptically transferred to sterilized petri dishes and stored in a refrigerator until use (normally the following day). No pH quality control measurement was carried out on the final agar.

3.6.2 Sample Processing

Water samples were transported to the laboratory within approximately ½ to 1 ½ hours after collection and placed in a refrigerator until they were processed. Processing occurred within 6 hours of sampling for 97% of samples and the rest of the samples were processed before 7 ½ hours after sampling. This meets the recommended goal for storage time of water samples between collection and processing and is well within the maximum recommended limit of 24 hours in Standard Method 9060 (American Public Health Association et al. 1992).

Water samples were processed with membrane filtration (see Standard Methods 9222 or ISO 9308-1 for examples of the membrane filtration method) in duplicate in approximately the order of their collection. The volume of filtered water from the sample depended on the expected colony counts of the sample based on previous testing; an attempt was made to maintain the colony count at approximately 70 colonies per plate. If the sample volume was less than 50 mL, sterilized distilled water was added to the membrane filtration funnel to help spread the colonies on the filter. Samples were then filtered through mixed cellulose ester, 0.45-µm pore-size, 47-mm gridded membrane filter (LabExact, Hawthorne, NJ, USA) and drawn through with a mechanical pump. The filters were aseptically transferred to and from the filtering apparatus with forceps sterilized in a Bunsen burner. The filters were placed on the medium after filtering, carefully avoiding air bubbles under the filter.

Then the petri dishes were inverted and placed into a laboratory incubator at 37° ± 1 C; approximately 93% of the samples processed were incubated for 23-24 hours and the rest were incubated between 18-22 hours.

Blank controls were run on every sampling day at the end of the processing session with 100 mL of distilled water to check the sterilization process on both the media and the distilled water used in processing. All controls had zero colony growth except for 2 CFU/100 mL on 3 March 2017 and 1 CFU/100 mL on 6 April 2017.

3.6.3 Colony Enumeration

All non-pin point, individual colonies on test plates were counted regardless of color. It is known from Gram staining (see Section *3.7 Gram Staining and Limitations of Media*) that even colonies that presented as characteristic colonies are not gram negative bacilli so this counting method gives a gross level of bacteria concentration that grow at 37° C. All plates that had resolvable individual colonies were recounted. Plates with confluent growth were labeled as detected. The data was discarded as errors if plates were more than about 100% different in count except if the plate counts were very low (i.e. below 15 CFU per plate).

3.7 Gram Staining and Limitations of Media

As explained in Section *3.6.1 Media Preparation*, this study used RAPID'Ecoli 2 media from Bio-Rad without a proprietary suppression supplement for interfering flora. The media *without* the supplement is meant to test food for *E. coli* and other coliforms at 37° C and *with* the supplement it is meant for detection of *E.coli* and other coliforms at 37° C in drinking and non-treated water. Due to an error the supplement was not included in media preparation and it was prohibitively expensive and unreliable to get the supplement shipped through Malagasy customs.

To learn what type of bacteria was being grown by the media without a supplement gram staining was performed. Part of the definition of Total Coliforms and *E.coli* are that they are Gram negative bacilli so any bacteria that are cocci or Gram positive cannot be Total Coliform, which is the target group of bacteria of the media with a supplement.

A wide range of colony presentations were selected for Gram staining including non-characteristic colonies and presumptive Total Coliform colonies (non-characteristic and presumptive colonies were based on the presentation of the colony, i.e. shape, color, size, etc.). Gram staining samples were taken from 82 colonies from 26 plates grown from water samples of 23 different wells sampled on the 23rd and 26th of April 2017. From the results, it appeared like the media used in this study could grow Gram positive and negative cocci and bacilli, in every combination. This was even true for colonies that presented as characteristic colonies. It is therefore likely that the entire data set of this study includes contamination from a wide spectrum of bacteria including, but not exclusively, Total Coliform. Even with this error, the data presented in this study is still useful and represents a measure of gross bacteria concentration grown at 37° C in well water. The limitations that this causes in the study are discussed in detail in Section *4.1.2 Limitations of the Study.*

3.8 Rainfall Measurement

Rainfall data for Tamatave was acquired from a government weather station at the Tamatave Airport (airport code: TMM) and was measured with a pluviometer. The weather station was between 2.7 and 3.6 kilometers from the closest and farthest pumps. Data used in this study was collected in tenth of a millimeter increments and one hour intervals.

3.9 Statistical Analysis

A histogram of the base-10 logarithmic transforms of bacteria concentrations showed that the data was non-parametric so only non-parametric statistical tests were used on this data set.

Spearman's correlation test was used to find correlations between 24-hour, 48-hour, 72-hour, 120-hour, and 168-hour antecedent rainfall depth and the base-10 logarithmic transforms of bacteria concentrations from data sets of wells separated by different levels of well head protection. The

Spearman correlation coefficient, ρ, quantifies the strength and direction of a correlation with 0 being no correlation and either -1 or +1 being the strongest correlation. This test was selected since it finds relationships in more general cases (i.e. monotonic) than other correlation tests (which tend to test linear relationships) and it is non-parametric.

Within and between subjects statistical tests were also performed on the data set. Between subjects, non-parametric statistical tests were performed with the Mann-Whitney U Test and the Kruskal-Wallis H Test. This allowed for different types of well head protection to be compared with control wells during the same experimental phase which controlled for seasonality. Within subject, non-parametric statistical analysis was performed on the data set with the Friedman Test and Wilcoxon Sign-Rank Test. This allowed for different types of well head protection to be compared on the same wells, which helps to control for local variations in ground water quality.

CHAPTER 4 RESULTS AND DISCUSSION

The purpose of this study was to develop recommendations on appropriate levels of affordable well head protection that could be integrated with Malagasy Pitcher Pumps and reduce contamination in water. To this end, the objectives of this study were:

1. Test the effect of two appropriate well head protection designs at different protective diameters surrounding a well on bacteria concentrations grown at 37° C in the water.
2. Develop design requirements of an appropriate well head protection design based on testing and user interest and preferences.

4.1 Objective 1: Testing of Well Head Protection

4.1.1 Experimental Results

4.1.1.1 Rainfall Data

Rainfall data was acquired from a government weather station at the Tamatave Airport which is located 2.7 to 3.6 km away from the closest and farthest pumps, respectively. Incomplete, qualitative notes on rainfall patterns (i.e. presence or absence of rain during segments of the day) where recorded by the author over two different weeks during the study and qualitatively matched the data collected by the weather station. Antecedent rainfall depth was calculated from 07h00 UT+3 in the morning on each day of data collection for the previous 24 hours, 48 hours, 72 hours, 120 hours, and 168 hours to the nearest millimeter; 07h00 was chosen because it was before the start of sample collection on each sampling day.

Figure 4.1 shows the 24-hour antecedent rainfall depth during the study. Note that water samples were not collected on a daily basis so the data used for calculating statistics in this study is a subset of the data shown here. The major spike in rainfall shown in the data (5-8 March 2017) is from Cyclone Enawo which hit Tamatave while the study was in the middle of constructing concrete aprons.

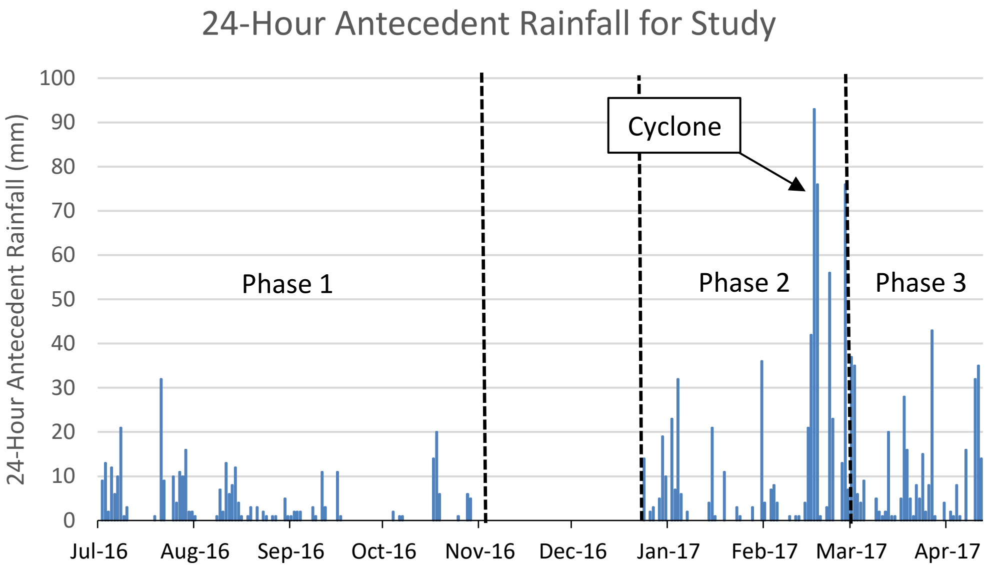

Figure 4.1 24-hour antecedent rainfall depth for every day in all three phases of the study. Data used in analysis is a subset of this data since samples were not collected daily. The major tick marks on the x-axis are on the 19th day of every month labeled. (N=238)

Figure 4.2 is a box plot of the antecedent rainfall depth for different study phases. Examination of Figure 4.1 and Figure 4.2 shows that the Phase 2 and Phase 3 study phases had more rainfall than Phase 1. Phase 2 also had many large outliers in rainfall due to Cyclone Enawo.

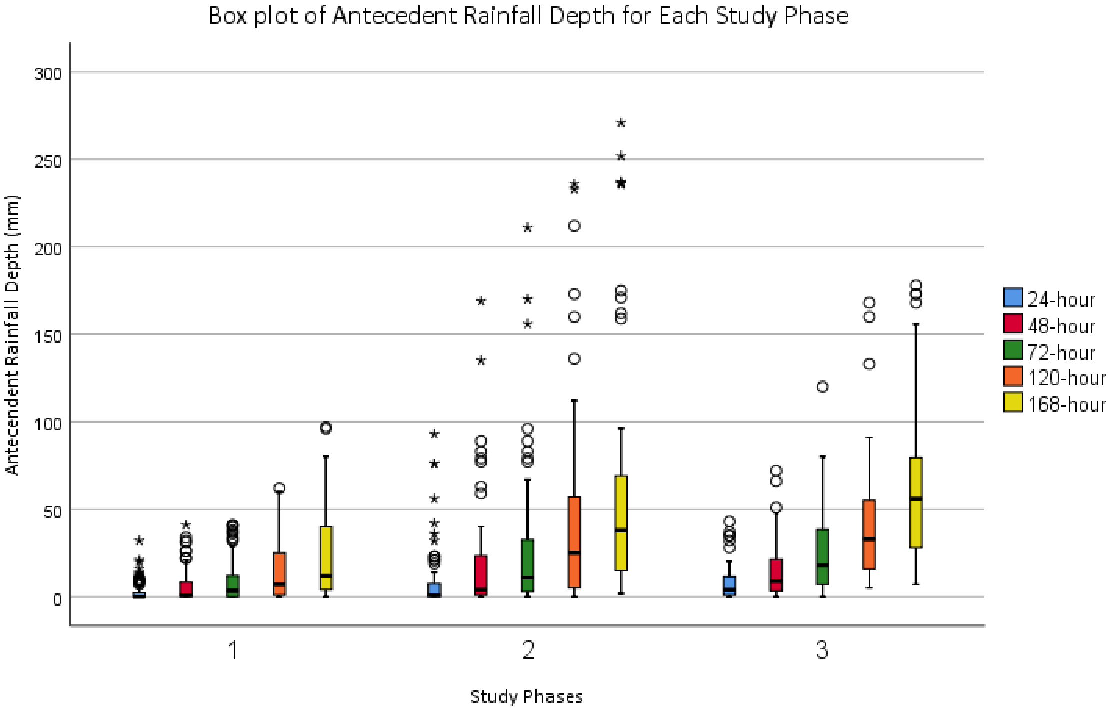

Figure 4.2 Box plot for antecedent rainfall depth for each of the three study phases. Data used in analysis is a subset of this data since samples were not collected daily. Phase 2 has many large outliers due to Cyclone Enawo. (N=238)

4.1.1.2 Microbial Water Quality Data

4.1.1.2.1 Well Head Protection and Microbial Water Quality

No clear relationship between well head protection and microbial water quality appears in the data from visual inspection (Figure 4.3 and Figure 4.4). There does seem to be a slight decrease in median bacteria concentrations in every study group as the study progressed, however, differences in median values for every study group across each phase do not appear to be statistically significant (discussed in greater detail in Section *4.1.1.3 Statistical Analysis*).

Figure 4.3 shows a scatter plot of the base-10 logarithmic transform[11] of bacteria concentration data (in units of $\log_{10}$ CFU/100mL)[12] for all the analyzed data versus sampling date (see Appendix C for

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[11] All values <1 used the logarithmic transform of $\log_{10}(x + 1)$, where x is a data value <1, to avoid negative and undefined values.

[12] CFU is Colony Forming Units, i.e. the number of colonies counted on a sampling plate.

data). In this figure, the shape of the data point matches the type of well head protection used in the phase (triangle is no protection, square is the pipe collar added, and circle is the apron added). The color of a data point represents the experimental group (blue is the control group, red is the pipe collar group, and gray is the apron group). From review of this figure, it does not appear like there is a relationship between bacteria concentration and type of well head protection given the spread of the data for every date and type of well head protection.

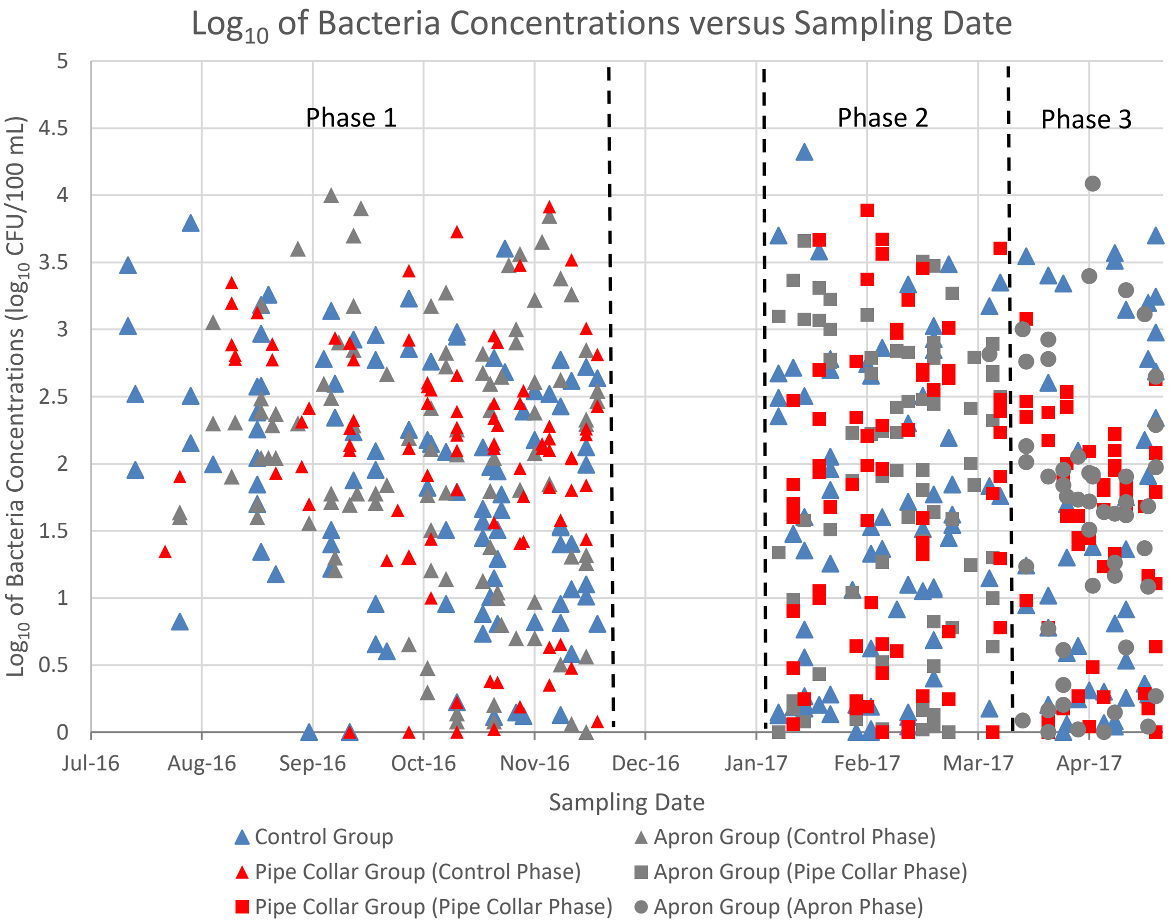

Figure 4.3 Logarithmic transform of bacteria concentration versus sampling data for every study group and type of well head protection. A single data point for Apron Group (Apron Phase) is in Phase 2 because Cyclone Enawo occurred in the middle of concrete apron construction and the author wanted to get data for wells immediately after Cyclone Enawo instead of continuing construction. (N=690)

Figure 4.4 is a box plot of the base-10 logarithmic transform of bacteria concentration data for every study phase. This figure suggests there is a slight downward trend in median values of bacteria concentration with every group, however, the distribution of values is very wide, spanning from 0 $\log_{10}$ CFU/100 mL to between 3 to 4 $\log_{10}$ CFU/100 mL.

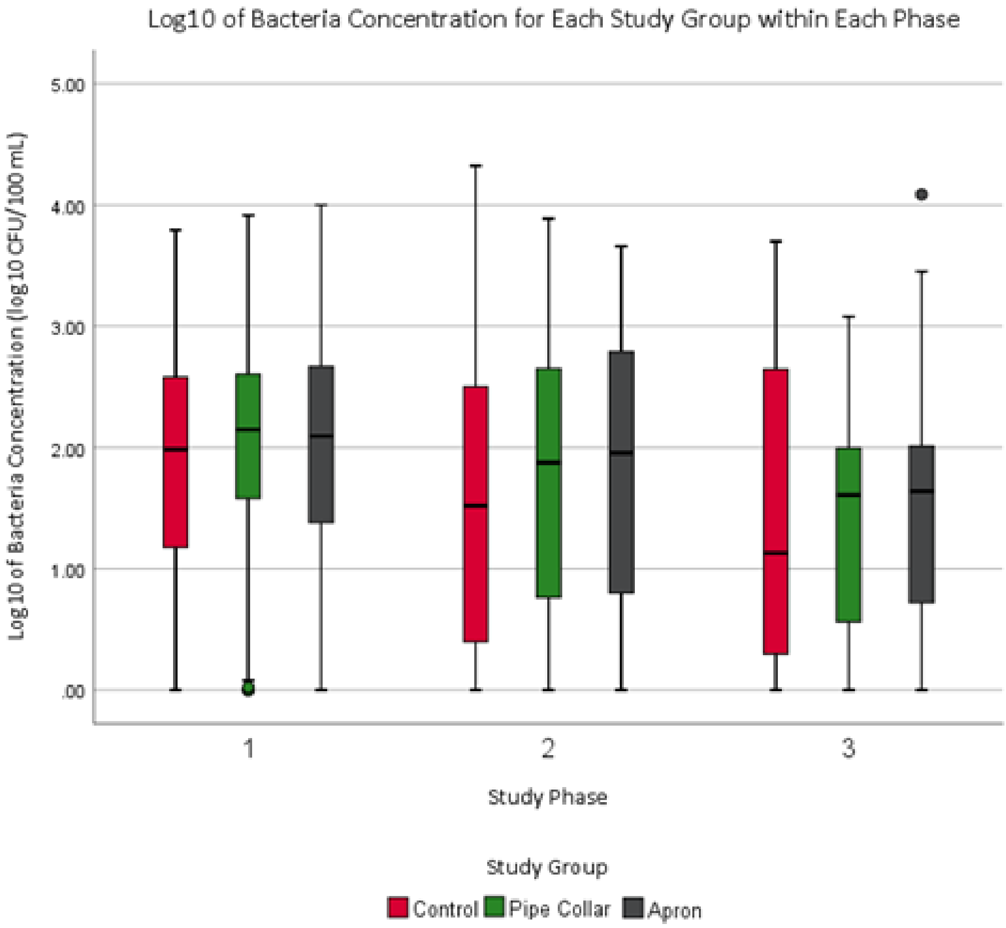

Figure 4.4 Box plots of bacteria concentration for every study group and study phase. (N=690)

Figure 4.5 and Figure 4.6 show differences in the means for different study phases for every individual well included in data analysis. In Figure 4.5 a negative value indicates a decrease in mean bacteria concentration with an increase in well head protection and a positive value indicates an increase in mean levels of bacteria concentration with increasing well head protection. Figure 4.6 is shown for comparison of these wells with controls. For Figure 4.6 there does appear to be a decrease over study phases for most wells but this does not appear to be due to well head protection since control wells with no well head protection show similar decreases over the same time period. There appears to be a trend in bacteria concentration levels but it is not clear from this data that it is related to well head protection. Statistical tests were performed on the data found no statistically significant relationship between bacteria concentrations and well head protection (see Section *4.1.1.3 Statistical Analysis*).

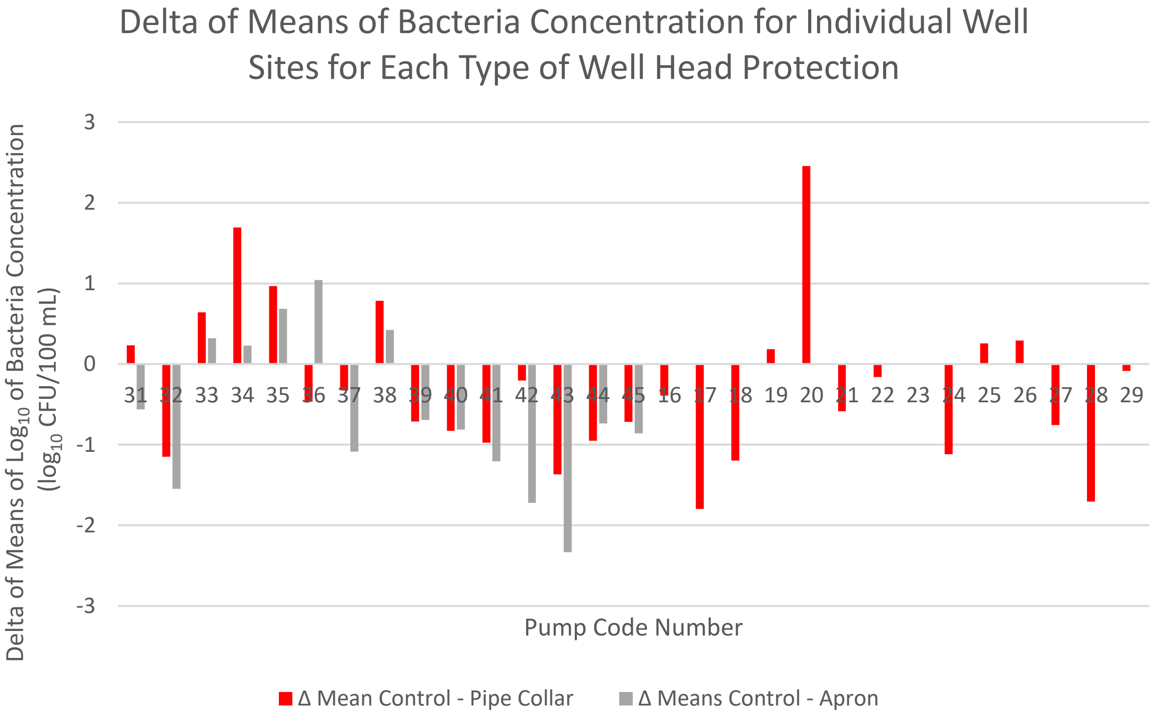

Figure 4.5 Differences in means for wells in both experimental groups when well head protection type changes. For apron group wells (wells 31-45) the delta of means was between Phase 1 and Phase 2 for "Δ Mean Control – Pipe Collar" (red bars) and between Phase 1 and Phase 3 for "Δ Mean Control – Apron" (grey bars). For pipe collar group wells (wells 16-29) the delta of means for "Δ Mean Control – Pipe Collar" (red bars) was between the mean for Phase 1 and the mean for Phase 2 and 3 combined since that group had pipe collars for both Phase 2 and 3.

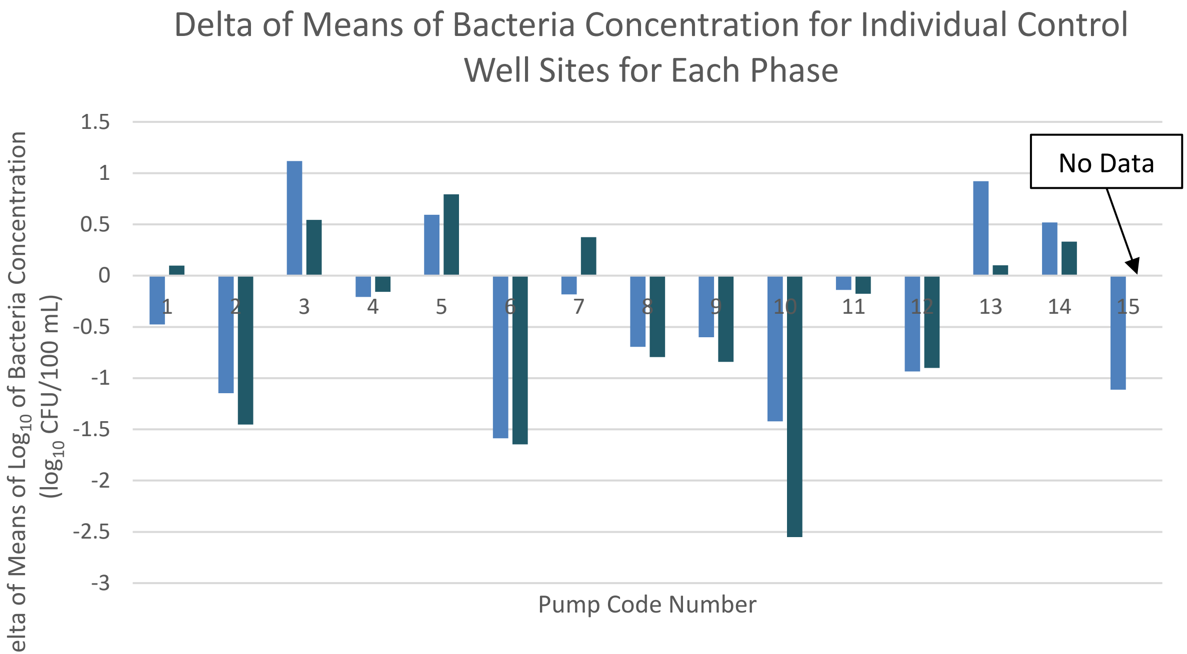

Figure 4.6 Differences in means for wells for control group wells across phases.

4.1.1.2.2 Antecedent Rainfall and Bacteria Concentration

Figure 4.7, Figure 4.8, and Figure 4.9 plots the relationship between the logarithmic transform of bacteria concentrations and antecedent rainfall depth for every type of well head protection at the well during the time of sampling in this study. In these three figures, the data appears to be equally scattered across several orders of magnitude of bacteria concentration for every depth of antecedent rainfall.

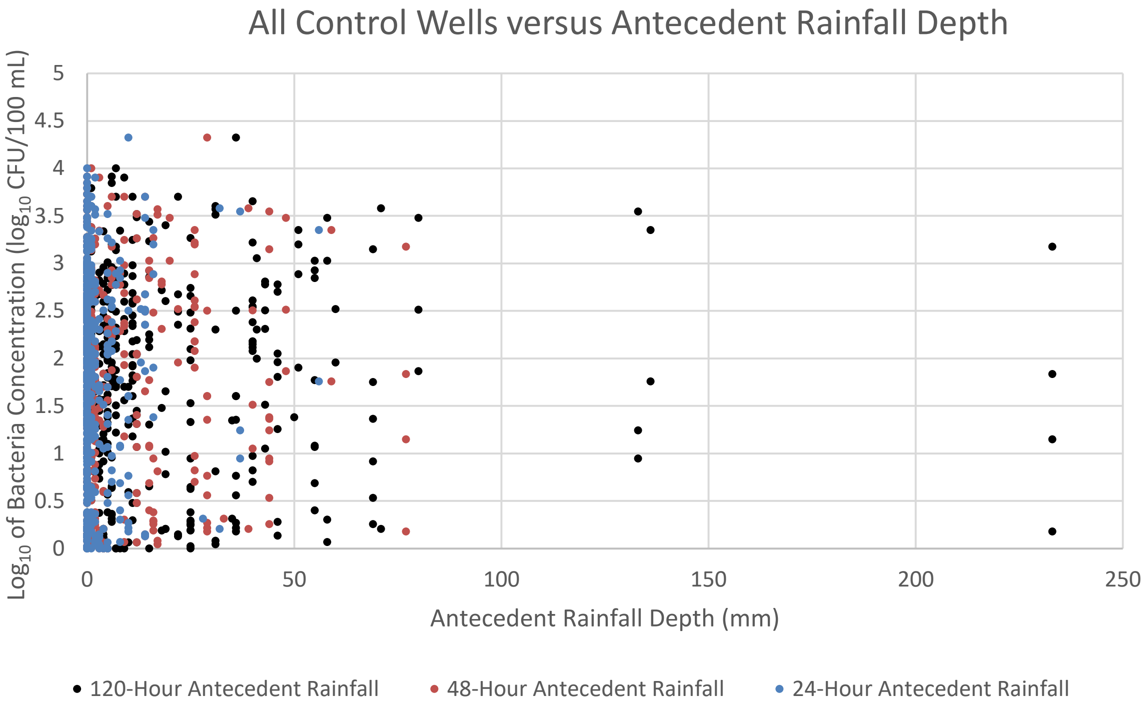

Figure 4.7 Graph of data from all wells that had no well head protection at the time of sampling in every study phase and study group versus antecedent rainfall depth. (N=423)

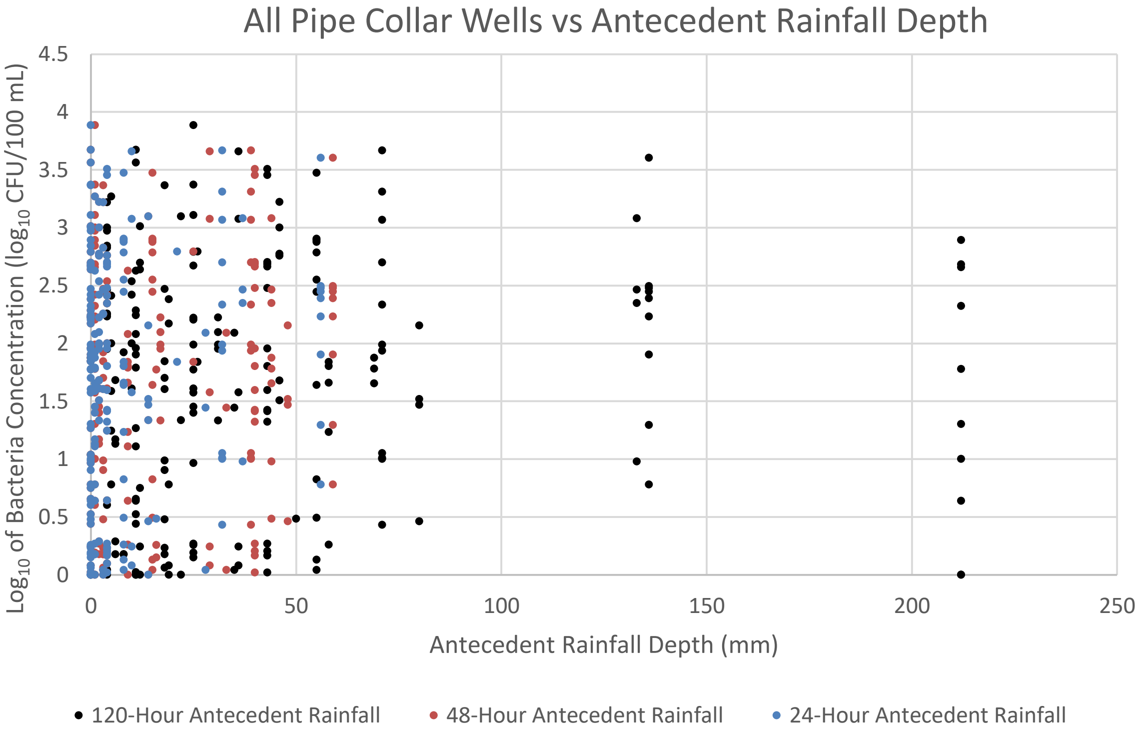

Figure 4.8 Graph of data from all wells that had pipe collars at the time of sampling from Phase 2 and 3 versus antecedent rainfall depth. (N=202)

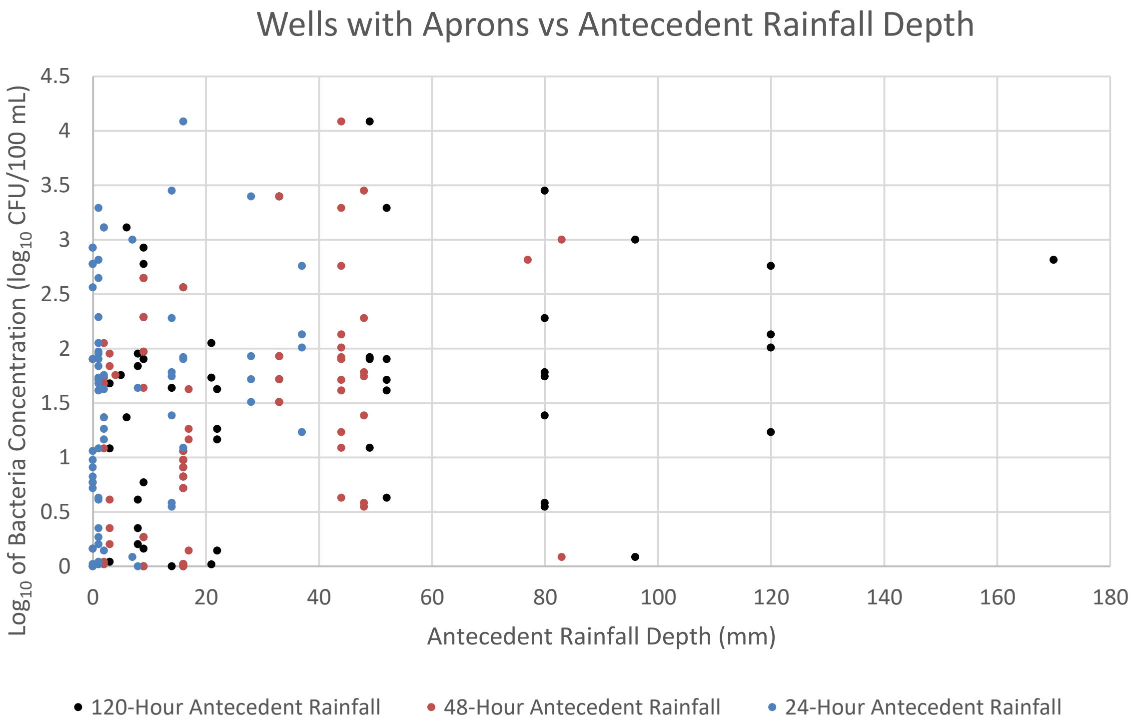

Figure 4.9 Graph of data from all wells that had aprons at the time of sampling versus antecedent rainfall depth. (N=65)

4.1.1.3 Statistical Analysis

Statistical analysis was performed with SPSS (version 25). Histograms of the bacteria concentration data showed that it was non-parametric therefore analysis was limited to non-parametric tests. There is not a single, mainstream test that is non-parametric, can take into account a covariant (i.e. antecedent rainfall), and can work with a within/between subjects study design. Due to that fact, different aspects of the data were examined with different statistical tests as discussed in this section.

4.1.1.3.1 Correlation with Rainfall: Spearman’s Correlation

Spearman’s correlation is used to find monotonic relationships between two variables; in this case, it was used to examine the relationship between the base-10 logarithmic transform of bacteria concentration and antecedent rainfall depth for wells with different levels of well head protection. The Spearman correlation coefficient, ρ, quantifies the strength and direction of a correlation with values ranging from -1 to +1. This test was selected since it finds relationships in more general cases (i.e.

monotonic) than other correlation tests (which tend to test linear relationships) and it is non-parametric. Normally, this test would not be applied to the type of data collected in this study because there is no apparent monotonic relationship when graphed (Figure 4.7, Figure 4.8, and Figure 4.9).

Table 4.1 provides the Spearman correlation coefficients for the logarithmic transforms of bacteria concentration and antecedent rainfall depth and their p-values for wells with different types of well head protection. The p-values are not statistically significant ($p \le 0.05$) or marginally statistically significant ($0.05 < p \le 0.10$) for correlations between bacteria concentration and antecedent rainfall depth for control wells and wells with a pipe collar. Weak but statistically significant or marginally statistically significant positive correlations were found for bacteria concentrations of wells with aprons at all antecedent rainfall depths (see Table 4.1 for values).

Table 4.1 Spearman correlations and other test statistics.

Spearman's Correlation of Log$_{10}$ of Bacteria Concentration and Antecedent Rainfall Depth						
		24-Hour	48-Hour	72-Hour	120-Hour	168-Hour
All Control Wells	Correlation Coefficient	- 0.021	- 0.043	- 0.044	- 0.027	- 0.027
	p-value	0.661	0.381	0.367	0.586	0.579
	N	423	423	423	423	423
All Wells with Pipe Collars	Correlation Coefficient	0.105	0.064	0.063	0.113	0.084
	p-value	0.138	0.369	0.376	0.110	0.232
	N	202	202	202	202	202
All Wells with Aprons	Correlation Coefficient	0.289	0.213	0.241	0.204	0.238
	p-value	0.020*	0.088**	0.053*	0.103**	0.056**
	N	65	65	65	65	65

*Statistically Significant ($p \le 0.05$) **Marginally Statistically Significant ($0.05 < p \le 0.10$)

Figure 4.10 and Figure 4.11 plot the statistically significant correlations between bacteria concentrations and rainfall for wells with aprons. It is clear when looking at the data in this figure that there is an upward trend in bacteria concentration with increasing rainfall but for almost every rainfall depth with more than one data point there is a multi-order of magnitude spread of bacteria concentrations.

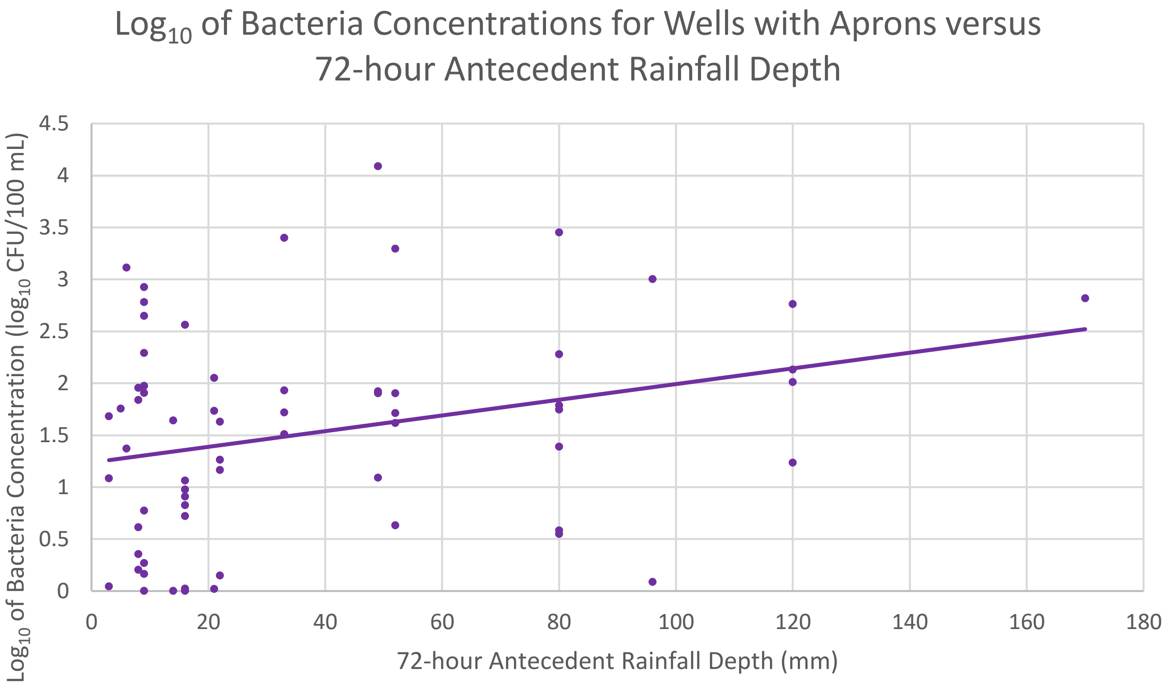

Figure 4.10 Plot of bacteria concentration versus 72-hour rainfall depth for all wells with aprons. (N=65)

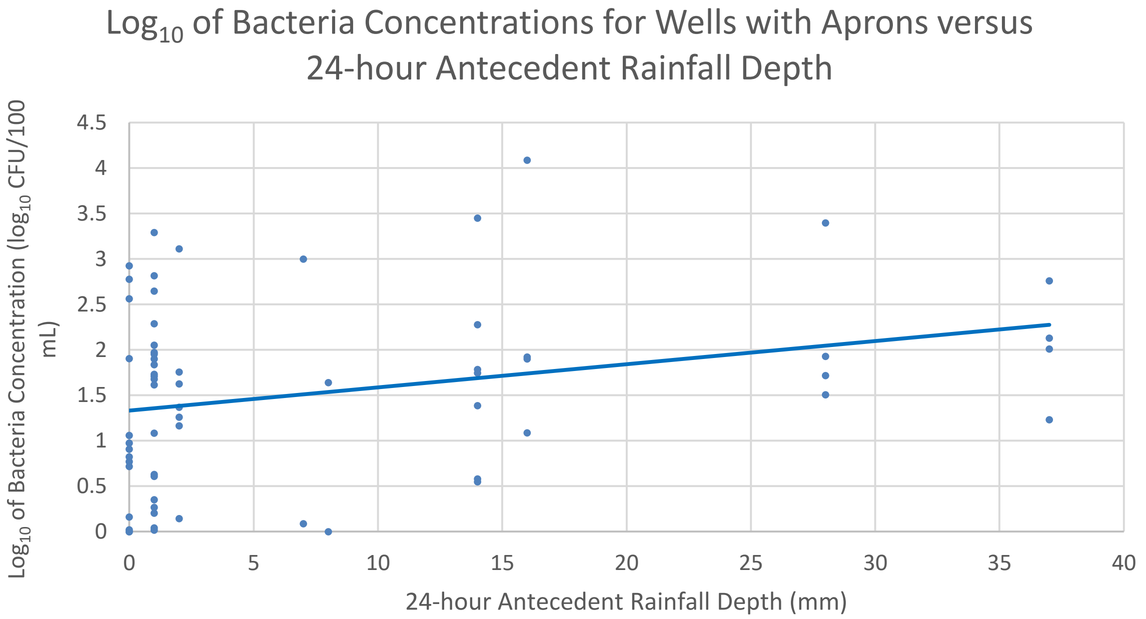

Figure 4.11 Plot of bacteria concentration versus 24-hour rainfall depth for all wells with aprons. (N=65)

While it makes intuitive sense to obtain a positive correlation between rainfall and bacteria concentrations, it was unexpected to only find a correlation for wells that were modified with aprons. If well head protection was the sole factor in preventing or allowing localized pathways of contamination one would not expect to see these results. One would expect to see control wells (with no well head protection) having a stronger correlation and wells with aprons having a weaker or no correlation, but the opposite is shown by the Spearman correlation tests. Additionally, it would be consistent with some literature to not see any correlations given the vulnerability of the aquifer at the study site (Luby et al. 2008; Leber et al. 2011). Any explanation for this data would thus need to include a hypothesis of why wells with aprons would have increasing bacteria concentrations from rainfall and other groups would not which will require future research.

There are multiple factors that could reveal a signal from rainfall in the data from wells with aprons and mask a signal from rainfall for other wells. Even though great effort was made to identify wells that were similar, wells in the apron study group could be less vulnerable to aquifer contamination than other well groups by chance, i.e. they may be deeper or located farther from on-site sanitation systems used in the study area. This reduction in contamination from the aquifer pathway could allow for the detection of a relationship between rainfall and bacteria concentration.

Upstream on-site sanitation distance was not the same for all wells. Sanitation sites all met the study criteria of being greater than 5.0 meters from the study wells, however, the exact distance varied, especially for the one or two upstream on-site sanitation structures that would in theory have the greatest effect on the well water quality. For example, there was variability in the number of on-site sanitation structures with each well site having 2 to 7 on-site sanitation structures located near it.

Furthermore, distance of upstream on-site sanitation systems may also have a great effect on water quality. The direction of groundwater flow was not measured but it could be assumed that it was flowing towards a canal located in the area. A complete analysis of this was outside the scope of this thesis, however, there are some specific wells that this would explain variations in water quality. For example, well 13 had lower bacteria concentrations than other wells but had a pit latrine 5.7 meters away that was suspected to be downstream for groundwater flow from the pump. Well 25, 26, and 36 had unusually narrow ranges and higher bacteria concentrations than other wells and all had pour-flush latrines that were suspected to be upstream for groundwater flow from those pumps.

Also, the bacterial loading from on-site sanitation is an uncontrolled variable. All the pour-flush latrines had an uncontrolled and unknown number of users and this could cause variable loading of bacteria into the aquifer due to varying volumes of water flowing into a pour-flush latrine's sewage tank on a daily basis. Additionally, it is unknown which pit latrines were constructed in ways to prevent rain-runoff from entering them; more run-off flowing into latrines and then into the aquifer could increase their bacterial loading of the aquifer.

It is unknown if the depths of the pit latrines and tanks for pour-flush latrines are substantially different, although they probably do not vary more than 1 to 2 meters in depth because of standard construction practices employed in this location. Deeper on-site sanitation systems would result in a shorter distance available for attenuation of microorganisms in the vadose zone. Additionally, a rising water table under the wells in this study might cause the bottom of the on-site sanitation to be at or below the water table and directly contaminate the aquifer with no attenuation in the vadose zone.

Well screen depth and water table depth are other factors that could mask the effect of rainfall on bacteria concentrations in wells with aprons. Figure 4.12 shows a boxplot of depths of the top of the well screens, the depths of water tables, and depth of well screens into the water table for well sites in the study measured in either June, July, or beginning of September 2016 at the beginning of the study (see Appendix C for data). The bottom of the range of water table depths for the control and pipe collar groups is lower than for the apron group. Due to the shallower water tables, it is possible that there may have been more wells in the control and pipe collar study groups that had ground water intersect with near-by on-site sanitation and had direct contamination of the aquifer when the water tables rose in the more rainy portions of the study. The wells with a shallower water table in the control and pipe collar groups may have skewed the results for those groups and made it harder to see the effect of rainfall on well water quality.

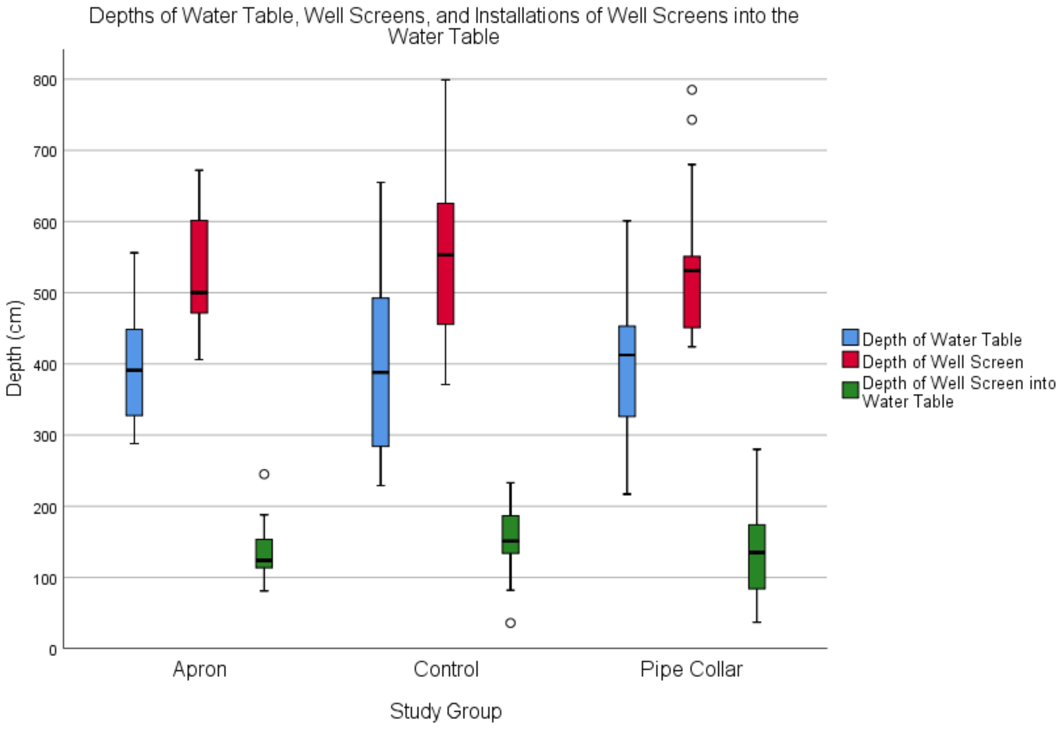

Figure 4.12 Box plots for depths of water table, depth of top of well screen, and depth of top of well screen into the water table for all wells analyzed in this study. Water table was measured in June, July, or beginning of September 2016 for all 44 wells represented on this graph.

The catchment area for rainfall around well heads was an uncontrolled and unmeasured variable. Well sites were visited during heavy rainfall to try to determine the catchment area of the well head. It was impossible to make direct comparisons of the catchment areas since all the wells could not be observed at the same rainfall rate. Additionally, the size of the catchment area was a function of the rainfall rate since with increasing rainfall, the depth of water on the ground surface would overcome contours of the ground and form larger, continuous puddles which could then wash contamination into the well via a local pathway. There was not a good way to make comparisons of catchment areas for each well site.

Interaction between the variables of distance between the water table and bottom of on-site sanitation, distance of water table from ground surface, bacterial loading from on-site sanitation, distance of upstream on-site sanitation, and size of the catchment area around the well head likely all interact to influence water quality for a well. All of these variables might cause systematically higher bacteria concentrations in some well water and perhaps may allow for a relationship between rainfall and bacteria concentrations to be seen in water for the wells with aprons but not other wells in the study.

4.1.1.3.2 Between Subjects Analysis Tests

Between subjects statistical tests were performed on the three different test phases of the data (Table 4.2). This allowed for different types of well head protection to be compared with control wells during the same experimental phase. Control wells and wells with pipe collars were compared during Phase 2 with the Mann-Whitney U Test which allows for comparison of two groups with non-parametric data. Control wells, wells with pipe collars, and wells with aprons were compared in Phase 3 with the Kuskal-Wallis H Test. All experimental groups were compared in Phase 1 (i.e. when there was no well head protection installed) to make sure that there were not statistical differences between the groups as a result of some uncontrolled variable. During testing, box plots were determined to be the same shape by inspection for both Kuskal-Wallis H Tests. Histograms for both groups for the Mann-Whitney U Test were also determined to be similar by inspection. In all cases, no statistically significant differences were found between experimental groups with different types of well head protection or no well head protection. A limitation of these tests is that they do not take into account the fact that repeated measures were taken on the same subject.

Table 4.2 Between subjects statistical tests.

Between Subjects Statistical Tests			
Test	Study Phase	N	*p*-value
Kruskal-Wallis H Test	1	293	0.388
Mann-Whitney U Test	2	221	0.126
Kruskal-Wallis H Test	3	176	0.902

4.1.1.3.3 Within Subjects Analysis Tests

Within subject analysis was performed on all three experimental groups (Table 4.3). This allowed for different types of well head protection to be compared on the same wells, which helps to control for local variations in ground water quality. Specifically, the Friedman test was performed comparing the apron group across three phases and all states of well head protection used in the study and was also used to compare the control group across three different phases. The Wilcoxon Sign-Rank test was used to compare the control phase (i.e. Phase 1) of the apron and pipe collar group to the phases of those groups when they had a pipe collar (i.e. Phase 2 for the apron group and Phase 2 and 3 for the pipe collar group). Median values for bacteria concentrations were used in the test instead of an array of data since the tests require paired data and each wells had an unequal number of samples in each condition that could not be paired sensibly across different study phases. Like with the between subjects analysis, the control group in different phases was compared to itself to make sure that there was no statistical differences that were unaccounted for in the study design. The histogram of the differences of medians for the Wilcoxon Sign-Rank Test was symmetrical and therefore the test was valid to apply. No statistically significant differences were found between the different well head conditions within every study group.

Table 4.3 Within subjects statistical tests.

Within Subjects Statistical Tests			
Test	Group	N	*p*-value
Friedman Test	Control Group	14	0.807
Wilcoxon Sign-Rank Test	Apron Group in Phase 1 and 2 only and Pipe Collar Group	29	0.144
Friedman Test	Apron Group	15	0.165

4.1.2 Comments about Study Variables and Data

This was a field study and therefore could not be as well controlled as a laboratory experiment. The main variable that needed constant effort to control was the priming of well pumps and their repair. Commonly, the foot check valve on Malagasy Pitcher Pumps does not seal well and the pump requires priming after a period of no use (depending on the size of the leak this could be under an hour to overnight). As stated in Section *3.5 Sample Collection*, the standard study sampling procedure was to ask the owner or any person that could be found on the pump's property if the pump was working properly or was running dry when water samples were collected, however, it is estimated that in about 1 in 10 samples that no person could be found to ask about the operation of the pump. This is not of foremost concern because if there was a major problem with the check valve requiring priming it would be noticed before pumping. Also, there was not a large set of consecutive data points for any pump where the functioning of the pump was completely unreported since people were generally available to ask if the pump required priming the following sampling. If a repair took place on a pump it was not sampled until at least 5 days after the pump was operating normally without priming, but in most cases it was longer than 5 days.

Additionally, a number of wells needed to be removed from the ground to make repairs to their well screens due to an error in the design of the leadless well point that cause well screens to clog with fine soil. The same rule of at least waiting 5 days before sampling was adhered to and, again, in most cases it was longer.

Data associated with one pipe collar group well was removed from data analysis. This was because near the end of the study a pump technician reported to the author that the pump owner stated to him that she was not being truthful about their pump needing priming. This pump in particular needed multiple repairs and the owner stated to the technician that she did not want to bother the study author with making more repairs. It was removed from analysis due to the reason that there was uncertainty about when this started and the fact that this pump's bacteria concentration level fluctuated widely through the study. It is not believed that any other wells had this same issue with the pump owner not being direct with reporting issues of their pump needing priming.

The frequencies of errors, all plates in a sample being non-detected for bacteria, and plates too overcrowded to count for every study group in every phase are shown in Table 4.4. It does not appear like errors, non-detects, or uncountable plates are unevenly distributed in any group and could thus cause biases in the data.

Table 4.4 Frequencies of errors, non-detects, and uncountable plates.

Study Group	Phase	Errors		All Plate in Sample Non-detects		Uncountable		Total Plates
		N	Percent of Total	N	Percent of Total	N	Percent of Total	
Control	1	6	5.36%	1	0.89%	4	3.57%	112
Control	2	10	10.87%	1	1.09%	8	8.70%	92
Control	3	5	7.35%	0	0.00%	7	10.29%	68
Pipe Collar	1	12	11.32%	3	2.83%	5	4.72%	106
Pipe Collar	2	6	7.06%	0	0.00%	11	12.94%	85
Pipe Collar	3	8	11.76%	0	0.00%	5	7.35%	68
Apron	1	8	6.90%	0	0.00%	6	5.17%	116
Apron	2	12	11.76%	4	3.92%	11	10.78%	102
Apron	3	13	15.48%	3	3.57%	6	7.14%	84

Some of the data collected in this study is censored but it is a small fraction. In this study, 63 of the 833 samples that were not errors were too overgrown with colonies and were uncountable. Uncountable plates were not included in the analysis. On the other extreme, a very low number of the low count plates are censored. Of all the plates included in the analysis 107 have plate counts ≤ 5 colonies per plate for both duplicate and of those 30 have sample volumes ≤10 mL; additionally, there are 47 that have plate counts ≤1 colonies per plate for both duplicates and of those 10 have sample volumes ≤ 10 mL. Given the small number of plates that have low colony counts at small volumes it is unlikely that the data set as a whole is biased due to censoring of data.

4.1.3 Limitations of the Study

The main limitations of this study stem from not using a proprietary interfering flora suppression supplement with the media. As explained in *Chapter 3 Methods* the lack of supplement means that the data presented in this study is only useful as a measure of gross bacteria concentration grown at 37° C from well water but not of Total Coliform.

One limitation of this study due to the lack of a suppression supplement is that it is not possible to directly compare the results in this study with others studies of well contamination because they mostly have measured *E.coli*, thermotolerant coliform, or Total Coliform. Furthermore, no definitive statements of health risk can be made from this study's data because there is no certainty to exactly what type of bacteria was grown in this study. The bacteria grown here have the potential to grow inside a human body since they have been incubated at 37° Celsius but it is unknown what percentage of the colonies are pathogenic or are associate with pathogenic organisms. It is likely that bacteria associated with fecal contamination, such as *E.coli*, *could* be grown by the media. Thusly, while a positive sample with this media may just possibly indicate that the water is *harmful* for health to consume directly, a non-detected sample more strongly suggests *safety* of the water since no colonies of any type have grown.

Even if the data in this study represented contamination associated with a health risk, one could not draw conclusions for the water quality of all the Pitcher Pumps in Tamatave. Well sites were selected with great effort to be at low risk for aquifer pathway contamination and high risk for localize pathway contamination relative to other wells in the study area. Many sites were eliminated for not being deep enough, having on-site sanitation too close, or being on locally elevated ground in someone's property. The wells represented here are at least in the top quartile of low aquifer pathway contamination risk since it is estimated that about 200 to 400 wells were examined to select the wells in this study. Additionally, pumps were not measured if they needed priming which is a common issue with Pitcher Pumps. The wells in this study probably represent the best case scenario for water quality from Pitcher Pumps *in high density areas like Tamatave* given that closer on-site sanitation and water table shallowness will likely cause higher quantities of pathogens from feces and the soil to contaminate the water. The conclusions of this study also cannot be extended to less dense rural areas with fewer and farther on-site sanitation structures near-by or to areas that have deeper tube wells because those wells will be at even lower risk for aquifer contamination than the wells in this study.

4.1.4 Implications of Study for Malagasy Pitcher Pump Users

No associations were found between well head protection and bacteria concentration, therefore, no recommendations can be made to implement well head protection as constructed in this study. One can also learn something very important about the functioning of Malagasy Pitcher Pumps from examining the variation in bacteria concentration levels of each individual pump through the study (Figure 4.13). Individual wells in this study can produce water with consistently low bacteria concentration, consistently high bacteria concentration, or can fluctuate in between low and high bacteria concentration. Even wells that are direct neighbors of each other may have very different bacteria concentration ranges in this study, although it is not the case most of the time. The same well could possibly be producing water that is safe and dangerous to drink. This fact could actually cause users to not associate gastro-intestinal illnesses with water from their wells since it may inconsistently cause illnesses. This is a very important fact since previous surveys (MacCarthy 2014) showed that about 1 in 4 Pitcher Pump users that obtained their drinking water from their Pitcher Pump consume it directly without treatment (also see Section *2.5 Past Research on Pitcher Pumps in Madagascar* for more discussion of this).

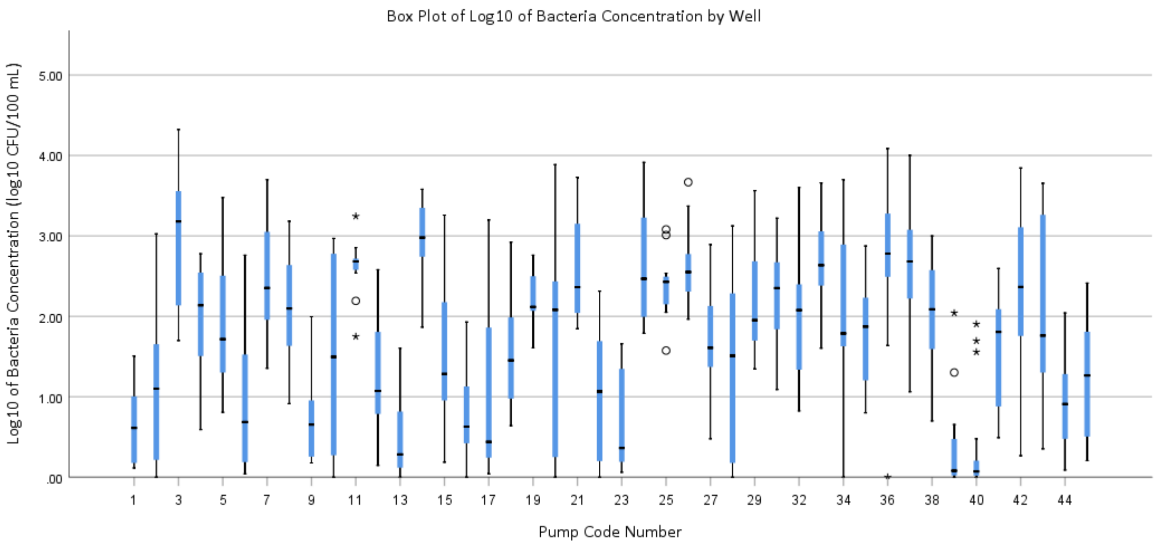

Figure 4.13 Box plot of the logarithmic transform of bacteria concentration for every individual pump use in this data analysis throughout the entire study, regardless of well head protection. Pump code numbers 1-15 are the control group, 16-29 are the pipe collar group, and 31-45 are the concrete apron group. (N=690)

4.2 Objective 2: Recommendations for Low-Cost Well Head Protection

Based on the results of this study, construction of a ≤ 50 cm diameter well apron is *not* recommended for Pitcher Pumps in Tamatave, Madagascar. This study selected wells that had the greatest chance to benefit from well head protection, i.e. relatively deep wells for the area at relatively far distances from on-site sanitation for the area and in flat terrain, and there was no benefit observed for improving water quality found over the entire group of wells examined (total number examined is 44). However, it is possible that the low-cost well head protection designed for this study could be useful in other settings. For example, in a more rural setting with a smaller population density it is *possible* that this well head protection could help if the well was sited sufficiently far away from on-site sanitation. Additionally, if the water table was deeper and less vulnerable to aquifer contamination then it is *possible* that the well head protection could reduce the risk of the water in the well.

The author also believes that it is not possible to increase the size of the concrete well apron due to cost to the end user. Currently, the cost of the 50-cm diameter concrete apron used in this study

(Figure 4.14 left) will range from about 12,000 to 16,000 Malagasy Ariary (MGA)[13] fully installed. MacCarthy (2014) found through surveys that the cost of a fully installed Pitcher Pump in the Tamatave area varied between about 75,000 to 220,000 MGA[14]. With these prices, adding the current 50-cm apron design would increase the costs of a Pitcher Pump system by 5 to 20%. Increasing the diameter of the apron to 100 cm or 200 cm would increase the cost of the apron to approximately 40,000 or 150,000 MGA[15], respectively. Based on the author's experience of living in Madagascar as a Peace Corps volunteer for over 3 years, increasing the cost of the apron this much is almost certainly prohibitively expensive and will cause most Malagasies to not even consider the purchase. Given the fact that it is already uncommon to see any well head protection and the well head protection that is observed appears to be incidental to building a bucket pad, it would be difficult to convince Malagasies to make the additional upgrade given the cost.

Figure 4.14 Left: The 50-cm diameter concrete apron is at the base of the pump. The wider diameter, shorter pipe coming out of the concrete is the pipe collar. Right: The pipe collar is the grey PVC pipe at the base of the pump. This is installed directly into the soil.

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[13] Cost variation is because of the quality of the pipe collar, cement, and potential labor cost of the mason.

[14] The cost variation is mainly due to the depth of the well.

[15] Estimate is based on scaling the cost of the concrete but not the cost of the pipe collar and labor which would be the same.

If a larger apron at low cost is desired, it may be possible to construct well head protection with a large, buried water-proof tarp. Because this material is lower cost than concrete, it may be possible to build a larger diameter, more affordable well head protection from it.

If the pipe collar (Figure 4.14 right) is used the author recommends lengthening the pipe from 25 cm to 35 cm and installing it 20 cm below grade instead of 10 cm (and maintaining the pipe collar 15 cm above grade). The pipe collar is already reasonably sturdy but occasionally it was observed that it was knocked crooked (and then corrected). This crookedness would unlikely greatly effect protection against run-off but it is better if it is sturdier so it is not as easily moved around.

One recommendation is that it is essential that for Malagasy Pitcher Pumps that any concrete apron have a pipe collar casing surrounding the rising main so that it can be removed to perform maintenance on the well screen and rising main as well as prevent damage to the concrete while pumping (see Section *2.6 Morondava, Menabe Survey of Well Aprons* and *3.2.3 Circular Concrete Apron* for more discussion). This may or may not be a concern for other low-cost self-supply well pumps globally. For example, if the rising main is PVC plastic there may not be a reason to remove it for maintenance since the plastic will not rust. Additionally, if the tubewell casing does not vibrate during pumping there would not be a concern with the concrete of the apron cracking around the edges. It is also important that any apron design either accommodate a bucket pad (like in the design used here) or have a bucket pad extend forward in front of the pump outlet.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Addressing Study Objectives

This study represents the first known research into sizing of well head protection for low-cost, self-supply tubewells in developing countries. Previous research has studied the effects of presence or absence of well aprons wells on water quality in developing countries but the research is vague on specific aspects of the design, such as size. Most recommendations found in textbooks and documents about implementing wells in developing countries are for community wells and are not applicable to a self-supply context with fewer users and no financial subsidies.

The first objective of this research was to test the effect of two well head protection designs for Malagasy Pitcher Pumps on the concentration of bacteria grown at 37° C in the well water. The two well head protections tested were: 1) a partially buried short 100 mm diameter PVC pipe collar placed around the rising main and 2) a 50-cm diameter, circular concrete apron. Rainfall data was obtained from a local weather station to try to find correlations between rainfall and bacteria levels in water.

A Spearman's correlation was used to investigate if any relationship existed between bacteria concentration and rainfall for each well head protection type. Logarithmic transforms of concentrations for bacterial growth at 37° C from wells with the same type of well head protection (i.e. none, pipe collar, or concrete apron) were compared to antecedent rainfall over the previous 24 hours, 48 hours, 72 hours, 120 hours, and 168 hours from 07h00 in the morning on the day of sample collection.

Only wells with aprons showed statistically significant ($p \leq 0.05$) or marginally statistically significant ($0.05 < p \leq 0.10$) weak positive correlations between bacteria concentrations and antecedent rainfall depth. Control wells and wells with pipe collars did not show any statistically significant correlations. It is unclear what the reason is for wells with aprons having a correlation between antecedent rainfall and bacteria concentration and not having this correlation for wells with other well head protection types. It is likely this is due to the apron study group having by-chance differences in variables that affect aquifer pathway contamination. These variables may be distance between the water table and bottom of on-site sanitation used in the study area, distance of water table from ground surface, bacterial loading from on-site sanitation systems, distance of upstream on-site sanitation, and size of catchment area around the well head. It is likely these all interact to influence water quality for a well. Differences in these variables might allow for a relationship between rainfall and bacteria concentrations to be seen in well water for the wells with aprons and mask it in the other study wells.

The study involved use of a mixed between-subject, within-subject design. This design allowed for between-subject comparison of the same well site with different levels of well head protection at different points in the year and within-subject comparisons of different well sites with different levels of well head protection at the same point in the year (and therefore similar rainfall patterns). No statistically significant ($p \leq 0.05$) differences were found with between-subject tests of different well site groups with either of the two types of well head protection or no well head protection. Additionally, no statistically significant differences were found with within-subject tests for the same well site with either of the two different types of well head protection or wells with no well head protection compared over the same time intervals. Accordingly, there does not appear to be any effect of well head protection on water quality of Malagasy Pitcher Pumps in Tamatave. It is likely that this will hold for all Pitcher Pumps in Tamatave given that the wells in this experiment were chosen to have the lowest risk of aquifer pathway contamination and largest risk of local pathway contamination.

The second objective was to develop design requirements for appropriate well head protection for Malagasy Pitcher Pumps. At this time, it is not recommended to build well head protection for Malagasy Pitcher Pumps in urban Tamatave given the results addressed above for the first objective. It is possible that well head protection might be more effective in an area with lower risk of aquifer contamination. If further testing is done, it is recommended that the pipe collar should be lengthened to increase stability in the soil. If a concrete apron is constructed, it should have a pipe collar to allow for removal of the rising main for repairs and to prevent damage of the apron from the deflection of the rising main during pumping.

In addition to the objectives, it was observed that bacterial concentrations in water from Malagasy Pitcher Pumps can vary widely. In some cases, the same pump could produce water with no detected bacteria to a concentration as high as 4 $\log_{10}$ CFU/100 mL concentration over the 9 month time period of the study. Pumps neighboring each other were found to also consistently produce water with bacterial counts orders of magnitude different. Wahlstrom-Ramler (2014) and MacCarthy (2014) also found variability between pumps for thermotolerant coliform but did not collect enough samples from the same pump to see the same intra-pump variability shown in this study.

5.2 Recommendations for Future Research

Further research into low-cost well head protection may be useful in an area that has less risk of aquifer contamination than the neighborhoods in urban Tamatave that this study took place in. For example, in a rural area on-site sanitation may be farther away or non-existent so it is possible that rainfall may have a stronger effect on water quality. Additionally, an area (rural or urban) that has a consistently deeper water table closer to the 7 meter deep operating range of suction pumps may also have stronger effects on water quality from well head protection.

It is not financially possible for Malagasies to increase the size of the concrete well apron proposed in this study but it may be possible to use another material to build the apron. For example, it may be feasible to use a buried water proof tarp around the well head as well head protection. Since the material is lower cost, it should be possible to build large diameter, more affordable well head protection from it.

The microbial water quality data obtained from samples with the addition of a well aprons suggests that there may be multiple variables that influence water quality of Pitcher Pumps. More complex statistical analysis of this data could be done that takes into account distances of presumptive upstream on-site sanitation or water table depths. A new study that measures groundwater flow and knows precisely which on-site sanitation structures may be contaminating groundwater flowing into Pitcher Pump wells would also be useful in better understanding the Pitcher Pump system. Additionally, a new study with more continuous measurements of water table depth could be useful in sorting out the effect of water table depth on water quality in urban Tamatave.

5.3 Practical Recommendations for Malagasy Pitcher Pump Users

It appears that based on the overall results of this study and others that the most feasible recommendation for producing reliably safe drinking water from Malagasy Pitcher Pumps is to employ point-of-use treatment. Fortunately, there is already a common practice of boiling water to make *ranon'ampango* which is a drink made from boiling water in a pot with burnt rice to give it flavor. A practical recommendation would be to promote and extend the use of this practice as a method of safe water treatment. Malagasies could be encouraged to completely bring to a boil or pasteurize their water while they make *ranon'ampango* instead of dealing with the challenges of building a new behavior. This would thus be a habit that is potentially more likely to be sustained over time.

5.4 Final Thoughts

The people of Madagascar have greatly benefited from installation of Pitcher Pumps for several decades and these pumps have many benefits despite the already documented issues with lead and microbial contamination (Akers 2014; Akers et al. 2015; MacCarthy 2014; MacCarthy et al. 2013; Wahlstrom-Ramler 2014). Pitcher Pumps provide ample quantity of water that is accessible 24-hours a day at the home at a price that is affordable to Malagasy users. Despite these documented water quality issues, they should not be ignored as an illegitimate source of water since they provide benefits beyond being a source of drinking water, for example, hygiene, sanitation, and cooking.

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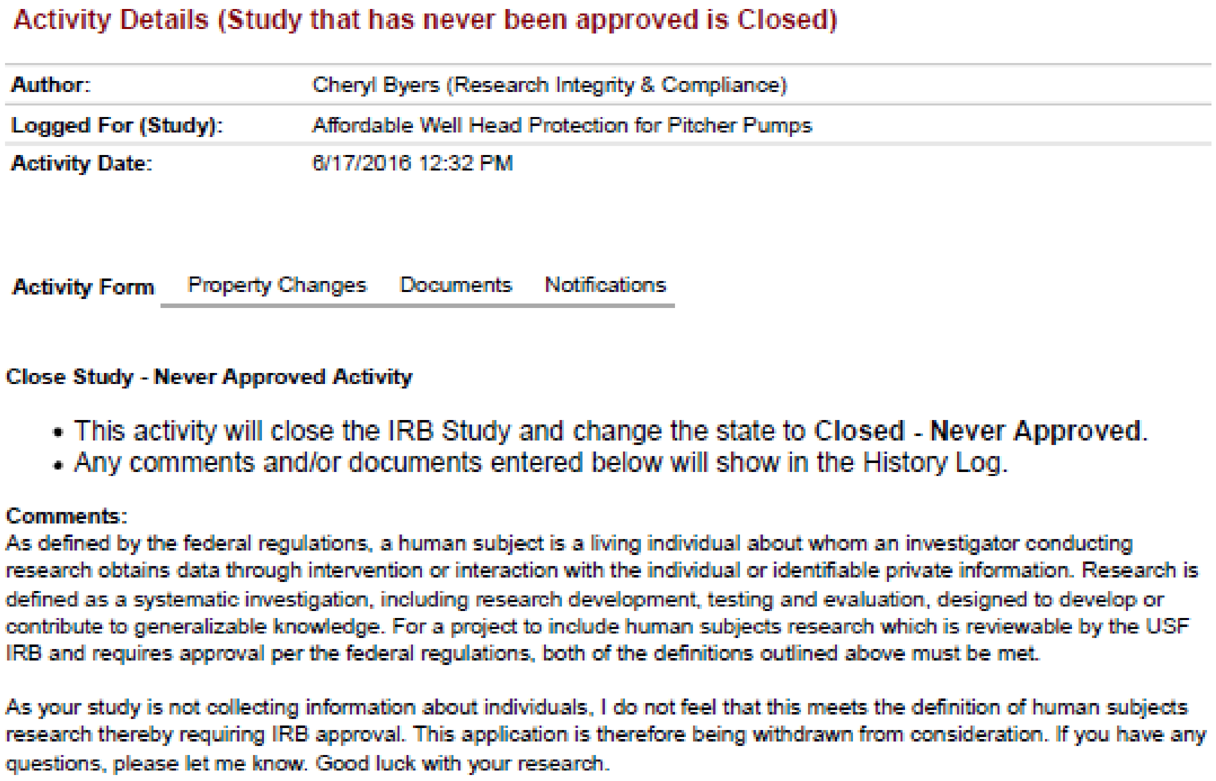
APPENDIX A: IRB DOCUMENTATION



Activity Details (Study that has never been approved is Closed)

Author:	Cheryl Byers (Research Integrity & Compliance)
Logged For (Study):	Affordable Well Head Protection for Pitcher Pumps
Activity Date:	6/17/2016 12:32 PM

Close Study - Never Approved Activity

- This activity will close the IRB Study and change the state to Closed - **Never Approved**.
- Any comments and/or documents entered below will show in the History Log.

Comments:
As defined by the federal regulations, a human subject is a living individual about whom an investigator conducting research obtains data through intervention or interaction with the individual or identifiable private information. Research is defined as a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge. For a project to include human subjects research which is reviewable by the USF IRB and requires approval per the federal regulations, both of the definitions outlined above must be met.

As your study is not collecting information about individuals, I do not feel that this meets the definition of human subjects research thereby requiring IRB approval. This application is therefore being withdrawn from consideration. If you have any questions, please let me know. Good luck with your research.

APPENDIX B: PERMISSION TO USE FIGURES

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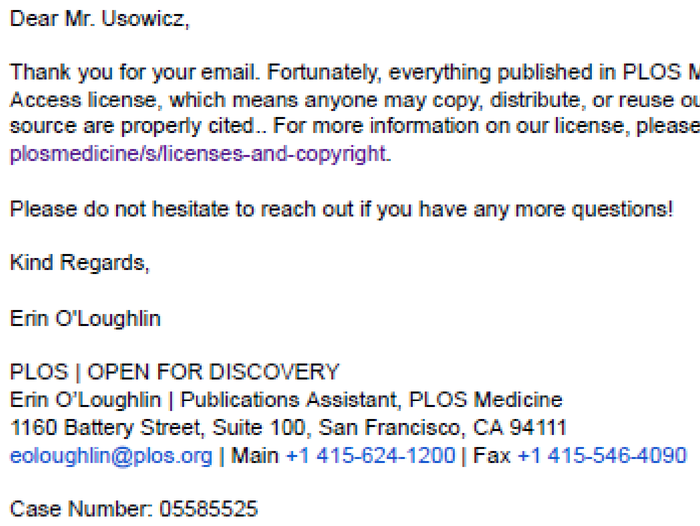

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Erin O'Loughlin | Publications Assistant, PLOS Medicine
1160 Battery Street, Suite 100, San Francisco, CA 94111
eoloughlin@plos.org | Main +1 415-624-1200 | Fax +1 415-546-4090

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APPENDIX C: DATA

Table C.1 Antecedent rainfall data by date from 07h00 UT +3.

		Antecedent Rainfall Depth (mm) from 07h00 UT+3				
Study Phase	Date	24 hour	48 hour	72 hour	120 hour	168 hour
1	19-Jul-16	0	20	38	58	96
1	20-Jul-16	9	9	29	62	97
1	21-Jul-16	13	22	22	60	80
1	22-Jul-16	2	14	24	44	76
1	23-Jul-16	12	14	27	36	74
1	24-Jul-16	6	18	20	41	62
1	25-Jul-16	10	15	27	42	51
1	26-Jul-16	21	31	36	50	72
1	27-Jul-16	1	22	32	50	64
1	28-Jul-16	3	4	25	40	54
1	29-Jul-16	0	3	4	35	52
1	30-Jul-16	0	0	3	25	40
1	31-Jul-16	0	0	0	4	35
1	01-Aug-16	0	0	0	3	25
1	02-Aug-16	0	0	0	0	4
1	03-Aug-16	0	0	0	0	3
1	04-Aug-16	0	0	0	0	0
1	05-Aug-16	0	0	0	1	1
1	06-Aug-16	1	2	2	2	2
1	07-Aug-16	0	1	2	2	2
1	08-Aug-16	32	32	33	34	34
1	09-Aug-16	9	41	41	43	43
1	10-Aug-16	0	9	41	42	43
1	11-Aug-16	0	0	9	41	43
1	12-Aug-16	10	10	10	51	52
1	13-Aug-16	4	14	14	23	55
1	14-Aug-16	11	15	25	25	66
1	15-Aug-16	10	21	25	35	44
1	16-Aug-16	16	26	37	51	51
1	17-Aug-16	2	18	28	43	53
1	18-Aug-16	2	3	20	40	54
1	19-Aug-16	1	3	4	30	45
1	20-Aug-16	0	1	3	21	41

Table C.1 (Continued)

1	21-Aug-16	0	0	1	4	30
1	22-Aug-16	0	0	0	3	21
1	23-Aug-16	0	0	0	1	4
1	24-Aug-16	0	0	0	0	3
1	25-Aug-16	0	0	0	0	1
1	26-Aug-16	1	2	2	2	2
1	27-Aug-16	7	8	9	9	9
1	28-Aug-16	2	9	11	11	11
1	29-Aug-16	13	15	22	24	24
1	30-Aug-16	6	19	21	29	30
1	31-Aug-16	8	14	27	36	38
1	01-Sep-16	12	20	26	41	49
1	02-Sep-16	4	16	25	43	52
1	03-Sep-16	1	5	17	31	46
1	04-Sep-16	0	1	5	25	44
1	05-Sep-16	1	1	2	18	32
1	06-Sep-16	3	5	5	9	30
1	07-Sep-16	0	3	5	5	21
1	08-Sep-16	3	3	6	8	13
1	09-Sep-16	0	3	3	8	8
1	10-Sep-16	2	2	6	9	10
1	11-Sep-16	1	4	4	7	11
1	12-Sep-16	0	1	4	7	10
1	13-Sep-16	1	1	2	4	7
1	14-Sep-16	1	1	1	5	8
1	15-Sep-16	0	1	1	3	5
1	16-Sep-16	0	0	1	1	5
1	17-Sep-16	5	5	5	7	8
1	18-Sep-16	1	6	6	7	7
1	19-Sep-16	1	2	7	7	8
1	20-Sep-16	2	3	4	9	10
1	21-Sep-16	2	4	5	11	11
1	22-Sep-16	2	4	6	7	13
1	23-Sep-16	0	2	4	7	13
1	24-Sep-16	0	0	2	6	7
1	25-Sep-16	0	0	0	4	7
1	26-Sep-16	3	3	3	5	9
1	27-Sep-16	1	4	4	4	8
1	28-Sep-16	0	1	4	5	6
1	29-Sep-16	11	11	12	16	16
1	30-Sep-16	3	14	14	19	19
1	01-Oct-16	0	4	15	16	19

Table C.1 (Continued)

1	02-Oct-16	0	0	4	15	19
1	03-Oct-16	0	0	0	15	16
1	04-Oct-16	11	11	11	14	26
1	05-Oct-16	1	11	11	12	26
1	06-Oct-16	0	1	11	11	15
1	07-Oct-16	0	0	1	11	12
1	08-Oct-16	0	0	0	11	11
1	09-Oct-16	0	0	0	1	11
1	10-Oct-16	0	0	0	0	11
1	11-Oct-16	0	0	0	0	1
1	12-Oct-16	0	0	0	0	0
1	13-Oct-16	0	0	0	0	0
1	14-Oct-16	0	0	0	0	0
1	15-Oct-16	0	0	0	0	0
1	16-Oct-16	0	0	0	0	0
1	17-Oct-16	0	0	0	0	0
1	18-Oct-16	0	0	0	0	0
1	19-Oct-16	0	0	0	0	0
1	20-Oct-16	0	0	0	0	0
1	21-Oct-16	0	0	0	0	0
1	22-Oct-16	2	2	2	2	2
1	23-Oct-16	0	2	3	3	3
1	24-Oct-16	1	2	4	4	4
1	25-Oct-16	1	2	3	5	5
1	26-Oct-16	0	1	2	4	5
1	27-Oct-16	0	0	1	3	5
1	28-Oct-16	0	0	0	2	4
1	29-Oct-16	0	0	0	1	3
1	30-Oct-16	0	0	0	0	2
1	31-Oct-16	0	0	0	0	1
1	01-Nov-16	0	0	0	0	0
1	02-Nov-16	0	0	0	0	0
1	03-Nov-16	0	0	0	0	0
1	04-Nov-16	14	14	14	14	14
1	05-Nov-16	20	34	34	34	34
1	06-Nov-16	6	26	40	40	40
1	07-Nov-16	0	6	26	40	40
1	08-Nov-16	0	0	6	40	40
1	09-Nov-16	0	0	0	26	40
1	10-Nov-16	0	0	0	6	40
1	11-Nov-16	0	0	0	0	26
1	12-Nov-16	1	1	1	1	7

Table C.1 (Continued)

1	13-Nov-16	0	1	1	1	1
1	14-Nov-16	0	0	1	1	1
1	15-Nov-16	6	6	6	7	7
1	16-Nov-16	5	12	12	12	12
1	17-Nov-16	0	5	12	12	12
1	18-Nov-16	0	0	5	12	12
1	19-Nov-16	0	0	0	12	12
1	20-Nov-16	0	0	0	5	12
1	21-Nov-16	0	0	0	0	12
1	22-Nov-16	0	0	0	0	5
1	23-Nov-16	0	0	0	0	0
2	11-Jan-17	14	14	14	22	53
2	12-Jan-17	0	14	14	14	48
2	13-Jan-17	2	2	16	16	24
2	14-Jan-17	3	5	5	18	19
2	15-Jan-17	0	3	5	18	19
2	16-Jan-17	5	5	7	9	23
2	17-Jan-17	19	24	24	28	42
2	18-Jan-17	10	29	33	36	38
2	19-Jan-17	0	10	29	33	38
2	20-Jan-17	23	23	32	56	58
2	21-Jan-17	7	29	29	58	62
2	22-Jan-17	32	39	61	71	94
2	23-Jan-17	6	37	44	67	95
2	24-Jan-17	0	6	38	67	77
2	25-Jan-17	2	2	8	46	69
2	26-Jan-17	0	2	2	39	69
2	27-Jan-17	0	0	2	8	46
2	28-Jan-17	0	0	0	2	39
2	29-Jan-17	0	0	0	2	8
2	30-Jan-17	0	0	0	0	2
2	31-Jan-17	0	0	0	0	2
2	01-Feb-17	4	4	4	4	4
2	02-Feb-17	21	24	24	25	25
2	03-Feb-17	1	22	25	25	26
2	04-Feb-17	0	1	22	25	26
2	05-Feb-17	0	0	1	25	25
2	06-Feb-17	11	11	11	32	36
2	07-Feb-17	0	11	11	12	36
2	08-Feb-17	0	0	11	11	32
2	09-Feb-17	0	0	0	11	12
2	10-Feb-17	3	3	3	14	14

Table C.1 (Continued)

2	11-Feb-17	1	4	4	4	15
2	12-Feb-17	0	1	4	4	15
2	13-Feb-17	0	0	1	4	4
2	14-Feb-17	0	0	0	4	4
2	15-Feb-17	3	3	3	4	7
2	16-Feb-17	0	3	3	3	7
2	17-Feb-17	0	0	3	3	4
2	18-Feb-17	36	36	36	40	40
2	19-Feb-17	4	40	40	43	43
2	20-Feb-17	0	4	40	40	43
2	21-Feb-17	7	7	11	47	50
2	22-Feb-17	8	15	15	55	55
2	23-Feb-17	4	12	18	22	59
2	24-Feb-17	0	4	12	19	59
2	25-Feb-17	0	0	4	19	22
2	26-Feb-17	0	0	0	12	19
2	27-Feb-17	1	1	1	5	19
2	28-Feb-17	0	1	1	1	12
2	01-Mar-17	1	1	2	2	6
2	02-Mar-17	1	2	2	2	3
2	03-Mar-17	0	1	2	2	2
2	04-Mar-17	4	4	4	5	6
2	05-Mar-17	21	25	25	26	27
2	06-Mar-17	42	63	67	68	69
2	07-Mar-17	93	135	156	160	162
2	08-Mar-17	76	169	211	236	236
2	09-Mar-17	1	77	170	233	237
2	10-Mar-17	0	1	77	212	237
2	11-Mar-17	3	3	4	173	236
2	12-Mar-17	56	59	59	136	271
2	13-Mar-17	23	79	83	83	252
2	14-Mar-17	0	23	79	83	159
2	15-Mar-17	0	0	23	83	83
2	16-Mar-17	13	13	13	93	96
2	17-Mar-17	76	89	89	112	171
2	18-Mar-17	7	83	96	96	175
3	19-Mar-17	37	44	120	133	156
3	20-Mar-17	35	72	79	168	168
3	21-Mar-17	6	40	77	160	173
3	22-Mar-17	4	10	44	89	178
3	23-Mar-17	9	14	19	91	173
3	24-Mar-17	0	9	14	54	98

Table C.1 (Continued)

3	25-Mar-17	0	0	9	19	91
3	26-Mar-17	0	0	0	14	54
3	27-Mar-17	5	5	5	14	24
3	28-Mar-17	2	6	6	6	20
3	29-Mar-17	1	3	8	8	17
3	30-Mar-17	2	4	5	10	10
3	31-Mar-17	20	22	23	30	30
3	01-Apr-17	1	20	23	26	30
3	02-Apr-17	1	2	21	25	31
3	03-Apr-17	0	1	2	24	27
3	04-Apr-17	5	5	6	26	30
3	05-Apr-17	28	33	33	35	57
3	06-Apr-17	16	44	49	50	70
3	07-Apr-17	5	21	49	54	56
3	08-Apr-17	1	6	21	55	55
3	09-Apr-17	8	9	14	58	63
3	10-Apr-17	5	13	14	34	67
3	11-Apr-17	15	20	28	33	77
3	12-Apr-17	2	17	22	31	51
3	13-Apr-17	8	10	25	38	44
3	14-Apr-17	43	51	53	73	82
3	15-Apr-17	1	44	52	69	82
3	16-Apr-17	0	1	44	55	74
3	17-Apr-17	0	0	1	52	70
3	18-Apr-17	4	4	4	48	58
3	19-Apr-17	0	4	4	5	57
3	20-Apr-17	2	2	6	6	50
3	21-Apr-17	1	2	3	6	7
3	22-Apr-17	8	8	10	14	14
3	23-Apr-17	1	9	9	11	15
3	24-Apr-17	0	1	9	11	15
3	25-Apr-17	16	16	18	26	28
3	26-Apr-17	0	16	16	25	28
3	27-Apr-17	0	0	16	18	26
3	28-Apr-17	32	32	32	48	57
3	29-Apr-17	35	66	66	83	84
3	30-Apr-17	14	48	80	80	97

Table C.2 Data for base-10 logarithmic transform of bacteria contamination and associated antecedent rainfall depth.

Pump Code Number	Date Sample Collection	Study Group	Phase	Antecedent Rainfall Depth (mm)					Log$_{10}$ of Bacteria Concentrations (log$_{10}$ CFU/100mL)
				24-hr	48-hr	72-hr	120-hr	168-hr	
2	19-Jul-16	Control	1	0	20	38	58	96	3.03
3	19-Jul-16	Control	1	0	20	38	58	96	3.48
4	21-Jul-16	Control	1	13	22	22	60	80	1.95
5	21-Jul-16	Control	1	13	22	22	60	80	2.52
29	29-Jul-16	Pipe	1	0	3	4	35	52	1.35
1	2-Aug-16	Control	1	0	0	0	0	4	0.82
36	2-Aug-16	Apron	1	0	0	0	0	4	1.64
44	2-Aug-16	Apron	1	0	0	0	0	4	1.60
29	2-Aug-16	Pipe	1	0	0	0	0	4	1.90
5	5-Aug-16	Control	1	0	0	0	1	1	2.51
4	5-Aug-16	Control	1	0	0	0	1	1	2.15
3	5-Aug-16	Control	1	0	0	0	1	1	3.79
31	11-Aug-16	Apron	1	0	0	9	41	43	3.05
9	11-Aug-16	Control	1	0	0	9	41	43	2.00
33	11-Aug-16	Apron	1	0	0	9	41	43	2.30
40	16-Aug-16	Apron	1	16	26	37	51	51	1.90
18	16-Aug-16	Pipe	1	16	26	37	51	51	2.89
17	16-Aug-16	Pipe	1	16	26	37	51	51	3.20
21	16-Aug-16	Pipe	1	16	26	37	51	51	3.35
27	17-Aug-16	Pipe	1	2	18	28	43	53	2.81
26	17-Aug-16	Pipe	1	2	18	28	43	53	2.78
41	17-Aug-16	Apron	1	2	18	28	43	53	2.31
28	23-Aug-16	Pipe	1	0	0	0	1	4	3.12
4	23-Aug-16	Control	1	0	0	0	1	4	2.58
2	23-Aug-16	Control	1	0	0	0	1	4	2.04
34	23-Aug-16	Apron	1	0	0	0	1	4	1.70

Table C.2 (Continued)

3	23-Aug-16	Control	1	0	0	0	1	4	1.70
33	23-Aug-16	Apron	1	0	0	0	1	4	1.60
6	23-Aug-16	Control	1	0	0	0	1	4	2.38
5	23-Aug-16	Control	1	0	0	0	1	4	1.85
7	23-Aug-16	Control	1	0	0	0	1	4	2.26
10	24-Aug-16	Control	1	0	0	0	0	3	2.97
39	24-Aug-16	Apron	1	0	0	0	0	3	2.04
8	24-Aug-16	Control	1	0	0	0	0	3	3.18
9	24-Aug-16	Control	1	0	0	0	0	3	1.34
12	24-Aug-16	Control	1	0	0	0	0	3	2.58
36	24-Aug-16	Apron	1	0	0	0	0	3	2.49
35	24-Aug-16	Apron	1	0	0	0	0	3	2.39
37	24-Aug-16	Apron	1	0	0	0	0	3	3.18
15	26-Aug-16	Control	1	1	2	2	2	2	3.26
44	26-Aug-16	Apron	1	1	2	2	2	2	2.04
27	27-Aug-16	Pipe	1	7	8	9	9	9	2.89
42	27-Aug-16	Apron	1	7	8	9	9	9	2.29
26	27-Aug-16	Pipe	1	7	8	9	9	9	2.77
31	28-Aug-16	Apron	1	2	9	11	11	11	2.04
1	28-Aug-16	Control	1	2	9	11	11	11	1.18
16	28-Aug-16	Pipe	1	2	9	11	11	11	1.93
38	28-Aug-16	Apron	1	2	9	11	11	11	2.37
32	3-Sep-16	Apron	1	1	5	17	31	46	3.60
45	3-Sep-16	Apron	1	1	5	17	31	46	2.30
21	4-Sep-16	Pipe	1	0	1	5	25	44	1.98
22	4-Sep-16	Pipe	1	0	1	5	25	44	2.31
40	6-Sep-16	Apron	1	3	5	5	9	30	1.56
17	6-Sep-16	Pipe	1	3	5	5	9	30	2.41
13	6-Sep-16	Control	1	3	5	5	9	30	0.00
19	6-Sep-16	Pipe	1	3	5	5	9	30	1.70

Table C.2 (Continued)

10	10-Sep-16	Control	1	2	2	6	9	10	2.78
41	10-Sep-16	Apron	1	2	2	6	9	10	2.60
31	12-Sep-16	Apron	1	0	1	4	7	10	1.78
1	12-Sep-16	Control	1	0	1	4	7	10	1.51
5	12-Sep-16	Control	1	0	1	4	7	10	1.40
8	12-Sep-16	Control	1	0	1	4	7	10	3.14
9	12-Sep-16	Control	1	0	1	4	7	10	1.22
36	12-Sep-16	Apron	1	0	1	4	7	10	2.49
35	12-Sep-16	Apron	1	0	1	4	7	10	1.72
37	12-Sep-16	Apron	1	0	1	4	7	10	4.00
39	13-Sep-16	Apron	1	1	1	2	4	7	1.30
12	13-Sep-16	Control	1	1	1	2	4	7	2.34
44	13-Sep-16	Apron	1	1	1	2	4	7	1.20
28	13-Sep-16	Pipe	1	1	1	2	4	7	2.94
15	13-Sep-16	Control	1	1	1	2	4	7	2.60
33	14-Sep-16	Apron	1	1	1	1	5	8	2.90
40	17-Sep-16	Apron	1	5	5	5	7	8	1.69
13	17-Sep-16	Control	1	5	5	5	7	8	0.00
17	17-Sep-16	Pipe	1	5	5	5	7	8	2.14
19	17-Sep-16	Pipe	1	5	5	5	7	8	2.10
21	17-Sep-16	Pipe	1	5	5	5	7	8	2.90
22	17-Sep-16	Pipe	1	5	5	5	7	8	2.26
20	17-Sep-16	Pipe	1	5	5	5	7	8	0.00
4	18-Sep-16	Control	1	1	6	6	7	7	2.23
7	18-Sep-16	Control	1	1	6	6	7	7	2.93
3	18-Sep-16	Control	1	1	6	6	7	7	1.88
34	18-Sep-16	Apron	1	1	6	6	7	7	3.70
26	18-Sep-16	Pipe	1	1	6	6	7	7	2.77
27	18-Sep-16	Pipe	1	1	6	6	7	7	2.32
42	18-Sep-16	Apron	1	1	6	6	7	7	3.18

Table C.2 (Continued)

38	18-Sep-16	Apron	1	1	6	6	7	7	2.28
43	18-Sep-16	Apron	1	1	6	6	7	7	2.85
34	19-Sep-16	Apron	1	1	2	7	7	8	1.78
37	20-Sep-16	Apron	1	2	3	4	9	10	3.90
3	24-Sep-16	Control	1	0	0	2	6	7	2.09
7	24-Sep-16	Control	1	0	0	2	6	7	1.95
34	24-Sep-16	Apron	1	0	0	2	6	7	1.78
4	24-Sep-16	Control	1	0	0	2	6	7	2.77
5	24-Sep-16	Control	1	0	0	2	6	7	0.95
8	24-Sep-16	Control	1	0	0	2	6	7	2.96
9	24-Sep-16	Control	1	0	0	2	6	7	0.65
35	24-Sep-16	Apron	1	0	0	2	6	7	1.71
16	27-Sep-16	Pipe	1	1	4	4	4	8	1.28
1	27-Sep-16	Control	1	1	4	4	4	8	0.60
32	27-Sep-16	Apron	1	1	4	4	4	8	2.67
31	27-Sep-16	Apron	1	1	4	4	4	8	1.84
23	30-Sep-16	Pipe	1	3	14	14	19	19	1.65
11	3-Oct-16	Control	1	0	0	0	15	16	2.85
14	3-Oct-16	Control	1	0	0	0	15	16	3.23
21	3-Oct-16	Pipe	1	0	0	0	15	16	3.44
20	3-Oct-16	Pipe	1	0	0	0	15	16	0.00
22	3-Oct-16	Pipe	1	0	0	0	15	16	1.30
18	3-Oct-16	Pipe	1	0	0	0	15	16	2.92
39	3-Oct-16	Apron	1	0	0	0	15	16	0.65
12	3-Oct-16	Control	1	0	0	0	15	16	2.25
17	3-Oct-16	Pipe	1	0	0	0	15	16	2.12
41	3-Oct-16	Apron	1	0	0	0	15	16	2.19
44	8-Oct-16	Apron	1	0	0	0	11	11	1.76
28	8-Oct-16	Pipe	1	0	0	0	11	11	2.57
15	8-Oct-16	Control	1	0	0	0	11	11	2.18

Table C.2 (Continued)

18	8-Oct-16	Pipe	1	0	0	0	11	11	2.60
19	8-Oct-16	Pipe	1	0	0	0	11	11	2.45
39	8-Oct-16	Apron	1	0	0	0	11	11	0.30
12	8-Oct-16	Control	1	0	0	0	11	11	1.82
17	8-Oct-16	Pipe	1	0	0	0	11	11	1.91
40	8-Oct-16	Apron	1	0	0	0	11	11	0.48
23	9-Oct-16	Pipe	1	0	0	0	1	11	1.00
41	9-Oct-16	Apron	1	0	0	0	1	11	2.11
26	9-Oct-16	Pipe	1	0	0	0	1	11	2.55
27	9-Oct-16	Pipe	1	0	0	0	1	11	1.44
37	9-Oct-16	Apron	1	0	0	0	1	11	3.18
35	9-Oct-16	Apron	1	0	0	0	1	11	1.20
6	9-Oct-16	Control	1	0	0	0	1	11	2.76
8	9-Oct-16	Control	1	0	0	0	1	11	2.15
38	9-Oct-16	Apron	1	0	0	0	1	11	1.51
45	9-Oct-16	Apron	1	0	0	0	1	11	2.41
6	13-Oct-16	Control	1	0	0	0	0	0	2.09
4	13-Oct-16	Control	1	0	0	0	0	0	1.51
9	13-Oct-16	Control	1	0	0	0	0	0	0.95
36	13-Oct-16	Apron	1	0	0	0	0	0	3.28
35	13-Oct-16	Apron	1	0	0	0	0	0	1.14
37	13-Oct-16	Apron	1	0	0	0	0	0	2.72
32	13-Oct-16	Apron	1	0	0	0	0	0	2.83
31	13-Oct-16	Apron	1	0	0	0	0	0	1.79
25	16-Oct-16	Pipe	1	0	0	0	0	0	2.39
39	16-Oct-16	Apron	1	0	0	0	0	0	0.08
14	16-Oct-16	Control	1	0	0	0	0	0	2.98
12	16-Oct-16	Control	1	0	0	0	0	0	1.79
17	16-Oct-16	Pipe	1	0	0	0	0	0	1.81
18	16-Oct-16	Pipe	1	0	0	0	0	0	2.21

Table C.2 (Continued)

40	16-Oct-16	Apron	1	0	0	0	0	0	0.14
19	16-Oct-16	Pipe	1	0	0	0	0	0	2.10
13	16-Oct-16	Control	1	0	0	0	0	0	0.22
41	16-Oct-16	Apron	1	0	0	0	0	0	2.07
26	16-Oct-16	Pipe	1	0	0	0	0	0	2.66
27	16-Oct-16	Pipe	1	0	0	0	0	0	2.27
42	16-Oct-16	Apron	1	0	0	0	0	0	2.26
10	16-Oct-16	Control	1	0	0	0	0	0	2.95
21	16-Oct-16	Pipe	1	0	0	0	0	0	3.73
22	16-Oct-16	Pipe	1	0	0	0	0	0	0.22
20	16-Oct-16	Pipe	1	0	0	0	0	0	0.00
35	23-Oct-16	Apron	1	0	2	3	3	3	1.13
9	23-Oct-16	Control	1	0	2	3	3	3	0.73
8	23-Oct-16	Control	1	0	2	3	3	3	1.66
37	23-Oct-16	Apron	1	0	2	3	3	3	2.68
36	23-Oct-16	Apron	1	0	2	3	3	3	2.82
5	23-Oct-16	Control	1	0	2	3	3	3	0.88
7	23-Oct-16	Control	1	0	2	3	3	3	1.57
6	23-Oct-16	Control	1	0	2	3	3	3	1.45
4	23-Oct-16	Control	1	0	2	3	3	3	2.12
3	25-Oct-16	Control	1	1	2	3	5	5	1.98
34	25-Oct-16	Apron	1	1	2	3	5	5	1.80
38	25-Oct-16	Apron	1	1	2	3	5	5	1.38
33	25-Oct-16	Apron	1	1	2	3	5	5	2.59
16	25-Oct-16	Pipe	1	1	2	3	5	5	0.38
1	25-Oct-16	Control	1	1	2	3	5	5	1.00
32	25-Oct-16	Apron	1	1	2	3	5	5	2.40
19	26-Oct-16	Pipe	1	0	1	2	4	5	2.12
13	26-Oct-16	Control	1	0	1	2	4	5	0.11
21	26-Oct-16	Pipe	1	0	1	2	4	5	2.95

Table C.2 (Continued)

14	26-Oct-16	Control	1	0	1	2	4	5	2.79
18	26-Oct-16	Pipe	1	0	1	2	4	5	2.15
40	26-Oct-16	Apron	1	0	1	2	4	5	0.20
17	26-Oct-16	Pipe	1	0	1	2	4	5	1.56
12	26-Oct-16	Control	1	0	1	2	4	5	1.15
39	26-Oct-16	Apron	1	0	1	2	4	5	0.08
20	26-Oct-16	Pipe	1	0	1	2	4	5	0.02
41	26-Oct-16	Apron	1	0	1	2	4	5	2.04
25	26-Oct-16	Pipe	1	0	1	2	4	5	2.45
26	26-Oct-16	Pipe	1	0	1	2	4	5	2.34
44	27-Oct-16	Apron	1	0	0	1	3	5	1.04
28	27-Oct-16	Pipe	1	0	0	1	3	5	2.29
15	27-Oct-16	Control	1	0	0	1	3	5	1.51
29	27-Oct-16	Pipe	1	0	0	1	3	5	2.90
45	27-Oct-16	Apron	1	0	0	1	3	5	1.00
23	27-Oct-16	Pipe	1	0	0	1	3	5	0.37
5	27-Oct-16	Control	1	0	0	1	3	5	0.81
6	27-Oct-16	Control	1	0	0	1	3	5	1.29
4	27-Oct-16	Control	1	0	0	1	3	5	1.94
2	28-Oct-16	Control	1	0	0	0	2	4	1.77
2	28-Oct-16	Control	1	0	0	0	2	4	1.65
36	28-Oct-16	Apron	1	0	0	0	2	4	2.65
35	28-Oct-16	Apron	1	0	0	0	2	4	0.80
11	29-Oct-16	Control	1	0	0	0	1	3	2.68
7	29-Oct-16	Control	1	0	0	0	1	3	3.60
43	30-Oct-16	Apron	1	0	0	0	0	2	3.48
1	1-Nov-16	Control	1	0	0	0	0	0	0.15
31	1-Nov-16	Apron	1	0	0	0	0	0	2.90
33	1-Nov-16	Apron	1	0	0	0	0	0	3.00
34	1-Nov-16	Apron	1	0	0	0	0	0	0.70

Table C.2 (Continued)

23	2-Nov-16	Pipe	1	0	0	0	0	0	0.19
41	2-Nov-16	Apron	1	0	0	0	0	0	1.81
25	2-Nov-16	Pipe	1	0	0	0	0	0	2.45
24	2-Nov-16	Pipe	1	0	0	0	0	0	3.48
26	2-Nov-16	Pipe	1	0	0	0	0	0	1.96
27	2-Nov-16	Pipe	1	0	0	0	0	0	1.41
42	2-Nov-16	Apron	1	0	0	0	0	0	3.56
19	3-Nov-16	Pipe	1	0	0	0	0	0	2.54
18	3-Nov-16	Pipe	1	0	0	0	0	0	1.76
17	3-Nov-16	Pipe	1	0	0	0	0	0	1.42
13	3-Nov-16	Control	1	0	0	0	0	0	0.12
14	3-Nov-16	Control	1	0	0	0	0	0	2.39
35	6-Nov-16	Apron	1	6	26	40	40	40	0.97
31	6-Nov-16	Apron	1	6	26	40	40	40	3.22
1	6-Nov-16	Control	1	6	26	40	40	40	0.82
11	6-Nov-16	Control	1	6	26	40	40	40	2.54
37	6-Nov-16	Apron	1	6	26	40	40	40	2.38
32	6-Nov-16	Apron	1	6	26	40	40	40	2.08
36	6-Nov-16	Apron	1	6	26	40	40	40	2.61
8	6-Nov-16	Control	1	6	26	40	40	40	2.18
6	6-Nov-16	Control	1	6	26	40	40	40	2.18
4	6-Nov-16	Control	1	6	26	40	40	40	2.54
38	6-Nov-16	Apron	1	6	26	40	40	40	0.70
26	8-Nov-16	Pipe	1	0	0	6	40	40	2.15
43	8-Nov-16	Apron	1	0	0	6	40	40	3.65
25	8-Nov-16	Pipe	1	0	0	6	40	40	2.11
19	10-Nov-16	Pipe	1	0	0	0	6	40	2.10
18	10-Nov-16	Pipe	1	0	0	0	6	40	1.83
14	10-Nov-16	Control	1	0	0	0	6	40	2.52
22	10-Nov-16	Pipe	1	0	0	0	6	40	0.63

Table C.2 (Continued)

23	10-Nov-16	Pipe	1	0	0	0	6	40	0.35
41	10-Nov-16	Apron	1	0	0	0	6	40	1.85
24	10-Nov-16	Pipe	1	0	0	0	6	40	3.91
25	10-Nov-16	Pipe	1	0	0	0	6	40	2.19
26	10-Nov-16	Pipe	1	0	0	0	6	40	2.28
42	10-Nov-16	Apron	1	0	0	0	6	40	3.85
2	13-Nov-16	Control	1	0	1	1	1	1	1.54
34	13-Nov-16	Apron	1	0	1	1	1	1	0.51
33	13-Nov-16	Apron	1	0	1	1	1	1	2.62
4	13-Nov-16	Control	1	0	1	1	1	1	1.40
5	13-Nov-16	Control	1	0	1	1	1	1	0.81
43	13-Nov-16	Apron	1	0	1	1	1	1	3.38
3	13-Nov-16	Control	1	0	1	1	1	1	2.43
15	13-Nov-16	Control	1	0	1	1	1	1	0.95
28	13-Nov-16	Pipe	1	0	1	1	1	1	1.58
6	13-Nov-16	Control	1	0	1	1	1	1	1.53
14	13-Nov-16	Control	1	0	1	1	1	1	2.77
7	13-Nov-16	Control	1	0	1	1	1	1	2.77
16	13-Nov-16	Pipe	1	0	1	1	1	1	0.65
1	13-Nov-16	Control	1	0	1	1	1	1	0.13
13	16-Nov-16	Control	1	5	12	12	12	12	0.58
40	16-Nov-16	Apron	1	5	12	12	12	12	0.06
18	16-Nov-16	Pipe	1	5	12	12	12	12	1.80
11	16-Nov-16	Control	1	5	12	12	12	12	2.62
20	16-Nov-16	Pipe	1	5	12	12	12	12	0.48
24	16-Nov-16	Pipe	1	5	12	12	12	12	3.52
25	16-Nov-16	Pipe	1	5	12	12	12	12	2.05
19	16-Nov-16	Pipe	1	5	12	12	12	12	2.04
2	16-Nov-16	Control	1	5	12	12	12	12	1.40
43	16-Nov-16	Apron	1	5	12	12	12	12	3.26

Table C.2 (Continued)

45	16-Nov-16	Apron	1	5	12	12	12	12	1.31
12	16-Nov-16	Control	1	5	12	12	12	12	1.06
14	20-Nov-16	Control	1	0	0	0	5	12	2.12
41	20-Nov-16	Apron	1	0	0	0	5	12	0.56
43	20-Nov-16	Apron	1	0	0	0	5	12	2.85
21	20-Nov-16	Pipe	1	0	0	0	5	12	2.22
29	20-Nov-16	Pipe	1	0	0	0	5	12	3.01
26	20-Nov-16	Pipe	1	0	0	0	5	12	2.26
27	20-Nov-16	Pipe	1	0	0	0	5	12	1.84
44	20-Nov-16	Apron	1	0	0	0	5	12	1.32
28	20-Nov-16	Pipe	1	0	0	0	5	12	1.44
15	20-Nov-16	Control	1	0	0	0	5	12	1.01
45	20-Nov-16	Apron	1	0	0	0	5	12	1.26
32	20-Nov-16	Apron	1	0	0	0	5	12	2.33
6	20-Nov-16	Control	1	0	0	0	5	12	1.99
34	20-Nov-16	Apron	1	0	0	0	5	12	0.00
2	20-Nov-16	Control	1	0	0	0	5	12	1.10
33	20-Nov-16	Apron	1	0	0	0	5	12	2.30
11	20-Nov-16	Control	1	0	0	0	5	12	2.72
42	23-Nov-16	Apron	1	0	0	0	0	0	2.54
25	23-Nov-16	Pipe	1	0	0	0	0	0	2.43
24	23-Nov-16	Pipe	1	0	0	0	0	0	2.81
22	23-Nov-16	Pipe	1	0	0	0	0	0	0.08
11	23-Nov-16	Control	1	0	0	0	0	0	2.64
12	23-Nov-16	Control	1	0	0	0	0	0	0.81
37	23-Nov-16	Apron	1	0	0	0	0	0	2.47
37	23-Nov-16	Apron	1	0	0	0	0	0	2.47
32	11-Jan-17	Apron	2	14	14	14	22	53	1.34
7	11-Jan-17	Control	2	14	14	14	22	53	2.35
6	11-Jan-17	Control	2	14	14	14	22	53	0.12

Table C.2 (Continued)

4	11-Jan-17	Control	2	14	14	14	22	53	2.49
8	11-Jan-17	Control	2	14	14	14	22	53	2.67
36	11-Jan-17	Apron	2	14	14	14	22	53	0.00
37	11-Jan-17	Apron	2	14	14	14	22	53	3.10
2	11-Jan-17	Control	2	14	14	14	22	53	0.15
3	11-Jan-17	Control	2	14	14	14	22	53	3.70
23	15-Jan-17	Pipe	2	0	3	5	18	19	0.06
41	15-Jan-17	Apron	2	0	3	5	18	19	0.99
18	15-Jan-17	Pipe	2	0	3	5	18	19	0.90
21	15-Jan-17	Pipe	2	0	3	5	18	19	1.85
22	15-Jan-17	Pipe	2	0	3	5	18	19	1.60
10	15-Jan-17	Control	2	0	3	5	18	19	1.48
11	15-Jan-17	Control	2	0	3	5	18	19	2.72
24	15-Jan-17	Pipe	2	0	3	5	18	19	2.47
27	15-Jan-17	Pipe	2	0	3	5	18	19	0.48
42	15-Jan-17	Apron	2	0	3	5	18	19	3.37
45	15-Jan-17	Apron	2	0	3	5	18	19	0.23
44	15-Jan-17	Apron	2	0	3	5	18	19	0.18
29	15-Jan-17	Pipe	2	0	3	5	18	19	1.70
15	15-Jan-17	Control	2	0	3	5	18	19	0.19
9	18-Jan-17	Control	2	10	29	33	36	38	0.56
8	18-Jan-17	Control	2	10	29	33	36	38	1.60
32	18-Jan-17	Apron	2	10	29	33	36	38	1.58
37	18-Jan-17	Apron	2	10	29	33	36	38	3.08
1	18-Jan-17	Control	2	10	29	33	36	38	0.18
12	18-Jan-17	Control	2	10	29	33	36	38	0.76
7	18-Jan-17	Control	2	10	29	33	36	38	1.35
3	18-Jan-17	Control	2	10	29	33	36	38	4.32
4	18-Jan-17	Control	2	10	29	33	36	38	2.50
33	18-Jan-17	Apron	2	10	29	33	36	38	3.66

Table C.2 (Continued)

6	18-Jan-17	Control	2	10	29	33	36	38	0.27
40	18-Jan-17	Apron	2	10	29	33	36	38	0.08
13	18-Jan-17	Control	2	10	29	33	36	38	1.60
17	18-Jan-17	Pipe	2	10	29	33	36	38	0.24
2	18-Jan-17	Control	2	10	29	33	36	38	0.21
22	22-Jan-17	Pipe	2	32	39	61	71	94	1.00
14	22-Jan-17	Control	2	32	39	61	71	94	3.58
21	22-Jan-17	Pipe	2	32	39	61	71	94	1.99
19	22-Jan-17	Pipe	2	32	39	61	71	94	2.70
18	22-Jan-17	Pipe	2	32	39	61	71	94	1.05
24	22-Jan-17	Pipe	2	32	39	61	71	94	1.93
26	22-Jan-17	Pipe	2	32	39	61	71	94	3.67
43	22-Jan-17	Apron	2	32	39	61	71	94	3.31
42	22-Jan-17	Apron	2	32	39	61	71	94	3.07
44	22-Jan-17	Apron	2	32	39	61	71	94	0.43
29	22-Jan-17	Pipe	2	32	39	61	71	94	2.33
28	22-Jan-17	Pipe	2	32	39	61	71	94	1.01
15	22-Jan-17	Control	2	32	39	61	71	94	0.20
16	25-Jan-17	Pipe	2	2	2	8	46	69	1.68
1	25-Jan-17	Control	2	2	2	8	46	69	0.28
32	25-Jan-17	Apron	2	2	2	8	46	69	1.51
31	25-Jan-17	Apron	2	2	2	8	46	69	3.00
7	25-Jan-17	Control	2	2	2	8	46	69	1.96
6	25-Jan-17	Control	2	2	2	8	46	69	0.13
4	25-Jan-17	Control	2	2	2	8	46	69	2.05
36	25-Jan-17	Apron	2	2	2	8	46	69	2.77
37	25-Jan-17	Apron	2	2	2	8	46	69	2.76
8	25-Jan-17	Control	2	2	2	8	46	69	1.80
11	25-Jan-17	Control	2	2	2	8	46	69	2.70
10	25-Jan-17	Control	2	2	2	8	46	69	2.78

Table C.2 (Continued)

33	25-Jan-17	Apron	2	2	2	8	46	69	3.22
2	25-Jan-17	Control	2	2	2	8	46	69	1.26
44	31-Jan-17	Apron	2	0	0	0	0	2	1.04
28	31-Jan-17	Pipe	2	0	0	0	0	2	1.85
45	31-Jan-17	Apron	2	0	0	0	0	2	2.23
38	31-Jan-17	Apron	2	0	0	0	0	2	1.88
15	31-Jan-17	Control	2	0	0	0	0	2	1.06
40	1-Feb-17	Apron	2	4	4	4	4	4	0.10
17	1-Feb-17	Pipe	2	4	4	4	4	4	0.23
18	1-Feb-17	Pipe	2	4	4	4	4	4	0.64
13	1-Feb-17	Control	2	4	4	4	4	4	0.00
19	1-Feb-17	Pipe	2	4	4	4	4	4	2.76
21	1-Feb-17	Pipe	2	4	4	4	4	4	2.35
22	1-Feb-17	Pipe	2	4	4	4	4	4	0.18
12	1-Feb-17	Control	2	4	4	4	4	4	0.20
24	4-Feb-17	Pipe	2	0	1	22	25	26	2.20
26	4-Feb-17	Pipe	2	0	1	22	25	26	3.37
23	4-Feb-17	Pipe	2	0	1	22	25	26	0.19
14	4-Feb-17	Control	2	0	1	22	25	26	2.74
20	4-Feb-17	Pipe	2	0	1	22	25	26	3.89
25	4-Feb-17	Pipe	2	0	1	22	25	26	1.57
27	4-Feb-17	Pipe	2	0	1	22	25	26	1.99
42	4-Feb-17	Apron	2	0	1	22	25	26	3.11
6	5-Feb-17	Control	2	0	0	1	25	25	0.19
1	5-Feb-17	Control	2	0	0	1	25	25	0.62
16	5-Feb-17	Pipe	2	0	0	1	25	25	0.96
4	5-Feb-17	Control	2	0	0	1	25	25	1.53
10	5-Feb-17	Control	2	0	0	1	25	25	0.00
37	5-Feb-17	Apron	2	0	0	1	25	25	2.22
35	5-Feb-17	Apron	2	0	0	1	25	25	2.79

Table C.2 (Continued)

2	5-Feb-17	Control	2	0	0	1	25	25	0.02
8	5-Feb-17	Control	2	0	0	1	25	25	1.33
4	5-Feb-17	Control	2	0	0	1	25	25	2.66
31	5-Feb-17	Apron	2	0	0	1	25	25	2.67
18	8-Feb-17	Pipe	2	0	0	11	11	32	0.65
17	8-Feb-17	Pipe	2	0	0	11	11	32	0.44
40	8-Feb-17	Apron	2	0	0	11	11	32	0.02
19	8-Feb-17	Pipe	2	0	0	11	11	32	2.28
13	8-Feb-17	Control	2	0	0	11	11	32	1.37
44	8-Feb-17	Apron	2	0	0	11	11	32	0.52
5	8-Feb-17	Control	2	0	0	11	11	32	1.60
43	8-Feb-17	Apron	2	0	0	11	11	32	1.90
28	8-Feb-17	Pipe	2	0	0	11	11	32	0.00
29	8-Feb-17	Pipe	2	0	0	11	11	32	3.56
45	8-Feb-17	Apron	2	0	0	11	11	32	1.27
38	8-Feb-17	Apron	2	0	0	11	11	32	2.24
14	8-Feb-17	Control	2	0	0	11	11	32	2.86
20	8-Feb-17	Pipe	2	0	0	11	11	32	3.67
21	8-Feb-17	Pipe	2	0	0	11	11	32	1.96
39	8-Feb-17	Apron	2	0	0	11	11	32	0.00
24	12-Feb-17	Pipe	2	0	1	4	4	15	3.00
37	12-Feb-17	Apron	2	0	1	4	4	15	1.95
31	12-Feb-17	Apron	2	0	1	4	4	15	2.42
36	12-Feb-17	Apron	2	0	1	4	4	15	2.84
35	12-Feb-17	Apron	2	0	1	4	4	15	2.23
16	12-Feb-17	Pipe	2	0	1	4	4	15	0.60
9	12-Feb-17	Control	2	0	1	4	4	15	0.91
26	12-Feb-17	Pipe	2	0	1	4	4	15	2.97
17	15-Feb-17	Pipe	2	3	3	3	4	7	0.04
39	15-Feb-17	Apron	2	3	3	3	4	7	0.04

Table C.2 (Continued)

20	15-Feb-17	Pipe	2	3	3	3	4	7	3.22
22	15-Feb-17	Pipe	2	3	3	3	4	7	0.00
21	15-Feb-17	Pipe	2	3	3	3	4	7	2.25
12	15-Feb-17	Control	2	3	3	3	4	7	0.15
1	15-Feb-17	Control	2	3	3	3	4	7	0.11
32	15-Feb-17	Apron	2	3	3	3	4	7	2.26
5	15-Feb-17	Control	2	3	3	3	4	7	1.71
3	15-Feb-17	Control	2	3	3	3	4	7	3.34
4	15-Feb-17	Control	2	3	3	3	4	7	1.10
7	15-Feb-17	Control	2	3	3	3	4	7	2.30
33	15-Feb-17	Apron	2	3	3	3	4	7	2.46
6	15-Feb-17	Control	2	3	3	3	4	7	0.04
43	15-Feb-17	Apron	2	3	3	3	4	7	1.60
38	15-Feb-17	Apron	2	3	3	3	4	7	2.83
13	19-Feb-17	Control	2	4	40	40	43	43	1.05
19	19-Feb-17	Pipe	2	4	40	40	43	43	2.70
40	19-Feb-17	Apron	2	4	40	40	43	43	0.02
18	19-Feb-17	Pipe	2	4	40	40	43	43	1.41
23	19-Feb-17	Pipe	2	4	40	40	43	43	0.27
41	19-Feb-17	Apron	2	4	40	40	43	43	1.42
31	19-Feb-17	Apron	2	4	40	40	43	43	2.48
34	19-Feb-17	Apron	2	4	40	40	43	43	3.51
5	19-Feb-17	Control	2	4	40	40	43	43	2.51
10	19-Feb-17	Control	2	4	40	40	43	43	1.51
24	19-Feb-17	Pipe	2	4	40	40	43	43	3.45
26	19-Feb-17	Pipe	2	4	40	40	43	43	2.66
42	19-Feb-17	Apron	2	4	40	40	43	43	1.95
27	19-Feb-17	Pipe	2	4	40	40	43	43	1.32
45	19-Feb-17	Apron	2	4	40	40	43	43	0.20
43	19-Feb-17	Apron	2	4	40	40	43	43	1.80

Table C.2 (Continued)

28	19-Feb-17	Pipe	2	4	40	40	43	43	1.59
29	19-Feb-17	Pipe	2	4	40	40	43	43	2.68
44	19-Feb-17	Apron	2	4	40	40	43	43	0.17
34	22-Feb-17	Apron	2	8	15	15	55	55	3.47
3	22-Feb-17	Control	2	8	15	15	55	55	3.03
2	22-Feb-17	Control	2	8	15	15	55	55	0.40
5	22-Feb-17	Control	2	8	15	15	55	55	2.93
36	22-Feb-17	Apron	2	8	15	15	55	55	2.79
42	22-Feb-17	Apron	2	8	15	15	55	55	2.44
41	22-Feb-17	Apron	2	8	15	15	55	55	0.49
35	22-Feb-17	Apron	2	8	15	15	55	55	2.88
37	22-Feb-17	Apron	2	8	15	15	55	55	2.90
32	22-Feb-17	Apron	2	8	15	15	55	55	0.82
12	22-Feb-17	Control	2	8	15	15	55	55	1.08
39	22-Feb-17	Apron	2	8	15	15	55	55	0.04
38	22-Feb-17	Apron	2	8	15	15	55	55	2.89
43	22-Feb-17	Apron	2	8	15	15	55	55	1.64
44	22-Feb-17	Apron	2	8	15	15	55	55	0.13
15	22-Feb-17	Control	2	8	15	15	55	55	1.77
29	22-Feb-17	Pipe	2	8	15	15	55	55	2.55
7	22-Feb-17	Control	2	8	15	15	55	55	2.85
6	22-Feb-17	Control	2	8	15	15	55	55	0.69
4	22-Feb-17	Control	2	8	15	15	55	55	1.06
20	26-Feb-17	Pipe	2	0	0	0	12	19	2.64
21	26-Feb-17	Pipe	2	0	0	0	12	19	2.69
14	26-Feb-17	Control	2	0	0	0	12	19	3.48
17	26-Feb-17	Pipe	2	0	0	0	12	19	0.24
11	26-Feb-17	Control	2	0	0	0	12	19	2.19
18	26-Feb-17	Pipe	2	0	0	0	12	19	0.75
13	26-Feb-17	Control	2	0	0	0	12	19	1.45

Table C.2 (Continued)

40	26-Feb-17	Apron	2	0	0	0	12	19	0.00
25	26-Feb-17	Pipe	2	0	0	0	12	19	3.01
5	27-Feb-17	Control	2	1	1	1	5	19	1.54
34	27-Feb-17	Apron	2	1	1	1	5	19	3.27
8	27-Feb-17	Control	2	1	1	1	5	19	1.85
10	27-Feb-17	Control	2	1	1	1	5	19	1.62
43	27-Feb-17	Apron	2	1	1	1	5	19	1.59
45	27-Feb-17	Apron	2	1	1	1	5	19	0.78
31	4-Mar-17	Apron	2	4	4	4	5	6	2.41
35	4-Mar-17	Apron	2	4	4	4	5	6	2.00
44	4-Mar-17	Apron	2	4	4	4	5	6	1.24
35	5-Mar-17	Apron	2	21	25	25	26	27	1.84
34	5-Mar-17	Apron	2	21	25	25	26	27	2.79
9	9-Mar-17	Control	2	1	77	170	233	237	0.18
35	9-Mar-17	Apron	3	1	77	170	233	237	2.82
7	9-Mar-17	Control	2	1	77	170	233	237	3.17
6	9-Mar-17	Control	2	1	77	170	233	237	1.15
2	9-Mar-17	Control	2	1	77	170	233	237	1.83
44	10-Mar-17	Apron	2	0	1	77	212	237	0.64
27	10-Mar-17	Pipe	2	0	1	77	212	237	1.78
41	10-Mar-17	Apron	2	0	1	77	212	237	1.00
40	10-Mar-17	Apron	2	0	1	77	212	237	0.00
31	10-Mar-17	Apron	2	0	1	77	212	237	2.66
37	10-Mar-17	Apron	2	0	1	77	212	237	2.68
34	10-Mar-17	Apron	2	0	1	77	212	237	2.89
38	10-Mar-17	Apron	2	0	1	77	212	237	2.32
43	10-Mar-17	Apron	2	0	1	77	212	237	1.30
28	10-Mar-17	Pipe	2	0	1	77	212	237	0.00
17	12-Mar-17	Pipe	2	56	59	59	136	271	0.78
23	12-Mar-17	Pipe	2	56	59	59	136	271	1.29

Table C.2 (Continued)

19	12-Mar-17	Pipe	2	56	59	59	136	271	2.45
12	12-Mar-17	Control	2	56	59	59	136	271	1.76
42	12-Mar-17	Apron	2	56	59	59	136	271	2.49
26	12-Mar-17	Pipe	2	56	59	59	136	271	2.39
24	12-Mar-17	Pipe	2	56	59	59	136	271	2.48
14	12-Mar-17	Control	2	56	59	59	136	271	3.35
20	12-Mar-17	Pipe	2	56	59	59	136	271	2.23
21	12-Mar-17	Pipe	2	56	59	59	136	271	3.60
22	12-Mar-17	Pipe	2	56	59	59	136	271	1.90
38	18-Mar-17	Apron	3	7	83	96	96	175	3.00
44	18-Mar-17	Apron	3	7	83	96	96	175	0.09
33	19-Mar-17	Apron	3	37	44	120	133	156	2.76
3	19-Mar-17	Control	3	37	44	120	133	156	3.54
4	19-Mar-17	Control	3	37	44	120	133	156	1.24
6	19-Mar-17	Control	3	37	44	120	133	156	0.94
32	19-Mar-17	Apron	3	37	44	120	133	156	1.23
31	19-Mar-17	Apron	3	37	44	120	133	156	2.13
16	19-Mar-17	Pipe	3	37	44	120	133	156	0.98
42	19-Mar-17	Apron	3	37	44	120	133	156	2.01
26	19-Mar-17	Pipe	3	37	44	120	133	156	2.35
25	19-Mar-17	Pipe	3	37	44	120	133	156	3.08
24	19-Mar-17	Pipe	3	37	44	120	133	156	2.46
41	25-Mar-17	Apron	3	0	0	9	19	91	0.77
17	25-Mar-17	Pipe	3	0	0	9	19	91	0.08
18	25-Mar-17	Pipe	3	0	0	9	19	91	0.78
40	25-Mar-17	Apron	3	0	0	9	19	91	0.16
13	25-Mar-17	Control	3	0	0	9	19	91	0.20
10	25-Mar-17	Control	3	0	0	9	19	91	0.78
38	25-Mar-17	Apron	3	0	0	9	19	91	2.78
14	25-Mar-17	Control	3	0	0	9	19	91	3.40

Table C.2 (Continued)

20	25-Mar-17	Pipe	3	0	0	9	19	91	2.17
21	25-Mar-17	Pipe	3	0	0	9	19	91	2.38
22	25-Mar-17	Pipe	3	0	0	9	19	91	0.00
12	25-Mar-17	Control	3	0	0	9	19	91	1.02
39	25-Mar-17	Apron	3	0	0	9	19	91	0.00
8	25-Mar-17	Control	3	0	0	9	19	91	2.60
9	25-Mar-17	Control	3	0	0	9	19	91	0.20
35	25-Mar-17	Apron	3	0	0	9	19	91	1.90
37	25-Mar-17	Apron	3	0	0	9	19	91	2.93
16	29-Mar-17	Pipe	3	1	3	8	8	17	0.18
31	29-Mar-17	Apron	3	1	3	8	8	17	1.84
3	29-Mar-17	Control	3	1	3	8	8	17	3.34
2	29-Mar-17	Control	3	1	3	8	8	17	0.00
34	29-Mar-17	Apron	3	1	3	8	8	17	1.95
44	29-Mar-17	Apron	3	1	3	8	8	17	0.61
28	29-Mar-17	Pipe	3	1	3	8	8	17	0.18
29	29-Mar-17	Pipe	3	1	3	8	8	17	1.92
43	29-Mar-17	Apron	3	1	3	8	8	17	0.35
45	29-Mar-17	Apron	3	1	3	8	8	17	0.20
42	30-Mar-17	Apron	3	2	4	5	10	10	1.76
27	30-Mar-17	Pipe	3	2	4	5	10	10	1.61
24	30-Mar-17	Pipe	3	2	4	5	10	10	2.00
26	30-Mar-17	Pipe	3	2	4	5	10	10	2.42
25	30-Mar-17	Pipe	3	2	4	5	10	10	2.53
4	30-Mar-17	Control	3	2	4	5	10	10	0.59
5	30-Mar-17	Control	3	2	4	5	10	10	1.30
7	30-Mar-17	Control	3	2	4	5	10	10	1.70
6	30-Mar-17	Control	3	2	4	5	10	10	0.06
23	2-Apr-17	Pipe	3	1	2	21	25	31	1.40
17	2-Apr-17	Pipe	3	1	2	21	25	31	0.27

Table C.2 (Continued)

18	2-Apr-17	Pipe	3	1	2	21	25	31	1.45
40	2-Apr-17	Apron	3	1	2	21	25	31	0.02
12	2-Apr-17	Control	3	1	2	21	25	31	0.64
19	2-Apr-17	Pipe	3	1	2	21	25	31	1.61
8	2-Apr-17	Control	3	1	2	21	25	31	2.10
9	2-Apr-17	Control	3	1	2	21	25	31	0.24
35	2-Apr-17	Apron	3	1	2	21	25	31	1.73
37	2-Apr-17	Apron	3	1	2	21	25	31	2.05
6	5-Apr-17	Control	3	28	33	33	35	57	0.31
42	5-Apr-17	Apron	3	28	33	33	35	57	1.51
27	5-Apr-17	Pipe	3	28	33	33	35	57	1.44
33	5-Apr-17	Apron	3	28	33	33	35	57	3.40
28	5-Apr-17	Pipe	3	28	33	33	35	57	0.04
43	5-Apr-17	Apron	3	28	33	33	35	57	1.72
24	5-Apr-17	Pipe	3	28	33	33	35	57	2.09
38	5-Apr-17	Apron	3	28	33	33	35	57	1.93
34	6-Apr-17	Apron	3	16	44	49	50	70	1.92
16	6-Apr-17	Pipe	3	16	44	49	50	70	0.48
31	6-Apr-17	Apron	3	16	44	49	50	70	1.09
36	6-Apr-17	Apron	3	16	44	49	50	70	4.09
37	6-Apr-17	Apron	3	16	44	49	50	70	1.90
8	6-Apr-17	Control	3	16	44	49	50	70	1.38
10	9-Apr-17	Control	3	8	9	14	58	63	0.07
17	9-Apr-17	Pipe	3	8	9	14	58	63	0.26
18	9-Apr-17	Pipe	3	8	9	14	58	63	1.23
19	9-Apr-17	Pipe	3	8	9	14	58	63	1.80
40	9-Apr-17	Apron	3	8	9	14	58	63	0.00
13	9-Apr-17	Control	3	8	9	14	58	63	0.30
23	9-Apr-17	Pipe	3	8	9	14	58	63	1.66
20	9-Apr-17	Pipe	3	8	9	14	58	63	1.84

Table C.2 (Continued)

44	9-Apr-17	Apron	3	8	9	14	58	63	1.64
42	12-Apr-17	Apron	3	2	17	22	31	51	1.16
27	12-Apr-17	Pipe	3	2	17	22	31	51	1.33
26	12-Apr-17	Pipe	3	2	17	22	31	51	2.22
24	12-Apr-17	Pipe	3	2	17	22	31	51	1.99
21	12-Apr-17	Pipe	3	2	17	22	31	51	2.10
12	12-Apr-17	Control	3	2	17	22	31	51	0.81
39	12-Apr-17	Apron	3	2	17	22	31	51	0.15
14	12-Apr-17	Control	3	2	17	22	31	51	3.51
6	12-Apr-17	Control	3	2	17	22	31	51	0.08
3	12-Apr-17	Control	3	2	17	22	31	51	3.57
2	12-Apr-17	Control	3	2	17	22	31	51	0.04
34	12-Apr-17	Apron	3	2	17	22	31	51	1.63
29	12-Apr-17	Pipe	3	2	17	22	31	51	1.95
38	12-Apr-17	Apron	3	2	17	22	31	51	1.26
8	15-Apr-17	Control	3	1	44	52	69	82	0.91
9	15-Apr-17	Control	3	1	44	52	69	82	0.53
35	15-Apr-17	Apron	3	1	44	52	69	82	1.90
37	15-Apr-17	Apron	3	1	44	52	69	82	1.62
31	15-Apr-17	Apron	3	1	44	52	69	82	1.71
36	15-Apr-17	Apron	3	1	44	52	69	82	3.29
1	15-Apr-17	Control	3	1	44	52	69	82	1.36
14	15-Apr-17	Control	3	1	44	52	69	82	3.15
42	15-Apr-17	Apron	3	1	44	52	69	82	0.63
24	15-Apr-17	Pipe	3	1	44	52	69	82	1.88
20	15-Apr-17	Pipe	3	1	44	52	69	82	1.65
22	15-Apr-17	Pipe	3	1	44	52	69	82	1.78
10	15-Apr-17	Control	3	1	44	52	69	82	0.26
11	15-Apr-17	Control	3	1	44	52	69	82	1.75
29	20-Apr-17	Pipe	3	2	2	6	6	50	1.68

Table C.2 (Continued)

28	20-Apr-17	Pipe	3	2	2	6	6	50	0.29
2	20-Apr-17	Control	3	2	2	6	6	50	0.36
33	20-Apr-17	Apron	3	2	2	6	6	50	3.11
3	20-Apr-17	Control	3	2	2	6	6	50	2.18
34	20-Apr-17	Apron	3	2	2	6	6	50	1.37
22	21-Apr-17	Pipe	3	1	2	3	6	7	1.13
17	21-Apr-17	Pipe	3	1	2	3	6	7	0.18
18	21-Apr-17	Pipe	3	1	2	3	6	7	1.17
14	21-Apr-17	Control	3	1	2	3	6	7	3.20
40	21-Apr-17	Apron	3	1	2	3	6	7	0.04
13	21-Apr-17	Control	3	1	2	3	6	7	0.31
43	21-Apr-17	Apron	3	1	2	3	6	7	1.08
38	21-Apr-17	Apron	3	1	2	3	6	7	1.68
5	21-Apr-17	Control	3	1	2	3	6	7	1.91
6	21-Apr-17	Control	3	1	2	3	6	7	0.28
4	21-Apr-17	Control	3	1	2	3	6	7	2.78
35	23-Apr-17	Apron	3	1	9	9	11	15	1.97
33	23-Apr-17	Apron	3	1	9	9	11	15	2.65
5	23-Apr-17	Control	3	1	9	9	11	15	2.34
7	23-Apr-17	Control	3	1	9	9	11	15	3.70
31	23-Apr-17	Apron	3	1	9	9	11	15	2.29
16	23-Apr-17	Pipe	3	1	9	9	11	15	0.00
11	23-Apr-17	Control	3	1	9	9	11	15	3.24
4	23-Apr-17	Control	3	1	9	9	11	15	2.69
42	23-Apr-17	Apron	3	1	9	9	11	15	0.27
27	23-Apr-17	Pipe	3	1	9	9	11	15	1.11
26	23-Apr-17	Pipe	3	1	9	9	11	15	2.63
24	23-Apr-17	Pipe	3	1	9	9	11	15	1.79
14	23-Apr-17	Control	3	1	9	9	11	15	2.98
22	23-Apr-17	Pipe	3	1	9	9	11	15	0.64

Table C.2 (Continued)

20	23-Apr-17	Pipe	3	1	9	9	11	15	2.08
2	26-Apr-17	Control	3	0	16	16	25	28	0.94
6	26-Apr-17	Control	3	0	16	16	25	28	0.19
33	26-Apr-17	Apron	3	0	16	16	25	28	2.56
3	26-Apr-17	Control	3	0	16	16	25	28	2.48
7	26-Apr-17	Control	3	0	16	16	25	28	3.27
9	26-Apr-17	Control	3	0	16	16	25	28	0.26
32	26-Apr-17	Apron	3	0	16	16	25	28	0.98
10	26-Apr-17	Control	3	0	16	16	25	28	0.29
1	26-Apr-17	Control	3	0	16	16	25	28	0.38
37	26-Apr-17	Apron	3	0	16	16	25	28	1.06
44	26-Apr-17	Apron	3	0	16	16	25	28	0.91
43	26-Apr-17	Apron	3	0	16	16	25	28	0.83
23	26-Apr-17	Pipe	3	0	16	16	25	28	0.15
17	26-Apr-17	Pipe	3	0	16	16	25	28	0.26
18	26-Apr-17	Pipe	3	0	16	16	25	28	1.77
40	26-Apr-17	Apron	3	0	16	16	25	28	0.02
13	26-Apr-17	Control	3	0	16	16	25	28	0.28
41	26-Apr-17	Apron	3	0	16	16	25	28	0.72
39	26-Apr-17	Apron	3	0	16	16	25	28	0.00
22	30-Apr-17	Pipe	3	14	48	80	80	97	1.52
14	30-Apr-17	Control	3	14	48	80	80	97	1.87
20	30-Apr-17	Pipe	3	14	48	80	80	97	2.15
33	30-Apr-17	Apron	3	14	48	80	80	97	2.28
4	30-Apr-17	Control	3	14	48	80	80	97	2.51
5	30-Apr-17	Control	3	14	48	80	80	97	3.48
36	30-Apr-17	Apron	3	14	48	80	80	97	3.45
16	30-Apr-17	Pipe	3	14	48	80	80	97	0.46
34	30-Apr-17	Apron	3	14	48	80	80	97	1.74
29	30-Apr-17	Pipe	3	14	48	80	80	97	1.47

Table C.2 (Continued)

43	30-Apr-17	Apron	3	14	48	80	80	97	0.58
45	30-Apr-17	Apron	3	14	48	80	80	97	1.39
38	30-Apr-17	Apron	3	14	48	80	80	97	1.78
44	30-Apr-17	Apron	3	14	48	80	80	97	0.55

Table C.3 Distances of on-site sanitation. Pit is pit latrine, Septic is the sewage tank for a pour-flush latrine, sani. is sanitation type, and dist. is distance.

Pump Code Number	Sani. 1	Dist. 1	Sani. 2	Dist. 2	Sani. 3	Dist. 3	Sani. 4	Dist. 4	Sani. 5	Dist. 5	Sani. 6	Dist. 6
1	Pit	25.1	Pit	15.5	Septic	13.1	Septic	9.1				
2	Septic	9.3	Septic	9.2	Septic	>50	Pit	>50	Unknown	Very long distance		
3	Septic	12.6	Septic	20.6	Septic	22.2	Pit	33.9				
4	Pit	16.1	Septic	23.1	Septic	20.4	Septic	14.5	Septic	14.8		
5	Pit	20.6	Pit	6.2	Septic	11.6	Septic	~20				
6	Septic	8.6	Septic	15.4	Septic	8.2	Septic	13.0 to 14.6				
7	Septic	13.2	Pit	15.5	Septic	8.2 to 8.6	Septic	9.8 to 10.8	Pit	12.1	Buried Pit (long-time)	14.1
8	Septic	11.5	Pit	9.6	Septic	10.5	Pit	9.6	Septic	8.3	Septic	22 to 22.9
9	Septic	~40	Septic	19	Septic	~30	Pit	12.4	Septic	12.5	Septic	12.7 to 16.5
10	Pit	~19.0	Septic	16.3	Septic	~20.0	Pit	30 to 40	Pit	>40		
11	Septic	14.2	Septic	15.3	Pit	15.3	Septic	>30				
12	Septic	9.6	Septic	14.4	Septic	15 to 20	Septic	~15				

Table C.3 (Continued)

13	Septic	15.3	Pit	14.2	Pit	18.7	Pit	5.7	Pit	9.1		
14	Septic	8.7	Septic	8.5	Pit	20 to 25						
15	Septic	18.8	Septic	11.8	Pit	22.1	Septic	17.5	Pit	22	Septic	23
16	Septic	12.1	Pit	26.0	Septic	21.8	Pit	9.5				
17	Pit	15.3	Pit	22.2	Pit	29.2						
18	Septic	~25	Septic	~20	Septic	~25	Septic	12.0	Septic	10.3	Septic ~14, Septic ~40	
19	Pit	15.7	Septic	6.0	Pit	11.5						
20	Septic	8.4	Septic	13.3	Septic	19.4 to 23.5	Pit	~25				
21	Septic	5.5 to 6.4	Pit	10.7								
22	Septic	~30	Septic	15.1	Septic	12.6	Septic	>30				
23	Septic	19.1	Pit	8.4								
24	Septic	15.1	Septic	17	Septic	17.8						
25	Septic	17.6	Septic	18.9 to 19.6	Septic	18.7						
26	Septic	12.7	Septic	19.6 to 20.0	Unknown	24.6						
27	Pit	22.1	Septic	9.9	Pit	24						
28	Pit	13.6	Septic	8.4	Septic	5.2 to 5.6	Pit	13.8				
29	Septic	10.9	Septic	~16	Septic	6.9						
30	Pit	14.8	Pit	19.9	Pit	~40						

Table C.3 (Continued)

31	Pit	4.0	Septic	6.8	Pit	13.1	Septic (2 tanks)	8.0 and 9.0	Pit	10.0	Pit	10
32	Pit	14.8	Pit	15.8	Pit	14.5	Buiried Pit (Mar '16)	13.0	Burried pit (yr 2015)	4	Septic	~20 to 25
33	Septic	13 to 15	Pit	13.7	Pit	11.8	Septic	16 to 18	Septic	13 to 14	Latrine ~30 and ~50	
34	Septic	>30	Septic	7.6	Septic	13.1 to 15.5	Septic	16.0	Pit	18 to 19.2		
35	Septic	24.5	Septic	19.6	Septic	10.4 to 12.4	Septic	7.5				
36	Septic	7.5	Septic	~17	Septic	13.1 to 14.2						
37	Pit	21.2	Septic	12.9 to 15.9	Septic	17.9	Pit	10.1				
38	Septic	9.6	Septic	8.0	Septic	21.5	Septic	11.0	Septic	13.6		
39	Septic	12.9 to 16.0	Septic	14.6	Pit	20	Septic	22.3	Pit	~40		
40	Pit	23.7 to 24.1	Pit	12.1	Unknown	18.7						
41	Septic	10.9	Pit	13.3	Septic	18.6						
42	Septic	>30	Pit	11.9	Septic	19.6						
43	Septic	8.5	Pit	10.8	Septic	16.9	Pit	10 to 13				
44	Pit	20.2	Septic	18.8	Septic	18.5						
45	Pit	18.0	Pit	22.0	Septic	16.6 to 19.3	Septic	31.7				

Table C.4 Miscellaneous information about well sites and surrounding area.

Pump Code Number	Animals	Tree cover	Households	People	Notes	Bucket Pad
1	Free chickens	Yes	3 households	7 adults, 3 children	Washing cloths 3-6 m, no kitchen near-by	flat rock, ~30x30
2	No	No	3 households	6 adults, 8 children	Washing cloths ~5m	--
3	Free chickens	Yes	8 households	~20 people, 5 children	Washing food, dishes, and kitchen ~ 2 m	Small tire and wood
4	Free ducks	No	3 households	7 adults, 2 children	Kitchen ~ 5 m	broken concrete, ~28x30
5	Free chickens	No	6 households	Approximately 4-6 people per house	washing cloths 2 m, no kitchen near-by	2 pieces of wood, 5x50 and 3x50
6	Free chickens and ducks, 1 dog	No	1 households	3 adults, 4 children	Washing near by, kitchen 6.5 m away, Has a lot of songno, about ~70x40	2 CMUs, ~40x40
7	No	No	2 households	3 adults, 1 child	No specific washing or cooking activities observed	Metal box, 50x40
8	--	No	4 households	~12 people	Washing cloths ~3 m	Wooden box

Table C.4 (Continued)

9	Free chickens	No	4 households	16 people		Rock, 40x30
10	No	Yes	1-2 households	2 adults, 2 children, additional household but they left in middle of study	washing about 2 m away, Dense foliage above pump and got hardly any water when during heavy rain	--
11	No	Plant cover	7 households	13 adults	Kitchen ~ 1 m, washing cloth 4 m	concrete ~40x40
12	--	--	3 households	6 adults, 8 children	Washing ~2 m	Plastic box, ~15x30
13	chickens, ducks, and turkeys free and penned	No	1 households	4 adults, 3 children	washing cloths 2-3 m away, kitchen and dish washing ~2 m	Concrete 50x50
14	no animals	small amount of cover from moringa	8 households	10 adults, 5 children	dish washing and kitchen 1 m, shower stall 5 m, possible waste water dumping near-by	plastic box, ~25x20

Table C.4 (Continued)

15	free chickens	No	~10 households	~20 adults, 7 children	Kitchen 5-6 m and graded away, possible cloth washing near-by	concrete, ~20x30
16	No	Yes	2 households	7 adults	Cloths line near-by, never saw washing	Wood, 20x20
17	Free chickens	No	5 households	10 adults, 3 children	Washing cloths ~2 m, Two kitchens ~3 m	Small rocks that covered an area ~30x40
18	Free chickens and dogs, pump is not fenced in	Yes	5 households	14 adults, 4 children	cloths washing but not always near pump, no kitchen near by	flat rock, ~27x20
19	chickens, coop 1.5 m away starting January 2017	No	2 households	4 adults, 7 children	cloths washing 1 m, organic trash pile 2.5 m	rocks and wooden frame, 60x80
20	Penned chickens, cats	No	4 households	8 adults, 2 children	Kitchen and dishwashing ~2 m, probably washing cloths near-by, soak pits nearby	rocks, 30x30

Table C.4 (Continued)

21	Free chickens	Small amount of cover from moringa	7 households	10 adults, 6 children	Washing cloths ~3 m, Kitchen ~ 5 m, Dishwashing ~ 3 m	Wood pieces 15x35 each
22	Free chickens, in new year chicken coop 2 m	Yes	5 households	7 adults, 8 children	washing cloths and dishes 2-3 m, muddy and poor drainage	pieces of concrete, 16x25, 20x12
23	Free ducks and pigeons	No	5 households	8 adults, 6 children	Cloths washing probably within 3-4 m, kitchen ~1 m, dish washing ~3 m	broken concrete, ~50x30
24	free chickens, cat	No	6 households	10 adults, 7 children	close washing ~2 m, dish washing ~1 m	cinder blocks 37x40
25	free chickens, cat	Tree and plant cover	--	8 Adults, 4 children	No specific washing or cooking activities observed	rock, 35x35
26	Free chickens and 1 dog	barely tree cover	--	~20 adults, 3 children	Dish washing ~2 m, no kitchen near-by	broken concrete, 30x50
27	free chickens, cat	No	7 households	15 adults, 5 children	Dish washing 2-3 m, kitchen 5 m	No material, 20 x 25

Table C.4 (Continued)

28	no chickens	yes, partially covered with moringa	6 households	6 adults, 10 children	dish washing and cloths washing 3-4 m	
29	free and chicken pen 4-5 m away	No	10	23 adults 7 children	dish washing 2 m and cloths washing 2-4 m	concrete 30x50
30	Free chickens	No	6 households	5 adults, 4 children	Washing dishes ~2 m up grade	Wood
31	cat and chickens	edge of tree cover	3 households	10 adults, 6 children	kitchen and cloths washing ~2 m	rocks, ~20x40, after building apron 18 cm deep
32	free chickens	Yes	4 households	7 adults, 5 children	Kitchen 1/2 m, very steeply down grade of surroundings	concrete, ~30x50
33	Free chickens	tree cover barely over pump	4 households	7 adults, 2 infants	Washing cloths 1-2 m, dish washing 1-2 m	Wood and tiles, 30x50

Table C.4 (Continued)

34	Ducks	Yes	1 households	3 adults, 3 children	No specific washing or cooking activities observed, shower ~6m and graded away	Broken concrete, 27x25
35	free chickens	No	4 households	7 adults, 4 children	No specific washing or cooking activities observed	wood and TV tube, 40x40
36	cats	Some Tree cover	4 households	6 adults, 2 children	Kitchen 1/2 - 1 m, cloth washing probably 2-3 m	10x10
37	cat, no other animals	A little but branches spread out	1 households	2 adults, 3 teenagers	Kitchen, washing, dish washing ~2 m, Some plants around well head, gutter ends ~1 m away from pump	side of TV body 30x38
38	No	Yes	--	13 adults, 4 children	Washing cloths 2-3 m away, kitchen ~5m	2 cinder blocks and a concrete slab (I don't remember before construction)
39	No	No	2 households	6 adults, 2 children	Clothes washing ~2 m, dish washing 4-5 m	2 cinder Blocks 40x18

Table C.4 (Continued)

40	--	No	4 households	9 adults, 7 children	Closth washing ~4 m, no kitchen	Concrete 38x27
41	Open area so possible animals	No	4 households	8 adults, 7 children	Washing cloths 5-6 m away	broken concrete, ~60x40
42	Free chickens	No	2 households	4 adults, 6 children	No specific washing or cooking activities observed	broken concrete, 45x40
43	no chickens	Yes	3 households	4 adults, 2 children	No specific washing or cooking activities observed	CMU 40x20
44	no chickens	Yes	3 households	11 adults, 3 children	dish washing and cloths washing 1-2 m	wood, ~30x20
45	free chicken	edge of palm tree	4 households	9 adults, 7 children	kitchen/dish washing 2-5 m	rocks and wood 30x40

Table C.5 Water table and well screen depths.

Pump Code Number	Measurement Date	Depth of Top of Well Screen from Ground Surface (cm)	Depth of Water Table from Ground Surface(cm)	Depth of Top of Well Screen in Water Table (cm)
1	24-Jun-16	590	554	36
2	13-Jun-16	553	388	165
3	13-Jun-16	799	655	144
4	14-Jun-16	447	258	189
5	18-Jun-16	464	382	82
6	17-Jun-16	432	293	138.5
7	22-Jun-16	442	275	167
8	18-Jun-16	371	229	142
9	18-Jun-16	538	338	200
10	16-Jul-16	653	450	203
11	05-Sep-16	583	486	97
12	02-Jul-16	759	575	184
13	11-Jul-16	628	499	129
14	09-Jul-16	623	472	151
15	24-Jun-16	464	231	233
16	29-Jun-16	439	402	37
17	02-Jul-16	785	601	184
18	02-Jul-16	743	597	146
19	05-Jul-16	533	439	94
20	05-Jul-16	472	323	149
21	13-Jul-16	451	367	84
22	13-Jul-16	438	281	157
23	13-Jul-16	680	506	174
24	13-Jul-16	530	453	77
25	16-Jul-16	424	358	66
26	16-Jul-16	532	444	88
27	18-Jul-16	547	423	124

Table C.5 (Continued)

28	22-Jun-16	551	326	225
29	24-Jun-16	497	217	280
30	29-Jun-16	621	487	134
31	29-Jun-16	595	455	140
32	29-Jun-16	638	497	141
33	17-Jun-16	446	319	127
34	18-Jun-16	655	410	245
35	22-Jun-16	500	379	121
36	22-Jun-16	406	288	118
37	22-Jun-16	505	325	180
38	16-Jul-16	483	391	92
39	02-Jul-16	498	417	81
40	11-Jul-16	672	556	116
41	13-Jul-16	593	469	124
42	16-Jul-16	608	442	166
43	24-Jun-16	484	296	188
44	22-Jun-16	460	362	98
45	24-Jun-16	441	330	111