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An Evaluation of the Water Lifting Limit of a Manually Operated Suction Pump: Model Estimation and Laboratory Assessment

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by

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DEDICATION

To my wonderful parents, for all that you contributed! Without your unending love, patience, support and encouragement, this thesis would have forever remained an incomplete process. Know that, with all my love, in the act of this dedication I express immense appreciation and gratitude for your integral role in the realization of this accomplishment.

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ABSTRACT

With 663 million people still without access to an improved drinking water source, there is no room for complacency in the pursuit of Sustainable Development Goal (SDG) Target 6.1: "universal and equitable access to safe and affordable drinking water for all" by 2030 (WHO, 2017). All of the current efforts related to water supply service delivery will require continued enthusiasm in diligent implementation and thoughtful evaluation. This cannot be over-emphasized in relation to rural inhabitants of low-income countries (LICs), as they represent the largest percentage of those still reliant on unimproved drinking water sources. In that lies the motivation and value of this thesis research- improving water supply service delivery in LICs.

Manually operated suction pumps, being relatively robust, low cost, and feasible to manufacture locally, are an important technology in providing access to improved drinking water sources in LICs, especially in the context of Self-supply. It seems widely accepted that the water-lifting limit of suction pumps as reported in practice is approximately seven meters. However, some observations by our research group of manually operated suction pumps lifting water upwards of nine meters brought this "general rule of thumb" limit into question. Therefore, a focused investigation on the capabilities of a manually operated suction pump (a Pitcher Pump) was conducted in an attempt to address these discrepancies, and in so doing, contribute to the understanding of this technology with the intent of providing results with practical relevance to its potential; that is, provide evidence that can inform the use of these pumps for water supply.

In this research, a simple model based on commonly used engineering approaches employing empirical equations to describe head loss in a pump system was used to estimate the suction lift limit under presumed system parameters. Fundamentally based on the energy equation applied to incompressible flow in pipes, the empirically derived Darcy-Weisbach equation and Hydraulic Institute Standards acceleration head equation were used to estimate frictional and acceleration head losses. Considering the theoretical maximum suction lift is limited to the height of a column of water that would be supported by atmospheric pressure, reduced only by the vapor pressure of water, subtracting from this the model was used to predict the suction lift limit, also referred to herein as the practical theoretical limit, assuming a low (4 L/min) and high (11 L/min) flow rate for three systems: 1) one using 1.25-inch internal diameter GI pipes, 2) one using 1.25-inch internal diameter PVC pipes, and 3) one using 2-inch internal diameter PVC pipes. In all considered cases, with an elevation equal to sea level, the suction lift limit was estimated to be over nine meters. At a minimum, the suction lift limit was estimated to be approximately 9.4 meters for systems using 1.25-inch internal diameter pipe and 9.8 meters for systems using 2-inch internal diameter pipe, with essentially no discernable effects noticed between pipe material or pipe age. Additionally, laboratory (field) trials using a Simmons Manufacturing Picher Pump and each of the aforementioned pipe specifications were conducted at the University of South Florida (Tampa, FL, USA) to determine the practical pumping limit for these systems. Results from the pumping trials indicated that the practical pumping limit- the greatest height at which a reasonable pumping rate could be consistently sustained with only modest effort, as perceived by the person pumping- for a Pitcher Pump is around nine meters (9 meters when using 1.25-inch internal diameter GI or PVC pipe and 9.4 meters when using 2-inch internal diameter PVC pipe). Therefore, results from this research present two pieces of evidence which suggest that the practical water-lifting limit of manually operated suction pumps is somewhere around nine meters (at sea level), implying that reconsideration of the seven-meter suction lift limit commonly reported in the field might be warranted.

CHAPTER 1: INTRODUCTION

In 2000, the United Nations (UN) established the 15-year initiative known as the Millennium Development Goals (MDGs) to guide international development efforts in advancing the realization of basic human rights and needs amongst the global population and especially amongst the world's poorest. MDG Target 7c addressed the human right to water and sanitation, calling for the reduction by half of the proportion of the population without sustainable access to safe drinking water and basic sanitation by 2015 relative to 1990 baseline data (www.un.org/millenniumgoals/). The World Health Organization (WHO)/United Nations International Children's Emergency Fund (UNICEF) Joint Monitoring Program for Water Supply and Sanitation (JMP) was tasked with tracking progress towards MDG Target 7c. Due to monetary and logistical challenges of systematic water quality testing, progress related to drinking water was determined through the use of a proxy indicator, which established use of improved drinking water sources as the measure for access to safe drinking water. Drinking water sources that are thought to be protected from outside contamination, particularly fecal matter, by the nature of their construction are considered improved. These include piped water into the dwelling or plot/yard, public tap or standpipe, tubewell or borehole, protected dug well, protected spring, and rainwater collection (WHO/ UNICEF, 2015). The MDG target for drinking water was met in 2010 when an estimated 88 percent of the global population was using improved drinking water sources. As of 2015, the JMP estimated that 91 percent of the global population was using improved drinking water sources. While this indicates tremendous progress, there are still some 663 million people without access to an improved drinking water source (WHO/ UNICEF, 2015; WHO, 2017).

In 2015, the UN adopted the Sustainable Development Goals (SDGs) to build on the progress made during the MDG era and to provide a new framework to promote actions that address the challenges negatively influencing quality of life throughout the world. SDG Goal 6 has replaced MDG Target 7c in addressing the human right to water and sanitation. The new target for drinking water, SDG Target 6.1, calls for "universal and equitable access to safe and affordable drinking water for all" by 2030 (WHO, 2017). To monitor progress towards SDG Target 6.1, the JMP has developed a ladder based on service level (Table 1.1) to categorize access to safe drinking water which includes collection time along with the improved source classification.

Table 1.1: Service ladder for household drinking water (from WHO, 2017)

Service Level	**Definition**
Safely Managed	Drinking water from an improved water source which is located on premises, available when needed and free of fecal and priority contamination
Basic	Drinking water from an improved source provided collection time is not more than 30 minutes for a roundtrip including queuing
Limited	Drinking water from an improved source where collection time exceeds 30 minutes for a roundtrip to collect water, including queuing
Unimproved	Drinking water from an unprotected dug well or unprotected spring
No Service	Drinking water collected directly from a river, dam, lake, pond, stream, canal or irrigation channel

The scope of SDG Target 6.1 includes institutional level (i.e. schools and health facilities) access; however, the JMP will continue to emphasize household level access. While extending service to those still using unimproved sources is priority, from Table 1.1, it is clear that increasing the number of people utilizing at-home (on premises) improved water sources, in contrast to community (off premises) improved water sources, is also part of the SDG agenda and should be a consideration in water supply development strategies.

The estimated 663 million people still using unimproved drinking water sources primarily reside in low-income countries (LICs) with the majority living in two regions, nearly 50 percent in Sub-Saharan Africa (SSA) followed by 20 percent in Southern Asia (UNICEF/WHO, 2015; WHO, 2017). Thirty-eight of the 48 Least Developed Countries, as defined by the UN, are located in these two regions (UN, 2016). As this implies, generally, overall national socioeconomic status and level of water coverage are closely correlated, so that the poorest countries have the worst drinking water coverage (Hutton, 2013; GBD 2015 SDG Collaborators, 2016). This is an intuitive connection, as with few resources there are few services, but it has important implications. There are significant health, economic, social and environmental costs associated with poor water quality and/or insufficient water quantity (Hutton, 2013). With limited economic agency at national and local levels, the people of LICs suffer the most acutely from the burden of inadequate water supply because they lack the resources to prevent the problem or treat the consequences. It is, however, important to note that the correlation between a country's socioeconomic status and level of water coverage is a global phenomenon. When comparing only LICs, the relationship fails to hold and a country's socioeconomic status is no longer a reliable predictor of water coverage (GBD 2015 SDG Collaborators, 2016; Jahan, 2016; Roche et al., 2017). This is likely due to several complexly interacting factors including, but not limited to, unequal geographical distribution of water (i.e. some countries receive more annual rainfall, have more surface water bodies and/or have more easily attainable groundwater resources than others), investment and influence from foreign aid, government (in)effectiveness, political environment, intra-country population distribution (i.e.

percentage of urban vs. rural dwellers) and intra-country wealth distribution (Hunter et al., 2010; GBD 2015 SDG Collaborators, 2016; Roche et al., 2017).

Given the highly context-dependent nature of water resource development, there is no easy strategy for attaining universal safely managed drinking water service coverage and the integration of several approaches will be needed as progress towards SDG Target 6.1 advances. One strategy that has the potential to greatly contribute to moving people up the drinking water service ladder, regardless of their current level, is Self-supply. Self-supply is a demand-driven approach in which improvements to water supply systems are initiated by user investment. The users choose the technologies they want and accept the financial onus of installation and upkeep. The concept of Self-supply is not new and can be adapted to any situation, but, in recent years, it has been somewhat formally associated with rural water resource development in LICs and has gained particular attention in SSA (Sutton, 2009). In this context, the Self-supply model promotes locally appropriate technologies which allow users to make incremental improvements to their water supply systems as they see fit (Sutton, 2009).

Rural inhabitants of the poorest countries comprise a disproportionately large fraction of the population still using unimproved drinking water sources, which represents a focus area requiring increased attention in the SDG era (UNICEF/WHO, 2015; Hutton and Chase, 2016; GBD 2015 SDG Collaborators, 2016; WHO, 2017). Additionally, of the rural inhabitants in LICs using improved sources, few have access to sources that would be considered safely managed. In dispersed populations, centralized water supply systems are not practical. Due to this, point source water infrastructure (e.g. wells with pumps and rainwater harvesting systems) has been and will continue to be the predominant mechanism for rural water resource development. In LICs, and especially in SSA, shallow groundwater development, which can rely solely on low-cost technologies, may be one of the most viable opportunities to improving access to increasing levels of water service. Groundwater is Africa's largest freshwater resource. While sustainable use and management cannot be neglected, especially in light of increasing climate variability, estimated storage far exceeds current abstraction, indicating the potential for expanded use. An estimated 60 percent of Africa's population lives in areas where the depth to groundwater is 0-25 meters below the ground surface (mbgs) and an estimated eight percent lives in areas where the depth to groundwater is 0-7 mbgs, representing a substantial number of people who could benefit from shallow groundwater use (Bonser and MacDonald, 2011; MacDonald et al., 2012).

Manually operated suction pumps are one technology option that allows people to access shallow groundwater. They have several advantages (including being relatively robust, low cost, and feasible to manufacture locally), but the depth from which they can lift water is a limitation. It is accepted fundamentally that suction pump lift is limited by local atmospheric pressure, which, at sea level, can be converted to a head of approximately ten meters. However, it is commonly stated in the literature that the water-lifting limit of suction pumps is around seven meters. In Madagascar our research group observed manually operated suction pumps (commonly known as Pitcher Pumps) lifting water from depths upwards of nine meters.

In reviewing the literature, little justification or evidence of failed attempts at lifting water from depths greater than seven meters was found in support of the widely accepted limit of seven meters. These pumps are widely used in Asia and to a lesser extent in Africa. Following from the discussion above, millions of people in SSA live within a hydrogeologic environment that is potentially suitable to the use of manually operated suction pumps. Therefore, a reevaluation of the water-lifting limit of manually operated suction pumps could be of benefit to both past and future groundwater development projects, and confirming the ability of suction pumps to lift water more than seven meters is of particular value to the Self-supply sector. Accordingly, the objective of this research is to determine the maximum and practical pumping limit of a manually operated suction pump based on theoretical calculations, considering physical principles and applied fluid mechanics, and field tests evaluating pump performance.

CHAPTER 2: LITERATURE REVIEW AND MOTIVATION

2.1 Water Supply and Health

The connections between water and human health have been recognized for centuries. The start of modern epidemiology is often credited to a study concerning just that- John Snow's investigation of a South London Cholera epidemic in which he found the source of the outbreak to be a community water pump. Since then, numerous studies have shown direct and indirect negative health outcomes associated with poor water quality and/or insufficient water quantity (e.g. see Selendy, 2011). In SSA, arguably, contact with or ingestion of fecal contamination is the most salient public health concern related to water. When considering the inextricable links between water, sanitation, and hygiene (WaSH), this only becomes more evident. According to the Global Burden of Disease, Injuries, and Risk Factors Study 2015, in SSA, diarrheal disease was the fourth leading cause of death and disability-adjusted life years (DALYs) [1] for people of all ages and the third leading cause of death and DALYs for children under five years old (GBD 2015 Risk Factors Collaborators, 2016; IHME, 2016). Though diarrheal disease has etiologies other than microorganisms of fecal origin, these causes represent a small fraction of the diarrheal disease burden (Reisinger et al., 2005; Kotloff et al., 2013). Many pathogenic microorganisms are passed from an infected host to the environment, or directly to another host, through fecal matter. Without proper water treatment, sanitation and/or hygiene interventions, these pathogens

[1] Disability-adjusted life years (DALYs) = years lived with disability (YLD) + years of life lost (YLL). A measure of overall disease burden (morbidity and mortality) expressed as years lost due to ill-health, disability or early death.

infect new hosts, or re-infect their original hosts, perpetuating disease transmission (Wagner and Lanoix, 1958). An estimated 86 percent of all deaths and DALYs in SSA due to diarrheal disease were attributable to unsafe water, and an estimated 97 percent were attributable to unsafe water, sanitation, and hygiene combined (GBD 2015 Mortality and Causes of Death Collaborators, 2016; IHME, 2016).

WaSH-attributable diarrheal disease is a major contributor to morbidity and mortality in itself, but it is also thought to indirectly contribute to the morbidity and mortality from other diseases as well. Diarrhea can weaken the immune system, making an individual more susceptible to other infections, like tuberculosis, pneumonia, or influenza (Sedgwick and MacNutt, 1910; Fink, 1917; Cutler and Miller, 2005; Ferrie and Troesken, 2007; The World Bank, 2008). This is particularly true for individuals who are already immunocompromised, for example, Human Immunodeficiency Virus (HIV)-positive, a condition that is very prevalent in SSA. Diarrheal disease is also particularly detrimental to children under five years for its links to malnutrition, which was the leading risk factor for death in children under five in 2015 (GBD 2015 Mortality and Causes of Death Collaborators, 2016; IHME, 2016). Children who have suffered repeated bouts of diarrhea are more likely to be malnourished (Brown, 2003; The World Bank, 2008; Cumming and Cairncross, 2016; others). Along with increasing the risk of death, malnutrition in infancy and early childhood has been correlated to reduced cognitive function, poor educational attainment and may be a risk factor for development of some chronic diseases (Brown, 2003; The World Bank, 2008; Hunter et al., 2010).

Besides the direct and indirect consequences of diarrheal disease, there are many other WaSH-related health outcomes negatively impacting the public health status of communities throughout LICs. Also related to fecal contamination, soil-transmitted helminthes and schistosomiasis continue to infect millions of people (IHME, 2016). Water that is adulterated with chemical contamination, whether it be natural or anthropogenic in origin, is associated with various health outcomes ranging in severity from skin rashes to cancer (Hunter et al., 2010; Selendy, 2011). The spread of eye (e.g. trachoma) and skin (e.g. scabies) infections are likely in part the result of poor hygiene, and many respiratory infections are also thought to be the result of poor hygiene (Selendy, 2011; Evans et al., 2013). Though less widely studied, there is evidence that water collection, particularly manual water transport (i.e. carrying heaving loads of water), can have detrimental impacts on the musculoskeletal system (Geere et al., 2010; Graham et al., 2016). The labor of water collection is also metabolically taxing which can worsen the nutritional status of individuals without a stable and sufficient food supply, as is not uncommon in LICs (Thompson et al., 2001; Geere et al., 2010; Graham et al., 2016).

2.2 Self-Supply

To date, the prevailing strategy for rural water resource development in LICs, particularly SSA, has been community-level water supply; that is, installation of one or two point sources (e.g. boreholes or protected springs) to serve a given community. In SSA, boreholes fitted with handpumps are by far the most common community-level water supply systems for rural populations (Sansom and Koestler, 2009). This is largely a supply-driven approach initiated by foreign aid and/or government investment. Low levels of sustainability, as indicated by high system failure rates, are often cited as a shortcoming of this strategy (Sutton, 2005; Foster, 2013; Starkl et al., 2013; Walters and Javernick-Will, 2015). There have been numerous studies assessing water point (handpump) functionality rates; i.e., the percent of functional/nonfunctional handpumps in a defined geographical area. While the reported range is quite large (estimates from 10-90 percent for various countries), the most common estimate for nonfunctional community handpumps installed throughout SSA at any given point is 30-40 percent (Sutton, 2005; RWSN, 2010; Improve International, 2015). With attention shifting toward service delivery under the SDGs, it has been noted that these estimates rely on a dichotomous functional/nonfunctional classification and provide no information regarding service delivery; for example, on an annual basis, what is the average time a water point is nonfunctional (Foster, 2013; Walters and Javernick-Will, 2015; Carter and Ross, 2016). There is currently a paucity of rigorous studies concerning the service delivery of rural water points, but it is likely that a substantial portion are nonfunctional for, at a minimum, weeks out of a year (Fisher et al., 2015; Carter and Ross, 2016; Hutton and Chase, 2016). Regardless, for rural inhabitants that often have to collect water daily, even short interruptions in service can have detrimental health impacts (Hunter et al., 2010; Carter and Ross, 2016).

Many potential challenges inherent to the community-level model for rural water supply have been recognized for decades (Arlosoroff et al., 1987). As outlined by Arlosoroff et al. (1987), structural issues with the pump or well, lack of technical knowledge or available assistance for maintenance, poor supply chain for spare parts, lack of community involvement and willingness to pay, and inappropriate well siting have been repeatedly offered as important factors to community-level water point functionality (Harvey, 2004; others). In more recent years, studies employing more robust statistical methods and modeling approaches have found many of these same factors still to be important determinants of community-level water point functionality (Foster, 2013; Starkl et al., 2013; Fisher et al., 2015; Walters and Javernick-Will, 2015). In an attempt to address some of the persistent challenges of rural water supply in LICs, Self-supply has been promoted as a strategy to complement the community-level model. As stated in Chapter 1, Self-supply is a demand-driven approach in which improvements to water supply systems are initiated by user investment (Sutton, 2009). The key features of Self-supply and the importance of each to helping improve the sustainability of rural water supplies are outlined in Table 2.1.

Table 2.1: Key features of Self-supply (reproduced from Olschewski, 2016)

Key feature	**Particular impact**
Broad range of benefits	■ Households investing in improving their own water sources do list a broad range of benefits of having their own source close to their home. First of all, there is the aspect of convenience, saving time for fetching water and having less of a burden. Further benefits include having more water available for income generation and improving food security, more water with better quality, a high level of service (24/7), reliability, privacy and security.
Strong ownership	■ Self-supply is based on household initiative. It is fully demand driven. As almost all investments are covered by households, there is strong ownership.
High potential for sustainability	■ There is inherent knowledge on how to operate Self-supply sources or where to go to ask for support. ■ Households care for their assets and do proper maintenance, so that the functionality of their supply is very high. Sustainability of Self-supply is very high as long as water quality and resources are managed properly.
Self-supply sources as shared supply	■ In most regions, Self-supply sources are shared with neighbours at no additional cost for the well owner and no cost for sharer. These sources serve several families, including the most vulnerable and poorest ones.
Multiple uses of water	■ Self-supply sources are mostly used for domestic purposes. In many areas, there is a huge potential to expand the use of water also for productive purposes, such as gardening, cattle, or brick making, which provides opportunities for income generation. Self-supply sources have a huge role to play in terms of water security.
Demand driven	■ The number of Self-supply systems is growing in many countries as people see the benefit and start investing in their own sources.

As seen in Table 2.1, Self-supply systems are typically owned by a household, but often are utilized by a small group of households (generally less than ten) which are located within a relatively close proximity to the water point (Sutton, 2005; Sutton, 2011; MacCarthy et al., 2013; Akers, 2014). Several studies have shown that decreased distance to a water source is associated with increased health gains (Geere et al., 2010; Pickering and Davis, 2012; Graham et al., 2016). Also, the inverse relationship between distance to a water source or collection time and the estimated daily quantity of water used by a household has been reported numerous times (Howard and Bartram, 2003; Mihelcic et al., 2009). Furthermore, a recent review by Stelmach and Clasen (2015) found that increases in water quantity at the household level were positively associated with improved health outcomes. Though not explicitly stated, Self-supply systems are generally sited within the yard or compound of the owner and would be considered on premises for the owner and any households that share the plot. A recent review by Overbo et al. (2016) and a research report by Evans et al. (2013) indicate improved WaSH-attributable health outcomes in households using on premises water supplies compared to households using off premises water supplies. Often, on premises supplies only consider piped water (Pruss-Ustun et al., 2014; Wolf et al. 2014), but Fry et al. (2010) demonstrated the potential for Self-supply systems specifically to improve health outcomes.

In addition to improved health outcomes, Self-supply potentially offers social and economic benefits as well. In SSA, the burden of water collection overwhelmingly falls on women and children, and recent estimates suggest that more than a quarter of the population in SSA take longer than 30 minutes per water collection trip and often multiple trips are made in a day (The World Bank, 2008; Geere et al., 2010; Pickering and Davis, 2012; Graham et al., 2016; Hutton and Chase, 2016). By reducing the time and energy spent on water collection, Self-supply could potentially help improve gender equality, giving women more opportunity to engage in other activities. It has also been suggested that with reduced time spent on water collection, women spend more time with their children, which has been suggested as a possible factor in improved health and developmental outcomes (The World Bank, 2008).

Improving health outcomes has implicit economic advantages at both household and national levels. When individuals are healthy, there is less healthcare-related spending. Additionally, when individuals are healthy, generally, they are more productive (i.e. more time is spent engaging in income generating activities). Hutton (2013) outlines these along with other advantages and suggests that, in SSA, for every US dollar invested in interventions to improve water supply, there is potentially a 2.5 US dollar return. In addition to being utilized for domestic use (consumption, cooking, bathing, cleaning), Self-supply systems can be utilized for productive use (see Table 2.1). This is particularly important in SSA where the majority of rural inhabitants rely on subsistence agriculture. Finally, in many circumstances, Self-supply might be the most financially viable option for water access. This is particularly true for very dispersed populations and in many peri-urban areas that are not disaggregated from urban areas yet do not receive coverage from centralized piped water systems.

The concept of Self-supply is not new, and is likely a component of rural water provision in nearly every country, but in the past decade, has gained increased attention in SSA (Sutton, 2009; others). Often, Self-supply systems emerge entirely by the initiative of the local residents; that is, without any support or subsidy from foreign aid or government institutions. A few examples include Madagascar (MacCarthy et al., 2013; Akers, 2014), Uganda (Carter, 2006; Carpenter, 2014; Thayil-Blanchard and Mihelcic, 2015) and Zimbabwe (Olschewski, 2016). Due to the increasing recognition of the role that Self-supply can have in improving rural water supply service, the Rural Water Supply Network (RWSN), an influential global network of professionals and practitioners dedicated to advancing water supply service for all, has adopted the promotion and support of Self-supply as a formal strategy to rural water resource development for LICs (see http://www.rural-water-supply.net/en/self-supply). With that, many more Self-supply systems have emerged through initiatives led by foreign aid and/or government institutions. Under supported and/or subsidized Self-supply schemes, the role of foreign aid and government is to recognize where Self-supply has the potential to contribute to expansion of water service coverage and create an enabling environment for successful implementation, growth, and sustainability (Sutton, 2009). This could include direct subsidies, increasing the availability of affordable financing options, improving the local supply chain, training artisans and technicians, providing educational material to local residents, or supporting local enterprises dealing with water supply (Sutton, 2009). A few examples of supported Self-supply initiatives include Zambia (Sutton, 2011; Olschewski, 2016), Ethiopia (Sutton, 2011; Sutton et al., 2012), Mali (Sutton, 2010; Sutton, 2011), Uganda (Danert and Sutton, 2010; Sutton, 2011) and Zimbabwe (Olschewski, 2016).

The Self-supply model promotes locally appropriate technologies which allow users to make incremental improvements to their water supply systems so that users can progressively move up the water service ladder (Sutton, 2009; Butterworth et al., 2014; Olschewski, 2016). Users are financially responsible for installation, upkeep, and upgrades; therefore, a primary consideration in promoted technology options should be cost. In LICs, Self-supply systems should be relatively low-cost. In addition, in LICs, technologies which are simple to operate yet robust and are easily manufactured and maintained with local materials are primary candidates for Self-supply systems. Self-supply technologies must also be amenable to the local economic, social/cultural and environmental/hydrogeological context. Table 2.2 provides examples of some common Self-supply technologies. It does not provide an exhaustive list, but rather indicates some of the more prevalent technologies. In the context of LICs, shallow groundwater and domestic rainwater harvesting (DRWH) systems are the most predominant. Shallow groundwater systems typically include hand-dug or manually drilled wells fitted with low-cost water lifting devices. Water quality is often cited as a concern when using shallow groundwater. This is important to recognize, but, considering the aforementioned potential benefits, it should not negate the use of Self-supply systems. Additionally, point-of-use (POU) water treatment can be incorporated with the supply infrastructure to address water quality concerns.

Table 2.2: Example Self-supply systems

Example Systems[1]	Example Technologies	
Shallow Groundwater (development + water lifting)	Development Methods	Water Lifting Devices
	Hand-dug wells - Unprotected to fully lined with sanitary seals Manually drilled wells* - Sludging - Jetting/Washboarding - Percussion - Hand auguring	- Rope and Bucket - Windlass - Rope Pump - EMAS Pump - Pitcher Pump (suction pump)
Domestic Rainwater Harvesting	- Plastic Tanks - Cement Tanks	
Point-of-Use Water Treatment	- Boiling - Chlorine disinfection - Sand filters - SODIS (solar disinfection)	

1- Systems are shown separately (e.g. shallow groundwater systems vs. DRWH systems vs. POU systems) to indicate the main classifications, but are often not exclusive of one another

*- See Danert, 2009 for information on manual drilling techniques

2.3 Manually Operated Suction Pumps

This section provides a brief discussion on the definition of a manually operated suction pump as it is used throughout this paper. Manually operated suction pumps are devices which use human power to produce a partial vacuum within a cylinder to cause a fluid to flow into a region of low pressure. The primary force moving the fluid is atmospheric pressure. Herein, a manually operated suction pump will refer to a type of handpump that is used to lift water in which a piston is repeatedly moved up and down within a cylinder that is placed above the water level. The main components of a manually operated suction pump are shown in Figure 2.1. They include a rising main, a cylinder, an operating rod connected to a piston, a one-way foot valve, a sliding seal, and a one-way piston valve. With the exception of the rising main, all the components of a manually operated suction pump are located above the water table. The theory of suction pump operation will be further explained in section 2.4.

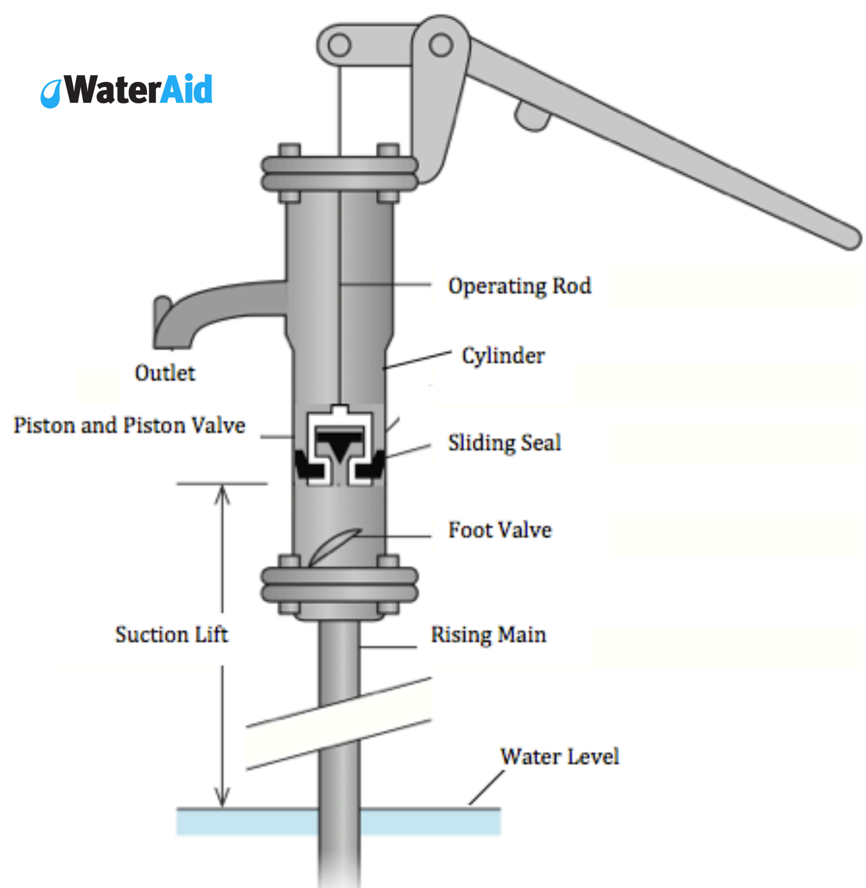

Figure 2.1: Diagram of the main components of a manually operated suction pump (reproduced from WaterAid, 2013)

2.3.1 Historical Context

A complete historic investigation of manually operated suction pumps is beyond the scope of this paper. However, in the reevaluation of the water-lifting limit of these pumps, a brief historic review is necessary and potentially insightful to understanding the commonly stated seven-to-eight-meter limit that these types of pumps can lift water. Some pertinent background information is provided below.

Water is essential to the prosperity of society, and thus, humans have manipulated the movement of water since the beginning of civilization. Though many primary records have been lost, it has been postulated that pumps that could fall under the classification of manually operated suction pumps have been in existence from at least the third century B.C. Written records by later historical figures and some archaeological evidence suggests that Ctesibius, a Greek inventor and mathematician, invented a two-cylinder pump in which a piston in each were moved up and down by connecting rods attached to a single rocking arm (Bjorling, 1895; Shapiro, 1964; Eubanks, 1971; Yannopoulos et al., 2015). Manually operated suction pumps all have the same basic operating cycle (see Section 2.4), and it is likely that this cycle was first employed in Ctesibius' pump (third century B.C.). However, the cylinders of Ctesibius' pump were placed directly in water and therefore, water would have been forced through the foot valve into the cylinder primarily by water pressure opposed to by atmospheric pressure (Shapiro, 1964; Yannopoulos et al., 2015). Due to this, Ctesibius' pump was not actually a manually operated suction pump as it is defined in this thesis. Ctesibius' pump was likely the predecessor to many of the community-level handpumps that are used extensively throughout LICs and had several similarities to manually operated suction pumps; therefore, it is mentioned to provide a notion of the antiquity of the basic technology being investigated in this research.

Manually operated suction pumps, in the form very similar to what is commonly known today, appear in records from Mesopotamia from the early thirteenth century (Hill, 1991; Yannopoulos et al., 2015). In Europe, manually operated suction pumps appear in the fifteenth century and were likely relatively common by the sixteenth century. Other than discussions of inventors, scientists and engineers of the time, the earliest records of suction pumps from Europe are associated with mining operations- being used to drain water- (Bjorling, 1895; Shapiro, 1964; Yannopoulos et al., 2015). To that point, there was only a practical understanding of suction pump operation, as atmospheric pressure was not yet understood. It was not until the seventeenth century when the curiosity of suction pumps only being able to lift water approximately ten meters incited theoretical investigations to explain this occurrence. Though continuing from work of his predecessors, Torricelli's experiments to explain atmospheric pressure and invention of the mercury barometer in 1643 arguably established the foundation for the theoretical understanding of suction lift- with these he posed that atmospheric pressure was the force responsible for supporting a column of mercury in a glass tube, the bottom of which was open and placed in a dish of mercury and the top of which contained a partial vacuum- (Bjorling, 1895; Shapiro, 1964; Garbrecht, 1987). Following this, understanding that a suction pump could only lift water to height equivalent to that which the atmospheric pressure could support was developed. Though generally remembered for his contributions to gas principles, this was exemplified by Boyle in 1667 in experiments he conducted to demonstrate the greatest height to which water could be lifted using a manually operated suction pump. Assuming the ratio of specific gravity of mercury to water to be 1:14, observing a mercury column of 29 inches in a Torricelli barometer, Boyle predicted that using an air pump (a type of manually operated suction pump) he should be able to lift water from an open barrel to a height of 34 feet (~10.4

meters). Boyle found that the maximum height he could lift water was approximately 33.5 feet (~10.2 meters), a result that was repeated by several of his contemporaries as well. He credited the discrepancy to the fact that the ratio of specific gravities of mercury to water was not exactly 1:14 (Boyle, 1669).

After the seventeenth century, theoretical consideration of manually operated suction pumps seems to have received little attention in scientific and/or engineering literature. Perhaps this is a result of the introduction of steam and other motorized mechanisms for pump operation; however, manually operated suction pumps were undoubtedly still a relevant technology. For example, during the eighteenth and nineteenth centuries in America, households or small communities using manually operated suction pumps for water supply was common (Eubanks, 1971; Carpenter, 2014). This was likely the case throughout Europe as well. In the twentieth and twenty-first centuries, manually operated suction pumps have become somewhat obsolete in developed countries, being used on a limited basis for small scale applications rather than for significant water supply; but, manually operated suction pumps have become an integral part of water supply in developing countries (see Section 2.3.2).

2.3.2 International Development Context

Arlosoroff et al. (1987) suggested that more suction pumps were in use than any other type of handpump, citing that more than a million had been installed in Bangladesh alone and several more million were in use throughout Asia. As of 2011, it was estimated that more than ten million suction pumps had been installed throughout Asia and Africa (Baumann, 2011). Though many of these pumps are likely in disrepair, the sheer volume of pump installations supports the significance manually operated suction pumps have in providing access to improved water sources.

Throughout the developing world, with a particularly widespread presence in Asia, there are three main types of manual suction pumps being used that can be broadly categorized by the pumping action. They include lever operated pumps (No. 6 Pump), rowing motion pumps (Rower Pump), and peddle operated pumps (Treadle Pump). In reality, there is a vast array of materials used and slightly differing configurations, but the major attributes of each type of pump are fairly similar. The following information is intended to highlight these attributes and provide a representative notion, rather than a complete cataloguing, of the current state of manually operated suction pump technology. These three pump types are stated to lift water around six to seven meters as shown in the following three tables.

The No. 6 Pump is a lever operated pump. The configuration of this type of pump was previously depicted in Figure 2.1. Table 2.3 provides a summary of the important features of the No. 6 Pump.

The Rower Pump, as the name implies, is operated using a rowing motion. The pump handle is inclined at an angle of approximately thirty degrees from horizontal and the operator is often, though not always, in a seated position, making the pump operation ergonomically favorable (Baumann, 2000; Baumann, 2011; Hussey, 2007). Table 2.4 provides a summary of the important features of the Rower Pump.

The Treadle Pump is a foot operated pump. This pump has two pistons that are activated via pedals. As the operator steps down on one pedal, the extended pedal serves as a balance to bring the piston attached to it back up. The operator alternates steps, and the cycle continues. The Treadle Pump exploits leg muscles, which are, generally, more powerful than arm muscles (Baumann, 2011; Hussey, 2007; Olley, 2008). Table 2.5 provides a summary of the important features of the Treadle Pump.

Table 2.3: Technical details, common materials used, applications and approximate cost associated with the No. 6 Pump (Baumann, 2000; Baumann, 2011)

Technical Details		**Common Materials used**		**Application**	**Approximate Cost**
Lift	0-7 m	Pump Head	Cast Iron	Providing drinking water for a family or small community. Limited irrigation use.	100-200 USD, including tubewell
Cylinder Diameter	89 mm	Handle	Cast Iron		
Stroke	215 mm	Pump Rod	Mild Steel		
Yield	~ 4.5 m^3/hr with 75 watt input at 5 m head	Rising Main	PVC		
Population Served	50-100 people	Cylinder	Cast Iron		
Well Type	Collapsible tubewell or dug well	Piston/Foot Valve	Brass or leather		

Table 2.4: Technical details, common materials used, applications and approximate cost associated with the Rower Pump (Baumann, 2011)

Technical Details		**Common Materials used**		**Application**	**Approximate Cost**
Lift	0-8 m	Pump Head	Plastic	Small scale irrigation Limited drinking water use.	100-200 USD, including tubewell
Cylinder Diameter	54.4 mm	Handle	Plastic		
Stroke	Variable	Pump Rod	Plastic		
Yield	~ 4.5 m^3/hr with 75 watt input at 5 m head	Rising Main	PVC		
Population Served	50-100 people	Cylinder	Plastic		
Well Type	Collapsible tubewell or dug well	Piston/Foot Valve	Rubber		

Table 2.5: Technical details, common materials used, applications and approximate cost associated with the Treadle Pump (Baumann, 2011)

Technical Details		**Common Materials used**		**Application**	**Approximate Cost**
Lift	0-6 m	Pump Head	Mild Steel	Small scale irrigation Limited drinking water use.	100-200 USD, including tubewell
Cylinder Diameter	3.5 and 5 in	Handle	Mild Steel		
Stroke	Variable	Pump Rod	Mild Steel		
Yield	~ 4.5 m^3/hr with 75 watt input at 5 m head	Rising Main	PVC or bamboo		
Population Served	0.25 hectare	Cylinder	Mild Steel		
Well Type	Collapsible tubewell or dug well	Piston/Foot Valve	Leather		

2.4 Basic Principles of Pump Operation

This section will present the basic theory of the operation of a manually operated suction pump. This research was motivated by its practical implications for water supply in low-income countries, and therefore, the following discussion will focus on the principles of operation necessary to understanding how manually operated suction pumps work.

Suction pumps are generally classified into two broad categories: kinetic/dynamic or positive displacement. Manually operated suction pumps are positive displacement-type suction pumps. Positive displacement-type suction pumps are also generally classified into two broad categories: reciprocating or rotating. Manually operated suction pumps are reciprocating positive displacement pumps. Such pumps operate by trapping a fixed volume of fluid within a cavity and then pushing that volume out of the cavity through the back-and-forth motion of a piston within the cavity. As discussed in Section 2.3, manual suction pumps can be broadly categorized by their pumping action. The remainder of this thesis will primarily consider lever operated pumps, as shown before in Figure 2.1.

Figure 2.2 illustrates the operation of the pump, highlighting the position of the valves and piston over a complete cycle of pump operation. Figure 2.2A shows the piston at its lowermost position (the pump handle would be at its highest position). The foot valve is closed, and the piston valve is open. The operator would then push the pump handle downward, raising the piston; an intermediate position is shown in Figure 2.2B. The pressure of the water above the piston closes the piston valve, and the decreased pressure (suction) created by the upward movement of the piston opens the foot valve, drawing water from the rising main into the pump cylinder. The piston with its closed piston valve displaces the water above it in the cylinder, pushing that water out of the pump outlet. Figure 2.2C shows the piston at its highest point (the pump handle would be at its lowest point). The foot valve is open, and the piston valve is closed. Figure 2.2D shows an intermediate position during the descent of the piston, achieved by raising the pump handle upward. The descending piston increases the pressure in the pump cylinder below the piston, closing the foot valve and opening the piston valve, forcing water to flow through the piston valve into the pump cylinder above the piston. The piston subsequently returns to its lowermost position as shown in Figure 2.2A, and the cycle would then be repeated.

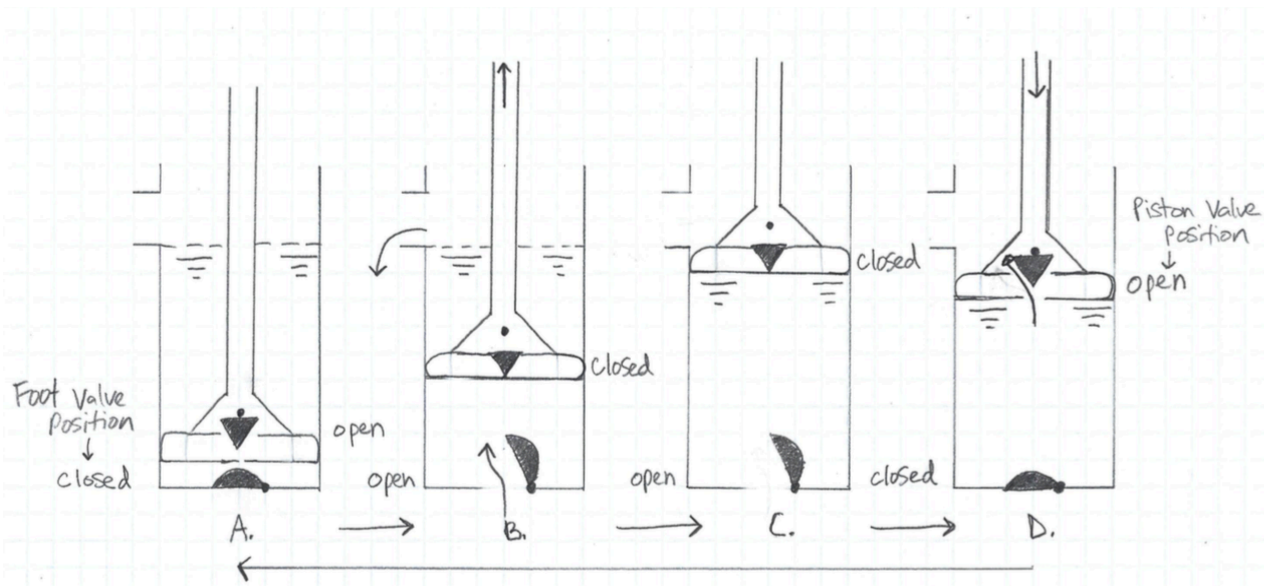

Figure 2.2: Diagram illustrating the operation of a manually operated suction pump over one complete pump cycle (adapted from Yau, 1985)

For the application of manually operated suction pumps it is assumed that the rising main terminates in a surficial aquifer with a screened pipe at or below the water table. The water table is the pressure surface at some depth below the ground where pore water pressure is equal to local atmospheric pressure. Hence the water level in the rising main before operation of the pump will coincide with the water table and therefore will be at local atmospheric pressure.

As shown in Figure 2.3A, prior to operation of the pump, the rising main will be filled with air at atmospheric pressure, and no water movement will occur. As shown in Figure 2.3B-E, as the pump is operated, air is displaced from the pump cylinder and rising main, creating lowered pressure in the rising main. The atmospheric pressure at the water table surface will force water into and up the rising main against the lowered pressure of the partially evacuated system. The operation of the valves essentially isolates the rising main from atmospheric pressure at the surface, and consequently the (static) pressure at any point in the rising main will be equal to atmospheric pressure minus the pressure that would be generated by the column of water in the rising main at that height, as shown in Figure 2.3C.

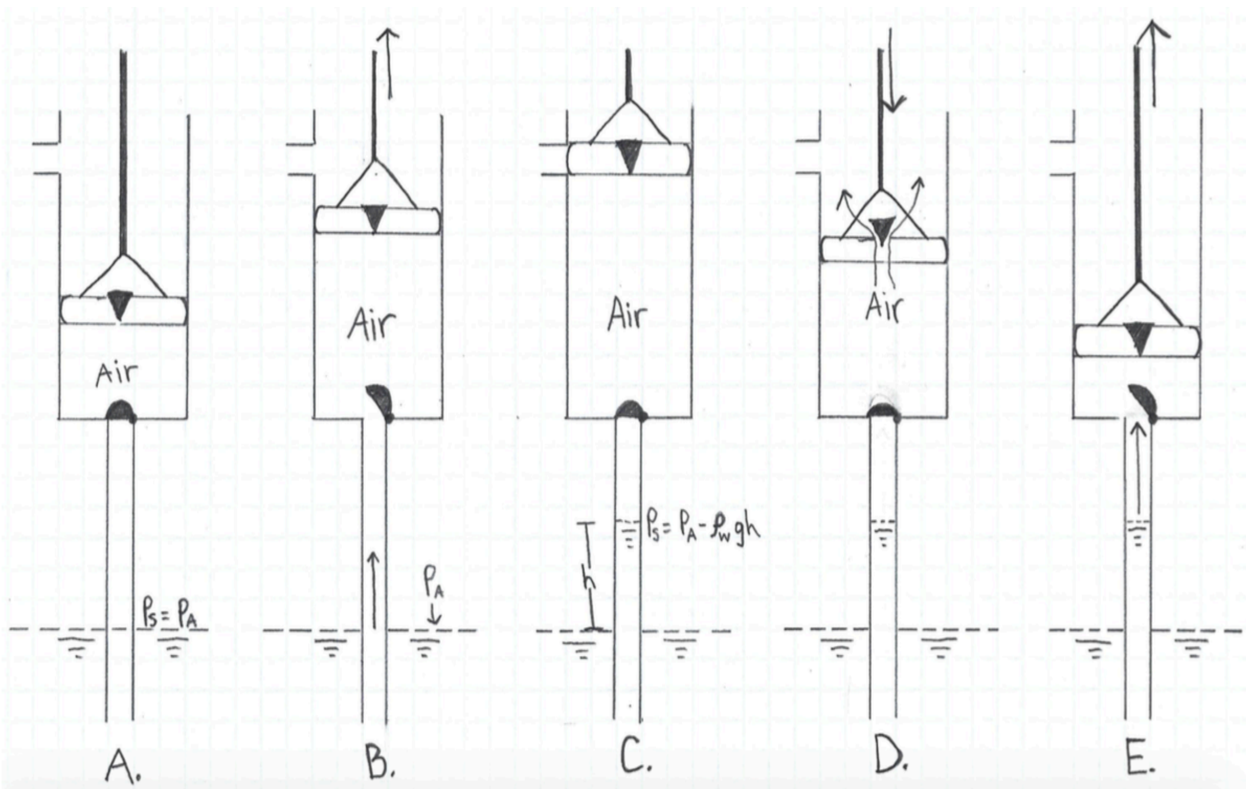

Figure 2.3: Initial stage of pump operation. Water is pushed up the rising main due to the pressure gradient between atmospheric pressure and low pressure region generated through pump operation. (P_s is the static pressure; P_A is atmospheric pressure; ρ_w is the mass density of water; g is acceleration due to gravity; h is the height (distance) the water moved) (adapted from McJunkin, 1977).

Head (h), water energy per unit weight, is equivalent to water elevation above a specified point, and therefore can be used to represent the height water will rise in a pipe (Bloomer, 2000;

Fitts, 2002; Mihelcic et al., 2009). Water energy, or head, is related to pressure (P) according to the following equation:

$$h = \frac{P}{\rho_w g} \qquad (2.1)$$

where ρ_w is the mass density of water and g is acceleration due to gravity (typically 9.81 m/s^2) (Bloomer, 2000; Fitts, 2002; Mihelcic et al., 2009). Considering only hydrostatics, given that the cylinder of a suction pump is located above the water table, the theoretical maximum lift is limited to the height that would be supported by atmospheric pressure, reduced only by the vapor pressure of water. Note that vapor pressure must be taken into account in a comprehensive theoretical model because no matter how effective the pump suction is, there will always be water vapor present above any available free water surface, such as in the rising main as water ascends the rising main towards the pump cylinder. This may limit the minimal suction pressure actually achievable.

The maximum theoretical lift of a suction pump is conventionally cited assuming elevation is equal to sea level (atmospheric pressure = 101.33 kPa) and water temperature is equal to 20 ^{o}C (mass density = 998.2 kg/m^3; vapor pressure of water = 2.34 kPa). Then, by converting these pressures to head using equation 2.1, the maximum theoretical lift of a suction pump is shown to equal approximately 10.1 meters (Fraenkel 1997; Baumann 2000; Mihelcic et al. 2009).

2.4.1 Impact of Local Conditions

Atmospheric pressure and water temperature are both dynamic variables that change both spatially and temporally, and therefore, maximum theoretical suction lift is not expected to be a constant. The following explanation is only intended to highlight the major effects of altitude and temperature on the aspects of pressure most influential to suction lift.

As altitude increases, atmospheric pressure decreases, which means the height of the column of water that can be supported by atmospheric pressure will decrease. Therefore, higher altitudes will further limit the suction lift. The reduction in suction lift is approximately proportional to the increase in elevation; that is, at an elevation of 1,500 meters, suction lift would be reduced by about 1.5 meters, and at an elevation of 3,000 meters, suction lift would be reduced by about three meters (Fraenkel, 1997). Table 2.6 indicates changes in atmospheric pressure with increasing elevation and the corresponding maximum theoretical suction lift associated with the given atmospheric pressure conditions. Note that the atmospheric pressure values associated with each elevation are from the International Standard Atmosphere (ISA) model (ISO 2533:1975), a commonly used reference for describing atmospheric changes with altitude. The maximum theoretical suction lift values presented in Table 2.6 were determined using equation 2.1 assuming a water temperature of 20 ^{o}C (mass density = 998.2 kg/m^3) and acceleration due to gravity equal to 9.81 m/s^2. Also, note that the maximum theoretical suction lift values in Table 2.6 only reflect atmospheric pressure; that is, the reduction in suction lift due to the presence of water vapor pressure is not considered in the maximum theoretical suction lift values shown in Table 2.6. In neglecting the affect of water vapor pressure, the maximum theoretical suction lift values in Table 2.6 emphasize that atmospheric pressure is the foundation of suction lift and exclusively highlight the influence of altitude. However, it is important to recall that vapor pressure should be considered in a comprehensive theoretical model, and thus should be subtracted from the values presented in Table 2.6 when considering the maximum theoretical suction lift at a given place and time. The potential impact of water vapor pressure will be discussed below.

Table 2.6: Change in maximum theoretical suction lift corresponding to change in atmospheric pressure associated with increasing altitude (elevation above sea level)

Elevation, ft	Elevation, m	Atmospheric Pressure, kPa	Maximum Theoretical Suction Lift, m
0*	0	101.33	10.35
500	152	99.49	10.16
1000	305	97.63	9.97
1500	457	95.91	9.79
2000	610	94.19	9.62
2500	762	92.46	9.44
3000	914	90.81	9.27
3500	1067	89.15	9.10
4000	1219	87.49	8.93
4500	1372	85.91	8.77
5000	1524	84.33	8.61
6000	1829	81.22	8.29
7000	2134	78.19	7.98
8000	2438	75.22	7.68
9000	2743	72.40	7.39
10000	3048	69.64	7.11

*- Elevation of 0 feet corresponds to sea level. Note that, here, maximum theoretical suction lift does not account for vapor pressure of water and is therefore slightly higher than the value reported in Section 2.4 for maximum theoretical suction lift at sea level and water temperature of 20 ^{o}C

Similar to changes in altitude, as water temperature increases, suction lift decreases. Reduced suction lift with increased water temperature is a result of changes in the vapor pressure of water. The vapor pressure of any liquid, water included, is a function of its temperature and vapor pressure increases as the liquid temperature increases. Thus, because maximum theoretical suction lift equals atmospheric pressure minus vapor pressure of water, increased water temperature results in decreased lift (Fraenkel, 1997; Crittenden et al., 2012). For example, Fraenkel (1997) states that an increase in water temperature from 20 ^{o}C to 30 ^{o}C would result in approximately seven percent reduction in suction lift. However, the opposite relationship should be noted as well; vapor pressure decreases as the water temperature decreases. This potentially has implications relevant to the affects of changes in elevation. Modeling groundwater temperatures is not an easy task as they are highly dependent on local hydrogeologic contexts, and this is especially true for mountainous terrain that is often typical of high elevation regions (Garfias, 2002; Benz et al., 2017). However, in the past, groundwater temperature approximations have been made relative to mean surface air temperatures, indicating a relationship between the two. In an area with lower annual mean surface air temperatures, average groundwater temperatures might also be lower, relative to an area with higher annual mean surface air temperatures (Fitts, 2002; Benz et al., 2017). As elevation increases, air temperature decreases (ISO 2533:1975), which means that groundwater temperatures could potentially be lower at higher elevations and vapor pressure would have less of an impact on suction lift.

While these issues related to atmospheric pressure and water temperature are important to note, they likely receive less attention because of the various practical considerations related to the pumping system itself that reduce the lift below the maximum theoretical limit. For example, there will be frictional losses such as water movement against the inner surface of the rising main, and efficiency losses imposed by movement of the water through the valves, and by the action of the valves themselves. Additionally, there will be efficiency losses imposed by any back leakage through the valves, and also across the piston. These losses can be calculated using the concept of total dynamic head (TDH), which accounts for loss of available pressure to move/lift water imposed by these dynamic and system efficiency issues. TDH is the energy required to pump water at a specific flow rate, and is equal to the sum of the static lift, back pressure, frictional losses, and drawdown (Fraenkle, 1997; Mihelcic et al., 2009). It is also convenient to think of TDH as the total equivalent height to which a fluid is to be pumped.

Therefore, in the case of suction pumps, the TDH is limited to the maximum theoretical suction lift, so any contribution from back pressure, frictional losses, or drawdown reduces the static lift capable, or the height to which water can be raised. A full treatment of these issues is beyond the scope of this thesis. However, applying these concepts to the experimental model used in this thesis research allows for at least an estimate of achievable suction lift with this experimental model, which will be further discussed in Section 3.1. It should be noted that elevation, temperature, and humidity could potentially impact pump functionality as most pump materials perform slightly differently under different environmental conditions (e.g. leather expands when exposed to moister and iron experiences thermal expansion). The impact of environmental conditions (elevation, temperature, humidity) on material performance might have a minor impact on pump efficiency; however, the changes in material performance due to environmental conditions are not expected to fundamentally change the maximum theoretical suction lift, which is based on physical principles.

It is curious that in the 1600s, statements, and supporting evidence, indicate that suction pumps could lift water approximately ten meters (Boyle, 1669), but by the 1800s it was commonly stated that the practical suction lift was not more than approximately 25 feet (7.6 meters). A solid *(confirmed)* explanation for this deviation has eluded the author. However, in the seventeenth century early steam engines were frequently used to pump water, and the "practical limits" of these engines were typically described as about 25 feet. For reasons unclear, it seems that this limit of about 25 feet has become widely accepted as the practical limit of all suction pumps, regardless of type. In both development literature dealing with water supply and in engineering literature, it is commonly stated, with few exceptions, that the limit of suction lift is 7-8 meters. As the context of this thesis is water supply LICs, Table 2.7 provides several examples from development literature.

The 7-8 meter limit is very pervasive, but the explanations as to the basis for this limit are vague, if given at all. Theoretical and/or empirical evidence is lacking, which is especially true for development literature. There might be potentially insightful information in pump manufacturers' literature/data/reports, but given the application of motorized pumps are generally concerned with flow rates rather than the height to which water can be pumped, there still might not be direct or explicit explanations for the 7-8 meter limit.

Table 2.7: Example sources claiming 7-8 meters as the practical suction lift limit

Source	**Stated Practical Suction-lift Limit**	**Context (technology in reference to) and Rationale (if given)**
Grier, 1876	20-25 feet	Suction-lift pumps (example of a lever operated handpump is given). Imperfections in construction and imperfections as a result of use
Colyer, 1882	25 feet	Lift pumps ("For pumping water from wells to the ground surface…")
Bjorling, 1895	20-25 feet	Suction-lift pumps (example of a lever operated handpump is given). "…the imperfection of different parts of the pump…"
Eubanks, 1971	25 feet	Made in reference to several pump variations which operate on the principle of suction lift.
McJunkin, 1977	22 feet (6.7 meters)	"Practical value for design is 2/3 of theoretical"
Urban Resource Consultants, Inc., 1979	8 meters	"[Hand]Pumps with the cylinder at the top of the well ('suction pumps')…"
Fraenkel, 1986	7 meters	Human powered suction pumps
Arlosoroff et al., 1987	7 meters	"Operating limit is set by…effectiveness of the seals, which make the practical limit only about two-thirds of full barometric pressure"
Orr et al., 1991	30 feet	Treadle Pumps
Parker, 1994	20-25 feet (6-8 meters)	Motorized pumps (surface centrifugal pumps and peristaltic pumps) for groundwater sampling classified as suction lift devices
Skinner, 1996	7.5 meters	Suction pumps
Skinner and Shaw, 1999	7-8.5 meters	Manual handpumps, including suction pumps

Table 2.7: Continued

Bauman, 2000	7-8 meters	Suction pumps (handpumps with the cylinder located above the water table)
Kay and Brabben, 2000	7 meters	"…a sensible limit is 7 m because of friction losses in the suction pipe and the effort required to create a vacuum"
Skinner, 2003	7 meters	Suction pumps
Harvey and Reed, 2004	7 meters	Suction pumps
Olley, 2008	7 meters	Human-powered reciprocating suction pumps ("…atmospheric pressure difference between the inside and outside of the cylinder is only large enough to raise water up to a maximum of 7 meters from the water table.")
Mihelcic et al., 2009	7 meters	Pitcher Pump- manually operated suction-lift pump (lever-operated)
Bauman, 2011	6-9 meters	6 meters- Treadle Pump; 7 meters- No. 6 Pump; 8 meters- Rower Pump; 9 meters- Monkey Maker Pump
WaterAid, 2013	7 meters	Suction pumps- a type of low lift handpump
Simmons Manufacturing, 2015	25 feet	Pitcher Pump (actual pump used for this research)
Sarkar and Jha, 2015	7 meters	Suction pumps- a type of low lift handpump
Yannopoulos et al., 2015	7.62 meters	Piston pumps used circa 1300s-1600s. "…altitude, friction loss, temperature, suspended particles or the inability to create a perfect vacuum." (rationale from personal email communication with lead author)

CHAPTER 3: METHODS

3.1 Calculations

As discussed in Section 2.4, it is accepted that suction pump lift that can be defined by fundamental physical principles is limited by local atmospheric pressure, and the maximum theoretical lift, at sea level, will generally be around 10.1 meters. As also discussed in Section 2.4, there are many practical considerations which potentially further limit the suction lift that is actually achievable. This section will describe the methodology used to theoretically estimate the expected suction lift, herein referred to as practical theoretical lift, based on the experimental model specific to this thesis research. The practical theoretical suction lift is largely governed by principles of fluid mechanics and will so be discussed through applied fluid dynamics related to flow in pipes.

After conducting a literature review and to the best of the author's knowledge, rigorous analytical assessments of manual suction pump operation have not yet been performed. Additionally, only one theoretical and/or experimental investigation specifically addressing the height to which manually operated suction pumps can lift water was found (Boyle, 1669). Therefore, the methodology used in this research is based primarily on examples related to analysis and design of motorized suction pump systems (note that throughout this thesis "pump systems" refers to the pump itself and the piping). Such analyses invoke strategies ranging from the utilization of simple algebraic approximations to complex numerical methods. Translating the advanced mathematical models applied to motorized pumping systems to manual pumping systems is a question of mechanical engineering making development of a comprehensive theoretical model beyond the scope of this thesis. Instead, as is often done with the initiation of (local scale) international development engineering fieldwork projects, the focus here was a less complex model allowing for simple mathematical solutions.

As discussed previously, TDH is equal to the sum of the static lift, back pressure, frictional losses, and drawdown (Fraenkle, 1997; Mihelcic et al., 2009). Previously, TDH was defined as the energy required to pump water at a specific flow rate. Work, which is related to mechanical energy, is the integral of force multiplied by distance, so TDH can also be thought of as the force required to pump water over a given distance. In this model, as is most often the case with the use of suction pumps, atmospheric pressure is the force driving the fluid movement and is therefore the maximum available force to move/lift the water. This implies that, for the pump to work, the TDH cannot exceed local atmospheric pressure. It then follows that contributions from back pressure, frictional losses, or drawdown reduce the static lift capable, or the height to which water can be raised. The practical theoretical lift equals the maximum theoretical lift minus the sum of back pressure, frictional losses, and drawdown.

The following discussion describes the experimental system of this study. A suction pump is attached to some length of straight piping. The pump is elevated above a freshwater reservoir (an open tank filled with water), the surface of which is at local atmospheric pressure. Extending vertically down from the pump, the piping, being open at the bottom, terminates below the water surface of the reservoir. The pump is then operated so that water is pushed up through the rising main into the cylinder and then discharged from the system. In this model, drawdown - drop in water level due to pumping - was assumed to be negligible, as would be the case when pumping from an open tank whose volume is much greater than the volume to be extracted, and therefore not considered in the determination of the practical theoretical lift. In reality, drawdown will occur when water is pumped from a well. However, in the context of Self-supply, it is not unreasonable to presume that the volume of water to be extracted from a well at any given time, or use of the pump, would be small relative to available aquifer storage. Additionally, along with pumping duration, the amount of drawdown that will occur is dependent on the hydrogeologic environment in which the well is located. A small volume pumped from a highly transmissive aquifer would likely result in insignificant drawdown, representing a situation in which the model is relevant (Arlosoroff et al., 1987; Fitts, 2002; MacDonald et al., 2005). Similarly, back pressure is assumed to not be an issue with this model. Generally, back pressure is only considered significant when there is some length of pipe attached above the pump and/or when pumping to a tank, neither of which apply here (Bloomer, 2000). Water discharges directly from the pump into a vessel that is completely separate from the pumping system, which is representative of how manually operated suction pumps are used in the context of water supply in low-income countries.

For the experimental model, as just described, the practical theoretical lift equals the maximum theoretical lift minus frictional losses. When estimating frictional losses in the analysis and design of motorized suction pump systems, the assumptions of uniform, steady, incompressible flow are often adopted (Bloomer, 2000; Crowe et al., 2001). For manual suction pump systems, only the lattermost assumption of incompressible flow is actually realized. For most engineering design issues, present case included, water can be considered incompressible. However, given that during the operation of a manual suction pump the fluid movement cycles from no flow to some maximum and then back to no flow through each complete cycle, the flow (average velocity) is neither constant with respect to position (uniform) nor time (steady).

Recognizing that the conditions of uniform and steady flow are not realized with the use of manual suction pumps, it should be acknowledged that the following methods for determining frictional losses may not be entirely appropriate. However, these methods are commonly used and do allow for rough initial estimates of practical theoretical lift to be obtained with simple mathematical solutions. Additionally, the concept of acceleration head will be used to account for the unsteady flow behavior that occurs during pump operation.

Before describing the specific equations used to estimate the suction lift limit, it should be noted that the following methods are fundamentally based on the energy equation for fluid flow. Specifically, the Bernoulli equation is the energy equation for one-dimensional, incompressible flow in pipes, which is the foundation for the following discussion. Practical considerations of energy losses were then incorporated into the Bernoulli equation. The following discussion describes these practical considerations.

In determining energy losses, the following are typically considered: losses due to fluid entering and/or exiting the system, losses due to pipe friction, losses due to valves and fittings, losses due to bends, and losses due to changes in flow areas (Bloomer, 2000; Crowe et al., 2001). These losses can be summarized as "head loss" according to

$$h_L = \sum f \frac{LV^2}{D2g} + \sum K \frac{V^2}{2g} \quad (3.1)$$

where f is the Darcy-Weisbach friction factor, L is the pipe length, V is the mean velocity of the fluid, D is the internal pipe diameter, g is acceleration due to gravity, and K is a loss coefficient. The first term on the right side of the equal sign, which is the Darcy-Weisbach equation, represents losses associated with pipe friction (often referred to as "major losses"). The second term on the right side of the equal sign represents losses that arise due to turbulence associated with entrance and exit geometry, valves, fittings, bends, and changes in flow area, which will be collectively referred to as system losses in this thesis, but are often referred to as “minor losses.” Each of these factors (entrance and exit geometry, valves, fittings, bends, and changes in flow area) has an associated loss coefficient, K, the values for which can be obtained from resources such as the *Hydraulic Institute Engineering Data Book* (Hydraulic Institute, 1990) and the *Handbook of Hydraulics* (Brater et al., 1996).

In the application of the Darcy-Weisbach equation to this study, the mean velocity, V, was assumed to equal the volumetric flow rate, Q, divided by the wetted cross-sectional area of a full-flowing pipe, $A = \pi/4 \times D^2$. The Darcy-Weisbach equation was then expressed in terms of volumetric flow rate as

$$h_f = f\frac{L8Q^2}{\pi^2 D^5 g} \qquad (3.2)$$

where h_f is head loss due to pipe friction, f is the Darcy-Weisbach friction factor, L is the pipe length, Q is the volumetric flow rate, D is the pipe diameter, and g is acceleration due to gravity. The friction factor, f, is a function of the pipe Reynolds number, Re, which indicates if flow is laminar or turbulent. For most engineering applications, laminar flow is assumed when the Reynolds number is less than 2,000 and turbulent flow is assumed when the Reynolds number is greater than 3,000. When the Reynolds number is greater than 2,000 but less than 3,000, flow is considered transient (Crowe et al., 2001). Reynolds number is determined by

$$Re = \frac{VD}{\nu} \qquad (3.3)$$

where ν is kinematic viscosity and again, V is mean velocity, and D is pipe diameter. As discussed above, Reynolds number was also calculated in terms of volumetric flow rate assuming $V = Q/(\pi/4 \times D^2)$. Typically, under laminar flow conditions (Re<2,000), $f = 64/Re$. Under turbulent flow conditions (Re>3,000), there are several methods that can be used to determine the friction factor. The standard engineering approach, and the one employed here, is use of the Colebrook equation, which is shown below in equation 3.4. In this equation, ε is the absolute surface roughness coefficient, expressed in units of length, associated with a given pipe material.

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad (3.4)$$

For transient flow conditions (2,000<Re<3,000), it is very difficult to define the friction factor. For this thesis, when the Reynolds number was between 2,000 and 3,000, the Colebrook equation was again used to determine the friction factor.

Recall that the second term on the right side of the equal sign from equation 3.1 (system friction losses) represents losses associated with entrance and exit geometry, valves, fittings, bends, and changes in flow area. The model used in this study consisted only of straight piping, making losses due to bends irrelevant. As noted previously, the loss coefficient, K, values for the remaining factors were taken from the *Hydraulic Institute Engineering Data Book* (Hydraulic Institute, 1990) and the *Handbook of Hydraulics* (Brater et al., 1996). A sharp-edged inlet geometry was assumed, which has a K value of 0.5. All exit geometries have a K value of 1. The considered system had one swing check valve, which has a K value of 2. For determination of frictional losses, the experimental system was considered to have three threaded unions, the maximum number present in the actual experimental set-up. Each union has a K value of 0.08. The model considered two pipe (internal) diameters, 1.25-inch and 2-inch. The pump had a 3.5-inch diameter cylinder and a 1.25-inch pipe connection. For the 1.25-inch pipe scenarios, a sudden enlargement was assumed to represent flow from the rising main into the pump cylinder. The K value was calculated as $K = [1-(d/D)^2]^2$ where d is the internal pipe diameter and D is the pump cylinder diameter, giving a value of 0.76. For the 2-inch pipe scenarios, there was a sudden contraction as the pipe was reduced to 1.25-inch at the pump connection followed by a sudden enlargement between the pipe connection and the pump cylinder. The K value for a sudden contraction is dependent on the ratio of the different flow areas, and values are reported for given diameter ratios. The ratio of the internal pipe diameter (2 inches) to the pump connection diameter (1.25 inches) was 1.6, which has a K value of 0.26. The sudden enlargement from the 1.25-inch pipe connection to the 3.5-inch pump cylinder was calculated as it was for the 1.25-inch pipe scenarios, again giving a K value of 0.76.

To make initial estimates of practical theoretical suction lift, volumetric flow rates based on observations of manual suction pump systems in Madagascar made by members of our research group were used. All other inputs were based on the materials actually used for the field testing component (Section 3.2) of this research. Table 3.1 summarizes the input values used in the determination of energy (friction and system) losses for the initial estimates of practical theoretical suction lift. Energy losses were calculated assuming water temperatures of 20 ^{o}C and 25 ^{o}C. A water temperature of 20 ^{o}C was used because this is the condition most often assumed in discussions of maximum theoretical suction lift, making results comparable to previously stated suction lift limits, like those presented in Table 2.7. A water temperature of 25 ^{o}C was used because, given the field location (Tampa, FL), it was anticipated that water temperatures might exceed 20 ^{o}C. Also, in Madagascar, groundwater temperatures in the range of 25-28 ^{o}C have been reported by members of our research group (Akers, 2014).

Table 3.1: Input parameters for the determination of energy (frictional and system) losses

Pipe Material	PVC		GI
Surface Roughness, ε	1.5×10^{-6} m		1.5×10^{-4} m
Pipe Diameter, D	0.0318 m	0.0508 m	0.0318 m
Loss Coefficient, K	4.50	4.76	4.50
Pipe Length, L* At 20 °C At 25 °C	 $(10.1 - h_f)$ m $(10.04 - h_f)$ m		
Volumetric Flow Rate, Q 4 L/min 11 L/min	 6.67×10^{-5} m^3/s 1.83×10^{-4} m^3/s		
Acceleration due to Gravity, g	9.81 m^2/s		
Kinematic Viscosity, ν At 20 °C At 25 °C	 1.003×10^{-6} m^2/s 0.893×10^{-6} m^2/s		

*- Pipe length appears in the Darcy-Weisbach equation. The theoretical maximum suction lift, at a given temperature, minus the pipe friction will indicate the pipe length associated with the practical theoretical lift. In making L = 10.1/10.04 - h_f, pipe friction is not overestimated.

To this point, the discussion of practical theoretical lift has assumed that frictional losses associated with a pump system account for the reduction from the maximum theoretical achievable lift. In the design and analysis of motorized reciprocating suction pump systems, the concept of acceleration head is also frequently employed. In reciprocating suction pumps, as the fluid cycles from essentially motionless to some maximum velocity through each stroke, pressure pulsations are generated in the system. The concept of acceleration head is an attempt to model this phenomenon by considering the energy required for the fluid to accelerate (Miller, 1987; Singh and Able, 1996; Tackett et al., 2008). As with frictional losses, acceleration head is expressed as head loss.

Acceleration head loss is commonly estimated using the Hydraulic Institute Standards equation

$$h_a = \frac{LVNC}{kg} \qquad (3.5)$$

where L is the pipe length, V is the mean flow velocity, N is pump speed (e.g., strokes per minute), C is a pump constant factor, k is a fluid compressibility constant factor, and g is acceleration due to gravity. The applicability of the acceleration head concept has been questioned for more complex pump systems (Singh and Madavan, 1987; Wachel et al., 1989; Singh and Able, 1996). However, for simple pump systems, such as the one considered in this research, it is reasonable to apply this approach. Equation 3.5 is considered valid if $L < 3c/nN$, where L is pipe length, c is the speed of sound, N is the pump speed in strokes per minute, and n is the number of cylinders (1 in this case) (Singh and Able, 1996). L is well under the calculated limit for all trials conducted in this investigation.

The pump investigated in this research would be considered a simplex single acting pump, which has an associated C value of 0.400 (Miller, 1987; Tackett et al., 2008). Of the commonly reported k values, the one generally associated with water (k = 1.5) was used (Miller, 1987; Tackett et al., 2008). Similar to calculations of frictional losses, acceleration head losses were calculated assuming pipe lengths of $10.1 - h_a$ and $10.04 - h_a$, for 20 ^oC and 25 ^oC water temperature, respectively, for internal pipe diameters of 1.25 and 2 inches at flow rates of 4 and 11 L/min. Pump speeds of 20 and 31 strokes per minute (see Section 3.2) were used with the 4 and 11 L/min flow rate calculations, respectively. Again, mean flow velocity was assumed as $V = Q/(\pi/4 \times D^2)$.

Though discussions of acceleration head do not explicitly address frictional and system head losses, often, they imply that frictional and system losses should also be considered in the evaluation of pump systems (Miller, 1987; Singh and Able, 1996; Tackett et al., 2008). Therefore, in this thesis, estimated frictional, system and acceleration head losses were combined to provide overall initial estimates of head loss. These overall head loss values were then subtracted from the maximum theoretical suction lift assuming elevation equal to sea level. Therefore, in this thesis, practical theoretical suction lift was modeled as

$$Practical\ Theoretical\ Limit = Max\ Theoretical\ Suction\ Lift - (h_L + h_a) \quad (3.6)$$

3.2 Laboratory (Field) Testing

As will be seen in Chapter 4, when accounting for estimates of frictional, system and acceleration head losses, the estimated practical theoretical limit for manually operated suction pumps should be approximately 10 to 9.4 meters, depending on pipe diameter, material, and flow rate. Field tests were conducted to assess the appropriateness of the estimated practical theoretical limits through comparison to observed results from tested capabilities. For field results, the maximum pumping limit was defined as the maximum height at which water could be produced from the pump outlet regardless of pumping rate or flow rate. Additionally, recognizing that pumping to the maximum possible height was likely to be overly strenuous, field tests were also used to determine the practical pumping limit. The practical pumping limit is defined here as the maximum height water could be lifted at which the prescribed pumping rates would result in values as close as practical to a low and high target flow rate.

The field test methodology employed in this research was intended to approximate actual field conditions, but allowed for evaluation of pump performance in a controlled environment. Field test procedures were developed based on the functionality of the Pitcher Pump systems observed in Madagascar. In determining the maximum and practical pumping limits, field test procedures were designed to evaluate the influence of pipe diameter and pipe material on pump performance. In Madagascar, and most SSA countries, there is variability in both of these factors. Understanding the effect of each on pump system performance has practical implications for recommendations concerning optimal system design.

Field tests were conducted at the University of South Florida (USF) (Tampa, FL) in November/December 2016 and April 2017. All testing took place at the outside staircase located at the Northwest corner of the Engineering Three building (ENC). Tests were performed at heights between seven and ten meters using 1.25- and 2-inch inside diameter poly(vinyl chloride) (PVC) Schedule 40 and 1.25-inch inside diameter galvanized iron (GI) pipes. All piping was purchased new from Buck's Wholesale Plumbing Supply (Tampa, FL) in November 2016. PVC Schedule 40 is typically sold in 10-foot sections with the option to purchase half sections. To accommodate testing needs, four 10-foot sections and one 5-foot section were purchased of both 1.25- and 2-inch PVC. GI pipe is typically sold in 30-foot sections. At the purchase location, the GI pipe was cut and threaded into the following segment lengths: 15-foot, 10.5-foot (two), 6-foot and 5-foot. All tests were conducted using a Simmons Manufacturing Pitcher Pump #1160 (McDonough, GA). The pump was purchased new and had not been used until the experiments described herein.

A Simmons Manufacturing Pitcher Pump was used, opposed to a Pitcher Pump locally manufactured in Madagascar, because it was readily available at the time of testing. The Simmons Manufacturing Pitcher Pump was deemed an appropriate alternative to a Pitcher Pump from Madagascar because the two are very similar in design and are constructed using similar materials. As observed in Madagascar, there are many small enterprises with welding workshops that manufacture Pitcher Pumps. Typically, Madagascar Pitcher Pumps have cylinders made of cast iron and two weighted check valves (foot valve and piston valve) made of leather and weighted with lead (MacCarthy et al., 2013; Akers et al., 2015). The Simmons Manufacturing Pitcher Pump also has a cylinder made of cast iron and two weighted check valves (foot valve and piston valve) made of leather. However, the valves of the Simmons Manufacturing Pitcher

Pump are weighted with iron. The handle of the Madagascar Pitcher Pumps is generally longer than the handle of the Simmons Manufacturing Pump, so, based strictly on pump configuration, it would be expected that the Simmons pump would be require slightly more effort to operate, as both are lever-operated pumps. The locally manufactured Pitcher Pumps in Madagascar would have more variation in their dimensions, which could influence pump performance, but generally there are only minor differences between the locally manufactured Madagascar pumps and the Simmons Manufacturing pump, so similar results might be expected using either pump.

The practical and maximum pumping limits are a product of the entire pumping system, not just the pump itself, so these values were determined for each of the three pipe material/diameter combinations that were used. Table 3.2 provides a general outline of the testing scheme. Each pipe material/diameter combination was tested at two predetermined pumping rates at heights from seven to ten meters. Each cell in Table 3.2 represents a unique system as defined by the combination of pipe material, pipe diameter, test height and pumping rate. For example, 1A was 1.25-inch PVC at seven meters with a pumping rate of 20 strokes per minute and 5B was 2-inch PVC at eight meters with a pumping rate of 31 strokes per minute. Eighteen systems were tested and three trials were conducted for each, so 54 trials were conducted as shown in Table 3.2.

Table 3.2: Work plan defining pumping systems (combination of pipe material, pipe diameter, test height and pumping rate) tested and number of trials

Pumping Rate (strokes/min)	1.25-inch PVC			2-inch PVC			1.25-inch GI		
	7 m	8 m	9 m	7 m	8 m	9 m	7 m	8 m	9 m
20	1A 3 trials	2A	3A	4A	5A	6A	7A	8A	9A
31	1B 3 trials	2B	3B	4B	5B	6B	7B	8B	9B

During November/December 2016, preliminary testing was performed to define and pilot the specific testing protocol. During that time period, first, pumping rate - the rate at which the pump handle is repeatedly moved from its highest point to its lowest point, or strokes per time - calibration trials were conducted. In Madagascar, MacCarthy et al. (2013) observed flow rates between 4 and 11 liters/minute (L/min) associated with Pitcher Pump systems. The high and low values for the observed range (4 L/min and 11 L/min) were selected as the target flow rates. The pumping rates that would produce flow rates of 4 and 11 L/min were then determined.

Pumping rates were determined from the lowest height to be tested, seven meters, using 1.25-inch PVC. A clean, unused plastic five-gallon paint bucket was calibrated to 4 and 11 liters by using a laboratory cylinder to fill the bucket to the stated volumes and then marking the respective water levels. Then, always counting the number of strokes, trial and error iterations were repeated until four liters were pumped in one minute followed by trial and error iterations until 11 liters were pumped in one minute. A digital metronome (iMetronome- GLP Software, 2009) was set to the number of strokes needed to pump each volume in one minute so that one beat would correspond to one full stroke. A final trial was performed for each volume in which the pumper took one full stroke for every beat of the metronome to verify that four and 11 liters were pumped in one minute according to the determined pumping rates. The lowest setting on the metronome is 20 beats per minute (bpm) (several digital metronome applications were tested, all of whose lowest setting was 20 beats per minute). A pumping rate of 20 strokes per minute produced a flow rate closer to 6 L/min. Therefore, because of limitations of the metronome technology, the target flow rate of 4 L/min was adjusted to 6 L/min and a pumping rate of 20 strokes per minute was used as the low range of flow rate in all later experiments. A pumping rate of 31 strokes per minute produced a flow rate of approximately 11 L/min and was therefore used throughout testing.

Recalling Table 2.6 from Section 2.4, somewhere from seven to eight meters is the most commonly stated limit for suction pump installation. Having confidence the pump system should work from a height of seven meters, "pilot" trials were started there. A failure to pump water at this height would likely indicate a need to adjust testing procedures. The set-up is shown in Figure 3.1. First, two 10-foot sections and one 5-foot section were attached to the base on the pump. Prior to the first fieldwork day, one male and one female 1.25-inch PVC adapter were glued on each of the 10-foot sections. One male 1.25-inch PVC adapter was glued on the 5-foot section. When actually installing PVC in boreholes, pipe adapters are not used; instead, pipes are glued directly together. For logistical convenience in material transport and storage and to facilitate easy set-up modification, pipe adapters were used. The pump has a 1.25-inch pipe connection. The male end of one of the 10-foot sections was screwed onto the pump. Then, another 10-foot section was added, followed by the 5-foot section. Teflon was added to all male adapters before pipes were joined. Once connected, using a measuring tape, a distance of seven meters from the pump inlet was marked on the bottom pipe. With the pipes attached, the pump was then raised to the staircase landing that is between the second and third level of the building - the second North-facing landing. The base of the pump was rested on the railing and secured using several straps. The tank was then positioned so that the pipe was suspended in the center. The 7-meter mark on the bottom pipe was slightly above the top of the tank. The tank was slightly elevated so that the mark would be below the tank rim. To allow for the tank to be elevated, approximately six inches was removed from the 5-foot section using a handsaw. The tank was then filled until the water level was even with the 7-meter mark, and an outdoor tube thermometer was placed in the tank so water temperature could be recorded. Once set up, trials for the systems labeled as 1A and 1B in Table 3.2 were conducted as follows.

For each trial, tap water was pumped from an open 32-gallon plastic tank. Tap water was accessed from a hose connection on the outside of the Engineering Three building directly adjacent to the bottom of the staircase being utilized. An open tank was used to simulate a surficial aquifer. In a shallow unconfined aquifer partially penetrated by an open pipe, the surface of the water level in the pipe is at local atmospheric pressure. The same condition is true for the surface of the water level in a pipe partially penetrating an open tank. With the dimensions of the tank, for each trial, drawdown - drop in water level- was minimal, so it was therefore deemed an appropriate option. During November/December 2016, healthy male and female individuals aged 20-30 weighing approximately 55-70 kilograms conducted preliminary trials.

Figure 3.1: Testing set-up at seven meters using 1.25-inch PVC (Photo: Monica Resto)

The plastic bucket that was used for the pumping rate calibration trials was also used throughout testing. A line was marked three inches below the top rim of the bucket, which was equal to a volume of approximately 17 liters. For each trial, water was pumped until the bucket was filled to the just mentioned mark. According to Akers (2014), the most common water collection vessel in Madagascar used in association with the Pitcher Pump systems was a 15-liter bucket. Of the households interviewed by Akers (2014), half reported having only one water collection vessel. Therefore, as designed, each trial was representative of at least some individuals' water collection efforts during one use of the pump.

For several hours prior to the start of testing, the plunger was soaked in tap water to allow the leather to expand. This reduced the need for priming water[2]. However, the plunger seemed to move more smoothly within the cylinder when water was added through the opening at the top of cylinder, so some priming water was still required. At any given test height, during the first trial while the water was being progressively moved up the pipe to the pump inlet, the pumper would operate the handle under no specified conditions and would generally pump relatively vigorously until water was consistently discharged from the pump outlet. Once a consistent discharge had been established, the pumper would take a few strokes to match their pumping rate with the beat of the metronome, ensuring he/she was taking one complete stroke for each beat. During this time, any water discharged from the pump was collected in a plastic bucket. When the pumper was at the correct pumping rate, immediately the first bucket was removed and replaced with the empty marked bucket. Simultaneously as the marked bucket was placed under the pump outlet, a timer was started. The time was stopped on the last down-stroke when the water had reached the

[2] Priming is the process of adding water into the pump system prior to operation. Priming helps to expand the seals and lubricate the system so that the components move smoothly within the pump cylinder and adequate suction (low pressure) can be generated.

mark. The time to fill the bucket was recorded with a digital stopwatch. For each trial, the number of strokes taken was also counted and recorded. At the end of each trial, the full marked bucket was weighed using a portable luggage scale. Prior to testing, the weight of the empty bucket was recorded. The bucket weight was subtracted from the total weight read on the scale and the weight of the water pumped for each trial was recorded. Later, recorded water weights were converted to volumes based on the density of water given the water temperature recorded for each trial. When all data had been recorded, both buckets were taken downstairs and poured back into the tank so that the water level would be at the appropriate height for the next trial.

"Pilot" trials were conducted for the systems labeled as 2A and 2B in Table 3.2. The pump assembly was lowered to the ground and the bottom pipe was removed. Again, prior to the first fieldwork day, two feet had been cut off of one of the 10-foot sections to make an 8-foot section. As with the 5-foot section, one male 1.25-inch PVC adapter was glued on the 8-foot section. The 8-foot section was then added to the two 10-foot sections already attached to the pump, again using Teflon on the male adapter. Once connected, using a measuring tape, a distance of eight meters from the pump inlet was marked on the bottom pipe. With the pipes attached, the pump was then raised to the third level staircase landing - the top landing. The base of the pump was rested on the railing and secured using several straps. The top of the third level railing is 33 feet above the ground, meaning the tank had to be elevated just over five feet for the 8-meter mark to be below the tank rim. The tank was then positioned so that the pipe was suspended in the center of it. Again, to allow for the tank to be elevated, approximately six inches was removed from the 8-foot section using a handsaw. The tank was then filled until the water level was even with the 8-meter mark, and an outdoor tube thermometer was placed in the tank so water temperature could be recorded. Once set-up, trials for the systems labeled as 2A and 2B in Table 3.2 were conducted as previously explained.

Having achieved target flow rates at eight meters, a final set of “Pilot” trials were conducted for the systems specified as 3A and 3B in Table 3.1. The pump assembly was lowered to the ground and the bottom pipe was removed. An additional 10-foot section was added to the two 10-foot sections already attached to the pump, again using Teflon on the male adapter. Once connected, using a measuring tape, a distance of nine meters from the pump inlet was marked on the bottom pipe. As with the trials at eight meters, the pump was again raised to the third level staircase landing - the top landing. The base of the pump was rested on the railing and secured using several straps. Again, the tank was positioned so that the pipe was suspended in the center of it and was elevated so that the 9-meter mark would be below the tank rim. Once positioned, the tank was then filled until the water level was even with the 9-meter mark, and an outdoor tube thermometer was placed in the tank so water temperature could be recorded. Trials were conducted as previously discussed.

In April 2017, all testing was completed on six days during the first two weeks of the month. All of the trials conducted were performed by six (three male, three female) healthy individuals aged 23-30, weighing approximately 45-70 kilograms. For each suite of parameters, three individuals- at least one male and one female- conducted one trial each at both pumping rates. There was no defined groups or order for individuals to pump, so each suite of parameters would have a random set of three individuals of the six. Multiple pumpers were used so more trials could be completed on a given day. Additionally, a different pumper conducted each trial for a given suite of parameters to add some generalizability to the results. Individuals of varying height, weight, and strength produced similar results, indicating that results were not contingent on one individual's abilities; they were reproducible, albeit amongst a small and somewhat homogeneous representation. On a given testing day, work would generally start in the morning and proceed through the afternoon. The schedule varied, but most trials were conducted between 10 AM and 4 PM, local time. As the water in the tank was exposed to sun, its temperature increased by a few degrees Celsius. Water temperature varied from approximately 22-27 ^{o}C.

After having successfully completed trials at seven, eight, and nine meters, it was felt that the testing protocol was sound. However, to verify the procedures, the trials with 1.25-inch PVC were repeated in April 2017. The only modification was the incorporation of a stand that the pump rested on that could be attached to the railing (Figure 3.3). The railings are slightly set back from the edge of the walls, which caused some bending in the pipe. The stand eliminated the bend, allowing the pipe to hang straight. The results from the repeated trials were very similar to those from November/December 2016. Therefore, testing proceeded with the procedures outlined above.

Figure 3.2: Simmons Manufacturing Pitcher Pump #1160 secured on pump stand

Two-inch PVC was the next pipe specification tested, so systems 4A/B, 5A/B, and 6A/B as outlined in Table 3.1 were tested. Identical pipe sections were purchased for 1.25-inch and 2-inch PVC. Therefore, the 2-inch PVC pipes were prepared based on the modifications that were made to the 1.25-inch pipes. Approximately six inches were removed from the 5-foot section and approximately two-and-half feet were removed from one of the 10-foot sections using a handsaw. One male 2-inch PVC adapter was glued on the 4.5-foot section and on the 7.5-foot section. One male and one female 2-inch PVC adapters were glued on two of the 10-foot sections. On the third 10-foot section, one female 2-inch PVC adapter was glued on one end and on the other end, a reducer coupled with a 1.25-inch male PVC adapter were glued. The reducer coupled with a 1.25-inch male PVC adapter had to be used so the 2-inch pipe could be attached to the pump. The set-ups for the trials testing 4A/B, 5A/B, and 6A/B were the same as those for 1A/B, 2A/B, and 3A/B (see Figure 3.1 above for example).

After achieving target flow rates for all trials conducted with 1.25- and 2-inch PVC pipes, trials were conducted at heights between nine and 10 meters. First, trials to find the maximum pumping limit were conducted starting at 10 meters and progressively reducing the height. Three 10-foot sections and the 4.5-foot section were attached to the pump. Measuring from the pump inlet, the bottom pipe was marked in tenth-meter increments from 10 to 9.5 meters. Again, the bottom of the 4.5-foot section was cut using a handsaw so that the pipe would be hanging a few inches above the ground when secured in the stand attached to the third level staircase landing railing. The pump was then raised, and the tank was positioned so that the pipe was suspended in the center of it and filled until the water level was even with the 10-meter mark. The pump was continuously operated for several minutes rotating between pumpers as each would tire. If unable to produce water from the pump outlet, water was added to the tank to reduce the distance from the water level to the pump inlet by 0.2 meters. Again, the pump was continuously operated for several minutes rotating between pumpers as each would tire. At each step, if unable to produce water from the pump outlet, water was added to the tank to reduce the distance from the water level to the pump inlet by 0.2 meters, and the same pumping procedure ensued. When at least one pumper was able to produce water from the pump outlet, the water level in the tank was lowered to increase the distance from the water level to the pump inlet by 0.1 meters. If at least one pumper was able to produce water at this height, that was said to be the maximum pumping limit. If unable to produce water, the previous height was said to be the maximum pumping limit.

Anticipating the practical limits to be closer to nine meters than 10 meters, to find the practical pumping limit, trials were conducted progressively increasing the height from nine meters. An example set-up for the tests to determine the practical pumping limit is shown in Figure 3.4. The pipes that were used to determine the maximum pumping limit were used to determine the practical pumping limit. Measuring from the pump inlet, the pipe was marked in tenth-of-a-meter increments from nine to 9.4 meters. The bottom pipe was again cut so the tank could be elevated to the appropriate height. The pump was then raised, and the tank was positioned so that the pipe was suspended in the center of it and filled until the water level was even with the 9.2-meter mark. If target flow rates were achieved, the water level in the tank was lowered to increase the distance from the water level to the pump inlet by 0.2 meters. The distance from the water level to the pump inlet would continue to be increased by 0.2 meters until target flow rates were no longer achieved. The greatest height at which target flow rates were achieved was determined to be the practical pumping limit. In determining the practical pumping limits, 0.1- meter increments were not tested. When considering local drawdown that occurs while pumping, it is likely that the water level in the well would drop by more than 0.1

meters, especially if attempting to fill more than one collection vessel. By not testing 0.1-meter increments, the practical pumping limits incorporate this consideration. However, aquifer dynamics are highly specific based on the local hydrogeological environment and practical limits will vary from location to location based on actual drawdown. Trials to determine maximum and practical pumping limits were first conducted with 1.25-inch PVC pipes. The same procedures were then repeated with 2-inch PVC pipes.

Figure 3.3: Testing setup to determine the practical pumping limit using 2-inch PVC

When all testing had been completed with the PVC pipes, 1.25-inch GI was tested, which corresponds to systems 7A/B, 8A/B, and 9A/B in Table 3.2. The GI pipe sections were different lengths than the PVC pipe sections, so the setups were slightly different with GI, but all other procedures remained the same. The 15-foot section and one 10.5-foot section were used for the seven-meter trials. Again, using Teflon on all threads, the 15-foot section was screwed onto the pump and the 10.5-foot section was then attached using a GI coupling. However, once the pump assembly had been secured on the stand attached to the railing of the second North-facing landing, the 7-meter mark was slightly above the top of the tank. The tank was elevated slightly, but the length of the pipe prohibited the tank from being raised to a height that would place the 7-meter mark below the rim. Due to this, trials were conducted from 7.2 meters, as opposed to seven meters. Due to the results obtained with 1.25-inch PVC pipes, the practical and maximum pumping limits for 1.25-inch GI were expected to be well above seven meters, so this discrepancy in height of 0.2 meters was considered acceptable. However, to avoid further issues with setup constraints, one of the 10.5-foot sections was cut into a 7-foot section and a 3.5-foot section at the USF Engineering Machine Shop (Tampa, FL).

Most of the remaining trials for the GI pipe were conducted at the same heights as those done with the PVC pipes. The only difference was that no test was done at 10 meters using the GI pipes. With the given pipe sections, 9.9 meters was the greatest height that could be tested. For the eight-meter trials, the 15-foot, 7-foot, and 5-foot sections were used. For the nine-meter trials, the 15-foot, 10.5-foot, and 5-foot sections were used. To determine the practical pumping limit, the sections used for the nine-meter trials were again used. To determine the maximum pumping limit, the 15-foot, 10.5-foot, and 7-foot sections were used.

CHAPTER 4: RESULTS AND DISCUSSION

The objective of this research was to determine the theoretical and practical pumping limit of a manually operated suction pump. This involved application of calculations considering physical principles and applied fluid mechanics in a simple mathematical model (Section 3.1) and laboratory (field) trials evaluating pump performance (Section 3.2). First, results from the mathematical model will be presented. Then, results from the field trials will be presented, followed by comparison of the model and field trial results.

4.1 Calculations Results

The results obtained from the (mathematical) methodology presented in Section 3.1 are summarized in Table 4.1. The energy loss (frictional and system head loss) and acceleration head loss values provided in this table are the results calculated using equations 3.1 and 3.5, respectively. The overall head loss values are the sum of the frictional, system and acceleration head losses. The practical theoretical limit values are the results calculated using equation 3.6 for water temperatures of 20 and 25 ^{o}C. The maximum theoretical suction lift values used in this thesis, which assumed an elevation equal to sea level, were 10.10 meters for a water temperature of 20 ^{o}C and 10.04 meters for a water temperature 25 ^{o}C. Recall that the maximum theoretical suction lift is atmospheric pressure minus the vapor pressure of water expressed as head. As stated in Section 2.4, there will always be water vapor present above any available free water surface, such as in the rising main as water ascends the rising main toward the pump cylinder. As the temperature of water increases, its vapor pressure increases. This may limit the suction (lowered) pressure achievable, reducing the pressure gradient that causes the water to ascend in the rising main, and ultimately the height to which the water can be pumped. Therefore, the practical theoretical suction lift assuming a water temperature of 25 ^{o}C is slightly less than practical theoretical suction lift assuming a water temperature of 20 ^{o}C. The practical theoretical limit values represent the estimated practical theoretical suction lift for each pipe material/diameter combination considered in the experimental set-up under "low" (4 L/min) and "high" (11 L/min) flow rate conditions.

Table 4.1: Practical theoretical head loss calculations by pipe material/diameter, volumetric flow rate and water temperature

Water Temp.		**2-inch PVC**		**1.25-inch PVC**		**1.25-inch GI**	
		4 L/min	11 L/min	4 L/min	11 L/min	4 L/min	11 L/min
20 ^{o}C	Energy Head Loss, m	0.003	0.023	0.021	0.150	0.022	0.155
	Acceleration Head Loss, m	0.054	0.217	0.134	0.499	0.134	0.499
	Overall Head Loss, m	0.057	0.239	0.155	0.649	0.155	0.654
	Practical Theoretical Limit, m	**10.043**	**9.861**	**9.945**	**9.451**	**9.945**	**9.446**
25 ^{o}C	Energy Head Loss, m	0.003	0.023	0.021	0.149	0.021	0.154
	Acceleration Head Loss, m	0.054	0.217	0.134	0.499	0.134	0.499
	Overall Head Loss, m	0.057	0.239	0.155	0.648	0.155	0.653
	Practical Theoretical Limit, m	**9.983**	**9.801**	**9.885**	**9.392**	**9.885**	**9.387**

The results presented in Table 4.1 suggest that, under the conditions investigated in this thesis, pipe material would have some influence on the practical theoretical limit, but less influence than pipe diameter. Remembering that the practical theoretical limit is directly related to overall head loss, a discussion of the latter provides an explanation. For example, when comparing the results at a flow rate of 4 L/min (25 ^{o}C), there was roughly a 93 percent difference between the overall head loss estimated for 2-inch PVC and 1.25-inch PVC, but less than one percent difference between the overall head loss estimated for 1.25-inch PVC and 1.25-inch GI. With the model used in this research, overall head loss was equal to sum of pipe friction, system friction and acceleration head. With this approach, the potential impact of pipe material was considered in the pipe friction component, which was determined using the Darcy-Weisbach equation (equation 3.2). The impact of pipe material appears in the Colebrook equation (equation 3.4) as the absolute surface roughness coefficient, ε, which is used to estimate the Darcy-Weisbach friction factor when the Reynolds number was greater than 3,000. In the Colebrook equation, ε is relative to internal pipe diameter (seen as ε /D), so even though the ε values used for PVC (1.5×10^{-6} m) and GI (1.5×10^{-4} m) were two orders of magnitude different, both values are small compared to the diameters considered (0.0318 and 0.0508 m), indicating that the friction factor, essentially, would be a function of the Reynolds number and only minimally impacted by surface roughness. Therefore, given the absolute surface roughness coefficients used, at a given flow rate, the model predicted a smaller difference in the practical theoretical limit when comparing pipe material relative to when comparing pipe diameter, implying pipe diameter may have a greater effect on system performance. It should be noted that because new pipes were used during field testing, the surface roughness coefficient values used in calculations are typical values associated with new pipes. The potential impact of surface roughness coefficient values associated with aged pipes will be discussed in Section 4.3.

Comparing the pipe diameters considered in this research, for a given flow rate, the model predicts that the practical theoretical limit would be lower for the smaller internal pipe diameter (1.25-inch) relative to that of the larger internal pipe diameter (2-inch). Recall that for both frictional and acceleration head loss calculations, mean flow velocity, V, was assumed to equal volumetric flow rate, Q, divided by the wetted cross-sectional area of a full-flowing pipe,

$A = \pi/4 \times D^2$. This indicates that, at a given flow rate, as the internal pipe diameter decreases (meaning the cross-sectional area decreases), the mean flow velocity increases, which is a fundamental relationship seen in one-dimensional flow in pipes. From equations 3.1 and 3.5, frictional head loss is shown to be proportional to V^2 and acceleration head loss is proportional to V, respectively. Therefore, with a smaller internal pipe diameter, greater frictional and acceleration head losses would be expected compared to a larger internal pipe diameter, assuming the same constant flow rate.

Another consideration presented in Table 4.1 is the influence of flow rate on the practical theoretical limit. The results suggest that for a given pipe material/diameter combination, overall head loss will be greater at a higher flow rate, which implies a lower practical theoretical limit. It should also be noted that frictional and acceleration head loss are proportional to pipe length (see equations 3.1 and 3.5). In the typical application of these methods to determine head loss in motorized pump systems, generally, the goal is to predict flow rates, determine power requirements, and/or ensure efficient pump operation (i.e. avoid cavitation[3]) associated with certain operating conditions. In that, a known fixed pipe length, or several pipe lengths are considered. However, the underlying question of this research was not how fast can water be moved with the considered pump system, but how high can water be moved with the considered pump system. Therefore, pipe length was essentially the parameter in question; the pipe length would correspond to the practical theoretical limit. To reflect this concept, a pipe length of L= maximum theoretical suction lift – h_f was used in the Darcy-Weisbach equation and L= maximum theoretical suction lift – h_a was used in the acceleration head equation.

[3] Cavitation is a phenomenon that occurs when the suction pressure falls below the vapor pressure of water causing bubbles to form which then subsequently collapse as the pressure increases again. Cavitation is a major concern with motorized suction pump systems as it can affect pump operation and cause pump damage.

4.2 Laboratory (Field) Assessment Results

The results obtained from the field testing methodology outlined in Section 3.2 are presented in Tables 4.2 and 4.3. Note that the elevation of the testing site is approximately 14 meters above sea level. As discussed in Section 3.2, field methods were modeled after manual suction pump (Pitcher Pump) systems that were observed in Madagascar by members of our research group. In an attempt to represent the range of flow rates observed in Madagascar, it was decided that each pipe material/diameter combination would be tested at two pumping rates, one to roughly produce the flow rate at the low end of the range and one to roughly produce the flow rate at the high end of the range. Table 4.2 summarizes the results that were observed for the trials that were conducted at the slow pumping rate (20 strokes per minute). Table 4.3 summarizes the results that were observed for the trials conducted at the fast pumping rate (31 strokes per minute). Trials were performed at heights (distance from the water surface in the tank to the pump inlet) from seven to 10 meters. At a given height, three trials were conducted for each pipe material/diameter combination at the slow and fast pumping rates. A different individual performed one of the three trials, so that three different individuals tested each complete pumping system (height, pipe material/diameter, pumping rate combination). This is reflected in the columns labeled “Trial # 1, 2, and 3” in Tables 4.2 and 4.3. For each trial, the time to fill the collection vessel, number of complete pump strokes taken, and liters of water pumped were recorded. Flow rate was then calculated as liters of water pumped divided by time to fill the collection vessel. The columns labeled “Mean” show the mean of the trials (n= 3) of each of the recorded measurements for each complete pumping system. For each pipe material/diameter combination, the greatest height for which data are presented represents the practical pumping limit, as was defined in Section 3.2.

Table 4.2: Field testing results for trials conducted at the slow pumping rate (20 strokes per minute)

Slow- Metronome set at 20 bpm													
Water level to pump inlet		**2-inch PVC**				**1.25-inch PVC**				**1.25-inch GI**			
	Trial #	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
7 Meters	Time, min	2.72	2.77	2.62	2.70	3.08	2.63	2.58	2.77	2.96	2.68	2.88	2.84
	# of Strokes	55	55	55	55	62	58	52	57	60	56	58	58
	Liters Pumped	17.7	18	18.2	18.0	17.3	17.5	17.5	17.4	17.7	17.5	17.7	17.6
	Flow Rate, L/min	6.5	6.5	6.9	**6.6**	5.6	6.6	6.8	**6.3**	6.0	6.5	6.1	**6.2**
8 Meters	Time, min	2.67	2.63	2.68	2.66	2.75	2.73	2.83	2.77	2.75	2.63	2.55	2.64
	# of Strokes	54	54	54	54	56	55	56	56	56	54	52	54
	Liters Pumped	18.2	18.2	18.2	18.2	18	18	18.2	18.1	17.7	17.7	18	17.8
	Flow Rate, L/min	6.8	6.9	6.8	**6.8**	6.5	6.6	6.4	**6.5**	6.4	6.7	7	**6.7**
9 Meters	Time, min	3.02	2.9	2.6	2.84	2.88	2.98	3.2	3.02	3.18	3.03	3.02	3.1
	# of Strokes	60	58	55	58	58	59	62	60	64	62	62	63
	Liters Pumped	18.2	18.2	18	18.1	18.2	18.2	17.7	18.0	17.9	18	18.2	18.0
	Flow Rate, L/min	6.0	6.3	6.9	**6.4**	6.3	6.1	5.5	**6.0**	5.6	5.9	6.0	**5.8**
9.2 Meters	Time, min	2.78	2.81	2.72	2.77								
	# of Strokes	56	56	55	56								
	Liters Pumped	18	18.2	18.2	18.1								
	Flow Rate, L/min	6.5	6.5	6.7	**6.6**								
9.4 Meters	Time, min	2.88	3.07	2.87	2.94								
	# of Strokes	62	60	56	59								
	Liters Pumped	18	18.2	18	18.1								
	Flow Rate, L/min	6.2	5.9	6.3	**6.1**								

Table 4.3: Field testing results for trials conducted at the fast pumping rate (31 strokes per minute)

Fast- Metronome set at 31 bpm													
Water level to pump inlet		**2-inch PVC**				**1.25-inch PVC**				**1.25-inch GI**			
	Trial #	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
7 Meters	Time, min	1.72	1.75	1.72	1.73	1.67	1.68	1.63	1.66	1.7	1.72	1.72	1.71
	# of Strokes	54	55	54	54	50	53	52	52	54	54	54	54
	Liters Pumped	18.2	18	18.2	18.1	16.4	18.2	17.3	17.3	17.7	17.7	17.7	17.7
	Flow Rate, L/min	10.6	10.3	10.6	**10.5**	9.8	10.8	10.6	**10.4**	10.4	10.3	10.3	**10.3**
8 Meters	Time, min	1.78	1.75	1.68	1.74	1.55	1.52	1.58	1.55	1.67	1.65	1.73	1.68
	# of Strokes	56	56	53	55	50	48	49	49	53	52	55	53
	Liters Pumped	18.2	18.4	18.2	18.3	17.7	18.2	18	18.0	18.4	18.1	18.2	18.2
	Flow Rate, L/min	10.2	10.5	10.8	**10.5**	11.4	12	11.3	**11.6**	11	11	10.5	**10.8**
9 Meters	Time, min	1.7	2	1.73	1.81	2.15	1.93	2.38	2.15	1.78	2.05	1.83	1.9
	# of Strokes	54	64	55	58	66	61	69	65	56	63	58	59
	Liters Pumped	17.3	18.2	18	17.8	18.2	18	18	18.1	18.2	18	18.2	18.1
	Flow Rate, L/min	10.2	9.1	10.4	**9.9**	8.5	9.3	7.5	**8.4**	10.2	8.8	9.9	**9.6**
9.2 Meters	Time, min	1.88	2.08	1.72	1.89								
	# of Strokes	60	64	54	59								
	Liters Pumped	18.2	18	18	18.1								
	Flow Rate, L/min	9.7	8.6	10.5	**9.6**								
9.4 Meters	Time, min	2.02	2.07	1.98	2.02								
	# of Strokes	64	65	64	64								
	Liters Pumped	18	18.2	18	18.1								
	Flow Rate, L/min	8.9	8.8	9.1	**8.9**								

As seen in Tables 4.2 and 4.3, the practical pumping limit when using 2-inch PVC was 9.4 meters, and the practical pumping limit when using 1.25-inch PVC and 1.25-inch GI was 9 meters. The practical pumping limit represents the greatest distance from the water surface to the pump inlet at which the pump could be consistently operated at, approximately, both the slow (20 strokes per min) and fast (31 strokes per min) pumping rates, without being overly strenuous (as perceived by the individual pumping), to produce flow rates that were “reasonably” close to the low (6 L/min) and high (11 L/min) target flow rates. With 1.25-inch PVC and 1.25-inch GI, when the distance from the water surface in the tank to the pump inlet was increased to 9.2 meters, target pumping rates were no longer consistently achieved, observed flow rates dropped noticeably, and the individual pumpers stopped before filling the collection vessel due to fatigue. With 2-inch PVC, these same observations occurred when the distance from the water surface in the tank to the pump inlet was 9.6 meters. In determining the practical pumping limits, 0.1- meter increments were not tested. When considering local drawdown that occurs while pumping, it is likely that the water level in the well would drop by more than 0.1 meters, especially if attempting to fill more than one collection vessel. By not testing 0.1-meter increments, the practical pumping limits incorporate this consideration. However, aquifer dynamics are highly specific based on the local hydrogeological environment and practical limits will vary from location to location based on actual drawdown.

Figure 4.1 provides a visual summary of the field testing results, combining the data presented in Tables 4.2 and 4.3 into a single graph. Figure 4.1 contains the same data as Tables 4.2 and 4.3, but only shows the mean observed flow rate for each complete pumping system (height, pipe material/diameter, pumping rate combination).

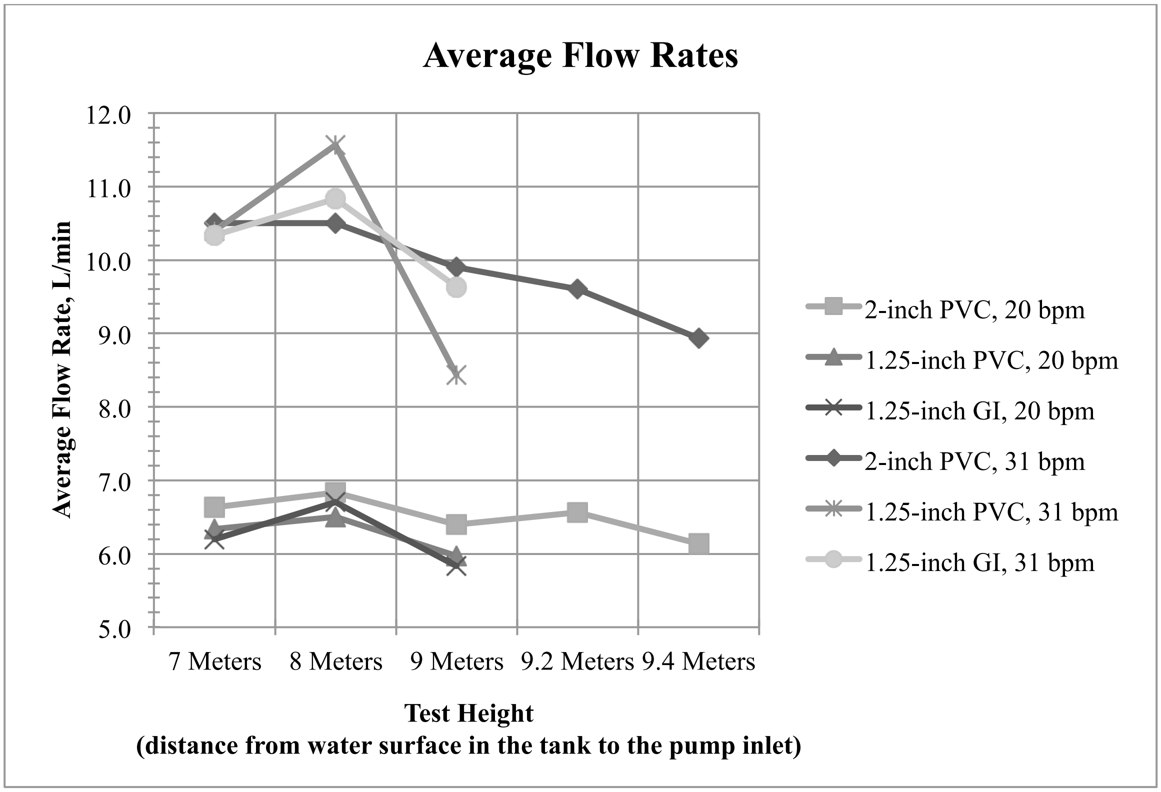

Figure 4.1: Summary of field testing results- average flow rate for each unique system (the combination of pipe material, pipe diameter, test height and pumping rate) tested

From Figure 4.1, a few interesting observations become evident. First, for each pipe material/diameter combination, at both pumping rates, the mean observed flow rate was the highest when the distance from the water surface to the pump inlet was eight meters. This implies that, for the test heights considered up to and including the practical pumping limit, pump operation in terms of volumetric efficiency was the best at the height of eight meters. Second, for each pipe material/diameter combination, at both pumping rates, the mean observed flow rate was the lowest at the practical pumping limit. This implies that, for the test heights considered up to and including the practical pumping limit, pump operation in terms of volumetric efficiency was the worst at the practical pumping limit. Any conclusive explanation for these observations would require a much more complex analytical assessment than was considered in this thesis. As indicated in studies related to motorized suction pumps, direct pressure measurements recorded at various points in the pump cylinder and consideration of valve motion could be insightful (Singh and Madavan, 1987; Wachel et al., 1989; Singh and Able, 1996; Iannetti et al., 2015). However, considering some of the realities of the actual pumping operation observed during field testing, a possible (conceptual) explanation can be offered. Trials were designed to be conducted at a constant pumping rate, so the individual pumpers were instructed to complete one full pump stroke for every beat of the metronome. At a height of seven meters, because it was easy to move the pump handle from its highest point to its lowest point, often, the pumper would pause at the top of the stroke (handle at its highest point) before lowering the handle again to stay on the beat of the metronome. During the down-stroke (the suction stroke), the piston is ascending in the pump cylinder and water is flowing into the pump cylinder from the rising main. If the duration of the down-stroke is shortened (relative to the duration of the down-stroke at eight meters), it seems plausible that less water might enter the pump cylinder per stroke. At the practical pumping limit, it was difficult to move the pump handle from its highest point to its lowest point, and once the lowest point was reached, the handle would begin to "snap back" during the initial movement of the up-stroke. To pump water at the practical pumping limit, a lower pressure (relative to any lower height) must be generated in the pump cylinder. As the magnitude of the lower pressure (suction) increases in the pump cylinder, it seems possible that more back leakage (of air and water) through the piston valve and across the piston seal could occur. This would affect volumetric efficiency, and could perhaps explain the tendency of the handle to snap back during the initial movement of the up-stroke.

An overall summary of the field testing results is presented in Table 4.4. Recall that the practical pumping limit represents the greatest distance from the water surface to the pump inlet at which the pump could be consistently operated at, approximately, both the slow (20 strokes per min) and fast (31 strokes per min) pumping rates, without being overly strenuous (as perceived by the individual pumping), to produce flow rates that were "reasonably" close to the low (6 L/min) and high (11 L/min) target flow rates. Therefore, as designed, for each pipe material/diameter combination considered, the field methods should have produced similar results from the lowest test height (distance from the water surface to the pump inlet) to the practical pumping limit height for both pumping rates. The results presented on the left side of Table 4.4 indicate this. The mean overall flow rate and sample standard deviation, at each pumping rate, for all of the trials conducted with a given pipe material/diameter combination are shown. For example, using 1.25-inch GI, three trials were conducted at 7-, 8-, and 9-meter test heights under the slow pumping rate condition. Results from these nine trials were combined to determine the mean observed flow rate and corresponding sample standard deviation using 1.25-inch GI at a pumping rate of 20 strokes per minute. The low standard deviation values indicate there was consistency in the methods. However, the standard deviation for 1.25-inch PVC seems large relative to the others. No definitive reason was concluded for this observation, but it might have been due to the fact that the 1.25-inch PVC trials were conducted first. Since the same group of individuals performed all field trials, maybe pump operation became slightly more consistent as the participants gained experience with the pump.

On the right side of Table 4.4, field trials are summarized by test height. That is, the overall observed mean flow rate and sample standard deviation, at each pumping rate, for a given test height are shown. For example, at a test height of seven meters, three trials each were conducted with 2-inch PVC, 1.25-inch PVC, and 1.25-inch GI at the slow pumping rate. Results from these nine trials were combined to determine the mean observed flow rate and corresponding sample standard deviation at the 7-meter test height at a pumping rate of 20 strokes per minute. The low standard deviation values indicate that pipe material/diameter did not have a substantial influence on results. As all new pipes were used, this was not unexpected. The top of Table 4.4 presents the results for the trials conducted at the slow pumping rate (20 stroke per minute), and the results for the trials conducted at the fast pumping rate (31 strokes per minute) are presented at the bottom.

Table 4.4: Basic summary statistics of field trials arranged by pumping height and pipe material/diameter combination for slow and fast pumping rates

Slow- Metronome at 20 bpm					
	Average Flow Rate, L/min	Standard Deviation, L/min		Average Flow Rate, L/min	Standard Deviation, L/min
2-inch PVC n=15	6.5	0.32	**7 Meters n=9**	6.4	0.41
2-inch PVC n=9*	6.6	0.32	**8 Meters n=9**	6.7	0.22
1.25-inch PVC n=9	6.3	1.64	**9 Meters n=9**	6.1	0.42
1.25-inch GI n=9	6.2	0.49	**9.2 Meters n=3**	6.6	0.12
			9.4 Meters n=3	6.1	0.21
Fast- Metronome at 31 bpm					
	Average Flow Rate, L/min	Standard Deviation, L/min		Average Flow Rate, L/min	Standard Deviation, L/min
2-inch PVC n=15	9.9	0.77	**7 Meters n=9**	10.4	0.29
2-inch PVC n=9*	10.3	0.49	**8 Meters n=9**	11	0.55
1.25-inch PVC n=9	10.1	1.48	**9 Meters n=9**	9.3	0.96
1.25-inch GI n=9	10.3	0.67	**9.2 Meters n=3**	9.6	0.95
			9.4 Meters n=3	8.9	0.15

*- The rows labeled “2-inch PVC, n=9” do not include trials performed at 9.2 and 9.4 meters. These rows indicate the average flow rate and standard deviation for the trials conducted at 7, 8, and 9 meters with 2-inch PVC to provide continuity with the results of the other pipe material/diameter combinations.

To this point, the discussion has focused on results observed up to and including the practical pumping limit. This thesis research was motivated by its potential to enhance water supply efforts in LICs, particularly in the Self-supply context. Therefore, the practical pumping limits, as determined through field testing, were the results of most interest. However, determining the maximum pumping limit for the considered pump systems was also part of the objective of this research. The maximum pumping limit for each pipe material/diameter combination was defined as the greatest distance from the water surface in the tank to the pump inlet at which water could be produced from the pump outlet regardless of pumping rate or flow rate by at least one pumper. Before any discussion of the maximum pumping limit results, one must recall that the maximum theoretical suction lift is not expected to be a constant; the maximum theoretical suction lift will vary depending on local atmospheric pressure and water temperature (see Section 2.4.1). This implies that the maximum pumping limit will be affected by local atmospheric pressure and water temperature. Therefore, the maximum pumping limit results are only relevant for the specific environmental conditions under which they were determined. Additionally, given that maximum pumping limit trials were only conducted once for each pipe material/diameter combination, is not possible to make general conclusions about the maximum pumping limits. That is, many more trials would be necessary to determine if there would be significant variation in the maximum pumping limit (at sea level) for each pipe material/diameter combination with natural fluctuations in atmospheric pressure and/or water temperature.

With that, the maximum pumping limit results still provide some interesting points of discussion. The maximum pumping limit trials for each pipe material/diameter combination were performed on a different date, so first the environmental conditions should be noted.

Atmospheric pressure data was taken from station (atmospheric) pressure readings recorded at Tampa Vandenberg Airport (approximately eight miles from the USF testing location) accessed from ncdc.noaa.gov. The recorded values that were the closest in time to when the maximum pumping limit trials occurred were used. Then, the atmospheric pressure was approximately 29.91, 30.06, and 29.96 inHg for 1.25-inch PVC, 2-inch PVC, and 1.25-inch GI, respectively. Water temperature was recorded using a bulb thermometer and was approximately 25 ^{o}C for all pipe material/diameter combination trials. Keeping these conditions in mind, the maximum pumping limit for 1.25-inch and 2-inch PVC was 9.7 meters. The maximum pumping limit for 1.25-inch GI was 9.9 meters. The 9.9-meter limit for 1.25-inch GI was only achievable by one individual. This individual was not present during the maximum pumping limit trials for 1.25-inch PVC or 2-inch PVC. The 9.7-meter limit was achievable by several individuals. However, only one individual was ever successful at producing water from the pump at heights above 9.7 meters. At the maximum pumping limit, extreme effort, as perceived by the individual pumping, was required and flow was intermittent. Again, any conclusive explanation for these observations would require a much more complex analytical assessment than was considered in this thesis.

4.3 Comparison of Calculations to Laboratory (Field) Trials

Table 4.5 provides a summary of the results presented in Sections 4.1 (calculated practical theoretical limits) and 4.2 (practical and maximum pumping limits). During pump testing, water temperature varied from 22 to 27 ^{o}C; therefore, only the results for the practical theoretical limits calculated assuming a water temperature of 25 ^{o}C are presented in Table 4.5. The range of values presented for practical theoretical limit of each pipe material/diameter combination represent the practical theoretical limits calculated at 4 L/min and 11 L/min.

Table 4.5: Comparison of calculated results to field trial results

	Practical Theoretical Limit, m	Practical Pumping Limit, m	Maximum Pumping Limit, m
2-inch PVC	9.98-9.79	9.4	9.7
1.25-inch PVC	9.88-9.37	9	9.7
1.25-inch GI	9.88-9.36	9	9.9

First, a clarification on terminology must be expressed. It should be emphasized that the practical theoretical limit actually predicts the maximum pumping limit, not the practical pumping limit. This is because the practical theoretical limit is defined by the maximum theoretical suction lift, which is defined by (hydrostatic) physical principles, but attempts to recognize the influence of dynamic system components through empirical engineering approaches. The practical theoretical limit can be thought of almost as a characteristic of the pump system under an assumed set of conditions. There is no consideration of power requirements in the determination of the practical theoretical limit. For manually operated pump systems, power requirements would be an important consideration and, potentially, a limiting factor in the practical pumping limit.

At the maximum pumping limit, the pump had to be operated very vigorously for only a very small amount of water to be discharged from the pump outlet, and after a relatively short period of time (less than a minute), the individual pumping would stop due to fatigue. At the maximum pumping limit, neither the pumping rate or the flow rate could be accurately measured with the methodology employed in this research. Since the practical theoretical limit calculations are only relevant at the maximum water-lifting limit of the pump, the model used for estimating the practical theoretical limit cannot be validated by the results obtained during laboratory testing. This implies that toward the limit of suction lift, the specific mechanics of pump operation play an important role in defining the maximum pumping limit and the basic empirical approaches used in this thesis are not adequate to describe these complexities. As was stated previously, the intent of this thesis was not the development of a comprehensive theoretical model, but rather to use common, relatively simple, engineering methods to approximate the water-lifting limit of a manually operated suction pump. As such, the model results were in relatively close agreement with the field results, and both indicate that under the considered conditions, the pump being investigated should be able to lift water at least nine meters.

An obvious criticism of the methodology employed in this research would be the use of new pipes. In LICs, the use of new pipes is limited because of the associated cost, which is especially true in the context of Self-supply, and often, even new pipes are of sub-standard quality. However, in this research, access to new pipes was not an economic constraint and in fact was the most convenient option. Therefore, aged pipes were not considered in this study's field testing, but the potential impact of aged pipes was considered in the practical theoretical limit calculations. As mentioned in Section 4.1, the use of aged pipes would change the surface roughness coefficient values used in the determination of the Darcy-Weisbach friction factor. Generally, the surface roughness of aged pipes is expected to be greater than the surface roughness of new pipes; however, it is difficult to generalize how the surface roughness will change over time. Changes in surface roughness are highly dependent on the chemical, physical, and biological water quality and quantity conditions to which a pipe is subjected (Bennet and Glasser, 2011; Michalos, 2016). Without specific water quality information, predicting an appropriate surface roughness coefficient value for aged pipes was difficult. Some design criteria have discussions related to increasing the surface roughness coefficient by an order of magnitude (Michalos, 2016); that was the approach applied here. Practical theoretical limits were recalculated assuming friction factor coefficient values of 1.5×10^{-5} m for PVC and 1.5×10^{-3} m for GI. Results are presented in Table 4.6. The results seen on the bottom half of Table 4.6 are the same results presented on the bottom of Table 4.1. Here, the results are presented for "Aged Pipes" and "New Pipes" to allow for easy comparison of the effects of changing the surface roughness coefficient values. The "Practical Theoretical Limit" values are assuming a water temperature of 25 ^{o}C and an elevation equal to sea level.

Table 4.6: Practical theoretical head loss calculations by pipe material/diameter, volumetric flow rate and "pipe age" assuming water temperature of 25 ^{o}C at sea level

		2-inch PVC		**1.25-inch PVC**		**1.25-inch GI**	
		4 L/min	11 L/min	4 L/min	11 L/min	4 L/min	11 L/min
Aged Pipes	Energy Head Loss, m	0.003	0.023	0.021	0.150	0.025	0.183
	Acceleration Head Loss, m	0.054	0.217	0.134	0.499	0.134	0.499
	Overall Head Loss, m	0.057	0.239	0.155	0.649	0.159	0.682
	Practical Theoretical Limit, m	**9.983**	**9.801**	**9.885**	**9.392**	**9.881**	**9.358**
New Pipes	Energy Head Loss, m	0.003	0.023	0.021	0.149	0.021	0.154
	Acceleration Head Loss, m	0.054	0.217	0.134	0.499	0.134	0.499
	Overall Head Loss, m	0.057	0.239	0.155	0.648	0.155	0.653
	Practical Theoretical Limit, m	**9.983**	**9.801**	**9.885**	**9.392**	**9.885**	**9.387**

The results in Table 4.6 suggest that increasing the surface roughness coefficient value by an order of magnitude has little effect on the practical theoretical limit. As discussed in Section 4.1, in the methodology used in this thesis, the impact of surface roughness is only taken into account in the Darcy-Weisbach equation. The energy head loss due to pipe friction (Darcy-Weisbach) is small relative to system friction, and system friction is small relative to acceleration head loss, so that pipe friction only accounts for a small percentage of the overall head loss (see Appendix B for results). This explains the minimal change in the practical theoretical limit even when the surface roughness coefficient value is increased by an order of magnitude. In this model, it is likely that the effect of aged pipes is underestimated. An increase in surface roughness implies a decrease in the effective hydraulic radius, which would imply an increase in flow velocity, for a given diameter pipe. As flow velocity increases, frictional, system and acceleration head losses would be greater. Internal pipe diameter and flow rate values were not adjusted. Additionally, if a system with aged pipes is assumed, it seems reasonable to assume that that system would also have aged valves and seals, which would affect performance. However, discussions on how to quantifiably estimate the effects of old valves and seals on head loss were not present in the utilized reference sources, and therefore not considered.

There are inherent limitations in laboratory testing as it is not possible to exactly simulate field conditions. For example, differences in water composition may influence results and aquifer dynamics would impact field testing results. Making the model more complicated would take focus away from the practical implications motivating this thesis. Regardless of the shortcomings in methodology, the results of this research present a compelling argument for the reevaluation of the water-lifting limit of manually operated suction pumps.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This thesis research sought to contribute to the understanding of the capabilities of manually operated suction pumps through: 1) consideration of the physical principles and applied fluid mechanics impacting pump operation and 2) laboratory (field) testing evaluating pump performance. A model employing common, relatively simple, engineering methods was used to approximate the water-lifting limit of a manually operated suction pump, and in all cases, predicted the suction lift limit, what is also referred to as the practical theoretical limit elsewhere in this thesis, to be upwards of nine meters. At a minimum, the suction lift limit was estimated to be approximately 9.4 meters for systems using 1.25-inch internal diameter pipe and 9.8 meters for systems using 2-inch internal diameter pipe. Then, understanding the model provided an incomplete description of pump operation, pumping field trials were conducted to evaluate actual pump performance. The pumping trial results suggested a practical pumping limit of around nine meters, at an elevation of approximately 14 meters above sea level (9 meters when using 1.25-inch internal diameter GI or PVC pipe and 9.4 meters when using 2-inch internal diameter PVC pipe). Therefore, the results from this research present two pieces of evidence which suggest that the practical water-lifting limit of manually operated suction pumps is approximately nine meters, at sea level, implying that reconsideration of the seven-meter suction lift limit proposed previously in practice might be warranted. A few suggestions on continuing the development of our understanding of this technology are presented below.

First, because there is very little evidence of suction pumps being used to heights greater than approximately seven meters, replicating the "laboratory" methods used in this thesis would provide useful information. For example, with a different sample of pumpers, could similar results be achieved? Additionally, while the methods employed in this research were intended to emulate field conditions, results were based on a "model" system rather than an actual field system. Therefore, given the practical motivation of supporting water supply efforts in low-income countries (LICs), field testing would be a logical next step. Field confirmation of the results of this research would add confidence to the suggestion that the practical water-lifting limit of manually operated suction pumps is around nine meters. In Madagascar, members of our research group have observed suction pumps lifting water over nine meters, but replication of these observations in different locations would verify that in the field, manually operated suction pumps can indeed lift water nine meters.

Presuming additional verification of a nine-meter water-lifting limit, it could be of value to develop an economic model that would specify the cost vs. benefit of drilling manually operated suction pumps routinely to a depth of nine or more meters as opposed to seven meters. Although the marginal cost of the additional drilling and use of a longer rising main would be small, it would not be zero. The benefit would be more secure access to a convenient improved water source (i.e. improved water supply service delivery). This is particularly relevant in areas where the water table varies seasonally, which is common in regions with distinct dry and rainy seasons, such as much of Sub-Saharan Africa and many LICs throughout the tropics and subtropics. The additional two meters of pump operational lift could result in extended periods of water service delivery and perhaps even continuous, as opposed to seasonal, access to a convenient improved water source. In the context of Self-supply, seasonal failure of the water point (i.e. the suction pump) could result in the use of unimproved water sources with increased risk of water borne disease, or the use of improved water sources that were located at a greater distance from the user, implying more time and effort in obtaining water with associated explicit and implicit economic costs. The specifics of these potential impacts would vary greatly by location, based on local costs for pump installation and maintenance, the actual seasonal variation of the water table, the costs of using alternative water sources, and the costs of disease burden from the users returning to unimproved water sources. Nonetheless a model framework for assessing these costs could prove very useful for analyzing the economic impact of widespread adoption of a nine-meter practical limit for the use of manually operated suction pumps, as opposed to the currently accepted limit of seven meters, and for informing such a decision in individual circumstances.

Another potential cost of using these pumps at nine meters opposed to seven meters is the enhanced "wear and tear" that would be associated with increasing the operating depth. As the operating depth is increased, the forces required to lift the water will increase, which will put more stress put on the pump system. This might result in more frequent failures of pump components, especially with regard to the handle, connecting rod, piston seal, and valves, which would increase operation and maintenance costs. An evaluation of the added stress and associated impacts on pump performance would then be beneficial to more accurately define the cost of using manually operated suction pumps at depths greater than seven meters. Methodology similar to that presented by The World Bank (1984) and Yau (1985) could be used to design an assessment of the forces and resultant stresses associated with pump operation at nine meters.

Related to the analysis of the forces involved in pump operation but user focused (in a very practical manner), it might be of interest to characterize the ergonomics of operating this kind of manually operated suction pump in more detail. As alluded to previously in this thesis (Chapter 4), the participants- the individuals performing the pumping (field) trials- did report that the operation of the pump required noticeably additional effort at nine meters as opposed to seven meters; however, all participants agreed that operation at nine meters required only modest and easily sustainable effort, but observations of (perceived) effort were not measured with any formal procedure. A more precise and quantitative description of this finding could be accomplished by measuring energy expenditure during operation of the pump, and comparing this measured energy expenditure to other common activities. Although the "gold standard" for measuring human energy expenditure is direct calorimetry while inside a whole body thermal isolation chamber (Leonard, 2010), much simpler methods using heart rate monitoring would suffice, as changes in heart rate correlate with changes in energy expenditure (Achten and Jeukendrup, 2003). Carpenter (2014) and MacCarthy et al. (2017) described the use of heart rate monitoring to characterize energy expenditure associated with the use of a handpump. Given that the practical pumping limit will also involve perceived effort by the user- that is, how hard using the pump feels to the user-, utilizing a validated self report scale such as the Borg Rating of Perceived Exertion would quantitate how much exertion the user of the pump experienced (Borg, 1982; Scherr et al., 2013), answering directly the question of whether use of the pump at lift heights exceeding seven meters is "just too hard."

Finally, development of a more comprehensive theoretical model may be of interest to researchers interested in this topic. As used in this thesis, frictional and acceleration head losses are empirical approaches and do not model the pump system at a fundamental level. Due to this, as mentioned in Chapter 4, the model used in this thesis was not adequate to explain several of the observed field trial results. A more fundamental mathematical model might be able to describe the specific complexities of the operation of the investigated pump.

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APPENDICES

Appendix A Copyright Permissions for Use of Tables and Figures

A1.1 Permission to Reproduce Table 2.1

Permission Request Inbox x

Katherine Marshall <[redacted]> May 3
to andre.olschews.

Dear Andre,

I am an environmental engineering graduate student at the University of South Florida (Tampa, FL, USA). I am currently working on my masters thesis which is related to manually operated suction pumps and their use in the Self-supply context (working title: How high can a manually operated suction pump lift water? A theoretical and laboratory assessment). I would like to include a table from the document "UNICEF ESARO- Review of Self-supply and its support services in African Countries- Synthesis Report" (April 2016 version). The table is found at the top of page three and includes the key features of Self-supply and their particular impacts. I would appreciate any information you might be able to provide me in regards to obtaining permission to use the table mentioned above. My thesis will be made available online for free through the University of South Florida Scholar Commons.

Thank you for your time.

Best Regards,

Katherine Marshall

Andre Olschewski <[redacted]> May 5
to me

Hi Katherine
thank you for getting in touch with me.
It is great to see that there are people reading these reports at least.
I think there is no problem if you use the data as long you put in the proper reference. I am sure also UNICEF ESARO would agree this proposal.
Is this sufficient for you to move on?
Best regards André

A1.2 Permission to Reproduce Figure 2.1

WaterAid America <inquiries@wateraid1.onmicrosoft.com> Sep 29 (7 days ago)
to me

Hi Katherine,

Thanks for you email! We're glad one of our figures will be able to supplement your report. With regards to use, as long as our watermark is left on the figure or our name is included next to it, you're good to go!

Good luck with the report and thank you for reaching out!

Best,

Olivia
Supporter Care
WaterAid America
Tel: 212-683-0430
Fax: 212-683-0293
www.wateraid.org

WaterAid **ranked #1 non-profit by Philanthropedia** - a division of GuideStar

From: inquiries@wateraidamerica.org <inquiries@wateraidamerica.org> on behalf of Katherine Marshall via WaterAid America <inquiries@wateraidamerica.org>
Sent: Monday, September 25, 2017 10:45 AM
To: WaterAid America
Subject: WaterAid Contact Us Submission Form

Submitted on Monday, September 25, 2017 - 10:45
Submitted by anonymous user: 2602:304:6ed7:cb70:b51b:c49a:f29:be52
Submitted values are:

Reason you are contacting us: Other
Where do you live? United States
Full Name: Katherine Marshall
Email: k[redacted]u
Zip Code: 33617
Company/Organization: University of South Florida
Phone Number: [redacted]
Message:
I am an environmental engineering graduate student at the University of South Florida (Tampa, FL, USA). I am currently working on my masters thesis which is related to manually operated suction pumps and their use in the Self-supply context (working title: How high can a manually operated suction pump lift water? A theoretical and laboratory assessment). I would like to include a figure in my report based on a figure that appears in one of WaterAid's technical briefs. The figure I would like to use is Figure 1: Typical Handpump Design found in Technical Brief: Handpumps (January 2013). I would appreciate any information you might be able to provide me in regards to obtaining permission to use the figure mentioned above. My thesis will be made available online for free through the University of South Florida Scholar Commons.

Thank you for your time.

Best Regards,

Katherine Marshall

Appendix B Practical Theoretical Limit Calculation Results

The following tables provide summary results for the energy (frictional and system) head loss, acceleration head loss and practical theoretical limits calculated for each pipe material/diameter combination considered in this thesis research. Here, pipe friction (calculated using the Darcy-Weisbach equation, equation 3.2) is shown separately from total energy head loss (the sum of pipe friction and system friction, equation 3.1) so as to highlight the potential impact of changing the surface roughness coefficient value to reflect the consideration of systems with "aged pipes," as would often be the reality with the use of these manually operated suction pump systems in low-income countries. For all pipe material/diameter combinations, the acceleration head loss results for 4 and 11 L/min reflect the methodology presented in Section 3.1, but the acceleration head loss results for flow rates from 5 to 10 L/min required a slightly different approach. Recall that pumping rate is a factor in the acceleration head equation (equation 3.5). The pumping rates associated with 4 and 11 L/min were 20 and 31 strokes per minute, respectively, which were based on field trials. Note that the stroke rate calibration trials indicated that a pumping rate of 20 strokes per minute actually produced a flow rate of approximately 6 L/min, but due to equipment limitations, 20 strokes per minute was also assumed to correlate to a flow rate of 4 L/min. Since there were no stroke rate calibration trials conducted for flow rates between 5 and 10 L/min, for each of the flow rates from 5 to 10 L/min, acceleration head was calculated assuming a pumping rate of 20 strokes per minute and assuming a pumping rate of 31 strokes per minute. The average of the results at 20 and 31 strokes per minute was then determined and used as the acceleration head loss value. All the calculation results presented in this appendix assume a water temperature of 25 ^{o}C and an elevation equal to sea level.

Table B1: Frictional head loss, acceleration head loss, and practical theoretical limit calculation results by volumetric flow rate and "pipe age" for 1.25-inch GI (assuming water temperature of 25 ^{o}C at sea level)

New Pipes (ε : 1.5 × 10^{-6} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.005	0.021	0.134	0.155	9.885	3.477
5	0.008	0.033	0.207	0.240	9.800	3.332
6	0.011	0.047	0.245	0.292	9.748	3.778
7	0.015	0.063	0.282	0.346	9.694	4.205
8	0.018	0.082	0.318	0.401	9.639	4.614
9	0.023	0.104	0.353	0.457	9.583	5.004
10	0.028	0.128	0.388	0.515	9.525	5.384
11	0.033	0.154	0.499	0.653	9.387	5.043
Aged Pipes (ε : 1.5 × 10^{-5} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.009	0.025	0.134	0.159	9.881	5.505
5	0.013	0.038	0.207	0.246	9.794	5.449
6	0.019	0.055	0.245	0.300	9.740	6.339
7	0.026	0.075	0.282	0.357	9.683	7.187
8	0.033	0.097	0.318	0.416	9.624	8.004
9	0.042	0.123	0.353	0.476	9.564	8.786
10	0.051	0.151	0.388	0.539	9.501	9.525
11	0.062	0.183	0.499	0.682	9.358	9.067

Table B2: Percent difference between new pipe and aged pipe results calculated for pipe friction, overall head loss, and practical theoretical limit for 1.25-inch GI

	Percent Difference Between Calculated Values for New Pipes and Aged Pipes		
Flow Rate, L/min	Pipe Friction	Overall Head Loss	Practical Theoretical Limit
4	47.160	2.123	0.034
5	50.281	2.213	0.055
6	53.146	2.697	0.082
7	55.290	3.163	0.115
8	57.082	3.619	0.153
9	58.588	4.062	0.198
10	59.660	4.475	0.248
11	60.999	4.330	0.308

Table B3: Frictional head loss, acceleration head loss, and practical theoretical limit calculation results by volumetric flow rate and "pipe age" for 1.25-inch PVC (assuming water temperature of 25 ^{o}C at sea level)

New Pipes (ε : 1.5 × 10^{-4} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.005	0.021	0.134	0.155	9.885	3.219
5	0.007	0.032	0.207	0.240	9.800	3.041
6	0.010	0.046	0.245	0.291	9.749	3.408
7	0.013	0.062	0.282	0.344	9.696	3.751
8	0.016	0.080	0.318	0.399	9.641	4.081
9	0.020	0.101	0.353	0.454	9.586	4.378
10	0.024	0.124	0.388	0.511	9.529	4.674
11	0.028	0.149	0.499	0.648	9.392	4.338

Table B3: Continued

Aged Pipes (ε : 1.5×10^{-3} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.005	0.021	0.134	0.155	9.885	3.223
5	0.007	0.032	0.207	0.240	9.800	3.047
6	0.010	0.046	0.245	0.291	9.749	3.424
7	0.013	0.062	0.282	0.344	9.696	3.771
8	0.016	0.080	0.318	0.399	9.641	4.105
9	0.020	0.101	0.353	0.454	9.586	4.418
10	0.024	0.124	0.388	0.511	9.529	4.705
11	0.028	0.149	0.499	0.649	9.391	4.381

Table B4: Percent difference between new pipe and aged pipe results calculated for pipe friction, overall head loss, and practical theoretical limit for 1.25-inch PVC

	Percent Difference Between Calculated Values for New Pipes and Aged Pipes		
Flow Rate, L/min	Pipe Friction	Overall Head Loss	Practical Theoretical Limit
4	0.126	0.004	0.000
5	0.189	0.006	0.000
6	0.500	0.017	0.001
7	0.558	0.021	0.001
8	0.607	0.025	0.001
9	0.940	0.041	0.002
10	0.693	0.033	0.002
11	1.034	0.045	0.003

Table B5: Frictional head loss, acceleration head loss, and practical theoretical limit calculation results by volumetric flow rate and "pipe age" for 2-inch PVC (assuming water temperature of 25 ^oC at sea level)

New Pipes (ε : 1.5 × 10^{-4} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.000	0.003	0.054	0.057	9.983	0.658
5	0.001	0.005	0.085	0.089	9.951	0.897
6	0.001	0.007	0.101	0.108	9.932	1.010
7	0.001	0.009	0.117	0.126	9.914	1.120
8	0.002	0.012	0.133	0.145	9.895	1.223
9	0.002	0.015	0.149	0.164	9.876	1.322
10	0.003	0.019	0.165	0.183	9.857	1.421
11	0.003	0.023	0.217	0.239	9.801	1.279
Aged Pipes (ε : 1.5 × 10^{-3} m)						
Flow Rate, L/min	Pipe Friction, m (Darcy-Weisbach)	Total Energy Head Loss, m (Pipe Friction + System Friction)	Acceleration Head Loss, m	Overall Head Loss, m (Total Energy + Acceleration Head)	Practical Theoretical Limit, m	Pipe Friction as Percent of Overall Head Loss, %
4	0.000	0.003	0.054	0.057	9.983	0.658
5	0.001	0.005	0.085	0.089	9.951	0.901
6	0.001	0.007	0.101	0.108	9.932	1.017
7	0.001	0.009	0.117	0.126	9.914	1.125
8	0.002	0.012	0.133	0.145	9.895	1.232
9	0.002	0.015	0.149	0.164	9.876	1.332
10	0.003	0.019	0.165	0.183	9.857	1.428
11	0.003	0.023	0.217	0.239	9.801	1.289

Table B6: Percent difference between new pipe and aged pipe results calculated for pipe friction, overall head loss, and practical theoretical limit for 2-inch PVC

	Percent Difference Between Calculated Values for New Pipes and Aged Pipes		
Flow Rate, L/min	Pipe Friction	Overall Head Loss	Practical Theoretical Limit
4	0.000	0.000	0.000
5	0.424	0.004	0.000
6	0.673	0.007	0.000
7	0.471	0.005	0.000
8	0.734	0.009	0.000
9	0.760	0.010	0.000
10	0.522	0.007	0.000
11	0.805	0.010	0.000