FIELD STUDY INVESTIGATING THE POTENTIAL OF WATER QUALITY TESTING TO PREDICT CORROSION IN BOREHOLES IN NORTHERN UGANDA

by

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DEDICATION

In loving memory of my dear paw-paw, one of my greatest fans.

Me-maw used to always say we got our brains from you, because she still has hers…

so thanks for that.

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ABSTRACT

FIELD STUDY INVESTIGATING THE POTENTIAL OF WATER QUALITY TESTING TO PREDICT CORROSION IN BOREHOLES IN NORTHERN UGANDA

Under the direction of DR. LAURA W. LACKEY

Water sources are often abandoned by communities for two reasons: (1) the aesthetics of water quality that affects user acceptability and (2) the breakdown of pump parts that prohibits use of the borehole. Both can be related to the aggressiveness of water and both are important. Electroconductivity and pH and indices can indicate the potential of galvanic corrosion and electrochemical corrosion, respectively. Electrochemical corrosion contributes most to the high levels of iron from boreholes. The purpose of this study was to investigate the efficacy of pH strips in predicting groundwater pH and aggressiveness, compare the reliability of three different pH test strips to a Hanna pH probe, determine the origin of iron measured in boreholes, and make relevant recommendations.

Qualitative and quantitative data were collected at 16 borehole sites in the Amuru and Gulu Districts of Northern Uganda. Water quality testing measuring pH and iron concentration and two types of pump tests–a pump performance test and a

Water Aid pump test–were performed at specified boreholes. Interviews with members from the community at each borehole were conducted and observational data was collected. The pH was measured in triplicate using three different pH test strips (Youth Waters, MN, and Extended Range) and compared to the pH measured with a Hanna probe. Paired t-tests and the Bland-Altman difference method were used to compare pH test strip and Hanna probe measurements.

Results suggest pH strips are an inexpensive method for reliably measuring the pH. Paired t-tests conducted at α=0.05 showed that the Youth Waters pH test strip measurements were significantly different than the Hanna probe measurements. Statistical analysis using paired t-tests and the Bland-Altman difference method suggests that the MN and Extended Range test strips are statistically acceptable replacements for the Hanna probe for measuring pH at boreholes in Northern Uganda. Based on the cost, the ease of use, and the statistical analyses, the use of the MN test strips is highly recommended if they are accessible to the user. Results from pump tests suggest that much of the iron observed in borehole water pump effluent is from corrosion of pump components. Iron concentration, pH of groundwater, and electroconductivity should be considered when constructing or rehabilitating a borehole. Future work should follow the methods outlined in this study, measure additional water quality parameters including dissolved oxygen and ammonium concentrations, and include a detailed analysis of the local supply chain of pH test strips and pipe materials available in Gulu, Uganda.

LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
ASM	American Society of Metals
CLSI	Clinical and Laboratory Standards Institute
DO	Dissolved Oxygen
DWD	Directorate of Water Development
DWRM	Directorate of Water Resources Management
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
FRP	Fibre Glass Reinforced Plastic
GADM	Global Administrative Areas
GI	Galvanized iron
GIS	Geographic Information System(s)
GV	Guideline Value
HTN	Handpump Technology Network
IRB	Iron Related Bacteria
JMP	Joint Monitoring Programme
MAV	Maximum Acceptable Value
MDG	Millennium Development Goal

LIST OF ABBREVIATIONS (Continued)

MOM	Mercer on Mission
MWE	Ministry of Water and Environment
NACE	National Association of Corrosion Engineers
NB	Nominal borehole
NGO	Non-governmental Organization
NTU	Nephelometric Turbidity Units
OTC	Open-Top Cylinder
PVC	Polyvinylchloride
RWSN	Rural Water Supply Network
SKAT	Swiss Centre for Appropriate Technology
SS	Stainless Steel
TDS	Total Dissolved Solids
U2M	U2 Modified
U3M	U3 Modified
UNBS	Uganda National Bureau of Standards
UNICEF	United Nations Children’s Fund
uPVC	unplasticized Polyvinylchloride
USEPA	United States Environmental Protection Agency
VLOM	Village Level Operation and Maintenance
WHO	World Health Organization

CHAPTER 1. INTRODUCTION

1.1 The Joint Monitoring Program & Improved Water Supply

The Joint Monitoring Programme (JMP) is an initiative by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) to monitor countries' access to water supply and sanitation in order to monitor the progress of Millennium Development Goal (MDG) 7, Target 7c, the objective being to "Halve, by 2015, the proportion of people without sustainable access to safe drinking-water and basic sanitation" [1]. For monitoring purposes, a set of standards was established to identify categories within drinking water and sanitation. According to JMP, "An "improved" drinking-water source is one that, by the nature of its construction and when properly used, adequately protects the source from outside contamination, particularly faecal matter" [2]. *Figure 1* identifies specific "improved" and "unimproved" sources.

According to the 2014 WHO Progress on Drinking Water & Sanitation update, Uganda has met the MDG target for improved drinking water sources [4]. There has been a 33% increase in access to improved water sources from 1990-2012 in Uganda–42% improved drinking water coverage in 1990 to 75% improved drinking water coverage in 2012. The JMP 2014 Update reported 70% of Uganda's drinking water sources to be considered "other improved" and 5% to be "piped on premises" (*Figure 2*) [5]. "Other improved" being improved sources that are not piped systems.

IMPROVED Drinking-Water	Use of the following sources: • Piped water into dwelling, yard or plot • Public tap or standpipe • Tubewell or borehole • Protected dug well • Protected spring • Rainwater collection
UNIMPROVED Drinking-Water	Use of the following sources: • Unprotected dug well • Unprotected spring • Cart with small tank or drum • Tanker truck • Surface water (river, dam, lake, pond, stream, canal, irrigation channel) • Bottled water

Figure 1. Types of drinking water sources as identified by WHO/UNICEF JMP for Water Supply and Sanitation [2], [3].

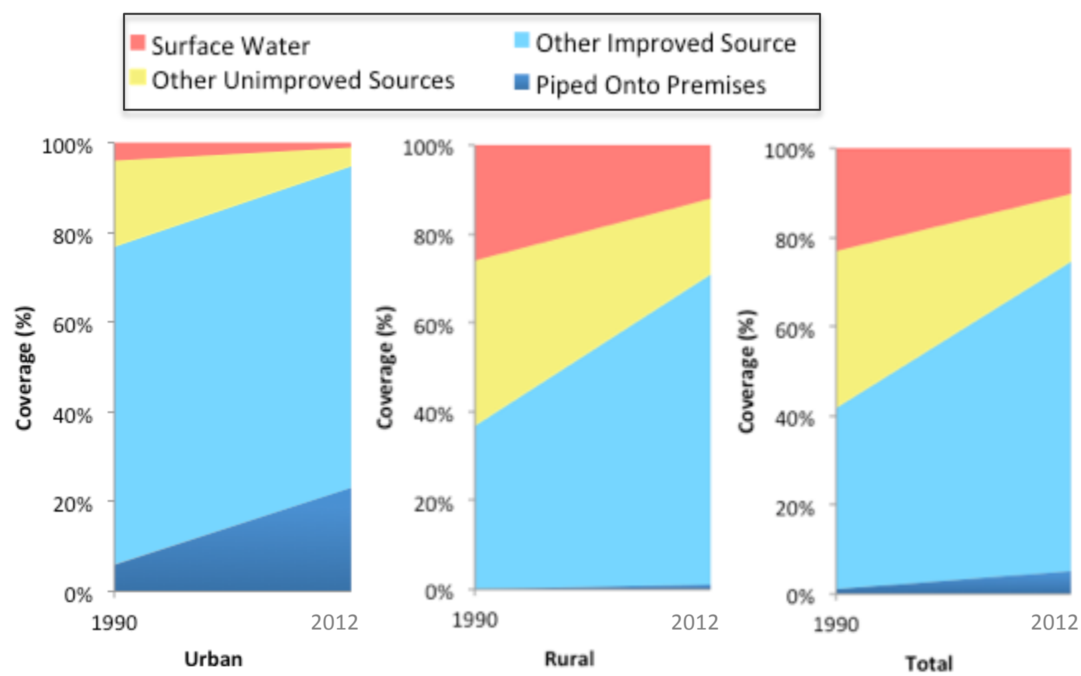


Figure 2. Urban, rural, and total drinking water trends in Uganda from 1990-2012 [5].

As a part of JMP's efforts to keep drinking water trend progress per country up to date, the organization maintains a database of surveys conducted by in-country groups. Surveys in Uganda have been documented every 1-3 years since 1989. In 2011 the National Panel Survey estimated 35.1% of Uganda's drinking water sources were "Tubewell, borehole," specifically identifying this estimate as "Bore-hole" data [5].

1.2 International Iron Concentration Guidelines for Drinking Water

The World Health Organization has not established any guideline values for iron because it is "not of health concern at levels causing acceptability problems in drinking-water"[6]. In general, users will stop drinking water with higher concentrations of iron because of the change in taste or odor before iron concentrations reach a level of health concern.

Uganda has established a drinking water requirement of 0.2-1 mg/L of iron depending on the classification of the source. The two classes are described as follows:

> "Class I potable water available from conventional treatment processes…This water is comparable to current international standards for water quality. This water is to be considered acceptable for lifetime consumption, and is the recommended compliance limit.

Class II (untreated water) potable water available for water consumers through boreholes, protected springs, shallow wells, gravity flow schemes and harvested rain water…This class specifies a water quality range that poses an increasing risk to consumers depending on the concentration of the determinant within the specified range and the possibility of monitoring its quality. It is considered to represent drinking water for consumption for a limited period.”

The treated water (Class I) is held at a higher standard of 0.2 mg/L of iron, while the untreated water (Class II) is set at 1 mg/L of iron [7].

In the United States, the Environmental Protection Agency (EPA) has set National Secondary Drinking Water Regulations. These regulations are non-enforceable guidelines for contaminants that could cause cosmetic or aesthetic issues. The recommended secondary maximum contaminant level of iron in drinking water is 0.3 mg/L [8].

1.3 Effects of Close Access to Water Sources

Living in close proximity to an improved water source can provide many benefits to the community. Basic Access as defined by WHO is within 100-1000 m away or 5-30 minutes collection time [9]. The availability of 20 L of water per person per day is considered "reasonable access" [3], [10].

The infrastructure that exists in northern Uganda is aging and the water quality from the studied pumps—specifically the India Mark II and U-Series

Handpumps— is declining, forcing the community members to either continue using the low quality water or travel further to collect water of satisfactory quality. The Ministry of Water and Environment (MWE) of Uganda stated, "Despite the increase in national access to safe water, women and children in Northern Uganda which has just emerged from civil war and semi-arid districts are still burdened with collecting water from long distances" [11]. Collecting water in these conditions can be burdensome and time consuming.

Living close to water sources can benefit women and children greatly. Instead of spending hours collecting water (*Figure 3)* women can use that time to work, to further provide for their families. WHO completed a study titled the *Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level*. This study estimated, "In developing regions, the return on a US$1 investment was in the range of US$5 to US$28 for intervention 1." Intervention 1 involved "halving the proportion of people without access to improved water sources" [12]. Water has much potential to build an economy.

Without the burden of spending many hours each day collecting water, children are more likely to attend school. Koolwal and Walle found that "in countries where substantial gender gaps in schooling exist, both boys' and girls' enrollments improve with better access to water" [13]. This could also be attributed to the health effects of better access to water. Children who are sick from water-related infections often do not or cannot attend school.

Figure 3. After the women or children reach the borehole, they could have to wait hours to fill their jerry cans. (borehole 4) Photo courtesy of Jake Carpenter.

David Bradley defined disease transmission routes related to water infections (*Table 1*). The transmission of water-washed, water-based, and water-related insect vector infections can be minimized and routes can be interrupted when there is access to improved water sources [14].

Table 1. The Bradley Classification of Water-Related Infections

Transmission route	Description	Disease Group	Examples
Waterborne	The pathogen is in water that is ingested	Feco-oral	Diarrheas, dysenteries, typhoid fever
Water-washed (or water-scarce)	Person-to-person transmission because of a lack of water for hygiene	Skin and eye infections	Scabies, trachoma
Water-based	Transmission via an aquatic intermediate host (for example, a snail)	Water-based	Schistosomiasis, guinea worm
Water-related insect vector	Transmission by insects that breed in water or bite near water	Water-related insect vector	Dengue, malaria, trypanosomiasis

1.4 Motivation and Research Goals

Much of the borehole infrastructure in northern Uganda is in need of repair or replacement. Water sources are often abandoned by community members for two reasons: (1) the aesthetics of water quality that affects user acceptability and (2) the breakdown of pump parts that prohibits use of the borehole. Both can be related to the aggressiveness of water and both are important.

The WHO recognizes the role acceptability plays in water use habits. For example, as mentioned in Section 1.2, they do not have a guideline for iron concentration in water, because they have observed that people will stop using the water because of aesthetic/acceptability reasons before the concentration of iron in the water becomes a health concern [6]. Water may give off an odor or may turn a different color due to high concentrations of different contaminants. This can lead to the abandonment of a water source and can result in families having to travel further to collect their daily water (*Figure 4).*

Figure 4. Water color of a sample of water taken from a Northern Uganda borehole progressively darkened as it was heated to a boil (left to right). The image in the fourth quadrant shows the state of the water once removed from the fire. The borehole has been chained up because the community did not deem the water acceptable for use. Many prefer collecting water from the unprotected spring. (Photos courtesy of Jake Carpenter)

Families cannot be expected to use the water from boreholes like that shown above for any tasks that require boiling water. The boiled water would certainly stain food, clothing, etc. (*Figure 5).*

Figure 5. A piece of paper dipped in the water from the fourth quadrant pictured above in *Figure 4*. Photo courtesy of Jake Carpenter.

Many of the borehole systems have been constructed using galvanized iron (GI) rods for raising/lowering the plunger and galvanized iron riser pipes for conveying the pumped water from a depth to the surface. This material when repeatedly in contact with aggressive water will corrode. Aggressive water is defined as water with qualities (acidic or soft) that are conducive to the corrosion of pipe components. Corrosion of the GI pipes can lead to high concentrations of iron in the water supply and/or to the breakdown of the pump. Both have the potential to lead to the abandonment of the borehole.

Mercer on Mission (MOM) is a five week service-learning program that strives to provide students from Mercer University with opportunities to learn while serving others in an international context. One of the goals of the MOM-Uganda 2014 trip was to conduct water-related research that would improve the quality of life for some people in Uganda. Water quality data was collected at a number of borehole sites in the surrounding area of Gulu town to further understand the relationship between iron concentration, pH and pump configuration, and address the needs of the local communities and government.

The goals of this research include:

1. To investigate the efficacy of using pH test strips to predict groundwater pH and aggressiveness,
2. To compare the reliability and validity of three different pH test strips to a Hanna pH probe,
3. To determine if the origin of the iron measured in borehole pump effluent is from groundwater geography or from the corrosion of GI material associated with the pump rods and riser pipes, and
4. To provide recommendations to field workers and the district water authorities about parameters to consider during borehole construction and rehabilitation.

The rehabilitation of boreholes throughout this document refers to (1) replacing pump components with appropriate corrosion resistant materials and/or (2) replacing broken pump parts due to corrosion with corrosion resistant ones.

CHAPTER 2. LITERATURE REVIEW

2.1 Corrosion

Corrosion is an issue in water systems across the world. In 2002 the United States Federal Highway Administration (FHWA) with the help of CC Technologies Laboratories, Inc. and the National Association of Corrosion Engineers (NACE) released a 2-year corrosion study, “Corrosion Costs and Preventative Studies in the United States.” The study reported, “The total annual direct cost of corrosion for drinking water and sewer systems is $36 billion, which includes the costs of replacing aging infrastructure, lost water from unaccounted-for leaks, corrosion inhibitors, internal mortar linings, external coatings, and cathodic protection.” This is 75% of the annual corrosion cost for utilities in the U.S. [15].

Uganda estimates 5% of their water sources are piped on premises and 70% are "other improved" [5]. There is no data available similar to that reported by the United States. However, the effect of corrosion in water supply sources in Uganda has been observed [16]. Complaints of high levels of iron in boreholes have caused the water sector in Uganda to make changes in design to create a corrosion-resistant handpump option, the U3M [17].

There are several different methods that are useful for predicting if water is corrosive or aggressive. Langenegger recommends using a pH index [18](*Table 2)* and an electroconductivity index to indicate the potential of electrochemical and galvanic corrosion, respectively. Electrochemical corrosion is what contributes most to the high levels of iron at borehole sites. Galvanic corrosion can contribute to mechanical pump failures and generally occurs where different materials come in contact with each other [19]. These pH and electroconductivity indices are just as effective at estimating the corrosion potential as the more complex Langelier Saturation Index [20].

Table 2. pH-based Index for Applicability of Galvanized Downhole Components

pH	Aggressivity of Water	Application of Galvanized Material
pH >7	Negligible	Suitable
6.5 < pH ≤ 7	Light to Medium	Limited
6 < pH ≤ 6.5	Medium to Heavy	Not Recommended
pH ≤ 6	Heavy	Not Recommended

2.1.1 Iron Corrosion Chemistry

Corrosion can be defined as the gnawing away of a material over time. Iron and steel are found in their natural state as iron ore. In this context, corrosion is simply the oxidation of metal to return to its natural state, its lowest, most stable energy level [19], [21]. The World Health Organization explains corrosion of iron as follows:

> "The corrosion of iron is a complex process that involves the oxidation of the metal, normally by dissolved oxygen (DO), ultimately to form a precipitate of iron(III). This leads to the formation of tubercules on the pipe surface. The major water quality factors that determine whether the precipitate forms a protective scale are pH and alkalinity. The concentrations of calcium, chloride and sulfate also influence iron corrosion" [6].

WHO suggests adjusting several water quality parameters in order to control iron corrosion (*Table 3*) [6].

Table 3. Recommendations by WHO in order to control iron corrosion

Parameter	Target Range
pH	6.8-7.3
Hardness (as $CaCO_3$)	≥ 40 mg/L
Alkalinity (as $CaCO_3$)	≥ 40 mg/L
Oversaturation w/ $CaCO_3$	4-10 mg/L
Alkalinity:Chloride + Sulfate (both as $CaCO_3$)	5

Equations 1-4, below, are the most basic chemical equations that occur during the electrochemical corrosion of iron. Corrosion is a very complex process and many more reactions are likely to occur. The equations include (1) the oxidation of iron in its solid state to form metallic ions, (2) the reduction of oxygen, and (3) & (4) the formation of iron hydroxides (rust) [19].

Anodic Reaction: $Fe_{(s)} \rightarrow Fe^{2+} + 2e^-$ Equation 1

Cathodic Reaction: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$ Equation 2

Secondary Reactions: $Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2,\ Iron(II) - hydroxide$ Equation 3

$2Fe^{2+} + \frac{1}{2}O_2 + 4OH^- \rightarrow 2FeOOH,\ Iron(III)\ oxyhydroxide(goethite) + H_2O$ Equation 4

Equation 2 is considered the most important cathodic reaction. When this reaction is dominant, the process is referred to as "oxygen corrosion." The reduction of hydrogen (hydrogen ion to hydrogen), however, is also an important cathodic reaction. When this reaction is dominant the process is referred to as "hydrogen corrosion"[19].

2.1.2 Kuch Mechanism

The Kuch mechanism proposes a pathway for corrosion to continue when dissolved oxygen is depleted. Stagnation occurs overnight in boreholes when they are not in use, resulting in low DO levels. The overall reaction, shown in Equation 5, results in ferrous iron and hydroxide.

Overall Reaction: $Fe(s) + 2FeOOH(s) + 2H^+ \leftrightarrow 3Fe^{2+} + 4OH^-$ Equation 5

Kuch suggests that the cathodic reduction in the scale maintains the anodic oxidation of the iron metal. Once flow continues again in the well, oxygen concentration increases and the ferrous iron is oxidized. The oxidation of Fe(II)-ions can result in a red effluent [22]–[24].

2.1.3 Iron Related Bacteria

Iron related bacteria (IRB) originate from the soil or from contaminated equipment or parts used during the construction, operation and maintenance of the well. It can be difficult to rid the well of IRB once contaminated. One method used to eliminate the bacteria includes chlorinating the borehole. This, however, does not usually eliminate all of the bacteria, thus chlorination is a temporary fix that may need to be repeated occasionally [25].

Iron "promotes the growth of “iron bacteria”, which derive their energy from the oxidation of ferrous iron to ferric iron [Equations (3) & (4)] and in the process deposit a slimy coating on the piping” [6]. The buildup of this coating is often referred to as iron biofouling [26]. These coatings, usually denoted as biofilms, are a result of microbiological activity of iron bacteria (*Figure 6*). The presence of ammonium (NH_4^+) is often an indicator of the presence of iron bacteria, and the ammonium concentration increases as the biofilm develops. Temperatures near 30°C also play a role in promoting microbiological activity [19].

Figure 6. Results of corrosion from rehabilitated borehole in Northern Uganda. Photo courtesy of Jake Carpenter.

2.1.4 Observations of Corrosion

The RWSN 2013 Hand Pump Survey quotes several organizations in Uganda that have experienced issues with high iron concentrations. In the survey the Government of Uganda and an NGO in Uganda cited complaints of poor color and taste of water due to corrosion [16]. “At levels above 0.3 mg/l, iron stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations below 0.3 mg/l, although turbidity and colour may develop" [6]. Water with high iron concentrations can also stain foods when cooking.

"The incidence and extent of corrosion damage depends mainly on three factors – pump component materials, groundwater quality, and (often overlooked) the pumping regime" [26]. These three areas will be further discussed in this chapter.

2.2 Appropriate Pump Component Materials

Determining whether water is aggressive can help determine if the borehole or handpump should be constructed with corrosion resistant materials. Certain materials can help prevent breakdowns due to corrosive water. The Uganda National Bureau of Standards (UNBS) provides recommendations on handpump materials to use based on water quality and chemistry (*Table 4*) [28], [29].

Table 4. UNBS recommendations for U2/U3 parts based on water quality and chemistry taken from US:404:1995 & US:405:1995.

WATER QUALITY	CONNECTING RODS	RISER PIPES	CYLINDER
-pH value of 5.5 or more -Oxygen level 2mg/L or less	Galvanised Mild Steel (GI)	Galvanised Mild Steel (GI)	Cast Iron with Brass Liner
-pH value of 5.5 or less -Chloride level up to 200 mg/L	Stainless Steel AISI 314	Stainless Steel AISI 304	Cast Iron with Brass Liner or SS AISI 304
-pH value 5.5 or less -Chloride level more than 200 mg/L	Stainless Steel AISI 316	Stainless Steel AISI 316	Cast Iron with Brass Liner or SS AISI 316

Local communities are responsible for performing maintenance and minor repairs of boreholes and handpumps [30]. If spare parts of certain materials are too expensive or not readily available, maintenance and repair can be delayed. *The Community Water Supply-The Handpump Option* states, “the best corrosion resistance is provided by those using plastic rising mains, stainless steel, brass or plastic cylinders, and stainless steel, wooden, or fiber glass rods” [27].

2.2.1 Galvanized Iron

Galvanized Iron (GI) is typically used when constructing India Mark II handpumps. GI materials, however, cannot be recommended where the pH of groundwater is less than 6.5 [18]. Given time, GI will corrode under these conditions.

2.2.2 Stainless Steel

Langenegger states that, “As a general rule…stainless steel rising mains and rods are about 3-5 times more expensive than galvanized ones” [18]. In terms of capital cost, stainless steel (SS) is the most expensive corrosion resistant option for handpumps, but SS may be the best option financially when considering maintenance costs long-term. “Steel pumps have the additional advantage that they are less vulnerable to the sort of shock loads sometimes imposed during loading and unloading in developing countries.” However, SS is heavier, which can be an issue when replacing pipes [31]. *Figure 7* shows SS handpump components.

Figure 7. Stainless steel rising mains and rods used to rehabilitate two boreholes in Northern Uganda. Photo courtesy of Jake Carpenter.

The Handpump Technology Network (HTN) conducted a study on corrosion of stainless steel. Baumann recommended using AISI 316 SS instead of AISI 304 SS pipes, because AISI 316 proved to be more corrosion resistant and to have more tensile strength. HTN could not guarantee the sustainability of a SS solution because they could not guarantee that spare parts would be available or that communities would be able to finance repairs [32].

2.2.3 Polyvinylchloride (PVC)

PVC is also a corrosion resistant option, but it is only applicable at certain depths. A pilot project conducted by HTN introducing PVC as a down-hole component reported PVC to be, "very notch-sensitive. Applications with threaded joints have not been used at deep installations with good results" [32]. In 1989 the IRC stated that PVC rising mains could be successfully implemented at depths of around 30 m. There are several benefits to using plastic parts: they are corrosion resistant, lighter weight providing ease of maintenance, generally can be mass-produced, and are not as expensive as stainless steel [31]. However, the number of breakdowns with PVC rising mains when compared to SS rising mains will most likely be higher. HTN estimated the lifetime of PVC to be no more than 8 to 12 years [32].

The use of unplasticised polyvinylchloride (uPVC) riser pipes is recommended when constructing a U3M handpump [17], [33]. In 1989 the IRC also included uPVC as a material that could be successfully implemented as rising mains to depths of around 30 m [31]. In 2001, SKAT and HTN released specifications for the U3M handpump recommending implementation of uPVC for depths of 10-45 m [34]. When deciding between PVC and uPVC for potable water applications, it is recommended that uPVC be used, since uPVC does not contain phthalates or BPA and is more rigid and durable than PVC [35], [36].

2.3 Water Quality

The Uganda National Bureau of Standards (UNBS) is responsible for creating and maintaining national standards, including water quality standards and water monitoring standards [16]. The UNBS provides drinking water standards for Class I and Class II sources (defined in Section 1.2). Class II sources include untreated potable water such as that from boreholes. Class II iron and pH standards are as follows: 1 mg/L iron and pH ranging from 6.5-8.5 [7]. *Table 5* compares drinking water standards set by Uganda and the United States. The USEPA sets primary and secondary regulations for drinking water. Primary regulations must be adhered to; Secondary regulations are not required to be met, but are recommended.

Table 5. Drinking Water Standards

Contaminant	Uganda National Bureau of Standards [a]		United States Environmental Protection Agency [b]
	Class I	Class II	
Color	15 true color units	15 true color units	15 color units
Copper	2 mg/L		1 mg/L
Electro-conductivity at 25°C	1500 µS/cm	2500 µS/cm	
Iron	0.2 mg/L	1 mg/L	0.3 mg/L
Odor	Acceptable to consumers and no abnormal changes	Acceptable to consumers and no abnormal changes	3 threshold odor number
pH	5.5-8.5	6.5-8.5	6.5-8.5
Total Coliforms	5%	5%	5% each month [c]
Total Dissolved Solids (TDS)	500 mg/L	1500 mg/L	500 mg/L
Turbidity	5 NTU	10 NTU	0.3 NTU [d]

[a] UGANDA STANDARD Drinking (potable) water –Specification, Second Edition 2008 [7].
[b] USEPA National primary and secondary drinking water regulations, May 2009 [8].
[c] No more than 5.0% of total coliform testing samples can have a positive result each month.
[d] 95% of samples must meet this standard in any month. Systems that use conventional or direct filtration may never exceed 1 NTU. Systems using other filtration methods may never exceed 5 NTU.

The Water Resource Monitoring & Assessment Department under Uganda's Ministry of Water and Environment (MWE) collects water quality data from districts across the country. Water quality data is not available from the Amuru or Gulu

Districts (where water quality data was collected for this research) but it is available from five other districts (*Figure 8*). The Oyam District was the closest district geographically, bordering the southern region of the Gulu District.

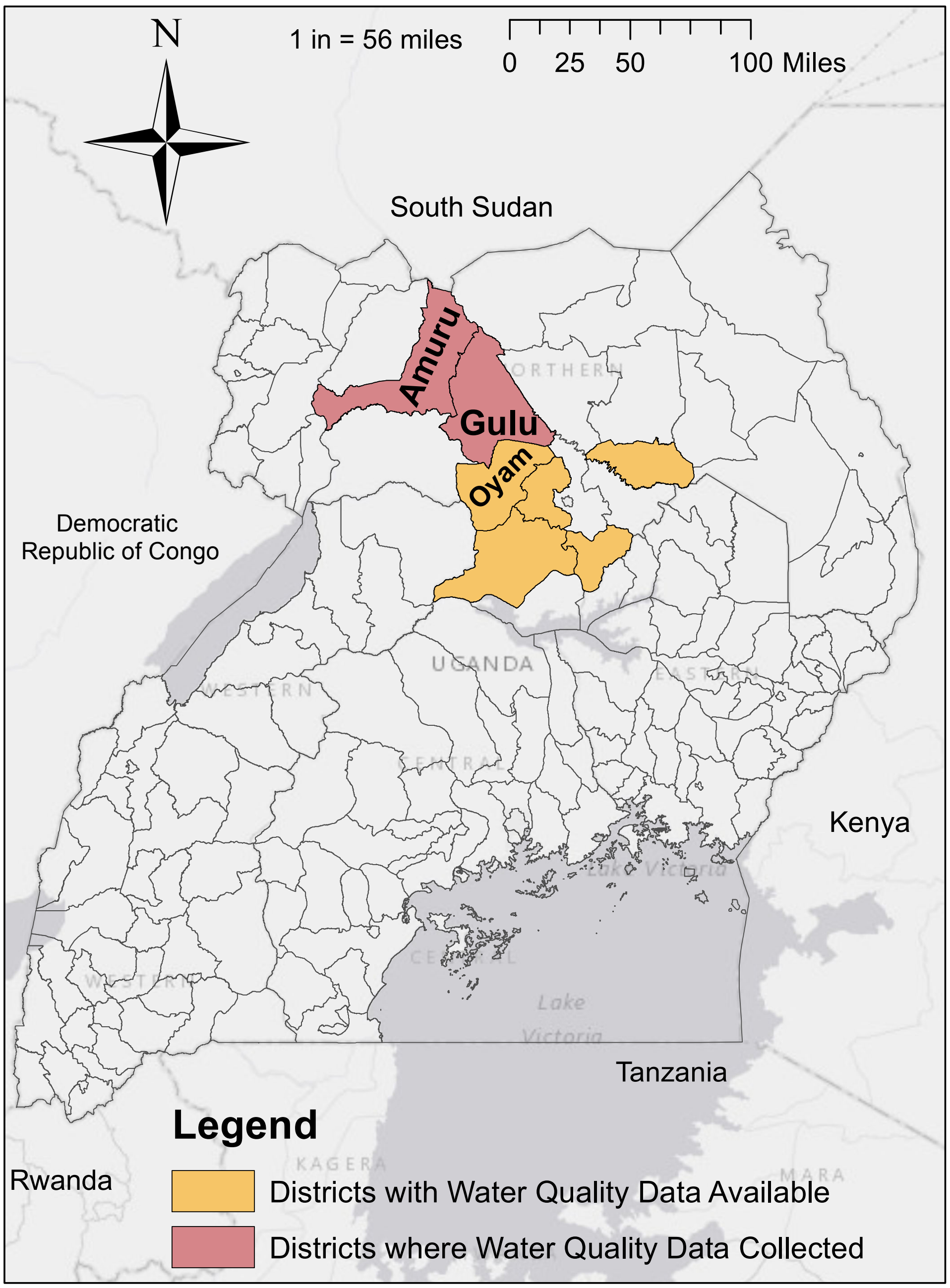


Figure 8. Total iron was analyzed at 203 locations in the Oyam District, just south of the Gulu District.

When a borehole or well is constructed, the Water Resource Monitoring & Assessment Department strongly recommends collecting initial water quality data from the site. *Table 6* summarizes groundwater data that was collected in the Oyam District at various sites over time [37]. The average water sample is acidic at a pH of 6.71. However, the majority of iron concentrations measured did not exceed the Guideline Value (GV) or Maximum Acceptable Value (MAV) set for total iron concentration.

Table 6. Summary Statistics for Groundwater Quality in the Oyam District

	Total iron (mg/L)	**pH**	**EC (µS/cm)**	**TDS (mg/L)**	**Hardness (mg/L $CaCO_3$)**
Minimum	0.01	5.82	40	28	11
Maximum	7.53	8.51	1300	823	340
Average	0.23	6.71	318	191	124
Median	0.05	6.60	273	166	109
No. of data points	203	215	223	216	221

The GV for iron is set at 1 mg/L and the MAV at 2 mg/L. The Directorate of Water Resources Management (DWRM) reported that, "Ninety six percent of the concentrations recorded are below 0.8 mg/L. Three boreholes have concentrations between the GV and MAV and 5 boreholes recorded concentrations greater than the MAV" [37]. The distribution of this iron concentration data is displayed statistically and spatially in *Figure 9.* Further details concerning groundwater quality data can be found in the Oyam District Report.

(a)

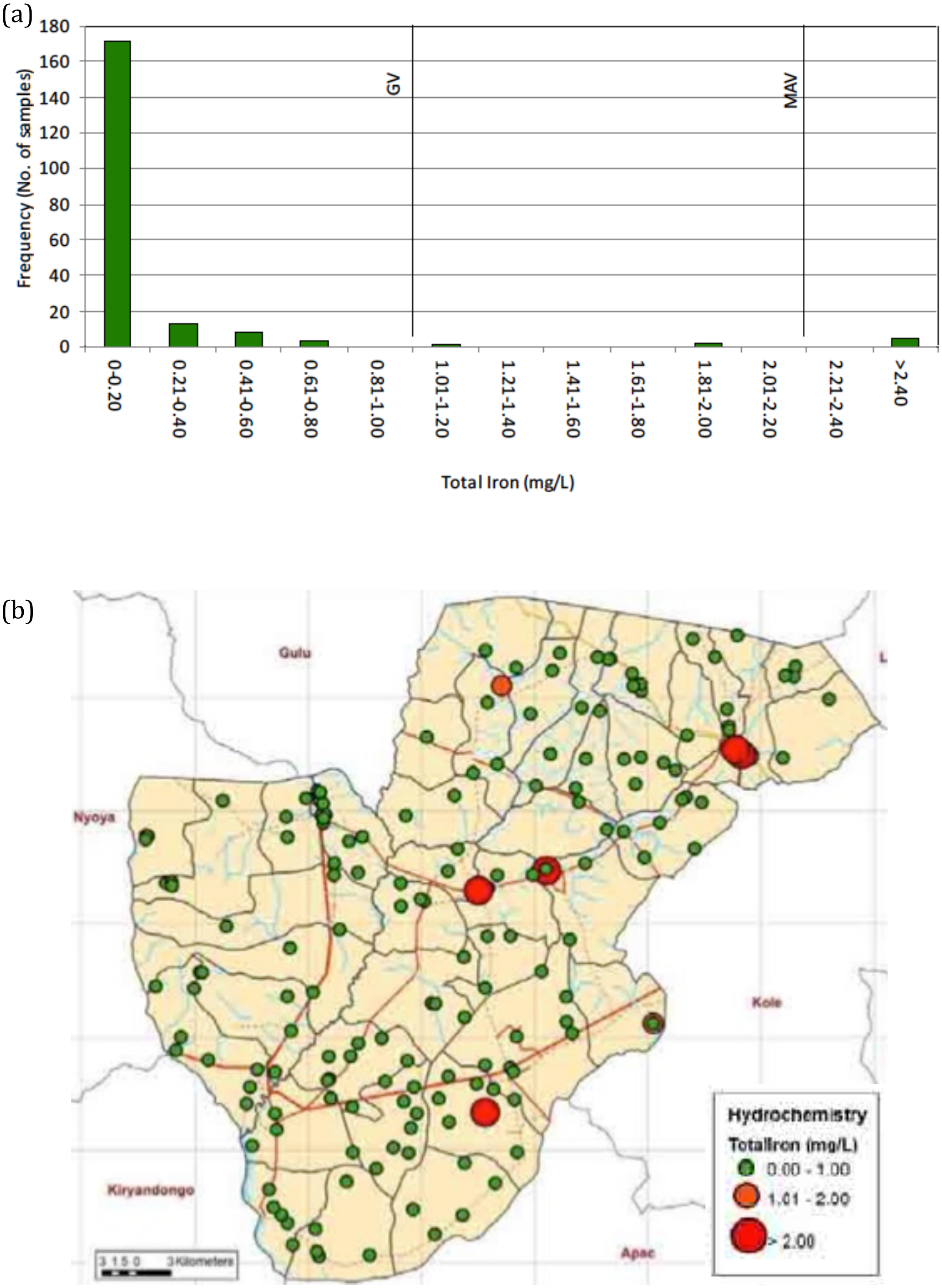


Figure 9. Total Iron concentration data for the Oyam District (a) statistically distributed (b) spatially distributed

2.4 Pumping Regimes

The MWE manages a Water Supply Database for Uganda. This database includes locations of different water supply types across each district. Water sources in the Amuru and Gulu Districts include protected springs, shallow wells, deep boreholes, rainwater tanks, and public stand posts. Deep boreholes, however, are the most prevalent means of water coverage in the district of Gulu (*Figure 10*) and the district of Amuru (*Figure 11*).

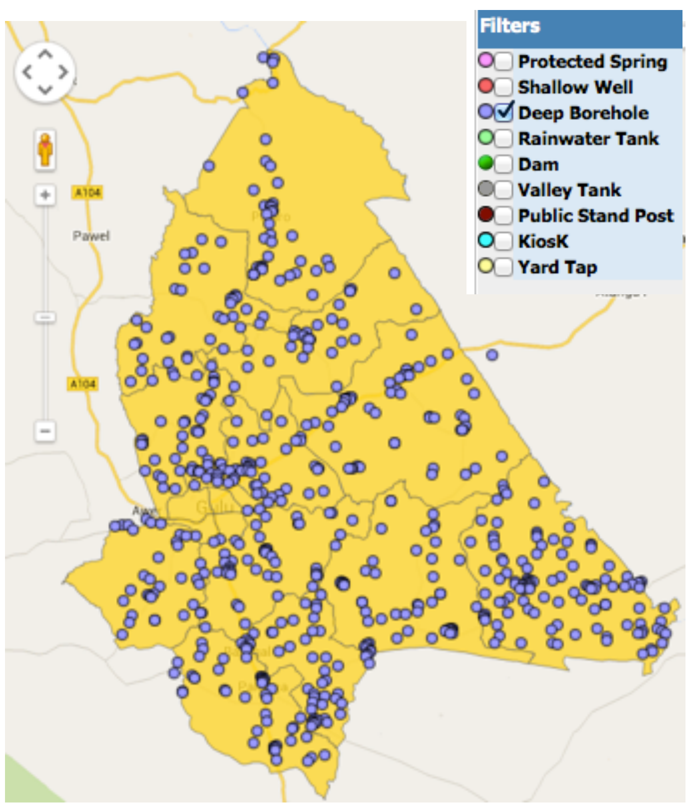


Figure 10. Deep Borehole coverage across Gulu District [38]

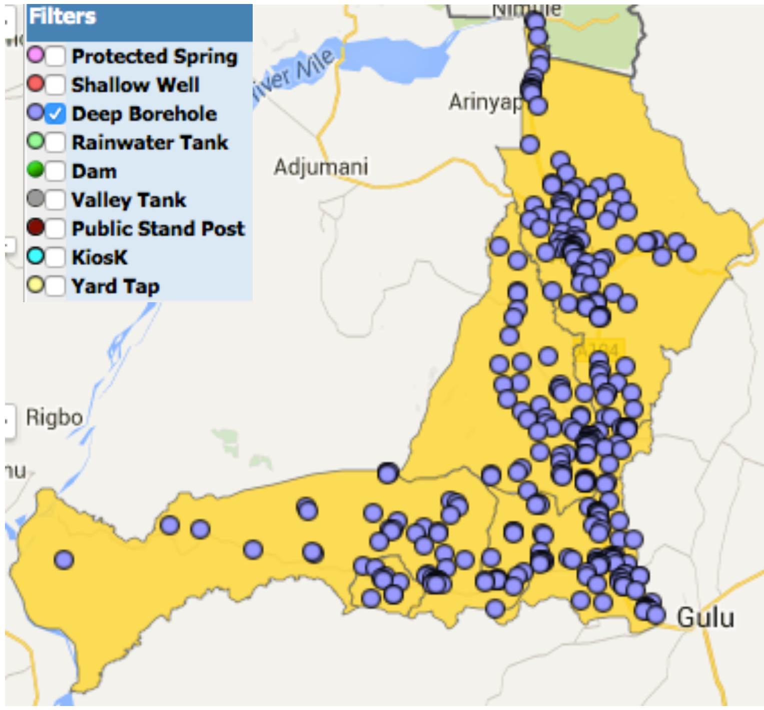


Figure 11. Deep Borehole coverage across Amuru District [39]

The Directorate of Water Development (DWD) of the MWE released water coverage information from data collected in districts across the country. It is estimated that 56% of functional water supply technologies in the Amuru District and 54% in the Gulu District are deep boreholes. In the Amuru District 208 of 269 deep boreholes (77%) are functional [40], and in the Gulu District 405 of 511 deep boreholes (79%) are functional [41].

2.4.1 U-Series Handpumps

A majority of the boreholes constructed in Uganda are a variation of the India Mark II hand pump (*Figure 12*). With the influence of UNICEF, Uganda began the standardization process for the Uganda manufactured India Mark II (U2) in 1995 (US:406:1995). The policy to designate the U2 as the standard handpump for deep well boreholes (24-50m) in Uganda was adopted in 1999 by the UNBS. The government wanted to create a market for VLOM handpumps that would allow for the accessibility of spare parts across the country [42]. The U2 replaced the non-VLOM Bush pump, and Victoria Pumps Limited became the established U2 manufacturer. The handle of the U2 handpumps was lengthened to closer resemble the Bush pump. Pumps are sometimes imported from India at a lower price and of lesser quality, but the government does little to stop this because of their economic liberalization policy [43].

The modified version of the U2 (U2M) is designed to allow for easier maintenance. The U2M has an open top cylinder (OTC) design and “pumping elements which can be removed without having to lift out the rising main” [27]. The U2 and the Uganda manufactured India Mark III (U3) are the standard shallow well handpumps (3-21 m) (US:405:1995). The difference is the riser pipes: 32 mm nominal borehole (NB) for the U2 and 65 mm NB for the U3 [29]. The modified U3 (U3M) was designed as an alternative to resist corrosion. Materials were modified to include the use of uPVC riser mains and stainless steel or fibre glass reinforced plastic (FRP) connecting rods [17], [33]. The U3M also incorporates an OTC for ease of maintenance and is designed to lift water from depths of 10-45 m [34].

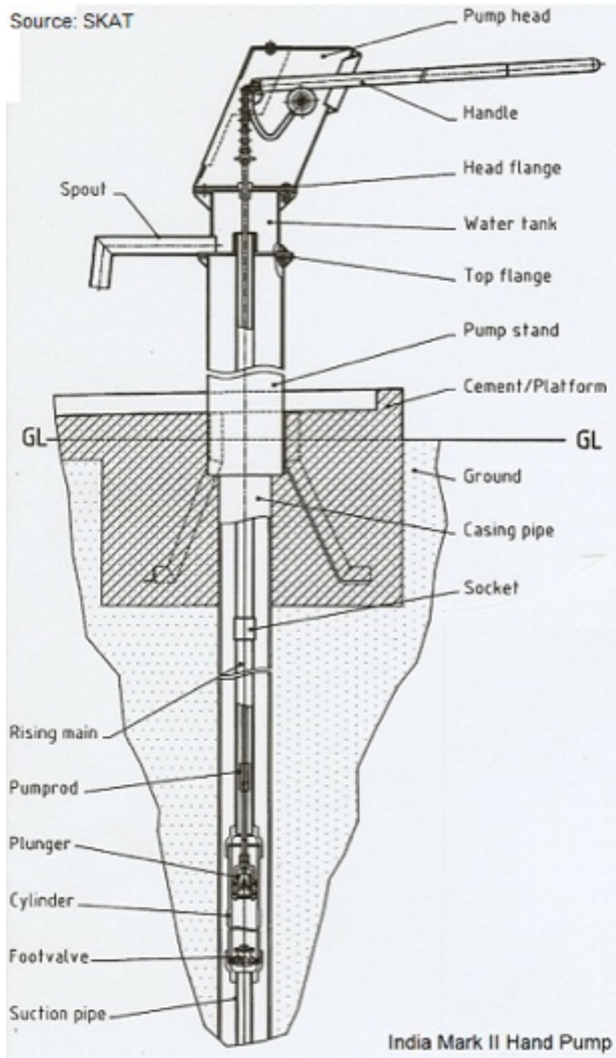


Figure 12. India Mark II Hand Pump Drawing [58]

CHAPTER 3. MATERIALS AND METHODS

Latitude, longitude, and elevation were recorded using the application 'GPS Location' offered by V_Firefighter for Android for sixteen borehole sites in northern Uganda (*Figure 13*). No additional data were collected at borehole 15 because its U2 pump was no longer in working condition. Several different water quality tests were conducted and interviews were used to collect qualitative data from the remaining fifteen boreholes. In addition, observational data were collected at each site.

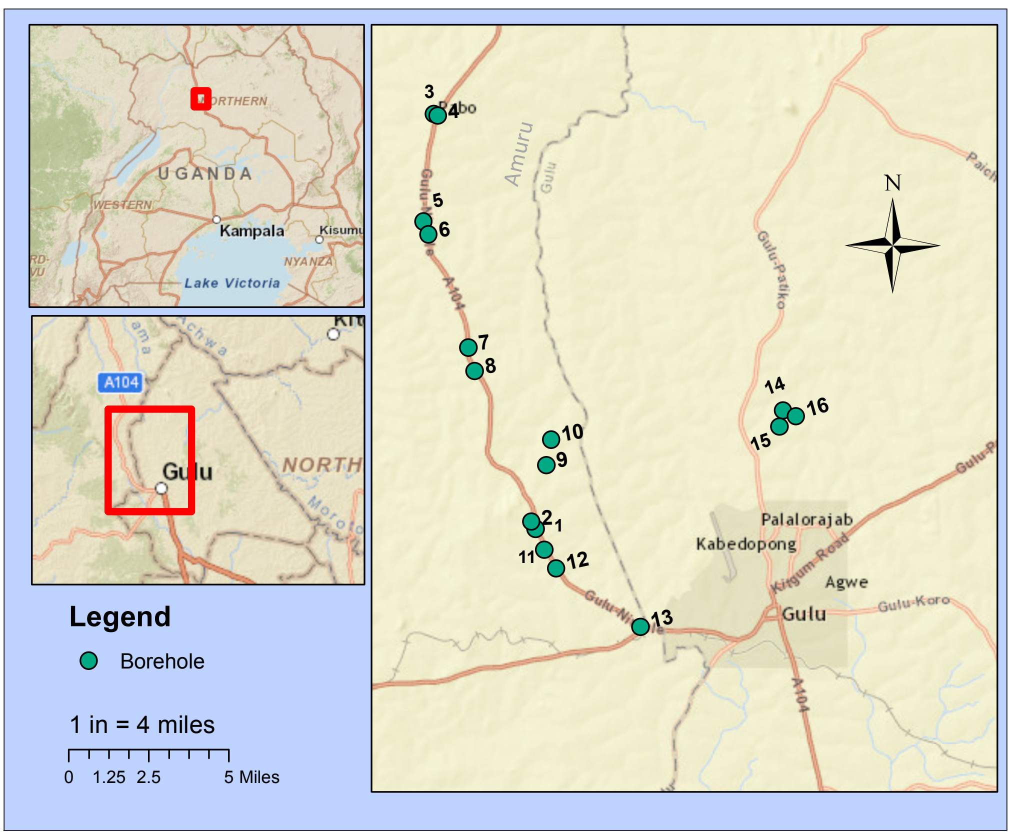


Figure 13. Locations of 16 boreholes in Northern Uganda from which data were collected.

3.1 Water Quality Testing

Conductivity, total dissolved solids (TDS), pH, and iron concentration were measured at 15 borehole locations in the Gulu and Amuru districts. See Appendix A for details on measurement values recorded from each borehole.

3.1.1 pH Study

The reliability and accuracy of pH strips were compared to measurements recorded by a pH probe. The pH probe (Hanna probe) was considered the reference method for this study. Three different pH strips were used. Details of the probe and pH stripes used are shown in *Table 7.*

Table 7. Details concerning materials used in the pH Study

	Intended Use	Cost	Range (pH)	Test Time
Macherey Nagel (MN) pH-Fix test strips –REF 921 10[a]	Single-use, rapid test for "dangerous, poisonous, or aggressive liquids"	~$14 for 100 strips	0-14	10 sec/strip
(WaterWorks™) Extended Range pH Check Test Strips-481104[b]	Single-use, broad application of water quality testing	~$10 for 50 strips	2-12	30 sec/strip
Youth Waters pH Test Strips[c]	Single-use, body pH for saliva and urine	~$10 for 160 strips	4.5-9	
Hanna Instrument-HI 9813-5 probe[d]	Agricultural application, accuracy @ 20°C ±0.1pH	$175-200+	0.0-14.0	

[a][44] [b] [45] [c] [46] [d] [47]

At each borehole site, four 100-mL water samples were taken within the same pump stroke. Three of the water samples collected were dedicated to a different pH strip type, and pH measurements were conducted in triplicate with each type of pH strip (*Figure 14*). The fourth beaker of water was used to measure conductivity, pH, and TDS with the Hanna probe. A three-point calibration curve was performed daily for the portable probe using commercial buffers of pH = 4, 7, and 10.

Figure 14. From left to right: Youth Waters, Extended Range, MN pH test strips in triplicate (Photo courtesy of Jake Carpenter)

3.1.2 Iron Concentration

The iron concentration at each borehole was measured using the SenSafe™ Iron Check test kit. A water sample was collected from the pump and appropriately diluted; iron concentration was then quantified using the procedure provided by the manufacturer (*Figure 15*). The SenSafe™ strips allowed iron concentrations to be quantified from 0.1-5.0 ppm (mg/L) with a detection sensitivity of 0.1 ppm (mg/L).

Figure 15. L: 30 seconds of gentle stirring followed by a 2-minute wait time with the strip removed from the sample. R: Matching strip to closest color on the container. (Photos courtesy of Jake Carpenter)

3.2 Pump Tests

Two types of pump tests were performed—a pump performance test and a WaterAid pump test. These tests provide information on the efficiency of the pump and the characteristics of borehole water quality, respectively. The borehole sites where these tests were completed are specified in each of the following subsections.

3.2.1 Pump Performance Testing – Leak Test (Two Minute Stroke Test)

A pump performance, or leakage test [48], was completed at 12 of the 15 borehole sites. This test was conducted by first fully priming the pump. Once primed, pumping was suspended for two minutes. After the 2-minute wait period, the user would pump until water flowed from the pump spout. The number of pump strokes required to reach this point was recorded. Ideally this number would be one. Anything greater than one may be an indication of a leak, which typically occurs as a result of "worn rubber components in the cylinder, leaking rising main joints or severely corroded riser pipes" [48].

3.2.2 WaterAid Pump Test

Pump tests were performed following the WaterAid pump test method (Appendix B) to determine if the origin of iron is naturally occurring in the groundwater or related to the corrosion of the pump components [49]. The reader should take note that the radius equations in the WaterAid pump test method document are incorrect. Calculate the radius by multiplying the diameter by 0.5 or dividing the diameter by 2 (r=d*0.5=d/2).

Two sites were tested—boreholes 14 and 16 (*Figure 13*). At each site, community members were asked to estimate the number of jerry cans that had already been pumped on that day. An initial sample was taken, the start time was recorded, and the iron concentration, pH, conductivity, and TDS were measured. For every subsequent 20 L of water pumped the time was noted and the pH, conductivity, and TDS were measured using the Hanna probe (*Figure 16*). Iron concentrations at borehole 14 were measured every 20 L up to 160 L and every 40 L from 160-320 L.

Figure 16. Measuring pH, conductivity, and TDS with the Hanna probe during a pump test at borehole 16.

At borehole 16, two pump tests were conducted. For the first pump test, 1000 L were pumped and iron concentrations were measured every 100 L. During the second pump test, 2400 L were pumped and iron concentrations were measured at 800, 1000, and 1100 L, and every 200 L from 1200-2400 L. The raw data from these tests can be found in Appendix C.

3.3 Observational and Qualitative Data Collection

Several observations were made at each borehole site including determining a landmark to identify the location of the borehole, the pump type, the pump's condition and any repairs that may have been made, the drainage conditions, and approximately how old the borehole may be. Nearby community members were also asked about the usage patterns of the borehole, the estimated amount of water pumped so far that day, who the primary users of the pump are, the quality of the water, whether the soap lathers, and if there had been any repairs made, by whom, and when.

3.4 Analysis Methods

Geographical and statistical methods were used to analyze the data collected in Uganda. The three main programs used during this analysis were ArcMap 10.1.4, Microsoft Excel, and Minitab® 16.2.4. Several maps were created and an initial difference method comparison and paired t-tests were performed on the data collected.

3.4.1 ArcGIS

ArcMap 10.1.4 was used to create *Figures 8 , 13, 24* . A shapefile from Global Administration Areas (GADM), version 1.0, downloaded from DIVA-GIS, was used in creating *Figure 8*. The shapefile contained district boundaries of Uganda [50]. Uganda continues to rezone districts. Highlighted districts were modified as necessary to match the most recent district zoning.

Figure 8 in Section 2.3 displays the districts where water quality data was available from the MWE. *Figure 13* in Section 4.2.2 maps all of the borehole locations. *Figure 24* in Section 5.2.2 maps the measured iron concentration (mg/L) at each borehole.

3.4.2 Statistical Analysis

Two types of statistical analysis were used to investigate the pH data collected at each borehole. Paired t-test and Bland-Altman difference method analyses were performed to compare the Hanna probe measurements to each of the pH test strip measurements. Minitab® 16.2.4 and Microsoft Excel were used in performing the analysis methods.

A paired t-test is performed when measurements are paired in order to minimize differences in measurement due to technician, weather or seasonal conditions, time, etc. Conducting a paired t-test, as opposed to an independent t-test, eliminates variation due to uncontrollable experimental factors. Experiments are designed to ensure that uncontrollable and unknown factors contribute equally to each measurement. The average of paired differences, $\bar{d}$, is analyzed in a paired t-test:

$$\bar{d} = \frac{\sum d_i}{n} = \frac{1}{n}\sum(y_{1,i} - y_{2,i}) \qquad \text{Equation 6}$$

where y_1 and y_2 are random variables observed as matched pairs and n = number of paired observations.

The standard deviation of the differences, s_d, and the standard error of the average difference, $s_{\bar{d}}$, (Equations 7 & 8) are calculated in order to determine the 1-α confidence interval for δ (Equation 9) [51].

$$s_d = \sqrt{\frac{\sum(d_i - \bar{d})^2}{n-1}}$$ Equation 7

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}}$$ Equation 8

$$\bar{d} - s_{\bar{d}} t_{n-1,\propto/2} < \delta < \bar{d} + s_{\bar{d}} t_{n-1,\propto/2}$$ Equation 9

δ is defined as the true mean of differences between the two pH measurement methods observed. $\bar{d}$ is an estimate of the true mean difference (δ). For the three paired t-tests conducted $\alpha = 0.05$.

The Bland-Altman difference method is used to analyze the difference in measurement techniques by comparing the difference in methods to the average of the methods. An initial analysis of the data includes directly graphing each pH test strip versus the Hanna probe. A line of equality is included in the initial plot. The second plot in the Bland-Altman method compares the difference in measurement techniques (Probe-Test Strip) to the average of the methods[(Probe + Test Strip)/2]. The mean difference ±2 standard deviations is also indicated in the second plot. Graphically displaying this information can help reveal any bias or trends in the data that are not always evident in the first plot of pH strip versus Hanna probe [52]. Ideally the results and conclusions from the Bland-Altman method will match the results from the paired t-tests and will help to further distinguish between the three pH test strip methods. The Bland-Altman method is used as a supplementary analysis to the paired t-tests [53].

There are many different techniques to compare measurement methods, each applicable under certain circumstances. Literature is unclear whether any one technique is best. It is disputed whether correlation or regression analyses, difference of means or the Bland-Altman plot are appropriate to use when comparing measurement methods [54], [55]. The Clinical and Laboratory Standards Institute (CLSI) suggests plotting the difference in methods versus the standard method (the golden standard or reference method) [56]. Bland and Altman specifically defend why differences in methods should be plotted versus the average of the methods instead of versus the standard method. Plotting versus the latter will always show a relationship between the difference and magnitude even if there actually is none [57].

CHAPTER 4. FIELD RESULTS AND DATA ANALYSIS

Quantitative and qualitative data collected and data analysis and interpretation from each borehole are presented in this chapter. Observational and qualitative data collected – pump type, condition of the pump, any repairs made, drainage conditions, borehole age, usage patterns, quality of water, etc. – are provided in Appendix A.

4.1 pH Analysis

An initial analysis of the pH data collected from the three different pH test strips and the Hanna probe was conducted by performing paired t-tests. Additional statistical analysis was completed using the Bland-Altman method and compared to the findings from the initial analysis. The second analysis further distinguished between the three pH test strips.

4.1.1 Paired t-Tests

pH strips from three different vendors (refer to *Table 7*) were used to test the pH at 15 boreholes. As shown in *Table 8* , the results indicate that only the Youth Waters strips were statistically different from the Hanna probe. The MN and Extended Range strips were both indistinguishable from the probe at α=0.05.

Table 8. Paired t-Test Results Comparing pH Strip Readings to the Hanna probe Readings

Variables	n	Mean Diff.	St.Dev.	St. Error	t_{n-1}	95% CI for Mean Diff.	P-value
Probe-MN	15	-0.026	0.26	0.066	2.145	(-0.17, 0.12)	0.71
Probe-ER[a]	15	0.18	0.32	0.083	2.145	(-0.0024, 0.35)	0.053
Probe-YW[b]	15	0.25	0.17	0.044	2.145	(0.16, 0.35)	0.00

[a]Extended Range, [b]Youth Waters

The Youth Waters measurements consistently underestimated the pH when compared to the Hanna probe measurements. See Appendix D for further details from each paired t-test.

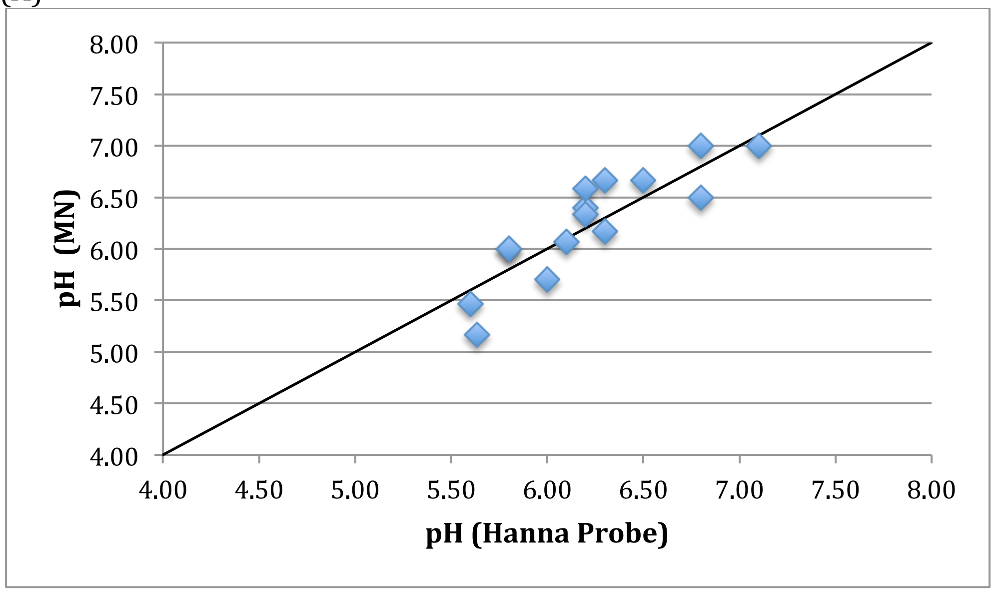
4.1.2 Bland-Altman Difference Method

Figure 17 shows good agreement between the Hanna probe and the MN test strips, which confirms the t-test results. The Extended Range test strip measurements are not as randomly distributed as the MN test strips, but still appear to agree with the reference method (*Figure 18*). Readings between 6.0 and 7.0 pH are more accurate than readings outside of this range for the Extended Range test strips. pH levels below 6.0 were underestimated by the Extended Range strips. The one instance where pH was above 7.0 was overestimated using the Extended Range test strip. More measurements need to be taken to determine if these trends hold.

As shown in *Figure* 19, the Youth Waters test strips consistently underestimate the pH compared to the Hanna probe measurements. The Youth Waters measurements are the most precise of the three test strips (SD of difference=0.17), but it is not clear from these graphs if the Youth Water strips are an acceptable replacement for the reference method.

The mean difference of the MN test strips is smaller than that of the Extended Range test strips (mean difference = -0.03 and 0.18, respectively). The standard deviation of the difference in MN test strips versus the Hanna probe is also smaller than the standard deviation of the difference in Extended Range test strips versus the Hanna probe (SD=0.26 and 0.32, respectively). This suggests that the MN test strip is more accurate than the Extended Range test strip.

(A)



(B)

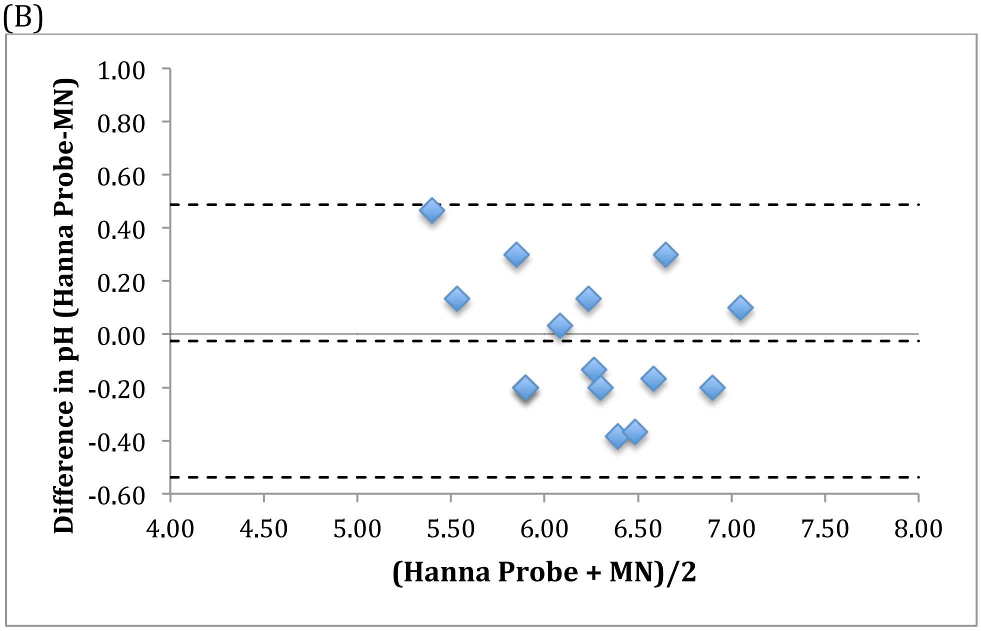
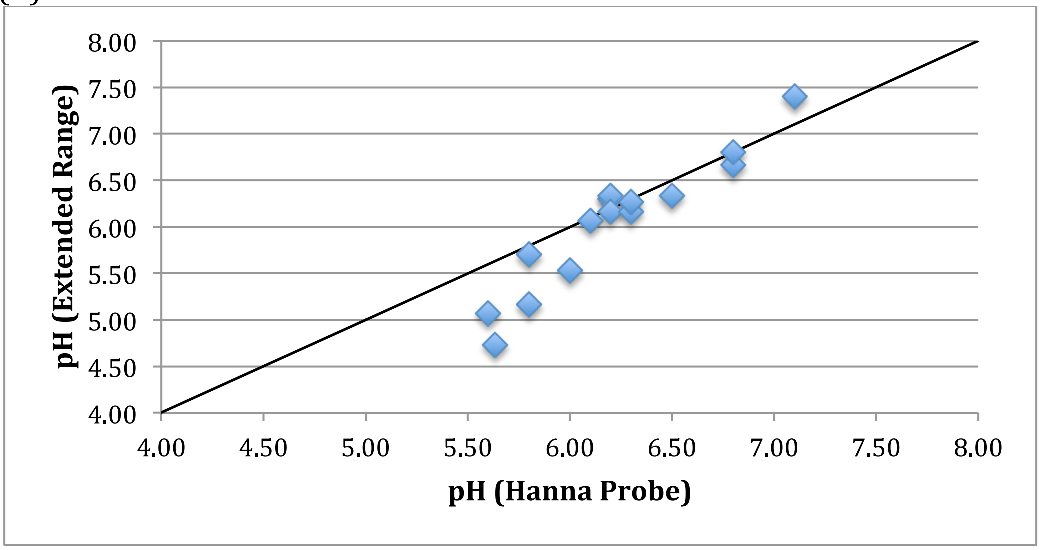


Figure 17. Comparison of the MN pH test strip to the Hanna probe reference method from the measurement of pH in 15 boreholes in the Amuru and Gulu Districts of Northern Uganda. (A) Comparing methods with a line of equality (y=x). (B) The Bland-Altman plot with ± 2 standard deviations from the mean difference (dashed lines) and line of equality (solid line). Mean difference= -0.03. SD= 0.26.

(A)



(B)

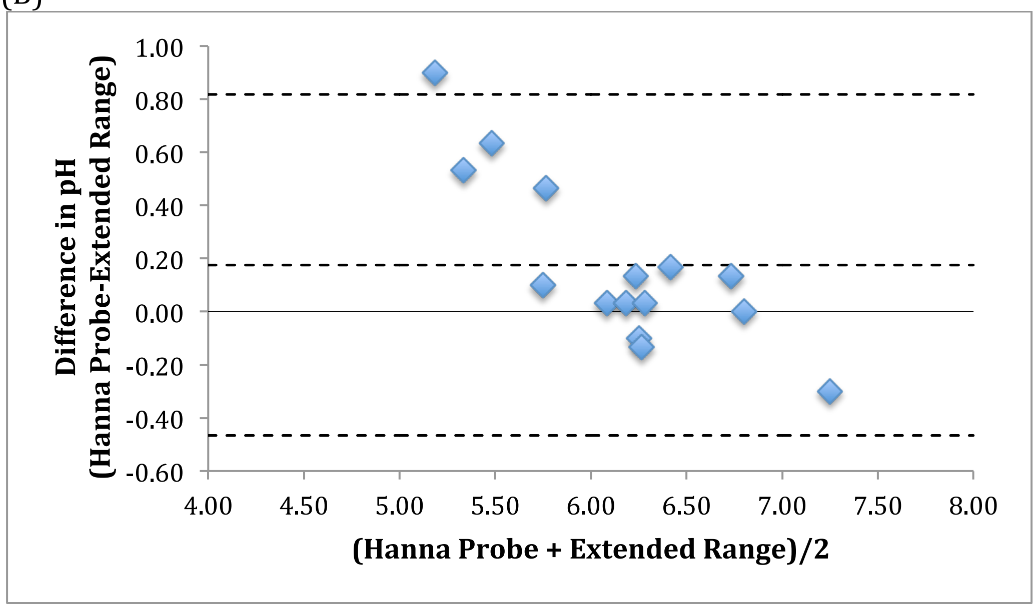
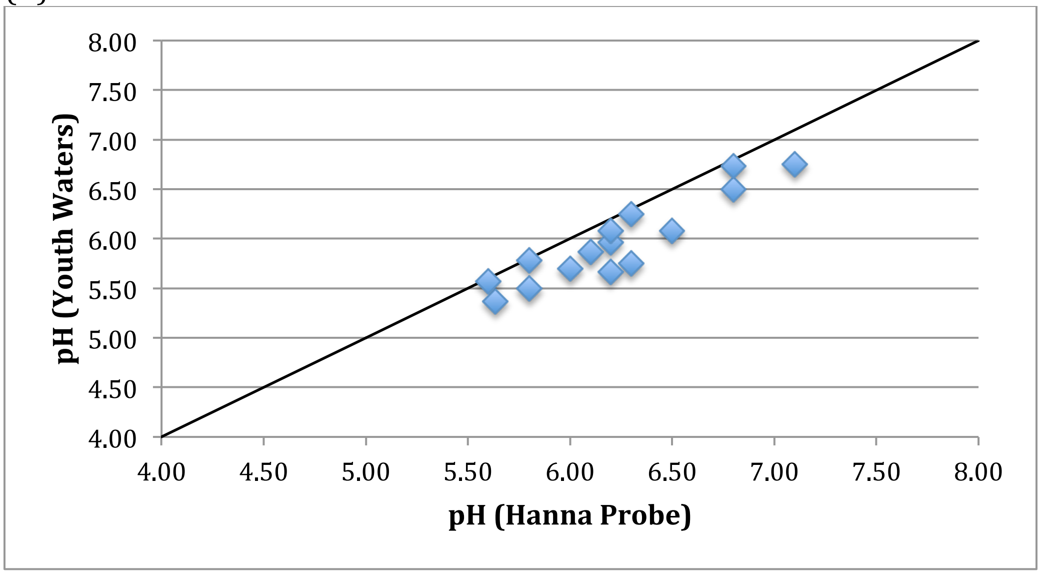


Figure 18. Comparison of the Extended Range pH test strip to the Hanna probe reference method from the measurement of pH in 15 boreholes in the Amuru and Gulu Districts of Northern Uganda. (A) Comparing methods with a line of equality (y=x). (B) The Bland-Altman plot with ± 2 standard deviations from the mean difference (dashed lines) and line of equality (solid line). Mean difference= 0.18. SD= 0.32.

(A)



(B)

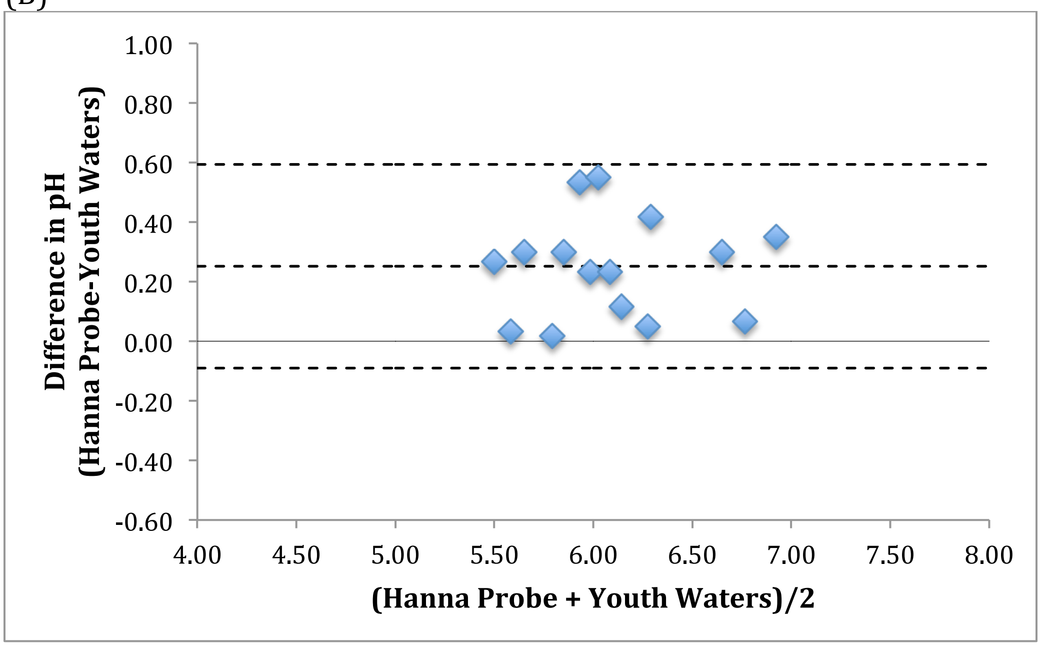


Figure 19. Comparison of the Youth Waters pH test strip to the Hanna probe reference method from the measurement of pH in 15 boreholes in the Amuru and Gulu Districts of Northern Uganda. (A) Comparing methods with a line of equality (y=x). (B) The Bland-Altman plot with ± 2 standard deviations from the mean difference (dashed lines) and line of equality (solid line). Mean difference= 0.25. SD= 0.17.

4.1.3 pH Correlations

At 11 of the boreholes, women of the community that were collecting water during water sampling were asked to approximate the number of jerry cans of water that had already been pumped that day. The relationship between pH and the estimated number of jerry cans pumped can be linearly modeled as:

$$pH = 6.6 - 0.0066J, \quad R^2 = 0.43 \qquad \text{Equation 10}$$

where J = number of jerry cans. See *Figure 20*. These data suggest that with continued pumping of the borehole, pH decreases.

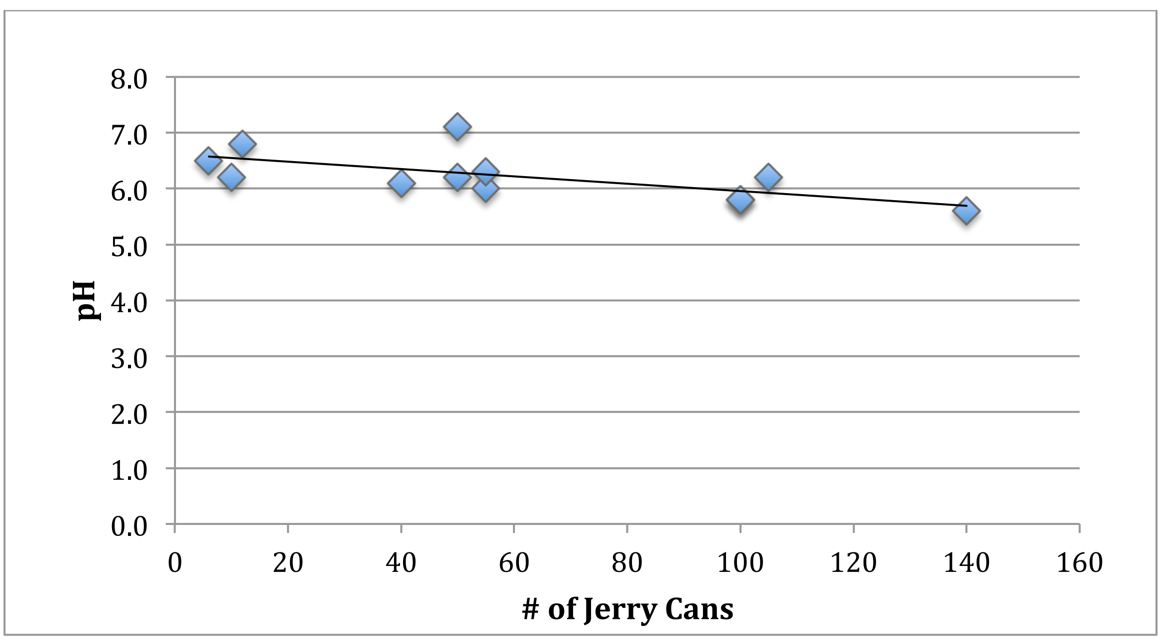


Figure 20. There is a negative linear relationship between the pH and the number of jerry cans pumped.

4.2 Iron Concentration

Iron concentration was analyzed quantitatively and geographically at the 15 borehole sites. Eleven of the fifteen boreholes (73%) met the UNBS, Class II standards set for iron concentration (1 mg/L) (*Table 5*) [7].

4.2.1 Iron Concentration, Number of Jerry Cans Pumped, and Time

Iron concentration, the estimated number of jerry cans pumped, and the time of day were compared to determine a relationship between each. There is no discernible correlation between iron concentration and time of day (*Figure 21*) or the estimated number of jerry cans pumped and the time of day (*Figure 22*).

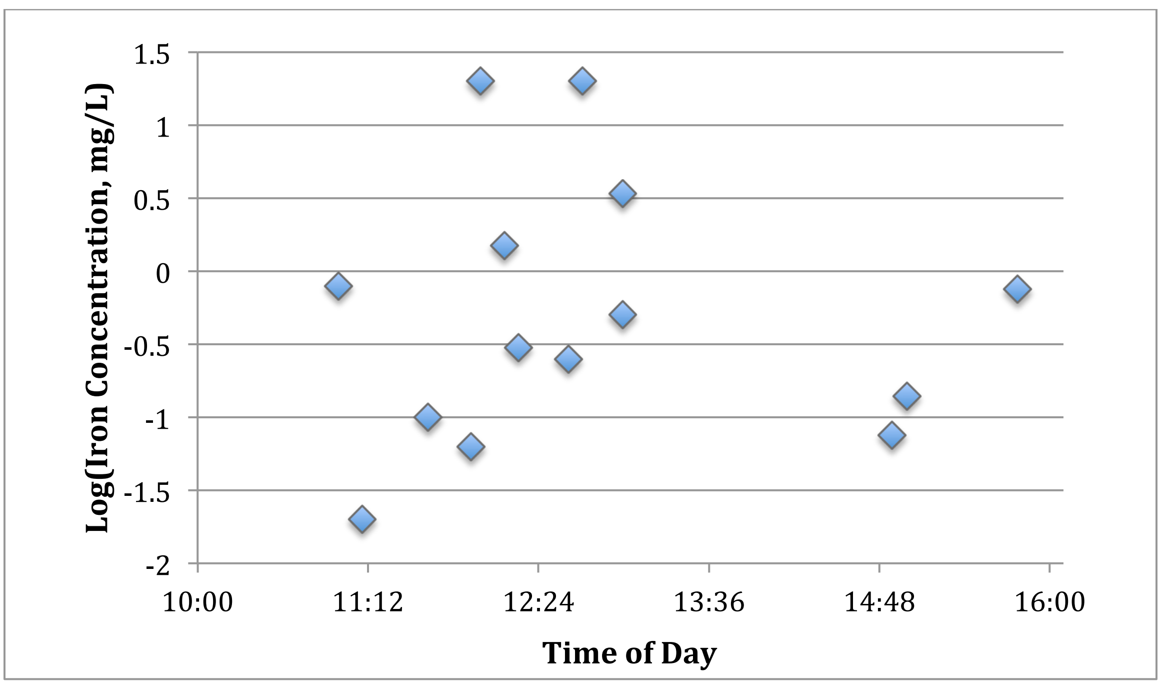


Figure 21. A relationship between the logarithmic of iron concentration and the time of day cannot be deducted.

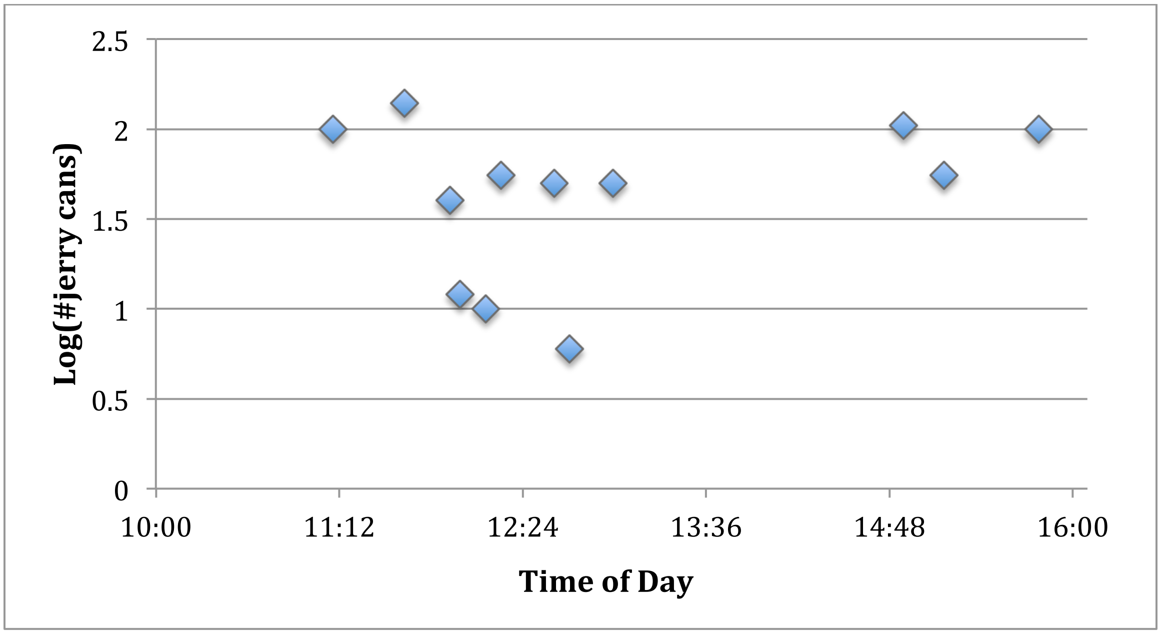


Figure 22. A relationship between the logarithmic of the number of jerry cans pumped and the time of day cannot be deducted.

However, the relationship between iron concentration and the estimated number of jerry cans pumped can be linearly modeled as:

log(iron conc. (mg/L)) = -1.73(log(J)) + 2.45, R^2 = 0.68 Equation 11

where J = number of jerry cans. See *Figure 23*. As the number of jerry cans pumped increases, the iron concentration decreases. This relationship suggests that the iron levels in the boreholes tested were at least partially due to corrosion. Langenegger et al. observed similar trends in their research of iron concentration in boreholes in Ghana [18], [19], [27]. They observed that as more water was pumped, the iron levels dropped and stabilized.

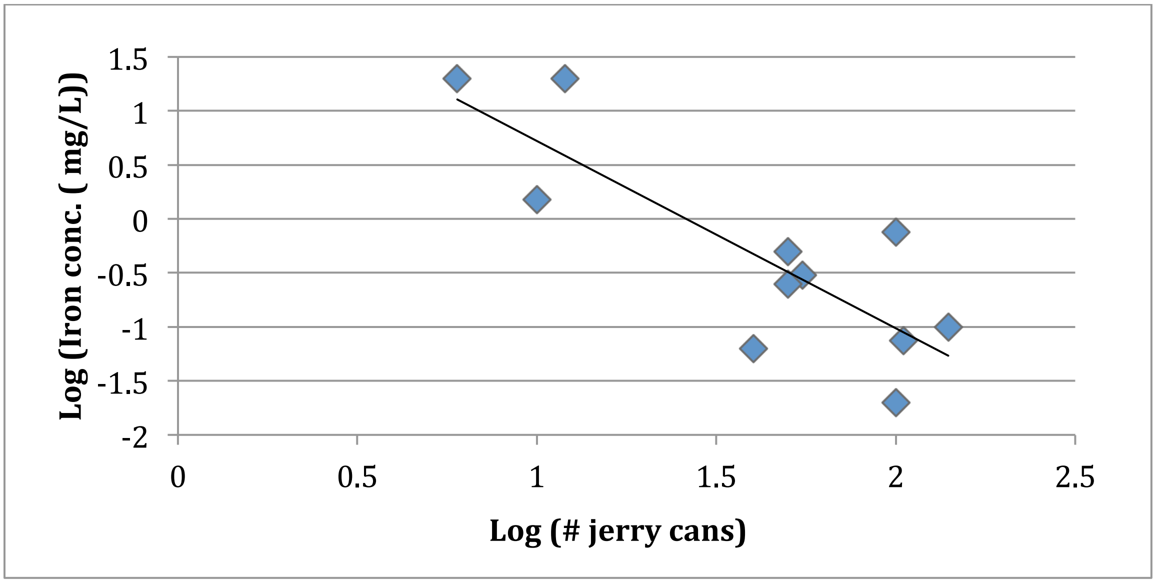


Figure 23. A relationship between the logarithmic of iron concentration and the number of jerry cans pumped can be deducted.

4.2.2 Geographic Iron Concentration

ArcGIS was used to map iron concentrations measured at 15 borehole sites (see Figure 24). The farther the borehole site from a main road, the higher the iron concentrations. This observation may be related to usage. Boreholes that are further from main roads may not be used as frequently. The idea that higher iron concentrations are measured at boreholes that are less frequently used is similar to previous findings that the more jerry cans pumped, the lower the iron concentration. Langenegger explains,

> "Field experience suggests that handpump equipped water points having an iron concentration of more than 5 mg/L are generally little used. The iron concentration can be taken as an indicator of handpump use where corrosion is a problem"[18].

The iron concentrations in boreholes 10 and 16 were 20 mg/L (see raw data in Appendix A). From interviews conducted on site: Many prefer unprotected springs as their water source to borehole 16; and borehole 10 is used only for washing; families collect their drinking water from a nearby spring instead.

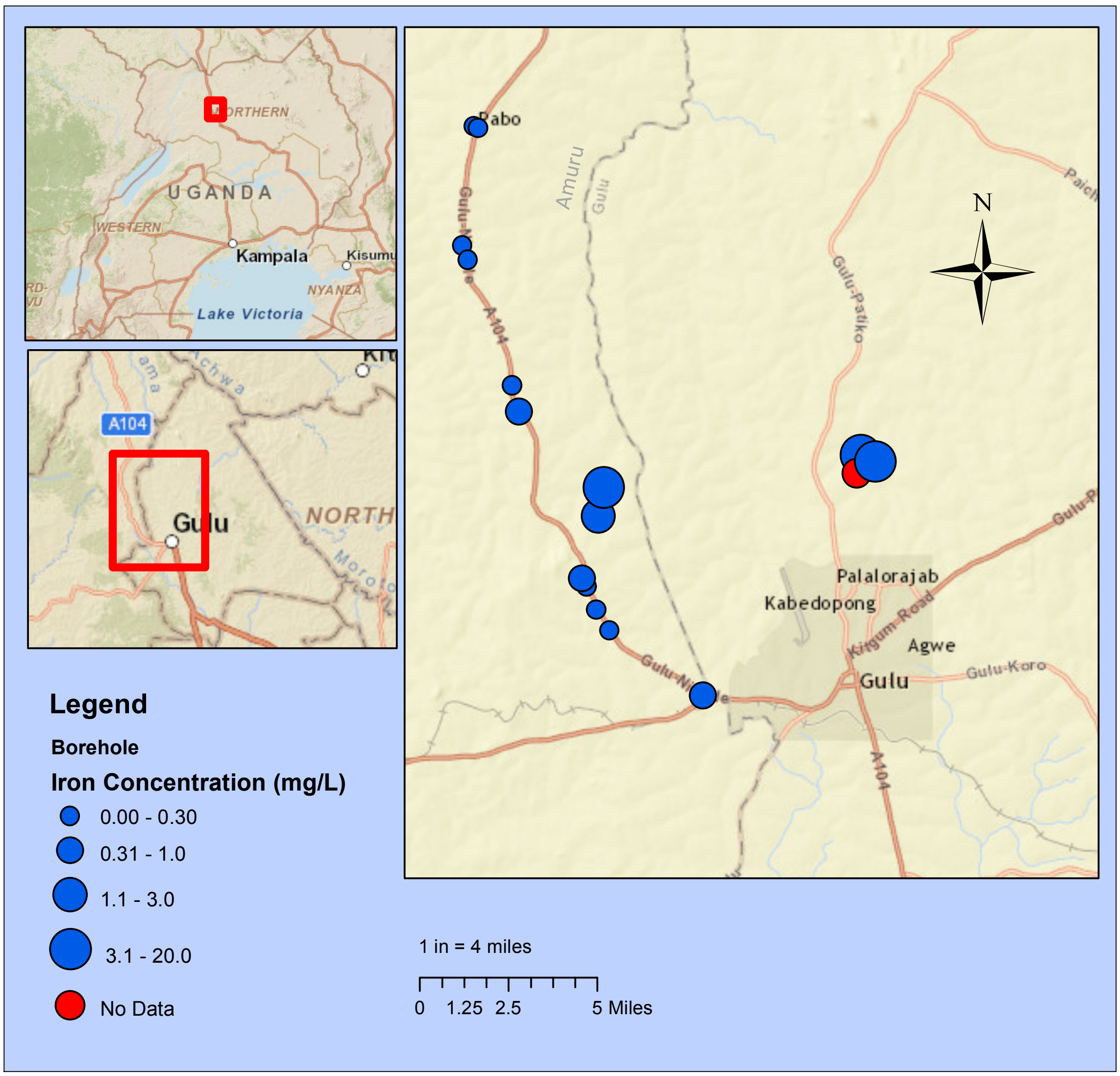


Figure 24. Iron Concentrations measured at 15 sites in the Amuru and Gulu Districts.

4.3 Pump Performance Tests – Leak Test (Two Minute Stroke Test)

The pump performance of twelve of the sixteen identified boreholes was evaluated (*Table 9*). The Swiss Centre for Appropriate Technology (SKAT) and the Rural Water Supply Network (RWSN) suggest priming the pump and waiting 30 minutes before counting the number of pumps required for water to flow. It should be noted that pump performance testing at each borehole deviated from this suggestion. The wait time observed was two minutes instead of thirty minutes. When following SKAT and RWSN suggestions, in order for a borehole to pass the test the number of pumps after the borehole was primed must be 10 or less [48]. Nine boreholes (75%) passed under these conditions. Five boreholes (42%) only required one pump stroke. The average number of pumps after priming the borehole was 11, and the standard deviation was 18 pumps. Three boreholes required more than 10 pumps. This indicates that 25% of the boreholes are not working efficiently. Leaking could be due to “worn rubber components in the cylinder, leaking rising main joints or severely corroded riser pipes” [48].

Table 9. Pump Performance Results

Borehole No.	No. of Pumps
1	--
2	--
3	3
4	--
5	2
6	1
7	1
8	5
9	13
10	30
11	64
12	7
13	1
14	1
15	--
16	1
Average:	11
Standard Dev:	18
% Passed:	9/12= 75%

4.4 WaterAid Pump Tests

The results from each pump test are analyzed in two parts: Part A—iron concentration and pH and Part B—conductivity and TDS.

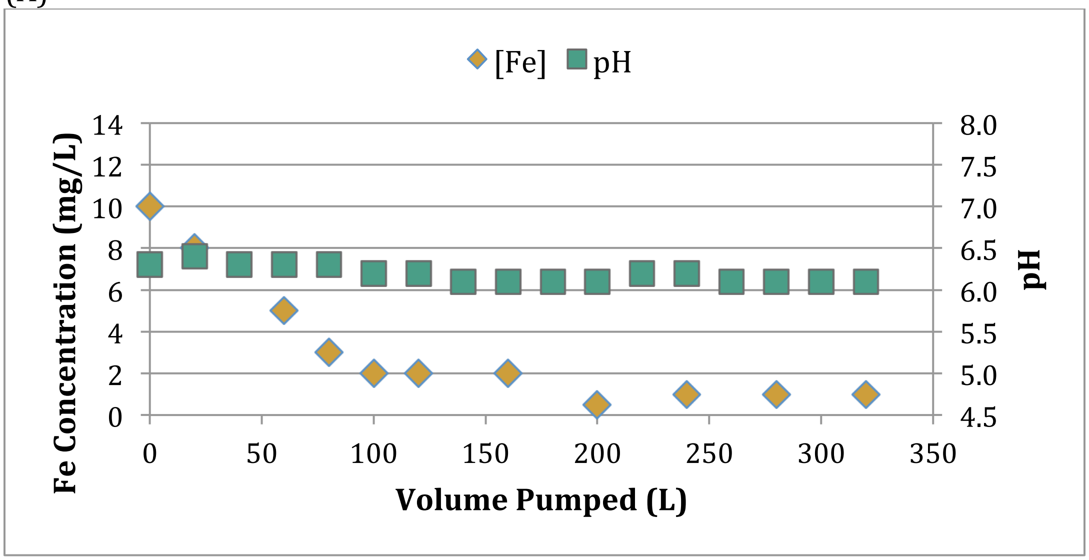
The pump test for borehole 14 suggests that iron concentrations can be attributed to the corrosion of pump components because the iron concentration drops rapidly in the beginning of the test [49]. For example, initial iron concentration was measured as 10 mg/L and after 320 L of water was pumped, the iron concentration was 1 mg/L, showing a drop in concentration of an order of magnitude. The pH for borehole 14 stayed between 6.0 and 6.5 throughout the pump test (*Figure 25*). These results suggest that the iron concentration observed at borehole 14 is mostly attributed to corrosion. In *Groundwater Quality and Handpump Corrosion in Africa,* Langenegger concluded that iron concentrations in groundwater do not typically exceed 1 mg/L naturally [19]. Therefore the 1 mg/L stabilized iron concentration in borehole 14 is most likely a result of the groundwater geography.

The data collected from all three pump tests confirmed that conductivity and TDS are directly related (*Figures 25B, 26B*, and *27B*). If conductivity or TDS increases, the other increases, and vice versa. For borehole 14 (*Figure 25*B), as more water was pumped, the conductivity and TDS decreased until they leveled off around 0.15 mS/cm and 115 ppm, respectively. Conductivity and TDS trends seem to correspond with the iron concentration levels for each pump test.

Two pump tests were conducted for borehole 16. The iron concentrations during the first pump test conducted on borehole 16 (Pump Test 1) decreased from an initial value of 12.5 to 2.33 mg/L, but never stabilized. The initial pH was 7.0, but stabilized at 6.2 after 480 L had been pumped(*Figure 26A*). For borehole 16-Test 1 (*Figure 26B*), as more water was pumped conductivity and TDS decreased (excluding the initial measurement) until they leveled off around 0.17 mS/cm and 128 ppm, respectively, after 600 L had been pumped.

The iron concentrations measured during the second pump test for borehole 16 (Pump Test 2) was initially 30 mg/L and stabilized at 2 mg/L after 2400 L of water was pumped. As with Pump Test 1, the initial pH of Pump Test 2 was 7.0, but stabilized at 6.2 (*Figure 27A*). This trend may be attributed to the Kuch mechanism[22]–[24]. A product of the Kuch mechanism, hydroxide, could increase the pH of the water as it sits overnight. Once dissolved oxygen is reintroduced to the bulk water by pumping, ferrous iron is converted to ferric iron causing the initial red color of the effluent. The pH drop observed in Pump Tests 1 and 2 of borehole

(A)



(B)

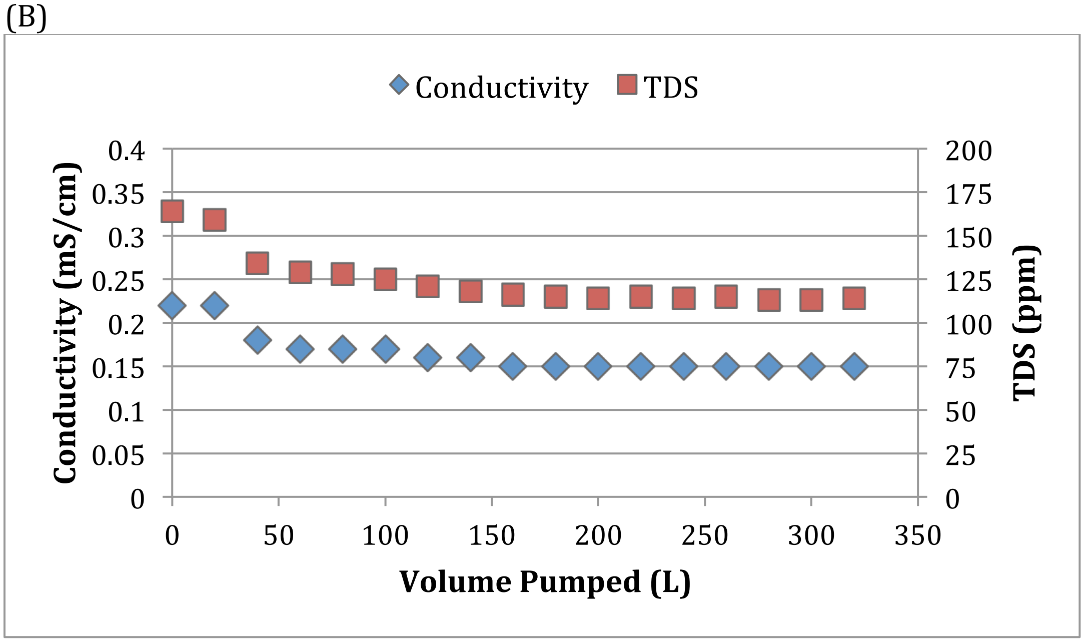


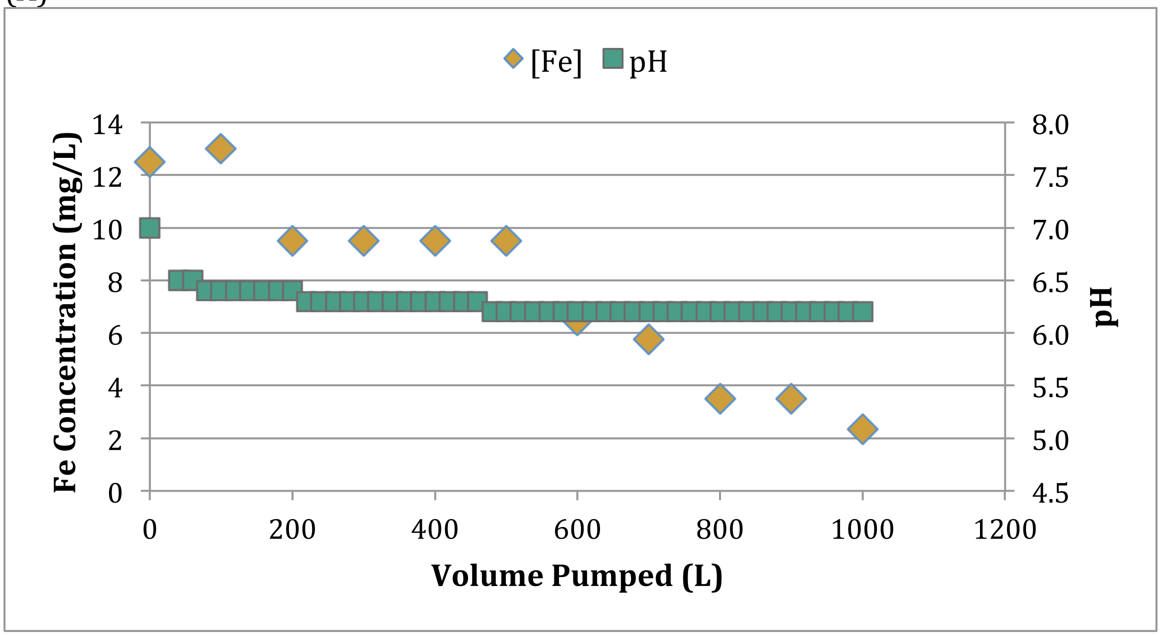
Figure 25. Borehole 14 pump test results (A) pH stabilizes around 6.15 and iron concentration stabilizes at 1.0 mg/L. (B) Conductivity and TDS stabilize at 0.15 mS/cm and approximately 114 ppm, respectively.

16 is a result of the borehole being flushed. The stabilized pH is representative of the groundwater source. For borehole 16-Test 2 (*Figure 27B*), conductivity and TDS stabilized around 0.17 mS/cm and 127 ppm, respectively.

Results from the two pump tests at borehole 16, when compared to pump studies performed by the UNDP-World Bank Water and Sanitation Program and Langenegger, suggest that the iron concentration levels in borehole 16 are mostly caused by corrosion [18], [19], [27]. The 2 mg/L stabilized iron concentration is most likely a result of the groundwater geography.

A complaint of the community at borehole 16 was that the water turned black when boiled. This phenomenon was observed at pumped volumes of 0.1, 260, and 680 L (iron concentrations of 12.5, 9.5, and 5.9 mg/L, respectively) (*Figure 28*). As a sample from the borehole was boiled, iron cations were released into solution. At an iron concentration of 12.5 mg/L, the final product of boiled water was dark and cloudy. As the iron concentration decreased, the darkness and cloudiness of the water lessened. At an iron concentration of 5.9 mg/L the final product of the boiled sample was still not clear enough to be deemed aesthetically acceptable. As a result, many families prefer collecting water from an unprotected spring than from the borehole, although the spring water is much more likely to contain biological contaminants.

(A)



(B)

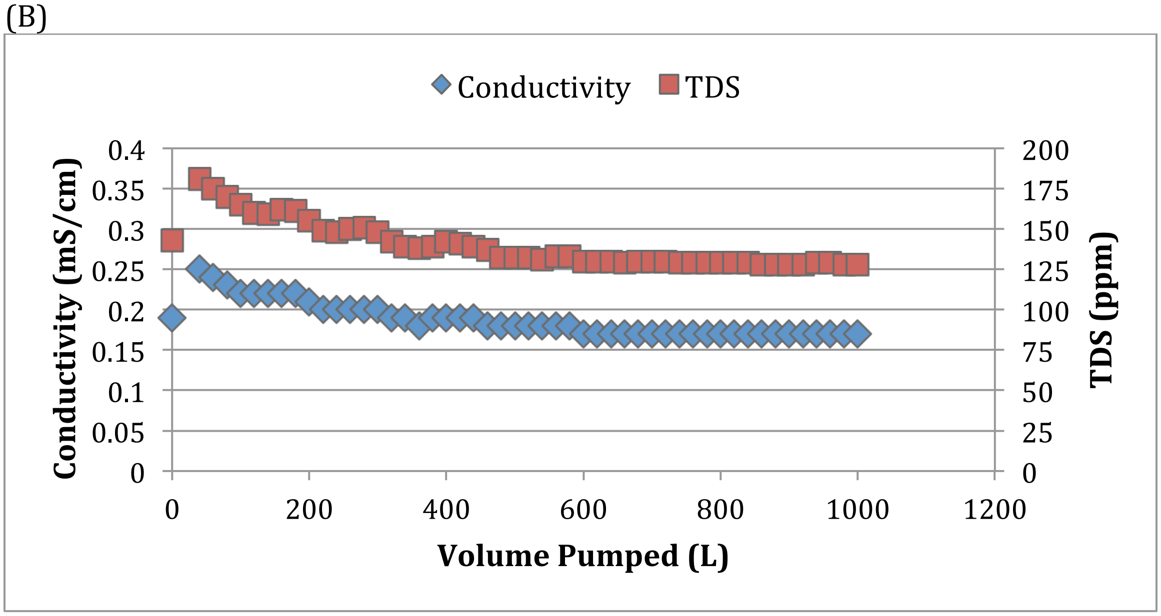
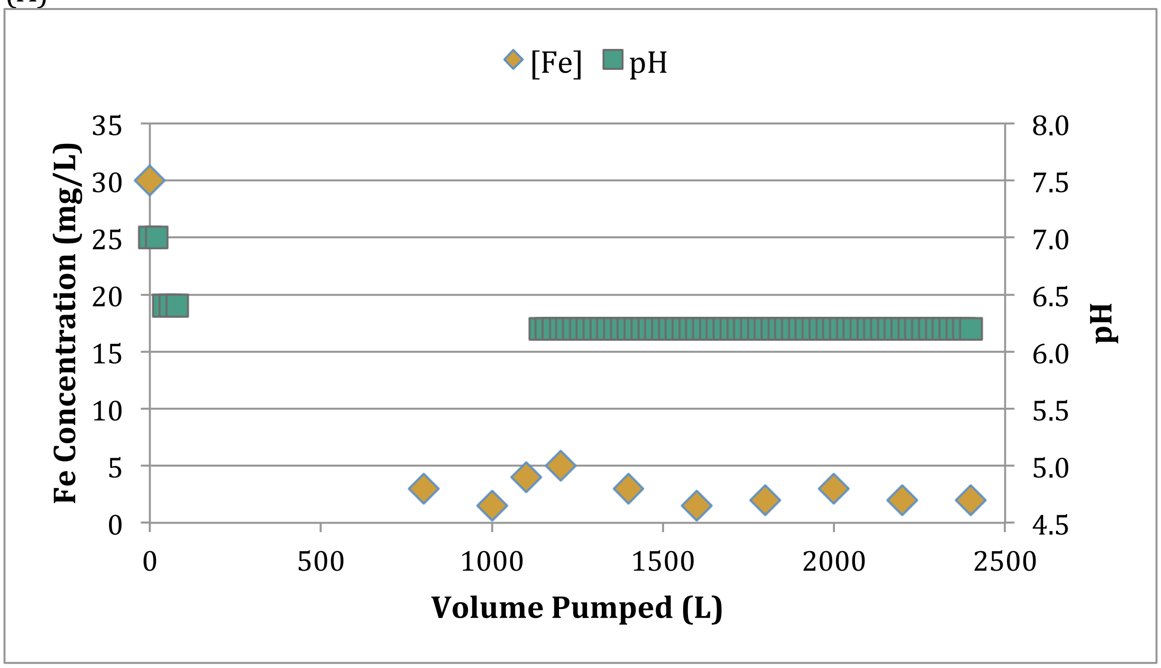


Figure 26. Borehole 16 Test #1 pump test results (A) pH stabilizes at 6.2 and the last iron concentration measurement taken equals 2.33 mg/L. (B) Conductivity and TDS stabilize at 0.17 mS/cm and 128 ppm, respectively.

(A)



(B)

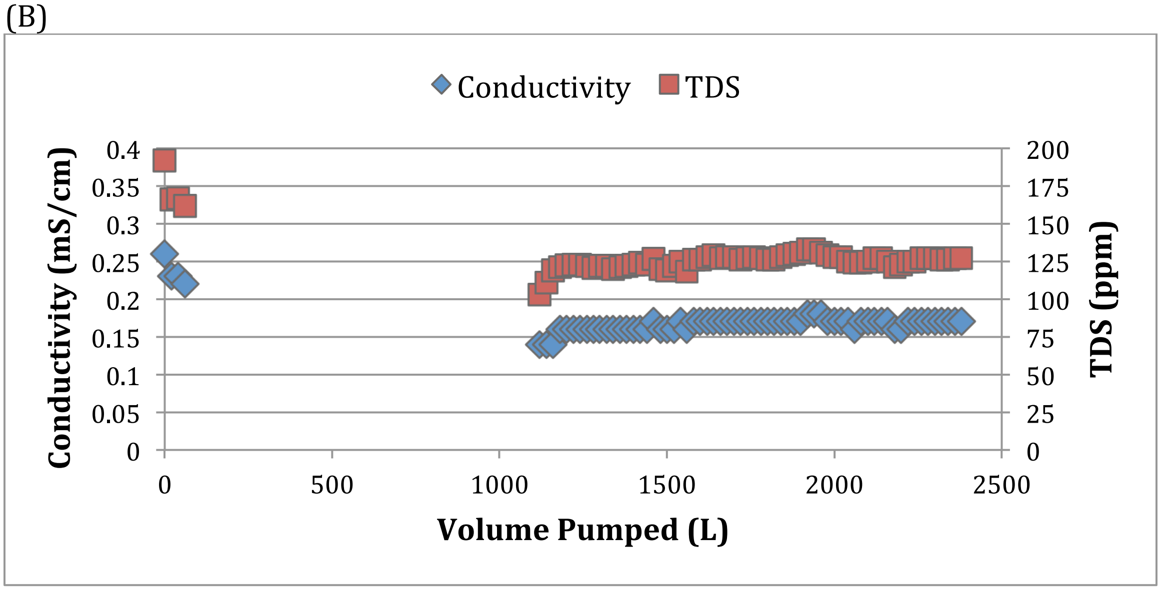


Figure 27. Borehole 16 Test #2 pump test results (A) pH stabilizes at 6.2 and iron concentration stabilizes at 2.0 mg/L. (B) Conductivity and TDS stabilize at 0.17 mS/cm and approximately 127 ppm, respectively.

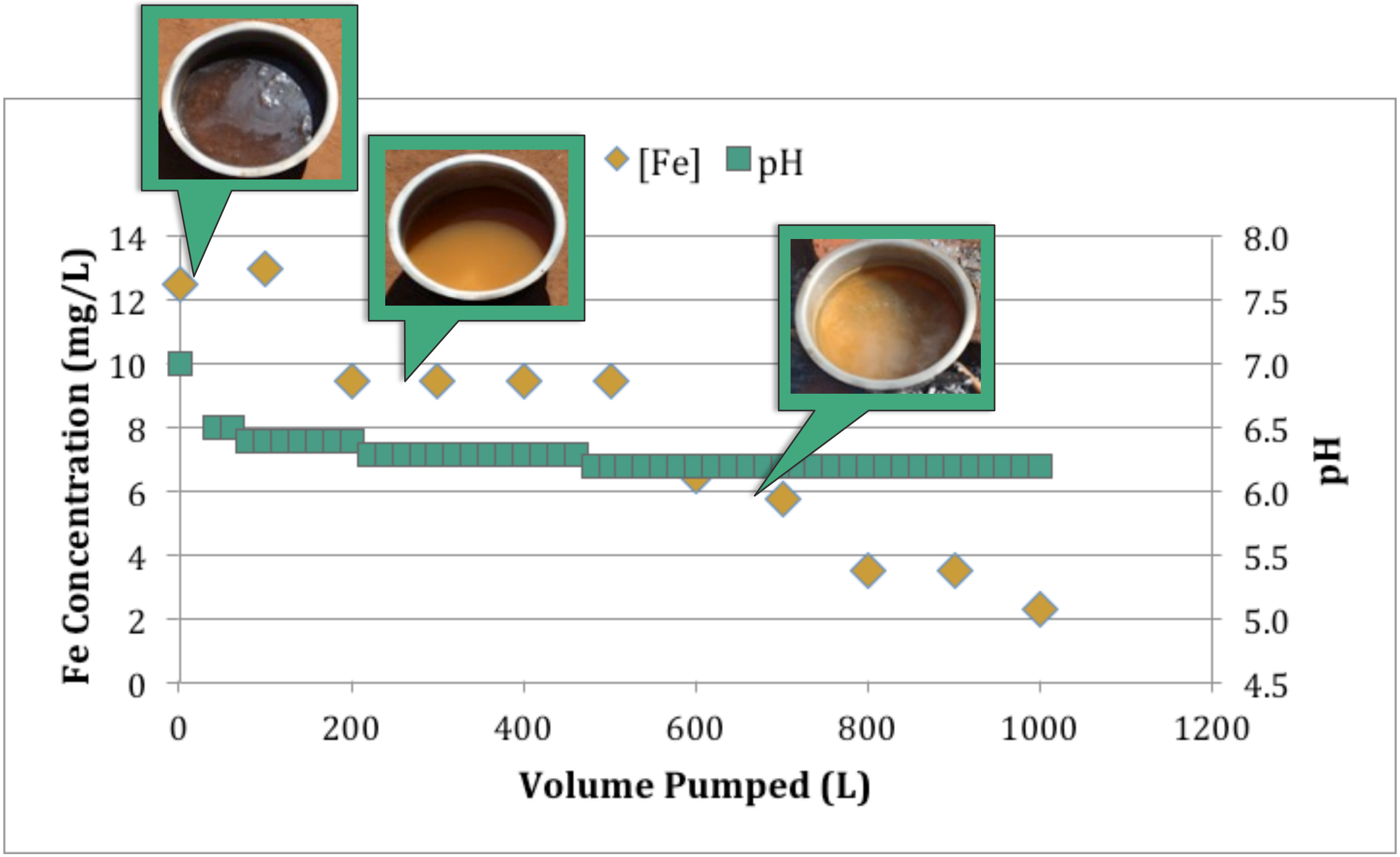


Figure 28. As the iron concentration in the sample decreased the final darkness and cloudiness of the boiled sample lessened. (left to right: 12.5, 9.5, 5.9 mg/L of iron at 0.1, 260, and 680 L pumped)

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research investigated the origins of iron concentration in boreholes, pH measurement methods, and corrosion resistant advances in handpump design. The following conclusions were made.

pH is an important indicator of the aggressivity of groundwater. Three pH test strips were compared to a Hanna probe in order to determine if any of the three could replace the Hanna probe as a reliable, cost-effective option. Statistical analysis using paired t-tests and the Bland-Altman difference method suggests that the MN and Extended Range test strips are statistically acceptable options for measuring pH at boreholes in Northern Uganda. Due to their low cost and ease of use, MN test strips are recommended if accessible.

Results from Pump Tests at boreholes 14 and 16 suggest that much of the iron observed in borehole water pump effluent is from corrosion. A similar conclusion is drawn from Figure 23 that plots iron concentration with respect to the estimated volume of water pumped from the borehole prior to sampling. These data suggest that at boreholes where red or cloudy water has been observed in the morning, it is recommended that the user pump approximately 100 L or 12 minutes before collecting any water that day [18], [19]. This should be repeated daily.

This will help to ensure that most of the iron build-up from overnight is flushed out before collection begins. At the least, the user should understand that iron concentration decreases as pumping volume increases. This method will temporarily address high iron concentrations in boreholes, but further investigation may be necessary to determine if rehabilitation of the pump is necessary.

The district water authority and any other applicable personnel should consider the following parameters when determining whether a borehole should be rehabilitated: iron concentration, pH of groundwater, and electroconductivity [19], [27]. It would be valuable to conduct a WaterAid pump test to better understand the origins of the iron levels [49]. Measuring the pH during this test will also help indicate the corrosivity of the groundwater. If (1) the iron concentration is high at a borehole, (2) the pump test suggests the high iron concentration does not originate from the groundwater, and (3) the water is identified as aggressive based on pH, then the user should consider replacing pump parts with corrosion resistant materials. Electroconductivity predicts the potential for electrochemical or galvanic corrosion [19], and can be an indicator of iron particulate in the water.

5.2 Recommendations to Field Workers

Field workers in the development sector can use the findings from this research to improve their water quality studies and borehole rehabilitation and corrosion prevention efforts. The following items should be noted:

- Literature and this work show a correlation between aggressive groundwater and GI pipe and U2 pump corrosion [18], [19], [27].
- Boreholes will continue to be abandoned unless methods are implemented to reduce iron concentration levels. High iron concentrations become an acceptability issue for user [16], [19].
- pH of groundwater is a good indicator of its corrosivity and the potential for corrosion of well casings, riser pipes, and handpumps [18], [19] .
- Dissolved oxygen, alkalinity, hardness, temperature, TDS, electroconductivity, ammonium [19], calcium, chloride, and sulfate concentrations can give insight into the source of iron in a borehole [6]. If corrosion is the source of the iron, dissolved oxygen can help determine if the Kuch mechanism is a contributor to the iron concentration [22]–[24]. Electroconductivity can help predict electrochemical and galvanic corrosion in handpumps, and ammonium can indicate the presence of iron related bacteria in a borehole [19].
- pH test strips are an inexpensive method for reliably measuring the pH (see *Table 7*). This study found the MN test strips to be in close agreement with the Hanna probe measurements. The Extended Range test strips were also determined to be a statistically acceptable replacement for the Hanna probe.
- Before installing borehole equipment, the pH of the groundwater should be measured. When the aggressivity of groundwater is defined as medium to heavy based on pH [18](*Table 2*), PVC or stainless steel pipes should be used.

Deciding between PVC and SS will depend mostly on technical considerations and the availability of materials and funding for the materials. If possible, follow recommendations made for U3M handpumps, which are specifically designed to be corrosion resistant [17].

- When boreholes are first constructed thorough pump testing should be completed to provide a baseline [37].
- Use pump performance test results and pH measurements to determine if rehabilitation is needed for existing wells. A pump performance test can indicate if there is leaking in the borehole because of severely corroded well components [48]. WaterAid recommends pumping at least one well volume, preferably two, in order to accurately determine the characteristics of the groundwater [49]. If the groundwater is defined as aggressive based on the Langenegger pH Index [18](*Table 2)* then the pipes should be replaced with PVC or SS based on technical considerations and the availability of funds and materials. If possible, follow recommendations made for U3M handpumps, which are specifically designed to be corrosion resistant [17].

5.3 Recommendations for Future Work

Future work focused on understanding the aggressiveness of groundwater in Northern Uganda and on improving borehole and handpump performance should consider adding the following to the methods outlined in this document:

- Repeat the current study for reliability and validity of pH strips for use in Northern Uganda using pH test strips that are readily available in the Gulu area. Identify a local supply chain and the cost of available pH strips.
- Measure dissolved oxygen (DO). Take continuous readings during pump testing after an overnight stagnation period. Use this data to further investigate whether the Kuch Mechanism is a contributing factor to the observed increase of pH in the borehole overnight or during periods of stagnation [22]–[24].
- Measure ammonium concentration to determine if iron related bacteria are a contributor to iron concentrations in the borehole [19].
- Measure alkalinity, hardness temperature, calcium, chloride, and sulfate concentrations to gain further insight into the source of iron in boreholes [6].
- Identify the cost of all pipes available in the Gulu area supply chain and note their composition.

Experiments should be designed so that the same statistical analysis can be conducted using paired t-tests and the Bland-Altman method to determine the most valid, reliable, and cost effective pH test strip.

Further investigation into the composition of the GI pipes that are available in the Gulu area is also recommended. The galvanized layers could be of varying qualities and compositions. Determining the makeup of the material could help explain why the pipes are corroding so quickly.

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APPENDICES

APPENDIX A: Raw Data Collected from 16 Boreholes in Northern Uganda

Table A1. Borehole Data from the Amuru and Gulu Districts of Uganda

BH #	pH				Location			Pump Regime	Iron Conc. (mg/L)	Conductivity (mS)	TDS (ppm)
	Hanna Probe	MN	Extended Range	Youth Waters	Latitude	Longitude	Elevation				
1	6.80	7.00	6.67	6.50	2.8120	32.1876	3710	U2	0.14	---	---
2	5.63	5.17	4.73	5.37	2.8153	32.1856	3708	U2	0.79	---	---
3	5.80	6.00	5.70	5.78	2.9997	32.1415	3372	U2	0.02	0.64	458
4	5.60	5.47	5.07	5.57	2.9990	32.1432	2375	U2	0.10	0.59	424
5	6.10	6.07	6.07	5.87	2.9511	32.1369	3339	U2	0.0625	0.16	119
6	6.00	5.70	5.53	5.70	2.9453	32.1390	3343	U2	0.30	0.12	94
7	7.10	7.00	7.40	6.75	2.894	32.1571	3395	U2	0.25	0.41	303
8	6.20	6.40	6.30	5.97	2.8833	32.1599	3405	U2	0.50	0.12	95
9	6.20	6.33	6.33	5.67	2.8407	32.1924	3448	U2	1.50	0.22	161
10	6.50	6.67	6.33	6.08	2.8524	32.1946	3490	U2	20	0.20	152
11	6.20	6.58	6.17	6.08	2.8025	32.1915	3608	U2	0.075	0.13	103
12	6.30	6.67	6.17	5.75	2.7941	32.1968	3615	U2	0	0.13	97
13	5.80	6.00	5.17	5.50	2.7676	32.2349	3595	U2	0.75	0.09	69
14	6.30	6.17	6.27	6.25	2.8655	32.2995	3412	U2M	3.4	0.23	174
15	---	---	---	---	2.8582	32.2979	3398	U2	---	---	---
16	6.80	6.50	6.80	6.73	2.8629	32.3053	3392	U2	20	0.30	218

APPENDIX A (continued):

Table A2. Qualitative Data Collected from Boreholes in the Amuru and Gulu Districts

BH #	Date (2014)	Time	Qualitative Information
1	June 2	15:00	Community + primary school use. Poor drainage because of grade change due to road construction.
2	June 3	11:00	Borehole owned and used by secondary school only. Drainage was lacking at end of key drain. Needs a rock-filled drainage pit
3	June 4	11:10	Interviewed Christine: In a.m., water is red, after pumping becomes clear and stays clear for the day. Worse in rainy season. Pumped ~ 100 jerry cans of so far today. This borehole reported to have harder water than others nearby. (described as how easy soap suds)
4	June 4	11:38	Rehabilitated 2005; built 1940's or 50's; had windmill originally. BH GS 1459 - identification on cement borehole. No top plate on pump. Interview: morning water is brown. ~140 jerry cans filled prior to testing. Probably steel casing.
5	June 4	11:56	Jengari Church. Interview: ~ 40 jerry cans pumped today prior to testing. Soak pit available (bricked), but needs to be retrenched. Water brown in a.m. Easy to soap/rinse. Poor drainage. Drain is short and water drains back to base of platform. Possible contamination of water source
6	June 4	12:16	Soak pit could be better. Water not quite coming back to base from pit. Rehab by WanAinKi on 4/8/2011. Brown in a.m. 50 - 60 jerry cans filled prior to sampling. Lathering soap is difficult. ~6 months since last repair - replace pipes?
7	June 4	12:37	Using run off for irrigation. Platform cracked; potential for contamination. Interview with Christine: Repaired last year. ~50 jerry cans filled before sampling. Water brown in a.m., then clear.
8	June 4	13:00	Rehabbed 5/4/2012. Think this is an old borehole and might have a metal casing. ~50 jerry cans pumped prior to testing. Water red in a.m.
9	June 5	12:10	Drilled in 2011. No repairs since drilling. ~10 jerry cans before sampling. Interview comments; rust flakes in water.

APPENDIX A (continued):

Table A2. -continued

10	June 5	12:43	17 pipes, ~170 ft of pipe. Yellow/red water. Used for washing only. 5-6 jerry cans filled prior to sampling. Family drinking water from a nearby spring. Long, deephandle on pump. Very deep. U2 extra deep well pump. Owner wants to use plastic pipe, but it is too deep. Iron sample diluted with bottled drinking water.
11	June 5	14:54	Reddish color in a.m., then clear. Using for all purposes. More than 100 jerry cans prior to sampling. Pump moves while being pumped; may cause backflow and possible contamination from leaking. Assuming this is an old borehole.
12	June 5	15:10	>50 jerry cans today prior to testing. Across from Restore School. Handle has been fixed by welding. Repair maybe ~3 months ago.
13	June 5	15:47	No color. Only pump in area. "Milton" interview- he has started primary school in this location. ~100 jerry cans today prior to sampling. UNICEF installed-drilled. Drilled July 23, 2011.
14	June 11	13:00	Polycarp drilled. 15 m of pipe.
15	June 11	12:50	Abandoned and not in use.
16	June 11	12:00	16 pipes were installed originally. 14 pipes remain. (33m of pipe) Drilled by World Vision March 14, 2011. From interview: water becomes yellow after sitting in jerry can for approximately 6 hrs. More than 10 jerry cans filled prior to sampling. 90 households get water in pm. Color in water in a.m. Many prefer unprotected spring for water source.

APPENDIX B: WaterAid Pump Testing Method to Determine Iron Origin

Water quality testing to establish whether high iron originates from corrosion of pump components or the aquifer

The Problem:

(1) Production of a red/brown coloured discharge first thing in the morning. This is caused by the discharge of corrosion products that have accumulated in the well during the night when there was no pumping. In most cases, the discharge clears up as the solid corrosion products are removed from the well.

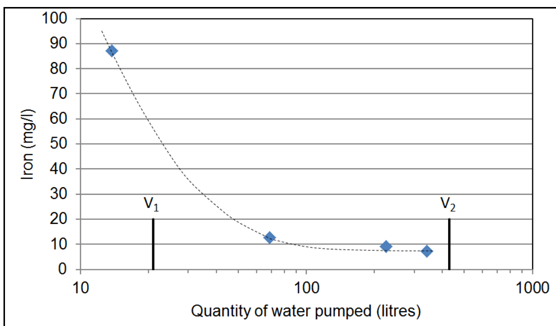
(2) Discolouration of water which was clear when pumped, but develops a red/brown discolouration after a few minutes to hours. This is the result of the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which causes the precipitation of iron hydroxides and oxides. This could be caused by either naturally high ferrous iron in the aquifer, or the addition of iron to the well water from corrosion of handpump components.

Some wells may produce a red coloured discharge that does not clear after several hours of pumping. This does not necessarily indicate a problem with high iron, rather it is likely to be caused by poor well development, a badly positioned screen, or poor quality gravel pack, resulting in entry of fine clay or silt particles from the aquifer into the well. The well is likely to be unacceptable in this condition and requires further development to ensure clear water is produced.

Test for origin of iron:

To identify if corrosion of pump components is the cause of high iron concentrations, a simple pumping test can be carried out with periodic measurements of iron content. If iron concentrations fall rapidly after a few minutes (see graph below), corrosion is likely to be the major source of iron. The objective of the pumping is to replace the well water with fresh water from the aquifer so that iron concentrations are representative of the aquifer water.

The test should be undertaken first thing in the morning, before any pumping has taken place.



Example from a test on a non-corrosion resistant pump, West Africa (after *Langenegger, 1994*) :

Total iron concentration vs quantity pumped.

V_1 = volume of rising main

V_2 = volume of well

Most of the solid corrosion products will be removed once the water within the rising main has been removed, volume V_1 on the graph.

This method was commissioned by WaterAid and prepared by Lawrence Brown.
Lawrence.Brown@hafrenwater.com 28/07/13

APPENDIX B (continued):

WaterAid

Calculate volume of rising main (V_1) using: 3.1415 x r^2 x h x 1000 litres
Where: h = (RM) – (WL) and r = d/0.5
• Length of rising main, RM (m) — From pump installers report • Depth of water table, WL (m) — From drillers report, or borehole dip before the test • Diameter of rising main, d (m) — Take as 0.05 m (2 inches)

The length of test depends on the well volume, as you should aim to pump at least 1 well volume (point V_2 on the graph), but preferably 2 well volumes, to ensure fresh aquifer water has started to enter the well.

Details of the borehole construction required to calculate the well volume will be contained in the drilling report. Borehole and casing diameters are usually recorded in millimetres and must be converted to metres for the calculations. It is suggested that all the calculations are undertaken in the office prior to the test.

Calculate the total volume of water in the well (V_2):

Boreholes are usually drilled at several diameters and these need to be taken into account when calculating the well volume.

Volume = 3.1415 x r^2 x h x 1000 litres

Volume in casing 1:

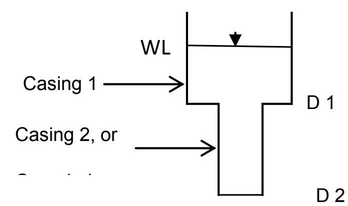
h = Depth to base of casing 1 (D1) - WL

r = Casing 1 diameter ÷ 0.5

Volume in casing 2:

h = Depth to casing 2 (D2) - D 1

r = Casing 2/borehole diameter ÷ 0.5



Add the calculated volumes to get the total well volume

Either measure pumping rate or assume 12 - 18 litres/minute (India MKII)

Minimum pumping time (V_2) = well volume (litres) ÷ pumping rate (litres/minute)

Recommended pumping time 2 well volumes.

Concentrations of iron can be measured with the Wagtech Comparator and the requisite reagents. It is important to note that a highly coloured or turbid sample is likely to give incorrect results.

Samples should be tested immediately after they have been taken as dissolved iron may begin to precipitate giving inaccurate results for the true iron content.

If possible, pH and electrical conductivity (EC) should be measured at the same time.

As more water is pumped from the well, smaller and smaller changes in iron concentration will be observed (See graph) and the time between sample testing can be increased

For each sample, record:	Sampling frequency:
• Time of sampling (since start of pumping) • Volume abstracted - calculated (litres) • Iron concentration (mg/l) (also pH and EC)	• Up to 6 samples • 1st sample at or just after V_1 • 4th sample at V_2 • Further samples up to 2 well volumes

This method was commissioned by WaterAid and prepared by Lawrence Brown.
Lawrence.Brown@hafrenwater.com 28/07/13

APPENDIX C: Raw Data from WaterAid Pump Testing

Table C1. Pump Testing Results from Borehole 14

started pumping at 12:24 pm; this is t = 0

pump had been used prior to starting pump test. Unknown how much water had been pumped prior to test starting

Time	Pump Rate	Volume Pumped	Iron Conc	Hanna Probe	Conductivity	TDS
	L/min	L	mg/L	pH	mS	ppm
12:24		0.1	10	6.3	0.22	164
12:26	9.95	20	8	6.4	0.22	159
12:29	6.67	40		6.3	0.18	134
12:31	10.00	60	5	6.3	0.17	129
12:33:30	8.00	80	3	6.3	0.17	128
12:36	8.00	100	2	6.2	0.17	125
12:39	6.67	120	2	6.2	0.16	121
12:41:30	8.00	140		6.1	0.16	118
12:44	8.00	160	2	6.1	0.15	116
12:46:30	8.00	180		6.1	0.15	115
12:49:30	6.67	200	0.5	6.1	0.15	114
12:52	8.00	220		6.2	0.15	115
12:54:30	8.00	240	1	6.2	0.15	114
12:57	8.00	260		6.1	0.15	115
12:59	10.00	280	1	6.1	0.15	113
13:01:30	8.00	300		6.1	0.15	113
13:04	8.00	320	1	6.1	0.15	114
average Pump Rate	8.12					
st.dev	1.03					

APPENDIX C (continued):

Table C2. Pump Test 1 Results from Borehole 16

water turns red/black when boiled
started pumping at 2:15 pm; this is t = 0
This pump had not been used prior to starting this pump test.
Pump handle was chained by owner.
boiled water pictures for these volumes

Time	Volume Pumped	Pumping Rate	Iron Conc.	Hanna Probe	Conductivity	TDS
	(L)	(L/min)	(mg/L)	(pH)	(mS)	(ppm)
14:15:00	0.1		12.5	7	0.19	143
14:17:00	20	9.95				
14:19:00	40	10.00		6.5	0.25	181
14:21:00	60	10.00		6.5	0.24	175
14:23:00	80	10.00		6.4	0.23	170
14:25:00	100	10.00	13	6.4	0.22	165
14:27:00	120	10.00		6.4	0.22	160
14:29:00	140	10.00		6.4	0.22	159
14:31:00	160	10.00		6.4	0.22	162
14:33:00	180	10.00		6.4	0.22	161
14:35:00	200	10.00	9.5	6.4	0.21	155
14:37:00	220	10.00		6.3	0.2	149
14:40:00	240	6.67		6.3	0.2	148
14:43:00	260	6.67		6.3	0.2	150
14:45:00	280	10.00		6.3	0.2	151
14:47:00	300	10.00	9.5	6.3	0.2	148
14:49:00	320	10.00		6.3	0.19	142
14:51:00	340	10.00		6.3	0.19	139
14:54:00	360	6.67		6.3	0.18	138
14:56:00	380	10.00		6.3	0.19	139
14:59:00	400	6.67	9.5	6.3	0.19	142
15:01:00	420	10.00		6.3	0.19	141
15:04:00	440	6.67		6.3	0.19	139
15:06:00	460	10.00		6.3	0.18	137
15:08:00	480	10.00		6.2	0.18	132
15:10:00	500	10.00	9.5	6.2	0.18	132

APPENDIX C (continued):

Table C2. -continued

15:12:00	520	10.00		6.2	0.18	132
15:13:30	540	13.33		6.2	0.18	131
15:16:00	560	8.00		6.2	0.18	133
15:18:00	580	10.00		6.2	0.18	133
15:20:00	600	10.00	6.5	6.2	0.17	130
15:22:00	620	10.00		6.2	0.17	130
15:24:30	640	8.00		6.2	0.17	130
15:26:00	660	13.33		6.2	0.17	129
15:28:00	680	10.00		6.2	0.17	130
15:30:30	700	8.00	5.75	6.2	0.17	130
15:32:30	720	10.00		6.2	0.17	130
15:34:30	740	10.00		6.2	0.17	129
15:36:30	760	10.00		6.2	0.17	129
15:39:00	780	8.00		6.2	0.17	129
15:41:30	800	8.00	3.5	6.2	0.17	129
15:43:30	820	10.00		6.2	0.17	129
15:45:30	840	10.00		6.2	0.17	129
15:48:00	860	8.00		6.2	0.17	128
15:50:00	880	10.00		6.2	0.17	128
15:52:30	900	8.00	3.5	6.2	0.17	128
15:55:00	920	8.00		6.2	0.17	128
15:57:00	940	10.00		6.2	0.17	129
15:59:00	960	10.00		6.2	0.17	129
16:02:00	980	6.67		6.2	0.17	128
16:04:00	1000	10.00	2.33	6.2	0.17	128

Average Pump Rate	9.41	L/min
st.dev.	1.44	

APPENDIX C (continued):

Table C3. Pump Test 2 Results from Borehole 16

Time	Volume Pumped	Pumping Rate	Iron Conc.	Hanna Probe	Conductivity	TDS
	(L)	(L/min)	(mg/L)	(pH)		(ppm)
11:39:00	0.1		30	7	0.26	191
11:41:00	20	10.0		7	0.26	192
11:42:00	40	20.0		6.4	0.23	166
11:43:00	60	20.0		6.4	0.23	167
11:44:00	80	20.0		6.4	0.22	162
11:46:00	100	10.0				
11:48:00	120	10.0				
11:50:00	140	10.0				
11:52:00	160	10.0				
11:55:00	180	6.7				
11:57:00	200	10.0				
11:59:00	220	10.0				
12:01:00	240	10.0				
12:03:00	260	10.0				
12:05:00	280	10.0				
12:07:00	300	10.0				
12:09:00	320	10.0				
12:11:00	340	10.0				
12:13:00	360	10.0				
12:15:00	380	10.0				
12:16:00	400	20.0				
12:18:00	420	10.0				
12:20:00	440	10.0				
12:22:00	460	10.0				
12:25:00	480	6.7				
12:27:00	500	10.0				
12:29:00	520	10.0				
12:31:00	540	10.0				
12:32:00	560	20.0				
12:34:00	580	10.0				
12:35:00	600	20.0				
12:37:00	620	10.0				
12:39:00	640	10.0				
12:41:00	660	10.0				
12:44:00	680	6.7				
12:46:00	700	10.0				
12:47:00	720	20.0				
12:49:00	740	10.0				
12:51:00	760	10.0				

APPENDIX C (continued):

Table C3.- continued

Time	Volume Pumped	Pumping Rate	Iron Conc.	Hanna Probe	Conductivity	TDS
	(L)	(L/min)	(mg/L)	(pH)		(ppm)
12:52:00	780	20.0				
12:54:00	800	10.0	3			
12:56:00	820	10.0				
12:58:00	840	10.0				
13:00:00	860	10.0				
13:02:00	880	10.0				
13:04:00	900	10.0				
13:05:00	920	20.0				
13:07:00	940	10.0				
13:09:00	960	10.0				
13:11:00	980	10.0				
13:13:00	1000	10.0	1.5			
13:15:00	1020	10.0				
13:17:00	1040	10.0				
13:20:00	1060	6.7				
13:22:00	1080	10.0				
13:24:00	1100	10.0	4			
13:26:00	1120	10.0				
13:28:00	1140	10.0		6.2	0.14	103
13:33:00	1160	4.0		6.2	0.14	111
13:35:00	1180	10.0		6.2	0.14	119
13:37:00	1200	10.0	5	6.2	0.16	121
13:38:30	1220	13.3		6.2	0.16	122.5
13:40:00	1240	13.3		6.2	0.16	123
13:42:00	1260	10.0		6.2	0.16	123
13:43:30	1280	13.3		6.2	0.16	122
13:45:00	1300	13.3		6.2	0.16	120.5
13:46:30	1320	13.3		6.2	0.16	122
13:48:00	1340	13.3		6.2	0.16	122
13:50:00	1360	10.0		6.2	0.16	120
13:52:00	1380	10.0		6.2	0.16	121
13:54:00	1400	10.0	3	6.2	0.16	122
13:55:30	1420	13.3		6.2	0.16	123
13:57:30	1440	10.0		6.2	0.16	124
13:59:00	1460	13.3		6.2	0.16	123
14:00:30	1480	13.3		6.2	0.17	126.5
14:02:00	1500	13.3		6.2	0.16	120
14:04:00	1520	10.0		6.2	0.16	119

APPENDIX C (continued):

Table C3. - continued

Time	Volume Pumped (L)	Pumping Rate (L/min)	Iron Conc. (mg/L)	Hanna Probe (pH)	Conductivity	TDS (ppm)
14:06:00	1540	10.0		6.2	0.16	122
14:07:30	1560	13.3		6.2	0.17	125
14:09:00	1580	13.3		6.2	0.16	118
14:11:00	1600	10.0	1.5	6.2	0.17	126
14:13:00	1620	10.0		6.2	0.17	126
14:15:00	1640	10.0		6.2	0.17	128
14:17:00	1660	10.0		6.2	0.17	129
14:18:30	1680	13.3		6.2	0.17	127
14:20:30	1700	10.0		6.2	0.17	128
14:22:30	1720	10.0		6.2	0.17	128
14:24:30	1740	10.0		6.2	0.17	126
14:26:00	1760	13.3		6.2	0.17	127
14:27:30	1780	13.3		6.2	0.17	128
14:28:30	1800	20.0	2	6.2	0.17	127
14:30:00	1820	13.3		6.2	0.17	126
14:33:30	1840	5.7		6.2	0.17	126
14:35:00	1860	13.3		6.2	0.17	128
14:37:00	1880	10.0		6.2	0.17	129
14:38:30	1900	13.3		6.2	0.17	130
14:41:00	1920	8.0		6.2	0.17	131
14:43:00	1940	10.0		6.2	0.18	133
14:45:00	1960	10.0		6.2	0.18	133
14:47:00	1980	10.0		6.2	0.18	131
14:49:00	2000	10.0	3	6.2	0.17	129
14:51:00	2020	10.0		6.2	0.17	128
14:52:30	2040	13.3		6.2	0.17	128
14:54:30	2060	10.0		6.2	0.17	125
14:56:30	2080	10.0		6.2	0.16	124
14:58:00	2100	13.3		6.2	0.17	124
15:00:00	2120	10.0		6.2	0.17	125
15:01:30	2140	13.3		6.2	0.17	127
15:02:30	2160	20.0		6.2	0.17	127
15:05:00	2180	8.0		6.2	0.17	125
15:07:00	2200	10.0	2	6.2	0.16	121
15:08:30	2220	13.3		6.2	0.16	123
15:10:00	2240	13.3		6.2	0.17	125
15:12:00	2260	10.0		6.2	0.17	125
15:14:00	2280	10.0		6.2	0.17	127

APPENDIX C (continued):

Table C3. - continued

Time	Volume Pumped	Pumping Rate	Iron Conc.	Hanna Probe	Conductivity	TDS
	(L)	(L/min)	(mg/L)	(pH)		(ppm)
15:16:00	2300	10.0		6.2	0.17	127
15:17:30	2320	13.3		6.2	0.17	127
15:19:00	2340	13.3		6.2	0.17	126
15:21:00	2360	10.0		6.2	0.17	126
15:23:00	2380	10.0		6.2	0.17	127
15:25:00	2400	10.0	2	6.2	0.17	127

average pump rate:	11.4	L/min
st.dev:	3.24	L/min

APPENDIX D: Paired t-Test Data

Table D1. Paired t-test comparing pH of MN pH test strips and Hanna probe

pH				
VAR	*Sample size*	*Mean*	*StDev*	*SE Mean*
Hanna probe	15	6.222	0.438	0.113
MN	15	6.248	0.530	0.137
Difference	15	-0.0256	0.2566	0.0662
Summary				
Degrees Of Freedom	14	*Hypothesized Mean Difference*		0.0000E+0
Test Statistics	-0.39	*95% CI for Mean Difference*		(-0.1676, 0.1165)
Two-tailed distribution				
p-level	0.705	*t Critical Value (5%)*		2.145

Table D2. Paired t-test comparing pH of Extended Range pH test strips and Hanna probe

pH				
VAR	*Sample size*	*Mean*	*StDev*	*SE Mean*
Hanna probe	15	6.222	0.438	0.113
Extended Range	15	6.047	0.704	0.182
Difference	15	0.1756	0.3213	0.0830
Summary				
Degrees Of Freedom	14	*Hypothesized Mean Difference*		0.0000E+0
Test Statistics	2.12	*95% CI for Mean Difference*		(-0.0024, 0.3535)
Two-tailed distribution				
p-level	0.053	*t Critical Value (5%)*		2.145

APPENDIX D (continued):

Table D3. Paired t-test comparing pH of Youth Waters pH test strips and Hanna probe

pH				
VAR	*Sample size*	*Mean*	*StDev*	*SE Mean*
Hanna probe	15	6.222	0.438	0.113
Youth Waters	15	5.971	0.429	0.111
Difference	15	0.2511	0.1710	0.0441
Summary				
Degrees Of Freedom	14	*Hypothesized Mean Difference*		0.0000E+0
Test Statistics	5.69	*95% CI for Mean Difference*		(0.1564, 0.3458)
Two-tailed distribution				
p-level	0.000	*t Critical Value (5%)*		2.145