May 2014

An Assessment of the EMAS Pump and its Potential for Use in Household Water Systems in Uganda

Jacob Daniel Carpenter
University of South Florida, jcarpenter@mail.usf.edu

Scholar Commons Citation

Carpenter, Jacob Daniel, "An Assessment of the EMAS Pump and its Potential for Use in Household Water Systems in Uganda" (2014). *Graduate Theses and Dissertations.*
http://scholarcommons.usf.edu/etd/4996

An Assessment of the EMAS Pump and its Potential for Use in Household Water Systems in Uganda

by

Jacob D. Carpenter

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

Major Professor: James R. Mihelcic, Ph.D.
Laura W. Lackey, Ph.D.
Kenneth E. Trout, Ph.D.

Date of Approval:
March 17, 2014

Keywords: handpump, Self-supply, sub-Saharan Africa, groundwater, Rope Pump, Millennium Development Goals

DEDICATION

To SCC, a beloved friend and a true inspiration

ACKNOWLEDGMENTS

I would like to thank the people of Uganda for the generous hospitality and friendship offered to me during my thirty months in their wonderful country. Specific appreciation is due to the North Kigezi Diocese (Church of Uganda) and NKKD WATSAN for hosting me during my two years of Peace Corps Service and to Peace Corps Uganda administration and staff for supporting me in so many ways.

I would also like to thank my thesis committee: Jim Mihelcic for giving me the opportunity to be a part of the Masters International Program and for his support and friendship over the past few years; Laura Lackey for her support, encouragement, and many years as a valuable mentor and friend; and Ken Trout, for sharing his groundwater expertise and showing a keen interest in this work from its humble beginnings at the USF GeoPark. Sincere thanks go also to Michael F. MacCarthy, the catalyst for my interest in the topic who has served as both a guide and a partner in this research; and to Patrick Woodson and Dustin Bales, who were instrumental in the completion of field work associated with this study.

Appreciation is also due to many stakeholders in Uganda who supported my work and/or shared their expertise with me: Dr. Callist Tindigumaya, Eng. Moses Enangu, and Joel Kiwanuka of MWE, Paul Kimera of the MWE Appropriate Technology Centre, John Stiefel of World Vision, Sean Granville-Ross and Melaku Yirga of Mercy Corps. Sincere appreciation is also due to Andre Olschewski, Sean Furey, and Dr. Kerstin Danert (all of SKAT), Jon Naugle (Enterprise Works / Relief International), Robert Vuik (PRACTICA), and Dr. Bob Yoder (IDE),

and others not listed for their insights, sharing of resources, and generous guidance. A very special thanks is due to “Mr. Rope Pump” Henk Holtslag, for his vital support, generous mentoring, and inspiring passion.

Finally, I would like to thank Rev. Eric Kamuteera of Rukungiri, Uganda for his treasured friendship, my family for their unwavering love and support, and to Candace Girod for being the extraordinary woman that she is.

This material is based upon work supported by the National Science Foundation under Grant No. DUE 0965743. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Rural improved water supply coverage in Uganda has stagnated around 64% for a number of years and at this point more than 10 million rural people do not have access to an improved drinking water source. It has been recognized that progress toward improved water supply coverage and increased service levels may be gained through Government and nongovernmental organization (NGO) support of private investment in household and shared water supplies, commonly known as Self-supply. Self-supply can be promoted by introducing and building local capacity in appropriate and affordable water supply technologies such as hand-dug wells, manually drilled boreholes, low-cost pumps, and rainwater harvesting. Support can also be focused on technical support, marketing, financing, and strategic subsidies that promote and enhance user investment. The Uganda Ministry of Water and Environment has embraced Self-supply as a complementary part of its water supply strategy while government and NGO programs that support Self-supply have emerged.

The EMAS Pump is a low-cost handpump appropriate for use in household water systems in the developing world. There are more than 20,000 in use in Bolivia, with many constructed through Self-supply. The EMAS Pump is constructed from simple materials costing about $US 10-30, depending largely on installation depth, and can be fabricated with simple tools in areas with no electricity. The EMAS Pump is used with low-cost groundwater sources such as hand-dug wells and manually drilled boreholes or with underground rainwater storage tanks. It can lift water from 30 m or more below ground and pump water with pressure overland or to an elevated tank. The objectives of this research were to conduct an assessment of the EMAS Pump that considers pumping rates, required energy, and associated costs, to characterize the EMAS Pump for its potential for use in household water systems in Uganda, and to make relevant recommendations.

The potential of the EMAS Pump was assessed through testing its use with 2 subject participants (male and female) on wells of 5.1 m, 12.6 m, 17.0 m, 18.4 m, 21.1 m, and 28.3 m static water levels as part of a side-by-side comparative assessment with the Family Model version of the Rope Pump, a more widely known low-cost handpump that has recently been introduced and promoted in Uganda. Shallow and deep versions of each pump were tested for 40-liter pumping trials. The selections of pumps for testing were based on the Rope Pumps currently promoted in Uganda and comparable EMAS Pumps. There are other variations of each pump that did not undergo testing, including the high-flow Rope Pump that is promoted elsewhere for depths of less than 10 m. The status and feasibility of low-cost groundwater development and underground storage tanks were also explored in order to help characterize the potential of the EMAS Pump as an option for low-cost household water systems in Uganda.

In the results of the pumping tests, it was generally observed that the EMAS Pump performed comparably to the corresponding Rope Pump in terms of pumping rates for shallow depths, but the Rope Pump outperformed it on deeper wells. The EMAS Pump required more energy for pumping during nearly all testing trials. A study of relevant supply chains in Uganda concluded that the EMAS Pumps tested have a material cost that is less than 50% of the comparable Rope Pump for most applications and 21% of the cost for shallow wells. It was also determined that the EMAS Pump could feasibly be produced nearly anywhere in the country. There are indications that low-cost wells and underground rainwater tanks are applicable in

many parts of Uganda and could be paired with an EMAS Pump to achieve significant affordability for Self-supply household water systems. Recommendations are provided in terms of the feasibility of introducing the EMAS Pump as a part of Self-supply strategies in Uganda.

CHAPTER 1: INTRODUCTION

1.1 Water Supply and sub-Saharan Africa

> *"The survival and well-being of humans are primarily related to their access to water resources, both in meeting their basic biological needs and as the major driver for socio- economic development."*[1]

The vital role of water supply in human health and economic development has been established by an ample body of literature spanning the fields of medicine, public health, anthropology, agronomy, economics, and others. Worldwide, there are great disparities in access to water supply. The United Nation's Millennium Development Goals includes MDG 7 Target c, which aims "*to reduce by half the proportion of people* [from the 1990 baseline] *without sustainable access to safe drinking water and basic sanitation by 2015*". Through the linkages between water supply, sanitation, health, well-being, and socio-economic development, MDG 7 has specific relevance to other MDGs including those relating to poverty (MDG 1), education (MDG 2), and the reduction of child mortality (MDG 4).

The Joint Monitoring Programme (JMP, http://www.wssinfo.org/introduction/) compiles water supply and sanitation data used to assess MDG Target 7c and has provided great detail of the progress of the past two decades in regular reports. Globally, the water aspect of the MDG 7c target has already been met, with the JMP reporting that 2.1 billion people have gained access to improved water since 1990. The most current estimate indicates that 12% of people (768

---

[1] Bocanegra, E., Hernandez, M., & Usunoff, E. (2005). *Groundwater and Human Development: International Association of Hydrogeologists Selected Papers on Hydrogeology Volume 6*. (E. M. Bocanegra, M. A. Hernandez, & E. Usunoff, Eds.). Leiden, The Netherlands: A.A. Balkema Publishers.

million) worldwide still lack reasonable access to an improved water source. Of these without access, more than 300 million live in sub-Saharan Africa and 80% live in rural areas (JMP, 2012). Billions of dollars of investment into the water supplies in the region has realized significant gains and increases in the proportion of people with access to improved water supply, however, the Joint Monitoring Progamme indicates that *the absolute number of people lacking access in sub-Saharan Africa has actually increased by 24% over the timeframe of the MDGs*. Rapid population growth, characteristic of most countries in the region, is often cited as a significant factor in this trend. Regardless of the reason, the increasing number of people unserved by improved water supplies lends itself to the argument that, despite progress worldwide, the water crisis in sub-Saharan Africa is actually becoming worse.

1.2 Water Supply and Human Health

The link between sufficient water supply and human health has been thoroughly established in literature. Beyond the rather obvious need of small amounts for drinking, water is essential to human health through its use for cooking, cleaning, sanitation and hygiene purposes (Esrey et al., 1985). Water used for these health-related purposes is typically described as domestic water use. The *quality* and the *quantity* of available water are fundamentally important factors of water supply that influence human health in different, but equally important ways (Howard & Bartram, 2003; Hunter et al., 2010). Poor drinking water *quality* and lack of sufficient water *quantity* for proper sanitation and hygiene are substantial risk factors in acute infectious diarrhea, which is the second biggest contributor to the disease burden and is estimated to cause 17% of child mortality in less-developed countries (Fewtrell et al., 2005; Clasen et al., 2006). Water supply is also a risk factor in the spread of many parasites and non-diarrheal diseases that can have significant negative health impacts. The availability of sanitation facilities and the behavioral practice of good hygiene are also very important risk factors in regard to human health and are related to water supply, though not addressed in this work.

1.3 Water Supply and Poverty

While the issue of health is the primary focus of much dialogue on the water crisis, linkages between water supply and poverty have been increasingly recognized. For example, the 2003 UNESCO World Water Development Report noted that "the poverty of a large percentage of the world's populations is both a symptom and a cause of the water crisis." Issues such as the productive use of water, the opportunity cost of time spent collecting water, and the relative cost of water are just a few of the linkages between water and poverty.

Many rural and peri-urban people require water for a wide range of other purposes such as livestock watering, small-scale irrigation, post-harvest processing, or other productive uses. In many cases, water requirements for productive uses far exceed those for domestic purposes. In aggregate, water used for agricultural purposes comprises more than 80% of water withdrawal in sub-Saharan Africa (UNESCO, 2012), though this includes large centralized irrigation schemes or large privately-owned farms. While water requirements for domestic needs are cited to be 20 – 50 liters per person per day, it has been indicated that quantities necessary for "at least some" productive use are between 50 and 150 liters per person per day (Moriarty et al., 2004). Since productive uses of water require these larger quantities of water, the ease and convenience with which water can be accessed is a very important factor.

1.4 Background and Classification of Water Supplies

Water supplies can be classified by such factors as the type of source, number and characteristics of users served, use(s) of the water, type of management, level of technology, source of capital for construction, and others. Differentiation of these characteristics is important to the classification of water supplies, their uses, and the populations they serve.

1.4.1 Water Supply Sources

The types of water sources and technologies available for water supply development have always been an important factor in human development patterns and continue to play a major role in the health and livelihoods of populations today. The three main sources of fresh water supply are surface water, groundwater, and captured rainwater. Each of these sources has relative advantages and disadvantages. Groundwater and rainwater are most relevant to this work.

Surface water can be found in large quantities in most places and utilized relatively easily due to its highly accessible nature. Surface water availability was a key aspect of all early human civilizations and for early productive water uses; simple irrigation by diversion of surface water and gravity flow is thought to have emerged relatively quickly after farming itself (Fagan, 2011). Surface water remains a primary source for millions of people in rural areas of low-income countries as well as a major source (after treatment) for urban populations in small and large cities around the world. The main drawbacks of surface water are that it is not available everywhere and it is vulnerable to natural and manmade pollutants, so generally requires some form of treatment to be made safe for human consumption.

Rainwater harvesting consists of capturing and storing rainwater directly from precipitation and has been dated as far back as 3000 BC in India, the Mediterranean, and the Middle East (Smet, 2003). Rainwater harvesting is constrained by the rainfall patterns of an area as well as the availability of materials needed for the collection and storage of rainwater. It has been noted that necessary conditions, such as the availability of “hard” roofing like corrugated iron, guttering and piping for conveyance, and sufficiently sized storage options are increasing in Africa (Thomas, 2006). When practiced at the household level, rainwater harvesting can provide significant convenience due to the fact that water is then available at the point of use, which entails benefits associated with increased water usage. Still, across the world, only 5% of the population practices any form of rainwater harvesting (Danert & Motts, 2009) though this statistic likely ignores “informal” rainwater harvesting where small amounts of water are collected from roofs in buckets and cooking pots during rain events.

While surface water has been used throughout human history, groundwater exploitation began to take place as human populations transitioned from primarily hunter-gatherer to agricultural lifestyles. Water wells of up to 5-m depths in the Mediterranean Region have been dated to between 9,000 and 11,000 years ago (Jones, 2012). Early civilizations in Mesopotamia and Egypt are referred to as “hydraulic” societies by some historians because they can be characterized by their efforts in collective water supply and resource management (Bocanegra et al., 2005). Groundwater has the important advantage of being relatively ubiquitous and is often found with generally high quality due to natural processes that remove contaminants during the hydrologic cycle. A main disadvantage of groundwater is that any effort to utilize it will require energy to lift it, with the exception of natural springs and artesian wells from which groundwater flows out at ground level. For this reason, a main aspect of groundwater development is its association with water lifting and water-lifting devices.

Groundwater has become a primary focus for rural water supply in the developing world due to its widely dispersed nature and relatively low development cost. Most rural water systems in the U.S. and other developed countries rely on groundwater wells (Gasteyer, 2011), but groundwater has also been very important in the developing world. A World Bank Technical Paper published in 2000 indicated that the "utilization of groundwater resources have facilitated the rapid, low-cost provision of more reliable, good quality, water supplies for the rural population across extensive areas of Asia, Africa and Latin America" (Foster et al., 2000) and the dependence of rural water supply in sub-Saharan Africa on groundwater has been characterized as "indisputable" (Foster et al., 2012).

1.4.2 Improved and Unimproved Water Supplies

Classification of water supply as "improved" is an important specification in regard to human health and well-being. Factors considered in this classification include likely water quality, amount of water available, and the distance from point of collection to point of use. In practice, the Joint Monitoring Programme measures progress toward the water supply aspect of MDG 7 by "reasonable access", which is defined as being "the availability of at least 20 liters per person per day from a source within one kilometer of the users dwelling" (WHO and UNICEF, 2000). To contribute to progress toward MDG Target 7c, a source must also be considered "improved", so classification as "improved" or "unimproved" is an important technological characterization of water supplies.

An improved source is one that, "through technological intervention, increases the likelihood that it provides safe water" (JMP, 2012), and includes examples such as boreholes, protected wells/springs, public standpipes, and household connections to piped systems. This relatively simple characterization is made because the costs and scale associated with water quality testing make it unfeasible at any large scale. Furthermore, the water required for most water uses does not need to be of drinkable quality, though cost-effective measures to promote water quality at the source are important and reflected in the "improved" classification.

1.4.3 Community Water Supplies

Community water supplies typically serve many households (200 - 500+ users) in an area. Groundwater wells with handpumps have long been considered a preferable option for community water supplies in most rural areas (Arlosoroff et al., 1987). Most community water supplies are either collectively or government-owned, though public-private partnerships that involve private ownership represent a growing model. The majority of documented rural water supply investment is made by governments and NGOs and is focused on the construction of community water supplies. The RWSN Executive Steering Committee estimates that 90%-100% of hardware costs for community rural water supply systems in sub-Saharan Africa are externally financed by governments or NGOs (RWSN Executive Steering Committee, 2010).

Community water supplies serve the vast majority of the 273+ million sub-Saharan Africans who have gained access to improved water supply since 1990, but a number of challenges have been identified that limit their potential to sustainably serve the growing population that remains unserved. These challenges include increasing unit costs, challenges with long-term functionality, and the dispersed nature of most rural populations (Sutton, 2011). Most community water systems are intended to provide water for domestic purposes and many are not for productive purposes, although those who happen to live very close to the source may be able to use it for productive activities.

1.4.4 Household Water Supplies

The term “household water supply” indicates water supply available at the household level. The main advantage of household water supply is convenience, which is very important to users and has significant health and livelihood implications. For these and other reasons, the Joint Monitoring Programme has recently proposed a post-2015 goal of “intermediate drinking-water supply at home” as an improvement over basic improved water supply water supply (JMP, 2013). Household water supply from municipal or community piped water systems is very common in the developed world and increasing in the developing world. *Household water systems* fall into the category of household water supply but are unlike household connections to community piped water because the water source is onsite.

Household water systems serve one household or a small group of households in a close proximity to one another. They can also be called “family systems” or “domestic systems”, especially when serving only one family. Household water systems are privately owned and constructed through individual or group investment, which typically places them into the category of Self-supply, an important approach that is discussed in detail in this and the next chapter.

Household water systems can involve a range of lower-cost technologies such as protected scoop-holes, traditional hand-dug wells, manually drilled boreholes, rainwater harvesting systems and others, but are mainly defined by their location (at or very close to the home) and ownership (private). Household systems can also include higher-level technologies such as deep boreholes with submersible pumps, which are a very common form of rural water supply in developed countries. In fact, 14% of the total population in the US use privately-owned household wells (Gasteyer, 2011). Household water supply is very common in many rural parts of the developing world, largely in the form of springs, scoop-holes, and hand-dug wells, though domestic rainwater harvesting systems, manually drilled boreholes, and other technologies are being increasingly adopted.

1.5 Self-supply

Self-supply involves the improvement of household or shared water systems through user investment. It is based on small, incremental improvements utilizing technologies that are affordable to users and is contrasted to conventional community water supply, which is generally government or NGO-funded (Sutton, 2008). To put it simply, Self-supply is regular people working within their own resources to improve their water supplies. Promotion of Self-supply is not meant to be a replacement for conventional community water supply, but a complementary mechanism through which "poor" rural people are already investing millions of dollars in their own water supplies (Sutton, 2009). As of 2004, Self-supply sources utilizing groundwater in Africa alone were more than 1 million (Sutton, 2004a), though the importance of Self-supply is not widely recognized by stakeholders in the water supply sector.

Household Self-supply systems are often more accessible, reliable and convenient to users, which allows for increased water availability at the household level. This is important to health because increased water use at the household level has been indicated to have significant positive effects on health (Howard & Bartram, 2003). Some common household water supply technologies appropriate for Self-supply include "family" wells (dug or drilled), water lifting devices (including low-cost pumps), and rainwater collection systems (MacCarthy et al., 2013a), though higher-level technologies are applicable as well to those that can afford them. Figure 1 indicates some examples of incremental steps that characterize Self-supply as well as the types of service providers and some applicable technologies.

Self-supply sources are privately managed and entail a strong sense of ownership, which coupled with other attributes such as the lack of outside (donor) investment and the utilization of local knowledge and practices, is suggested to result in increased sustainability (Sutton, 2004a; Foster, 2012; MacCarthy et al., 2013a). Efforts by governments, nongovernmental organizations (NGOs), or others to promote and build capacity for Self-supply are emerging across the developing world.

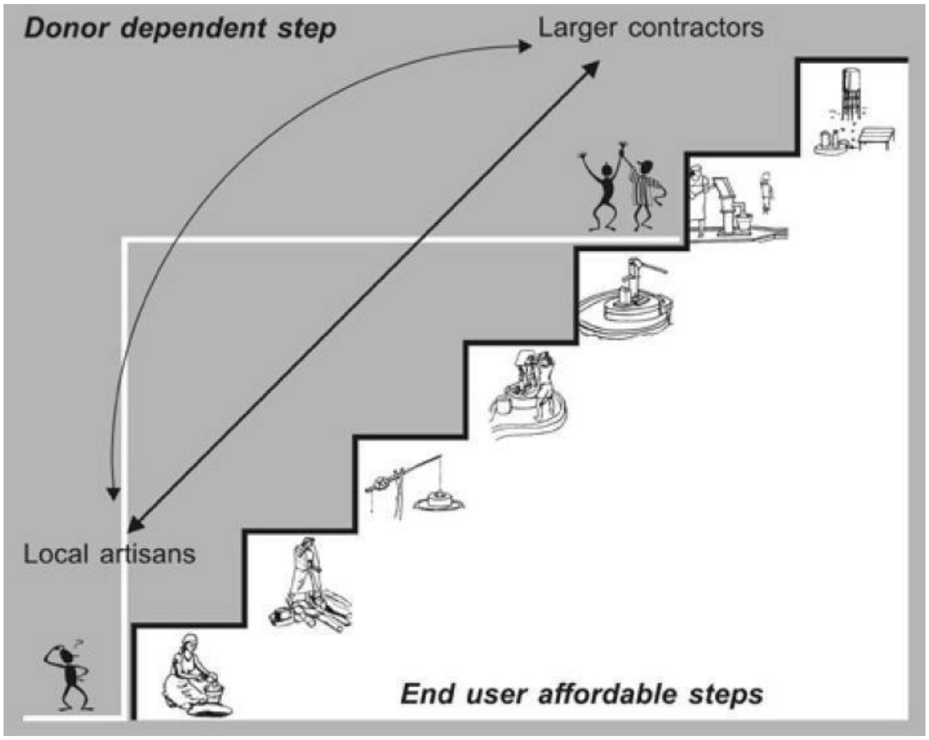


Figure 1: Water supply ladder (from Sutton (2008), with permission)

The concept of systematically promoting and supporting Self-supply is known as "Accelerating Self Supply" (Sutton, 2011). The Rural Water Supply Network (RWSN) has adopted Accelerating Self-supply as a main theme of its work and has advocated extensively for it in a number of African countries, including Uganda (see http://www.rural-water-supply.net/en/self-supply). Accelerating Self-supply is mainly focused on maximizing individual agency to move up the water supply ladder through enhanced local knowledge, choice, means, and voice. Sutton (2008) outlines four "building blocks" for the creation of a more enabling and sustainable environment for Self-supply, which are depicted in Figure 2.

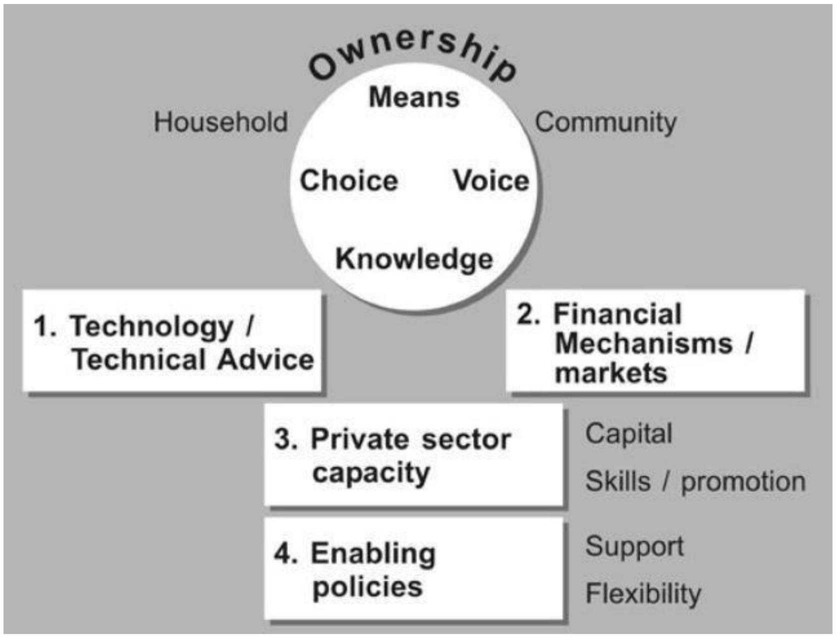


Figure 2: Building Blocks of an Enabling Environment for Self-supply (from Sutton (2008), with permission)

The first building block in Figure 2 is the availability of affordable and appropriate technologies as well as systematic technical support and advice. Accelerating Self-supply can be focused on the support of existing practices in water supply improvement or on the introduction of new technologies to an area, referred to as technology transfer. Low-cost handpumps, manual well drilling techniques, and rainwater harvesting storage tanks may be appropriate technologies, but this depends on many factors such as cost, supply chains for materials and spares, and desirability, among others. Systematic technical support could come in many forms; some examples include training programs in vocational schools, local government extension services, or NGO-funded technical training. The goal is that appropriate and affordable options are available and that there are long-term support mechanisms to bolster them.

The second building block for Self-supply is composed of financial and market mechanisms. Access to financing is specifically important. An example would be a micro-credit institution that makes loans to household for the purchase of a well and handpump, or to small well-drilling enterprises for capital investments in new tools or equipment. Market mechanisms are characterized by a wide range of options and competition among service providers and sellers. In addition to keeping prices down, market mechanisms promote innovation. Other financial mechanisms could include targeted subsidies for the adoption of Self-supply technologies, especially when they are relatively new to an area.

The third building block is private sector capacity in terms of technical and business skills, capital, and supply chains. Some or all of these factors may be lacking in many contexts, in general, and especially in regard to water supply. Water supply technologies rely on supply chains that bring materials. Government-run supply strategies have a very poor record of success, so the private sector must typically play a significant role. Small enterprises must have technical capacity in the technologies being used for Self-supply while business skills can improve their reach and competitiveness. Capital is often a limitation, but can be enhanced through financing or carefully targeted subsidies.

The final building block of Self-supply shown in Figure 2 is enabling policies, which include flexible regulation and official support of Self-supply. Governments should recognize the importance and potential of Self-supply and this recognition should be reflected in water supply strategies. Regulation of water resources is clearly necessary, but regulations must be designed in a way that they monitor and protect the resource without suppressing Self-supply. A main goal is for governments and donors to integrate Accelerating Self-supply into its strategies, which has been done to varying degrees already in Zimbabwe, Ethiopia, Mali, Zambia, and Uganda (Sutton, 2011; Morgan & Kanyemba, 2012).

Self-supply has played an important role in rural water supply throughout human history and there is no country in the world where Self-supply isn't practiced. Self-supply is especially important in rural areas that are harder to reach and have dispersed populations. In these areas, centralized water supply systems are less feasible. Self-supply continues to play a major role in rural water supply for countries around the world, including the U.S. and other developed countries. Strategies for Accelerating Self-supply may hold significant potential in achieving greater water supply coverage in developing countries.

1.6 Handpumps

Groundwater is already a significant water source for rural people in sub-Saharan Africa and great potential for further groundwater development has been identified (Foster et al., 2006). Even decades ago, the role of the handpump was widely recognized for its importance in rural water supply (McJunkin, 1977). Handpumps have become a very common technology for lifting water in rural areas of the developing world, especially after significant investments in handpump research and implementation for community water supply began in the 1980's. Some common community handpumps include the India Mark II, Afridev, and others, which often have an installed cost of more than $US 1000 in Uganda and are meant to serve 250 people or more. Many improved community water supplies in sub-Saharan Africa rely on these handpumps, which are characterized by robust components for heavy-duty use. In fact, handpumps are the most common form of improved rural water supply in many countries and will continue to serve millions of rural people for decades to come (Baumann & Furey, 2013).

Handpumps costing less than $US 150 have emerged as affordable options, mainly for household water systems but also for small community supplies in some instances. Low-cost handpumps have become increasingly important as the value of the Self-supply approach become more widely recognized and adopted (Baumann, 2011). Low-cost handpumps are characterized generally not only by their affordability, but also other aspects such as the potential for local manufacture, ease of installation and repair, and reliance on locally-available materials. Low-cost handpumps are most appropriate for household water supplies and are sometimes referred to as "family pumps." They are typically paired with low-cost wells, either hand-dug or manually drilled, but may also be appropriate for underground water storage tanks. Low-cost pumps are of particular importance to Self-supply because they represent an affordable water lifting option for incremental improvement over the buckets that many rural people use to lift groundwater. The low-cost EMAS Pump is the focus of this work and is described in the next chapter.

1.7 The Ugandan Context

Uganda is a landlocked country of around 35.7 million people in East Africa that borders South Sudan to the north, Rwanda and Tanzania to the south, Kenya to the east, and the Democratic Republic of Congo to the west. Uganda's demographics are characterized by many different ethnic groups and a very young population (median age of 15.5). The population continues to grow rapidly due to a fertility rate (5.97 children born per woman) that is among the highest in the world. The official unifying language is English, which is taught in schools as part of the Universal Primary Education program in place for more than ten years. An estimated 82%

of the population works primarily in agriculture, including subsistence farming, though only 23.5% of GDP originates in the agricultural sector. Uganda has seen significant economic growth for many years, though its GDP ranking on the world scale is far above its rankings in GDP-per capita, and most health and poverty indicators (CIA, 2014).

The Ugandan government, like many other African countries, adopted a decentralized system in the late 1990's wherein districts represent the largest subnational administrative unit. Districts are generally responsible for most service delivery regarding health, education, agricultural extension, water, and sanitation, though some of these services are also delivered by lower administrative units. It has been noted that local governments in Uganda struggle with many challenges including limited financial resources, corruption, staffing, and an overreliance on conditional grants from the central government (Bashaasha et al., 2011). These challenges are considered to be compounded by the rapid creation of new districts. The number of districts has nearly doubled from 56 in the year 2000 to 111 in 2014. Population per district is dropped to approximately 321,622, far lower than other sub-Saharan African countries (Green, 2008).

The status of access to improved water supply in Uganda has improved significantly in the past two decades. The Joint Monitoring Programme indicates that 45% of the 2011 population in Uganda has gained access to an improved water source since 1995 (JMP, 2013). Since 2002, the Government of Uganda has utilized a Sector-Wide Approach that emphasizes programs over individual projects and directs funding from Government and development partners through established mechanisms to coordinated efforts to address priorities in the sector. The Uganda Ministry of Water and Environment (MWE) is responsible for setting and guiding the implementation of water sector strategies. The MWE Sector Performance Report 2013 lists improved water access as 70% in urban areas and 64% in rural areas, where an estimated 29.7

million (83.7% of the population) people live (MWE, 2013). In 2010 it was estimated that 63.1% of the population with access to an improved water source used deep boreholes or shallow wells (MWE, 2010a). About 11% of the rural population is indicated to use unimproved surface water as a drinking water source (JMP, 2013).

Government of Uganda investment in rural water supplies in Fiscal Year 2012/2013 is estimated to extend new improved water supply to 716,981 people, but progress has stagnated for a number of years as investment struggles to keep up with population growth. The majority of sector funding is invested through District Local Governments in community water supplies that are maintained by Water User Committees. The average functionality of rural water supplies was indicated to be 84% in 2013, though this relied on incomplete reporting from local governments. While the primary focus of rural water supply is on community water sources, MWE has recently been developing policies to enable and promote Self-supply and low-cost technologies in particular (MWE, 2013).

1.8 Motivation and Objectives

The motivation for this research is grounded in an approach that has been gaining momentum in the water supply development sector for many years. The approach is characterized by the promotion of appropriate low-cost water supply technologies under the Self-supply model and is believed by many to hold potential for sustainably improving the lives of millions of people. Much exploration has already taken place in regard to this approach and there are many examples of successes and failures, all of which can be built upon to better inform strategy for future action. This thesis aims to contribute to the body of work through the assessment of a particular low-cost water supply technology.

The EMAS Pump is a technology that has not been extensively studied despite the significant success it has had as a part of household water supply systems in Bolivia and, to a lesser extent, other countries. Meanwhile, the Government of Uganda has been a forerunner in recent official support of Self-supply in sub-Saharan Africa and has established the promotion of Self-supply as a component of the water supply strategy. The EMAS Pump may be a viable candidate as a low-cost pump to be strategically promoted as part of the Accelerating Self-supply approach in Uganda, so a specific assessment is useful.

Many factors and issues contribute to the potential for a technology or approach to go to scale in a particular context. Affordability is of fundamental importance in regard to low-cost water supply technologies because cost serves as a major barrier to household water supply in low-income countries. Labor has a relatively low monetary value in these contexts, so material and transport costs become important factors. A relatively low cost is only one important factor though; technical performance also has significant influence on the success of a technology. One strategy for technical assessment of a handpump includes side-by-side performance comparisons to a more well-known alternative. The Rope Pump (also known as the “Rope and Washer Pump”) is a well-known and widely documented low-cost handpump that is very popular for small community and household water systems in parts of the developing world, so it can serve as an excellent comparison to the less-studied EMAS Pump. Additionally, the Rope Pump has been introduced in Uganda and other countries in sub-Saharan Africa and can serve as a point of reference for the introduction of other low-cost handpumps. Additional context-specific factors that contribute to the potential for the uptake and sustainability of a market-based water supply technology include trends in the water sector, supply chains, hydrogeology, and government regulations, among others.

The objectives for this work are to:

1. Conduct a comparative analysis of the EMAS Pump and the Rope Pump, considering pumping rates, required energy, and associated costs,
2. Assess the potential of the EMAS Pump as a component of affordable household water systems in Uganda, and,
3. Provide recommendations for the introduction of the EMAS Pump within the Self-supply Strategy in Uganda.

CHAPTER 2: LITERATURE REVIEW

Literature was reviewed on a number of topics for this research. Some general issues associated with rural water supply are first examined along with some examples of Self-supply. Low-cost handpumps and the EMAS Pump and Rope Pump in particular are also addressed. Finally, the measurement of human energy expenditure is discussed in order to provide background on the calculations of energy expended for pumping that were made during this study.

2.1 Household Water Supply and Water Quality vs. Water Quantity

Much criticism of low-cost water supply technologies used in household water systems are associated with health risks due to bacterial water quality. This is especially true with regard to shallow groundwater, which is generally more susceptible to contamination. A professional guide to the construction of drilled drinking water well universally discourages low-cost alternatives, citing water quality issues with shallow groundwater (Schneider, 2012). In addition, a comprehensive doctoral thesis on the transfer of a low-cost well drilling technology to Uganda indicated there were many concerns raised among government stakeholders about water quality from shallow wells (Danert, 2003). Others have indicated that an aversion to shallow groundwater is common among authorities, politicians, and water sector professionals in Uganda (Carter et al., 2005; McGourty, 2006; Mills, 2006).

Others have emphasized the relative importance of the quantity of water available. The supply of 20 liters per capita per day (l/c/d) of high quality water has been promoted by many in the rural water supply sector. The issue of 20 l/c/d as a standard target was addressed in RWSN's *Myths of the Rural Water Supply Sector*, which pointed out that costs associated with water quality improvements may place constraints on the impact of investment that limits water accessibility and does not always match up with users' needs or desires (RWSN Executive Steering Committee, 2010). Similarly, a paper published by the World Health Organization explores the issue of water quantity and health. It characterizes the supply of only 20 l/c/d as having a "high level of health concern" because it may be inadequate to address all health-related uses of water, including provision of basic hygiene and environmental sanitation (Howard & Bartram, 2003).

The quantity of water used at the household level has been shown to be closely related to the distance from dwelling to water source and time spent collecting water. In fact, it has been indicated that water collected per day decreases significantly when the water source is not within 1.5 minutes of the home and drops to minimal amounts when collection times exceed 30 minutes roundtrip (Mihelcic et al., 2009). Meanwhile, JMP data indicates that 18% of people in sub-Saharan Africa that are using "improved" water sources travel more than 30 minutes to collect water (RWSN Executive Steering Committee, 2010). Furthermore, a recent study in Uganda found that many people complained of water sources being too far from their homes and indicated that they often used lower quality unimproved sources out of convenience for their relative proximity to the home (Asaba et al., 2013). This aligns with the conclusions of others that while most users are concerned about taste, color, and odor, they are less concerned with quantitative measures of water quality and often prioritize water source convenience of water quality (e.g. Carter, 2006; Mills, 2006).

Clearly, both water quantity and water quality are important factors, but their relative importance has been the subject of some debate. For example, Hunter et al. (2010) advocate a nuanced perspective and rigorous research on the issue because both quality and quantity have implications on health and should be considered contextually. A Technical Note produced by the WELL Resource Centre for Water, Sanitation, and Environment (House et al., 1999) concluded that increases in water quantity may often be more beneficial than increases in source water quality, especially in rural areas, but that water quality must always be considered. Additionally, some studies have found that drinking water is often contaminated before consumption even when collected from a source with safe water quality (Wright et al., 2004, 2006).

The many issues surrounding the factors of water quantity and water quality are relevant to household water systems, which generally increase quantity due to convenient access, but may increase health risks associated with water quality. Additionally, simple upgrades to household water systems have shown significant improvements in water quality in a number of countries, including Uganda (Tillett, 2007). Specifically in regard to the consideration of Self-supply and household water systems in Uganda, Carter et al. (2005) recommends that water supply sources should be not be delineated merely on the basis of “improved/unimproved” or “safe/unsafe”, but conceptualized with considerations for access, water quality, reliability, cost, and management.

2.2 Background and Examples of Self-supply

Self-supply of water has existed in one form or the other throughout human history. Most historical documentation has focused on the water supply infrastructure and management systems that were centrally developed to meet the growing needs of the urban human settlements that have generally been the center of societal power. Meanwhile, Self-supply has almost always served as a main method of water supply in rural areas. Through ingenuity, entrepreneurial spirit, the use of increasingly advanced (yet affordable) technologies, and enabling policies, Self-supply has played a significant role in the story of water supply in the U.S. and other developed countries. Some historical aspects of Self-supply in the U.S. are presented in this section.

Self-supply has also played a major role in less developed countries, though generally with much simpler technologies and with less drastic strides at improving health and livelihood. In recent years, Self-supply has begun to progressively increase in scale and impact in some developing countries. Some of these examples have been the result of targeted action to promote Self-supply, while others have been mostly indigenous. Background on the emergence of Self-supply promotion and examples from other countries in sub-Saharan Africa can enable a better understanding of the concepts that help feed into strategy associated with Accelerating Self Supply and the importance of low-cost technologies. Some examples are discussed later in this section.

2.2.1 Historical Aspects of Self-supply in the United States

It can be safely assumed that nearly all early rural water supplies of the American Colonies (and later, the U.S.) relied on Self-supply through individual or shared investment among neighbors in household water systems. Surface water was clearly a vital source for many early settlements, but hand-dug wells were utilized in areas where they were feasible. Most information found on private water supply in the U.S. is focused on technology, but a picture of the significance of Self-supply and the factors of affordability and entrepreneurship emerges. As of 2010, 43.5 million people in the U.S. (about 14% of the population) use self-supply water sources, 99% of which are wells (Gasteyer, 2011).

Hand dug wells were made in the U.S. starting in its earliest days. An 1881 municipal report from the City of Charleston, South Carolina stated that private dug wells of 20 feet or less where the main source of groundwater for residents of the city from 1678 through 1820. This figure can likely be assumed to be similar for other parts of the U.S. with appropriate hydrogeological conditions over that time period. The same report also indicated that as population increased and shallow groundwater became polluted, wealthier residents invested in household rainwater harvesting systems and underground cisterns (Lynch et al., 1881). Hand-dug wells would continue to be a major source of household water supply, though more so in rural areas as municipal water supply systems were built in cities. Even as late as 1990, more than 1.6 million households in the U.S. still used an "individual dug well" (a separate category from drilled wells) as a primary water source (U.S. Census Bureau, 2011).

As new challenges to Self-supply were met, innovations were developed. In 1821 there were reports that obtaining water in some areas of Alabama was a problem as wells were being dug to more than 100 feet without finding water (Carlston, 1943). The first documented drilled water well in the U.S. was made in 1824 by Levi Disbrow using a simple manual auger and percussion method that was adapted from percussion rigs used for drilling brine wells to harvest salt, which was a valuable commodity at time. The process was first patented in 1825 and later reissued in 1843 (Disbrow, 1843; Carlston, 1943). Some, documentation found on early well drilling in the U.S. was focused on artesian (flowing) wells, which were thought by some to be inevitable if sufficient depths were reached (Carey & Lea, 1827). The first State Geologist of Mississippi reported in 1854 that many wells were being constructed with hand augering and percussion methods at the price of $0.33 per foot up to 200 feet, $0.50 per foot for 200-500 feet, and $1.00 per foot beyond 500 feet (Wailes, 1854). Based on a purchasing power calculator[2] that accounts for changes in the consumer price index in the U.S., these drilling prices in 2012 dollars based would be estimated at $6.74, $14.10, and $20.40 respectively.

Buckets, windlasses, and simple wooden suction pumps were commonly used to lift shallow groundwater into the 19th century, though there seems to be little documentation on such pumps prior to the 1830's. It is believed that the first mass-produced cast-iron suction handpumps in the U.S. were manufactured in 1832, though many millions would eventually be made (Eubanks, 1971). Wooden pumps were still manufactured through the beginning of the 20th century and Eubanks (1971) indicates that a Douglass lift pump was listed in company literature from 1890 for a retail price as little as $4.50 for a 6' depth and $11.70 for 30' depth (including suction pipe), with up to 50% price reduction for wholesale. These prices would correspond to $117 and $305, respectively in 2012 dollars. Meanwhile, the W&B Douglas 1903 *Catalogue of Hand and Power Pumps*[3] lists a large range of cast iron suction pumps at prices starting at $4.25 ($114 in 2012 dollars) without the suction pipe. "Deep well" handpumps are also listed in the 1903 catalogue and were marketed for drilled wells, as evidenced by the pump fixed on a small-diameter well to the left of Figure 3. The two pumps shown in Figure 3 ranged from $13.00 - $17.75 in price ($350 - $478 in 2012 dollars), depending on cylinder sizes and excluding the additional common piping that was needed below the pump in most applications.

It is estimated that there were as many as 3000 manufacturers of handpumps in the U.S. in the early 20th century, all of which made pumps that were primarily used by single families for domestic us and livestock watering on small farms (McJunkin, 1977). This indicates the tremendous demand from Self-supply. In an effort to quantify the extent of handpumps use,

---

[2] Relative value of the US dollar calculator, available at http://www.measuringworth.com/uscompare/
[3] Scanned copy from New York Public library available at http://hdl.handle.net/2027/nyp.33433066397708

Eubanks (1971) estimates that as many as 41 million handpumps were made in the U.S. between 1620 and 1925. As mechanization and (later) electrification spread in the 20th century, handpumps gave way to more convenient and productive improvements such as the windmill pump, which represents a significant step up the "water supply ladder."

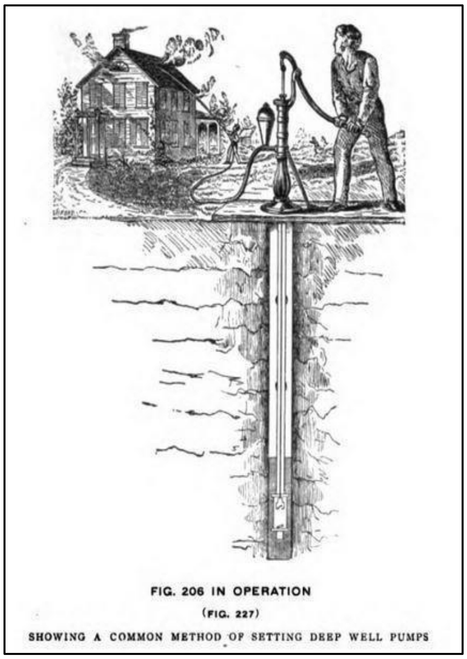
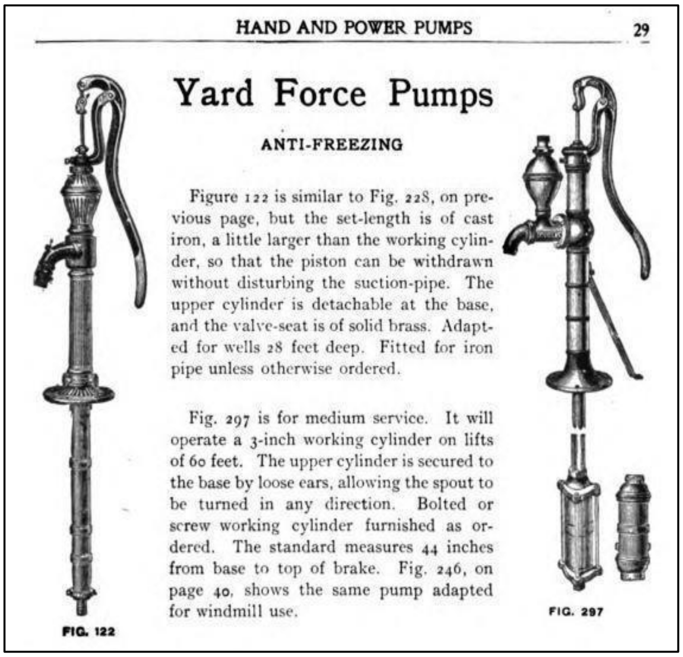


FIG. 206 IN OPERATION

(FIG. 227)

SHOWING A COMMON METHOD OF SETTING DEEP WELL PUMPS



HAND AND POWER PUMPS 29

Yard Force Pumps

ANTI-FREEZING

Figure 122 is similar to Fig. 228, on previous page, but the set-length is of cast iron, a little larger than the working cylinder, so that the piston can be withdrawn without disturbing the suction-pipe. The upper cylinder is detachable at the base, and the valve-seat is of solid brass. Adapted for wells 28 feet deep. Fitted for iron pipe unless otherwise ordered.

Fig. 297 is for medium service. It will operate a 3-inch working cylinder on lifts of 60 feet. The upper cylinder is secured to the base by loose ears, allowing the spout to be turned in any direction. Bolted or screw working cylinder furnished as ordered. The standard measures 44 inches from base to top of brake. Fig. 246, on page 40, shows the same pump adapted for windmill use.

FIG. 122

FIG. 297

Figure 3: Pages from W.B. Douglas 1903 *Catalogue of Hand and Power Pumps*

The caption for the advertisement on the left of Figure 4 found on the website of Iron Man Windmill Co. LTD (http://www.ironmanwindmill.com/windmill-history.html) demonstrates the importance of the concepts of Self-supply to rural Americans of the time. The caption indicates that the ad "*showed the greatly improved quality of life that came from having an abundance of good water and from the extra time available for profitable activities.*" This statement encapsulates the benefits of Self-supply in a historic example while the advertisement to the right of Figure 4 indicates the rapid scale-up of the Aeromotor windmill, which sold 45 units in 1888 and 60,000 units in 1892. It has been indicated that more than 6 million mechanical windmills, primarily for water pumping, were installed in the U.S. between 1850 and 1970 (Dodge, 2006).

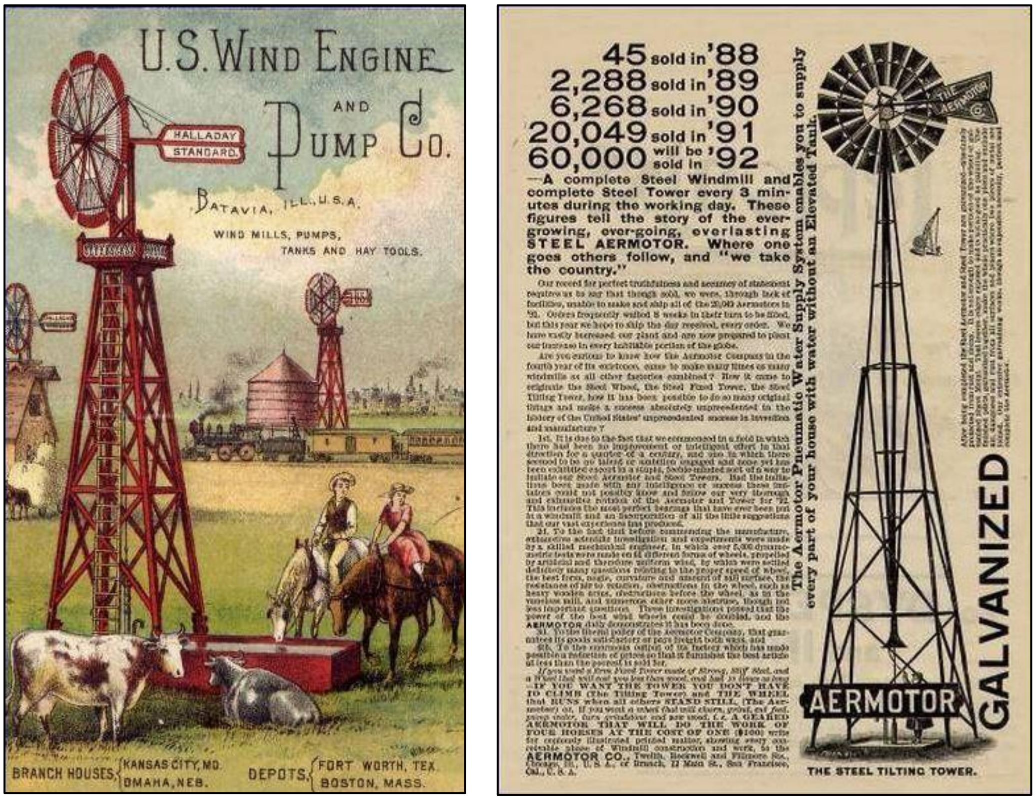


Figure 4: Advertisements for windmill for water pumping from the late 19th century (from www.ironmanwindmill.com)

In an extensively annotated article on the emergence of indoor plumbing in the U.S. in the mid to late 1800's, Ogle gravitates around the concept of convenience and highlights the importance of private investment in household water supplies as a driving force in rural areas. The author quotes essayist Frederick B. Perkins writing in 1861 that household water supply can "…save all water-carrying… The burdensome daily details of housework are… greatly lightened, and health, and time, and exertion, very much economized." Examples could include Eubank's drawings of and references to the $9.25 McDonald's House Pump (Eubanks, 1972) mounted inside the farm home or the household hand pump system depicted in Figure 5, showing a handpump outside of the home connected to a reservoir, wood stove for water heating, and a bath tub inside of the home. Pressure pumps were manufactured starting in the late 1800's that allowed pumping directly to elevated tanks placed in the attics of homes (Ogle, 1993). Indoor plumbing was certainly a luxury though and most households had to rely on more affordable water supply options. As late as 1950, more than 50% of rural households still had no indoor plumbing (Gasteyer, 2011). While it focused on plumbing more than water supply, Ogle's article touches on the foundational concepts of Self-supply. She references the diary of a Philadelphian in the mid-19th century that marveled at the conveniences such as on-site water supply available to Americans in frontier western states, which are attributed to "the magic power of free and intelligent industry… protected by wise laws" and the flexibility and affordability allowed by the lack of regulation on household plumbing works. These characterizations bring to mind the "Building Blocks for an Enabling Environment" for Self-supply depicted previously in Figure 2.

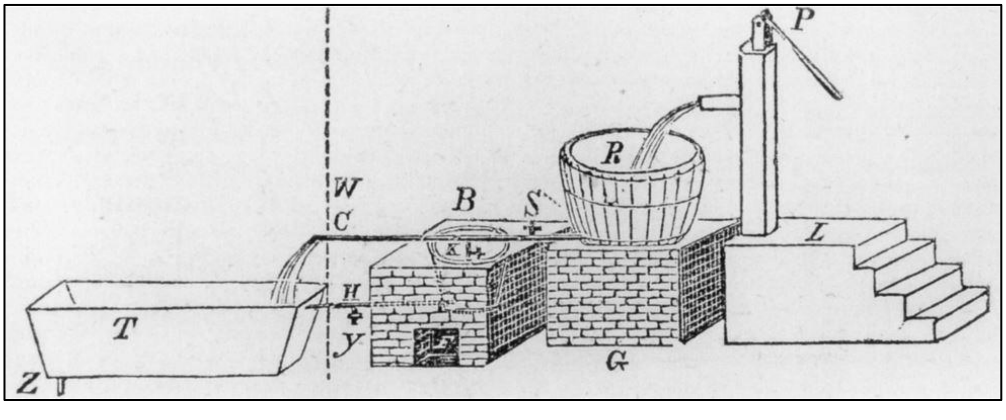


Figure 5: Household water system from 1848 (from Ogle (1993))

Self-supply has thus always been and remains an important part of water supply in the U.S. and there is little doubt that Self-supply contributed significantly to growth and economic development. It is clear that factors such as technological advancement, entrepreneurship, enabling policies, private sector competition, and government subsidies played significant roles. Though more research would allow a better understating of these factors, a cursory review of Self-supply in the U.S. reveals parallels to the concept of Accelerating Self-supply in other parts of the world and further reinforces the important role that household water supply can play, especially in rural areas.

2.2.2 Self-supply in sub-Saharan Africa

Experiences with Self-supply in other parts of sub-Saharan Africa can provide points of reference and lesson for the promotion of Self-supply in Uganda and elsewhere. RWSN and Dr. Sally Sutton have been extensively involved with much of the study, promotion, and documentation of Self-supply in the region. For example, in 2004, Sutton indicated that there was significant potential for Self-supply in many countries, including Cote d'Ivoire, Benin, the Democratic Republic of Congo, Liberia, Mali, Nigeria, Sierra Leone, and Zambia and parts of Chad, Malawi, Mozambique, Tanzania and Uganda (Sutton, 2004a). Studies that have examined existing Self-supply sources in sub-Saharan Africa, including Mali, Zambia, and Uganda, have concluded that significant investment was already taking place and that nearly all household systems were shared with neighbors (Sutton, 2011).

Examples of Self-supply from Zimbabwe, Zambia, and Uganda are discussed in the following sub-sections. There have also been relevant efforts to study and promote Self-supply in Mali (Maiga et al., 2006; Sutton, 2010a; Jones, 2011), Ethiopia (Sutton, 2010b; Sutton et al., 2012; Butterworth & Sutton, 2013; Weight et al., 2013), Malawi ((Danert et al., 2013), and

Tanzania (Haanen & Kaduma, 2011; Holtslag, 2011a; Olschewski, 2013). RWSN and Dr. Sutton, along with the Department for International Development (DFID) and the Water and Sanitation Program (WSP) of the World Bank, have been involved with most of the efforts in the promotion of Self-supply in many countries in sub-Saharan Africa, including Uganda.

2.2.2.1 Self-supply in Zimbabwe

Much of the groundbreaking work on Self-supply was focused on “family wells” in Zimbabwe (Carter, 2006), though the term “Self-supply” was not used at the time. In the 1980’s it was estimated that 30-40% of the population were served by family wells in Zimbabwe, all privately constructed and owned (Robinson, 2002). Dr. Peter Morgan and others at the Zimbabwe Ministry of Health’s Blair Research Laboratory took note of the significance of the family wells and, having already had success with promoting user investment in sanitation improvements, began to experiment with different strategies to promote the improvement of existing wells and construction of new wells. The “Upgraded Family Wells” program in 1988, in which pilot programs centered on offering support and small subsidies for the upgrading of family wells with brick linings, hygienic concrete headworks, a tin well cover, and a rope and bucket with windlass (Morgan & Chimbunde, 1991).

Research conducted by the Blair Research Laboratory at the time showed significant decreases in contamination associated with upgrading traditional systems (Rogenhofer, 2005). The program was progressively expanded and NGOs joined in partnership. By 1995, 18,000 units had been completed with owners paying 66% or more of all costs, and more than 1,000 artisans and builders had been trained to construct the upgrades. It was determined at the time that the upgraded family well strategy was more cost-effective than any other water supply strategy in Zimbabwe (Morgan et al., 1996). It is estimated that as many as 100,000 family wells were upgraded through the family well program by the year 2000 (Morgan & Kanyemba, 2012). A World Bank Field Note (Robinson, 2002) points out that users were willing to pay 80% or more of costs for upgrading and that one of the major benefits was increased availability of water for productive use. Robinson (2002) also notes that the practice of upgrading family wells had spread to Mozambique and suggested that the strategy had potential across the continent.

2.2.2.2 Self-supply in Zambia

One of the first in-depth studies aimed at Self Supply in sub-Saharan Africa took place in Zambia from 1997 to 2001 (Sutton, 2008). The study found that use of and investment in traditional Self-supply sources such as scoop-holes and wells were very common. Sutton noted that one “fully covered” district where most users lived with 500 meters of an improved water source still had 1,600 such Self-supply sources (Sutton, 2004b). Another 2001 study found that 94% of 3,640 family wells were found to be functioning (Smits & Sutton, 2012). Self-supply promotion pilots focused on well upgrading, household water treatment, and low-cost pumps were later initiated by government and NGOs that focused on marketing and training of service providers, but included no subsidies. Sutton (2008) describes the progress of the pilots in detail and recommends increased coordination among NGOs and the exploration of financing mechanisms as Self-supply is scaled up. Recent updates have indicated that Zambia’s government per-capita costs for the (relatively expensive) introductory phase of Self-supply promotion were still less than a third of the comparable per-capita costs for community supply.

2.3 Self-supply in Uganda

Little was known about user-led water supply investment in Uganda prior to 2004 (Carter, 2006). Since then, a significant amount of research has been focused on Self-supply.

Carter details the results of an early case study on Self-supply in central and eastern Uganda (Carter et al., 2005). It was found that as much as 39% of rural Ugandans relied on Self-supply sources, mostly from groundwater, despite no external support or promotion. In fact, it was found that many authorities and water sector professionals actively discouraged the low-cost water supply technologies commonly associated with Self-supply. Carter identified many barriers and opportunities in regard to Self-supply. The study was coordinated closely with Ministry of Water and Environment and local government officials and concluded with recommendations on policies to harness user investment and promote Self-supply.

A number of studies focused on Self-supply were undertaken around the same time by students from Cranfield University. Rogenhofer (2005) examined Self-supply in Busia Town, eastern Uganda, where it was determined that private hand-dug wells played an important role in water supply. It was estimated that 30 well-diggers operate in Busia, all of which learned their trade through experience, having received no formal training. One hundred eight private hand-dug wells were examined, most equipped with windlasses, and it was determined that they were significant to the owners for many reasons. The wells offered reliability of water supply compared to community alternative and many provided a significant income from selling water at rates that were affordable to their neighbors. Water quality testing was also conducted and it was found that none of the wells was free of contamination, but all users interviewed were happy with water quality from their wells. Well owners did indicate that they were open to chlorine treatment. It was concluded that Self-supply was of significant importance in the area and that it should be supported by authorities, possibly in the form of an upgraded well program similar to Zimbabwe (Rogenhofer, 2005). Another Cranfield master’s thesis noted water quality results from household wells and indicated that there was a need for promotion of household water treatment in Busia Town (McGourty, 2006).

Mills (2006) focused on user perceptions toward Self-supply in central Uganda. It was concluded that there was much interest and even enthusiasm for the concept of Self-supply among many stakeholders but identified a number of barriers. Challenges seemed to exist mostly with authorities and sector professionals and included difficulty with conceptualizing Self-supply in reference to conventional community supply, lack of understanding about water users' preferences, expectation that users would not be willing to invest in water supply, and the perspective that Self-supply did not have proven success in Uganda (Mills, 2006).

The Uganda Self-supply Pilot Project began in 2006 and focused on the promotion of Self-supply rainwater harvesting and shallow groundwater development at the household and community level by two NGOs (Carter et al., 2008). Extensive detail on the Pilot Project was documented by the MWE Directorate of Water Development (Magala Mpalanyi, 2008). The main challenges identified were associated with the difficulty with which implementers and other stakeholders had embracing the Self-supply concepts without blending with contradictory characteristics of conventional water supply, which all involved were more accustomed to (Alford, 2007; Tillett, 2007). Lessons learned from the Self-supply Pilot Project fed into planning for more formal support of Self-Supply by MWE and other authorities (Kiwanuka, 2009).

Much research has gone into household rainwater harvesting for Self-supply in Uganda in recent years. Danert and Motts (2009) provide a detailed analysis of the domestic rainwater harvesting sector and extensive recommendations for support, though its authors noted that many stakeholders seem to struggle with the concept of significant user investment. A number of technologies and associated costs are also discussed by Danert and Motts, a topic which has been extensively explored by others (Whitehead, 2001; Thomas, 2010; Blanchard, 2012).

A Ministry of Water and Environment Report from 2010 describes lessons learned about the promotion of Self-supply from a UNICEF-organized learning and exchange visit to Zambia, where groundwater Self-supply was already being promoted by the Zambian Government and nongovernmental organizations though advocacy, innovative financing, and support to private sector service providers (MWE, 2010b). The Ministry of Water and Environment held a forum on Self-supply to raise awareness and share experiences in 2011 and later published a report on the many different Self Supply efforts that have emerged around the country in the previous years (Steering Committee on Self Supply, 2011). The Ministry of Water and Environment has recently developed a formal strategy for Self-supply that includes providing guidance on Self-supply and low-cost technologies, raising awareness about Self-supply and documenting results of ongoing efforts. The Appropriate Technology Centre (ATC) in Mukono is taking the lead on technical research and guidance. Among other work focused on water and sanitation technologies, the ATC has published a manual on hand-dug well construction and has recently piloted EMAS underground storage tanks (MWE, 2013) fitted with EMAS Pumps, an initiative that the author supported with technical advice and demonstration of the EMAS Pump.

Recently, manual drilling has been reintroduced to Uganda by World Vision, though now for Self-supply. Three small enterprises in Gulu (northern Uganda) have been trained in Baptist Drilling and two others in Rope Pump and drilling equipment fabrication (Danert & Carpenter, 2013). At the end of 2013, 30 boreholes have been drilled by the small businesses. World Vision very recently initiated micro-finance loans for household boreholes, though only 3 people have taken loans so far (World Vision Uganda, 2013). Figure 6 depicts a Gulu woman that has invested in her own manually drilled well and Rope Pump, constructed by one of the small enterprises supported by World Vision. She now sells water to others at low cost and plans to use her pump to irrigate a vegetable garden during the dry season.

Figure 6: Self-supply borehole, Rope Pump, and owner in Gulu, Uganda (Photo: Author)

2.4 Low-Cost Handpumps

Low-cost handpumps are important to many household water systems in rural areas because users can benefit from affordable water-lifting devices for shallow (< 30m) groundwater sources. There is great potential for low-cost pumps for household and community supply in Africa (Sutton & Gomme, 2009) though some low-cost handpumps are not recommended for community sources and are most appropriate for Self-supply, especially those that can be made locally in rural areas. Low-cost pumps can be important components of household water systems that have many benefits including convenience and opportunity for multiple water uses, a concept that has received growing recognition and value (Alberts & Van Der Zee, 2003; Sutton & Gomme, 2009; Smits et al., 2010).

Baumann (2011) provides a concise overview of low-cost pumps as well as a number of examples, including the Rope Pump and the EMAS Pump, which are assessed in this research. It is pointed out that low-cost pumps are lightweight, easy to transport, and easy to install. Baumann links low-cost pumps to Self-supply and points out that they are, in general, most appropriately paired with similarly low-cost water supply options. It is emphasized that low-cost pumps are not appropriate in all situations and contexts, and that technical and economic feasibility should be explored for each unique context (Baumann, 2011).

This research aims to contribute to the assessment of the EMAS Pump in terms of technical ability and feasibility in Uganda. Part of this assessment includes a comparative analysis to the Rope Pump. A 2004 World Bank Field Note on low-cost handpump options in Honduras (Brand, 2004) is the only publication found that directly compares the EMAS Pump and the Rope Pump to each other, though the technical comparison was based on field reports as no testing was done.

2.4.1 EMAS Pump

The EMAS Pump (also known as the “Flexi Pump”) is a direct-action piston pump originally developed in Bolivia in the 1980’s by Wolfgang Buchner at the Mobile Water & Sanitation School (EMAS – a Spanish acronym). Recently, a peer-reviewed RWSN publication described an extensive study of EMAS technologies in Bolivia (MacCarthy et al., 2013b). It is estimated that there are more than 20,000 EMAS Pumps in use on manual-drilled wells in Bolivia (Danert, 2009) and 10,000 in Brazil (Baumann, 2011), around 1,750 in Honduras (Brand, 2004) and possibly a few hundred in Asia and Africa. The EMAS Pump can be fabricated in nearly any setting using materials and simple hand tools readily available at the district or small town level in most countries. Material costs for the EMAS Pump are generally indicated to be between $20 and $30 (Buchner, 2006; Baumann, 2011). It has been indicated that EMAS Pumps are sold for $US 30-45 in Bolivia for a 15 m deep well (MacCarthy et al., 2013b). EMAS also promotes a foot-pedal attachment to the EMAS pump for leg-powered operation, though it is not examined in this study. There is not wide range documentation on the EMAS pump and no independent technical assessment has been published to date.

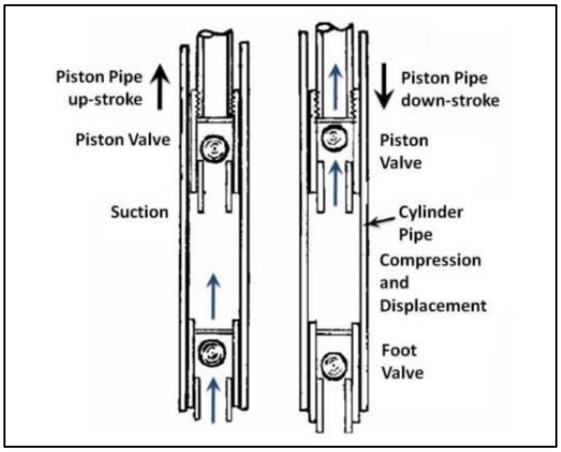


Figure 7: EMAS Pump check valves (from MacCarthy et al. (2013), with permission)

The EMAS Pump is composed of two PVC or polyethylene pipes, an outer static pipe and an inner "pumping" pipe that is connected to the handle and reciprocated up and down during pumping. The outer pipe is sometimes referred to as the "cylinder" pipe in EMAS literature. The handle is typically made of galvanized steel pipe for strength and also serves as the outlet spout. Like most piston pumps, the EMAS Pump relies on two check valves (one-way valves) to lift water. These valves are constructed of heat-formed PVC pipe and common glass marbles and an adjustable gasket is cut from a used tire. A diagram of the EMAS check valves can be seen in Figure 7. On the left side of Figure 7, the pumping pipe ("piston pipe") is moving upward while water from the well opens the foot valve open and fills the lower cylinder pipe due to displacement. To the right, the foot valve has closed due to gravity and the pumping pipe is moving downward and pressurizing the water in the cylinder, which then pushes the piston valve open and flows upward into the pumping pipe and eventually out of the spout. Figure 8 depicts an EMAS Pump in use.

Figure 8: Woman using EMAS Pump in Bolivia (Photo: Henk Holtslag)

The specifications and details of the EMAS Pump are presented in the EMAS manual (Buchner, 2006) and detailed fabrication instructions are available in videos published online by EMAS. Videos with detailed instructions for pump fabrication, well drilling, and many other water and sanitation technologies are available from EMAS at https://vimeo.com/emas. There are two variants of the EMAS Pump; the "Standard" pump, utilizing smaller pipes and recommended for pumping depths of up to 40m, and the "Quantity" pump that utilizes larger pipes and is recommend for pumping depths of 20m or less. In this thesis, the two EMAS Pumps are referred to by the size of the pumping pipe used in Uganda; the 20-mm pump is the "Standard" while the 25-mm is the "Quantity" pump. An advantage of the EMAS Pump is that it is capable of pumping water under pressure from the pump spout through a hose or tube to an elevation higher than the pump. This feature can allow for pumping to an elevated tank that can be used to supply running water to a home or irrigation water to a drip system. Additionally, the EMAS Pump is a "closed" pump that minimizes the potential of source contamination resulting from use.

Figure 9: Young girl in Bolivia using an EMAS Pump (Photo: Mike MacCarthy)

Buchner (2006) indicates that EMAS valves have a lifespan of about 500,000 liters, after which they can be replaced at very low cost. It is also recommended that the pump is removed and new connections made at all pipe joints after 1.5 million to 2 million liters are pumped. Brand (2004) indicated that the EMAS Pump has a design life of 4-9 years and that valves must be replace about every 2 years or so, which would only align with Buchner's guideline if 685 liters were pumped each day for 2 years. It has been noted that the EMAS Pump has achieved uncommon sustainability as a part of household water systems in Bolivia. In a recent study, 79 households with Self-supply EMAS household water systems were visited and it was found that 99% of EMAS Pumps were operational, though 12 of the pumps had some issues such as leaks. Of 18 EMAS Pumps that were 10 years or older, all were working and only 5 had any issues at all (MacCarthy et al., 2013b). Figure 9 depicts a young girl in Bolivia using the EMAS Pump installed on her family's Self-supply manually drilled borehole. EMAS technologies have had limited exposure in Africa, though a recent Self-supply program in Sierra Leone has focused on the promotion of EMAS Pumps and other EMAS technologies (Bunduka, 2013a, 2013b).

2.4.2 Rope Pump

The Rope Pump, also known as the Rope and Washer Pump, is an ancient technology that dates back more than 2,000 years to China and the Middle East (Sutton & Gomme, 2009). The Rope Pump is relatively well-known and much documentation has been published on it. There are many designs for the Rope Pump and it is used in many different forms around the world, though the basics include a continuous rope with a series of washers (pistons) attached to it that passes over a wheel, then down below the water level of a well or borehole, where it returns to ground-level inside of a pipe (Harvey & Drouin, 2006). As the wheel is turned, the washers lift water through the rising main pipe (also called the "pumping pipe") like an elevator. A diagram of the Rope Pump is depicted in Figure 10. Depth to water determines the size of the pumping pipe and common recommendations indicate that ½" pipe should be used up to 35m, ¾" pipe to 20m, and 1" pipe to 10m (Holtslag & de Wolf, 2010; Nederstigt & van der Wal, 2010). 25-mm and 20-mm pipes are used for the Rope Pump in this study, which are nominally equivalent to ¾" and ½", respectively. This is because metric standard pipes are more commonly available in Uganda. The Rope Pump has been promoted mostly for use with hand-dug wells, can also be adapted for use with boreholes (tubewells) (MacCarthy, 2004; Holtslag, 2011b).

As a low-cost pump, a main advantage of the Rope Pump is the potential for local manufacture. Materials needed for the pump include galvanized steel pipe for the frame and handle/wheel structure, the sidewalls of a used tire for the wheel surface, PVC pipe for the rising pipe and spout, and a rope. Washers are also needed, and options consist of punched discs from the sidewall of a used tire or molded plastic. Molded plastic discs can offer more efficient hydraulic operation (van Hemert et al., 1992; Harvey & Drouin, 2006), but the process for punched rubber discs may be easier to adopt for new pump fabricators. Material prices for Rope Pumps typically range from $US 50 - $US 150, depending on the version used. Rope Pumps have been more expensive in other places where a cumbersome fully-enclosed design was used.

There are at least 35,000 Rope Pumps in Nicaragua (Baumann, 2011), though some estimates reach as high as 90,000, while there are around 20,000 Rope Pumps in Africa and Asia (Holtslag, 2011a). Nicaragua is the model of success for the Rope Pump, where it has proven to be sustainable on the community and household level (Sutton & Gomme, 2009) and is indicated that a quarter of the rural population utilize a Rope Pump for daily water needs. Additionally, Rope Pumps in Nicaragua have been linked to increased family incomes of $225 per year from productive use of water (Alberts & Van Der Zee, 2003). Rope Pumps were first introduced for use in community water supplies in Uganda in 2005, using a relatively expensive ($US 240) design that included a full metal enclosure. A recent review of this effort concluded that implementation had weaknesses and that the Rope Pump should be targeted at Self-supply (NETWAS Uganda & WaterAid Uganda, 2013).

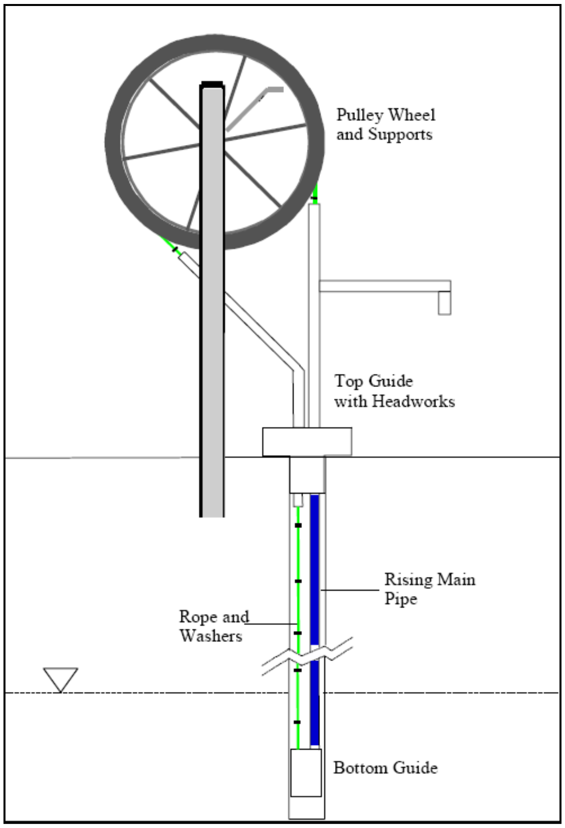


Figure 10: Basic diagram of the Rope Pump (from MacCarthy (2004), with permission)

A strong case has been made for the Rope Pump's usefulness to rural populations in sub-Saharan Africa (Harvey & Drouin, 2006) and many efforts have been made to transfer the Rope Pump to new places, in hopes that uptake similar to Nicaragua may take hold. Sutton and Gomme (2006) explore the fact that many such efforts in sub-Saharan were not seeing the success that was expected and make many pertinent conclusions regarding targeting approach, and technology. In 2011, there were more than 1,000 Rope Pumps in Njombe Region of Tanzania (Haanen & Kaduma, 2011), catalyzed by the efforts of the SHIPO Smart Centre (Holtslag, 2011a) to promote Rope Pumps for traditional dug wells and newly manually drilled boreholes. Recently, efforts have been made to introduce the Rope Pump to additional areas in Tanzania (Olschewski, 2013). The Rope Pump is currently being standardized in Tanzania and data indicates that there are 4,000 Rope Pumps across the country now as a number of organizations have begun to promote them (Holtslag, 2014). Figure 11 depicts a man in Njombe, Tanzania pumping from his Self-supply Rope Pump that he uses for domestic supply, watering livestock, and irrigating citrus trees.

Figure 11: Owner of a Self-supply well in Njombe using his Rope Pump (Photo: Author)

2.5 Human Energy Expenditure

The human body is capable of a wide variety of mechanical work through the expenditure of energy from metabolic processes. Human energy expenditure is composed of three main components: (1) basal energy expenditure (energy required to maintain basic processes required for sustaining life); (2) thermogenesis due to digestion (energy used for processing of dietary nutrients); and (3) energy used for physical activity. Resting energy expenditure (REE) is closely related to basal energy expenditure, but it is easier to measure and more representative of normal energy expenditure of free living humans, so it is the most commonly used measure. Gross energy expenditure for human activity can be found by subtracting REE from total energy expenditure during physical activity, though thermogenesis due to digestion can also be a small factor if a meal has been consumed within a few hours before activity (Williams, 2004).

Human mechanical energy is the ability to do physical work with the body as the energy source. Human mechanical work requires an increase in energy expenditure, but only a small percentage of energy expended from physical activity is actually translated into mechanical energy. In fact, overall mechanical efficiency of humans is estimated to be in the range of 7-11% (Fraenkel, 1986) while short, strenuous efforts may have mechanical efficiencies of up to 25% (Plowman & Smith, 2011). Energy expended that is not translated into physical work goes into other processes such as heat production, respiration, cardio-vascular processes, and metabolism itself, which are generally elevated during physical activity. In theory, it is possible to use energy expenditure to estimate actual mechanical energy output, though the mechanical efficiency of humans is complex and variable, depending on many factors such as intensity and timespan of activity, muscle groups used, ergonomics, and others.

2.5.1 Estimation of Human Energy Expenditure

Since the early 20th century the estimation of human energy expenditure has been a focus of doctors, physiologists, and ergonomists for medical and industrial purposes. More recently, the topic has been examined by nutritionists, sports scientists, and epidemiologists as well, and with the increasing utilization of new technologies for field measurements (Shephard & Aoyagi, 2012). A common laboratory method for measuring human energy expenditure is direct calorimetry, in which total heat production of the body is measured of the subject while inside of a thermally-isolated whole-body chamber, an accurate method but with limited applications because of expense and limitations on subject mobility (Leonard, 2010). Indirect calorimetry is typically focused on the estimation or measurement of oxygen consumption, which is the "main expression of metabolic rate" and thus energy expenditure (Ainslie et al., 2003; Williams, 2004). Accurate methods of indirect calorimetry include the precise measurement of respiration or the doubly-labeled water method, though these are not easy to utilize in field conditions and require expensive equipment (Li et al., 1993; Ainslie et al., 2003).

Estimation of human energy expenditure under field conditions is important to athletic training, exercise science, and many health-related fields. Devices for measuring respiration and oxygen consumption, long used for energy measurements in laboratory settings, are emerging as an option for field-based testing as more portable systems are being developed. There are still challenges with high costs and the difficulty with which some activities can be performed while subjects are connected to the device. Common field-based methods for the estimation of energy expenditure include those that estimate actual work done such as ergometers, motion sensors, accelerometers (such as the pedometer), or those that measure a proxy for oxygen consumption such as heart rate.

2.5.2 Heart Rate Monitoring

Prior to the invention of the stethoscope more than 200 years ago, medical practitioners monitored heart rate by touch at certain points of the body (wrist, neck, etc.) or by placing an ear on the subject's chest. The electro-cardiograph (ECG) was developed in the early 20th century and a progression of subsequent inventions have made it possible to monitor heart rate conveniently and with high precision. The first wireless heart rate monitors were developed in the 1980's and similar systems are still in use today. Relying on the relationship between heart rate and oxygen consumption (HR-VO_2), heart rate monitoring with these devices are the most common method to estimate exercise intensity (energy expenditure) in the field (Achten & Jeukendrup, 2003), mostly for personal fitness and training purposes.

These devices include a chest strap, which monitor and transmit electrical signals of the heart, and a wrist-watch style receiver, which records and displays signal information to the user. Such portable heart rate monitors are inexpensive, easy to use, and have seen widespread adoption in recent years by athletes and individuals seeking to closely monitor and quantify exercise intensity. Wireless heart rate monitors with chest electrodes have been tested extensively for accuracy and it has been concluded that they are accurate and reliable (Achten & Jeukendrup, 2003).

2.5.3 Energy Expenditure and Heart Rate

Human energy expenditure can be estimated by heart rate because of the established relationship between heart rate and oxygen consumption. This relationship exists because energy production is dependent on oxygen consumption through aerobic respiration. In general heart rate during physical activity is linearly related to oxygen consumption during physical activity (see Figure 12), though a key exception is that this relationship does not hold at low heart rates and also deviates near absolute maximal exercise (Johnson, 1991; Rennie et al., 2001; Charlot et al., 2014). The linear relationship of heart rate and oxygen consumption (HR-VO_2) generally holds true in the “moderate to vigorous” range of physical activity (Vanhees et al., 2005). The point at which the linear HR-VO_2 relationship begins is referred to as the “Flex heart rate”, and is determined by averaging the highest resting heart rate with the lowest heart rate during “light” exercise (Spurr et al., 1988; Ceesay et al., 1989). Any heart rate lower than the “Flex” is considered to be poorly correlated to oxygen consumption and thus indicates the resting energy expenditure (REE), so heart rate alone cannot serve as a reliable proxy for energy expenditure.

While the relationship of heart rate and oxygen consumption is reliably linear during activity, the slope of the line varies from person to person and can be altered by a number of factors. The slope of the HR-VO_2 line is unique for each person, though is not always constant for an individual over time and can be altered by ageing, exercise and changes in cardiovascular fitness, weight gain or loss, body composition, health status, and other factors (Li et al., 1993). The cardiovascular system has more functions than aerobic respiration for energy production, so the relationship between heart rate and oxygen consumptions can be altered by other factors as well.

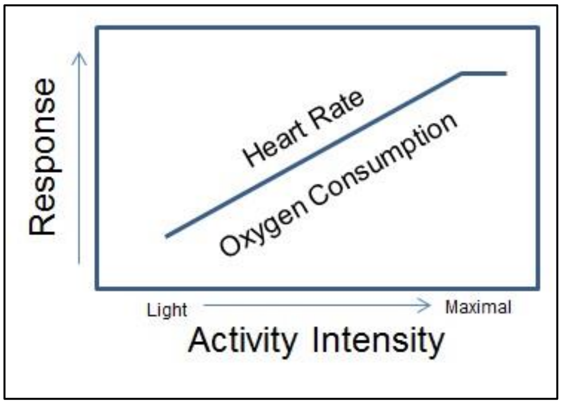


Figure 12: Heart rate and oxygen consumption during physical activity (adapted from Williams, 2004)

Variation in the slope of HR-VO_2 will have an affect the calculation of energy expenditure from heart rate. The HR-VO_2 slope can be modified depending on the type of physical activity and the muscle masses being used as well as posture during exercise (Achten & Jeukendrup, 2003). For instance, heart rate is elevated during arm exercises compared to leg exercises at the same oxygen consumptions level, so the use of energy expenditure equations derived from running or cycling (both commonly used) may overestimate energy expenditure for arm exercises (Ainslie et al., 2003; Mookerjee et al., 2005; Katch et al., 2010). This is partly due to the recruitment of other muscles in the shoulder, back, and core for the stabilization of the arms during arm exercises (Plowman & Smith, 2011). Additionally, static exertion exercises such as weight lifting have been shown to have a greater heart rate impulse than dynamic exercises such as running (Collins et al., 1991; Katch et al., 2010). Other limitations of heart rate monitoring that can lead to error in the estimation of energy expenditure include delays in heart rate response, effects of environmental conditions (such as heat), altitude, user emotion, posture, alcohol, caffeine, or nicotine use, dehydration, insufficient sleep, or infection (Johnson, 1991; Li et al., 1993; Achten & Jeukendrup, 2003; Ainslie et al., 2003). Generally, all of these result in increased heart rates compared to more typical conditions.

Modern physiological monitoring devices have enabled development of models for the relationships between heart rate, oxygen uptake, and energy expenditure. A number of studies have produced energy expenditure prediction equations that are based primarily on the measurement of heart rate (Spurr et al., 1988; Rennie et al., 2001; Keytel et al., 2005; Dugas et al., 2005; Charlot et al., 2014). All of these prediction models include variables that have been shown to be most relevant: heart rate, age, gender, and weight. Aerobic fitness of an individual has been determined to have significant impacts on the relationship of heart rate to energy expenditure, so some predictive models have included more specific factors that approximate fitness such as maximal oxygen consumption, body composition, and resting heart rate. It has been concluded that such equations can provide satisfactory estimations of energy expenditure among groups of test subjects, though are not necessarily accurate for individuals without individual calibration through more rigorous lab-based testing of heart rate and oxygen consumption during exercise.

CHAPTER 3: METHODS

3.1 Pumps Examined in Study

Two versions of the EMAS Pump and two versions of the Rope Pump underwent testing, differentiated by the size of the pumping pipe corresponding to a standard and shallow-well (high-flow) design. The deeper version of each pump uses a 20-mm pumping pipe while the shallow-well, high-flow versions use a 25-mm pumping pipe. These are metric standards that correspond roughly to ½” and ¾”, respectively. Information on the pump variants tested in this study are presented in Table 1. The selection of these pumping pipe sizes were based on the Rope Pumps currently promoted in Uganda. Other versions such as the Rope Pump with ~1” pumping pipe and high-flow EMAS Pump with ~½” pumping pipe were not tested.

Table 1: Variants of EMAS Pump and Rope Pump Tested

Pump Name	Recommended Depth Range (m)	Pumping Pipe	Casing Pipe
EMAS “Standard” (20mm)	30+	20 mm PN 16	32mm PN 10
EMAS “Quantity” (25 mm)	Up to 20	25 mm PN 10	1½ inch “drain” pipe
Rope Pump (20 mm)	30+	20 mm PN 16	N/A
Rope Pump (25 mm)	Up to 20	25 mm PN 10	N/A

The Rope Pumps tested included a version with 20-mm pumping (riser) pipe and pistons and another with 25-mm riser pipe and pistons; these are referred to as the 20-mm (or ½”) Rope Pump and the 25-mm (or ¾”) Rope Pump, respectively. These standard and metric unit pipe sizes are not exactly the same, but are very similar and nominally cross-referenced in low-cost pump literature because metric standards are common in some countries but not others. A version of the Rope Pump with 32-mm (~1”) pumping pipe is recommended for very shallow wells of up to 10 m (van Hemert et al., 1992), but was not examined in this study.

The Rope Pump tested in this study corresponds to the low-cost “Family Model” design promoted by Connect International (http://www.connectinternational.nl/index.html) and SHIPO (http://www.shipo-tz.org/), and manufactured locally by small enterprises in parts of Tanzania, Malawi, and Uganda. The EMAS Pump tested is nearly identical to the design recommended by EMAS (http://emas-international.de/index.php?id=32&L=3), though with a slight design variation to the valve construction for the 25-mm “Quantity Pump”. This modification was made to allow for simpler construction using the pipes commonly available in Uganda, and is not thought to have made any significant difference in the operation of the pump. In fact, such design variation is encouraged by EMAS in Bolivia, where the concept of the pump is taught along with the instruction that slight variations may be appropriate depending on the specifications of materials available in a given context. The frame of the Rope Pump tested in this study was modified to mount to a standard community handpump pedestal that is ubiquitous for boreholes in Uganda, including all testing sites. The EMAS Pump only required a fabricated mounting plate to be fitted to the standard handpump pedestals and a short hose connected to the spout of the EMAS Pump to ensure that no water was spilled during testing. An alternative version of the EMAS “Quantity” Pump with a 20-mm (~½”) pumping pipe was not tested in this study.

3.2 Technical Assessment of Rope Pump and EMAS Pump

Field work in Uganda included a number of pump tests that were carried out using variants of the EMAS Pump and the Rope Pump detailed in Table 1 for assessment and comparison purposes. These tests were undertaken by two Ugandan subjects (one adult male and one adult female) and included tests on boreholes and wells having a range of water levels in Kitgum and Gulu Districts, northern Uganda. Each pump underwent two 40-liter pumping trials by each test subject at five different sites with a range of water depths.

Pumping rates were the primary focus of the technical assessment, though it was recognized that the observed flow rate alone cannot fully explain the performance of a human-powered pump. To provide an additional basis of comparison, energy expenditure during each pumping trial was estimated by heart rate monitoring and empirical relationships were used to estimate energy expenditure from heart rate data. While there is error inherent in the *accuracy* of calculated energy expenditure in this study because of individual differences in physiological response, there is some confidence in the *precision* of these calculations; meaning that there is reason to believe that meaningful comparisons can be made between different pumps at various depths based on the relationship between energy expenditures calculated for the same individual subject. In other words, it is believed that energy data has significant internal validity for comparisons in this study, however external validity may be limited. Details of the implications of energy expenditure calculations are discussed below and in Chapter 4.

3.2.1 Selection of Test Users

The two pumping test users were selected based on a number of factors. Due to logistical constraints associated with the distance to field sites and the time required for installing and uninstalling pumps, only two subjects could undergo testing, so one male and one female were sought and reliability and proximity were primary concerns. The test users selected were a 24-year man and a 23-year woman (unrelated to each other) living in Kitgum Town, each of average build and both accustomed to collecting water from handpumps. Neither subject was previously familiar with the pump models tested in this study. The users were paid corresponding to the common local daily wage for skilled labor and provided with water and meals on testing days.

3.2.2 Details of Testing Trials

Pumping trials took place at five separate locations in northern Uganda, four in Kitgum District and one in Gulu District. Most sites were more than 50 km from the testing base of Kitgum Town and one was more than 100 km away. Throughout the test water levels were measured using a surveying tape measure with a weight attached to the end. One site (Site 3) was visited on two separate occasions (about 30 days apart) for testing of the two different pump sizes and it was found that the static water level had changed. The measured water levels for each testing site can be seen in Table 1.

Table 2: Static Water Level at Testing Sites (meters below ground)

	Site 1	Site 2	Site 3*	Site 4	Site 5
20-mm Pumps	5.1m	12.6m	18.4m	21.1m	28.3m
25-mm Pumps	5.1m	12.6m	17.0m	-	-

*Tests for 20-mm and 25-mm pumps at Site 3 took place at different times

All five sites had existing boreholes (wells) that were fitted with a standard pump pedestal, though only the Site 1 pump was operational. Non-functional handpumps were targeted to avoid any disturbance to operational community water supplies. The one operational pump was located at an unused borehole inside World Vision’s compound in the town of Gulu. Local handpump mechanics were hired at each site to assist with removing and reinstalling components of the community handpumps that were installed on the boreholes.

Ambient temperature was hot each day during testing, estimated to be around 29° - 35° C (84°- 95° F), though the temperature could change rapidly on partially overcast days. The availability of shade was limited at a few of the sites, forcing the test subjects to sit in the vehicle with limited breeze while resting. Two of the sites had large shade trees over the borehole, so test subjects were surely a bit cooler during these trials. In an effort to keep the test subjects properly hydrated, large bottles of water were made available during testing. Each test subject had more than two liters of water available to them and was encouraged to drink plenty of water to prevent dehydration.

The water inlet for each pump tested was placed approximately 2.5m below the static water level to eliminate any chance of well drawdown beyond the pump intake. For the Rope Pump, this measurement was made at the bottom of the pumping pipe while it was made at the bottom of the piston valve for the EMAS pump (in the lowest position).

3.2.3 Measurement of Pumping Rates

The object of each test trial was for the user to pump 40 liters of water at a normal pace, which was defined to the subjects as, “a pace that you would pump if you were collecting 40 liters of water on a typical day.” Each test was started with the pump primed (ready to immediately discharge water) and time was recorded to the second with a digital stopwatch. All pumped water was collected and each trial was timed to allow for a calculation of average pumping rates. Two marked containers of 20 liters each were used to allow for a “split” time and a comparison of pumping rate for the first 20 liters to second 20 liters of each trial. 20 liters was used because it is the nominal volume of the most common water collection container (i.e., the jerrycan) used in Uganda and many other countries in sub-Saharan Africa.

Marked volume measurements for testing containers were approximated under field conditions by weighing 20 kg of water with a calibrated baby-weighing scale and (assuming a density of 1kg/liter) and marking the 20-liter line with the container on a level surface. Actual measurement during pumping trials was judged by a member of the testing team who took into account the estimated effects of the slope of the ground surface. When the first container reached the 20 liter mark for each trial, it was swiftly exchanged with the second container and it is believed that no appreciable amount of water was lost. Water level in the well was measured before and after each test and pumped water was poured back into the well accordingly to ensure that changes in static water level from pumping did not introduce error to the following pump test. Figures 13 and 14 provide pictures taken during pump testing trials.

Figure 13: Testing trial of EMAS Pump with male subject (Photo: Bosco Okot)

Figure 14: Testing trial of Rope Pump with female subject (Photo: Bosco Okot)

3.2.4 Heart Rate Monitoring

The continuous heart rate (pulse) of the test subjects was measured and recorded during pumping trials with a Polar FT7™ system (Polar Electro, Kempele Finland) that consisted of the H1™ heart rate sensor (chest strap with sensor) and the FT7 training computer (wrist watch with display). The system relies on telemetry signals sent from the chest strap to the wrist-watch computer and was first introduced by Polar in the late 1970’s (Shephard & Aoyagi, 2012). Polar still is widely recognized as a leading manufacturer of quality heart rate monitoring hardware and it was noted that Polar devices with chest straps were used in many recent studies focused on energy estimations from heart rate monitoring (Bot & Hollander, 2000). Furthermore, the type of system utilized has been characterized as accurate in relevant literature (Achten & Jeukendrup, 2003). Prior to each round of testing, the chest strap was fitted to the user and the training computer (worn by the author) was checked for reliable signal reception. Heart rate was recorded prior to the start of the test and then at each 10-second interval during pumping.

3.3 Estimation of Energy Expenditure from Heart Rate

As discussed in Chapter 2, total energy expenditure by humans is composed of three components: basal energy expenditure to maintain life, increases due to food intake, and energy for physical activity. Heart rate during physical activity is linked to oxygen consumption and energy expenditure, but is decoupled at rest. For this reason, it was necessary to estimate resting energy expenditure for each test subject with a method other than heart rate. Energy expenditure during pumping trials was estimated using heart rate. Energy expenditure precipitated by pumping was then estimated by subtracting resting energy expenditure from measured total energy expenditure from heart rate during pumping trials.

3.3.1 Estimation of Resting Energy Expenditure

Resting energy expenditure (REE) is commonly used in exercise science as a more functional substitute for basal energy expenditure, though it is marginally higher because it includes small amounts of energy associated with diet and previous activity (Williams, 2004). An estimation of REE was necessary in this study so that it could be extracted from the total energy expenditure rates recording during the pumping trials to allow for an estimation of energy expended for pumping.

Direct metabolic measurements are preferable for accurate estimation of REE (Frankenfield et al., 2005), but only basic biometric data was available for the test subjects, so an appropriate equation to estimate REE was selected. The REE equation selected was developed based on a study of 498 American men and women of various ethnicities and demonstrated that they were an improvement over the commonly used methods at the time (Mifflin et al., 1990). These equations are known as the Mifflin-St Jeor Equations or MSJEs and are written as:

$$REE_{male} = (10 \times wt) + (6.25 \times ht) - (4.92 \times age) + 5 \qquad \text{[Eq. 1]}$$

$$REE_{female} = (10 \times wt) + (6.25 \times ht) - (4.92 \times age) - 161 \qquad \text{[Eq. 2]}$$

where *REE* has units of kcal/day, *wt* is the weight of the test subject and has units of kg, *ht* is the height of the test subject and has units of cm, and *age* is the subject's age in years. Some specific issues with the use of this equation are discussed in Chapter 4.

3.3.2 Estimation of Energy Expended During Pumping

A model developed by Keytel et al. (2005) was used to estimate energy expended by the test subjects during pumping trials. The model was developed for predicting energy expenditure from heart rate observations during physical activity based on observed data from 127 regularly exercising men and woman, aged 19 to 45. The study produced two models, one with a measure of fitness (maximal oxygen uptake, VO_{2max}) and the other without a measure of fitness. The accurate determination of VO_{2max} for an individual requires laboratory equipment not available in Uganda, therefore individual calibration was not undertaken and the model without a measure for fitness was used. Both models were validated for accuracy in prediction of energy expenditure with a second group of nine men and eight women (Keytel et al., 2005). It was found that results from the model with no measure of fitness (the model used in this study) correlated to observed energy with correlation coefficients of $r = 0.77$ for the validation sample and $r = 0.857$ for the original study sample (Keytel et al., 2005).

The exercises used for the development and validation of the models were running and cycling, but "good agreement" was found for stationary rowing, which appears to be a similar action to operating a handpump. Other literature indicates that heart rate during upper-body exercise is consistently higher than for low-body exercise at the same oxygen uptake rate (Katch et al., 2010), an issue that is revisited along with other sources of error in the next chapter. The equation (Keytel et al., 2005) used for the estimation of energy expenditure (EE) in the Uganda pumping trials is written as:

$$
\begin{aligned}
EE = gndr \times (-55.0969\ + 0.6309 \times HR + 0.1988 \times wt + 0.2017 \times age) + (1 - gndr) \\
\times (-20.4022\ + 0.4478 \times HR - 0.1263 \times wt + 0.074 \times age)
\end{aligned}
\qquad \text{[Eq. 3]}
$$

where *EE* has units of kJ/min, *HR* is heart rate and has units of beats per minute (bpm), *wt* is weight and has units of kg, *age* is the subject's age in years, and *gndr* is equated with a value of 0 for women and 1 for men.

3.3.3 Calculation of Energy Expenditure for Pumping

Heart rate was recorded for each 10-second interval during pump testing, so a rate of energy expenditure could be calculated and applied to each interval. When REE is subtracted from the total estimated energy expenditure, an estimation of energy expenditure specifically for pumping can be made. However, this is still a representation of energy rate (energy per unit time, also known as power). Energy expenditure rate for pumping was then applied step-wise to each 10-second interval of the pumping trial in order to determine the total energy spent for each interval. A sum of energy for each of these intervals gives an estimation of total energy for pumping.

3.4 Factors Associated with the Potential of the EMAS Pump in Uganda

The Rope Pump and the EMAS Pump can be fabricated locally in Uganda, using local supply chains. Retail costs of materials needed for the pumps were found by visiting manufacturers, importers, and retailers in Kampala, the capital and economic hub of Uganda. PVC materials are manufactured by two companies in Uganda while most galvanized piping suppliers are imported. Some up-country prices were noted as well, but Kampala prices are presented in this study because price differences in other parts of the country depend on supply chains.

There are some basic differences in skill and resource requirements for the fabrication of the EMAS Pump and the Rope Pump that were included in the assessment. The availability of electricity is a major delineation between areas where the Rope Pump can and cannot be fabricated. Additionally, the author's experience working in southern and northern Uganda for two and a half years provided for a nuanced, if anecdotal, perspective on the availability of relevant local skills during this time. Some preliminary conclusions on these issues are presented in Chapter 4.

The main applications of the EMAS Pump include pumping from shallow groundwater (wells or boreholes) and underground tanks (cisterns) for rainwater harvesting. Shallow groundwater development is most applicable in areas that have water tables within 30 m of the ground surface and where there are no hard rock formations above the water table. Rainwater harvesting is feasible nearly everywhere, but has the most potential where it is the more cost-effective, which is in areas where there is a significant amount of rainfall (Blanchard, 2012). Information was collected from official sources and other documentation on hydrogeology and rainfall patterns in order to characterize factors contributing to the potential for each of these applications of EMAS Pumps in Uganda and is presented in Chapter 4.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Pumping Rates at Various Water Depths

Pumping trials were undertaken by two test subjects with the EMAS Pump and the Rope Pump at five different locations in Kitgum and Gulu District, northern Uganda. Two variants of each pump were tested, one with a 20-mm pumping pipe and the other with a 25-mm pumping pipe, which roughly correspond to ½-inch and ¾-inch, respectively. The 20-mm EMAS Pump is commonly called the “Standard” EMAS pump while the 25-mm EMAS pump is called the “Quantity” Pump. The Rope Pump variants are identified only by the size of the pumping pipe, e.g. 20-mm Rope Pump and 25-mm Rope Pump. The specifications of these pumps were summarized in Table 1. The 20-mm variants of both pumps were tested at five wells with static water levels of 5.1 m, 12.6 m, 18.4 m, 21.1 m, and 28.3 m. Meanwhile, the 25-mm variants of each pump were tested at wells with static water levels of 5.1 m, 12.6 m, and 17 m. Each pump was tested for two timed trials for each user (male and female) in which 40 liters was to be pumped. The pumping rates were calculated based on the time to pump the first 20 liters of each trial and averaged for both users for each pump. These observed pumping rate results are presented in in Figures 15, 16, and 17.

There were considerable differences between the female user and the male user in regard to comparisons between pumping rates for the two pumps. Both EMAS pumps had higher pumping rates relative to the Rope Pumps for the male user on some wells. Pumping rates observed for each user are presented in Figures 16 (male) and 17 (female).

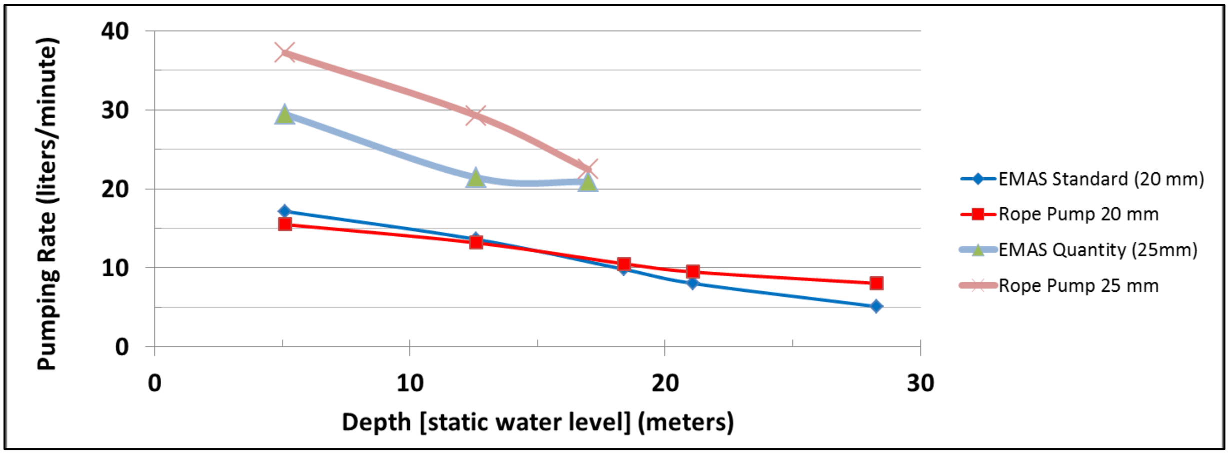


Figure 15: Average pumping rates for 1st 20 liters at various depths for all trials

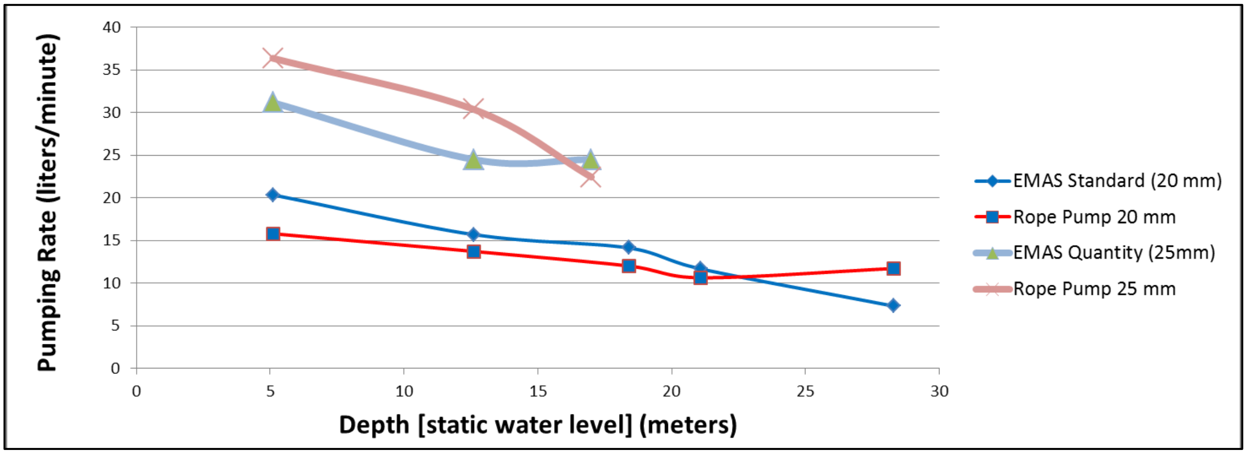


Figure 16: Average pumping rates for 1st 20 liters at various depths for male user

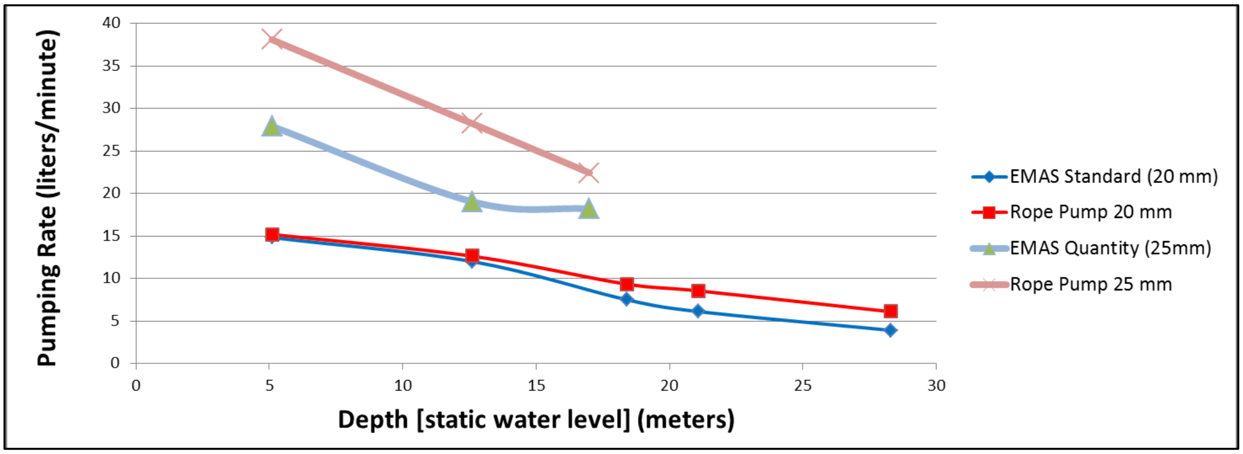


Figure 17: Average pumping rates for 1st 20 liters at various depths for female user

Figures 15-17 show that at shallower depths (i.e., < 18 m) the 20-mm EMAS Pump proved to be comparable to the Rope Pump in terms of pumping rate, though the pumps began to diverge around 20-m, especially for the female user. Tables 2 and 3 present the results of the pumping rate for the EMAS Pump as a percentage of the Rope Pump for the 20-mm and 25-mm pumps, respectively, where the static water level of the well is indicated by "SWL." This is based on the same data presented in Figures 15-17. Table 2 shows that the male subject had a significantly higher relative pumping rate for the 20-mm EMAS Pump than the female for all sites except for the 28.3-m well. Table 3 shows the relative pumping rates for the 25-mm EMAS pump were also greater for the male subject than the female subject.

Table 3: EMAS Pumping Rate as a Percentage of Rope Pump Pumping Rate for 20-mm

SWL	Male	Female	Combined
5.1	129%	98%	111%
12.6	114%	95%	103%
18.4	118%	80%	93%
21.1	110%	72%	85%
28.3	62%	64%	63%

Table 4: EMAS Pumping Rate as a Percentage of Rope Pump Pumping Rate for 25-mm

SWL	Male	Female	Combined
5.1	86%	73%	79%
12.6	81%	67%	73%
17	109%	81%	93%

The observed pumping rates for the female user were always lower with the EMAS Pump than with the Rope Pump (Figure 17, Tables 2 and 3), while a majority of trials showed the opposite result for the male user (Figure 16, Tables 2 and 3). It was observed during the trials that the male used longer strokes when pumping the EMAS pump, facilitated by his height, which would have led to more efficient pumping because less time was spent on changing directions in the pumping cycle. This finding is in line with the EMAS manual, which indicates that higher pumping rates are common for taller people (Buchner, 2006).

4.2 Energy Expenditure and Normalized Pumping Rates

Pumping rates alone do not offer a complete comparison for the EMAS Pump and the Rope Pump because the different motions of pumping may lend themselves to different energy and force inputs from the test subjects. The first strategy used in this study to create similar conditions for the pump comparison was represented in the instructions given to the test subjects to “pump at a comfortable rate, knowing that 40 liters would be pumped.” While this measure may give a good indication of user preference, the sample size was only one for each gender. A strategy for a better approximation of a true side-by-side comparison was to utilize a measure of user energy expenditure in order to normalize pumping rates. Heart rate monitoring of test subjects was undertaken during all pumping tests in order to provide an estimation of energy expenditure using empirical equations, as described in detail in Chapter 3. Charts that show the estimated energy expenditure for pumps tested are provided in Appendix B. Potential issues with the accuracy of the estimated energy expenditure are discussed later in this section.

This strategy was applied with the creation of “normalized” pumping rate charts in which the pumping rates for the EMAS pump were adjusted to reflect the ratio of energy expenditure for the EMAS pump to the corresponding Rope Pump. This calculation is an approximation of what the pumping rate would have been for the EMAS Pump if the energy expenditure had been equal to the Rope Pump. “Normalization” of the EMAS pumping rate involved the following calculation:

$$Pumping\ Rate_{EMAS,normalized} = \frac{EE_{RP}}{EE_{EMAS}} \times Pumping\ Rate_{EMAS,actual} \qquad \text{[Eq. 4]}$$

where EE_{RP} and EE_{EMAS} are the energy expenditures determined for the particular pumping trial for the Rope Pump and EMAS pump, respectively. Figures 18-20 present the data with the normalized pumping rates. In these three figures, EMAS pumping rate is adjusted by normalization using Equation 4 while the Rope Pump pumping rates are the same as the actual rates measured during the pumping trials.

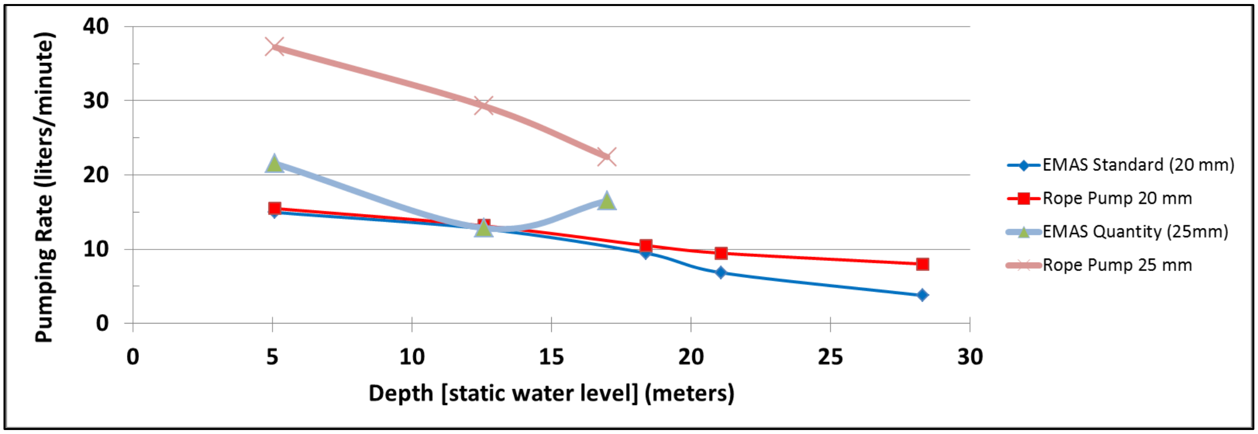


Figure 18: Average pumping rates for all trials at various depths with EMAS pumping rates normalized for energy expenditure

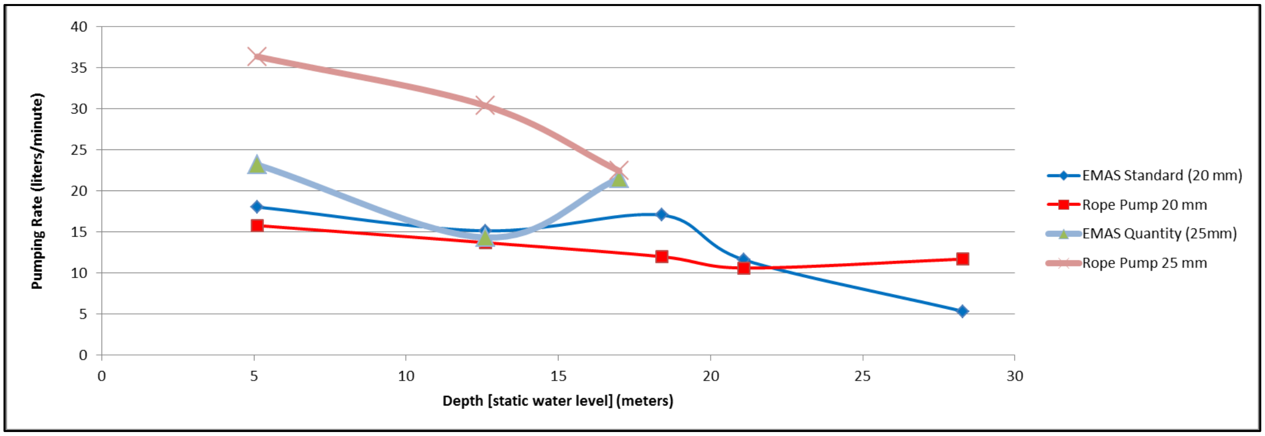


Figure 19: Male subject: Average pumping rates at various depths with EMAS pumping rates normalized for energy expenditure

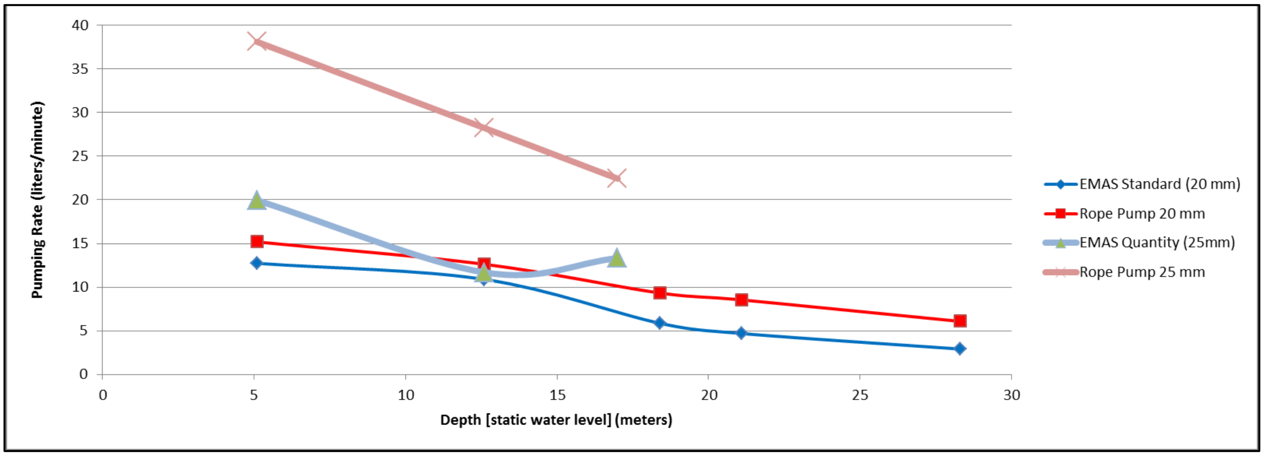


Figure 20: Female subject: Average pumping rates at various depths with EMAS pumping rates normalized for energy expenditure

It is believed that the normalized pumping rate calculation provides a more objective comparison between the pumps. In all instances except for the male subject using the 20-mm pump at the 18.4 m deep well, energy expenditure was always greater for the EMAS Pump than the Rope Pump. This means that the effective pumping rates of the EMAS Pump were reduced by normalization in all other instances.

There are a number of issues that suggest the energy expenditure data calculated from the pumping trials are not reliably accurate in terms of absolute energy expenditure. Details about these concerns are included in the following sections. Regardless, the same test subjects underwent the same methodologies for pumping, so it is believed with some confidence that the energy expenditure data has some precision and can be used to indicate relative energy expended for the two pumps. This provides validity to internal comparisons made in this study, but may potentially limit the external comparability of raw energy data. The normalized pumping rate calculations (and results presented in Figures 18-20) were made for this reason. Figures presenting the calculated pumping energy expenditures for each pumping trial are provided in Appendix B.

4.3 Potential Issues and Limitations of Pumping Tests

There are a number of issues associated with the interpretation of this study's results. First, the small sample size of two subjects and two tests per pump at each well does not allow for statistical comparison. Lack of control of some environmental conditions and day-to-day variability in test subjects may introduce some error. There may also be some error in the estimations of energy use that limit the broader comparability of the energy expenditure results. Other limitations apply to internal comparisons between the two pumps examined, but it is generally thought that the comparison between the two pumps is meaningful because most sources of error were applied uniformly across pumping trials and are not indicated to have great variability for individuals.

4.3.1 Sample Size and Testing Methods

Ideally, more test subjects would have participated in pumping trials and more iterations of each pump test would have taken place. Time and logistics on the ground in Uganda were the main limiting factors. It can be difficult to retain subjects that are reliably available on the same days. Additionally, a number of factors resulted in there being limited time for actual pumping trials. The wells at which the tests were performed represent a fairly wide range of static water levels and were distributed across a rather large geographical area (+2 hour drive for some sites). Installing, troubleshooting, and removing the pumps could also be a time consuming process.

A number of issues may have introduced some error to the pumping trials, though nearly all applied to both pumps and are thus not thought to have a significant impact on the comparative analysis. While these are estimated to be relatively marginal, there could be some effect of them in aggregate. For example, the containers used for water measurement had to have large openings to prevent spillage, but this resulted in reduced accuracy of volume measurement that depended on the judgment of the test facilitator (i.e., the author of this thesis). Lines calibrated at 20 liters were drawn on the sides of the buckets, but uneven testing surfaces and difficulty assessing the exact point that the line was reached were challenges. The EMAS pump was especially difficult since it pumps in pulses while the rope pump has a continuous flow. Though a hose was used to eliminate the spillage of water, the EMAS pump's impulse may have also resulted in some minor losses due to splashing. Changing out the measuring buckets at the 20-liter mark also resulted in occasional spillage of very small amounts of water.

The height of pump pedestals was not uniform among test sites which would result in variance in the ergonomics of both pumps. An attempt to minimize this issue was made through the use of a large spare tire as a platform that was adjusted vertically using bricks. Users indicated that the artificial platform was comfortable and it didn't seem to present any perceivable challenges.

4.3.2 Test Subjects and Pumping Rates

The test subjects for this study were chosen based on proximity and availability. Both test subjects were young, unemployed, had mobile phones, and lived in Kitgum Town. Previous attempts at pump testing from 2012 were challenging because of the reliability of the rural test subjects selected, who had challenges being available each day. The test subjects that participated had experience using handpumps, but it was in the past as they were currently using tap stands from the Kitgum Town water system most the time.

Additionally, the subjects may have pumped at higher rates than they would have under normal circumstances for fetching water. Although instructions to the test subjects were reiterated throughout testing, the author always had a concern that the test subjects operated both pumps at rates that are higher than they would under other circumstances. Accordingly, to minimize this error, test subjects were provided instructions throughout the trials to "pump at a comfortable rate as if you were filling two jerricans" (of 20 liters each). Observations showed that, especially at greater depths, the subjects were winded at the end of the test. In fact, the female test subject did not finish the second 20-liter bucket for either 20-mm pump at the deepest two wells or for the 25-mm Rope Pump at the 17 m well. Some literature indicates that most rural people prefer to pump at a high flow rate even if a much greater work input is required, especially at greater depths (Arlosoroff et al., 1987; van Hemert et al., 1992), This is a preference that the author has also noted in discussions with many rural people in Uganda, so this issue ,may not detract from the study conclusions. The fact that 40 liters was not pumped for all tests was also a factor in the use of the first 20 liter measurements for data analysis in this study though.

4.3.3 Rope Pump Efficiency

The efficiency of the Rope Pump can be highly variable depending on minor variances in the size of pipes and washers (pistons) used in the pump. The gap between the washer and the rising main have been identified as the most important factor in the efficiency of the pump (van Hemert et al., 1992). In addition, molded plastic washers are more efficient than rubber washers (MacCarthy, 2004; Harvey & Drouin, 2006). The washers used for this study were not molded plastic, but rubber cut from used tires. While the gap between the inner wall of the pumping pipe and the outer diameter of washers were within specification, the washers were slightly irregular, as rubber washers often are. This may have increased both friction and leakage of the pump and cause it to underperform compared to a Rope Pump with molded plastic washers. Nonetheless, rubber washers are being promoted by some, especially in the early stages of Rope Pump introduction, because they are easier to make without specialized fabricated tools like an injection mold.

4.3.4 Limitations to Resting Energy Calculation

There are indications that most error associated with the energy expenditure calculations was applied relatively uniformly to all pump tests undertaken in this study. Following from this, there is confidence that error associated with energy estimations has no significant effect on the internal validity of the comparison of the Rope Pump and the EMAS Pump based on pumping rates normalized by energy expenditure. However, there are limitations to the actual energy expenditure estimations and thus the external comparability of energy expenditure data. Some of these limitations are discussed in this and the next section.

Energy for pumping was estimated by subtracting resting energy expenditure from total energy expenditure during pumping. The Mifflin St Jeor Equations (Equations 1 and 2) used to calculate resting energy expenditure require inputs of test subject age, sex, height, and weight (Mifflin et al., 1990). Subsequent reviews and validation studies (Frankenfield et al., 2003, 2005; Frankenfield, 2013) have recommended the use of the MSJEs in healthy, non-obese people, or have confirmed their relative accuracy in an age group (18-29) relevant to this study (Hasson et al., 2011). A major weakness of the MSJEs for the present work is that they have not been validated for a tropical population, which are reported to have a 5-20% higher resting metabolism than populations from temperate climates like those that most REE studies have been focused on (Katch et al., 2010). Additionally, high ambient temperature, which characterized each pumping trial, increases REE as well (Williams, 2004). Energy expenditure is also increased a small amount due to digestion up to about four hours after eating, which would be a factor in most tests performed early each day and all tests performed after lunch .

4.3.5 Limitations to Energy Expenditure Calculation

A number of issues introduce error in the estimations of energy expenditure presented in this study, though (as stated above) it is not thought that they had an effect on the validity of the comparative analysis of the two pumps. The equation used for energy expenditure from heart rate measurements (Equation 3) was developed in a study of 118 men and women and validated with a second sample of 17 men and women, both examining energy expenditure during running and cycling (Keytel et al., 2005). The equation was found to predict energy expenditure of the validation sample with correlation coefficients of 0.857 (R^2=73.4%). There are a number of other factors that introduce additional error to the energy expenditure predictions made in this work, including the mode of exercise, environmental conditions, and lack of any individual calibration. A thorough statistical analysis was not completed, but qualitative assessments of some sources of error are discussed.

The mode of exercise used in most literature to determine energy expenditure from heart rate monitoring is running or cycling. While Keytel et al (2005) indicates “good agreement” was found with rowing, an activity that may be similar to pumping, there are a number of concerns regarding the accuracy of Equation 3 used for the specific pumping activities examined in this study. Several studies were found indicating that arm exercises result in higher heart rates than leg exercises at the same oxygen consumptions level (Rotstein & Meckel, 2000; Bot & Hollander, 2000; Ainslie et al., 2003; Mookerjee et al., 2005; Katch et al., 2010). This means that energy expenditure would likely be overestimated for arm exercises (such as operating a handpump) because the energy estimation equations were developed from running and cycling.

The lack of a measure of fitness such as maximal oxygen uptake ($VO_{2\ max}$) introduced error to the raw energy expenditure data in this study. Some literature indicates the potential to use a proxy for fitness, such as resting heart rate to improve energy expenditure calculations and offer alternative energy expenditure prediction equations that utilize resting heart rate (Rennie et al., 2001; Charlot et al., 2014). Standard field tests for the estimation of $VO_{2\ max}$ such as the "step test" could have been possible in this study and may have improved the accuracy of the energy expenditure calculations, though significant error (up to 20%) is associated with it as well (Katch et al., 2010). Additionally, a very recent study (Charlot et al., 2014) has produced new energy prediction equations that are indicated to be an improvement over Keytel et al. (2005), though they were also developed using leg exercises and are specifically intended for running, so may not be appropriate for the application in this study.

4.3.6 Factors Effecting Heart Rate

Numerous factors known to effect heart rate were described in Chapter 2. Some relevant to this study may have introduced additional error into energy calculations. Temperature is known to increase heart rate and the effects of temperature may have varied during testing, not because there was much variation in temperature, but because of the availability of shade at different test sites. Emotion is known to effect heart rate as well, a phenomenon that was observed as the subjects seemed to have elevated resting heart rates whenever there was a crowd of observers during testing. Dehydration also increases heart rate. However, water was made available and each subject drank more than 1.5 liters of water at each testing site. In addition, some trials were performed within four hours of eating, which may also increase energy expenditure. Test subjects also reported they drank caffeinated soft drinks at lunch during some tests, which may have also increased heart rate. All of these factors have been indicated to increase heart rate; therefore, the resulting energy expenditure for pumping may have been overestimated. Most of these issues would be applied to all of the trials though, so implications on internal comparisons of energy expenditures may have been marginal. Diet-induced energy expenditure is an exception and it is very likely that energy for pumping trials that took place after lunch were marginally increased.

4.4 Characterization of the Potential for the EMAS Pump in Uganda

There is evidence that the EMAS Pump has potential as an appropriate low-cost handpump in Uganda and similar countries. Some key factors include cost, available supply chains to obtain necessary materials for construction and repair, and the scale and potential for household water supply applications such as hand-dug wells, manual-drilled boreholes, and underground rainwater tanks. Some data have been collected on these factors and is presented in the following sections.

4.4.1 Supply Chains

Materials required for the fabrication of the EMAS Pump are currently available through existing supply chains in Uganda, though not in all parts of the country. PVC pipes are available in all towns large enough to have a hardware store, though many rural stores may not stock all of the pipes necessary. The lack of metric pipes in some areas is a challenge for the Rope Pump and the EMAS Pump as well as manually drilled boreholes that utilize larger metric pipes for well screens. Marbles are also not readily available upcountry (outside of Kampala), but can be bought at low prices in Kampala. Based on current supplies chains and the fact that all materials are readily available in Kampala, it is believed that improvement in the supply of relevant materials in most rural towns is quite feasible.

While all necessary pipes are manufactured by two different companies in Kampala (Gentex and Multiple Industries), it seems that metric pressure pipes (20-mm, 25-mm, 32-mm, etc.) are not stocked in many upcountry towns. In fact, the owner of one of the pipe manufacturers in Kampala informed the author that the majority of metric pipes are exported to the Democratic Republic of Congo and South Sudan. Meanwhile, standard unit pipes, such a Schedule 40 (blue) PVC pressure pipe and standard sanitary drainage pipes of 1¼" and 1½" are commonly available upcountry because they seem to be the paradigm for plumbing in Uganda. This was the situation in Gulu and was posing serious challenges to the manual drillers and Rope Pump manufacturers that have been supported by the World Vision Self-supply program. After being informed of the new demand in Gulu as well as the sources and prices of the pipes in Kampala, the owners of two different hardware stores began stocking the necessary pipes. In conclusion, the necessary supply chains for the EMAS Pump exist in Uganda, though effort may be needed to ensure that they are reaching targeted areas.

4.4.2 Material Costs

The EMAS Pump is undoubtedly one of the most affordable handpump designs available, especially in regard to pumps that can lift from great depths (up to 30m) and pump with pressure to elevations higher than ground level. Some published costs of the pump in other contexts were provided in Chapter 2. It was found that the EMAS Pump can be fabricated in Uganda for a very low price using locally available materials. Currently, the Rope Pump is the most affordable groundwater pump available in Uganda. The material costs for both pumps at selected depths (SWL) can be seen in Table 4, which also indicates the cost of each pump as well as the cost of the EMAS Pump as a percentage of the corresponding version of the Rope Pump. Full material costs estimates for selected EMAS Pumps and Rope Pumps are presented in Appendix B. All costs are based on retail prices found in Kampala in late 2013. The retail prices of materials upcountry may be >20% higher than those in Kampala, though this applies to both pumps, therefore relative material prices of the two pumps wouldn't be expected to change much in the upcountry setting.

Table 5: Material Costs for EMAS Pump Compared to the Rope Pump in Uganda (prices from Kampala, Cost % is the ratio of cost of EMAS Pump to Rope Pump)

SWL (m)	EMAS 20-mm	Rope Pump 20-mm	Cost %	EMAS 25-mm	Rope Pump 25-mm	Cost %
5	$9.10	$44.23	**21%**	$12.49	$44.66	**28%**
10	$13.63	$46.94	**29%**	$19.46	$47.93	**41%**
15	$18.16	$49.66	**37%**	$26.02	$51.93	**50%**
20	$22.70	$52.37	**43%**	$32.79	$54.46	**60%**
25	$27.23	$55.08	**49%**	-	-	-
30	$31.76	$57.80	**55%**	-	-	-

The EMAS Pump represents the greatest savings over the Rope Pump for shallow wells. For example, material cost for a 25-mm EMAS Pump is 28% that of a 25-mm Rope Pump for a well with 5 m static water level. Though savings decrease as depth increases, the material cost of EMAS Pump is only slightly more than half that of the Rope Pump at the deepest recommended depths for the 20-mm and 25-mm pumps, respectively. If pump fabrication were to be added, it is likely the gap between the rope pump and the EMAS Pump in terms of costs would increase more because the Rope Pump requires extensive welding and cutting that takes time and incurs electricity costs. In contrast, the EMAS Pump can be constructed with a few simple hand tools such as a hand saw, files, wrenches (spanners), files, and PVC glue, although it also requires marginal increased costs associated with the limited use of a heat source such as a gas flame, wood fire, or a charcoal stove.

Based on the differences in fabrication costs, it is not unreasonable to assume that the percentage savings presented in Table 4 for the EMAS Pump over the Rope Pump, would translate directly to similar (or greater) savings in regard to the retail price of complete pumps. In other words, this data is indicative that the 25-mm EMAS Pump could sell at 28% of the price of the comparable Rope Pump for a 5 m deep well, or that the 20-mm EMAS Pump could sell at 49% of the price of the 20-mm Rope Pump for a 25 m deep well. Considering Rope Pump manufacturers in Gulu are currently selling a 20-mm Rope Pump for a 20 m deep well for around UGX 250,000 ($US 100), a 20-mm EMAS Pump for the same well should sell for UGX 107,500 ($US 43) or less. This assumes that $US 1 = UGX 2,500.

Continuing with the example of the 20 m deep well, a pump fabricator should be able to make a profit while offering EMAS Pumps at a very affordable price, which can be imagined by way of an educated back-of-the-envelope calculation. Assuming a 30% increase in material prices upcountry, the material cost of the 20-mm EMAS Pump to the fabricator would be $US 29.5. Add another 10% in costs associated with fabricating the pump and the total costs to the fabricator reaches $US 32.5. If the fabricator then sells the pump for $US 43, the profit margin is about 25% and the fabricator has made $US 9.4 for a few hours' work (a significant wage in the context) and can charge an additional fee for installing the pump. Yet still, the consumer has spent less than half of what he or she would have spent on a Rope Pump at current prices in Gulu. These are very rough calculations based on a number of assumptions, but it is nonetheless clear that the potential costs savings associated with the EMAS Pump are significant. Some users may prefer to pay more for the Rope Pump, but the availability of the EMAS Pump would expand the low-cost pump market to include those who cannot afford the Rope Pump.

4.4.3 Potential for EMAS Pumps for Low-cost Groundwater Supply

A main application of low-cost pumps, including the EMAS Pump, is for pumping groundwater from low-cost household wells, either hand-dug or manually drilled. The potential of the EMAS Pump for groundwater pumping in Uganda is directly related to the current status of and potential for low-cost shallow (< 30m) groundwater development. The EMAS Pump has very little potential for groundwater supply in other areas where low-cost wells are unfeasible due to geology or where groundwater is deeper than 30 m. Ideal areas would be conducive to hand-dug wells or manually drilled boreholes and have groundwater levels of less than 20 m.

While hand-dug wells are used by households in Uganda, it seems that there is not the widespread tradition of well-digging that has been observed in Ethiopia or Zimbabwe, where large portions of the population use “family” wells. Even without hard data, the existence and significance of private hand-dug wells has been increasingly recognized by the Ugandan Government (Danert & Sutton, 2010). Carter et al. (2005) estimated that 4-5% of the population was using private hand-dug wells (differentiated from scoop-holes, which are sometimes called wells) in Uganda. This would translate to about 1.6 million people today, many of whom could likely upgrade to a low-cost handpump. Carter et al (2005) also reported interactions with artisanal well-diggers that indicated involvement with more than 160 private wells, and 108 private wells were documented in Busia Town alone (Rogenhofer, 2005). The author of this thesis has visited private hand-dug wells in Wakiso, Mukono, and Rukungiri Districts (Central and Southwestern Uganda) and has spoken with well-diggers who have indicated that there are many private hand-dug wells in Entebbe, Waskiso, and Luwero Districts (Central Uganda).

The Ministry of Water and Environment has used the term “shallow well” to describe any well or borehole less than 30 m deep. The Ministry of Water and Environment Water Supply Database (http://watsup.ug/) includes entries for 18,422 shallow wells complete with handpumps in 108 of the 111 districts, though 5,362 are listed as non-functional or decommissioned. Only 446 shallow wells are listed as privately owned and since MWE has no formal mechanism for capturing data on privately-owned water sources, it is likely a vast underestimate.

There is some recent history of manual drilling in Uganda. It has been estimated that there are up to 1,000 manually drilled wells in Uganda (Danert & Carpenter, 2013), some of which are likely included in the Ministry of Water and Environment’s tally of shallow wells referenced above. Hand augering was somewhat common for community water supply in the 1980’s and 1990’s, but it was supply-driven and fell out of use. Recently, manual drilling has been reintroduced by World Vision in Gulu (northern Uganda), where three small enterprises have been trained in Baptist Drilling and two others in Rope Pump and drilling equipment fabrication (Danert & Carpenter, 2013). As of the end of 2013, 30 boreholes have been drilled by the small businesses in Gulu, Lira, Nwoya, Amuru, and Wakiso Districts. World Vision very recently initiated micro-finance loans for household boreholes, though only three people have taken loans so far (World Vision Uganda, 2013).

Most of Uganda is underlain by Precambrian crystalline basement. Groundwater can be found in fractured (unweathered) bedrock and the weathered overburden (also known as the regolith), which is most important to shallow (<30 m) groundwater water development (MWE, 2012). There are also sedimentary alluvial deposits in valley bottoms and at the base of inselburgs that often form shallow aquifers. Low-cost groundwater development in these conditions is focused on shallow groundwater. Figure 21 indicates different groundwater development options in crystalline basement. The ‘shallow tubewell” (which can often be constructed with manual drilling techniques) and “improved dug well” are the most significant application for low-cost groundwater development, though they have slightly different applications and cost depends greatly on the context and technical details. In general, a hand-dug well may be more appropriate in some areas with low hydraulic conductivity (where water moves slowly though the ground) because their size allows for increased recharge and a significantly higher yield than a borehole in such conditions. The generalized nature of the weathered regolith in Uganda has been indicated to provide greater hydraulic conductivity at depths approaching the top of the unweathered basement (Taylor & Howard, 1998; MWE, 2012).

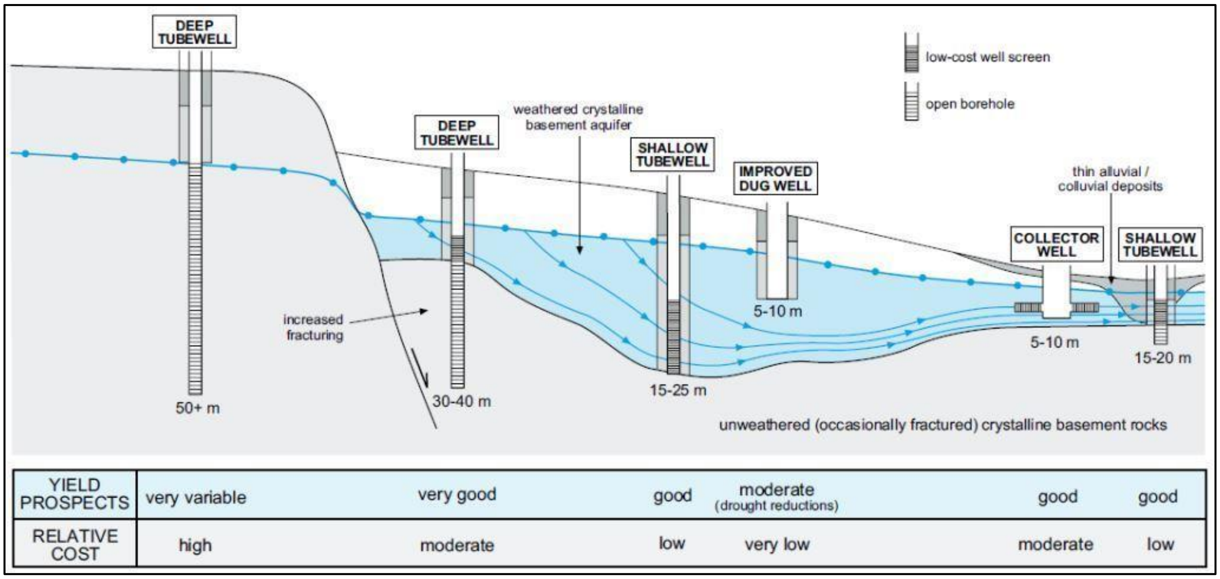


Figure 21: Groundwater development options in crystalline basement (from Foster (2006) with permission)

The Ministry of Water and Environment Directorate of Water Resources Management has published useful national, regional (by watershed), and district-level maps as part of the

Groundwater Mapping Programme. Example outputs of the programme can be downloaded at http://www.mwe.go.ug/index.php?option=com_docman&task=cat_view&gid=27&Itemid=223. These maps and the accompanying District Groundwater Reports should be useful in the development of new strategies for low-cost groundwater development.

Figure 22 depicts the national Technology Options map, which indicates that large areas of Uganda may be appropriate for "shallow wells" (< 15 m) and "shallow boreholes" (< 30 m). The map also indicates that there are other parts of Uganda that likely have very little potential for low-cost groundwater development. Central, eastern, mid-northern, northwestern, and some of western Uganda all contain considerable area indicated to be conducive to either shallow wells or shallow boreholes. Blue areas in Figure 22 (groundwater < 15 m) are the most feasible for low-cost groundwater development, but yellow areas (groundwater < 30 m) also have potential. Figure 22 was created taking geology into account as well. Many of the wells drilled by manual-drilling enterprises around Gulu have encountered groundwater at levels <10 m in areas indicated yellow in Figure 22.

Figure 23 is a map from the Water Supply Atlas, published by the Ministry of Water and Environment in 2010 (MWE, 2010a) indicating the scale of shallow wells in each district. Existing shallow wells are a likely good indicator of the potential for new shallow wells. It is clear that many of the areas identified to be appropriate for shallow groundwater development in Figure 22 are the same areas that have greater numbers of existing shallow wells in Figure 23.

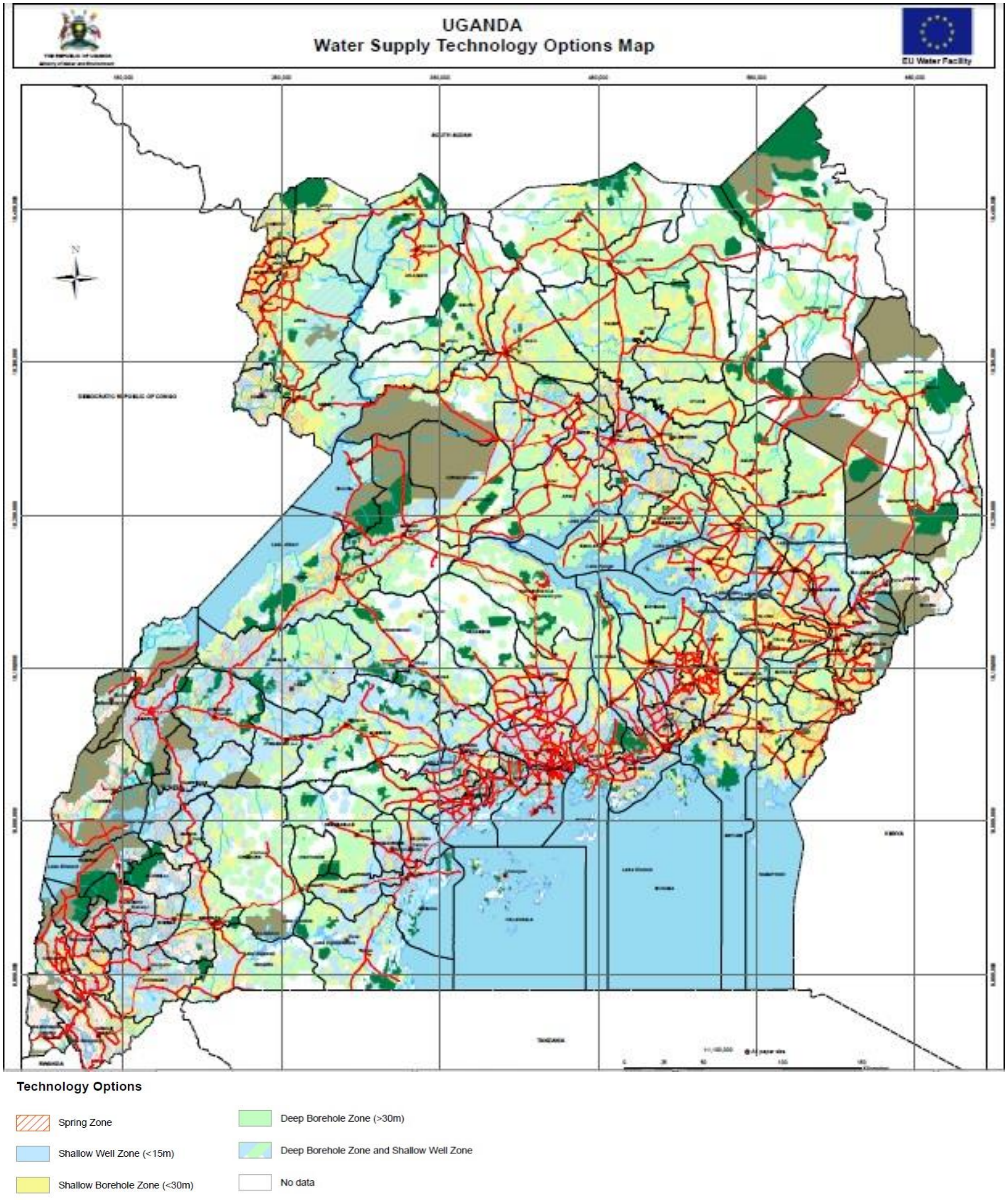


Figure 22: Water supply technology options in Uganda (from Groundwater Mapping Programme (from MWE 2012, with permission)

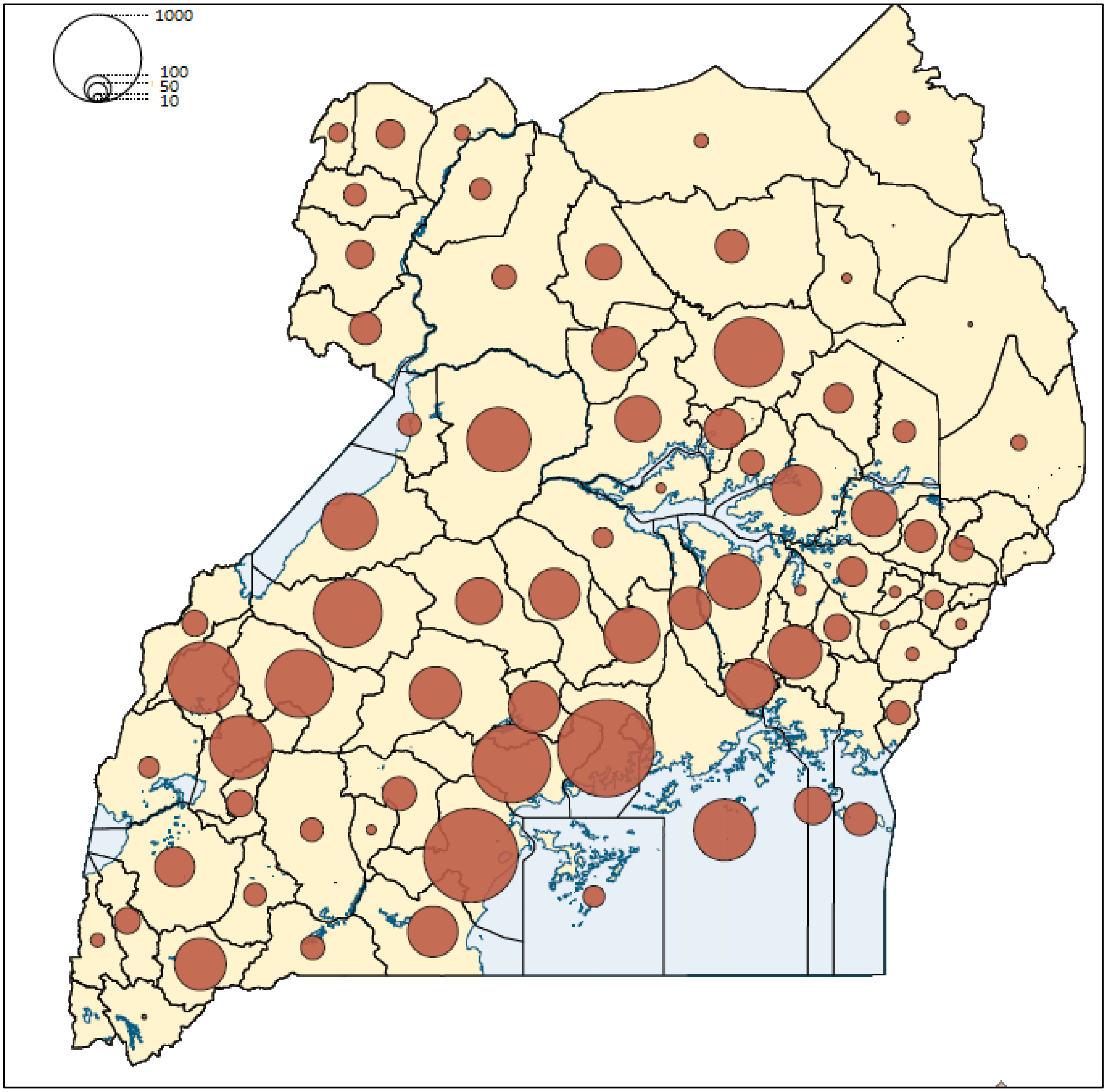


Figure 23: Shallow wells in Uganda by district (from Water Supply Atlas, MWE (2010), with permission)

4.4.4 Potential for EMAS Pumps in Rainwater Harvesting

EMAS Pumps are also applicable to underground storage tanks used in rainwater harvesting systems. About 60% of Uganda receives more than 1,200 mm of rain per year and more than 66% of households have hard roofs that lend themselves to collecting significant amounts of rainwater (Danert & Motts, 2009). There has already been significant interest and some adoption of rainwater harvesting systems at the household level in recent years. Adoption of rainwater harvesting nationally is estimated at 27% during the wet season (Danert & Sutton, 2010), while more than 100 rainwater harvesting systems were installed in Iganga district through Self-supply being promoted by the district between 2008 and 2010 (Steering Committee on Self Supply, 2011). The Ministry of Water and Environment, District Local Governments, and the Appropriate Technology Centre have all been involved with the promotion of rainwater harvesting (MWE, 2013).

Underground tanks are indicated to be lower cost than some other storage options and are being constructed in Uganda, though no reliable data was found on them. Underground tanks have been noted in different parts of southern Uganda (Rees et al., 2000; Blanchard, 2012) and have been observed by the author of this thesis. Recently, the MWE Appropriate Technology Centre (with support from the author) has begun to pilot EMAS underground tanks with EMAS Pumps. The Ministry of Water and Environment has taken note of this development (MWE, 2013) and MWE leaders have indicated a desire to promote EMAS rainwater harvesting systems on a wider scale (Kimera, 2014). Targeted promotion and technical training in the construction of underground tanks could prove useful in increasing adoption.

4.4.5 Local Skills and Facilities

The EMAS Pump does not require extensive technical skills to construct, but it does require sufficient training and practice. The most difficult skill associated with EMAS Pump construction involves the heating and forming of PVC components of the pump valves. Many plumbers in Uganda already have skills with heating and shaping pipes since prefabricated bends and curves are not always used in plumbing applications. This skill is already taught in plumbing courses in many vocational schools. There are also many Ugandans with some skill or experience in water supply work, either in well digging, handpump servicing, or other semi-skilled and skilled trades. Even so, the heating and forming skills required for making EMAS Pumps could be developed by most people with proper training and practice.

The facilities needed for fabricating EMAS Pumps are minimal. While a workshop with workbenches and clamps may seem to be a requirement, much technical work is done in the open and on the ground in Uganda. For example, the author fabricated components of the pumps used in the testing trials on his front porch in rural Uganda. Some Ugandans prefer to work on the ground even when workbenches are available because they have grown accustomed to it. Tools needed include commonly available hand tools such as a hack saw, hammer, knife, large nails, and heat source. The heat source can be a gas flame, but an open wood fire or a charcoal cooking stove is sufficient. All of these are available in more rural towns in Uganda and the latter two are available in any village.

Unlike any other pump available in Uganda, the EMAS Pump can be completely fabricated in areas where there is no electricity. This is a very important characteristic considering that most Ugandans live in such areas. As long as necessary materials can be acquired all repairs can be made onsite anywhere in Uganda. Three 6 m PVC pipes can be used to make dozens of EMAS valves, so supply chains for replacement valves in rural areas can be replenished at a low capital cost. The practice of ordering materials by phone to be sent to rural areas on top of mini buses (mutatu) is widely utilized in rural Uganda, so rural areas should be able to source necessary pipes from the closest small town relatively easily.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The EMAS Pump is a very low-cost handpump capable of pumping water from depths of < 30 m. Independent assessment has indicated that the EMAS Pump and other EMAS technologies are affordable, appropriate, scalable, and sustainable for household water systems in Bolivia (MacCarthy et al., 2013b). This study has assessed the EMAS Pump in regard to technical performance, cost, and applicability in Uganda. It is concluded that the EMAS Pump has considerable potential for success as a part of Self-supply household water systems in Uganda or other countries in sub-Saharan Africa. A number of other conclusions and recommendations are made in light of this research.

5.1 Assessment of the EMAS Pump and Comparisons with the Rope Pump

No independent testing of the EMAS Pump was found prior to this research, though others have described the pump’s capabilities (Brand, 2004; Baumann, 2011). This research demonstrated that the 20-mm pump (Standard EMAS Flexi-Pump) is capable of pumping from 30 m and possibly deeper, though pumping becomes more strenuous and pumping rates begin to diminish as depth increases beyond 20 m. Similarly, it was found that the 25-mm (Quantity EMAS Flexi-Pump) is capable of pumping at 17 m and possible a few meters deeper while maintaining flow rates above 20 l/min and with relatively low total energy expenditure. However, the 25-mm pump was found to be more demanding in terms of strength and is likely not appropriate for some users at the upper end of its depth range.

Compared to the Rope Pump, the EMAS Pump has lower flow rates at equivalent energy input, which may be a disadvantage. Thus, the Rope Pump has more potential for multiple use applications in which large volumes of water are needed. On the other hand, the EMAS Pump is likely preferable to the Rope Pump for many in light of affordability and the ability to lift water to an elevated tank to feed running water in the home or an irrigation system. In this respect, there is no handpump option currently being promoted in Uganda that compares to the EMAS Pump. The EMAS Pump also has the advantage of being a closed pump, in which there is minimal risk of water source contamination. A major delineating factor between the Rope Pump and the EMAS Pump is that the EMAS Pump can be fabricated in areas with no electricity. This is a significant factor in light of the fact that it is reported that only 5% of Uganda’s rural population has electricity service (Uganda Ministry of Energy and Mineral Development, 2012).

It is currently believed that Rope Pumps made by small businesses in Gulu (Uganda) offer the most affordable handpump option in the country, with pumps being sold at UGX 200,000 – UGX 250,000 ($US 80 - $US 100), without installation. This research concluded that the EMAS Pump could easily be the most affordable handpump in Uganda. Research into the relevant supply chains also determined that the EMAS Pump could be significantly more affordable because materials are 20% - 60% the cost of materials for the Rope Pump and fabrication is less expensive. Based on these figures, it is not unreasonable to believe that the EMAS Pump could be sold for most applications at a price of UGX 80,000 ($US 32) or less.

5.2 Characterization of Potential for the EMAS Pump in Uganda

There is considerable potential for the EMAS Pump in Uganda as a part of low-cost household water systems. There is much documentation on the potential for Self-supply in Uganda and it seems that there is a growing consensus that Self-supply has a significant role in water supply. The Ministry of Water and Environment has included Self-supply in its strategy and is taking steps to promote and support it. The EMAS Pump has specific potential as a component of household water systems that include hand-dug wells, manually drilled boreholes, or underground rainwater storage tanks. It can be made locally at a very low cost, using local materials and basic tools. This low cost positions it as an entry-level handpump option that expands the potential market of Self-supply in Uganda to those with less income. The potential for local manufacture of the EMAS Pump can lead to long-term sustainability.

Self-supply markets in hand-dug wells have been identified in eastern Uganda and it has been indicated that there may be more than 1 million rural people across the country using Self-supply wells, many of which could be upgraded with the addition of a handpump. The EMAS Pump could be the most affordable option for these people. Recent reports from northern Uganda indicate that there is a Self-supply market for low-cost household groundwater systems. Additionally, there is technical potential for the EMAS Pump in specific parts of Uganda indicated to have shallow groundwater. In these areas, low-cost groundwater technologies such as hand-dug wells or manually drilled boreholes may have significant potential and the EMAS Pump could be a very affordable pump option for these sources.

Based on rainfall patterns and the common use of metal roofing on houses in Uganda, there is significant potential for rainwater harvesting. Indeed, there has already been noteworthy success in some areas. Certain designs for underground rainwater storage tanks have been suggested to have lower costs than some above-ground storage options that are popular in Uganda, such as ferrocement, brick, or manufactured storage tanks. There is little available information on the current extent of underground rainwater storage tanks in Uganda, but it is known that they are used in different parts of the country. Recently, the MWE Appropriate

Technology Centre has begun to pilot EMAS underground tanks with EMAS Pumps, and the Ministry of Water and Environment has indicated that this work will be expanded.

Despite the apparent potential for the EMAS Pump in Uganda, the technology is only viable in light of other factors. The potential of the EMAS Pump is influenced by the strategy with which it is promoted. Strategies associated with introduction, promotion, and support may often have a greater effect on the success of a technology than its attributes and abilities. The Self-supply approach has proven successful in places such as Bolivia and Nicaragua, and recent indications from Tanzania and preliminary results in northern Uganda are promising. None of these successes though, are based only on the merits of the technologies involved. The key to the potential of the EMAS Pump and other low-cost technologies is inextricably linked with context and approach. Self-supply is a promising approach for household water systems, but its potential lies as much in the details of promotion strategies related to markets, policies, supply chains, local skills and support, financing arrangements, subsidization (or lack thereof), and opportunities for productive potential of water, among others.

5.3 Recommendations

This study concludes that the EMAS Pump has the potential to be an excellent low-cost handpump option in Uganda and should be considered for promotion as a part of Self-supply household water systems. It is very encouraging that the Ministry of Water and Environment has included the concept of Self-supply in its water development strategy and is taking steps to actively promote it. It is recommended that the EMAS Pump be integrated into the MWE's Self-supply Strategy as a low-cost option for pumping from groundwater sources and underground tanks, and that existing and additional pilot projects with the EMAS Pump should be carefully explored by MWE and NGOs in the sector. Particular attention should be paid to the Building

Blocks of Self-supply as they are important to any low-cost technology introduction. Examples of technology transfer and the promotion of Self-supply for low-cost pumps specifically should be examined, such as those from EMAS in Bolivia or SHIPO in Tanzania. Finally, technical quality must be assured in any effort to promote the EMAS Pump, as poor quality pumps are not likely to have success.

The Appropriate Technology Centre is already piloting the EMAS Pump along with EMAS-style underground rainwater tanks. This is currently the only example of the EMAS Pump being promoted in Uganda. It is recommended that this initiative proceeds with close attention to technical detail and the tenets of Self-supply. It is additionally recommended that details such as technical quality of EMAS Pumps be monitored closely. The EMAS Pump has been identified as a Self-supply handpump and its success has been linked to user investment, so it is not recommended that it be installed at households that have not been required to make a meaningful contribution. Additionally, it is recommended that this and any other pilots be closely monitored for quality in regard to technical and Self-supply implementation aspects.

In specific regard to the EMAS Pump's use with groundwater sources, efforts to create a strategy on low-cost groundwater development under Self-supply in Uganda could allow for the most appropriate areas to be targeted. The data associated with the Groundwater Mapping Programme could be very useful in this endeavor. Additionally, more detailed knowledge of areas where family wells exist could serve as an excellent starting point for developing this strategy. Such areas are certainly known to local people and some professionals in the sector, but no documentation has been found that aggregates this information. Areas with family wells could also be targeted for the implementation of upgrading programs similar to those that have been undertaken in Zimbabwe, Zambia and other places. People in these areas are already practicing

Self-supply, so may be more willing to invest in affordable improvements such as the EMAS Pump. These efforts could additionally help with identifying areas where manual drilling could have potential as an alternative to hand-dug wells. Manual drilling is likely to be more cost-effective than hand digging of wells in areas where water tables are deeper (> 10 m) and there are no hard consolidated geological formations.

Introducing the EMAS Pump to an existing program, such as the World Vision Self-supply program in Gulu, may be an effective strategy. This strategy could benefit from the growing awareness of low-cost water supply associated with promotional efforts in the existing program. Additionally, it could improve the program by increasing the options available to potential Self-supply consumers. New Self-supply pilot projects that incorporate the EMAS Pump could also be targeted in other areas appropriate for shallow groundwater development. Other studies have indicated that urban and peri-urban areas are promising initial targets for Self-supply programs because of a greater ability to pay and relative ease of awareness raising and marketing. There is evidence that areas in and around Mukono, Lira, Jinja, Entebbe, Waskiso, parts of western Uganda and others may have significant potential. One of these areas could be targeted for pilot introduction of the EMAS Pump. Mukono may be particularly attractive since the Appropriate Technology Centre is based there and such an initiative could be synergistic with the existing piloting of EMAS Pumps with underground tanks.

It is strongly recommended that any effort to promote Self-supply be focused not only on the technologies involved, but on the many other important aspects such as local technical and business skills, market research and user preferences, promotion and marketing, supply chain development, quality control, technical support mechanisms, and enabling policies. These aspects of Self-supply promotion may be known in concept, but are sometimes lost in practice. It is recommended that an organization with previous experience implementing similar Self-supply programs be involved. However, the many issues important to Self-supply should not overshadow the fact that the technology must actually work, which means that it must have quality in design, fabrication, and installation. Accordingly, it is recommended that special care be taken in regard to technical aspects of any promotion of the EMAS Pump. This research makes conclusions about individual EMAS Pumps fabricated by an individual with specific and relevant technical skills and experience. These conclusions do not necessarily apply to any pump that is made with the same design and called an EMAS Pump. Sufficient fabrication and installation quality in low-cost pumps is vital and lack of quality can make for a failed introduction of the technology. Like any new product, the EMAS Pump will have only one opportunity to make a first impression on its potential customers. Any technical problems with it can cause people to conclude that it is not valuable, regardless of whether the problems were avoidable or not. It is therefore recommended that any efforts to promote the EMAS Pump in Uganda involve professionals with previous specific technical experience with the EMAS Pump and its applications. The EMAS Pump is a simple technology that has great potential in Uganda, but simple does not necessarily mean easy.

5.4 Recommendations for Further Research

The inclusion of children as test subjects in a future study could be useful because they are reported to do a significant portion of domestic water collection in Uganda. Increases in water volumes pumped during testing would allow for the assessment of high-demand uses such as small-scale irrigation. Improvements to the heart rate based energy expenditure calculations could be made by the inclusion of individual calibration, or energy expenditure could be measured using a more accurate method such as portable respirometers, though the expense might not be justified unless associated testing costs were to decrease.

Further research could also include similar studies of the EMAS Pump with foot-pedal adaptor (leg-powered EMAS Pump) and the applicability of various models of EMAS Pumps to micro-irrigation. The high-flow EMAS Pump with 20-mm (~½”) pumping pipe could also be tested alongside the 25-mm (~¾”) version tested in this study. Examination of other EMAS technologies such as EMAS manual drilling for feasibility in the context of sub-Saharan Africa could show potential to increase shallow groundwater development options. Additionally, studies could be focused on the implementation of existing Self-supply projects such as the manual drilling and Rope Pump program supported by World Vision in Gulu. Examination of the EMAS underground storage tanks pilot being undertaken by the Appropriate Technology Centre in Uganda could also be valuable.

REFERENCES

Achten, J. & Jeukendrup, A.E. (2003). Heart rate monitoring: applications and limitations. *Sports Medicine*. 33 (7). pp. 517–538.

Ainslie, P.N., Reilly, T. & Westerterp, K.R. (2003). Estimating human energy expenditure: A review of techniques with particular reference to doubly labelled water. *Sports Medicine*. 33 (9). pp. 683–698.

Alberts, J.H. & Van Der Zee, J.J. (2003). A multi sectoral approach to sustainable rural water supply: The role of the rope handpump in Nicaragua. In: *International Symposium on Water, Poverty, and Productive uses of Water at the Household Level*. 2003, Muldersdrift, South Africa, pp. 21–23. Available from: http://www.irc.nl/page/8052.

Alford, D. (2007). *Impact and potential of self supply in Amuria Distric, Uganda*. Unpublished Master's Thesis. Cranfield University. Available from: http://rural-water-supply.net/fr/resources/details/257.

Arlosoroff, S., Tschannerl, G., Grey, D., Journey, W. & Roche, R. (1987). *Community Water Supply: The Handpump Option*. The World Bank, Washington, D.C. Available from: http://www.rural-water-supply.net/en/resources/details/409.

Asaba, R.B., Fagan, G.H., Kabonesa, C. & Mugumya, F. (2013). Beyond distance and time: Gender and the burden of water collection in rural Uganda. *The Journal of Gender and Water*. 2 (1). Available from: http://www.washdoc.info/docsearch/title/182491.

Bashaasha, B., Mangheni, M.N. & Nkonya, E. (2011). *Decentralization and Rural Service Delivery in Uganda*. International Food Policy Research Inistitute. IFPRI Discussion Paper 01063. Available from: http://www.ifpri.org/sites/default/files/publications/ifpridp01063.pdf.

Baumann, E. (2011). *Low Cost Hand Pumps* 2011-3. RWSN. St.Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/307.

Baumann, E. & Furey, S. (2013). *How Three Handpumps Revolutionised Rural Water Supplies: A brief history of the India Mark II/III, Afridev, and the Zimbabwe Bush Pump*. St.Gallen, Switzerland: RWSN. Available from: http://www.rural-water-supply.net/en/resources/details/475.

Blanchard, J. (2012). *Rainwater Harvesting Storage Methods and Self Supply in Uganda*. Unpublished Masters Thesis. University of South Florida.

Bocanegra, E., Hernandez, M. & Usunoff, E. (2005). *Groundwater and Human Development: International Association of Hydrogeologists Selected Papers on Hydrogeology Volume 6*. E. M. Bocanegra, M. A. Hernandez, & E. Usunoff (eds.). A.A. Balkema Publishers, Leiden, The Netherlands.

Bot, S.D. & Hollander, a P. (2000). The relationship between heart rate and oxygen uptake during non-steady state exercise. *Ergonomics*. 43 (10). pp. 1578–92. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11083138.

Brand, A. (2004). *Low-cost pump alternatives for rural communities in Honduras*. WSP, Lima.

Buchner, W.E. (2006). *EMAS: Water for Everybody: A Selection of Appropriate Technologies to be used for Drinkable Water*. 5th Ed. EMAS, La Paz, Bolivia.

Bunduka, E. (2013a). *Sierra Leone Pilots EMAS Technologies – Welt Hunger Hilfe* Welt Hunger Hilfe. Briefing Paper,

Bunduka, L.E. (2013b). *WASH Self-Supply Sierra Leone: Investing in household ownership and market-systems for sustainable water supply and sanitation*. Welthungerl. Available from: http://www.rural-water-supply.net/en/resources/details/502.

Butterworth, J. & Sutton, S. (2013). Self-supply as a complementary water services delivery model in Ethiopia. *Water Alternatives*. 6 (3). pp. 405–423. Available from: http://www.water-alternatives.org/index.php/allabs/225-a6-3-5/file.

Carey & Lea (1827). An essay on the art of boring the Earth (extract). *The Franklin Journal and American Mechanics' Magazine*. pp. 37–41.

Carlston, C.W. (1943). Notes on the early history of water-well drilling in the United States. *Economic Geology and the Bulletin of the Society of Economic Geologists*. 38 (2). pp. 119–136.

Carter, R. (2006). *Investigating Options for Self-help Water Supply: From field research to pilot interventions in Uganda*. RWSN and WSP. St.Gallen, Switzerland. Available from: http://www.rwsn.ch/documentation/skatdocumentation.2007-06-04.5483737723/file.

Carter, R., Mpalanyi, J.M. & Ssebalu, J. (2005). *Self-help Initiatives to Improve Water Supplies in Eastern and Central Uganda with an emphasis on shallow groundwater*. RWSN. Available from: http://www.rural-water-supply.net/en/resources/details/274.

Carter, R.C., Mpalanyi, J.M. & Kiwanuka, J. (2008). *The Uganda Self-Supply Pilot Project 2006-2008*. Kampala, Uganda. RWSN. Available from: http://www.rural-water-supply.net/en/resources/details/278.

Ceesay, S., Prentice, A.M., Day, K.C. & Scott, W. (1989). The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry. *British Journal of Nutrition*. 61. pp. 175–186.

Charlot, K., Cornolo, J., Borne, R., Brugniaux, J.V., Richalet, J.-P., Chapelot, D. & Pichon, A. (2014). Improvement of energy expenditure prediction from heart rate during running. *Physiological measurement*. 35 (2). pp. 253–266. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24434852.

CIA (2014). *The World Factbook: Uganda*. Available from: https://www.cia.gov/library/publications/the-world-factbook/geos/ug.html (Accessed: 29 January 2014).

Clasen, T., Roberts, I., Rabie, T., Schmidt, W. & Cairncross, S. (2006). Interventions to improve water quality for preventing diarrhoea. *Cochrane Database of Systematic Review*. (3).

Collins, M.A., Cureton, K.J., Hill, D.W. & Ray, C.A. (1991). Relationship of heart rate to oxygen uptake during weight lifting exercise. *Medicine & Science in Sports & Exercise*. 23 (5). pp. 636–640.

Danert, K. (2003). *Technology Transfer for Development: Insights from the Introduction of Low Cost Water Well Drilling Technology to Uganda*. Doctoral Thesis. Cranfield University.

Danert, K. (2009). *Hand Drilling Directory*. RWSN. St.Gallen, Switzerland.

Danert, K. & Carpenter, J. (2013). *Professionalising Manual Drilling: Uganda, A Country Summary* RWSN, St.Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/526.

Danert, K. & Motts, N. (2009). *Uganda Water Sector and Domestic Rainwater Harvesting Sub Sector Analysis*. Available from: http://www.rmportal.net/library/content/translinks/translinks-2009/enterprise-works-vita-relief-international/paper_ugandadomesticrainwaterharvesting.pdf.

Danert, K., Sitolo, T., Mcgill, J. & Holtslag, H. (2013). *Professionalising Manual Drilling: Malawi, A country summary* SKAT Foundation, UNICEF, RWSN, Available from: http://www.rural-water-supply.net/en/resources/details/523.

Danert, K. & Sutton, S. (2010). . *Accelerating Self Supply: A Case Study from Uganda 2010*. Rural Water Supply Network. Available from: http://www.rwsn.ch/documentation/skatdocumentation.2011-02-17.7706943265/file.

Disbrow, L. (1843). *Improvement in Apparatus for Boring Earth for Water*. Patent RX57 I2. United States Patent Office. Available from: http://pdfpiw.uspto.gov/.piw?docid=RX000057&PageNum=1&IDKey=27D62F1CBD18&HomeUrl=http://patft.uspto.gov/netahtml/PTO/patimg.htm.

Dodge, D.M. (2006). *Illustrated History of Wind Power Development: Early History Through 1875*. Available from: http://www.telosnet.com/wind/early.html (Accessed: 16 February 2014).

Dugas, L.R., Merwe, L. Van Der, Odendaal, H., Noakes, T.D. & Lambert, E. V. (2005). A novel energy expenditure prediction equation for intermittent physical activity. *Medicine & Science in Sports & Exercise*. 37 (12). pp. 2154–2161. Available from: http://content.wkhealth.com/linkback/openurl?sid=WKPTLP:landingpage&an=00005768-200512000-00021.

Esrey, S. a, Feachem, R.G. & Hughes, J.M. (1985). Interventions for the control of diarrhoeal diseases among young children: improving water supplies and excreta disposal facilities. *Bulletin of the World Health Organization*. 63 (4). pp. 757–72. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2536385&tool=pmcentrez&rendertype=abstract.

Eubanks, B.M. (1971). *The Story of the Pump and Its Relatives*. Privately Published, Salem OR.

Eubanks, B.M. (1972). A Pictorial History of the Hand Pump. *Water Well Journal*. (July).

Fagan, B. (2011). *Elixir: A History of Water and Humankind*. Bloomsbury Press, New YYork.

Fewtrell, L., Kaufmann, R.B., Kay, D., Enanoria, W., Haller, L. & Colford, J.M. (2005). Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *The Lancet infectious diseases*. 5 (1). pp. 42–52. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15620560.

Foster, S., Chilton, J., Moencg, M., Cardy, F. & Schiffler, M. (2000). *Groundwater in Rural Development. World Bank Technical Paper No. 463*. World Bank. Available from: http://elibrary.worldbank.org/content/book/9780821347034.

Foster, S., Tuinhof, A. & Garduno, H. (2006). *Groundwater development in Sub-Saharan Africa: A strategic overview of key issues and major needs*. World Bank.

Foster, S., Tuinhof, A. & Steenbergen, F. Van (2012). Managed groundwater development for water-supply security in Sub-Saharan Africa: Investment priorities. *Water South Africa*. 38 (3). pp. 359–366. Available from: http://www.ajol.info/index.php/wsa/article/view/80963.

Foster, T. (2012). *Private Sector Provision of Rural Water Services: A Desk Study for Water For People*. Water For People.

Fraenkel, P. (1986). *Water-Pumping Devices: A Handbook for Users and Choosers*. Food and Agriculture Organization of the United Nations (FAO), Rome.

Frankenfield, D., Roth-yousey, L. & Compher, C. (2005). Metabolic rate in healthy nonobese and obese adults : A systematic review. *Journal of the American Dietetic Association*. 105 (5). pp. 775–789.

Frankenfield, D.C. (2013). Bias and accuracy of resting metabolic rate equations in non-obese and obese adults. *Clinical Nutrition*. 32. pp. 976–982.

Frankenfield, D.C., Rowe, W.A., Smith, J.S. & Cooney, R.N. (2003). Validation of several established equations for resting metabolic rate in obese and nonobese people. *Journal of the American Dietetic Association*. 103 (9). pp. 1152–1159.

Gasteyer, S. (2011). *Lessons for Rural Water Supply; Assessing progress towards sustainable service delivery: United States of America*. IRC International Water and Sanitation Centre: The Hague. Available from: www.waterservicesthatlast.org/.../file/USA country study.pdf.

Green, E. (2008). *District Creation and Decentralisation in Uganda* 24. London Available from: http://www.lse.ac.uk/internationalDevelopment/research/crisisStates/download/wp/wpSeries2/WP242.pdf.

Haanen, R. & Kaduma, L. (2011). Low cost water aolutions: Sharing six year experience in private sector and sponsored programme. In: *6th Rural Water Supply Network Forum 2011*. 2011, RWSN, pp. 1–4.

Harvey, P.A. & Drouin, T. (2006). The case for the rope-pump in Africa : A comparative performance analysis. *Journal of Water and Health*. 04 (4). pp. 499–510. Available from: http://www.rural-water-supply.net/_ressources/documents/default/GENERAL_Tech-Selection-and-Buyers-Guide_Ed-2009.pdf.

Hasson, R.E., Howe, C.A., Jones, B.L. & Freedson, P.S. (2011). Accuracy of four resting metabolic rate prediction equations : Effects of sex , body mass index , age , and race / ethnicity. *Journal of Science and Medicine in Sport*. 14 (4). pp. 344–351. Available from: http://dx.doi.org/10.1016/j.jsams.2011.02.010.

Van Hemert, B., Orozco, O.S., Haemhouts, J. & Galiz, O.A. (1992). *The rope pump: the challenges of a popular technology*. Netherlands Development Organization, Juigalpa, Nicaragua.

Holtslag, H. (2011a). The SHIPO Smart Centre An example of dissemination of new low cost WASH technologies. In: *6th Rural Water Supply Network Forum 2011*. 2011, Kampala, Uganda.

Holtslag, H. (2011b). Low cost drilling with Baptist method. In: *6th Rural Water Supply Network Forum 2011*. 2011, Kamapla, Uganda.

Holtslag, H. (2014). *Personal Communication*

Holtslag, H. & de Wolf, J. (2010). *Rope Pump A-Model* Foundation Connect International, Leiden, The Netherlands Available from: http://www.ropepumps.org/English/RopepumpAmodel_manual_30-03-10.pdf.

House, S., Ince, M. & Shaw, R. (1999). *Water—- quality or quantity?* 52. WELL Technical Brief 52. WEDC. Leicestershire, UK Available from: http://www.lboro.ac.uk/well/resources/technical-briefs/52-water-quality-or-quantity.pdf.

Howard, G. & Bartram, J. (2003). *Domestic Water Quantity, Service Level, and Health*. World Health Organization, New York.

Hunter, P.R., Macdonald, A.M. & Carter, R.C. (2010). Water supply and health. *PLos Medicine*. 7 (11).

JMP (2012). *Progress on Drinking Water and Sanitation: 2012 Update*. New York.

JMP (2013). *Progress on Sanitation and Drinking-Water: 2013 Update*. New York. Available from: http://apps.who.int/iris/bitstream/10665/81245/1/9789241505390_eng.pdf.

Johnson, A. (1991). *Biomechanics and Exercise Physiology*. John Wiley & Sons, New York.

Jones, M.J. (2012). *Social adoption of groundwater pumping technology and the development of groundwater cultures: governances at the point of abstraction* Groundwater Governance: A Global Framework for Country Action. Thematic Paper 8. Rome

Jones, S. (2011). Promoting self-supply of improved traditional wells in Mali: a comparison of two approaches. In: *6th Rural Water Supply Network Forum 2011*. 2011, pp. 1–5.

Katch, V.L., McArdle, W.D. & Katch, F.I. (2010). *Essentials of Exercise Physiology*. Fourth. Lippincott Williams & Wilkens, Baltimore Maryland.

Keytel, L.R., Goedecke, J.H., Noakes, T.D., Hiiloskorpi, H., Laukkanen, R., Merwe, L. Van Der & Lambert, E. V (2005). Prediction of energy expenditure from heart rate monitoring during submaximal exercise. *Journal of Sports Sciences*. 23 (3). pp. 289–297. Available from: http://dx.doi.org/10.1080/02640410470001730089.

Kimera, P. (2014). *Personal Communication*

Kiwanuka, J. (2009). Achievements and lessons learned from Uganda Self- Supply Pilot Project 2006-2008. In: *34th WEDC International Conference: Water, Sanitation, and Hygiene: Sustainable Development and Multisectoral Approaches*. 2009, Addis Ababa, Ethiopia, pp. 1–4.

Leonard, W.R. (2010). Measuring human energy expenditure and metabolic function: basic principles and methods. *Journal of Anthropological Sciences*. 88. pp. 221–230.

Li, R., Deurenberg, P. & Hautvast, J.G. (1993). A critical evaluation of heart rate monitoring to assess energy expenditure in individuals. *American Journal of Clinical Nutrition*. 58. pp. 602–607.

Lynch, P.H., Shepard, C.U. & Geddins, J.F.M. (1881). *Artesian Wells: Municipal Report of the City of Charlston SC* Charleston, S.C.

MacCarthy, M.F. (2004). *The Development of the Rope and Washer Pump for use with Tubewells in Maputaland, South Africa*. Unpublished Master's Thesis. University of Southhampton.

MacCarthy, M.F., Annis, J.E. & Mihelcic, J.R. (2013a). Unsubsidised Self-Supply in Eastern Madagascar. *Water Alternatives*. 6 (3). pp. 424–438.

MacCarthy, M.F., Buckingham, J.W. & Mihelcic, J.R. (2013b). *Increasing Access to Low-Cost Water Supplies in Rural Areas: EMAS Household Water Supply Technologies in Bolivia* 2013-4. St. Gallen Available from: http://www.rural-water-supply.net/en/resources/details/518.

Magala Mpalanyi, J. (2008). *Uganda Self Supply Pilot Water Source History*. Kampala, Uganda. Available from: http://www.rural-water-supply.net/en/resources/details/271.

Maiga, H., Maiga, B. & Sutton, S. (2006). Self-supply in Mali. *Waterlines*. 25 (1). pp. 13–14.

McGourty, S. (2006). *An investigation into the potential of Household Water Treatment for users of hand dug wells in Busia, Uganda*. Unpublished Master's Thesis. Cranfield University.

McJunkin, F.E. (1977). *Handpumps for use in drinking water supplies in developing countries* 10. International Reference Center for Community Water Supply. Technical Paper 10. Voorburg (The Hague) Available from: http://www.cd3wd.com/cd3wd_40/JF/422/14-355.pdf.

Mifflin, M.D., StJeor, S.T., Hill, L.A., Scott, B.J., Daugherty, S.A. & Koh, Y.O. (1990). A new predictive equation for resting energy expenditure in healthy individuals. *The American Journal of Clinical Nutrition*. 51. pp. 241–247.

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

Mills, O. (2006). *Stakeholders' perceptions of self supply in the Ugandan rural water supply sector*. Unpublished Mater's Thesis. Cranfield University. Available from: http://www.rural-water-supply.net/en/resources/details/275.

Mookerjee, S., Surmacz, C., Till, M. & Weller, B. (2005). Validation of an equation for predicting energy cost of arm ergometry in women. *European journal of applied physiology*. 95 (2-3). pp. 115–20. Available from: http://www.ncbi.nlm.nih.gov/pubmed/16032417.

Morgan, P. & Chimbunde, E. (1991). Upgrading family wells in Zimbabwe. *Waterlines*. 9 (3). pp. 10–12.

Morgan, P., Chimbunde, E., Mtakwa, N. & Waterkeyn, A. (1996). Now in my backyard - Zimbabwe's upgraded family well programme. *Waterlines*. 14 (4).

Morgan, P. & Kanyemba, A. (2012). *A preliminary study of training artisans in upgradeable techniques for family owned wells*. Aquamor. Harare, Zimbabwe. Available from: http://www.rural-water-supply.net/en/resources/details/468.

Moriarty, P., Butterworth, J. & Van Koppen, B. (2004). *Beyond Domestic: Case studies on poverty and productive uses of water at the household level* IRC International Water and Sanitation Centre. Technical Paper 41. Delft, The Netherlands

MWE (2010a). *Uganda Water Supply Atlas*. Uganda Ministry of Water and Environment. Kampala, Uganda. Available from: http://www.mwe.go.ug/index.php?option=com_docman&task=cat_view&Itemid=223&gid=12.

MWE (2010b). *Report on the Ministry of Water and Environment and UNICEF officials' study tour to Zambia, Self-Supply Initiatives*. Uganda Ministry of Water and Environment. Kampala, Uganda. Available from: http://www.rural-water-supply.net/en/resources-top/details/269.

MWE (2012). *National Water Resources Assessment*. Kampala, Uganda: Ministry of Water and Environment: Directorate of Water Resource Management.

MWE (2013). *Water and Environment Sector Performance Report 2013*. Uganda Ministry of Water and Environment. Kampala, Uganda. Available from: http://www.mwe.go.ug/index.php?option=com_docman&task=doc_download&gid=623&Itemid=223.

Nederstigt, J. & van der Wal, A. (2010). *Rope Pump: Technical Training Handbook on Rope Pump Production, Installation, and Maintenance* Papendrecht, The Netherlands

NETWAS Uganda & WaterAid Uganda (2013). *WASHtechTAF Pilot Assessment: Recommendations for the sustainability and scalability of the rope pump in Iganga , Mayuge and Mpigi districts , Uganda*. Kampala, Uganda. Available from: http://www.rural-water-supply.net/en/taf/case-studies/details/19.

Ogle, M. (1993). Domestic reform and American gousehold plumbing, 1840-1870. *Winterthur Portfolio*. 28 (1). pp. 33–58. Available from: http://www.jstor.org/stable/1181497.

Olschewski, A. (2013). *Self Supply in Tanzania: SHIPO's Training* of local drillers and rope *pump producers in Makambako, 2012/2013 - Report on Follow up of Training*. Skat Foundation. St.Gallen, Switzerland. Available from: http://www.rural-water-supply.net/en/resources/details/534.

Plowman, S.A. & Smith, D.L. (2011). *Exercise Physilogy for Health, Fitness, and Performance*. Third Edit. Lippincott Williams & Wilkens, Baltimore Maryland.

Rees, D.G., Nyakaana, S. & Thomas, T.H. (2000). *Very-low-cost roofwater harvesting in the Great Lakes region of East Africa (Based on a Feasibility Study performed in the Great Lakes Region during May – July 2000)* 55. Development Technology Unit, Warwick University

Rennie, K.L., Hennings, S.J., Mitchell, J.O. & Wareham, N.J. (2001). Estimating energy expenditure by heart-rate monitoring without individual calibration. *Medicine & Science in Sports & Exercise*. 33. pp. 939–945.

Robinson, P. (2002). *Upgraded Family Wells in Zimbabwe: Household-Level Water Supplies for Multiple Uses* WSP Field Note 6. Nairobi, Kenya Available from: http://www.rural-water-supply.net/en/resources/details/280.

Rogenhofer, E. (2005). *Self Supply in Busia town, Eastern Uganda*. Unpublished Master's Thesis. Cranfield University. Available from: http://www.rural-water-supply.net/en/resources/details/272.

Rotstein, A. & Meckel, Y. (2000). Estimation of %VO2 reserve from heart rate during arm exercise and running. *European Journal of Applied Physiology*. 83. pp. 545–550.

RWSN Executive Steering Committee (2010). *Myths of the Rural Water Supply Sector* RWSN Pespective No 4. St.Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/226.

Schneider, S.J. (2012). *Water Supply Well Guidelines for use in Developing Countries*. 2nd Editio. Available from: http://www.rural-water-supply.net/en/resources/details/411.

Shephard, R.J. & Aoyagi, Y. (2012). Measurement of human energy expenditure , with particular reference to field studies: an historical perspective. *European Journal of Applied Physiology*. 112. pp. 2785–2815.

Smet, J. (2003). *WELL Factsheet: Domestic Rainwater Harvesting*. Available from: http://www.lboro.ac.uk/well/resources/fact-sheets/fact-sheets-htm/drh.htm (Accessed: 27 January 2014).

Smits, S., Van Koppen, B., Moriarty, P. & Butterworth, J. (2010). Multiple-Use Services as an alternative to rural water supply services : A characterisation of the approach. *Water Alternatives*. 3 (1). pp. 102–121.

Smits, S. & Sutton, S. (2012). *Self Supply: The Case for Leveraging Greater Household Investment in Water Supply* IRC International Water and Sanitation Centre, The Hague Available from: http://www.waterservicesthatlast.org/content/download/933/5861/file/Self supply.pdf.

Spurr, G.B., Reina, J.C. & Prentice, A.M. (1988). Energy expenditure from minute-by-minute recording : comparison with indirect curves. *The American Journal of Clinical Nutrition*. 48. pp. 552–559.

Steering Committee on Self Supply (2011). *Self Supply Experiences in Uganda: A Compilation of the Case Studies presented at the 3rd National Learning Forum, December 2011*. Kampala, Uganda. Available from:

http://www.mwe.go.ug/index.php?option=com_docman&task=doc_download&gid=240&Itemid=223.

Sutton, S. (2004a). *Preliminary Desk Study for Self Supply in sub-Saharan Africa*. WaterAid and RWSN.

Sutton, S. (2004b). *Self Supply: A Fresh Approach to Water for Rural Populations* RWSN, WSP, FDID, RWSN, WSP, FDID. Nairobi, Kenya / St. Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/273.

Sutton, S. (2008). *An Introduction to Self Supply: Putting the User First*. RWSN. St.Gallen, Switzerland. Available from: http://www.rwsn.ch/documentation/skatdocumentation.2007-12-22.4597254283/file.

Sutton, S. (2009). Integrating a new approach – the example of Self Supply. In: *34th WEDC International Conference, Addis Ababa, Ethiopia, 2009 Water, Sanitation And Hygiene Sustinable Ddevelopment and Multisectoral Approaches*. 2009.

Sutton, S. (2010a). *Accelerating Self Supply: A Case Study from Mali* Field Note. RWSN. St.Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/239.

Sutton, S. (2010b). *Accelerating Self Supply: A Case Study from Ethiopia* RWSN Field Note 2010-2. St.Gallen, Switzerland Available from: http://www.rural-water-supply.net/en/resources/details/238.

Sutton, S. (2011). *Accelerating Self Supply* Rural Water Supply Network, RWSN Field Note No 2011-2. St.Gallen, Switzerland Available from: http://www.rwsn.ch/documentation.

Sutton, S., Butterworth, J. & Mekonta, L. (2012). *A Hidden Resource: Household-led rural water supply in Ethiopia*. IRC International Water and Sanitation Centre, IRC International Water and Sanitation Centre. The Hague.

Sutton, S. & Gomme, J. (2009). Transferring the rope pump to Africa: A long and winding road? *Waterlines*. 28 (2). pp. 144–159. Available from: http://openurl.ingenta.com/content/xref?genre=article&issn=0262-8104&volume=28&issue=2&spage=144.

Taylor, R.G. & Howard, K.E.N.W.F. (1998). The dynamics of groundwater flow in the regolith of Uganda. In: P. Dillion & I. Simmers (eds.). *Shallow Groundwater Systems: IAH International Contributions to Hydrogeology Volume 18*. A.A. Balkema, Rotterdam, Netherlands, pp. 97–114.

Thomas, T.H. (2006). Roofwater harvesting in Africa. *Waterlines*. 24 (4). pp. 12–14.

Thomas, T.H. (2010). *Report on Tour of Roofwater Harvesting Systems in Southern Uganda – 22nd - 24th February 2010*.

Tillett, W. (2007). *An Investigation into the Impacts and Challenges of Implementing Self Supply in Eastern Uganda*. Unpublished Master's Thesis. Cranfield University. Available from: http://www.rural-water-supply.net/en/resources/details/245.

U.S. Census Bureau (2011). *Historic Census of Housing Tables*. Available from: http://www.census.gov/hhes/www/housing/census/historic/water.html (Accessed: 16 February 2014).

Uganda Ministry of Energy and Mineral Development (2012). *Rural Electrification Strategy and Plan 2013-2022*. Kampala, Uganda. Available from: http://www.rea.or.ug/.

UNESCO (2012). *The United National World Water Development Report 4*. UNESCO, Paris. Available from: http://unesdoc.unesco.org/images/0021/002156/215644e.pdf.

Vanhees, L., Lefevre, J., Philippaerts, R., Martens, M., Huygens, W., Troosters, T. & Beunen, G. (2005). How to assess physical activity? How to assess physical fitness? *European Journal of Cardiovascular Prevention & Rehabilitation*. 12 (2). pp. 102–114. Available from: http://cpr.sagepub.com/lookup/doi/10.1097/01.hjr.0000161551.73095.9c.

Wailes, B.L.C. (1854). *Report on the agriculture and geology of Mississippi* Mississippi State Printer, E. Barksdale

Weight, E., Yoder, R. & Keller, A. (2013). *Manual Well Drilling Investment Opportunity in Ethiopia* 155. Colombo, Sri Lanka Available from: www.iwmi.irg/publications/workng_papers/index.aspx.

Whitehead, V. (2001). *Development and Selection of Low Cost Handpumps for Domestic Rainwater Water Tanks in E . Africa*. Unpublished Master's Thesis. University of Warwick.

WHO and UNICEF (2000). *Global Water Supply and Sanitation Assessment 2000 Report*. Geneva/New York.

Williams, M. (2004). Human Energy. In: *Nutrition for Health, Fitness, and Sport*. McGraw Hill.

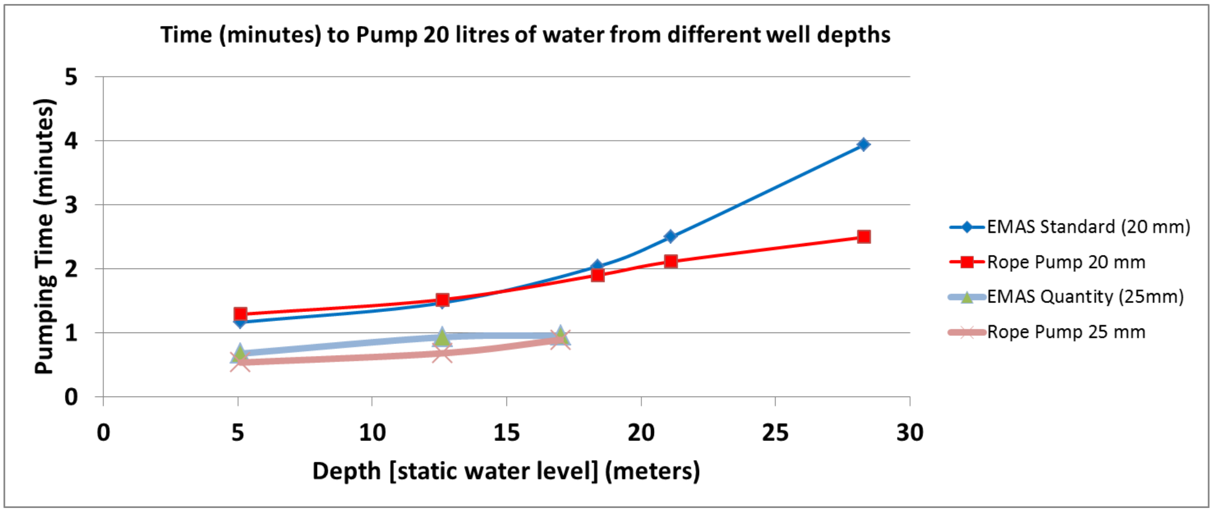
World Vision Uganda (2013). *Manual Drilling (Low-cost WASH) Quarterly Report (Internal Report)*

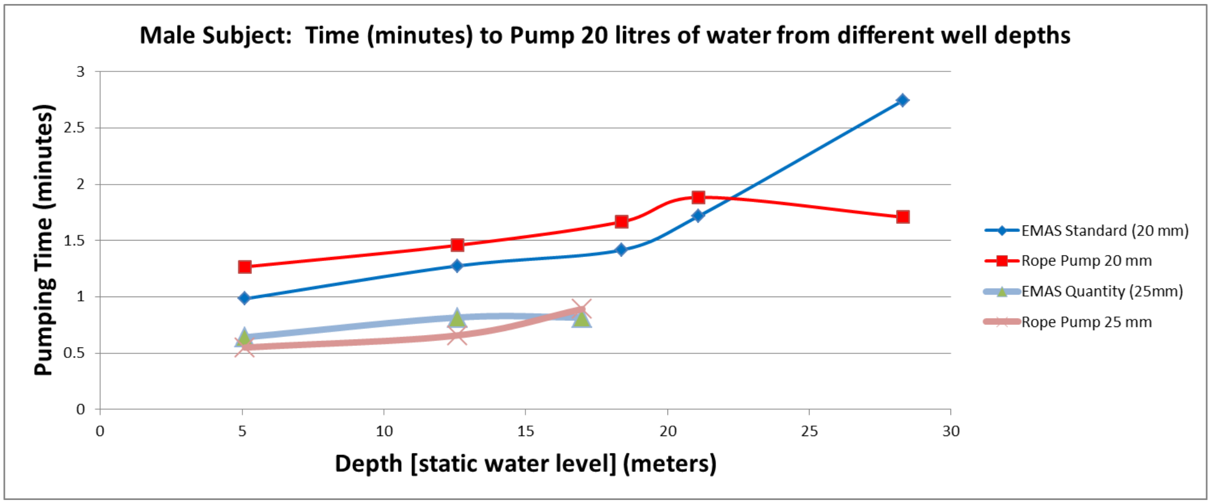
Wright, J., Gundry, S. & Conroy, R. (2004). Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine and International Health*. 9 (1). pp. 106–117.

Wright, J.A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., Mutisi, C. & Potgieter, N. (2006). Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: implications for monitoring the Millennium Development Goal for water. *Water Practice and Technology*. 1 (2). pp. 1–9. Available from: http://www.rural-water-supply.net/en/resources/details/250.

APPENDICES

Appendix A: Additional Charts and Data from Pumping Tests





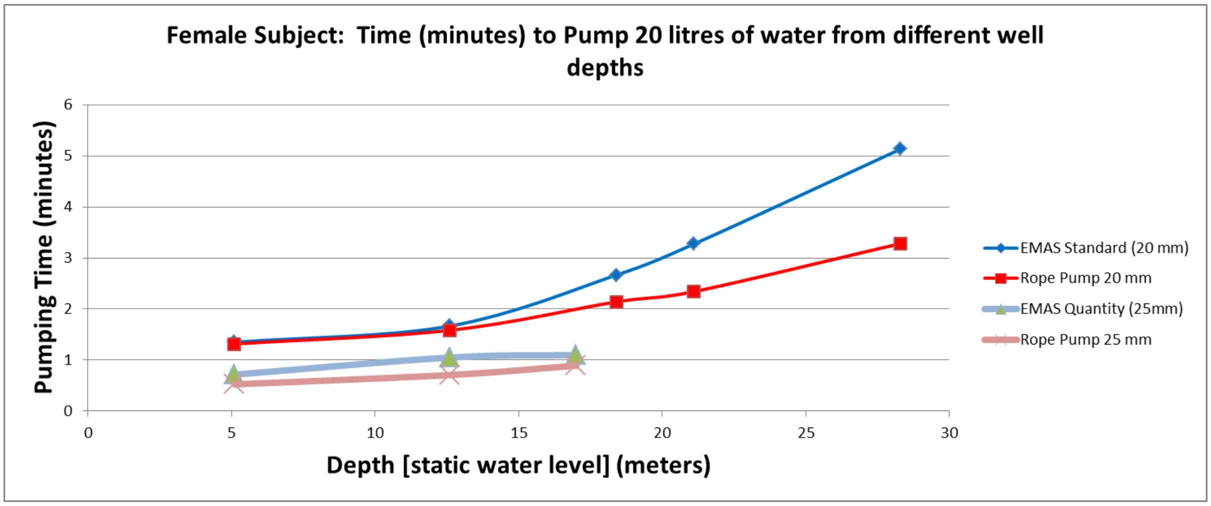
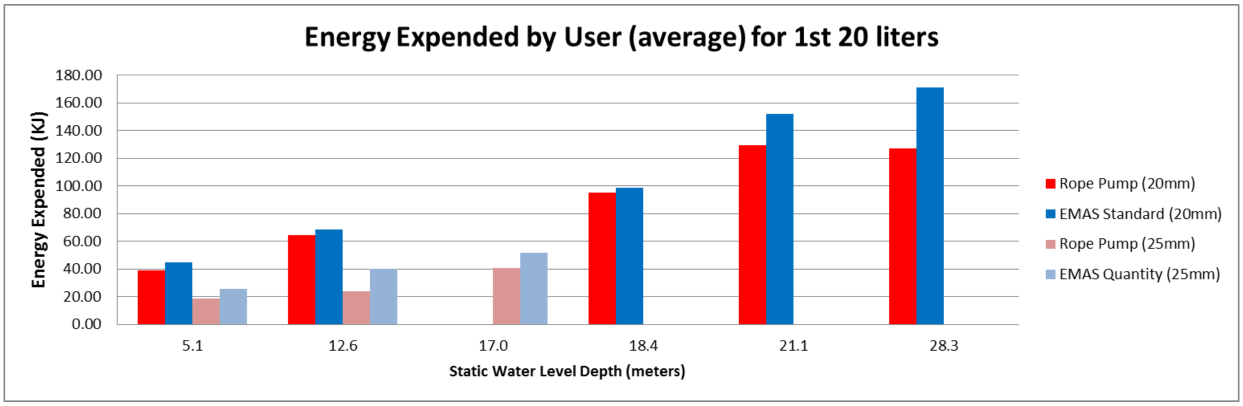
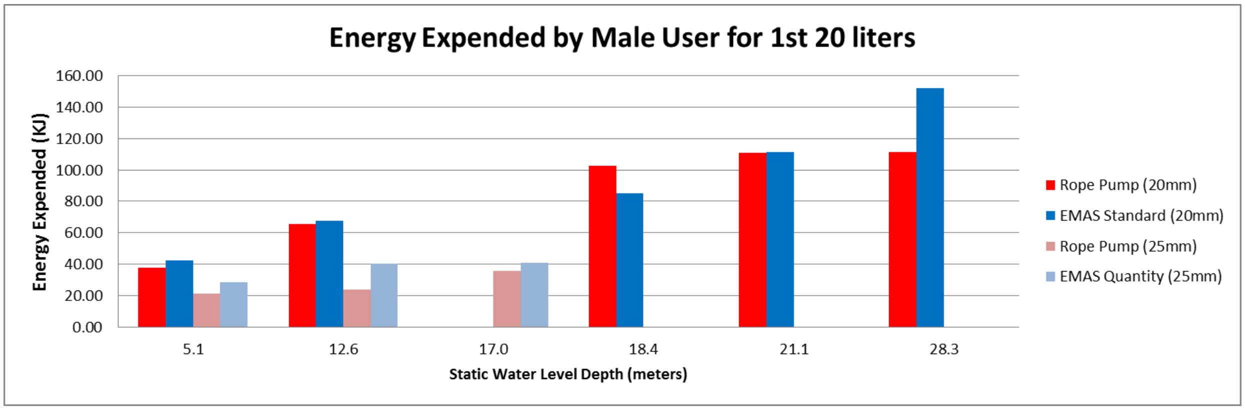


Figure A1: Graphs indicating average time to pump 20 liters at various depths

Appendix A (continued)





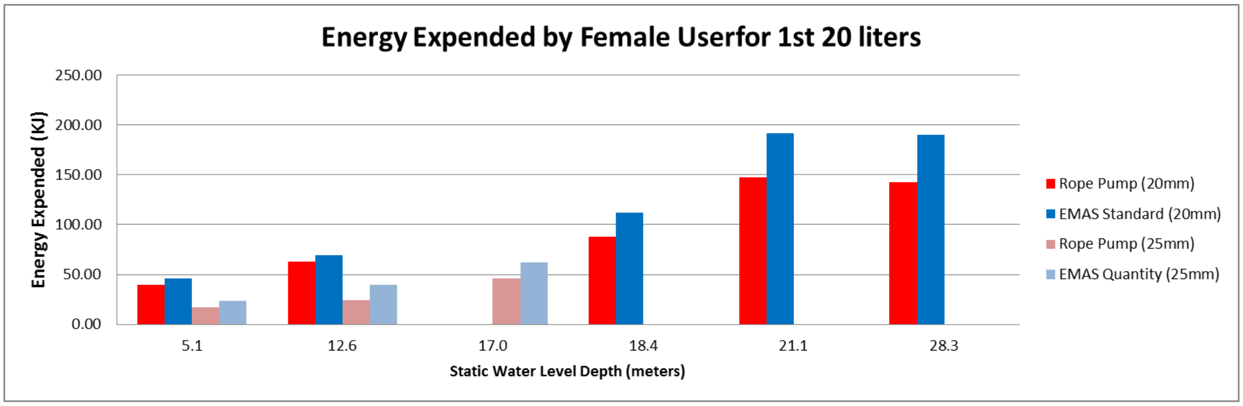


Figure A2: Graphs indicating estimated energy expended to pump first 20 liters at various depths

Appendix B: Material Costs for EMAS Pumps and Rope Pumps (Kampala)

Table B1: Material Costs for 20-mm Rope Pump – 10 m Depth

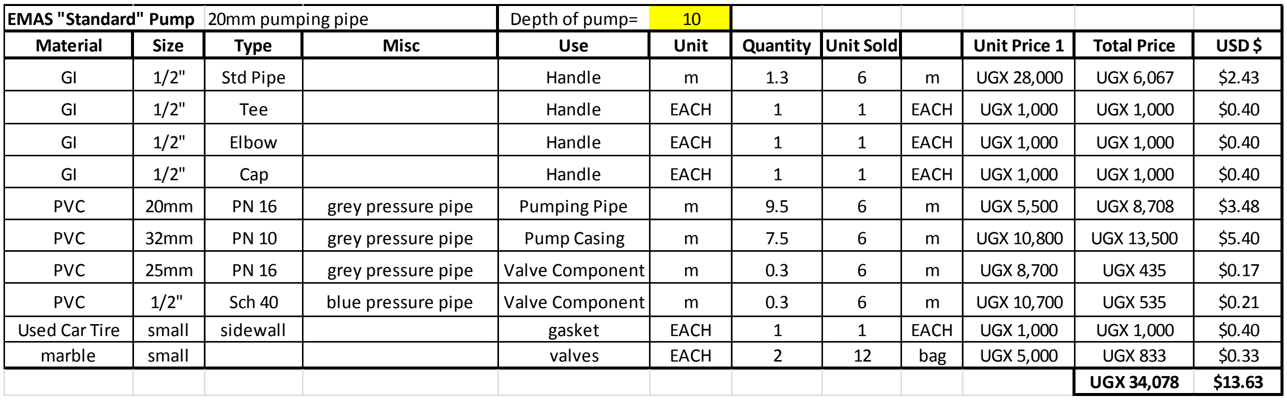
Family Model Rope Pump (20mm riser pipe)					Depth =	10					
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"	STD pipe	2.2mm wall	pump frame / guide box	m	5.75	6	m	UGX 28,000	UGX 26,833	$10.73
GI	3/4"	STD pipe		pump frame / guide box	m	1	6	m	UGX 35,000	UGX 5,833	$2.33
GI	1"	STD pipe		pump frame / guide box	m	0.3	6	m	UGX 68,000	UGX 3,400	$1.36
PVC	20mm	PN 16	(~1/2")	riser pipe	m	10.75	6	m	UGX 5,500	UGX 9,854	$3.94
PVC	25mm	PN10	(~3/4")	handle grip	m	0.1	6	m	UGX 6,800	UGX 113	$0.05
PVC	32mm	PN 10	(~1")	guide pipes	m	1.5	6	m	UGX 10,800	UGX 2,700	$1.08
PVC	50mm	PN 6	(~1.5")	pump spout	m	1	6	m	UGX 17,000	UGX 2,833	$1.13
PVC	50mm	Tee	fitting	spout connection	EACH	2	6	m	UGX 4,800	UGX 1,600	$0.64
PVC	50mm>32mm	Bushing	fitting	riser > spout adaptor	EACH	4	1	EACH	UGX 1,500	UGX 6,000	$2.40
PVC	32mm>25mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
PVC	32mm>20mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
polyrope	4mm		100m roll	rope	EACH	23	100	m roll	UGX 22,000	UGX 5,060	$2.02
Used Car Tire	14"	No Steel!!	whole tire	washers /wheel	EACH	1	1	EACH	UGX 10,000	UGX 10,000	$4.00
Iron round bar	8mm			rebar for install	m	2	12	m	UGX 20,000	UGX 3,333	$1.33
Paint	Rex Oxide			prevents rust	Small can	1	1	EACH	UGX 6,000	UGX 6,000	$2.40
Spray Paint	Any Color			coating	Can	1	1	EACH	UGX 15,000	UGX 15,000	$6.00
Welding Rods	2.5mm			welding	EACH	12	1	EACH	UGX 200	UGX 2,400	$0.96
Grinding Discs				cutting / grinding	EACH	1	1	EACH	UGX 14,000	UGX 14,000	$5.60
										UGX 117,361	**$46.94**

Table B2: Material Costs for 20-mm Rope Pump – 25 m Depth

Family Model Rope Pump (20mm riser pipe)					Depth =	25					
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"	STD pipe	2.2mm wall	pump frame / guide box	m	5.75	6	m	UGX 28,000	UGX 26,833	$10.73
GI	3/4"	STD pipe		pump frame / guide box	m	1	6	m	UGX 35,000	UGX 5,833	$2.33
GI	1"	STD pipe		pump frame / guide box	m	0.3	6	m	UGX 68,000	UGX 3,400	$1.36
PVC	20mm	PN 16	(~1/2")	riser pipe	m	25.75	6	m	UGX 5,500	UGX 23,604	$9.44
PVC	25mm	PN10	(~3/4")	handle grip	m	0.1	6	m	UGX 6,800	UGX 113	$0.05
PVC	32mm	PN 10	(~1")	guide pipes	m	1.5	6	m	UGX 10,800	UGX 2,700	$1.08
PVC	50mm	PN 6	(~1.5")	pump spout	m	1	6	m	UGX 17,000	UGX 2,833	$1.13
PVC	50mm	Tee	fitting	spout connection	EACH	2	6	m	UGX 4,800	UGX 1,600	$0.64
PVC	50mm>32mm	Bushing	fitting	riser > spout adaptor	EACH	4	1	EACH	UGX 1,500	UGX 6,000	$2.40
PVC	32mm>25mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
PVC	32mm>20mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
polyrope	4mm		100m roll	rope	EACH	53	100	m roll	UGX 22,000	UGX 11,660	$4.66
Used Car Tire	14"	No Steel!!	whole tire	washers /wheel	EACH	1	1	EACH	UGX 10,000	UGX 10,000	$4.00
Iron round bar	8mm			rebar for install	m	2	12	m	UGX 20,000	UGX 3,333	$1.33
Paint	Rex Oxide			prevents rust	Small can	1	1	EACH	UGX 6,000	UGX 6,000	$2.40
Spray Paint	Any Color			coating	Can	1	1	EACH	UGX 15,000	UGX 15,000	$6.00
Welding Rods	2.5mm			welding	EACH	12	1	EACH	UGX 200	UGX 2,400	$0.96
Grinding Discs				cutting / grinding	EACH	1	1	EACH	UGX 14,000	UGX 14,000	$5.60
										UGX 137,711	**$55.08**

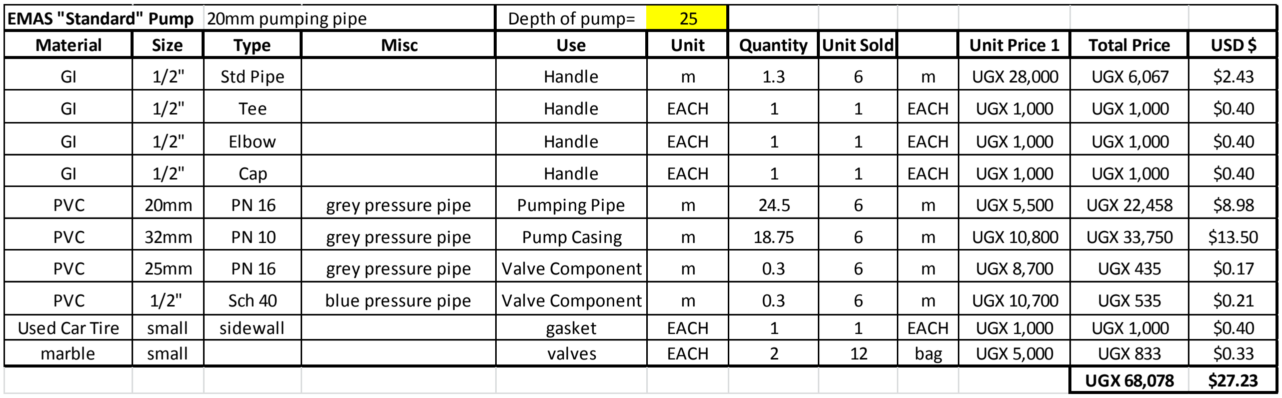
Appendix B (continued)

Table B3: Material Costs for 20-mm EMAS Pump – 10 m Depth



EMAS "Standard" Pump		20mm pumping pipe		Depth of pump=	10						
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"	Std Pipe		Handle	m	1.3	6	m	UGX 28,000	UGX 6,067	$2.43
GI	1/2"	Tee		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
GI	1/2"	Elbow		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
GI	1/2"	Cap		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
PVC	20mm	PN 16	grey pressure pipe	Pumping Pipe	m	9.5	6	m	UGX 5,500	UGX 8,708	$3.48
PVC	32mm	PN 10	grey pressure pipe	Pump Casing	m	7.5	6	m	UGX 10,800	UGX 13,500	$5.40
PVC	25mm	PN 16	grey pressure pipe	Valve Component	m	0.3	6	m	UGX 8,700	UGX 435	$0.17
PVC	1/2"	Sch 40	blue pressure pipe	Valve Component	m	0.3	6	m	UGX 10,700	UGX 535	$0.21
Used Car Tire	small	sidewall		gasket	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
marble	small			valves	EACH	2	12	bag	UGX 5,000	UGX 833	$0.33
										UGX 34,078	**$13.63**

Table B4: Material Costs for 20-mm EMAS Pump – 25 m Depth



EMAS "Standard" Pump		20mm pumping pipe		Depth of pump=	25						
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"	Std Pipe		Handle	m	1.3	6	m	UGX 28,000	UGX 6,067	$2.43
GI	1/2"	Tee		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
GI	1/2"	Elbow		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
GI	1/2"	Cap		Handle	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
PVC	20mm	PN 16	grey pressure pipe	Pumping Pipe	m	24.5	6	m	UGX 5,500	UGX 22,458	$8.98
PVC	32mm	PN 10	grey pressure pipe	Pump Casing	m	18.75	6	m	UGX 10,800	UGX 33,750	$13.50
PVC	25mm	PN 16	grey pressure pipe	Valve Component	m	0.3	6	m	UGX 8,700	UGX 435	$0.17
PVC	1/2"	Sch 40	blue pressure pipe	Valve Component	m	0.3	6	m	UGX 10,700	UGX 535	$0.21
Used Car Tire	small	sidewall		gasket	EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
marble	small			valves	EACH	2	12	bag	UGX 5,000	UGX 833	$0.33
										UGX 68,078	**$27.23**

Appendix B (continued)

Table B5: Material Costs for 25-mm Rope Pump – 5 m Depth

Family Model Rope Pump (25mm riser pipe)					Depth =	5					
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**			**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"		2.2mm wall	pump frame	m	5.75	6	m	UGX 28,000	UGX 26,833	$10.73
GI	3/4"			pump frame	m	1	6	m	UGX 35,000	UGX 5,833	$2.33
GI	1"			pump frame	m	0.25	6	m	UGX 68,000	UGX 2,833	$1.13
PVC	25mm	PN10	(~3/4")	riser pipe / handle grip	m	5.85	6	m	UGX 6,800	UGX 6,630	$2.65
PVC	32mm	PN 6	(~1")	guide pipes	m	1.5	6	m	UGX 10,800	UGX 2,700	$1.08
PVC	50mm	PN 6	(~1.5")	pump spout	m	1	6	m	UGX 17,000	UGX 2,833	$1.13
PVC	50mm	Tee	fitting	spout connection	EACH	2	6	m	UGX 4,800	UGX 1,600	$0.64
PVC	50mm>32mm	Bushing	fitting	riser > spout adaptor	EACH	4	1	EACH	UGX 1,500	UGX 6,000	$2.40
PVC	32mm>25mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
PVC	32mm>20mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
polyrope	6mm		100m roll	rope	EACH	13	100	m roll	UGX 25,000	UGX 3,250	$1.30
Used Car Tire	14"	No Steel!!	whole tire	washers / plungers	EACH	1	1	EACH	UGX 10,000	UGX 10,000	$4.00
Iron round bar	10mm			rebar for install	m	2	12	m	UGX 20,000	UGX 3,333	$1.33
Paint	Rex Oxide			prevents rust	Small can	1	1	EACH	UGX 6,000	UGX 6,000	$2.40
Spray Paint	Any Color			coating	Can	1	1	EACH	UGX 15,000	UGX 15,000	$6.00
Welding Rods	2.5mm			welding	EACH	12	1	EACH	UGX 200	UGX 2,400	$0.96
Grinding Disc				cutting /grinding	EACH	1	1	EACH	UGX 14,000	UGX 14,000	$5.60
										UGX 111,647	**$44.66**

Table B6: Material Costs for 25-mm Rope Pump – 15 m Depth

Family Model Rope Pump (25mm riser pipe)					Depth =	15					
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**			**Unit Price 1**	**Total Price**	**USD $**
GI	1/2"		2.2mm wall	pump frame	m	5.75	6	m	UGX 28,000	UGX 26,833	$10.73
GI	3/4"			pump frame	m	1	6	m	UGX 35,000	UGX 5,833	$2.33
GI	1"			pump frame	m	0.25	6	m	UGX 68,000	UGX 2,833	$1.13
PVC	25mm	PN10	(~3/4")	riser pipe / handle grip	m	15.85	6	m	UGX 6,800	UGX 17,963	$7.19
PVC	32mm	PN 6	(~1")	guide pipes	m	1.5	6	m	UGX 10,800	UGX 2,700	$1.08
PVC	50mm	PN 6	(~1.5")	pump spout	m	1	6	m	UGX 17,000	UGX 2,833	$1.13
PVC	50mm	Tee	fitting	spout connection	EACH	2	6	m	UGX 4,800	UGX 1,600	$0.64
PVC	50mm>32mm	Bushing	fitting	riser > spout adaptor	EACH	4	1	EACH	UGX 1,500	UGX 6,000	$2.40
PVC	32mm>25mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
PVC	32mm>20mm	Bushing	fitting	riser > spout adaptor	EACH	2	1	EACH	UGX 600	UGX 1,200	$0.48
polyrope	6mm		100m roll	rope	EACH	33	100	m roll	UGX 25,000	UGX 8,250	$3.30
Used Car Tire	14"	No Steel!!	whole tire	washers / plungers	EACH	1	1	EACH	UGX 10,000	UGX 10,000	$4.00
Iron round bar	10mm			rebar for install	m	2	12	m	UGX 20,000	UGX 3,333	$1.33
Paint	Rex Oxide			prevents rust	Small can	1	1	EACH	UGX 6,000	UGX 6,000	$2.40
Spray Paint	Any Color			coating	Can	1	1	EACH	UGX 15,000	UGX 15,000	$6.00
Welding Rods	2.5mm			welding	EACH	12	1	EACH	UGX 200	UGX 2,400	$0.96
Grinding Disc				cutting /grinding	EACH	1	1	EACH	UGX 14,000	UGX 14,000	$5.60
										UGX 127,980	**$51.19**

Appendix B (continued)

Table B7: Material Costs for 25-mm EMAS Pump – 5 m Depth

EMAS "Quantity" Pump (Uganda Version) 25mm pumping pipe				Depth of pump=	5						
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	3/4"	Std Pipe		Handle	m	1.3	6	m	UGX 35,000	UGX 7,583	$3.03
GI	3/4"	Tee		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
GI	3/4"	Elbow		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
GI	3/4"	Cap		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
PVC	1 1/2"	Pipe	gray drain pipe	Pump Casing	m	4.5	6	m	UGX 13,500	UGX 10,125	$4.05
PVC	25mm	PN 10	gray pressure pipe	Pumping Pipe	m	4.25	6	m	UGX 6,800	UGX 4,817	$1.93
PVC	1 1/4"	drain pipe	gray drain pipe	Valve Component	m	0.2	6	m	UGX 11,500	UGX 383	$0.15
PVC	3/4"	sch 40	blue pressure pipe	Valve Component	m	0.2	6	m	UGX 14,200	UGX 473	$0.19
PVC	1"	sch 40	blue pressure pipe	Valve Component	m	0.2	6	m	UGX 20,200	UGX 673	$0.27
Used Car Tire	small	piece			EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
marble	small			valves	EACH	2	6	bag	UGX 5,000	UGX 1,667	$0.67
										UGX 31,222	**$12.49**

Table B8: Material Costs for 25-mm EMAS Pump – 15 m Depth

EMAS "Quantity" Pump (Uganda Version) 25mm pumping pipe				Depth of pump=	15						
Material	**Size**	**Type**	**Misc**	**Use**	**Unit**	**Quantity**	**Unit Sold**		**Unit Price 1**	**Total Price**	**USD $**
GI	3/4"	Std Pipe		Handle	m	1.3	6	m	UGX 35,000	UGX 7,583	$3.03
GI	3/4"	Tee		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
GI	3/4"	Elbow		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
GI	3/4"	Cap		Handle	EACH	1	1	EACH	UGX 1,500	UGX 1,500	$0.60
PVC	1 1/2"	Pipe	gray drain pipe	Pump Casing	m	14.5	6	m	UGX 13,500	UGX 32,625	$13.05
PVC	25mm	PN 10	gray pressure pipe	Pumping Pipe	m	14.25	6	m	UGX 6,800	UGX 16,150	$6.46
PVC	1 1/4"	drain pipe	gray drain pipe	Valve Component	m	0.2	6	m	UGX 11,500	UGX 383	$0.15
PVC	3/4"	sch 40	blue pressure pipe	Valve Component	m	0.2	6	m	UGX 14,200	UGX 473	$0.19
PVC	1"	sch 40	blue pressure pipe	Valve Component	m	0.2	6	m	UGX 20,200	UGX 673	$0.27
Used Car Tire	small	piece			EACH	1	1	EACH	UGX 1,000	UGX 1,000	$0.40
marble	small			valves	EACH	2	6	bag	UGX 5,000	UGX 1,667	$0.67
										UGX 65,055	**$26.02**

Appendix C: Permissions for Use of Figures 1, 2, 7, 10, 21, 22, and 23

USF

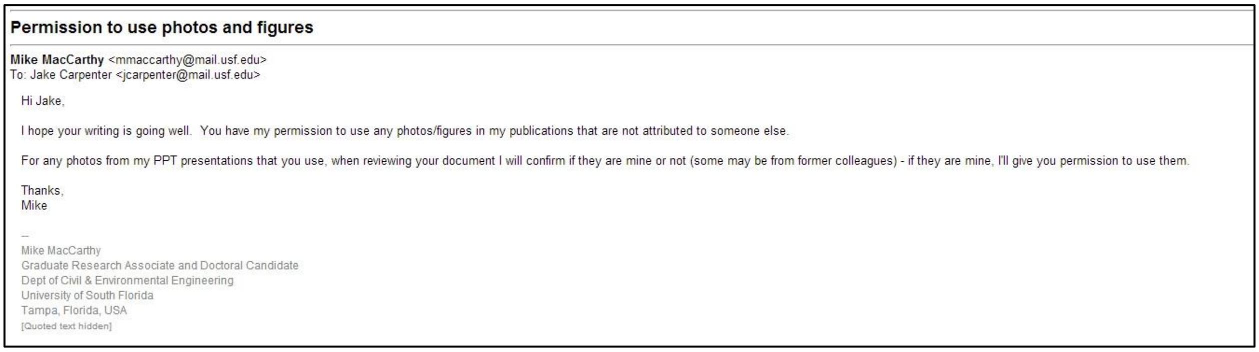
Jacob Carpenter <jcarpenter@mail.usf.edu>

Use of figures

Sally Sutton <sally_e_sutton@hotmail.com> Wed, Feb 26, 2014 at 2:12 AM
To: "jcarpenter@mail.usf.edu" <jcarpenter@mail.usf.edu>

This is just to confirm that I am very happy for Jake Carpenter to use any figures from any published work of which I am author or part author, especially if the source is acknowledged.
Best wishes
Sally Sutton

Dr S E Sutton
14 Kennedy Road
Shrewsbury
Shropshire SY3 7AB
Skype sallysut1
Tel 0044 1743351435



Permission to use photos and figures

Mike MacCarthy <mmaccarthy@mail.usf.edu>
To: Jake Carpenter <jcarpenter@mail.usf.edu>

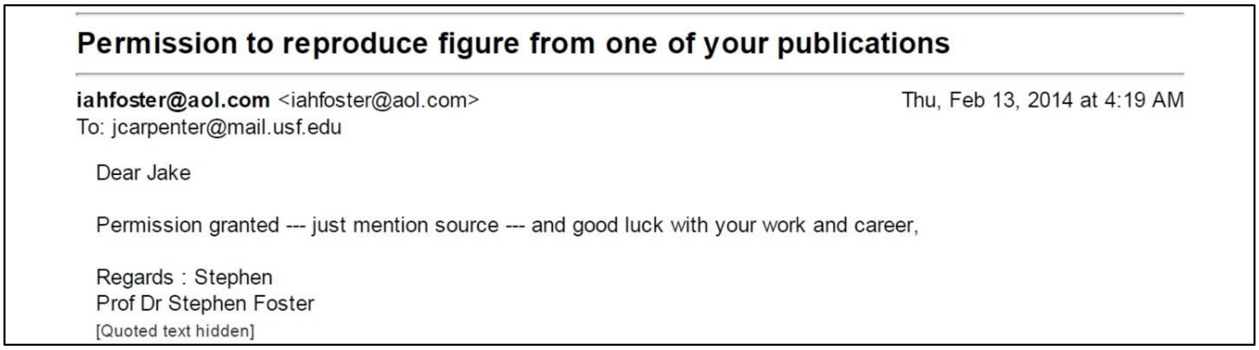
Hi Jake,

I hope your writing is going well. You have my permission to use any photos/figures in my publications that are not attributed to someone else.

For any photos from my PPT presentations that you use, when reviewing your document I will confirm if they are mine or not (some may be from former colleagues) - if they are mine, I'll give you permission to use them.

Thanks,
Mike

--
Mike MacCarthy
Graduate Research Associate and Doctoral Candidate
Dept of Civil & Environmental Engineering
University of South Florida
Tampa, Florida, USA
[Quoted text hidden]



Permission to reproduce figure from one of your publications

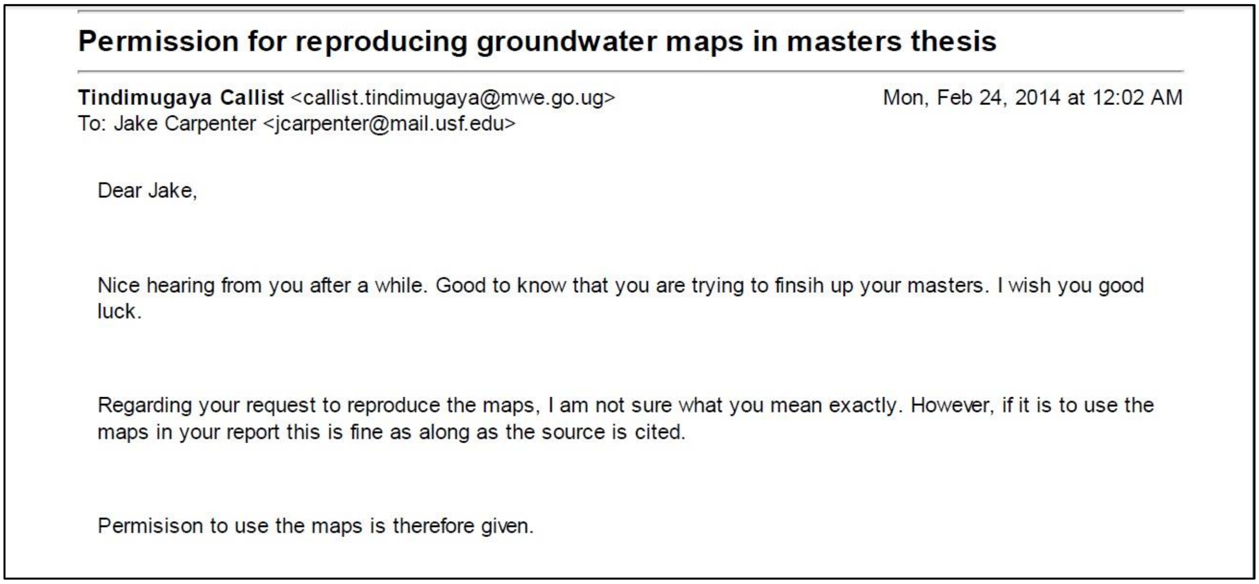
iahfoster@aol.com <iahfoster@aol.com> Thu, Feb 13, 2014 at 4:19 AM
To: jcarpenter@mail.usf.edu

Dear Jake

Permission granted --- just mention source --- and good luck with your work and career,

Regards : Stephen
Prof Dr Stephen Foster
[Quoted text hidden]

Appendix C (continued)



Permission for reproducing groundwater maps in masters thesis

Tindimugaya Callist <callist.tindimugaya@mwe.go.ug> Mon, Feb 24, 2014 at 12:02 AM
To: Jake Carpenter <jcarpenter@mail.usf.edu>

Dear Jake,

Nice hearing from you after a while. Good to know that you are trying to finsih up your masters. I wish you good luck.

Regarding your request to reproduce the maps, I am not sure what you mean exactly. However, if it is to use the maps in your report this is fine as along as the source is cited.

Permisison to use the maps is therefore given.

Appendix D: Raw Data from Pumping Trials

Table D1: Raw Data Summary for 20 mm EMAS Pump

Static Water Level (meters)		EMAS Pump Standard													
		Male							Female						
	Trial	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note
5.1	1	40.86	59	60.58	61	101.44	120		46.27	83	65.88	93	112.15	176	
5.1	2	44.26	59	68.55	63	112.81	122		46.50	79	60.61	79	107.11	158	
5.1	**AVG**	**42.56**	**59.0**	**64.57**	**62.0**	**107.12**	**121.0**		**46.38**	**81.0**	**63.25**	**86.0**	**109.63**	**167.0**	
12.6	1	67.61	81	98.88	89	166.49	170		68.05	106	79.77	99	147.82	205	
12.6	2	67.65	72	101.49	86	169.14	158		70.93	94	70.58	92	141.51	186	
12.6	**AVG**	**67.63**	**76.5**	**100.19**	**87.5**	**167.81**	**164.0**		**69.49**	**100.0**	**75.17**	**95.5**	**144.66**	**195.5**	
17.0	1														
17.0	2														
17.0	**AVG**														
18.4	1	81.64	85	134.36	105	216.00	190		110.55	160	142.57	176	253.12	336	
18.4	2	88.42	85	137.29	105	225.70	190		114.28	160	144.47	176	258.74	336	
18.4	**AVG**	**85.03**	**85.0**	**135.82**	**105.0**	**220.85**	**190.0**		**112.41**	**160.0**	**143.52**	**176.0**	**255.93**	**336.0**	
21.1	1	94.81	98.0	146.67	117.0	241.49	215		189.41	198.0					
21.1	2	127.96	108.0	174.68	130.0	302.64	238		194.71	195.0					
21.1	**AVG**	**111.39**	**103.0**	**160.67**	**123.5**	**272.06**	**226.5**		**192.06**	**196.5**					
28.3	1	145.38	160	196.20	185	341.58	345		189.07	**321**					
28.3	2	158.83	169	205.16	193	363.99	362		190.60	295					
28.3	**AVG**	**152.11**	**164.5**	**200.68**	**189.0**	**352.79**	**353.5**		**189.84**	**308**					

Table D2: Raw Data Summary for 20 mm Rope Pump

Static Water Level (meters)		Rope Pump 20mm													
		Male							Female						
	Trial	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note
5.1	1	36.79	77	53.46	78	90.25	155		39.14	78	67.28	90	106.42	168	
5.1	2	38.74	75	52.45	78	91.20	153		40.63	80	61.81	79	102.43	159	
5.1	**AVG**	**37.77**	**76**	**52.96**	**78**	**90.72**	**154.0**		**39.88**	**79.0**	**64.54**	**84.5**	**104.43**	**163.5**	
12.6	1	62.57	94	85.39	82	147.96	176		56.23	94	76.03	91	132.26	185	
12.6	2	68.05	81	92.19	84	160.24	165		70.03	96	80.76	96	150.79	192	
12.6	**AVG**	**65.31**	**88**	**88.79**	**83**	**154.10**	**170.5**		**63.13**	**95.0**	**78.40**	**93.5**	**141.53**	**188.5**	
17.0	1														
17.0	2														
17.0	**AVG**														
18.4	1	103.91	100	146.86	120	250.78	220		93.65	140	116.12	143	209.77	283	
18.4	2	101.60	100	147.79	123	249.39	223		82.29	117	123.67	145	205.96	262	
18.4	**AVG**	**102.76**	**100**	**147.33**	**122**	**250.08**	**221.5**		**87.97**	**128.5**	**119.90**	**144.0**	**207.87**	**272.5**	
21.1	1	97.71	100	152.27	108	249.98	208		149.66	146.0					
21.1	2	124.39	126	169.12	130	293.51	256		145.76	135.0					
21.1	**AVG**	**111.05**	**113**	**160.70**	**119**	**271.75**	**232.0**		**147.71**	**140.5**					
28.3	1	103.55	96	197.05	157	300.60	253		152.64	208					
28.3	2	119.29	109	211.02	170	330.31	279		132.16	186					
28.3	**AVG**	**111.42**	**103**	**204.03**	**164**	**315.45**	**266.0**		**142.40**	**197.0**					

Appendix D (continued)

Table D3: Raw Data Summary for 25 mm Rope Pump

Static Water Level (meters)		Rope Pump 25mm													
		Male							Female						
	Trial	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note
5.1	1	19.02	33	29.09	34	48.11	67		15.33	30	22.66	33	37.99	63	
5.1	2	23.12	33	28.62	32	51.75	65		18.08	33	23.45	34	41.53	67	
5.1	**AVG**	**21.07**	**33.0**	**28.86**	**33.0**	**49.93**	**66.0**		**16.70**	**31.5**	**23.06**	**33.5**	**39.76**	**65.0**	
12.6	1	24.35	38	38.30	42	62.65	80		23.81	45	34.30	48	58.11	93	
12.6	2	22.87	41	38.62	42	61.48	83		25.01	40	32.91	40	57.92	80	
12.6	**AVG**	**23.61**	**39.5**	**38.46**	**42.0**	**62.07**	**81.5**		**24.41**	**42.5**	**33.60**	**44.0**	**58.02**	**86.5**	
17.0	1	33.46	44.0	71.58	42.0	105.04	86		43.06	57.0					
17.0	2	38.09	63.0	93.52	75.0	131.61	138		48.32	50.0					
17.0	**AVG**	**35.77**	**53.5**	**82.55**	**58.5**	**118.33**	**112.0**		**45.69**	**53.5**					

Table D4: Raw Data Summary for 25 mm EMAS Pump

Static Water Level (meters)		EMAS Pump Quantity													
		Male							Female						
	Trial	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note	1st 20L (KJ)	Time (sec)	2nd 20L (KJ)	Time (sec)	Total (40L) (KJ)	Time (sec)	Note
5.1	1	27.08	38	42.25	41	69.33	79		23.03	41	34.04	45	57.07	86	
5.1	2	29.54	39	42.25	40	71.79	79		23.70	45	37.34	48	61.04	93	
5.1	**AVG**	**28.31**	**38.5**	**42.25**	**40.5**	**70.56**	**79.0**		**23.36**	**43.0**	**35.69**	**46.5**	**59.05**	**89.5**	
12.6	1	34.64	48	56.65	52	91.30	100		43.75	68	50.55	61	94.31	129	
12.6	2	46.02	50	69.08	55	115.10	105		35.74	58	51.96	60	87.70	118	
12.6	**AVG**	**40.33**	**49.0**	**62.87**	**53.5**	**103.20**	**102.5**		**39.75**	**63.0**	**51.26**	**60.5**	**91.00**	**123.5**	
17.0	1	39.16	53.0	78.40	64.0	117.57	117		61.91	71.0	89.35	99.0	151.26	170	
17.0	2	42.13	45.0	71.30	60.0	113.43	105		62.66	61.0	64.29	69.0	126.95	130	
17.0	**AVG**	**40.64**	**49.0**	**74.85**	**62.0**	**115.50**	**111.0**		**62.29**	**66.0**	**76.82**	**84.0**	**139.10**	**150.0**	

Appendix D (continued)

Table D5: Raw Data from Site 1

Location	**WV Gulu**	Site 1								
Static Water Level =	**5.1m**									
Pump Depth =	**7.8m**									
Rope Pump	**20mm PN 16 pumping pipe - guide box installed at 7.8m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	71		71		Resting HR:	85		85	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	78	one hand (right)	76	pump primed	**0**	87	pump primed	103	pump primed
	10	96		97	one hand	**10**	104	one hand	111	one hand R
	20	109		102		**20**	118		118	
	30	108		111		**30**	127		127	
	40	115		118		**40**	136		135	
	50	112		128		**50**	144		140	
	60	116		128		**60**	147		145	
	70	123	**1:17 - 20 L full**	128	**1:15- 20L full**	**70**	148	**1:18 - 20L full**	150	
	80	127	two hands	122	switch hands - L	**80**	146	switch hands	148	**1:20 - 20L full**
	90	115	one hand (left)	124		**90**	145		145	switch hands L
	100	118		122		**100**	151		147	switch hands R
	110	125		122		**110**	150		150	
	120	128		126		**120**	152		157	
	130	128		130		**130**	157		154	
	140	130		135		**140**	158	switch hands	152	
	150	134	**2:35 - 40L full**	136	**2:33 - 40L full**	**150**	155		155	**2:39 - 40L full**
						160	153	**2:48 - 40L full**		
EMAS Pump	**20mm PN 16 pumping pipe, 32mm PN 10 cylinder pipe - piston valve installed at 7.8m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	80		80		Resting HR:	90		9190	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	83	pump primed	93	pump primed	**0**	98	pump primed	91	pump primed
	10	107	long strokes	110		**10**	112		98	
	20	123		130		**20**	132		135	
	30	129		136		**30**	137	slow pumping	145	slow pumping
	40	137		140		**40**	137		153	
	50	150	**0:59 - 20L full**	156	**0:59 - 20L full**	**50**	137		156	
	60	155		162		**60**	155		158	
	70	157		166		**70**	157		159	**1:19 - 20L full**
	80	160		170		**80**	156	**1:23 - 20L full**	160	
	90	160		171		**90**	155		163	
	100	159		172		**100**	159		168	
	110	165		173		**110**	159		168	
	120	170	**2:00 - 40L full**	173	**2:02 - 40L full**	**120**	161		170	
	130					**130**	161		171	
						140	163		170	
					(46 strokes on 2nd 20L)	**150**	165		172	**2:38 - 40L full**
						160	163			
						170	162	**2:56 - 40L full**		(64 strokes on 2nd 40L)
Rope Pump	**25mm PN 10 pumping pipe - guide box installed at 7.8m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	80		82		Resting HR:	97		93	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	83	one hand (right)	89	pump primed	**0**	98	pump primed	108	pump primed
	10	113		120	one hand	**10**	115	one hand R	128	one hand R
	20	116		136		**20**	135		139	
	30	131	**0:33 - 20 L full**	143	**0:33 - 20 L full**	**30**	154	**0:30 - 20 L full**	149	**0:33 - 20 L full**
	40	143		150		**40**	150	one hand L	149	two hands
	50	152		153		**50**	159		158	
	60	149	**1:07 - 40L full**	153	**1:05 - 40L full**	**60**	164	**1:03 - 40L full**	163	**1:07 - 40L full**
EMAS Pump	**25mm PN 10 pumping pipe, 1.5" "drain" cylinder pipe - piston valve installed at 7.8m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	79		81		Resting HR:	87		89	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	87	pump primed	96	pump primed	**0**	101	pump primed	99	pump primed
	10	115	long strokes	123		**10**	121		102	
	20	138		141		**20**	139		132	
	30	141	**0:38 - 20 L full**	147	**0:39 - 20 L full**	**30**	146	slow pumping	149	slow pumping
	40	149		152		**40**	158	**0:41 - 20 L full**	153	**0:45 - 20 L full**
	50	156		160		**50**	160		159	
	60	165		167		**60**	166		164	
	70	172	**1:19 - 40L full**	173	**1:19 - 40L full**	**70**	169		172	**1:19 - 20L full**
					(21 strokes on 2nd 20L)	**80**	172	**1:26 - 20L full**	174	
						90			176	**1:33 - 20L full**

Appendix D (continued)

Table D6: Raw Data from Site 2 for 20 mm Pumps

Location	**Muchwini Central**			Site 2						
Static Water Level =	**12.6m**									
Pump Depth =	**15.1m**									
Rope Pump	**20mm PN 16 pumping pipe**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	76	pump primed	79	pump primed	**0**	108	pump primed	121	pump primed
	10	95	two hands	103		**10**	126	two hands	142	one hand
	20	109	one hand	127		**20**	140	one hand	150	
	30	112	switch hands	140		**30**	152	switch hands	159	two hands
	40	120		143		**40**	155		163	
	50	137		157		**50**	160		168	one hand
	60	135		163		**60**	164		172	
	70	144		170		**70**	169		173	two hands
	80	156	one hand - support	172	**1:21 - 20L full**	**80**	172	one hand - support	172	
	90	159	**1:34 - 20L**	171		**90**	175	**1:34 - 20L**	172	**1:36 - 20L full**
	100	151	two hands	171	two hands	**100**	172	two hands	172	one hand
	110	148	one hand supprt	171		**110**	175	one hand supprt	175	two hands
	120	150	switch hands	170		**120**	179	switch hands	177	
	130	155		172		**130**	178		179	**one hand**
	140	158	two hands	173		**140**	178	two hands	179	
	150	160	**switch hands**	173		**150**	178	**switch hands**	180	two hands
	160	163		172	**2:45 - 40L full**	**160**	178		180	
	170	163	faster			**170**	181	faster	180	one hand
	180		**2.56 - 40L full**			**180**	181	**3.05 - 40L full**	181	
						190			182	**3:12 - 40L full**
EMAS Pump	**20mm PN 16 piston pipe**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	85		84		**0**	88		85	
	10	114		121		**10**	120		118	
	20	136		151		**20**	130		138	
	30	146		159		**30**	139		145	
	40	148		163		**40**	150		155	
	50	150		167		**50**	156		162	
	60	156		170		**60**	157		167	
	70	159		173	**1:12 - 20L full**	**70**	159		169	
	80	162	**1:21 - 20L full**	170		**80**	164		171	
	90	169		179		**90**	168		175	
	100	173		178		**100**	170	**1:46 - 20L full**	172	**1:34 - 20L full**
	110	169		179		**110**	168		168	
	120	171		180		**120**	167		171	
	130	172		183		**130**	171		177	
	140	173		183		**140**	173		180	
	150	175		181	**2:38 - 40L full**	**150**	174		182	
	160	177				**160**	174		174	
	170	177	**2:50 - 40L full**			**170**	176		174	
	180					**180**	176		173	
	190					**190**	178		173	**3:11 - 40L full**
	200					**200**	179	**3:25 - 40L full**		
	210					**210**				
	220					**0**				
	User didn't stand on tire			user stood on tire						

Appendix D (continued)

Table D7: Raw Data from Site 2 for 25 mm Pumps

Location	**Muchwini Central**			Site 2						
Static Water Level =	**12.6m**									
Pump Depth =	**15.1m**									
Rope Pump	**25mm PN 10 pumping pipe**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	75	Pump primed	75	Pump primed	**0**	90	Pump primed	102	Pump primed
	10	106		112		**10**	118	one hand	130	one hand
	20	127		118		**20**	131	two hands	150	
	30	139	**0:38 - 20L full**	118		**30**	140		156	
	40	144		130	**0:41 - 20L full**	**40**	150	**0:45 - 20L full**	164	**0:40 - 20L full**
	50	150		153		**50**	156	slower	170	two hands
	60	153		154		**60**	157	faster	176	faster
	70	153		154		**70**	163	faster	180	
	80	162	**1:20 - 40L full**	157	**1:23 - 40L full**	**80**	165	one hand	180	**1:20 - 40L full**
	90					**90**	165	**1:33 - 40L full**		
	Like this pum very much. Feels little difference from other RP but much more flow						Says this pump is the easiest and likes that it is so fasr			
Qty EMAS Pump	**25mm PN 16 piston pipe**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	65	Pump primed	70	Pump primed	**0**	101	Pump primed	101	Pump primed
	10	120		107		**10**	125		121	
	20	125		150		**20**	137		138	
	30	135		161		**30**	150		141	
	40	146	**0:48 - 20L full**	174		**40**	159		162	
	50	158		182	**0:50 - 20L full**	**50**	163		165	**0:58 - 20L full**
	60	162		183		**60**	165	**1:08 - 20L full**	170	
	70	170		186		**70**	172		174	
	80	172		186		**80**	175		187	
	90	175		187		**90**	178		180	
	100	178	**1:40 - 40L full**	190	**1:45 - 40Lfull**	**100**	177		184	
	110					**110**	177		186	**1:58 - 40 L full**
						120	179	**2:09 - 40L full**		
	Prefers lighter emas pump									
						prefers lighter emas pump. Says that 25mm rope pump is the best				

Appendix D (continued)

Table D8: Raw Data from Site 3 for 25 mm Pumps

Location	**Wangowet**	(Amida)	Site 3*							
Static Water Level =	**17**		*25 mm Pumps							
Pump Depth =	**19.5**									
Rope Pump	**25mm PN 10 pumping pipe - guide box installed at 19.5m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	71		71		Resting HR:	91		91	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	92	OHR	95	pump primed	**0**	99	TH	104	TH
	10	107		124	OHR	**10**	124		122	
	20	138		150		**20**	140		139	
	30	147		162		**30**	153		151	
	40	159	**0:44 - 20 L full**	173	**0:42 - 20 L full**	**40**	159		158	
	50	158	TH	179	TH	**50**	161	:57 - stopped at 20L	168	:50 - 20L full
	60	170		176					171	
	70	170		174	OHR				174	1:15 stopped
	80	170		180						aprox 28 L
	90	171		186	TH					
	100	169	**1:47 - 40L full**	179						
	110			183	**1:57 - 40L full**					
EMAS Pump	**25mm PN 10 pumping pipe, 1.5" "drain" cylinder pipe - piston valve installed at 19.5m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	84		93		Resting HR:	87		90	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	85	pump primed	106	pump primed	**0**	91	pump primed	120	pump primed
	10	104		112		**10**	117		146	
	20	130		138		**20**	135		153	
	30	136		159		**30**	145		162	
	40	147		164	**0:45- 20 L full**	**40**	153		169	
	50	161	**0:53 - 40L full**	164		**50**	158		173	
	60	170		180		**60**	163		175	**1:01 - 20L full**
	70	173		183		**70**	166	**1:11 - 20L full**	179	
	80	173		185		**80**	168		180	
	90	175		186		**90**	170		183	
	100	180		185	**1:45 - 40L full**	**100**	172		184	
	110	183	**1:57 - 40 L Full**			**110**	173		185	
						120	174		186	**2:10 - 40L Full**
						130	175			
						140	175			
						150	177	2:50 - 40 L Full		
					Clair stated afterward that she prefers the EMAS pump to the RP for this applications.					
					Says that it is easier to pump and she doesn’t get so tired.					

Appendix D (continued)

Table D9: Raw Data from Site 3 for 20 mm Pumps

Location	**Wageowet**		Site 3*							
Static Water Level =	**18.4**		*20 mm pumps							
Pump Depth =	**20.9**									
Rope Pump	**20mm PN 16 pumping pipe - guide box installed at 20.95m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	80	pump primed	83	pump primed	**0**	87	pump primed	105	pump primed
	10	127	two hands	116	two hands	**10**	120	one hand	130	
	20	161		152		**20**	135	two hand	145	
	30	166		164		**30**	143		152	one hand / sideways
	40	167		165		**40**	150	one hand / sideways	160	
	50	167		167		**50**	153	two hand / sideways	165	two hand / sideways
	60	170		170		**60**	156	two hand	170	
	70	170		172		**70**	159	one hand	170	
	80	177		176		**80**	162	two hand	173	
	90	177		177		**90**	164		176	
	100	179	**1:40 - 20L full**	180	**1:40 - 20L full**	**100**	165		178	
	110	180		179		**110**	168		179	**1:57 - 20L full**
	120	181		170		**120**	169		177	two hand / sideways
	130	184		171		**130**	169		179	
	140	181		178		**140**	169	**2:20 - 20L full**	177	
	150	181		182		**150**	170		180	
	160	181		182		**160**	170	faster	180	
	170	186		182		**170**	175		180	
	180	185		185	semi-sideways	**180**	175		180	
	190	185		185		**190**	177		179	
	200	185		185		**200**	177		179	two hands
	210	187		187		**210**	177	faster	179	
	220	188	**3:40 - 40L full**	190	**3:43 - 40L full**	**220**	172	twohand / sideways	181	
						230	174	faster	182	
						240	175	one hand / sideways	184	two hand / sideways
						250	175	two hand / sideways	184	
						260	177		184	**4:22 - 40L full**
						270	178			
						280	178	**4:43 - 40L full**		
EMAS Pump	**20mm PN 16 pumping pipe, 32mm PN 10 cylinder pipe - piston valve installed at 20.95m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	86	pump primed	84	pump primed	**0**	100	pump primed	98	pump primed
	10	111		123		**10**	124		120	
	20	137		135		**20**	140		137	
	30	139		152		**30**	140		139	
	40	157		159		**40**	140		154	
	50	164		174		**50**	154		159	
	60	176		184		**60**	156		161	
	70	176		186		**70**	160		170	
	80	179	**1:25 - 20L full**	188	**1:25 - 20L full**	**80**	166		171	
	90	181		190		**90**	168		171	
	100	181		191		**100**	169		172	
	110	182		189		**110**	171		173	
	120	181		188		**120**	171		174	
	130	179		190		**130**	171		173	
	140	180		190		**140**	170		173	
	150	181		191		**150**	170		173	
	160	181		194		**160**	171	**2:40 - 20L full**	171	**2:40 - 20L full**
	170	180		194		**170**	169		168	
	180	183		195		**180**	169		169	
	190	184	**3:10 - 40L full**	195	**3:10 - 40L full**	**190**	171		172	
						200	171		174	
						210	172		176	
						220	174		176	
						230	175		176	
						240	175		178	
						250	175		179	
						260	174		178	
						270	175		178	
						280	175		178	
	User says that he prefers the EMAS pump to the rope pump at this depth					**290**	177		178	
						300	179		178	
						310	180		178	
						320	179		181	
						330	179	**5:36 - 40L full**	178	**5:36 - 40L full**
						User says that she prefers the rope pump to the EMAS pump at this depth				

Appendix D (continued)

Table D10: Raw Data from Site 4

Location	**Yepa**	Mucwini	Site 4							
Static Water Level =	**21.05**									
Pump Depth =	**23.55**									
Rope Pump	**20mm PN 16 pumping pipe - guide box installed at 23.55m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	88		103		Resting HR:	107		107	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	93	OHR	103	TH	**0**	107	OHR	110	TH
	10	121		127		**10**	126	TH	125	
	20	141		148		**20**	141		146	
	30	150	TH	155		**30**	151		156	
	40	163		159		**40**	156		166	
	50	170		170		**50**	161	Speed up	170	
	60	170		172		**60**	166		172	
	70	168		175		**70**	170		175	
	80	171		180		**80**	171		178	**Sideways**
	90	173		182		**90**	173		179	
	100	175	**1:40 - split**	183		**100**	174		180	
	110	178		182	1:48 - Split	**110**	173		180	
	120	178	OHR	181		**120**	172		178	
	130	179	TH	181		**130**	172		177	**2:15 - 20L full**
	140	180		180		**140**	171	**2:26 - 20L full**		Stop
	150	180		181				**Stop**		
	160	180		183						
	170	182		185						
	180	184		185						
	190	185		185						
	200	186	OHR	185						
	210	183		185						
	220	183	**3:46 - 40L Full**	186						
				187	**3:58 - 40L Full**					
EMAS Pump	**20mm PN 16 pumping pipe, 32mm PN 10 cylinder pipe - piston valve installed at 23.55m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	79		79		Resting HR:	86		86	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	93	pump primed	94	pump primed	**0**	95	pump primed	100	pump primed
	10	121	long strokes	131		**10**	99		115	
	20	134		158		**20**	130		137	
	30	138		166		**30**	132	slow pumping	141	slow pumping
	40	157		176		**40**	140		150	
	50	165		184		**50**	151		154	
	60	170		188		**60**	156		162	
	70	174		189		**70**	159		162	
	80	178		190		**80**	160		159	
	90	180	1:38 Split	192		**90**	160		166	
	100	180		191	1:48 Split	**100**	160		169	
	110	180		191		**110**	163		168	
	120	183		192		**120**	168		168	
	130	181		190		**130**	169		170	
	140	185		192		**140**	170		171	
	150	187		193		**150**	169		172	
	160	186		192		**160**	170		172	
	170	186		193		**170**	170		170	
	180	188		194		**180**	168		166	
	190	190		196		**190**	168	**3:18 - 20L full**	165	**3:15 - 20L full**
	200	192		197						
	210	192	3:35 - 40L Full	198						
	220			198						
	230			198	**3:58 - 40L full**					

Appendix D (continued)

Table D11: Raw Data for Site 5

Location	**Akara P/S**	Muchwini	Site 5							
Static Water Level =	**28.3**									
Pump Depth =	**30.4**									
Rope Pump	**20mm PN 16 pumping pipe - guide box installed at 30.4m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	67		67		Resting HR:	84		84	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	82	pump primed	83	pump primed	**0**	89	pump primed	85	pump primed
	10	118	one hand (fast)	123	one hand (fast)	**10**	120	two hands	126	two hands
	20	150		156	two hands	**20**	135		143	
	30	165		170		**30**	148	sideways	157	
	40	173		173	using body a lot	**40**	156		162	
	50	177		176		**50**	162		167	
	60	181		179		**60**	166		172	
	70	183		178		**70**	168		175	
	80	185	slower	178		**80**	168	slower	177	
	90	187	**1:36 - 20 L full**	188		**90**	169		178	
	100	186		183	**1:49 - 20L full**	**100**	169		180	
	110	186		182		**110**	170		180	sideways
	120	186	slower	183	slower	**120**	173		180	slower
	130	186	using body a lot	183		**130**	173		180	
	140	185		183		**140**	174		180	
	150	185	slower	182		**150**	174		180	
	160	186		184		**160**	174		180	
	170	186		185		**170**	174		180	
	180	187		186	semi-sideways	**180**	173	slower	179	**3:06 - 20L full**
	190	187		186		**190**	171			stopped at 20L
	200	188		187		**200**	170	**3:28 - 20L full**		
	210	188		186	slower (seems tired)			Stopped at 20L		
	220	188		185						
	230	188		186						
	240	188		187						
	250	186	**4:13 - 40L full**	187						
	260			187						
	4:30			187	**4:39 - 40L full**					
	4:40									
EMAS Pump	**20mm PN 16 pumping pipe, 32mm PN 10 cylinder pipe - piston valve installed at 30.4m from top of pedestal**									
		Sam - Test 1		Sam - Test 2			Clair - Test 1		Clair - Test 2	
	Resting HR:	75		75		Resting HR:	83		83	
	Time	Heartrate	Note	Heartrate	Note	**Time**	Heartrate	Note	Heartrate	Note
	0	79	pump primed	80	pump primed	**0**	93	pump primed	101	pump primed
	10	130		114	long strokes	**10**	109		115	
	20	137		143		**20**	116		120	
	30	137	long strokes	149		**30**	122	slow pumping	131	slow pumping
	40	144		150		**40**	134		141	
	50	152		157		**50**	138		149	
	60	158		165	steady pumping	**60**	142		154	
	70	163		162		**70**	145		158	
	80	162	steady pumping	159		**80**	148		159	
	90	163		155		**90**	148		159	
	100	159		159		**100**	147		160	
	110	156		166		**110**	146		161	
	120	159		167		**120**	149		158	
	130	160		164		**130**	145		157	
	140	158		164		**140**	146		155	
	150	161		163		**150**	150		154	
	160	160	**2:40 - 20L full**	162	**2:49- 20L full**	**160**	150		156	
	170	159		165		**170**	148		155	
	180	161		167		**180**	150		154	
	190	165		165		**190**	149		155	
	200	165		162		**200**	153		154	
	210	167		165		**210**	154		156	
	220	167		170		**220**	153		158	
	230	167		173	change grip	**230**	151		159	
	240	167		171		**240**	151		159	
	250	170		171		**250**	150		158	
	260	169		168		**260**	149		160	
	270	171		171		**270**	149		159	
	280	169		170		**280**	150		158	
	290	169		167		**290**	152		157	**4:55** - 20L full
	300	170		163		**300**	152			Stopped at 20L
	310	172		165		**310**	149			
	320	172		170		**320**	149	**5:21** - 20L full		
	330	171		169		**330**		Stopped at 20L		
	340	173	**5:45 - 40L full**	171						
	350			171						
	360			170	**6:02- 40L full**					