Self-Sustainable Well Water Supply: Remote Hand-Pumped Well and Monitoring System for Improved Well Up-time Through Prioritised Targeted Maintenance

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Abstract: This paper outlines a self-sustainable approach to shallow well water provision. Through extended and extensive local involvement combined with the development of a well monitoring system, accurate targeted maintenance decisions can be made improving water availability from remote rural hand-pumped wells. In Tanzania thirty percent of hand-pumped wells are non-functional. The aim is to have a reliable source of clean water for the community by the community developing a mind set and infrastructure to ensure wells remain functional and fit for purpose. Using all means to prevent issues arising, including technology, help identify signals that may lead to a non-performing well for maintenance activities. Current trials are encouraging and demonstrate how behavioural and cultural change in this sensitive and socially complex area combined with low-cost technology can be harnessed to improve well up-time and improved water provision.

1. Introduction

A UNICEF report[1] stated that, *"43 per cent of children drink unsafe water and one in five die before their fifth birthday"*. In addition, statistics on water point failures[2] show that in Tanzania thirty per cent of water points are non-functional. The Rural Water Supply Network (RWSN) stated in its Strategy paper[3] 2018-2023 (p26): "*Effective monitoring of rural water supply services is important to enable progress to be measured and to provide evidence for decision-making*."

This paper outlines a self-sustainable approach to water provision through extensive local involvement and the development of a system which provides well data upon which accurate, targeted maintenance decisions can be made. Self-sustainability of the remote rural hand pumped wells is considered of paramount importance. A combination of a number of different elements is required to attain the goal of self-sustainability and some of these are mentioned below. When combined with the well maintenance system, this is proving to be of significant benefit in continued well water provision.

The principal aim of the well maintenance system is to facilitate the timely maintenance of rural hand-pumped wells. Two previous well monitoring prototypes were technically successful but operationally flawed, these are also discussed as they provide the foundation on which the current system is based.

Simplicity is the key. Although large amounts of data could be collected, the principal focus is to answer the question; '*Is the well working?*' To establish the functionality of the well the well monitoring unit must also be checked. In addition to the time the wells are used each day (the Pump-Count) other information (including voltages and temperatures) are also transmitted to head office over the mobile 'phone network. It must be noted that minimal information is transmitted back to base as the purpose of the Unit is not research driven but simply to answer the question '*Is the well working*?'

From the Pump-Count and other data the water flow and the well's health can be established. Deterioration in the well's output can be identified and targeted, remedial maintenance carried out to ensure the continued provision of hand-pumped water.

2. Self-Sustainability

Non-Government Organisations (NGO's) come and go for various reasons such as the project has been completed, further funds cannot be raised, lack of on the ground support and resources, NGO ceases operations. It is therefore vital that when any project is undertaken a primary goal is that whatever is delivered by an NGO becomes self-sustainable. In rural Tanzania, and probably in many rural areas of emerging third world countries, this is easier said than done, as inevitably it will involve a change in behaviour. The Eleanor Foundation (EF) is involved in a number of projects in Chato and Biharmulo in North West Tanzania.

To meet Sustainable Development Goal (SDG) 6 requires pumps and wells to remain functional and this means a support and oversight structure to achieve that. But, more than that, it needs from the very start, even before a well is built, the buy-in, commitment and understanding of the local community of the importance and responsibility for the upkeep of the well and the consequences if this does not happen. Otherwise the funds made available to build the well, supply the pump etc. will be ultimately wasted, the donors will have been let down (which will impact on future fund raising), a huge amount of time and effort will have been wasted to no avail but, worst of all, this will usually result in the community reverting to traditional water sources with all the associated issues.

The summary below are the steps taken by EF in its attempt to best achieve that self-sustainability goal.

2.1. *Local Authority participation*

Work with the local authority to select the communities with which to provide improved water source. This makes the community accountable not only to the NGO/provider of the well but also the local authority that proposed the well be built. It also vital to work with the water engineer from the local authority to site the well so that it is functional during the dry seasons.

2.2. Community Buy In/Commitment/Trust

Meet and discuss the community needs with the local authority and the senior members of the community. It is important that this includes women representatives of the community. Do not make a promise of the improved water source until the community show that (a) they are collecting funds for the maintenance of the well and (b) they have collected certain of the materials to build the well. Only then, and once tests have been undertaken on the siting of the well during a dry season, should the promise be made to deliver the well. The NGO must then stick to its promise. This is the start of getting the behavioural change required to make the project self-sustainable.

2.3. Community Ownership

Taking responsibility and having pride in their improved water source is hugely helped by having also invested time and money into the construction of the well.

2.4. Community water users committee

From the start insist on the set up of a water users committee which will be responsible for collecting funds to maintain the pump, well and immediate area around the well and overseeing the use of the pump daily. The committee must be made up of 6 men and 6 women. EF periodically inspect the records to ensure funds are being collected and meet with the committee.

2.5. Community maintenance of the pump

Fixing the pump themselves when things go wrong with tools and basic training provided by EF. This will build up experience and know how within the community, especially a rural community, (versus getting in a plumber/engineer who may live far away) and therefore problems have a chance of being fixed quicker and probably at less cost.

2.6. Monitoring and Oversight

Regular monitoring especially at the start of a project but also for several years after the well has been built is essential. Such monitoring needs to be frequent for the first 18 months reducing thereafter but should be not less than twice a year. However, as more wells are built and with the distances involved this becomes more challenging when, like EF, the NGO is trying to keep its cost of overheads and resources as low as possible. This is where a unit such as AWSOM^{TM} (A Well System for Ongoing Maintenance) will come into its own as that will help in ensuring wells remain functional and are inspected when needed. The AWSOM^{TM} unit will also encourage behavioural change as the EF experience is that communities do not like reporting problems, whatever these are. An AWSOM^{TM} unit will encourage the community to make those calls that they are currently reluctant to do as EF will know there is an issue and the community will learn to trust that making a fault report is not received as a significant issue.

If EF and other NGOs could receive a call the moment there is an issue with the well that causes it not to be used then, arguably, there would be no need for a monitoring unit (other than to get additional data such as temperature, water volumes etc.). This would release the unit for deployment to another area and another well where similar results might be achieved.

2.7. Recognition

Praise when things go as planned and a reprimand when the pump is not managed or looked after as agreed with the community, each action could come with rewards/incentives or consequences.

2.8 Time

For self-sustainability to be achieved there needs to be effective collaboration between the NGO, the local authority and the recipient community which also requires, in the long run, behavioural change to become self-sustainable at the community level. The lesson that must be learned by NGOs is that a project is never finished until there is no need to monitor and that could take many years but when reached everyone will be a winner.

3. Monitoring System Design Considerations

The current monitoring system has taken over two years to develop. This paper not only describes the successful version of the AWSOM^{TM} unit, the system currently being tested in the UK and Tanzania, but also the prototypes that failed. It has been stated that "*good decisions come from experience, and experience comes from bad decisions".* So in order to demonstrate what has been learnt over the past two years, outlines of the failed prototypes are also provided.

There were six main considerations for the well monitoring unit:

1. Safety (User & environment)
2. Simplicity
3. Affordability
4. Reliability
5. Maintainability
6. Repeatability

3.1. Safety

Safety was of paramount importance for both the users of the well and protection of the environment. The AWSOM^{TM} monitoring unit must not introduce or attract any toxins into the water or environment. As a result certain batteries (including lithium) were not considered appropriate. The battery chemistry selected was nickel metal hydride (NiMH) which was considered one of the "least worst" options as they are made of 'environmentally friendly materials[4].' In addition to the improved safety aspect of these batteries, they can go flat and still recover.

Inserting sensors into the water flow was also not considered safe as, apart from jamming, they would promote mould growth and infection could ensue.

3.2. Simplicity

Simple sensors available for use on the well were limited. Mechanical flow-meters were dismissed on safety and reliability grounds. Ultrasonic and thermal sensors were considered briefly and dismissed on cost grounds; accelerometers were considered and dismissed early on in the design stage as, at that time, their frequency response was limited. (<10kHz) and, on the direct action type of pumps, there is limited space and no lever to attach the unit to.

Initially, the aim was to interrogate the well by simply listening to it. Using a microphone met the non-invasive requirements too. Microphones are low cost and by using spectral analysis (of up to ten kilohertz) well health could be established. (In a similar way a skilled car mechanic can listen to a car engine and determine its health).

This approach was altered a year ago due to the complex and power-hungry spectrum analysis elements required. In its place a Doppler radar system was adopted. Using radar meant that it could penetrate most ABS housings and even some walls and it did not need attaching to any moving part of the well. The radar units used are only a few pounds, have a straight forward digitally processed output and have proved very successful.

3.3. Affordability

Affordability was also key. Many components were sourced from China. It was realised that this approach would impact the time taken to construct the units due to the lengthy delivery times (sometimes over twelve weeks). However, from the reliability point of view, these low-cost, long-lead-time components were tested and found to work over 97% of the time.

3.4. Reliability

Reliability was considered important when selecting the components and when considering the environment in which the well monitoring unit was to be used. Mechanical vibration, high levels of water and water vapour, ultra violet stress etc., when combined with the high temperatures in the monitoring unit’s environment, were amongst those considered key. A reliability design target of three years was considered achievable. The principal concerns being; electrolytic capacitors, the batteries, perceived fragility of the solar cells and the unit’s housing. However, even with standard commercial components, MTBF calculations demonstrated that three years between visits are achievable.

3.5. Maintainability

Maintainability of the unit was not considered an essential feature. It was expected that much of the unit would be disposable. This approach would keep the initial costs down and enable the strategy to be adopted that, when something went wrong, the unit would simply be replaced.

3.6. Repeatability

Repeatability of the units results was considered a significant factor. Repeatable data means more accurate decisions can be made. However, levels of data accuracy were not considered important. The precise volume of water that had been pumped in a particular period was of relatively low importance since the main consideration was to answer the question, *was the well working*? This approach enabled costs to be kept low and had a significant simplifying impact on systems design.

Several other aspects were considered including system ownership. Unless the maintenance system was adopted by the local community it would not be looked after. It is hoped that with the involvement of local management, combined with the straightforward point-and-shoot spreadsheet menu and the easy-to-use charts etc. ownership will be encouraged for the benefit of all.

4. Prototypes

Over the past two and a half years three different prototypes have been designed, made and tested. Each prototype is outlined below in terms of; ***Concept, Considerations*** and ***Conclusions***. The first two prototypes were technical successes but failed in the field. They are included here for completeness and, at the risk of ridicule, as potential learning points for others.

4.1. Prototype One

The concept was to use a microphone as the sensor. It was relatively straightforward to split the audio signal into frequency bands, compare the spectral output with the well’s pre-recorded spectral signature and determine the well’s output rate, performance and condition. This prototype (Fig.1) was designed, constructed and tested in twelve weeks. It performed well and gave the promise of Big-Data benefits downstream.

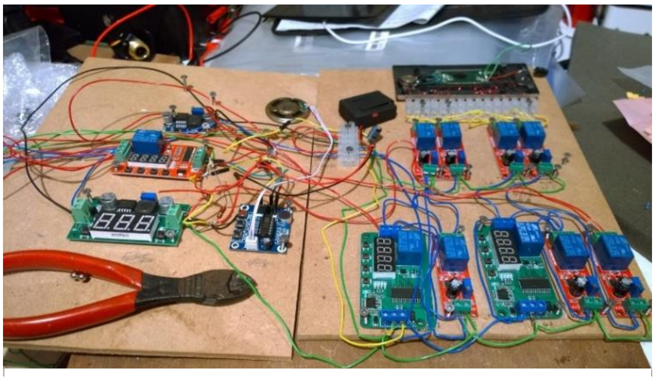

Fig. 1. *Prototype one*

However, although the concept of spectral analysis is, under certain circumstances, still considered a viable proposition, it was not appropriate in a rural environment owing to the high power consumption of the unit. The unit comprised of; four programmable logic controllers, seven momentary activated relay units, various filters, a talking calculator, three other active components, a phone module and just under a dozen passive components.

When specific frequency bands were detected the calculator added up the total time the well was used. When the output of the well was required, the well was ‘phoned and the user listened to the talking calculator. The user then transferred this ‘spoken’ number into a spreadsheet. The conclusions reached from prototype one were threefold:

(1) This prototype was produced quickly and worked well;

(2) Individual components and modules could be purchased at very low cost and,
(3) The power consumption of the unit was excessive (10Watts).

As a result of the power required, and as there is normally no significant power available in the proximity of the hand pumped wells, this implementation approach was abandoned.

4.2. Prototype Two

The concept here was to replace the previous prototype's logic boards with a couple of Arduino microcomputers (Fig.2). The microcomputers could be put to sleep when not in use which saved power. As not all members of the team had used Arduinos before there was a steep learning curve for some (including the authors). Also, due to the modular nature of the sub-components it was considered possible (erroneously) to avoid the expense of a printed circuit board (PCB) and wire these modules up locally.

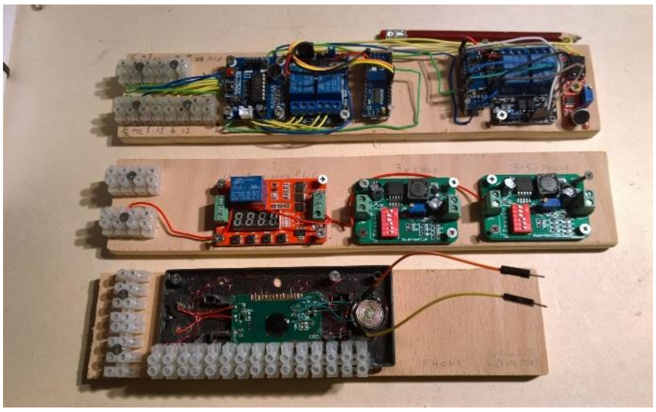

Fig. 2. *Prototype two*

The conclusions from prototype two were:
(1) This prototype took far longer to produce than planned (just over nine months).
(2) The power consumption was found to be still higher than expected at just under 5 Watts
(3) Small, spout-mounted solar cells could not supply the power required. Large solar cells would require a metal pole adjacent to the well, an armoured cable and modification to the well platform which was far in excess of budget.

As a result this approach was also abandoned.

4.3. Prototype Three

The concept in this prototype (Fig.3) was to transfer as much of the hardware as possible into software using the now ubiquitous Arduino microcomputer. When this type of microcomputer is put to sleep, the current consumption can be miniscule (<1mA). Also, the talking calculator was replaced as the Arduino sent a text message of the Pump-Count to a base station.

The technical team, coming from an avionics and radar background, preferred a Doppler radar unit as the main sensor over a microphone. Radar has no moving parts and should be reliable but possibly a bit complex and expensive?

The aim of the Doppler radar module was to detect well activity (Pump-Count). A suitable and highly innovative low cost (<$5) module was sourced and is now proving excellent. It contains few active components, even its PCB acts as a transmission line, feedback mechanism and part resonator for the radar. This module detects movement within an adjustable radius, sends a cleaned-up signal and, with a light dependent option, provides a time-period adjustable digital output.

The conclusions from prototype three are that:
(1) This prototype too took longer to make than expected (just over a year) but works perfectly.
(2) The postage stamp size micro-computer was low-cost, reliable and versatile and impressed the development team immensely.

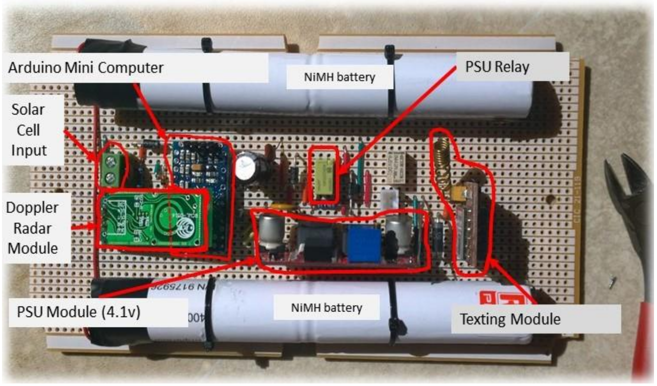

Fig. 3. *Prototype three*

(3) It was decided to take this route forward into the current field trials and develop system output charts and other displays.

5. System Output Charts

In order to answer the question, '*Is the well working?*' the *Helical Approach to Software Design*[5] was used where the starting point is the system outputs. Simulated required outputs were sketched (in PowerPoint) and by working 'backwards' it was possible to determine the inputs to achieve these outputs. Knowing the importance of the sustainability aspects, this led to the consideration of behavioural and ownership issues. As a result of these issues, specific charts were drafted, a selection are shown below.

System ownership can be enhanced if user input is collected and acted upon. The space under each individual well chart captures user comments. It is these comments that are used later in the recommended maintenance activities.

The following screen-shots are taken from the AWSOM™ spreadsheet. It is this spreadsheet that collects, collates and displays well data.

5.1. Typical Well Output Charts

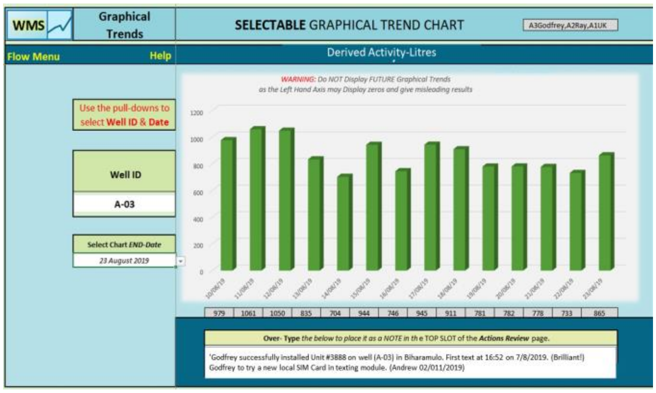

Fig. 4. *Well Performing as Expected*

Figure 4 is a two-week output chart from a well in Tanzania. After some initial output variability everything settled down and performed as expected.

Fig. 5. *This Well is Broken*

Figure 5 - This well is broken and has not been used for the past five and a half days. Further investigation is recommended. This issue must be noted by the User in the 'Enter Recommendations' area below the chart.

6. Well Output Summary

In addition to individual well trend charts above, well summary charts are also beneficial. The recognisable colours in Figure 6 indicate the spreadsheet's view of the state of the wells. This chart is parameter driven so it must be remembered that the traffic light system is for guidance only as there may be wells on the boundary that need attention.

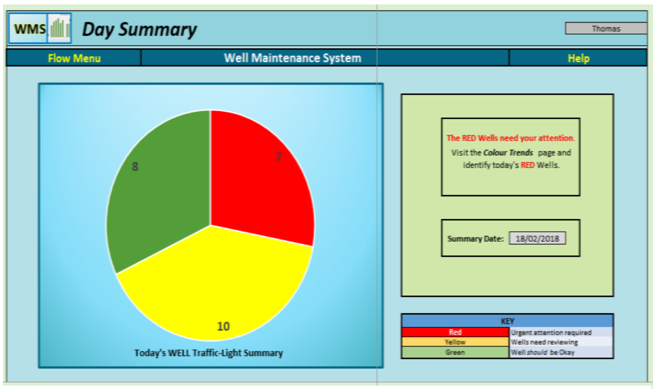

Fig. 6. *Triage pie-chart or Day Summary*

This triage pie-chart or Day Summary, (Fig. 6.) shows the output of all the wells for the day. In this case it shows that seven of the wells (in red) need urgent attention.

Another well summary chart is the Colour Trends chart (Figure 7). This shows a number of wells vertically, on the left hand side and their daily output for the past few weeks shown horizontally. This highlights the test wells that are, and have been, in trouble (Red) and others that are doing fine (Green) etc.

Fig. 7. *Colour Trends Chart*

An interesting example of further data analysis is the 'Traffic-Light-Video'. Here, time can be scrolled through day-by-day (i.e.: frame-by-frame) and the colours of the wells on a map over a wide geographic area change depending upon the date and in accordance with the Colour Trends Chart data. This enables wide-area analysis to be performed showing well colour changes that would otherwise be very difficult to identify directly from the raw spreadsheet. For example, is the water table level changing and sweeping down or across the country?

7. Spreadsheet Inputs

The spreadsheet collects and presents all the data from the wells. There are two principal inputs required on the spreadsheet, these are: a number which is received via the daily text message (the 'Pump-Count') and, the 'Recommended Actions' for each Well which is entered by the User.

The Pump-Count represents the amount of time the well has been active. It is this number that has to be entered (manually or automatically) into the AWSOM™ spreadsheet and then onto the website.

The Pump-Count is a measure of well activity in units of 30 seconds. This activity is a combination of each or any of the following; the water flowing from the spout, a water bucket being removed from under the spout, the pump handle moving up and down or the person themselves operating the pump handle. A calibration process on each well for men, women and children is available and recommended during system installation but is not essential.

8. Spreadsheet Navigation

The spreadsheet's tabs (or screens) are accessed using a game-like Point-and-Click Flow Menu, (Figure 8.) Here, the action of clicking on a green box takes the User to a screen of choice.

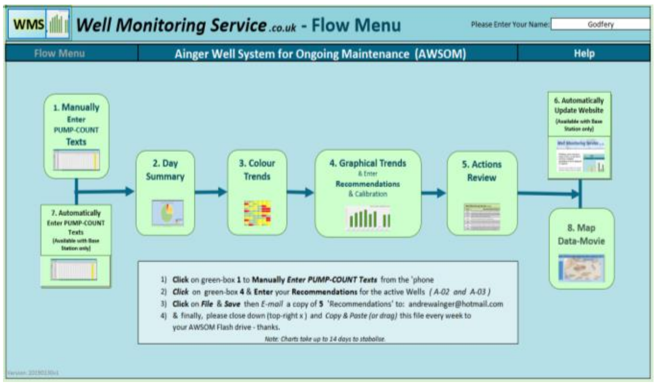

Fig. 8. *Spreadsheet Flow-Menu*

Although the boxes are normally clicked on from left-to-right, they can be clicked on at any time and in any order. Care should be taken when on the 'Manual Text Update' screen so as to avoid corrupting data. Making regular copies of the spreadsheet is recommended because of this and for when the PC's hard drive becomes corrupted.

9. How the Unit Works

The unit uses just four pre-built electronic modules, eight active devices and less than a dozen passive components, these are connected up as in Figure 10 below.

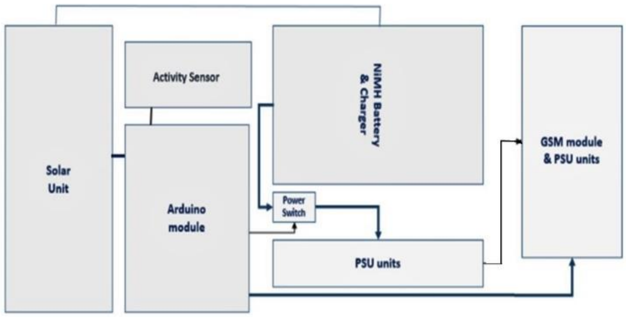

Fig. 9. *The Unit's Block Diagram*

The sun turns on the unit in the morning, the radar & mini-computer start counting the time (Pump-Count) the well is active. At dusk it sends the Pump-Count as a text to specified 'phones. The unit also sends the maximum temperature the unit has reached that day, the battery voltage at the time of the Text, the number of Work-Days the Unit has been in continuous operation and the number of main-loop cycles the mini-computer has gone through in collecting the data that day. The Unit then goes to sleep until it is woken up by the sun the next day.

The majority of the near thousand lines of (inefficient newbie) code was not in providing the main function of the unit. Most of the code (and some of the hardware) was involved in trapping and recovering from potential error events. For example, what happens when the solar cell voltage goes too high and starts to overcharge the batteries, what happens if the voltage gets too low, what happens if the solar cell output exceeds the 5.5v maximum input for the minicomputer, what happens if the regulator input voltage goes down to its critical self-oscillating voltage (3.8v), what happens if the microcomputer sends a text which is never received, how do you stop the unit from cooking in the African sun etc.? All this and more had to be taken into account in the hardware and software design.

10. Conclusion

Using the: seven-step self-sustainability criteria, a straightforward modular design and low cost electronic modules the system, after calibration, records and displays the amount of water pumped from individual, remote, rural hand-pumped water wells and answers the simple question, *"Is the well working"*. In addition, other data records the operational status of the AWSOM™ monitoring unit. This data results in a prioritised, targeted well maintenance schedule that provides improved Well up-time and water availability.

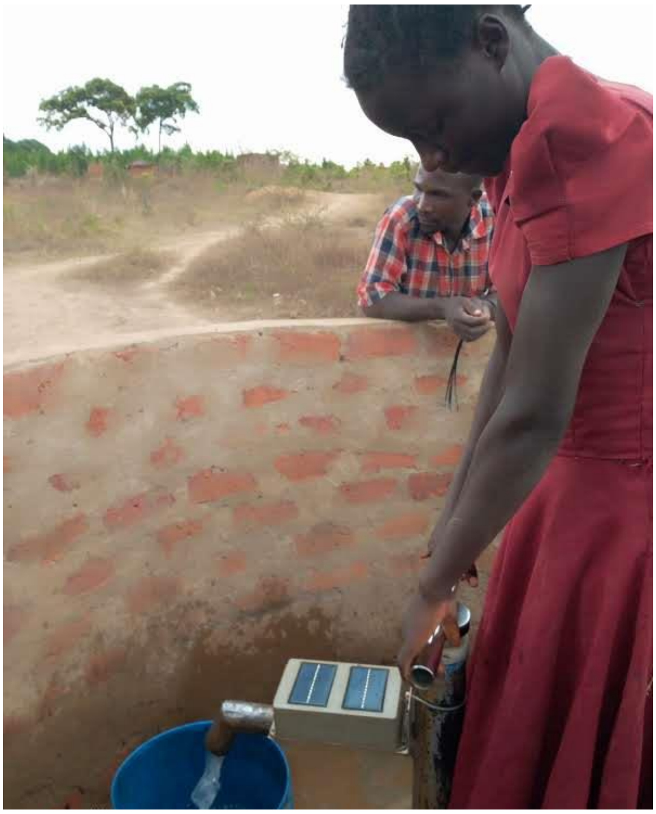

Fig. 10. *An AWSOM™ unit in Tanzania*

Post Script - Note

The challenge now is to construct several dozen of these units as the charity say they are needed for their other wells next year.

The development team are looking for volunteers to construct, contribute to and test more Units so, if you can help please contact us and we will forward the latest circuit diagram and the most up-to-date layout together with the Arduino software, all for free.

We will also send a well serial number plate for Your AWSOM™ unit so that credit for it can be attributed to yourself. You will be able to follow your Well Monitoring Unit's progress on the web.

11. Acknowledgments

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- Brian Skinner (Loughborough University)
- Maurice Smith MBE
- Rob Stratford
- Peter Jennings
- Bob Harry
- Graham Struthers

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