Low-Cost Household Groundwater Supply Systems: Pitcher Pump Systems and EMAS Technologies

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Authors Michael F. MacCarthy, Assistant Professor, Mercer University, USA, maccarthy_m@mercer.edu, tel: +1 478 301 5480; Jacob D. Carpenter, Independent WASH Consultant; Jonathan E. Annis, Tetra Tech ; James W. Buckingham, Independent Engineer; James R. Mihelcic, University of South Florida

Abstract/Summary

Self-supply is common throughout the world, filling service gaps left by other forms of water supply provision. This research assesses low-cost household groundwater supply technologies in developing country contexts in sub-Saharan Africa and Latin America, with a focus on the potential for improving Self-supply technology implementation in sub-Saharan Africa. Specifically, a Self-supply market for Pitcher Pump systems is studied in eastern Madagascar, EMAS low-cost water supply technologies are assessed in Bolivia, and a technical comparison is completed with the EMAS Pump and a family version of the Rope Pump in Uganda. Primarily technical and financial elements of sustainability are assessed. In Madagascar, the Pitcher Pump system market is found to be mature, unsubsidized, and sustainable, while there are some issues with the delivered water quality. In Bolivia, EMAS manually drilled well and pump systems are found to have a high rate of functionality. The pump comparison study concluded that, based on its relative low-cost, similar pumping rates to common versions of the Rope Pump from depths less than 20 m, and the minimal resources needed to construct it, the EMAS Pump has potential for success as a Self-supply technology in sub-Saharan Africa.

Introduction

Private household and small-group water supplies offer the potential to complement community water supply systems, either in their place (when public systems are non-existent or not accessible), or as secondary sources for households to use alongside community systems. When used in combination with community systems, household systems can offer several advantages, including reducing demand on community systems that struggle to supply sufficient quantities of water to all users.

The past decade has seen an increased interest in household water supply as a means of improving access to drinking water in developing countries. 'Self-supply' is a term that is commonly used, and is defined as "the improvement to household or community water supply through user investment in water treatment, supply construction and upgrading, and rainwater harvesting" (Sutton, 2009).

Self-supply encourages users to make affordable, incremental improvements to their private family or neighborhood (i.e. small group) water supply systems. Where it is possible implementation of Self-supply can result in "the obstacles to sustainability created by a lack of trust, cohesion, and co-operation within communities" being greatly reduced (Harvey and Reed, 2007). Self-supply can be complementary to community water supply systems, and has great potential as part of wider national strategies to reach the Sustainable Development Goal (SDG) target for safe and affordable drinking water for all and contribute to other SDG objectives related to health and livelihoods.

Low-cost household water supply technologies often make use of either groundwater in the immediate vicinity around a household, or rainwater that falls in a similar area. Common low-cost household water supply technologies include: (1) family wells, which can be either hand-dug or manually drilled; (2) water-lifting devices, which can range from being as simple as a rope attached to a bucket, to a manually-operated pump; and (3) rainwater harvesting systems. Low-cost water supply technologies are increasingly being promoted as sustainable solutions when implementing water supply projects at the small-community or household level in developing areas. Some low-cost technologies used in Self-supply are based on concepts that were originally developed in China over a thousand years ago (Missen, 2003; Sutton and Gomme, 2009).

Context, aims and activities undertaken

This research explores sustainable implementation of low-cost household groundwater supply systems in developing communities, with a focus on functional sustainability and primarily assessing technical and financial elements of sustainability. Different such technologies are investigated at two primary study locations (i.e., Bolivia and Madagascar) and one secondary study location (Uganda). Through these studies (each published separately), possibilities for improvements to household water supply technologies for developing communities are recommended, including further research, with an emphasis on the wider applicability of such technologies in sub-Saharan Africa.

Case Study 1 assesses the sustainability of a low-cost groundwater supply system, the Pitcher Pump system, which has been produced and sold in Madagascar for more than five decades. The Pitcher Pump, which is manufactured independently by many small businesses in eastern Madagascar and sold to private users at unsubsidized market prices, provides an example of a mature Self-supply market in a sub-Saharan African context that has proven to be sustainable over many years. Mixed methods are used to assess the Pitcher Pump technology and market in eastern Madagascar, including Pitcher Pump system construction practices, pump performance, system management, water quality, and household drinking water treatment practices. The scope of ongoing research is also discussed, and recommendations for potential improvements are provided.

Case Study 2 provides a brief overview of three types of low-cost household water supply technologies appropriate to Self-supply (manual water pumps, manual well drilling techniques, and rainwater harvesting systems), in the context in which specific models of these types of technologies have been developed by EMAS and implemented in Bolivia. Through assessing the technical capabilities and the context in which these technologies have proven to be effective, the research provides insight into the potential for introducing these technologies in other developing community contexts.

Case Study 3 offers a technical comparison between the EMAS Pump and the family Rope Pump, which has been introduced in many developing countries in recent years and most successfully marketed as a household-level pump in Nicaragua (Sutton and Gomme, 2009). The study allows development practitioners and researchers to better understand the technical attributes and capabilities of the EMAS Pump compared with the family Rope Pump (as well as other documented low-cost pumping devices) as a Self-supply option for developing communities and emphasizes the potential for the EMAS Pump in sub-Saharan Africa.

The lessons learned from the three case studies help to form recommendations for improving and introducing the studied low-cost water supply technologies in new contexts, and for further research.

<u>Research Questions</u>

The overall goal of the research is to assess low-cost household groundwater supply options for their suitability to sustainable use in developing communities, particularly in sub-Saharan Africa, and evaluate possibilities for improving and/or introducing household water supply technologies to such contexts. The research aims to address the following research questions:

1. What improvements can be made to the Pitcher Pump system in Madagascar to improve the quality of the product (including reliability, pumping rates, and/or quality of extracted water)?

2. Are low-cost water supply systems developed in Bolivia (EMAS technologies) suitable, affordable options for household water supply (Self-supply) for developing communities in sub-Saharan Africa?

3. Would the EMAS Pump be an effective, less-costly alternative to the family Rope Pump, potentially offering new opportunities for households or small groups of families in sub-Saharan Africa to improve their private water supplies?

4. Based on the results of Research Questions 1 through 3, what recommendations can be offered to improve sustainable low-cost water supply systems for use at the household level in developing contexts in sub-Saharan Africa?

Main results and lessons learnt

Case Study 1: Pitcher Pump Systems in Madagascar

This study highlights research carried out by the University of South Florida and the USAID-funded RANO HP project managed by CRS and CARE (see Akers, 2014; Akers et al., 2015; Akers et al., 2016; MacCarthy et al., 2013a; MacCarthy, 2014; Wahlstrom-Ramler, 2014). Further information on this case study can be found in *Unsubsidised Self-Supply in Eastern Madagascar* (MacCarthy et al., 2013a).

Context

According to the most recent Joint Monitoring Program (JMP) update, improved drinking water coverage in Madagascar in 2015 was estimated to be 35% in rural areas and 82% in urban areas (JMP, 2015). The national parastatal water and electric company, JIRIMA, who manages piped schemes that supply water to 65 urban municipalities, suffers from operational inefficiencies and lacks the capacity to upgrade aging infrastructure (USAID, 2010). In rural areas of Madagascar, coverage remains very low, with various challenges to maintaining existing systems and expanding services to the majority who are unserved.

Traditional Self-supply practices in Madagascar include household wells and household rainwater harvesting systems (to a more limited extent). Hand-dug wells using rope-and-bucket water-lifting systems are common at the household level in many parts of the high plateau region of central Madagascar. In coastal areas with sandy soils and shallow water table depths, manually drilled wells and suction handpump systems are prevalent in family compounds in many communities. This type of low-cost system, the Pitcher Pump system (locally called "Pompe Tany"), shown in *Figure 1*, was reportedly first introduced in Madagascar over five decades ago.

As shown in *Figure 1(b)*, the Pitcher Pump has two check valves (one on the lower end of the pump head, and a second one on a piston that attaches to the pump handle via a rod) and the pump is installed directly on a drilled well. In Madagascar, the check valves are usually made of leather and weighted with lead (Pb). The well is installed by manually boring (coring) down to near the water table, then hammering into the ground a permanent galvanized iron casing pipe that includes a well screen and a pointed drill bit (well-point) at its lower end.

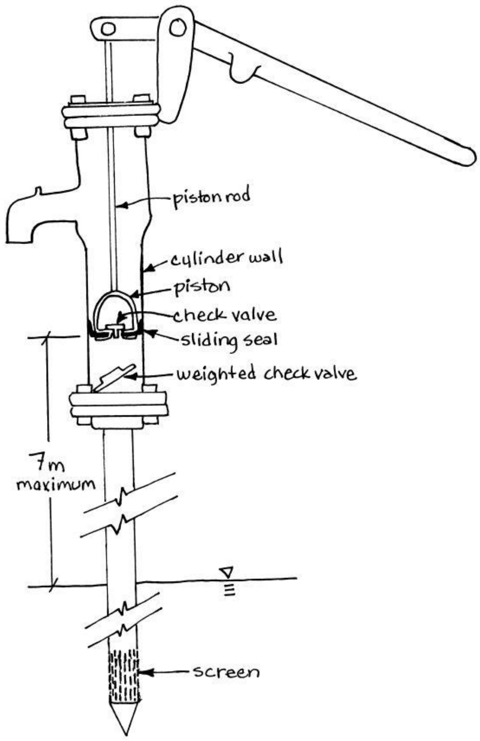

Figure 1: (a) Pitcher Pump in use in Tamatave, Madagascar [left] (Photo: M. MacCarthy); (b) Diagram of Pitcher Pump system [right] (Source: Artwork by Linda Phillips. Reproduced from Mihelcic et al. (2009); with permission from ASCE.)

Methodology

Data related to Pitcher Pump systems were collected in the city of Tamatave (estimated population of 280,000) and the nearby town of Foulpointe (estimated population of 15,000) in the Antsinanana Region of eastern Madagascar. The field research made use of mixed methods, consisting primarily of a quantitative survey of households that owned Pitcher Pump systems, semi-structured interviews with pump manufacturers, inspection/observation of household water and sanitation infrastructure, and testing of water quality (faecal coliforms, lead, nitrate, etc.). Supplementary methods consisted of focus group interviews with owners of Pitcher Pump systems. Primary field data were gathered over a four-week period in August-September 2011, and a local research assistant gathered additional data in 2012 and early-2013.

Main Results and Discussion

The primary findings of the research study include:

1) Strong evidence of a robust, sustainable market for Pitcher Pump systems in Tamatave, Madagascar

There are an estimated 9,000 Pitcher Pump systems in use throughout the city of Tamatave (and an estimated 12,000 total in Madagascar). 94% (50 of 53) of households surveyed reported that their Pitcher Pump system wells provide water throughout the entire year, with the other respondents saying that their wells provide water 10-11 months per year. It is estimated that more than 50 separate local small businesses in Tamatave (usually small welding workshops) manufacture Pitcher Pumps. This market is believed to be the most significant documented example of an unsubsidized household handpump market in sub-Saharan Africa.

2) Pitcher Pump systems built locally at an affordable price

Complete Pitcher Pump systems are commonly sold in Tamatave and Foulpointe at unsubsidized prices of $35-100. This price includes system construction and installation, with the variance in cost largely dependent on well depth. The price of the Pitcher Pump itself is typically US$15-25, with system components and installation costing an additional US$5-7 per metre of depth. All households surveyed reported paying the full purchase price of their Pitcher Pump system themselves, without subsidy.

3) System maintenance and repair effectively managed by local technicians
Pitcher Pump systems were shown to provide reliable and convenient access to water at a low cost relative to household connections to the piped water system. Owners commonly share maintenance and repair costs with their tenants and/or neighbors. System maintenance is done by local technicians or family members, with more significant repairs undertaken by local technicians or manufacturers.

4) Concerns with drinking water quality
There are, however, concerns with the quality of water supplied through these systems (i.e. its suitability for drinking and cooking), specifically microbiological and lead contamination. Only 55% of wells sampled provided water associated with low-risk of microbial contamination for household systems (i.e. 10 or less thermotolerant coliforms per 100 ml), and four out of a small sample of ten wells contained lead (Pb) in excess of guidelines set by the World Health Organization. Measured nitrite levels were below WHO guidelines, but suggest some impact on the groundwater supply by anthropogenic activities associated with waste disposal.

5) Users commonly drink Pitcher Pump system water, with water heating/boiling being common
75% of surveyed families reported drinking water from Pitcher Pump systems, with 15% of these families first chlorinating the water, and 58% boiling it prior to drinking (including two families reporting doing both). Considering the local practice of drinking heated rice water, it is unclear if proper boiling is being done to provide sufficient treatment against bacteriological contamination. In focus group discussions, a small number of Pitcher Pump system owners insisted that the water from their systems was potable (and of no risk to their health) without any treatment, while the great majority understood that the water from their systems was likely contaminated, yet said they commonly drink it without treating it. A minority of focus group participants reported the water from Pitcher Pump systems to be not of potable quality and reported either treating the water (through boiling) prior to drinking, or collecting drinking water from an alternative source.

<u>Further Research</u>
Further research is needed to determine potential improvements to Pitcher Pump systems, to understand how to create synergies between the Pitcher Pump market and utility piped water system, as well as to determine the feasibility of household water treatment and rainwater harvesting Self-supply options to improve access to drinking water.

To this point, continued research led by the University of South Florida and Mercer University has focused on the following aspects:

1) Technical Improvements to the Pitcher Pump system
(a) The identification of lead (Pb) contamination in Pitcher Pump systems in this study has been followed up with a more in-depth study, which confirmed Pb contamination in Pitcher Pump systems to be a significant issue, and identified the major source of this contamination as the Pb valve weights used by most system manufacturers. Secondary sources are lead in commonly used brass well screens, as well as lead-tin solder used to attach the screen to the well pipe (Akers, 2014; Akers et al., 2015; Akers et al., 2016). Recommendations include replacement of leaded valves with iron valves, and, in the absence of valve replacement, flushing of the well prior to using water for drinking, cooking, or bathing.

(b) A second follow-up study investigated fecal contamination in Pitcher Pump systems in Tamatave, Madagascar (Wahlstrom-Ramler, 2014). This study did not find any link between Pitcher Pump system well depth and level of contamination (which was a suggested possibility from the Madagascar case study analysis). However, the fecal contamination study found that Pitcher Pump priming (needed when pump valves don't seal properly) was a significant factor in microbiological water quality in these systems, due to priming with apparently contaminated water.

(c) An ongoing manual drilling study for Madagascar is exploring: (i) ways of improving water quality through use of alternative well-lining materials and drilling methods that reduce/eliminate the use of Pb-containing components in the well screen drilling (Wohlrabe, 2015); and (ii) expanding the household groundwater supply market to areas with more diverse hydrogeological conditions (i.e. deeper water tables, harder soils) through the use of alternative manual well drilling and water pumping technologies.

(d) A current study in Tamatave is exploring options for low-cost well-head protection (i.e. sanitary aprons) for the Pitcher Pump system as a measure to improve bacteriological water quality.

2) Formative Research in Social Marketing
Ongoing research is identifying the factors that Pitcher Pump users and Pitcher Pump manufacturers find important about Pitcher Pump systems (i.e. why do consumers continue to buy, use them; why do manufacturers keep making, selling them).

3) Development of the Self-Supply Market in Madagascar beyond Pitcher Pump systems
Ongoing research is focusing on assessing other traditional Self-supply practices in areas of Madagascar (e.g. hand-dug wells in the south-central highlands, rainwater harvesting systems in the south of the country, etc.). Field data has been collected during four field "rapid assessments", and will contribute to a future field note publication on the potential for accelerating Self-supply in Madagascar, aimed at disseminating the acquired knowledge to local stakeholders in Madagascar (and beyond).

Case Study 2: EMAS Water Supply Technologies in Bolivia
This study highlights research carried out by the University of South Florida. Further information can be found in *Increasing Access to Low-Cost Water Supplies in Rural Areas: EMAS Household Water Supply Technologies in Bolivia* (MacCarthy et al., 2013b).

<u>Context</u>
The most recent JMP estimate shows that, as of 2015, 76% of the rural population of Bolivia have access to improved drinking water sources. This rural water supply coverage statistic has increased significantly since 1990, when the percentage of rural users with improved drinking water sources was estimated at 40%. (JMP, 2015).

Bolivia has a significant recent history of developing low-cost water supply technologies, particularly of manual drilling and handpumps. The organisation EMAS (www.emas-international.de) has worked to develop manual drilling and handpump technologies in Bolivia, and it is estimated that over 20,000 manually-drilled well systems have been installed in households throughout Bolivia using their methods (Danert, 2009). Additionally, hand-auger drilling techniques have been largely promoted by a Mennonite missionary organization for several decades, and 'Water for All International' developed the 'Baptist' drilling technique and a low-cost water pump in Bolivia. EMAS Pumps (and variations) and Baptist Pumps are commonly used at the household level in numerous regions across the country.

EMAS Technologies in Bolivia
To encourage families to use EMAS water and sanitation technologies, and to incrementally improve their household infrastructure, EMAS has adopted a strategy which focuses on the 'added value' of EMAS technologies towards improving household living conditions and lifestyles. This added value comes from the higher level of service that is provided largely through having a reliable water system and water piped to taps in the house. EMAS implements its strategy primarily through the training of local independent technicians from various parts of Bolivia (subsidized by EMAS), as well as through the broadcasting of EMAS training videos on Bolivian television and on the internet. In their work outside of Bolivia, EMAS typically partners with other organisations and local/national governments for implementation, and promotes the same strategy through trainings and assessment trips.

EMAS manual water pumps are used to lift either groundwater from wells or rainwater from underground storage tanks. The EMAS Pump (also known as the Flexi-Pump, or 'Bomba Flexi' in Spanish) is a manually-operated pump capable of lifting water from depths of more than 30 metres (Buchner, 2006). Originally developed in the 1980s by Wolfgang Buchner, the EMAS Pump has been marketed extensively for local construction and use at the household level in Bolivia, and to a lesser extent in other developing countries, mostly in South and Central America (Akvo, 2012). The EMAS Pump has also been introduced on a relatively small-scale in several countries in sub-Saharan Africa, including recently in Sierra Leone (Bunduka, 2013).

The EMAS Pump consists of an outer PVC pipe ('pump cylinder' - typically of 20-40mm diameter) with a one-way foot valve on its lower end, and a smaller-diameter inner PVC pipe ('piston pipe' – typically of 16mm diameter) with a one-way piston valve on its low-er end. A rubber gasket on the outside of the piston valve provides a seal with the pump cylinder. The upper end of the piston pipe attaches to a handle, which is commonly made of galvanized iron. The pump is installed in a well or tank so that the piston valve and foot valve are below water. The pump cylinder remains static, and when the handle (piston pipe) is lifted, suction force causes the foot valve to open (while the piston valve remains closed), and water enters from the well into the pump cylinder. When the handle is then lowered, the foot valve closes and compression pressure causes the piston valve to open, and water flows into the piston pipe. *Figure 2(a)* shows how the EMAS pump valves function. *Figure 2(b*) and *Figure 2(c)* show EMAS Pumps installed on groundwater sources.

The simple design of the EMAS Pump, using materials commonly available in developing countries (e.g. PVC pipes, glass play marbles in the pump valves, and rubber cut from a used car tire) and basic tools, allows for the pumps to be fabricated by trained technicians in many developing communities. The ability of the EMAS Pump to lift water from significant depths to heights above the pump head (e.g. for pumping to elevated household tanks, reservoirs at higher elevations, or for installing multiple pumps on wells) adds to the pump's value. The EMAS Pump is designed for use on household systems (up to 5-6 families, or 30 users maximum), and is not meant to be used as a community pump.

EMAS manually-drilled well systems are primarily promoted for domestic water use. EMAS teaches a few different methods for manually drilling wells, with the most common (the 'Standard EMAS' method) incorporating percussion, jetting, and rotation drilling techniques. The standard EMAS method is capable of drilling to depths of up to 100m, through sand, clay, and thin layers of soft rock, with a team drilling with a trained technician commonly able to drill 20-30 metres per day (Buchner, 2011).

Additionally, EMAS promotes household rainwater harvesting systems (RWHS). **EMAS household RWHS** consists of a catchment area, which is commonly the roof of a house, to which a gutter/drainage system is attached, which guides the rainwater that falls onto the roof to a simple filter (to catch debris) and onwards to a storage tank. EMAS storage tanks can either be below-ground or above-ground. Where conditions permit, it is generally preferred to construct a below-ground tank, as the material costs are considerably less due to the walls of the underground tank being supported by the surrounding soil. From an underground tank, water can then be pumped to the surface (or above, to household or other elevated tanks) using a manual EMAS Pump.

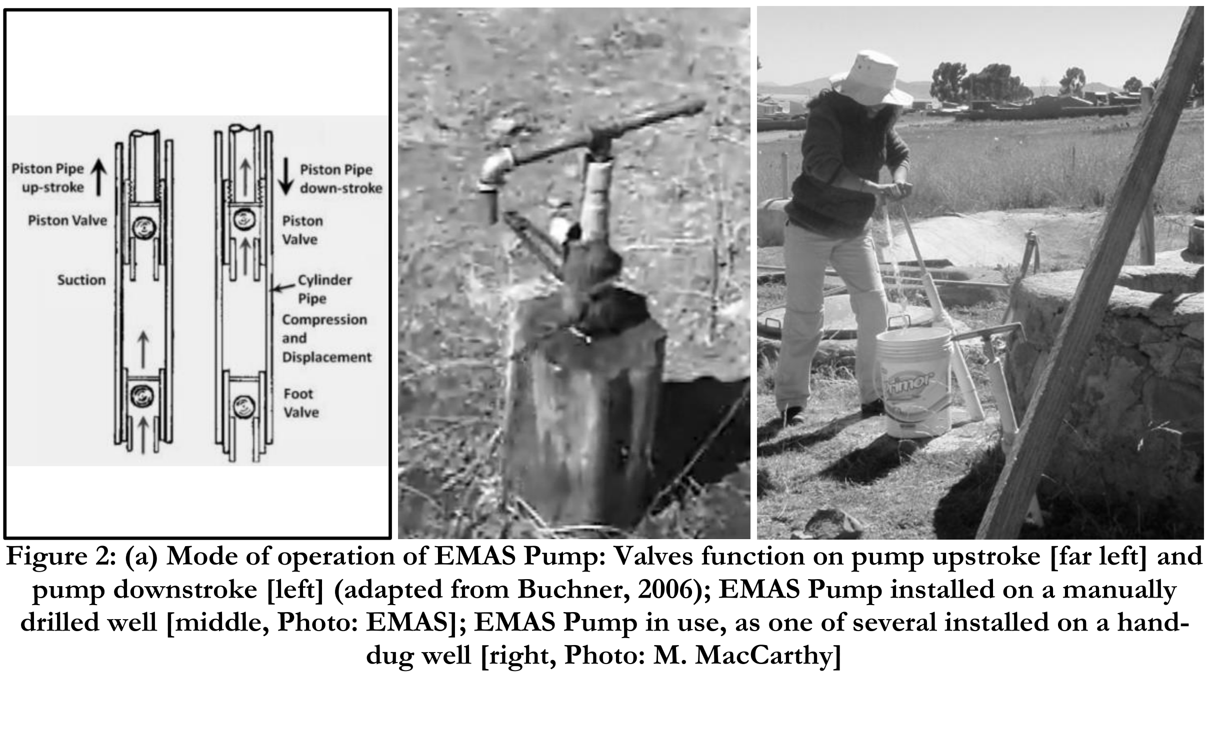

Figure 2: (a) Mode of operation of EMAS Pump: Valves function on pump upstroke [far left] and pump downstroke [left] (adapted from Buchner, 2006); EMAS Pump installed on a manually drilled well [middle, Photo: EMAS]; EMAS Pump in use, as one of several installed on a hand-dug well [right, Photo: M. MacCarthy]

Methodology

The research included an overview of EMAS low-cost water supply technologies and EMAS's approach to improving water supply, and provides an independent assessment of select EMAS water supply technologies as implemented at the household level in rural areas of Bolivia. Field data were gathered during two trips to Bolivia, in March-April 2011 and June-July 2011.

Qualitative data collection involved mixed methods, consisting of surveys, semi-structured interviews, and observation/inspection. Research was carried out in 3 regions of Bolivia (Santa Cruz, Beni, and La Paz). Surveys at the household level of users of EMAS water supply technologies provided the primary data, with questions focused on water and sanitation infrastructure/technologies used by the household; water usage; and costs and responsibilities for installation and repair of EMAS technologies. Semi-structured interviews were conducted with rural water supply technicians and organisations involved in the promotion, construc-tion, installation, and/or repair of EMAS household water supply systems. Household water and sanitation infrastructure was inspected for all surveyed households, including a sanitary risk inspection of the water system, and installed manual pumps were tested to determine state of functionality.

Main Results and Discussion

The primary findings of the study (MacCarthy et al., 2013b) include:

1) EMAS Pumps have a high rate of functionality, and low capital, maintenance costs. A very high percentage of households in the studied contexts in Bolivia were found to have functional EMAS Pumps. Visits to almost eighty households that use EMAS Pumps in their primary water supply systems (manually-drilled wells or RWHS) showed nearly all pumps to be operational (78 out of 79). As shown in *Figure 3*, 84% of the EMAS Pumps surveyed were found to be functioning normally (i.e. without significant issues, and with water discharging normally), including 72% of pumps (13 out of 18) that were reported to have been installed 11 or more years ago. The cost of a new EMAS Pump, to be installed to 15 metres depth, was reported by local technicians to be US$ 30-45 (for pump material and construction costs only, i.e. not including well drilling).

2) A majority of EMAS household water systems are unsubsidized. 62% (53 out of 86) of EMAS water supply systems surveyed were reported to have been paid for fully by the household, without any subsidy or loan. Loans were reported to have been used to help pay for systems by 5% of households (4/86), with 3 households having received a loan from a bank or official lender, and 1 household having received a loan from a relative. 28% of households reported receiving subsidies to partially fund their EMAS water systems, and 6% reported not knowing specifically how their water system was financed.

3) Considerable potential for RWHS. The use of EMAS-style RWHS in Bolivia was very limited at the time of the field research, with the only area with significant uptake of the technology being the villages surrounding the EMAS training center in La Paz region. However, in surveyed areas where EMAS-type RWHS are not in existence there was evidence of potential for household RWHS, as it is commonly practiced in very basic form (e.g. catching rainfall off of roofs using buckets or larger containers). Most (80%) of the houses surveyed without EMAS RWHS had either corrugated metal or clay shingle roofing, both of which are very suitable surfaces for rainwater catchment.

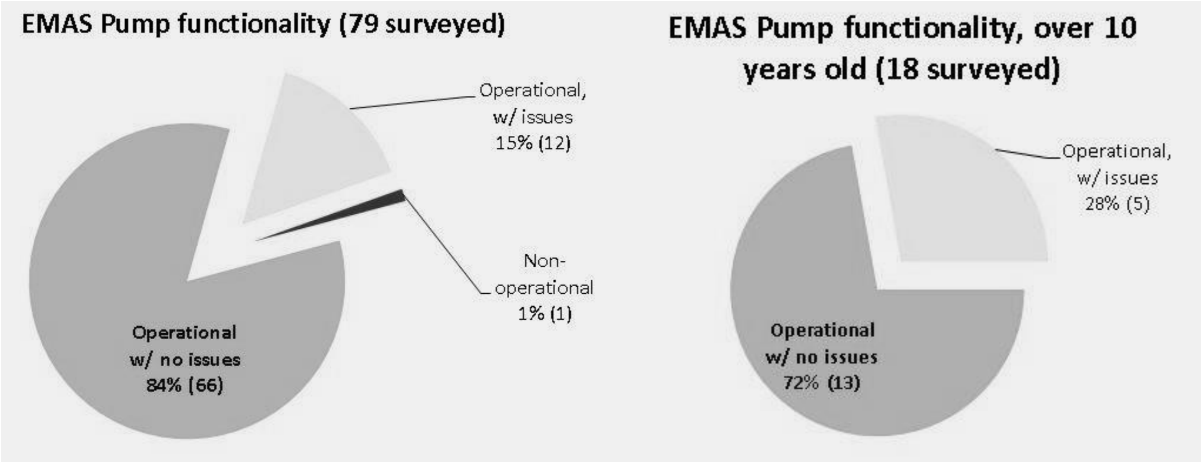

Figure 3: (a) Operational state of all EMAS Pumps surveyed [left]; (b) Operational state of sub-set of EMAS Pumps installed 11 or more years ago [right]

Case Study 3: EMAS Pump Technical Comparison with Rope Pump
This study highlights research carried out by the University of South Florida. Further information can be found in MacCarthy et al., 2016 (*in review as of May 2016*) and Carpenter, 2014.

Context
A comparative analysis was carried out in Uganda with two versions of the EMAS Pump (*Figure 4(a)*) and two versions of the Rope Pump. The Rope Pump (*Figure 4(b)*), which has been most successfully marketed as a household-level pump in Nicaragua, was selected for comparison with the EMAS Pump because the Rope Pump is very well-known in the international rural water supply sector. It has also been introduced in many other developing countries over the past fifteen years, with some success in Tanzania (ACRA, 2012) and varying degrees of success in other countries (Sutton and Gomme, 2009).

Over the past decade, there has been considerable attention paid to the Rope Pump as a low-cost water supply option for developing communities (e.g. Alberts, 2004; MacCarthy 2004; Harvey and Drouin, 2006; Sutton and Gomme, 2009), while little independent documentation has been published related to the EMAS Pump. A 2004 World Bank study compared and summarized experiences with the Rope Pump and the EMAS Pump in Honduras (Brand, 2004). However, while providing a comparison of various attributes of the EMAS Pump and Rope Pump, including initial cost, function and reliability, and overall sustainability, that publication did not present any scientific data on the technical performance of the two pumps. The Honduras study and the Bolivia study (*Case Study 2)* highlight multiple positive qualities of the EMAS Pump (e.g. low-cost, feasibility of local-manufacture in developing communities, and an ability for households to maintain its operation) that lend it to potentially be suitable as a Self-supply water-lifting option in sub-Saharan Africa.

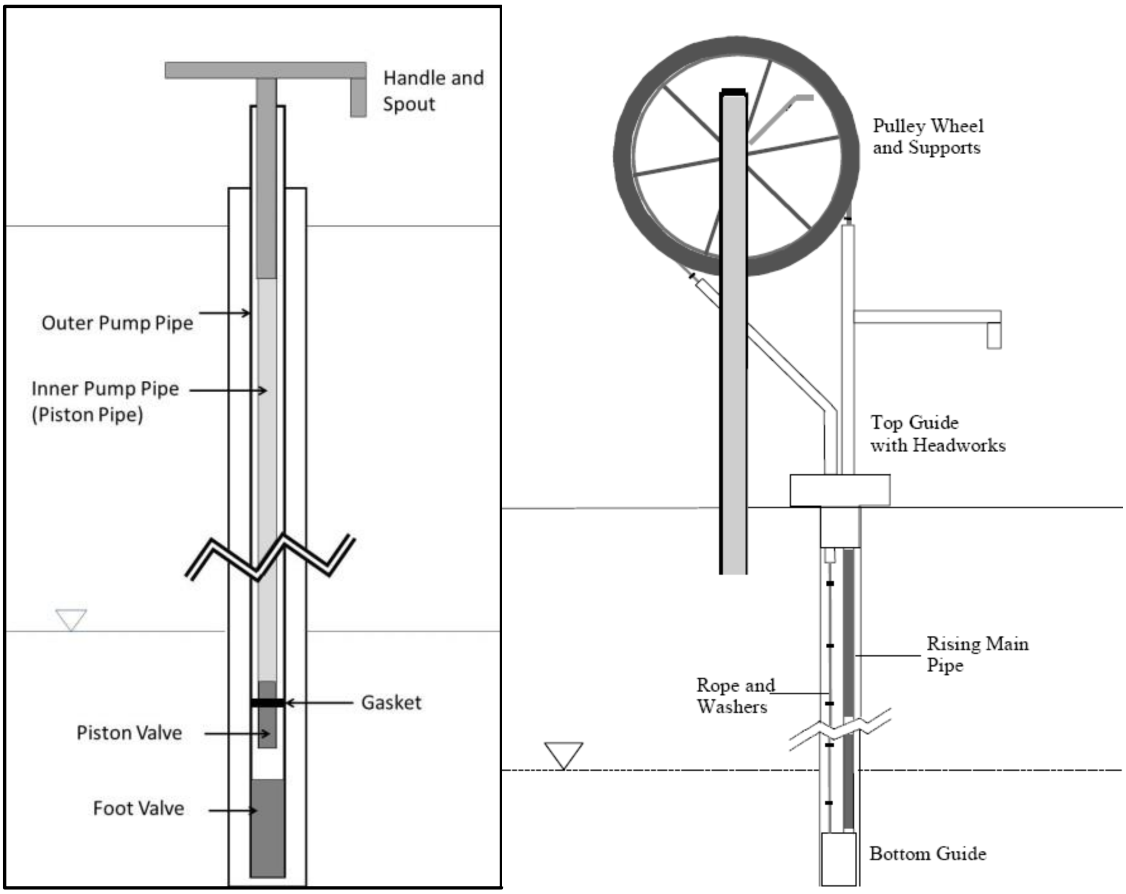

Figure 4: (a) Components of an EMAS Pump, installed on a drilled well (MacCarthy et al., 2016) [left], (b) Rope Pump components installed on a drilled well (MacCarthy, 2004) [right].

Methodology

Two variants of each pump were tested by a male and female user. Pumping trials took place at five separate locations in northern Uganda (in Kitgum and Gulu Districts) over a one-month period in September-October 2013, on wells with static water depths ranging from 5m to 28m. Pumping rates were averaged based on two trials, and normalized to take account for the amount of energy expended by the users during pumping (which was calculated using measured heartrate and established energy expenditure equations). Material costs for each pump are based on retail prices in Kampala, Uganda, in late-2013.

Main Results and Discussion

1) The EMAS Pump had similar pumping rates as the Rope Pump at depths of less than 20 m, for the most common versions of the pumps, and lower pumping rates at deeper depths

Results demonstrated that the EMAS Pump with a 20-mm diameter pumping pump can perform similarly to the Rope Pump with a 20-mm pipe, in terms of pumping rate at depths less than 20 m, but less so at deeper depths. For the versions of the EMAS Pump and Rope Pump with 25-mm diameter pipes, the pumping rates for the EMAS Pump were significantly less than for the Rope Pump. Normalized pumping rates accentuated differences between the EMAS Pump and Rope Pump, as shown in *Figure 5*.

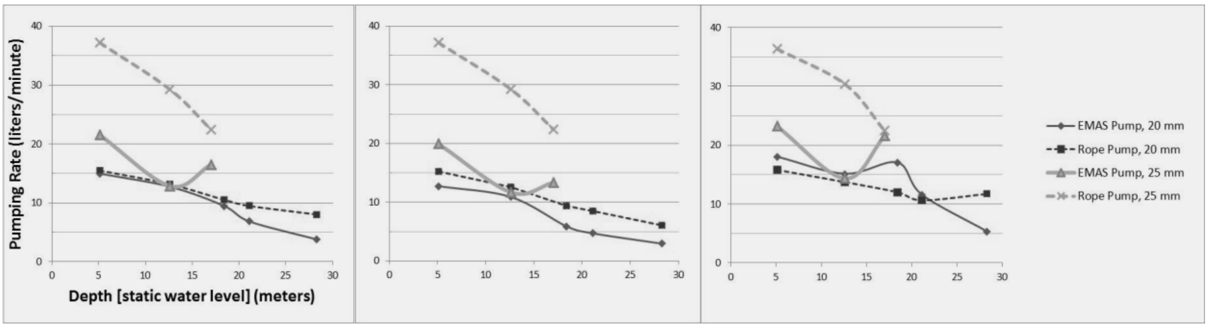

Figure 5. Average pumping rates at various depths with EMAS Pump pumping rates normalized for energy expenditure, for: (a) adult female and adult male subjects; (b) adult female subject, and (c) adult male subject. (MacCarthy et al., 2016)

2) EMAS Pump materials cost significantly less than Rope Pump
Cost of materials to construct the EMAS Pump were 21 to 60 percent lower than for the Rope Pump (*Table 1*).

Table 1: Material costs for EMAS Pump compared to the Rope Pump in Uganda (costs in US$, based on retail prices in Kampala in late-2013).

Static Water Level (m)	EMAS 20-mm	Rope Pump 20-mm	EMAS 25-mm	Rope Pump 25-mm
5	$9.10	$44.2	$12.5	$44.7
10	$13.6	$46.9	$19.5	$47.9
15	$18.2	$49.7	$26.0	$51.9
20	$22.7	$52.4	$32.8	$54.5
25	$27.2	$55.1	-	-
30	$31.8	$57.8	-	-

3) Construction requirements for the EMAS Pump are considerably less than for the Rope Pump
If costs for pump fabrication were to be assessed and added to pump material costs, the total difference in costs between the Rope Pump and the EMAS Pump would certainly increase because the Rope Pump requires extensive welding and cutting that takes time, specialized skill, and incurs electricity costs. In contrast, the EMAS Pump can be constructed with a few simple hand tools such as a hand saw, files, wrenches, files, and PVC glue, and a heat source such as a gas flame or a charcoal stove.

Conclusions and Recommendations

Conclusions and recommendations are summarized through revisiting the studies' four research questions:

1. What improvements can be made to the Pitcher Pump system in Madagascar to improve the quality of the product (including reliability, pumping rates, and/or quality of extracted water)?
It was found that Pitcher Pump systems are widely used in the research area, and are shown to provide reliable and convenient access to water at a low cost relative to household connections to the piped water system. The Madagascar Pitcher Pump market is believed to be the most significant documented example of an unsubsidized household handpump market in sub-Saharan Africa (MacCarthy et al., 2013a). As the systems are easily maintained/repaired by families or local technicians, recommendations for improvement focus on improving the quality of the extracted water. It is recommended that leaded components not be used in pump construction. Additionally, it is recommended that wellhead protection is installed around the wells, and further research is exploring options for low-cost well aprons.

2. Are low-cost water supply systems developed in Bolivia (EMAS technologies) suitable, affordable options for household water supply (Self-supply) for developing communities in sub-Saharan Africa?
Households are able to maintain low-cost EMAS Pumps, with repairs commonly done by local technicians or household members, and in some cases the same EMAS Pumps have been used for more than a decade.

Given their low cost and conduciveness to construction and repair by local technicians, these technologies offer considerable potential for success in accelerating self-supply in sub-Saharan Africa. The potential includes using the EMAS Pump on existing or new household manually drilled or hand-dug wells (with the possibility of installing multiple pumps on the same hand-dug well), manual drilling of wells using EMAS methods, upgrading of such systems as appropriate/feasible (e.g. pumping through hoses or pipes to a tank/reservoir), and RWHS.

3. Would the EMAS Pump be an effective, less-costly alternative to the family Rope Pump, potentially offering new opportunities for households or small groups of families in sub-Saharan Africa to improve their private water supplies?
The technical comparison of the EMAS Pump and the Rope Pump concluded that, based on its relative low-cost, similar pumping rates to common versions of the Rope Pump when pumping from depths less than 20m, and the minimal resources needed to construct it, the EMAS Pump has potential for success in household water supply systems in sub-Saharan Africa. Combined with the conclusion from the EMAS study in Bolivia (*Case Study 1*), which showed a high rate of functionality among surveyed household EMAS Pumps in rural areas of Bolivia, it is believed that there is considerable potential to introduce the EMAS Pump as a very low-cost option for sustainable Self-supply systems in sub-Saharan Africa.

4. *Based on the results of Research Questions 1 through 3, what recommendations can be offered to improve sustainable low-cost water supply systems for use at the household level in developing contexts in sub-Saharan Africa?*
Further research, much of which is now in progress, is needed to maximize the potential improvements to Pitcher Pump systems, determine the key factors of the systems that Pitcher Pump consumers and producers value, and determine the feasibility of household water treatment and rainwater harvesting Self-supply options to improve access to drinking water. As the research advances, more information on the success and sustainability of this market will be valuable to developing and supporting household water supply markets in other sub-Saharan African environments.

The EMAS Pump, which was shown to be sustainable over the medium- to long-term in the studied Latin American context, offers key attributes (i.e. lower-cost, easier to construct) that may allow it to have success as an unsubsidised household pumping option in a wider range of contexts than the Rope Pump has in sub-Saharan Africa.

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References
Akers, D.B. (2014). *Lead (Pb) contamination of water drawn from pitcher pumps in eastern Madagascar*. Master's Thesis. University of South Florida, Tampa, Florida, USA. http://scholarcommons.usf.edu/etd/4975
Akers, D.B.; MacCarthy, M.F.; Cunningham, J.A.; Annis, J.; Mihelcic, J.R. (2015). *Lead (Pb) contamination of self-supply groundwater systems in coastal Madagascar and predictions of blood lead levels in exposed children*. Environ. Sci. Technol., 49 (5), 2685–2693.
Akers, D.B.; MacCarthy, M.F.; Cunningham, J.A.; Mihelcic, J.R. (2016) (*In review*). *Estimates of blood lead levels (BLLs) for children in coastal Madagascar: Accounting for dietary uptake of lead (Pb) from contaminated cooking water.*
Akvo (2012). *EMAS*, Akvopedia. http://www.akvo.org/wiki/index.php/EMAS
Alberts, J.H. (2004). *The rope pump: An example of technology transfer*, Waterlines. 22(3): pp. 22–25.
Buchner, W. (2006). *EMAS: Water for everybody: A selection of appropriate technologies to be used for drinkable water.* 5th Ed. EMAS, La Paz, Bolivia.
Buchner, W. (2011). *EMAS-Bolivia*, Personal conversations, Puerto Perez, Bolivia, March 2011.

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

Carpenter, J.D. (2014). *An assessment of the EMAS Pump and its potential for use in household groundwater systems in Uganda.* Master's Thesis. University of South Florida, Tampa, Florida, USA. http://scholarcommons.usf.edu/etd/4996

Coloru, B, Mgaya, S, and Pozzi-Taubert, R. (2012). *A comparative study between "Rope pumps" and conventional piston pumps on water quality and other sustainability parameters.* Appropriate technologies for rural water supply, Fondazione ACRA-CCS, SHIPO.

Danert, K. (2009). *Hand drilling directory.* Rural Water Supply Network Field Note No. 2010-4. Available on http://www.rural-water-supply.net/en/resources/details/156

Harvey, P.A. and Drouin, T. (2006). *The case for the rope-pump in Africa : A comparative performance analysis. Journal of Water and Health.* 04 (4). pp. 499–510.

Harvey, P., and R. Reed (2007). *Community-managed water supplies in Africa: Sustainable or dispensable?* Community Dev. J. 42(3), 365.

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

MacCarthy, M.F., Annis, J.E. and Mihelcic, J.R. (2013a). *Unsubsidised self-supply in Eastern Madagascar.* Water Alternatives, 6(3): 424-438. http://www.water-alternatives.org/index.php/alldoc/articles/vol6/v6issue3/226-a6-3-6/file

MacCarthy, M.F., Buckingham, J.W., and Mihelcic, J.R. (2013b). *Increasing access to low-cost water supplies in rural areas: EMAS household water supply technologies in Bolivia* 2013-4. St. Gallen. http://www.rural-water-supply.net/en/resources/details/518

MacCarthy, M.F. (2014). *Low-cost household groundwater supply systems for developing communities.* University of South Florida, Tampa, Florida, USA. http://scholarcommons.usf.edu/etd/5261

MacCarthy, M.F., Carpenter, J.C., and Mihelcic, J.R. (2016) (*In press*). *Low-cost water-lifting from groundwater sources: A comparison of the EMAS Pump with the Rope Pump.* Hydrogeol. J.

Mihelcic, J.R.; Fry, L.M.; Myre, E.A.; Phillips, L.D. and Barkdoll, B.D. (2009). *Field guide in environmental engineering for development workers: Water, sanitation, indoor air.* Reston, VA: ASCE Press.

Missen,C. (2003). *Drilling wells by hand*, Wellspring Africa. http://www.wellspringafrica/org/WebManual/default.htm

JMP (2015). *Progress on sanitation and drinking water. 2015 update and MDG assessment.* New York. http://www.wssinfo.org/fileadmin/user_upload/resources/JMP-Update-report-2015_English.pdf

Sutton, S. (2009). *An introduction to Self supply: A case study from Ethiopia 2010.* Rural Water Supply Series Field Note No 2010-2. WSP and RWSN.

Sutton, S. and Gomme, J. (2009). *Transferring the rope pump to Africa: A long and winding road?* Waterlines. 28 (2). pp. 144–160.

USAID (2010). *Madagascar water and sanitation profile.* www.washplus.org/sites/default/files/madagascar2010.pdf

Wahlstrom-Ramler, M. (2014). *Drinking water in the developing world: Sources of fecal contamination in Pitcher Pump systems and measurement alternatives.* Master's Thesis. University of South Florida, Tampa, Florida, USA. http://scholarcommons.usf.edu/etd/5146

Wohlrabe, A.A. (2015). *The development of a low-cost, lead free wellpoint drilling system for use in household well systems in coastal areas of Madagascar.* Master's thesis. Mercer University, Macon, Georgia, USA.

Contact Details

Name of Lead Author: Michael F. MacCarthy
Email: maccarthy_m@mercer.edu

Name of Second Author: Jacob D. Carpenter
Email: jcarpenter@mail.usf.edu
Name of Third Author: Jonathan E. Annis
Email: Jonathan.Annis@tetratech.com