GSM-enabled remote monitoring of rural handpumps: a proof-of-concept study

Patrick Thomson, Rob Hope and Tim Foster

ABSTRACT

The continued expansion of mobile network coverage in rural Africa provides an opportunity for simple and low-cost hydroinformatic innovations to measure and transmit data on handpump use for policy and management improvements. We design, build and test a Waterpoint Data Transmitter to determine its robustness, functionality and scalability. Results demonstrate that this novel application using simple microprocessor, accelerometer and global system for mobile communications (GSM) components has significant potential in recording graduated time-step information flows of lever pumps which can be modelled into a reasonable water volume use approximation. Given the systemic informational deficit for rural waterpoints in Africa, where one in three handpumps is likely to be non-functioning, this innovation has the potential to provide universal, low-cost and immediate data to guide timely maintenance responses and planning decisions, as well as drive greater accountability and transparency in donor and government behaviour.

Key words | development, GSM, pump, sustainability, technology, water

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INTRODUCTION

Handpumps have been a key technology for accessing groundwater for decades. Given the importance of groundwater as a safe and reliable source of water for the world's rural poor (MacDonald & Calow 2009) significant levels of effort and investment have gone into understanding and improving handpump technology (Arlosoroff *et al.* 1987). However, despite their relative simplicity, the sustainable operation and maintenance of these pumps is an enduring challenge. It is estimated that across Africa around one in three handpumps are non-functioning at any given moment (RWSN 2010). However, there is lack of reliable and up-to-date information about rural water access (Jiménez & Pérez-Foguet 2010), and without widely available information on the status of pumps, operations and maintenance (O&M) is invariably conducted by local communities who face challenges with achieving economies of scale and a lack of technical and managerial expertise (Harvey & Reed 2006; Carter 2009).

Mobile phone coverage is now reaching rural areas that have to date enjoyed few other services (e.g. grid electricity or piped water supply). It is estimated that in 2012 more people in sub-Saharan Africa will have access to the mobile phone network than have access to improved water supplies (Hope *et al.* 2011). In many low to middle income countries, mobile voice and data networks are a key transforming technology, as they leapfrog past the traditional landline networks enjoyed elsewhere. There is innovation at all levels, from mobile phone charging with bicycle dynamos where there is no electricity supply, to mobile banking and payment services which has the potential to reach a vast segment of the population currently not served by traditional banks. Hope *et al.* (2011, p. 10) identify the increased mobile phone network penetration into rural areas as providing a 'platform for innovative technical, financial, and institutional solutions' to enable new management models for rural water services and enable effective regulatory oversight, through the provision of accurate and timely data about rural water use.

Telemetry has long been used in the water sector, for remotely monitoring river flows or reservoir level to aid

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water resources management or assist in flood early warnings. However, it has not been used before for monitoring handpump usage. This is partly due to there not having been a perceived need for metering in this context and partly due to the unsuitability of existing technology. Direct flow measurement devices are not designed to operate with handpumps, whose output is of low and varying pressure, through a relatively wide aperture. Attaching such a device directly to a handpump outlet would restrict the output, and thus raises issues for use-acceptability. Additionally, existing smart meters are relatively high cost in comparison to the cost of a typical handpump. The increasing global system for mobile communications (GSM) coverage of rural communities, along with the ever decreasing cost of electronic components, increasing energy efficiency and improving battery technology, also driven by the mobile phone sector, enables the use of telemetry to be investigated in this context.

This paper reports on the design and testing of a new Waterpoint Data Transmitter (WDT) that can provide reliable real-time data on handpump usage to address this information deficit. Using a low cost integrated-circuit (IC) based accelerometer, the WDT automatically monitors the number of strokes made in operating a handpump, and then transmits this information over the GSM network. This provides volumetric output estimates that can show daily to seasonal demand levels, including critical under- or over-usage information to inform repairs or to justify further investments. Information on rural water usage patterns can inform water supply infrastructure planning. The initial trials of the device, outlined in this paper, were conducted in Lusaka, Zambia, in July 2011 on India Mk.2 handpumps. The aim was to demonstrate proof-of-concept in a real environment, rather than conduct rigorous trials in a controlled laboratory environment.

METHODS

Waterpoint Data Transmitter

The WDT, the prototype of which is discussed in this paper, aims to be a robust, low-cost and scalable technology, and all design decisions were made with these three characteristics in mind. The WDT is attached to the handle of a handpump and consists of three essential elements: (a) an IC-based accelerometer; (b) a microprocessor; (c) a GSM modem. Elements were chosen on a criteria of ease of use for prototyping rather than optimal performance.

The use of an accelerometer to measure handle movement was chosen for a number of reasons. First, given the number of handpumps in use across the world, a design that could be easily retrofitted to existing in-service pumps and that (other than adding insignificant extra weight to the handle) did not interfere with the pump in any way was essential. This also has advantages at the prototyping and test stages. Second, by using a solid-state IC there are no moving parts, which should increase reliability over other options (e.g. direct water flow or handle movement measurement).

The accelerometer used is similar to those found in high-end mobile devices or certain games console controllers. In this case an Analog Devices ADXL335 was used. The accelerometer senses movement in X, Y and Z planes and produces three analogue outputs proportional to the acceleration sensed along that axis. The ADXL is capable of sensing $\pm 3\ \boldsymbol{g}$ which was deemed to be sufficient for the purposes of the WDT. The analogue output from the ADXL335 was filtered by a simple resistor–capacitor (RC) filter implemented in hardware to reduce the bandwidth of the signal reaching the microprocessor. This was to reduce any high frequency acceleration noise that could confound the tilt calculation while not being relevant to the measurement of pump handle movement. The −3dB frequency of this filter was 2.17 Hz, which is approximately four times the observed fundamental.

The microprocessor for signal processing and control was an ARM mbed (www.mbed.org). This is a generic prototyping platform and was chosen for ease of use during prototyping and field testing. It should be noted that this unit is significantly over-specified for this application. The processor takes the acceleration data from the accelerometer and calculates a pump handle tilt angle. This tilt angle is then monitored to produce a count of the number of times the pump handle has moved over a given time period and an estimate of the volume of water abstracted. This information is periodically sent as a short message service (SMS) message via the GSM modem. The GSM modem accepts standard AT commands from the microprocessor to send out periodic SMS messages. The test setup had the WDT sending messages to a recipient mobile phone once per minute. A full implementation of this system would involve a data terminal with a bespoke user interface and could use either SMS or global packet radio service (GPRS) data transmission protocols, sending data at the rate deemed most effective in terms of the trade-off between currency of data and cost of transmission.

Experimental setup and initial testing

Initial testing to characterise the pump and develop the algorithm was conducted on a pump owned by Geotech Ltd in Lusaka, Zambia, to which we were given unrestricted access. The WDT was strapped onto a pump handle towards the fulcrum to reduce distortion and to keep it from interfering with the users. The accelerometer within the WDT was approximately 30 cm from the fulcrum. To aid analysis a Nintendo Wii Remote (a.k.a. Wiimote) was also attached to the pump handle along with the WDT prototype (see Figure 1). The WDT sent periodic data to a mobile phone via SMS and the Wiimote sent real-time acceleration data via a Bluetooth link to a nearby PC. The raw acceleration data from the Wiimote were captured using freeware called g-force analyser.

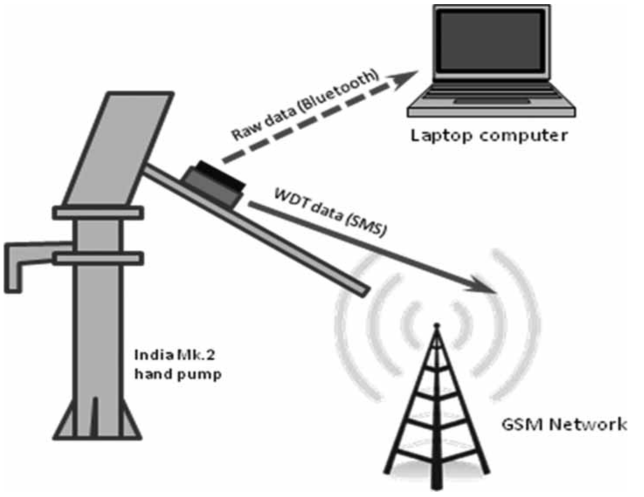

Figure 1 | Experimental setup with the prototype WDT and Wiimote attached to an India Mk.2 pump.

The basis of the WDT algorithm is that the tilt angle of a body with respect to the Earth's surface can be derived from the ratio of the acceleration component on each axis due to gravity according to the simple equation (illustrated in Figure 2):

$$\frac{A_x}{A_y} = \tan\theta \tag{1}$$

This is only valid for an object at rest. When the object is moving, there are other acceleration components that act on the body and confound the calculation of tilt (see Figure 3). In the case at hand, where the accelerometer mounted with its *x*-axis along the pump handle and its *y*-axis along the axis of handle rotation the acceleration components would be:

$$\begin{aligned} A_x &= g\sin\theta + r\omega^2 \\ A_y &= g\cos\theta - r\frac{\mathrm{d}\omega}{\mathrm{d}t} \end{aligned} \tag{2}$$

(The sign change arises due to the frame of reference of the inner workings of the accelerometer.)

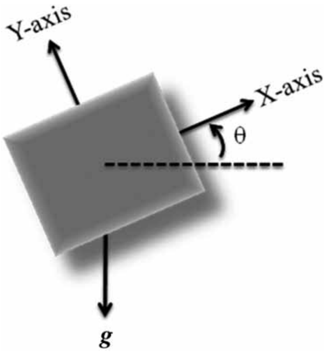

Figure 2 | Gravity components acting on *X* and *Y* axes of a static body.

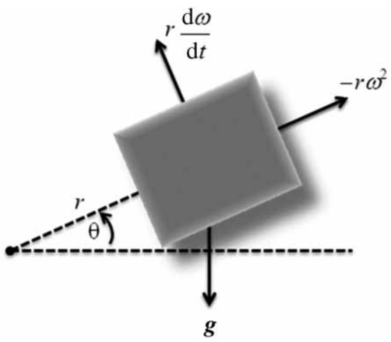

Figure 3 | Acceleration components acting on body rotating at distance *r* from a fulcrum.

These additional components will result in an erroneous reading for the tilt angle. As the measurement of tilt angle is being calculated in order to derive the number of strokes the pump makes and the water output, rather than because the tilt angle itself is of any interest, systematic errors such as this do not pose a problem if the apparent angle calculated is still useful. Figure 4 shows the theoretical relationship between the actual pump handle tilt for a moving handle and the tilt angle that would be calculated using the simple Equation (1). This is calculated for simplified but representative conditions: (a) a pump handle deviation of ±25° centred around the horizontal, (b) a sinusoidal pumping action at a frequency of 0.5 Hz, (c) an accelerometer 30 cm from the pump handle fulcrum. For these conditions the error term is not large enough to negate the usefulness of the simple tilt equation. However, if the pump were to be operated at a much higher rate than that typically observed for normal use, or if the accelerometer were to be positioned at the end of the handle, the apparent and actual tilts start to diverge significantly.

The WDT was programmed to increment a counter if the pump handle passed fully through a band between plus 15° and minus 15°, a range chosen to distinguish between meaningful use of the pump and, say, a child playing with it. A test bucket of a nominal 20 l capacity was used for testing, as this is the type and size of receptacle most often used for drawing and transporting water from a handpump. Twenty seven test runs were made to fill this bucket, for which the following information captured:

- number of strokes made (observed);
- time taken to abstract 20 l (observed);
- pumping characteristic, e.g. fast, slow, full stroke, half stroke (observed);
- WDT stroke count (mobile phone);
- raw acceleration data (Wiimote/PC).

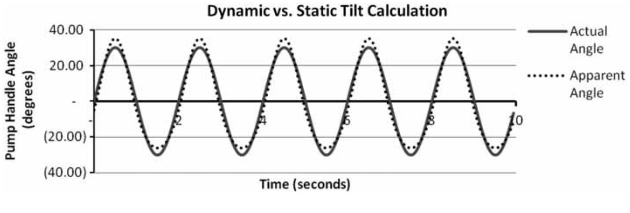

Figure 4 | Calculated tilt angle of a moving pump handle if assumed to be static.

The raw acceleration data captured by the Wiimote were analysed to see how the calculated tilt varied during pumping. Figure 5 shows raw data from a typical 20 l run calculated using Equation (1). These initial tests demonstrated that the simple algorithm counting the number of strokes worked for a typical pumping technique, but that it had limitations. A 20 l bucket could be filled in a number of ways, ranging from under 50 full strokes to over 200 very small strokes, with typical pumping being between 60 and 100 strokes. Speed had little effect on output, although very fast pumping could cause leakage through the casing as the pump was overpressured. Users settled on a natural tempo of around 0.5 Hz.

These data were also examined in the frequency domain using a Fast Fourier Transform. Figure 6 shows plot for both an experienced user with clear peaks at the fundamental of around 0.5 Hz and second and third harmonics, and for a novice user showing much noisier data with an identifiable, but less precise, fundamental frequency and smeared harmonics.

In order to estimate the volume of water abstracted by the pump the relationship between stroke length and number of strokes needed to be captured. What was also clear was that a simple product of the stroke length and the number of strokes would not produce an accurate measure of the volume abstracted with observation suggesting a 'sweet spot' below the horizontal where a give range of handle movement produced the greatest output of water. The gold-plated solution would be to characterise the contribution to output for the full range of pump movement and then programme the WDT to integrate this over the measured movement, thereby producing a measure of volume that would continually increment. To do this in a non-laboratory environment

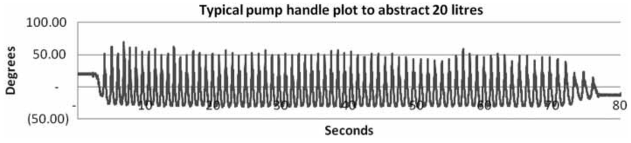

Figure 5 | Typical variation in pump handle tilt angle for an experienced pump user to abstract 20 litres.

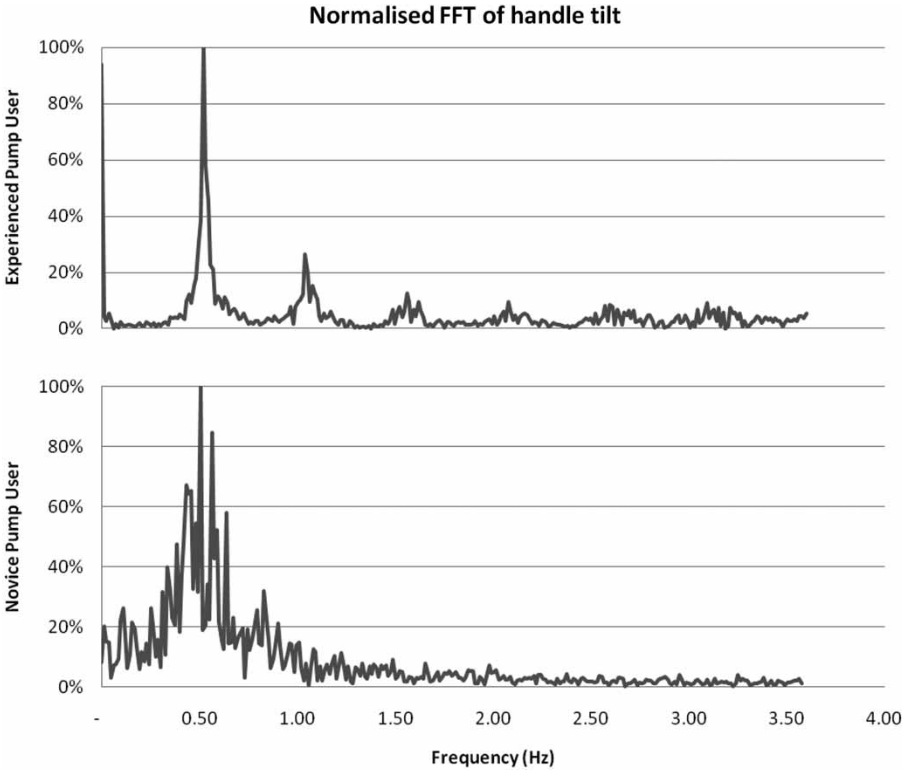

Figure 6 | Frequency domain plot of 20-litre abstraction, comparing a novice and an experienced user.

would be challenging. Even if such rigour resulted in a corresponding high level of accuracy, it would produce an estimate of volume unnecessarily precise for the task at hand given all the other factors affecting the volumetric output from a specific pump. It would also require all the computational effort to be made by the WDT and takes no account for variation between nominally identical pumps due to exogenous factors, e.g. borehole characteristics, and wear and tear over time.

Keeping in mind the cost of data transmission (both network charges and power) precludes continuous data transmission, a method that allows a degree of post-processing is preferable. This would allow for offline calibration without having to change the software in the WDT, and potentially enable an identical unit to be used for different pump types. Based on these considerations and understanding gained from pumping and observing pumping, the single $\pm 15^\circ$ window algorithm was changed to count the movement through four overlapping windows. The WDT would then transmit the four scores from each window, allowing weightings for calculating volume to be made at the data centre. The windows chosen were:

W_1 (High) 14° to -1°
W_2 (Upper Mid) 6° to -9°
W_3 (Lower Mid) -2° to -17°
W_4 (Low) -10° to -25°.

These windows were biased below the horizontal to reflect the observed pumping action, with the very high apparent excursions above the horizontal discounted on the grounds that they were quite dependent on pumping technique and movement here did not contribute to water output. They were overlapping due to the fact that to 'score' the pump handle would have to pass through the entire range of a window, not just into or out of a window. For example, if the pump handle moved consistently between -25° and $+5^\circ$, a range that would produce a significant output of water, only the WDT would only register a score for W_3 and not for either of W_2 or W_4.

While these windows did not cover all *possible* stroke ranges they did cover all *likely* stroke ranges observed under normal use. Another 14 test buckets of 20 l were filled, with the WDT transmitting the four counts from each run to a mobile phone. These were then analysed in order to derive the relative weightings for each window. The weightings *a, b, c, d* were calculated so as the minimise the average deviation of each volume from 20 l:

$$\begin{aligned} aW_{1,1} + bW_{2,1} + cW_{3,1} + dW_{4,1} &= \text{Volume}_1 \\ aW_{1,2} + bW_{2,2} + cW_{3,2} + dW_{4,2} &= \text{Volume}_2 \text{ etc. } \ldots \end{aligned} \tag{3}$$

The weights were calculated using MS Excel's Solver function. An additional simplified weighting was calculated. The results are given in Table 1. The higher weighting of the lower middle window corresponded with the observed 'sweet spot'. The WDT was programmed to transmit an estimate of volume based on the simplified weightings to act as a sanity check during testing, as live post-processing was not possible given the simple test setup being used. Future testing will review the number and range of the windows used.

Live testing

Live testing took place in the Valley View community in north-west Lusaka using three different pumps (located at 35L 647676E 8296299S, 35L 647651E 8296738S, and 35L 647943E 8297714S). These pumps had been installed by Geotech approximately 2 years previously and were managed by a Community Water Committee with water being charged at around USD0.02 per 20 l container (100 kwatcha at an exchange rate of 4,800 ZMK:USD). These water fees are used to pay the pump attendant and fund maintenance and repairs. The pumps were generally used between 06h00 and 12h00 and 13h00 and 18h00. Outside these times and when there was a breakage the pumps were padlocked shut. The pumps had been in constant use since they were installed, and were the main, but not exclusive, water source for the communities around them. No direct data were available for how many people or families each of these pumps served, but records kept by the community water committee for one of the pumps indicated that in 2010 it had abstracted around 1,050 m^3 of water. The boreholes had been drilled to 60 m, the pumps were at 30 m and the static levels of each pump varied from 6 to 18 m. The concrete apron around the pumps and the drainage channels were not very well maintained, and the pumps themselves were in a state consistent with usage record by the water committee.

Table 1 | The pump movement weightings corresponding to a 20-litre output

Window	Range	Solver weight	(Ratio)	Hand weight	(Ratio)
W_1	14° to –1°	0.0745	1.1	0.067	1
W_2	6° to –9°	0.0250	0.4	0.067	1
W_3	–2° to –17°	0.1636	2.3	0.133	2
W_4	–10° to –25°	0.0701	1	0.067	1

For the live testing the WDT data (four 'window' scores and volume estimate) were recorded automatically as they were received on a mobile phone and the Wiimote recorded the raw acceleration data. Figure 7 shows both the Wiimote and WDT attached to the pump. The timings for each 20 l bucket and the person who had pumped were recorded by hand. A few problems were encountered with the electronic data capture, but none that caused substantive difficulties. The mobile network occasionally dropped out, causing some accumulation of the SMS data and for SMSs to arrive in the wrong order, both issues that could be resolved at the data analysis stage. The link between the Wiimote and the PC dropped out from time to time, resulting in gaps in the raw data stream, but as this was a secondary data source, not critical to the study, this was not a problem.

Testing took place with the support of the Community Water Committee and with the consent of the pump users. In order to generate data that were as representative of

Figure 7 | Photo of experimental setup on India Mk.2 at pump #3 (Tim Foster).

normal use as possible we did not try to influence who used the pump. The only request made was that users abstracted water in discrete 20 l volumes rather than mixing different container sizes. Initially, our presence generated a certain level of interest, and it became obvious that a handful of the pump users (men and teenagers) rarely used handpumps, if at all. However, initial crowds soon dissipated and our presence seemed to be of less interest.

By chance the second pump/borehole tested was faulty, with much greater effort required to pump out a given volume of water than usual. The two sections of the borehole casing had become detached so water was leaking back into the aquifer above the pump cylinder. However, during the time we were at Valley View this was repaired, enabling us to return for a before and after comparison.

RESULTS AND ANALYSIS

Data were collected over 4 days for three pumps as summarised in Table 2. The filling of 214 nominal 20 l buckets was recorded amounting to 4,280 l. Out of a total of 76 different people who used the pumps to abstract this water, 35% were women, 23% boys, 22% men and 20% girls. As people were not individually identified some of the users at pump #2 may have been the same on different days.

Figures 8 to 12 show how the observed output (as measured by counting nominal 20 l buckets) and the output calculated from the four WDT window values (using the four weightings calculated in MS Excel) tracked over the observed period. Figures 8 and 9 show the data for pumps #1 and #3, respectively. These pumps were in good working order with no observable difference between them and the pump used for the initial testing and

Table 2 | Summary of data collection (data collection was stopped early on 16/7/11 due to low pump use)

Date	Pump	Start time	Duration	Litres	Users
13/7/11	#1	09h35	2hrs	1,180	19
13/7/11	#2 (leaking)	12h25	2hrs	680	17
15/7/11	#3	09h30	1hr	800	14
16/7/11	#2	13h50	45min	500	5
19/7/11	#2	09h00	1hr 45mins	1,120	21

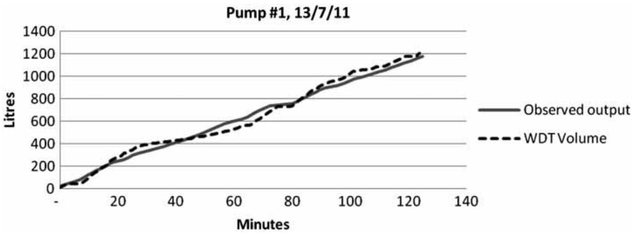

Figure 8 | WDT broadly tracks observed output over time.

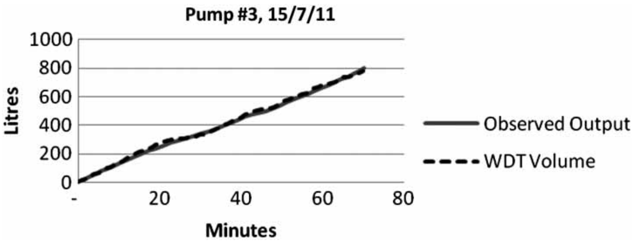

Figure 9 | More accurate tracking on third pump.

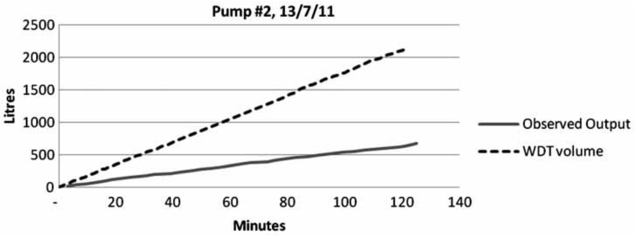

Figure 10 | Second pump before repair.

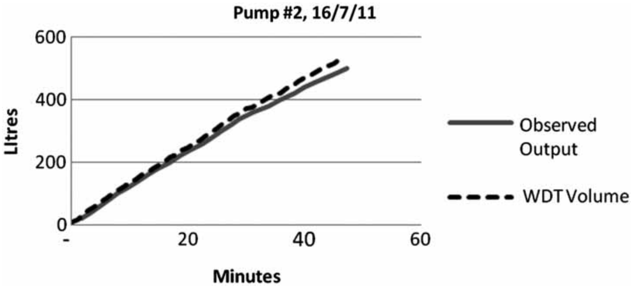

Figure 11 | Second pump after repair (mainly men using it).

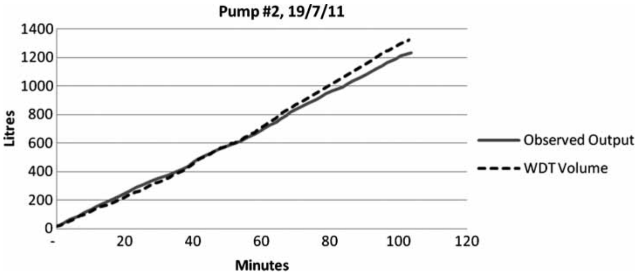

Figure 12 | Second pump after repair (mainly women – observed output adjusted for spillage).

algorithm generation, other than more wear and tear as they served a larger community. The WDT calculation tracks the observed output well over time, with the cumulative percentage error over the test runs being under 10%. To a certain extent this is down to the luck of when the test was stopped but an accuracy of the order of 10% is acceptable given the errors associated with the exact level to which buckets are filled and the spillage from buckets. It is also noticeable from looking at the raw data that periods when the WDT volume calculation and the observed output deviate significantly are associated with prolonged use of the pump by a certain category of user. For example, for pump #1 the first 30 min saw the pump being used by men, during which the WDT overestimated the volume of water produced. During the second 30 min the pump was used by boys and the WDT underestimated the pump output. Similarly, for pump #3 the first 15 min of user were by men, and the period from 20 to 30 min the pump was being used by girls. Over time, on the assumption that the WDT weightings have been generated from a representative range of users, these variations will average out: an operational system would be more likely to report data every hour rather than every minute, so these subtleties/errors would not be captured.

The data from pump #2 tell a slightly different story. Observation of pump #2 on 13/7/11 suggested a serious mechanical fault. A lot more effort was required by users to abstract water and a period with no pumping during the changeover between users of around 10 seconds would require around 20 strokes of pump priming before water was flowing again. This was in contrast to pump #1 where such priming required only one or two strokes. Figure 10 shows the difference between the WDT calculation and the observed output, suggesting that over three times the effort was required to abstract water in comparison to pump #1. Observing those doing the pumping and looking at the shape of the graph of observed output, also indicates a greater consistency of pumping technique in comparison to other pumps. This would indicate that as the effort required to get water increases, people take more care to expend energy in the most efficient way. This coincides with the observation in the 1987 World Bank Report on Hand Pumps that users are more interested in discharge rate rather than discharge with respect to effort, but only up to a point. In the case of a properly functioning India Mk.2 people adopt the technique they are most comfortable with, but in this case deviation from the most efficient technique bears a heavy cost, leading to convergence.

Figures 11 and 12 show the situation following the repair to the borehole casing. These both show a similar drift between the WDT calculation and the observed value of just under 10%. Given the lower proportion of male users, for whom the WDT tends to overestimate the output, it seemed that even following the repair there was some characteristic of pump #2, either the borehole or the pump itself that is different from pumps #1 and #3 leading to a systematic error. The static level of borehole #2 was stated to be 16 m when drilled in 2009, whereas that of borehole #1 was 6 m (borehole #3 not known), which would make a difference when initially priming the pump, and if the seals were leaking. Unfortunately, because the pumps were in constant use it was not feasible to conduct a proper test to compare priming/leakage between the three pumps.

What these differences do show is that to produce accurate data on pumped water volumes with the WDT, each pump/borehole combination needs to be characterised to generate the correct weightings. Depending on usage patterns and static level, the initial priming of the pump after a long break may be a greater or lesser issue. In the case of the pumps on which these tests were conducted, with their high usage levels, the number of times the pump will have to be primed each day in proportion to its total use will be quite low. For a pump supporting a smaller population with a deeper static level, priming will be a significant factor. Common to all pumps, however, will be the issue of leakage due to worn parts or poorly aligned casings.

The original thinking behind the WDT was that non-functioning pumps could be identified when their usage dropped from a normal level to near zero. What the problem encountered with pump #2 illustrates is that it may also be possible to identify another pump failure mode. If the apparent volume of water starts to deviate significantly from previously observed patterns or levels, this may indicate an issue with the borehole casing or another issue that similarly affects pump performance. A slowly increasing apparent volume may also indicate a problem with the pump. There are numerous exogenous factors that could also result in such an increase, for example an increasing number of people using the pump in question due to the failure of another water source, or a dry spell that requires more abstraction for non-domestic purposes. Looking only at data from one unit in isolation it would be very difficult to determine the exact cause, but with scale and time, temporal and longitudinal comparisons could be made that will reveal more.

APPLICATION AND IMPACT

The shift towards community participation and management in rural water supply from the late 1970s onwards was part of a wider demand-responsive approach (DRA) promoted by the World Bank in response to the weak sustainability of government water programmes (Kleemeier 2000). The World Bank emphasised the importance of community involvement at all stages of the design, delivery and maintenance of rural water projects, with handpumps considered suitable for Village Level Operations & Maintenance (VLOM) (Arlosoroff *et al.* 1987). Over time, the community water management model 'steadily gain[ed] the status of received wisdom' (Kleemeier 2000, p. 931). However, with one in three handpumps not functioning at one time in Africa, there is increasing demand for a more sustainable approach, particularly to know where and when handpumps fail to avoid the significant health, income and welfare costs for rural residents living in remote areas (Harvey 2007; RWSN 2010; Hope *et al.* 2012).

Studies have found that users are generally able to repair minor faults but struggle with major breakdowns and preventative maintenance (e.g. Kleemeier 2000; Gibson 2010; RWSN 2010). Having a handpump with a low failure rate and low-cost spare parts is of little relevance if specialist training and equipment is required to repair them. For example, it is unrealistic to expect an individual village, especially one with no electricity, to have access to welding equipment and an experienced welder (Gibson 2010). Even in cases where the community is able to undertake most repairs, the spare parts may not be readily available. In sparsely populated areas with low pump densities this it very difficult to sustain a spare parts supply chain run on a commercial basis (Harvey 2005, 2007; Harvey & Reed 2006). The level of spares required to be kept in stock to guarantee the quick provision of any spare to the pump in need is very high in relation to the turnover of parts. For an India Mark 2 it is estimated that on average one part is replaced each year (Arlosoroff *et al.* 1987). Harvey & Reed (2006) estimate that the profit per part for a typical handpump is around USD1.

In response to these challenges there is increasing interest in investigating professionally-oriented models for water service provision (Harvey 2005; Kleemeier 2006). There is potential for more clearly defined O&M responsibilities and potential for economies of scale and risk pooling. Harvey & Reed (2006) also suggest that private involvement is service provision as well as parts supply will allow for greater revenue generation and thus be a more sustainable business than spare parts provision alone. Carter (2009) argues that rural water services should more closely resemble urban services which are run professionally with a larger user base over which to spread cost and risk. He states that there is a need for 'rural utilities' or service providers with a strong customer and performance-orientation, with local government taking a regulator role.

Reliable and frequent flows of information are required for both the efficient running of a professional O&M regime and its effective oversight by a regulatory body. A private maintenance contractor who is maintaining a portfolio of handpumps in a number of villages may achieve the economies of scale that Harvey (2005) promotes, but will not be co-located with the handpumps and users it serves. Without information on handpump performance and failure a reliable, timely and efficient system to repair and maintain pumps is impossible. If no information is available, scheduled maintenance is possible but timely response to breakdowns is not. If repairs are only undertaken when faults are reported by users or village water committees, the system has a chance of working, but only in the case of a well-organised water committee and a motivated contractor. The WDT described in this article can provide this information. As well as providing timely and unambiguous data on the non-functioning of a pump which can be swiftly acted upon, analysis of recent historical usage data may provide some indication of the nature of the failure and thus speed up the repair cycle.

With identical handpump performance data being sent to those responsible for regulation and oversight, 'enforceable operation standards' become possible (Montgomery *et al.* 2009, p. 1021). When handpump performance data are held at an appropriate and competent institutional level it is then feasible in an accountable and transparent process to sub-contract the O&M of a network of rural handpumps to a private contractor. Information on the failure of pumps and the speed of repair will be immediately available via a simple computer interface, allowing a level of oversight previously impossible and without the need to be co-located with the sub-contractor or undertake regular costly field visits. This could enable performance incentives and penalty clauses to be built into contracts, leading to improving levels of service and reduced pump down-time. Such transparent performance reporting will hold maintenance providers to account, and develop performance benchmarks that are currently absent from the rural sector. There are equivalent benefits in the case where rural water service provision continues to be implemented by government. The government ministry or department responsible will have the ability to monitor the effectiveness of delivery by local government agencies, with the potential to benchmark performance between regions or districts.

The WDT will also provide a rich source of data on historical usage levels and patterns. This can inform future investment and resource planning decisions as it will be possible to differentiate between heavily used and lightly used pumps, between those which break regularly and those which are more reliable. Limited resources can then be better targeted at those areas most in need, instead of relying on proxy measures for use such as population size, or having decisions heavily influenced by local politics.

CONCLUSIONS

The results of this trial indicate that the real-time monitoring of rural handpump functionality is possible. This has the potential to bridge the information gap that currently hinders efforts to efficiently maintain rural handpump networks, and enable new O&M models to be investigated. A unit based around low-cost IC-based accelerometers and off-the-shelf GSM technology can monitor handpump usage and produce a useful, if imperfect, estimate of water abstraction. Four main challenges remain, which must be addressed before any comment about the larger-scale viability of the concept can be made.

First, the prototype was tested on only one type of pump, and the test pumps were all of similar age/condition and in a similar environment. Given the time constraints of this study this was the best approach. The system has been designed to be compatible with any lever-action handpump, with only offline calibration required for use with different pump types. However, further tests must be conducted on a wider range of pumps and boreholes to confirm that this is the case in practice.

Second, the issues for pump-priming and leakage will confound the volume calculation algorithm under its current implementation. (Simple spectral analysis of the signal produced when the pump is being primed and when it is producing water did not reveal any noticeable differences.) While requiring a more invasive approach to the pump, the integration of a water flow or temperature sensor would help resolve this problem, and provide the additional possibility of being able to monitor changes in the static level of the borehole in question.

Third, the battery life of the prototype was acceptable for these tests (of the order of a day). It used a highly over-specified processor whose current consumption was correspondingly high, and transmitted data more often than a production unit would be expected to. Nonetheless, power consumption remains the biggest technical challenge to be overcome before a viable production unit is possible. The options of solar power and using the kinetic energy of the handle movement should be investigated.

Finally, environmental durability and user acceptability must be considered. Any operational implementation has to acknowledge the possibility of children playing with footballs near water points and other day-to-day hazards. While a new iteration of the design that can be fitted *within* the pump is being developed, this is not simply an issue of product design. An item such as this is at risk of vandalism and theft if long-term user acceptability is not ensured in the design and implementation of the service delivery model. The residents of Valley View were gracious hosts and happy to assist in this study; however, no assessment was made of the consequences of having a WDT permanently attached to a pump in a less accommodating place.

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