Appropriate technologies for rural water supply

A comparative study between “Rope pumps” and conventional piston pumps on water quality and other sustainability parameters

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Summary

This study originates from the latest findings about the current functionality state of safe water supply systems in developing countries' rural areas.

Previous research to identify the main cause of failure in safe water provision demonstrates the underlying issue of sustainability. High installation and maintenance costs, demand for qualified technical skills, and outsourcing of spare parts, mean that traditionally imported pumps fail in most cases.

The scope of this study is to provide a comparative assessment of conventional piston pumps and Rope pumps, an arguably more appropriate and cost-effective technology for safe water provision. Rope pump is a simple technology based on locally available materials. It has several advantages, including being five to ten times cheaper that traditional piston pumps and suitable for extensive income generating purposes, especially in lower depth wells.

The following research is an analysis of the Rope pumps potential to ensure a sustainable and high-quality water supply service in rural areas. It is designed to determine whether this technology provides a viable alternative for community water supply.

This study was conducted in a fully participatory manner, in order to select and weight the most meaningful and relevant parameters of comparison. Using a mixed-methods approach, the study utilises interviews with water users, sanitary surveys, water quality analysis and the application of a Comparative Performance Analysis technique to obtain quantitative results. This analysis follows a previous analogous study conducted in Ghana in 2006 by Harvey and Drouin (Harvey & Drouin, 2006), with a view to provide a partial comparison of the two cases in order to validate our conclusions.

The first level of comparison considered is bacteriological contamination risk. Other potential influencing factors of contamination, established through a sanitary inspection, are taken into consideration in order to exclude other factors of risk not related to the type of pump installed. Results of this analysis show that, while at first sight water extracted by Rope pumps appears to be at higher risk of contamination, the higher percentage of bacteriological contamination is strongly related to unsatisfactory sanitary conditions of the wells surroundings. Moreover, water samples from wells equipped with both technologies show high rates of contamination, suggesting that the technology choice is not sufficient to guarantee water safety.

The second part of our comparison is an assessment of community-selected parameters (initial investment costs, reliability, reparation costs, turbidity and time for filling a bucket) to evaluate the performance of the pumps in providing high quality water supply services. The results for these parameters reflect a higher performance, and therefore community preference, for the Rope pump.

Following a Comparative Performance Analysis, we can demonstrate that Rope pumps reached a higher score for all parameters included in the study, with the exception of contamination rate.

In conclusion, the study shows, through a critical approach and a rigorous quantitative analysis, that the Rope pump is actually a valid low cost alternative to assure sustainable water supply in rural areas. Like most technology, it shows some minor drawbacks, mainly related to the necessity to assure the respect of minimum standards in the production, installation and maintenance of Rope pumps. This implies that strong commitment of water sector operators is needed to assure a favourable environment to optimize pump performance in the long term.

1. Background

1.1.The sustainability challenge

There are an estimated 250,000 hand-pumps in Africa, the majority manufactured in and imported from Asia. Depending on the country, hand-pump failure rates average around 30% continent wide (RWSN, 2004). It is estimated that 35% of improved rural water supplies in sub-Saharan Africa are out of service at any given time (RWSN, 2005). This means that each new water system provided effectively costs 50% more than estimated. Unless sustainability levels can be improved the funding gap will only widen, the MDG target will never be achieved and rural populations will continue to be denied the basic human right to water.

Several reasons for this unacceptably high failure rate and low level of sustainability have been identified, these include: inappropriate technology; poor construction; lack of community involvement; sense of ownership and willingness to pay; poor community organization or cohesion; lack of follow-up support and/or training; the unavailability or high cost of spare parts and technical capacity; and restrictive policies (Harvey & Reed, 2004).

Getting hand-pumps to work reliably in rural areas of Africa has proven to be a particularly intractable problem.

In order to limit the expenses and the logistical burden by aiming for realistic maintenance solutions, projects evolved towards what has been called the Village Level Operation and Maintenance (VLOM) system, now more often called “Community Management” or “Demand Responsive Approach”. The principle of these approaches is to involve the communities, as much as possible, in the management of their water supply, hoping to stimulate the sense of ownership on an affordable water supply system that uses an understandable and accessible technology, which ultimately costs less and lasts longer.

With regard to rural water supply, major technical advances tend to make hand pumps more readily available and easier to maintain. But even the Demand Responsive Approaches coupled with technological progress encountered many failures.

Communities still need outside support for some major repairs and for the provision of the spare parts. Thus, pump standardisation and privatisation of spare parts supply networks are currently considered pivotal issues by sector stakeholders. In this context, locally made pumps are of particular interest as far as their manufacture is affordable to the locals.

Technology choice is a key determinant influencing the sustainability of rural water services. Operation and maintenance (O&M) greatly improves when communities are allowed to select a technology which they believe is within their financial, managerial and technical capacity to sustain. The conventional hand-pump does not always fit this definition and users often prefer simpler technologies (Breslin, 2003). This however implies a centralised system of quality control to guarantee the respect of certain norms and the standardisation of the spare parts.

1.2.The technology

The Rope pump is a simple hand pump, consisting of a continuous rope, with pistons attached to it at intervals of one meter. The pistons are made out of car tyre and fit with a clearance of 1 millimetre in the PVC-pipe (called raising pipe or raising main). The rope and pistons are set in motion by turning a wheel, mounted with a handle on a structure on top of the well. The rope passes over a flywheel, down into the well or borehole, and up through a vertical pipe, the bottom of which is submerged in

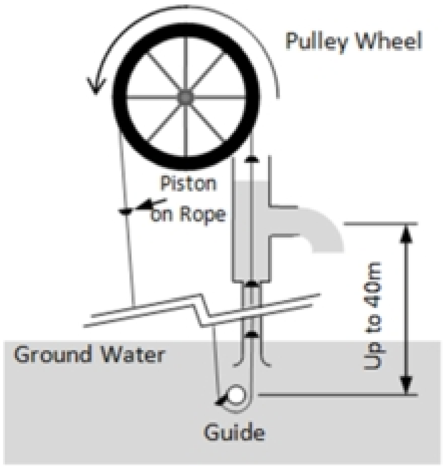

Figure 1: Rope pumps' functioning principle- USAID – Global Water for Sustainability Program

water (Harvey & Drouin, 2006). The rope, passing through the pipe, carries with it the pistons, which lift numerous aligned columns of water to the surface. Rope pumps can be used on hand dug wells as well as boreholes with a diameter as small as a 2 inch, up to a well depth of 45 m (with a double handle pump).

Ropes of polypropylene (PP) give the best results. Nylon is stronger than PP rope, but it tends to slip on the wheel.

The width of pumping pipes varies according to the depth of the well. The deeper the well, the smaller should be the diameter of the pipe. "Going beyond these limits can cause the rope to slide on the wheel over time. The rope with pistons can support the weight of the water column in the pumping pipe. The maximum weight of the water in the pipes is 10 kilograms and should not be exceeded" (Bomba de Mecate).

The capacity of the pump depends on the power of the users, which spans from 40 to 100 watts. "However, the diameters of the piston and its distance, the depth of the well and the diameters of the pipes and mechanical loss of the guide and in the bushings box are also determining factors" (Bomba de Mecate).

1.3.The Rope pump: Strengths and Weaknesses

1.3.1. Low costs, easy technology, economic benefits: towards increased sustainability

Numerous arguments are widely accepted in favour of adopting Rope pumps as an alternative technology to conventional piston pumps. As mentioned above, one of the main advantages of the Rope pump is that they are a very cheap technology. Rope pumps are five to ten times cheaper than piston pumps, particularly in wells deeper than six meter and they are therefore more affordable at the family level. Furthermore, their high capacity, especially in lower depth wells, makes them a valuable technology for more extensive purposes, including community water provision and income generating uses as irrigation, fish production and car washing, contributing to their increasing popularity in developing countries. It is estimated that a family possessing a dug well and a Rope pump earns about $220 more than a family with a dug well and rope and bucket (Alberts & Van Der Zee).

This technology also benefits from the advantage of being easy to install and having low maintenance costs: the installation process requires about 45 minutes and, after appropriate training, can easily be operated by the community due to its few and simple components. Furthermore, the community itself can also conduct maintenance works, given the design's straightforwardness. Although the rope may require more regular repairs, this is also available locally at low costs (WaterAid, 2004).

The Rope pump also outperforms traditional piston pumps at the level of sand interference. In fact, while in normal piston pumps the foot valve needs to be placed above the bottom of the well in order to prevent sand from entering the pump, the Rope pump can still collect water from the very bottom of the well. This quality is extremely relevant, especially during dry seasons, when water is scarce.

These features facilitate a greater sense of ownership within the community towards a technology that is suitable to different uses and geographical conditions. It is widely recognized that increased ownership, as a result of appropriate technology choices, is paramount to guarantee an efficient community-based operation and maintenance and, as a consequence, increased sustainability.

1.3.2. Weaknesses

Despite numerous benefits, there are some constraining factors and prejudices restricting its operational value at a wider scale. These include the conviction that, given its basic looks, it represents a backward technology. It also appears that rural communities tend to prefer conventional piston pumps because they can serve a higher number of users, about 250-300 against the 40-60 of the Rope pump.

Any water supply device should at least protect the water source from microbiological contamination. In fact, very few studies have tried to assess the impact of hand pumps on water quality. It is assumed that they protect groundwater, based on the fact that the more they isolate the source from contamination at the point of abstraction, the less pollution will enter the well. Thus, the Rope pump principle, in which the rope goes in and out of the well, is often considered as not entirely satisfactory in terms of protection of water sources (Gorter et al 1995) when compared to other pumps like the Nira AF85, which are more tightly sealed. For example, the rope is exposed to the external environment, and is therefore at risk from water contaminating agents, such as animal and human waste, and parasites.

However, it is important to acknowledge that critics have not found any strong evidence to demonstrate its ineffectiveness. Given the uncertainty surrounding these claims and the overall performance of the Rope pump, some authors have argued that piston pumps manufacturers and their champions might be exaggerating the downsides of this technology, due to a conflict of interests associated with the widespread international business of hand pumps (Bartle, 2004).

2. Scope of the study

The study presented hereby is an assessment of Rope pumps' potential to assure a sustainable and high quality water supply service in rural areas.

The main objective of the study is to address, analyse and discuss the most common presumptive constraints to the diffusion of Rope pumps to larger scale in Tanzania.

The methodological choice is to compare Rope pumps with other traditional piston technologies (Nira/Tanira, Afridev), which are more widely adopted in water supply initiatives in Tanzania, in order to determine whether or not the Rope pump provides a viable alternative for community water supply.

Users' interviews, sanitary surveys and water quality analysis were used to develop a comparative performances analysis for the two pumps types.

The main fields of comparison are the technologies' capacity to protect underground water from bacteriological contamination and some main sustainability parameters.

Participatory methods have been applied to select and weigh the most relevant parameters based on which the comparison is performed. Users were asked to express themselves on the main aspects to be considered in order to evaluate pumps' performances and to rank their importance. This is certainly an added value of this study in terms of validity of the results to the purpose of supporting the most appropriate choice for future initiatives in the area. On the other hand, this limits the validity of final conclusions on the technology's appropriateness to the target context.

The two pumps types are then compared using a Comparative Performance Analysis technique, in order to obtain a quantitative conclusion upon their appropriateness.

An analogous study aimed at comparing Rope pumps and conventional piston pumps has been conducted in Ghana in 2006 (Harvey & Drouin, 2006). Given context specific differences, the selected methodology for this study follows closely the one previously developed, allowing at least a partial comparison and validation of reached conclusions.

3. Water Quality

The most relevant parameters to be assessed and analysed for performances evaluation include the potential impact on water quality and human health as one of the major concern to the diffusion of Rope pumps at larger scale.

3.1. Sample selection

Rope pumps and traditional piston pumps are compared based on the risk of bacteriological contamination. In order to exclude other factors that could impact on water quality, apart from the type of extraction technology installed, it would ideally be necessary to select wells with identical hydro-geological and climatic conditions, subject to identical pollution risk and usage loads.

These aspects have been kept into consideration in determining sample selection criteria and in defining monitoring protocols.

The target area was limited to the District of Njombe, Iringa Region, Tanzania.

The starting point for sample selection is represented by the various databases available:

- Water Point Mapping, recently carried out by GeoData for the Region of Iringa
- Database availed by SHIPO

A GIS analysis of GPS coordinates of conventional piston pumps and Rope pumps installed in the District allowed the selection of specific areas with good representativeness of the two technologies under examination. In particular, areas with a significant number of Rope pumps and piston pumps coupled within a maximum distance of 200 m have been considered. A first on-the-spot inspection, permitted to select a sample of 30 conventional piston pumps and 30 Rope pumps. This method assures that at least couple of pumps with analogous hydro-geological conditions are represented in the sample.

It is however worth to mention that the whole District is characterized by a quite uniform hydro-geological situation, with a superficial layer of altered granite (sand and clay) with a thickness between 20 and 30 m, followed by rocky granite. Despite the low predictive ability of contaminant transport models, due to physical parameters uncertainty (Hamed, Conte, & Bedient, 1995), this soil characterization is likely to imply a substantial coliform removal within the first 30 cm and a complete removal within a distance of 120 cm (Gagliardi & Karns, 2000) (Hagedorn, Hansen, & Simonson, 1978)

(Romero, 1970).This implies that, apart from direct percolation in groundwater, the risk of contamination from latrines or other sources of contamination due to infiltration can be neglected.

The monitoring plan has been established by considering relevant factors that might affect bacteriological contamination (Bartram & Ballance, 2006), compatibly with available resources. In absence of migratory events affecting usage loads and of any other relevant seasonal phenomenon, the main factor considered is rains seasonal nature. Water from each sampled well has been tested both during the rainy season (November to March) and during the dry season (April to October).

3.2. Sanitary Inspection

Potential pollution sources and contaminant pathways have been identified by performing sanitary inspection to all the sampled pumps. This is considered essential to our analysis, in order to exclude other factors of risk, which could affect water quality results, despite being not related to the type of pump installed.

Sanitary inspection survey forms have been elaborated in order to be the most inclusive possible, by integrating and adapting forms suggested by WHO Guidelines (WHO, 2011; WHO, 2005), with other forms utilized in previous studies (Harvey & Drouin, 2006), RiPPLE 2010, WaterAid 2009).

Sanitary inspection parameters have been analysed for each well by assigning the value “1” in case of positive answer to the respective sanitary inspection question and the value “0” in case of negative answer.

Subsequently each sanitary inspection parameter has been analysed and ranked in terms of statistical correlation with water quality results.

Finally, the 12 most highly correlated parameters have been selected for further analysis.

Based on their correlation ranking, each parameter has been assigned a weight calculated as follows:

$$W_i^{SI} = \frac{Rank}{n.of\ parameters}$$

Rank	Sanitary inspection questions	Weight (W^{SI}_i)
1	**Was the digging conducted manually?**	1.00
2	**Is the lining incomplete or made of stone, bricks or mortal?**	0.92
3	**Do animals have access to the well's surroundings?**	0.83
4	**Is the length of drain less than 3.1 metres?**	0.75
5	**Is the height of the parapet less than 0.2 metres?**	0.67
6	**Is the distance of the nearest uncapped well less than 100 metres?**	0.58
7	**Is there any leakage back into the well around pump base plate?**	0.50
8	**Is the well on a slope?**	0.42
9	**Are there households less than 15 metres away from well?**	0.33
10	**Is the depth of water level less than 20 metres?**	0.25
11	**Are there cracks in the apron?**	0.17
12	**Does the apron have slope to allow water runoff?**	0.08

Table 1: High correlation sanitary inspection

Based on this weights system, the pumps sanitary inspection score (SS) for each well has been calculated as:

$$SS = \sum_{i=1}^{n} W_i^{SI},$$

where n is the number of sanitary inspection parameters assigned the value "1" during the inspection. Each well has been assigned a sanitary risk level based on the sanitary inspection score obtained, as shown in Table 2:

Sanitary inspection scores	Sanitary Risk
<1.625	Low (1)
1.626 - 3.25	Medium (2)
3.26 - 4.875	High (3)
4.876 - 6.5	Very high (4)

Table 2: Sanitary risk levels

3.3. Water quality test methodology

Water quality was tested through Colilert and Petrifilm Method.

Following the feedback from the first national Water Point Mapping workshop held in Iringa in 2010, ACRA, Iringa Region and TaWaSa.Net, asked for UN-Habitat's support for a workshop about low cost Water Quality Testing (WQT), involving of all district technical staff, Urban Water Authorities and Regional Water Advisors. The main objective of the workshop was to provide stakeholders with the required skills and knowledge to pilot Water Quality Testing activities within the WPM exercise in Iringa Region using low cost WQT kits. This new technique availed to local water sector operators consists of two tests: the IDEXX Colilert Presence/Absence test and the 3M Petrifilm E.coli/Coliform Count Plate test (IDEXX).

The Colilert test for water is a substrate medium, not containing organic sources of nitrogen and with only 2 carbon sources for bacteria to obtain energy:

- ONPG (Ortho-Nitro-Phenol-beta D-Galactopyranoside): coliform bacteria can be induced to produce the beta-galactosidase enzyme, which hydrolyses the bond between ONP and G. Despite ONPG is colourless, ONP has a bright yellow colour.
- MUG (4-methyl-umbelliferone-beta-D-Glucoronide): among the coliform bacteria, only E.coli produces the constitutive enzyme beta-glucuronidase, which hydrolizes the bond between MU and the G. The glucoronide in metobolized to enable growth of E.coli. MUG is colourless, whereas MU fluoresces blue when irradiated with a long wave UV light (340 nm).

The test has been developed to detect low levels of coliform bacteria and E.coli simultaneously within 24 hours. In this survey, 10 ml single tubes were used, eventually showing fluorescence after 12 to 18 hours of incubation at 35-37 ^{0}C, depending on the level of contamination.

Figure 2: Colilert tubes. Results: colourless=negative, yellow=coliforms, yellow and fluorescent=E.coli

The 3M Petrifilm E.coli/Coliform Count Plate test is a reliable, sample-ready medium system for enumerating E.coli and coliforms.

The E-coli Count Petrifilm contains:

- Violet red bile nutrients including lactose: bile salts and crystal violet in the medium inhibit Gram positive bacteria
- cold water soluble gelling agent
- glucoronidase indicator (BCIG, 5-bromo 4-chloro 3-indolyl-beta D glucoronide) to identify E.coli
- tetrazolium indicator which reduced to a red colour by Gram negative bacteria to enhance colony visualization.

All bacteria ferment lactose to produce gas bubbles that are trapped around the coliform colony. This will distinguish coliform bacteria from other Gram negative bacteria.

In addition, glucuronidase, produced by most E.coli, will hydrolyze the glucoronide from BCIG.

The BCI produces a blue precipitate around the colony, allowing visual identification of E.coli and distinguishing them from non-E.Coli colonies, which are red with gas bubbles.

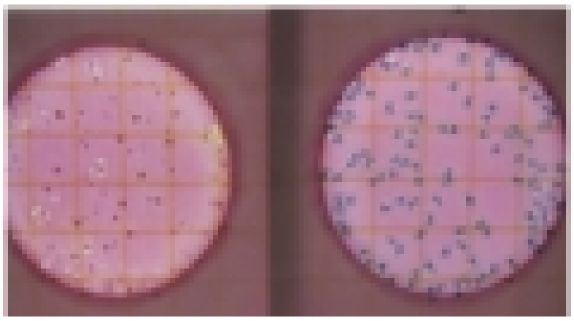

Figure 3: Coliforms (a) and E.coli (b) colonies on petrifilm tests

The Colilert and Petrifilm tests correlate with the relative risk of disease from drinking water (WHO, 2011). The table below shows how this risk assessment is done.

Risk level	E-Coli /sample	Colilert MUG	N. of blue Petrifilm
Low	<1/10ml	-	0
Moderate	1-9/10 ml	+	0
High	1-10/ml	+	1-10
Very High	>10/ml	+	>10

Table 3: Risk levels (WHO, 2011)

3.4. Results and discussion

Over 180 samples have been tested for Escherichia Coli and total coliforms (76 from wells with traditional piston pumps and 104 from wells with Rope pumps).

	Traditional piston pumps	**Rope pumps**
General Results	37%	49%
Dry Season	24%	32%
Rain Season	53%	65%

Table 4: Water Quality Test results, percentage of contaminated samples

Water samples from wells equipped with both technologies show quite high contamination rates. This implies that technological choice is not sufficient to assure safety of water supply and more effort is required to improve hygienic conditions and proper maintenance of water sources.

Moreover, water quality at the distribution point does not represent a guarantee in terms of diseases' prevention. Bacteriological contamination might still occur during transport and storage, revealing the importance of further treatment at household level.

As predictable, higher contamination rates were found during the rainy season, indicating that well are exposed to direct percolation of contaminated water. This phenomenon affects in the same way both wells equipped with piston pumps and wells equipped with Rope pumps.

At first sight, water quality analysis seem to confirm a higher contamination risk in wells equipped with Rope pumps compared to the ones equipped with hermetically sealed traditional piston pumps. Overall, 49% of samples from wells equipped with Rope pumps resulted contaminated, against 37% of samples from well equipped with conventional piston pumps.

The sanitary inspection analysis turns out to be fundamental here for a meaningful interpretation of water quality results.

According their sanitary risk conditions, sampled wells were divided into four groups.

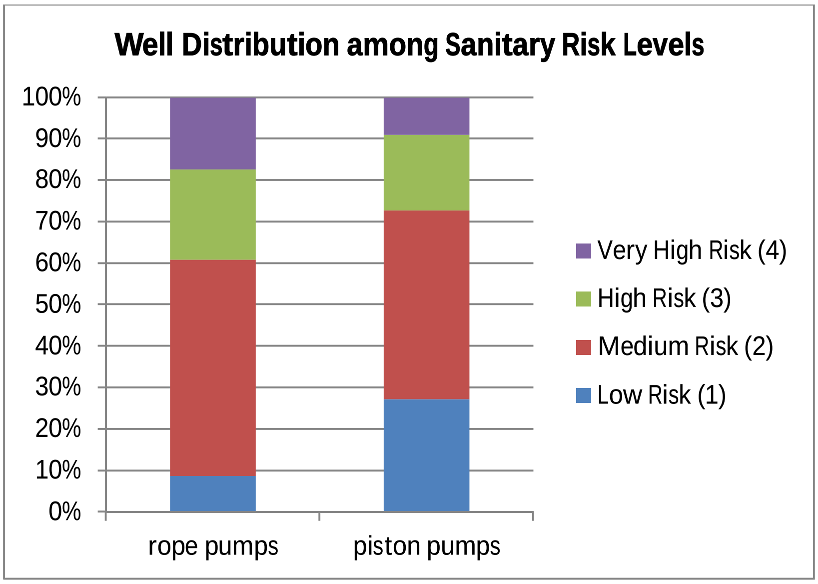

Figure 4: Wells distribution among sanitary risk levels

Figure 4, shows the wells distribution among the four sanitary risk levels. Only 9% of wells equipped with Rope pumps, against 27% of those equipped with piston pumps are found in good sanitary conditions, with low associated risk. On the other hand only 9% of piston pumps, against 17% of Rope pumps are in worrying hygienic conditions, associated with very high risk of water bacteriological contamination.

The much higher percentage of Rope pumps in unsatisfactory sanitary conditions is reflected in the higher rate of bacteriological contamination. This does not necessarily mean that the Rope pump is not suitable to protect the well, but that it is generally installed with less attention to hygienic standards. This consideration raises some questions concerning mechanisms to assure sufficient quality standards in case of Rope pumps diffusion at larger scale. In fact, the technology's simplicity and the local availability of all constituent, favour the establishment of a strong supply chain, with a larger number of producers and supplier, but hinder any possibility to effectively monitor the respect of minimum quality standards in production, installation and maintenance of Rope pumps.

A further analysis has been conducted in order to compare contamination rates in pumps having the same sanitary risk level. Rope pumps and piston pumps were grouped according to their sanitary inspection scores and contamination rates compared within each group. Outcomes are displayed in Figure 5.

A clear increasing trend is visible for Rope pumps, suggesting that, probably due to the fact that wells equipped with this technology are not hermetically sealed, hygienic conditions of the surroundings have a stronger impact on water safety. A constant increase in water contamination can also be observed for piston pumps from risk level 2 to risk level 4.

Overall, while Rope pumps clearly showed higher contamination rates when the whole sample is considered, when looking at the different sanitary risk levels, this feature appears less pronounced and the two technologies seem to be more equivalent. Rope pumps show in fact higher contamination rates only at intermediate sanitary risk levels, while water from piston pumps equipped wells is more contaminated in case of low and very high sanitary risks.

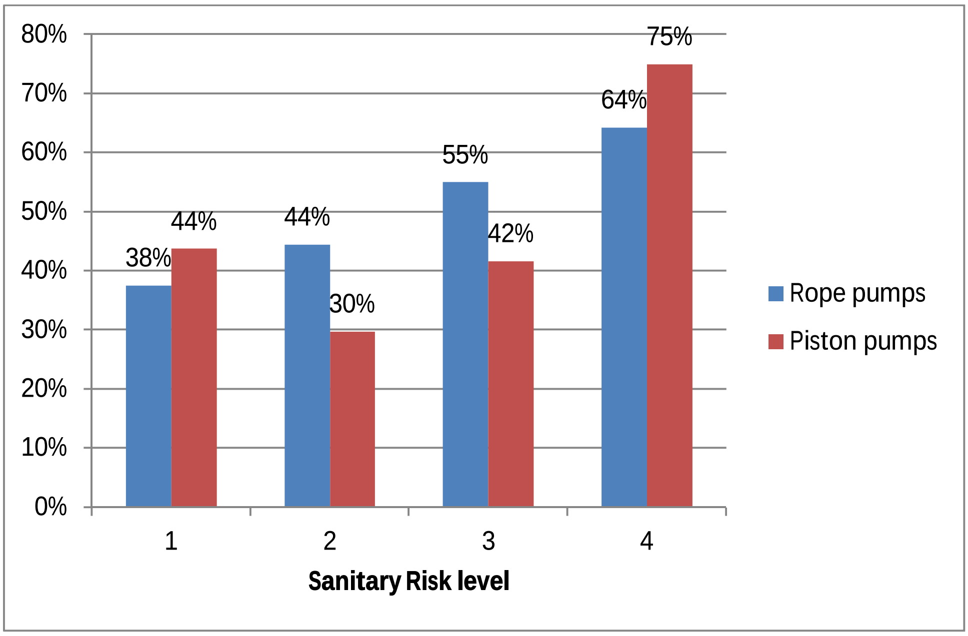

Figure 5: Contamination rates for Rope pumps and piston pumps with to comparable sanitary risk levels

4. Participatory selection and weighing of performance assessment parameters

Apart from impact on water safety, other parameters considered in this analysis have been selected in a participatory manner, in order to obtain a context-specific performance assessment and reach conclusions that actually represent users' perceptions of an appropriate technology to meet their needs and preferences.

Then, a sample of 143 users was asked to rank these aspects based on their perceived relative importance.

According to the ranking, parameters have been assigned a score from 12 (first position) down to 1 (last position). The average score gained by each parameter has been used to obtain the following final ranking, and to compute the relative weight to be attributed to each parameter. Weights were calculated as follows:

$$W_i\left(\text{importance weight for the i}^{\text{th}}\text{factor}\right) = \frac{\text{score for i}^{\text{th}}\text{factor}}{\text{sum of all factors score}}$$

Rank	Parameters	Average score	Weight (W)
1	Initial investment cost	10.16	0.1011
2	Reliability (functioning days per year)	10.14	0.1009
3	Maintenance frequency and cost	9.44	0.0939
4	Availability of technical assistance	9.15	0.0910
5	Availability of spare parts	8.74	0.0870
6	Reparation costs	8.40	0.0836
7	Supply cost	8.21	0.0817
8	Operation exertion	6.90	0.0687
9	Bacteriological contamination	6.84	0.0681
10	Time for filling a bucket	5.68	0.0565
11	Turbidity	5.03	0.0501
12	Smell of water	4.78	0.0476

Table 5: Ranking and weighing of relevant parameters

The ranked parameters, where possible, were estimated in a quantitative manner. Those parameters showing significant differences between the two technologies and quantitatively measurable (rows highlighted in yellow) were included in a Comparative Performance Analysis.

5. Sustainability assessment

5.1.Measurement of quantitative parameters

5.1.1. Initial investment costs

In order to assess initial costs, interviews were conducted with pumps' users, owners and suppliers. Answers from users showed a remarkable variability, partially due to lack of awareness about expenses allocation (pump purchase, transport, digging, installation costs) and about possible subventions from NGOs to cover part of the costs.

Only 6 users, among the interviewees, were able to answer about initial investment costs and all of them estimated an initial cost of 6,000,000 TZS (about 3,800 USD at the current exchange rate). This amount probably includes also digging and installation costs, as well as additional life-cycle costs estimated by the sponsoring project.

From an inquiry involving suppliers available in Tanzania we obtained the following quotations for conventional piston pumps:

Pumps Type	Price (TZS)	Price (USD)
Afridev (up to 30 m depth)	2,250,000	1,427
India Mark II (up to 30 m depth)	2,500,000	1,585

Table 6: Purchase costs of conventional piston pumps

Afridev pumps, with a depth of less than 30 m are the most represented both in our sample and in the target area.

It was found that 16 Rope pumps, out of 22, had been sold commercially to the community. Initial costs estimation, including digging and installation costs, range from 70,000 TZS (32 USD) to 230,000 TZS(146 USD). The average amount of 150,000 (95 USD) is consistent with the quotation given by SHIPO and can be considered a reliable datum for our purposes.

5.1.2. Reliability

Reliability is the ability of a system to perform its required functions under stated conditions for a specified period of time. Reliability is often measured as probability of failure, frequency of failures, or in terms of availability, a probability derived from reliability and maintainability.

In this research the measurement of reliability posed some major issues. Rural water supply systems' performances are not regularly monitored and no system is in place to keep record of failures over a period of time sufficient to allow significant statistics. Interviews to users permitted to estimate the number of days the pump was not functioning during the previous 12 months. Reliability is thus here calculated as the number of days the pump was functioning over the last year.

$$Reliability = \frac{n.of\ functioning\ days}{365\ days}$$

The percentage of pumps experiencing some kind of failure during the past 12 months is 86% of Rope pumps, against the slightly lower 80% for conventional piston pumps. Nevertheless, looking at the duration of the failures, Rope pumps show much higher reliability figures (see Figure 6).

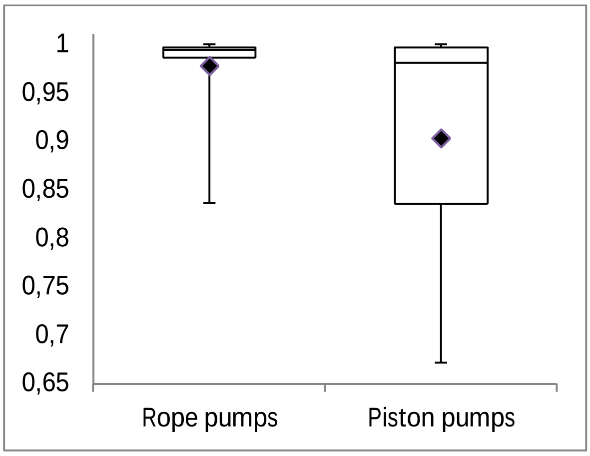

Figure 6: Box plots representing reliability figures for Rope pumps and piston pumps

Non-functioning Rope pumps were out of service for an average of 5 days, with a maximum of 60 days in a row. For piston pumps the average non-functioning time is 28 days, with a maximum of 120 days. This datum is interesting in terms of technical sustainability and, in addition to the reliability of the technology itself, it takes into account other sustainability factors such as availability of spare parts and technical assistance, as well as reparation costs.

Another factor to be considered in this analysis is certainly the age of pumps considered. No relevant correlation was found, for both technologies, between their age and reliability figures. Nevertheless, it is worth to mention that, despite piston pumps have on average been installed earlier, they seem to be slightly more robust towards failures if compared to Rope pump.

	Rope pump	Piston pump
Average out-of-service days	5	28

Maximum out-of-service days	60	120

5.1.3. Reparation costs

As already mentioned in the previous section, the great majority of pumps (more than 80%) experienced some kind of failure during the past 12 months. For the totality of cases, users contributed to the costs without any support from local government and/or NGOS, and this is often pleaded for the long time elapsed before the service was restored.

With regard to the type and entity of reparation intervention required, piston pumps users were able to answer only in 4 cases and mentioned the need to replace some sections of PVC pipes.

More than half of Rope pumps users interviewed managed to provide exhaustive answers and stated that the most common intervention needed is replacement of the rope, in fact considered the component most subject to wear and tear.

Reparation costs are here estimated on annual basis, both from users' interviews and from inquiries among pumps producers.

According to the users the average annual reparation cost for a Rope pump amounts to 19,750 TZS (12.5 USD). The estimation of annual expenditures to repair piston pumps is equal to 28,100 TZS (17.8 USD).

If one considers information obtained from pumps suppliers, figures appear to be comparable for the case of Rope pumps, while they are substantially different for piston pumps, mainly due to the absence of technical assistance locally available.

Rope pumps suppliers confirm that the most vulnerable part is the rope, whose cost is about 16,000 TZS. Labour cost can reach up to 5,000 TZS, depending on the distance covered by technicians to reach the intervention site. The total cost for rope replacement would result 21,000 TZS (13.3 USD).

For piston pumps, users would be assisted by technicians from Iringa or from Mbeya, for a total cost of 200,000 TZS. Rubber seals, which need to be replaced at least once a year are, cost 15,000 TZS.

Due to the limited capacity of piston pumps users to provide exhaustive answers, costs' estimations from supplier are considered more accurate and will thus be taken into account for further considerations.

	Rope pump	Piston pump
Annual Reparation Costs (users)	12.5 USD	17.8 USD
Annual Reparation Costs (suppliers)	13.3 USD	136.3 USD
Most frequent intervention needed	Rope replacement	Rubber seals
Cost of spare parts	10.1 USD	9.5 USD
Cost for technical assistance	3.2 USD	126.8 USD

Table 7: Reparation costs

5.1.4. Turbidity

Turbidity is mentioned among the most relevant parameters to judge pumps' performance, being considered by users as a perceivable indication of water quality.

Turbidity was measured with an electronic turbidity meter availed by the Laboratory of the Njombe Urban Water and Sanitation Authority. Measurements were performed in field, simultaneously with water sampling and provided instant reading of Formazin Turbidity Units (FTU) in the sample. Turbidity varied significantly among the different measurements, with a remarkable difference between dry and rainy season. The average turbidity of water delivered by Rope pumps (10.3 FTU) is considerably smaller than the average turbidity found in water delivered by piston pumps (31.4 FTU). One plausible explanation is that the reciprocating action of piston pumps, being discontinuous, produces more movement in the well and stirs up sediments settled at the bottom of the well in comparison to the smooth circular movement of the rope.

Bearing in mind the high contamination rates found in samples from both types of pumps, the introduction and promotion of treatment techniques, both at household and at well level, might be desirable. To this regard, turbidity must be kept into consideration. In fact, where chlorination of water is practised, even quite low turbidity will prevent chlorine from killing the germs in the water. Turbidity should be preferably less than 1 FTU for chlorination to be effective (WHO, 2011). Within our sample 48% of samples from Rope pumps fulfilled this requirement, while only 16% of sample from piston pumps resulted suitable for chlorination treatment.

5.1.5. Time for filling a bucket

Time for filling a bucket is perceived by water users as one of the main performance parameters, being closely related to waiting time at the distribution point and, therefore with time consumption for water fetching.

Water users interviewed during the survey were unable to provide accurate estimations of this parameter. Therefore, it has been estimated based on technical specifications provided by pumps producers and derived from pumps flow rates.

	Specified flow rates [l/min]	Time for filling a 20 litres bucket
Nira Tanira AF85	60	20 sec
Afridev	23	51 sec
Rope pump	8	2 min 27 sec

Table 8: Estimation of time to fill a 20 litres bucket from pumping capacity

As shown in Table 8 conventional piston pumps are characterized by higher pumping capacities.

With regard to Rope pumps, it must be considered that the specified figure refer to a 40 metres deep well. Due to the risk to excessively increase the operating exertion, the pipes diameter (and thus the pumping capacity) needs to be reduced as the well's depth increases (see Section 1.2). In our target area, the average depth is around 27 m and the Rope pumps flow rate could significantly increase.

Moreover, in order to understand the real meaning of this parameter, it is worth to go through short considerations about the number of users being supplied by those pumps. Time necessary to fill a single bucket, when in the order of few minutes, does not really affect users' perception of the service received. On the contrary, it becomes relevant when, due to the high number of people sharing the same water distribution point, long queues form and time for filling buckets sum up considerably increasing the overall waiting time. On average, piston pumps included in our sample are shared by 396 people (about 88 households), while community-owned Rope pumps by 67 people only (about 14 households).

In order to take these aspects into consideration in the following Comparative Performance Analysis, a new composite indicator have been developed as the product of waiting time for filling a single bucket and number of people being served (supposed to be proportional to the number of buckets being filled every day):

$$Total\ Filling\ Time\ (TFT): Time\ for\ filling\ a\ 20\ l\ bucket\ \times number\ of\ people\ served$$

The TFT indicator for piston pumps has been estimated by considering an average pumping capacity between Nira/Tanira AF85 pumps and Afridev pumps, both represented in our sample.

	Time for filling a 20 litres bucket	Average Number of Users	Total Filling Time (TFT)
Rope pumps	2 min 27 sec	67	2 h 43 min
Piston pumps	35 sec	396	3 h 55 min

Table 9: Total Filling Time

5.2.Comparative Performance Analysis

The Comparative Performance Analysis (CPA) method utilised in this study was adapted from the basic principles adopted in multi-attribute utility-measurement for social decision making (Edwards, 1976). The purpose of this method was to compare the performance of the two pumps on the basis of variable factors.

Additional variables were identical or near-identical for both pump types or impossible to measure in a quantitative rigorous manner, and hence were excluded from the CPA method.

Each pump type is assigned a location, on a scale from 0 to 1 for each factor, 0 being the score for the worst plausible value and 1 the best plausible value.

The location of each type of pump on the scale was computed as follows:

$$S_{ij} = \frac{|worst_i - value_{ij}|}{|best_i - worst_i|}$$

Where:

S_{ij} is the scaled position of the j^{th} pump type on i^{th} parameter;

$best_i$ and $worst_i$ are the best and worst plausible value of i^{th} factor respectively;

$value_{ij}$ is the value of j^{th} pump type on i^{th} factor

Parameter	$Best_i$	$Worst_i$	Rope pump		Piston Pump	
			$Value_{i1}$	S_{i1}	$Value_{i2}$	S_{i2}
Initial investment cost	10 [USD]	1,585 [USD]	95	0.946	1,506	0.050
Reliability	1	0.67	0.978	0.934	0.904	0.707
Reparation costs	3.2 [USD]	1,712 [USD]	13.3	0.994	136.3	0.922
Contamination rate	0%	100%	49	0.510	37	0.630
Turbidity	0 [FTU]	774 [FTU]	10.29	0.987	31.37	0.959
TFT	90 [sec·people]	342,628 [sec·people]	9,828	0.972	14,132	0.959

Table 10: Location of the two pumps types on a scale 0 to 1 for the different comparison parameters

The worst and best plausible values were determined based on field evidence (best and worst values obtained within the sample) for reliability, turbidity and TFT.

For the case of initial investment costs, the best value used for the analysis refers to the cost for a simple rope and bucket system, considered as one of the cheapest water supply systems locally available. The worst value is the Nira/Tanira AF85 cost, the highest among the collected quotations for Tanzanian suppliers. With regard to reparation costs, the best value is estimated as the labour cost from a local technician, for a hypothetical simple intervention, without any additional cost for replacing spare parts. The worst value is computed as the cost for the full replacement of an expensive Nire/Tanira AF85 pump, with labour costs for non-local technicians, as estimated by Tanzanian suppliers. For contamination rate best and worst values refer to a totally pure (0%) and a totally contaminated (100%) sample respectively.

Best and worst values are then compared to the mean values for each factor for each pump type (see Table 10) to obtain the scaled positions of the two technologies for each factor on a scale from 0 to 1. The final stages of CPA (see Table 11) were to determine the weighted scores (WS_{ij}) for each factor of both pump types as:

$$WS_{ij} = W_i \times 100 \times S_{ij}$$

and to sum these to determine the overall evaluation score (S_j) for each pump type:

$$S_j = \sum_{i=1}^{n} WS_{ij},$$

where n is the number of analysed parameters.

Parameter	W_i	Rope pump (S_{j1})	Piston Pump (S_{j2})	Rope pump (W_{i1})	Piston Pump (W_{i2})
Initial investment cost	0.1011	0.946	0.050	9.564	0.507
Reliability	0.1009	0.934	0.707	9.429	7.130
Reparation costs	0.0836	0.994	0.922	8.311	7.709
Contamination	0.0681	0.510	0.630	3.473	4.290
Turbidity	0.0565	0.987	0.959	5.575	5.421
TFT	0.0501	0.972	0.959	4.868	4.805
Overall evaluation scores (S_j)				**41.219**	**29.862**

Table 11: Weighted scores and overall evaluation scores

CPA's results are summarized in Table 11. The overall evaluation score for Rope pumps, on a scale 1 to 100 is equal to 41.2, while for piston pumps is 29.9. The parameter showing the biggest discrepancy between the two pumps types, as well as the one with the highest assigned weight, is initial investment cost. This is predictable, being one the best known advantage recognized to Rope pumps. Rope pumps seem to show highest scores for all parameters, with the exception of contamination rate. Apparently, this confirms the main argument constraining Rope pumps from spreading at larger scale in Tanzania and other countries. Nevertheless, these results are widely discussed in Section 3.4, where sanitary conditions and other influencing factors are taken into account for deeper insight into the issue of water contamination risks.

6. Conclusions

The study presents a critical performance assessment of the Rope pump technology, in comparison with other more widely accepted and used groundwater extraction technologies. The main outcome of this research is its contribution to the current debate regarding of water technologies performances.

It does so in offering some useful insight into the main constraints towards Rope pump diffusion at a larger scale.

i. The fact that rural communities tend to prefer conventional piston pumps because they can serve a higher number of users is strongly disproved by this research; instead this is mentioned only amongst the main critics to traditional piston pumps. In fact, due to the high investment and repair costs, piston pumps are generally shared among a higher number of households, implying a series of drawbacks in terms of service and sustainability:
    - Longer queues and waiting time
    - Higher use load and damage likelihood
    - Higher complexities in terms of management and accountability for pumps maintenance

ii. With regard to the Rope pumps capability to protect the water source from microbiological contamination, this study reveals that water samples from wells equipped with both technologies show quite high contamination rates, implying that the technological choice is not sufficient to assure safety of water supply and more effort is required to improve hygienic conditions and proper maintenance of water sources. Despite the apparent higher contamination rate for water samples extracted by Rope pumps, our analysis demonstrates that this is mainly related to poor hygienic conditions of the pumps surroundings and to the adopted excavation technique, rather than to the type of pump installed. This conclusion raises some concerns related to the necessity to put in place measures and innovative systems to assure the respect of minimum standards in the production, installation and maintenance of Rope pumps. In fact, the straightforwardness of design and installation together with the local availability of materials and main constituents facilitate the supply chain scale yet hinder the possibility to monitor the fulfilment of quality standards.

    However, water quality at the distribution point does not represent a guarantee in terms of disease prevention. Bacteriological contamination might still occur during transport and storage, revealing the importance of further treatment at household level.

As with every technological option, Rope pumps are undoubtedly characterised by a series of advantages and drawbacks, which is demonstrable from our analysis. The pumps appropriateness to specific needs and contexts needs to be carefully evaluated case by case.

Nevertheless, it is worth to highlight that, when compared to traditional piston pumps, widely adopted for rural water supply, Rope pumps seem to show better performances for most of the parameters considered.

In light of these findings, it might be necessary to shift the debate from the intrinsic appropriateness of Rope pumps as water supply devices, towards the identification of institutional and systemic arrangements to minimize drawbacks and optimize the impact of water pumps.

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