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821
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Field testing a remote monitoring system for hand water pumps

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Abstract

Throughout Africa, many hand water pumps malfunction and remain inoperable for long periods of time. Previous studies from a number of sub-Saharan countries have indicated that in some regions up to 65% of hand pumps may be broken. It is reported that robust monitoring of remote water pumps can help address some of these problems. However, traditional project monitoring strategies generally rely on physical site visits to remote locations. These visits can be time consuming and resource intensive, which in turn may delay the implementation of pump repairs. In contrast, recent years have seen the emergence of a range of new monitoring technologies that use mobile phone networks to rapidly report the operational status of water projects from remote sites. The authors describe the development of a new monitoring system, called MANTIS, which is intended for hand pumps in developing regions. The paper presents data from early field trials of MANTIS in Sierra Leone and The Gambia. The unit relays 'near real time' operational data from the water pump to an accessible online platform.

Key words: broken water pumps, remote sensing, telemetry

INTRODUCTION

Sustainable Development Goal 6/access to safe water

It is reported that approximately 768 million people in developing regions lack sustainable access to safe drinking water (WHO-UNICEF 2013). Poor access to safe water contributes to a significant level of preventable disease and death. The Sustainable Development Goals (SDGs), introduced by UN member states in 2015, cover a range of developmental targets, including ending poverty and hunger, and improving health and education (UN 2015). Sustainable Development Goal 6 (SDG6) specifically addresses access to clean water and sanitation, and aims to ensure universal access to safe and affordable drinking water by 2030. The SDGs seek to build upon progress made towards the Millennium Development Goals (MDGs). The MDGs were a previous set of development targets adopted by the UN in 2000. These included target 7.C to 'halve, by 2015, the proportion of people without sustainable access to safe drinking water' (UN 2008). Despite recent progress, including the achievement of MDG target 7.C, many sub-Saharan Africans still lack access to improved water sources. For instance, it has been reported (WHO-UNICEF 2013) that only 63% of the population in this region has access to improved water.

Broken water pumps

Many communities who are served by an improved water source (e.g., a hand pump or borehole) may still experience operational challenges and subsequent disruptions in service. Water pumps,

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

like most equipment, will deteriorate and exhibit worsening performance with age (Jiménez & Pérez-Foguet 2011). But when such water infrastructure malfunctions, local users will often need to revert to the use of less protected water sources, increasing their risk of exposure to waterborne diseases.

The problems associated with broken water infrastructure have been well documented (RWSN 2010; Chowns 2015; MacArthur 2015). For example, a previous study reported that between 20% and 65% of hand pumps installed in a range of African countries were broken, or out of use (RWSN 2010), whilst another recent report has claimed that between 30 to 40% of rural water systems are failing prematurely (USAid 2016). It has been estimated that some 62 million people across this region are impacted by broken water infrastructure (Swan *et al.* 2017). This issue threatens to undermine some of the recent progress that has been made as a result of the MDG targets (e.g., MDG 7.C). In addition to these social impacts, broken pumps also represent a financial loss in infrastructural investment. For example, it has been reported that over the last 20 years, broken hand pumps in Africa have represented between $1.2 and $1.5 billion of ineffective investment (IRC 2009; USAid 2016).

The poor operational performance levels of such water pumps have been attributed to a range of factors, including: insufficient local financial resources to fund necessary repairs; limited access to spare parts; limited technical capacity within the user community; inappropriate technology implementation and/or infrastructural choice; limited post-construction monitoring and support from external agencies (Moriarty *et al.* 2004; Whittington *et al.* 2009; Chowns 2015). In relation to this last point, it is reported that less than 5% of WASH (water, sanitation and hygiene) projects are visited after installation, and as such broken infrastructure frequently goes undetected or is not addressed by relevant stakeholders (USAid 2016). Regular post-construction monitoring of remote water projects can address some of these problems. However, in many instances such traditional monitoring programs require regular site visits to remote locations, which can delay the implementation of repairs and place heavy time and resource demands on supervisory bodies. There is growing interest in the use of mobile phone-based technologies as an alternative method of monitoring water projects.

Telemetry application for water projects in Africa

Remote sensing (or telemetry) is widely used for monitoring many remote activities across the globe. Many telemetry applications use mobile phone (GSM) networks to convey data from a remote location to a central data handling facility (Thomson *et al.* 2012). This data transfer can be achieved via a range of different protocols (e.g., SMS and GPRS). These may vary depending upon a number of factors, including the size and frequency of data packages to be sent (Nel *et al.* 2014). The main advantages of telemetry-based monitoring tools typically relate to the comparatively low costs and wide coverage offered by mobile phone networks. The timeliness of this approach corresponds to rapid recent growth in mobile phone network coverage, coupled with the emergence of low cost monitoring equipment (Thomson *et al.* 2012). In terms of network coverage, the 'GSM per capita' coverage of the African population reached 76% in 2012 (GSMA 2014). In this context, there appears to be growing interest in the use of telemetry tools for monitoring water projects across Africa. This is demonstrated by the emergence of an array of new technologies for monitoring water pumps in developing regions, most notably the SWEETSense (Thomas *et al.* 2013; Nagel *et al.* 2015), SMART pumps (Thomson *et al.* 2012; Behar *et al.* 2013), Dispatch monitor (charity: water 2015) and MoMo projects (WellDone 2017). These systems utilise a range of remote measurement approaches, including the use of accelerometers, pressure transducers or flow sensors (Swan *et al.* 2017).

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

METHODS

Development of the MANTIS system

The MANTIS (Monitoring & ANalytics To Improve Service) system was developed through collaborations between Leeds Beckett University (LBU), Environmental Monitoring Solutions Ltd (EMS) and VisualWind Ltd (VW). The MANTIS system is a self-contained, self-powered remote monitoring device for India Mark II and AfriDev water pump models. These models are respectively the first and second most popular community hand pump models in the world (WaterAid 2013).

The MANTIS system was developed around five key principles, which sought to address the opportunities and challenges that have been highlighted in previous publications (Swan *et al.* 2017).

- Simplicity: This was an overarching philosophy in terms of the development of the MANTIS system, which influenced many of the ensuing design requirements. The system was intended to represent an appropriate monitoring solution for its specific context (i.e., of water pumps in remote rural locations across sub-Saharan Africa).
- Low cost: This is primarily related to the production costs of individual monitoring units. However, the operational costs of data transfer, the online platform and the costs associated with the field deployment of this technology were also considered.
- Ease of deployment: It was considered that the installation of the MANTIS unit onto the hand pump needed to be a simple and straightforward process. Similarly, it was envisaged that technology commissioning needed to be automatic, and that the online platform needed to be easily accessible and to give clear and relevant information to the user.
- Longevity: The MANTIS monitor was designed to be a low maintenance device. For example, it was considered that the unit should be installed with an on-board power source, which would not need to be replaced for a number of years. An operational battery life of greater than five years has been calculated based on the power consumption of the units. Furthermore, it was envisaged that the unit should be inconspicuous and have no secondary value (i.e., any value other than for its intended use). The MANTIS units were design to be hidden within the pump casing and to be tamper-proof.
- Minimal data collection: The MANTIS system was designed to provide an appropriate level of field data to perform its primary function (i.e., to detect whether, or not, the pump is operational). In order to keep costs and power use to a minimum the device has also been designed to avoid excessive temporal data collection and does not provide direct observation of secondary field parameters.

In summary, the primary aim of MANTIS was to relay the simplest level of information to indicate whether monitored hand pumps are in use. This simplistic approach seeks to reduce both the unit's production costs and power requirements. Reducing power demand has the benefit of increasing the unit's operational life span. It is considered that the minimalistic monitoring approach employed by the MANTIS system may represent a more appropriate strategy than some of the more complex technologies previously highlighted in this paper.

Development of workshop prototype

In terms of functionality, the MANTIS system infers the operational status of the water pump by monitoring pump usage patterns. Operational data is conveyed from site, both on a routine basis and by exception to confirm inactivity and possible failure. This information can be processed locally with minimal power overhead. Succinct data packages are sent from the unit, via SMS messages and an SMS Gateway, in order to centralise information for access by an online user interface (UI).

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

MANTIS was developed in two stages. A workshop prototype (WP) was developed, deployed and end-to-end verified in workshop conditions. This was then developed into a field prototype (FP) with more functionality. Prior to producing and verifying the WP, the product definition for MANTIS was developed around the aforementioned principles. In line with the MANTIS team's experience in industrial applications, the design exercise focussed on the elimination of cost and complexity, and particularly on the elimination of points-of-failure that could threaten reliability. The WP was developed using Arduino hardware. Whilst useful for prototyping activities, the cost and power demands of this hardware rendered it inappropriate for field deployment. The WP sent the simplest of data; communicating by SMS only when the pump had not been used for a set period of time.

Additional functionality was added to the FP so that information on daily usage could be relayed in a compressed format in the daily or weekly SMS messages. This information was designed to reveal wear and allow distinction between failures and phenomena (e.g., weather or receding water table) affecting proximate pumps; maximising data utility was a foremost consideration.

The FP was also re-engineered using individually available components, so that costs could be driven down and power usage reduced much further. A target of 100 μA current draw was adopted for the monitoring mode. Obviously, power usage is much higher when the modem is engaged; a factor considered in the overall MANTIS concept and in the logic of communication once a day or week, or by exception. It is envisaged that the battery life of this device should exceed five years.

Development of FP

FP MANTIS units were installed upon India Mark II hand pumps at 11 locations in Sierra Leone (see Figure 1) and 12 locations in The Gambia. The field trials were supported by local representatives from the Rural Youth Development Organisation in the Bumpe Ngoa Chiefdom in Sierra Leone and the Glove Project non-governmental organisation (NGO) in The Gambia, who negotiated permission for the systems to be deployed with the appropriate authorities (including village and area chiefs) and who acted as guides for the MANTIS deployment teams.

The FP units relayed the monitored field data from each site, via SMS messages, to an online geo-referenced UI. This web tool (see Figure 2) is ultimately intended as a platform for water stakeholders, such as government agencies or NGOs, to observe both the operational status and performance of remote hand pumps. The tool is being developed to provide alerts when

Figure 1 | Field trials of MANTIS unit in Bumpe Ngao, Sierra Leone.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

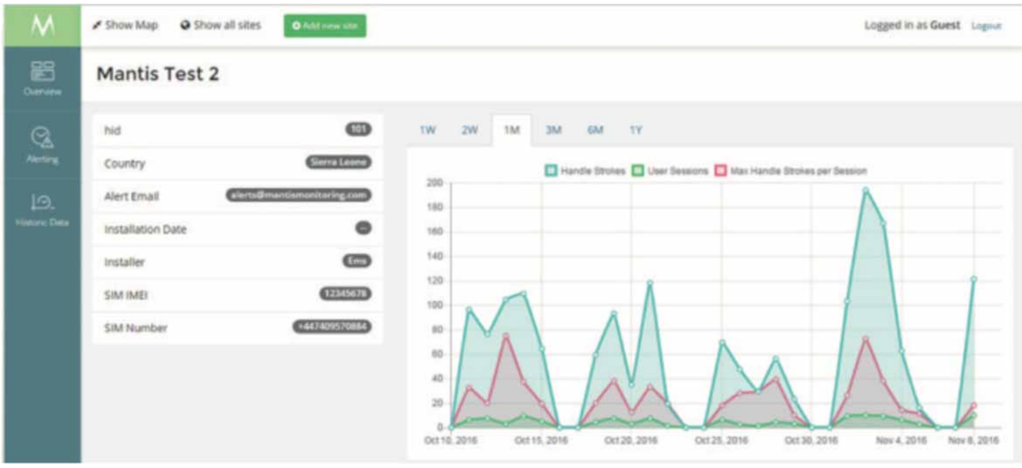

Figure 2 | MANTIS web-hosted dashboard.

pumps malfunction and to improve the prioritisation of pump maintenance and rehabilitation interventions.

RESULTS AND DISCUSSION

Field work: preliminary observations

Of the 23 hand pumps monitored in these field trials, there were three instances where the UI failed to receive any field data from site. At two of these locations (Bonto Koto 2 and Lewna Serere 2), the lack of field data was primarily attributed to low signal strength – which meant the respective FPs struggled to connect to the local mobile network. Vandalism was suspected as the cause of the third failure; however this problem was not encountered at any of the other 22 sites. This equates to 4.3% of the FP trial sample being deliberately damaged and was much lower than had initially been anticipated, but this experience still highlights the importance of establishing good local contacts and strong community involvement to help prevent any future field trials being sabotaged. Similarly, future designs of the FP will be re-engineered in an attempt to further mitigate this risk.

The FP units installed at the 20 remaining hand pumps generated data sets that varied from one day to over five weeks in length. Four of these units produced less than one week of data (Lewna Serere 1, Bongor, Bumpe police station, Mogiba). Once again, it is considered that low signal strength or intermittent mobile coverage may have hindered the FP units at these sites from connecting to the web-based dashboard. This experience appears to be consistent with mobile network problems that were reported from the SMART Pumps field trials conducted in Kenya (Behar *et al.* 2013). However, in the MANTIS trials it is not clear whether failures are due to GSM mast malfunctions, fuel shortages or low signal strength issues exacerbated by local climatic/environmental conditions. An enhanced antenna arrangement has been proposed for future revisions of the FP, which should help resolve such problems.

A further six field data sets were considered to contain 'unusual' records, such as negative or zeroed readings. Negative readings indicated the need for a firmware upgrade as the data collected from these sites exceeded the maximum levels that had originally been anticipated at the start of the trial, whereas zero readings typically indicated that the pump was not being used, or that the unit had been removed for whatever reason. For example, in one case the MANTIS unit interfered with the operation of the pump, and was hence removed. These issues will inform the design process and installation procedures employed for future versions of the FP. Finally, 12 FP units have recorded, or continue to record, useful field data from sites in Gambia and Sierra Leone. The authors have accessed this information from the UK via the aforementioned UI. The following sections highlight three case studies, which have been drawn from these field trials and highlight the potential of this technology.

Case study 1: Bumpe New Market, Sierra Leone – fluctuating usage

The MANTIS unit installed upon an India Mk II hand pump at Bumpe New Market in Sierra Leone (See Figure 3) collected the data set presented in Figure 4. This water pump was installed in 2010 and serves a community of approximately 400 people. The pump collects water from a 13 m-deep borehole.

Figure 3 | India MkII hand pump in Bumpe New Market, Sierra Leone.

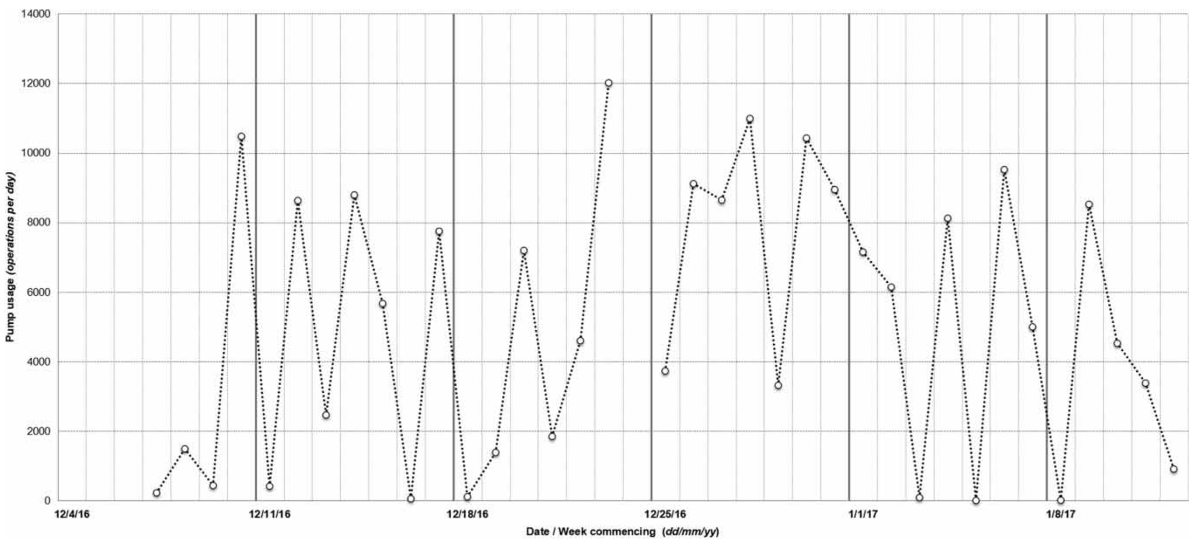

Figure 4 | MANTIS data from India MkII hand pump in Bumpe New Market, Sierra Leone.

Local stakeholders indicated that this pump often runs out of water during the dry season (February to March), as its borehole is reportedly too shallow to accommodate the consequent drop in water table. The monitored dataset covered a number of weeks just prior to this period. During this time the local water point committee regularly locked the hand pump for a 'few hours' at a time to let the water level rise. The effects of these regular interventions are evident in Figure 4 – as the daily usage regularly fluctuates from a high number of operations one day to zero operations the next.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

It is worth noting that there is some missing data during the week commencing 18/12/2016, but the general pattern, of fluctuating usage, is still evident.

Case study 2: Foya, Sierra Leone – stable usage

The variable usage pattern exhibited in Case Study 1 for the Bumpe New Market pump (Figure 4) notably differs from the more constant data sets collected from other hand pumps that did not appear to experience supply problems caused by a falling water table.

For example, the Foya hand pump (Figure 5) exhibited a steadier daily usage pattern than the previous pump (Figure 4), particularly during the period after 15/12/2016. The authors were not able to establish the reason for the elevated usage pattern in the preceding period, which culminated in a peak value on 14/12/2016. It is conceivable that this trend may have been due to local social reasons (such as a local community event), but this assumption has not been unsubstantiated. The MANTIS unit at the Foya site was attached to an India MkII hand pump, which lifts water from a 16 m-deep borehole.

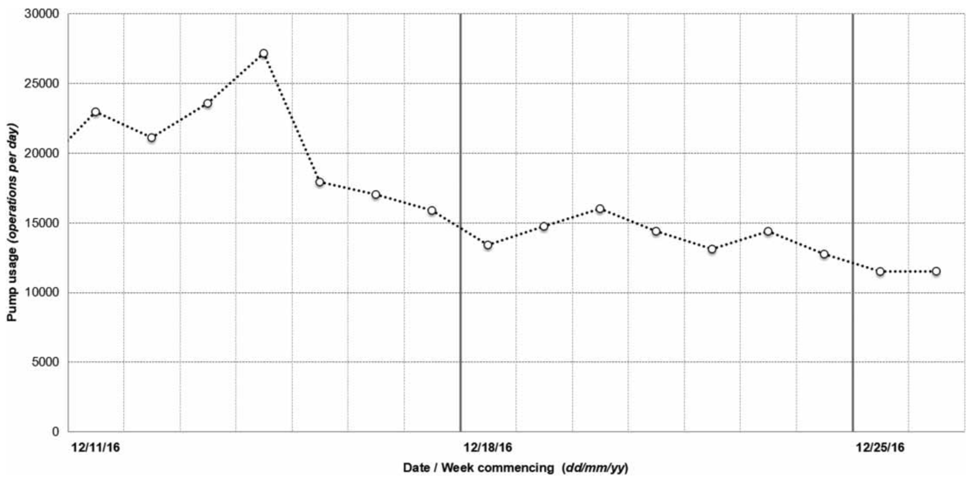

Figure 5 | MANTIS data from India MkII hand pump in Foya, Sierra Leone.

Case study 3: Hand pump failure at Mbankan – The Gambia

The MANTIS unit installed on a hand pump in Mbankan, Gambia recorded a dataset that contained the occurrence of a failure event (see Figure 6). Prior to 14/05/2017 this pump exhibited a relatively stable usage pattern of between 5,000 and 11,000 operations per day. The pump usage then drops dramatically to less than 2,000 uses per day, before gradually dropping over the following five days to almost zero uses. This 'unusual pattern' was reported to local partners, who physically visited the site. These investigations revealed that the pump had failed on 14/05/2017 due to a broken pump rod. The subsequent drop in operations therefore reflects fewer attempts to use the pump, and these attempts continue to fall in the subsequent days as the user community gradually become aware of the malfunction and begin to seek alternative water sources. By 21/05/2017 it appears that most of the local community knew of the problem as usage attempts virtually cease.

This example shows that the primary objective of the MANTIS FP and UI (i.e., to indicate whether monitored hand pumps are operational) has been successfully demonstrated. It is worth noting that this process was achieved through monitoring and interpretation of the pump usage patterns, with this analysis validated by local observations.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

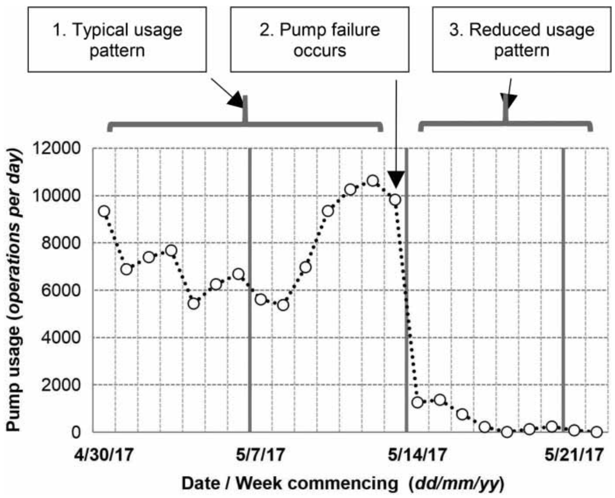

Figure 6 | Pump failure event on India MkII hand pump in Mbankan, The Gambia.

DISCUSSION

In future, it is intended that the simplistic information (i.e., pump usage patterns) collected from individual and proximate pumps could be analysed using rule-based algorithms; enabling differentiation between signatures that indicate pump wear, increasing use, falling water tables, and inactivity due to a completely receded water table. However, in order to automate the process of detecting pump failures, or even more importantly predicting when such failures are about to occur, it will be essential to establish when the usage patterns significantly deviate from a pump's normal operational range (see Figure 7). This is a complex task as any two pumps may have very different daily usage patterns that are influenced by a range of local environmental, societal and climatic factors. For example, it has been observed that the daily usage patterns associated with the hand pumps at Foya (Figure 5) and Bumpe New Market (Figure 4) were very different due to the depths of their respective borehole/local water table conditions. Furthermore, there are likely to be a variety of other factors that will influence the normal operational range of any given pump – these may include: temporal changes

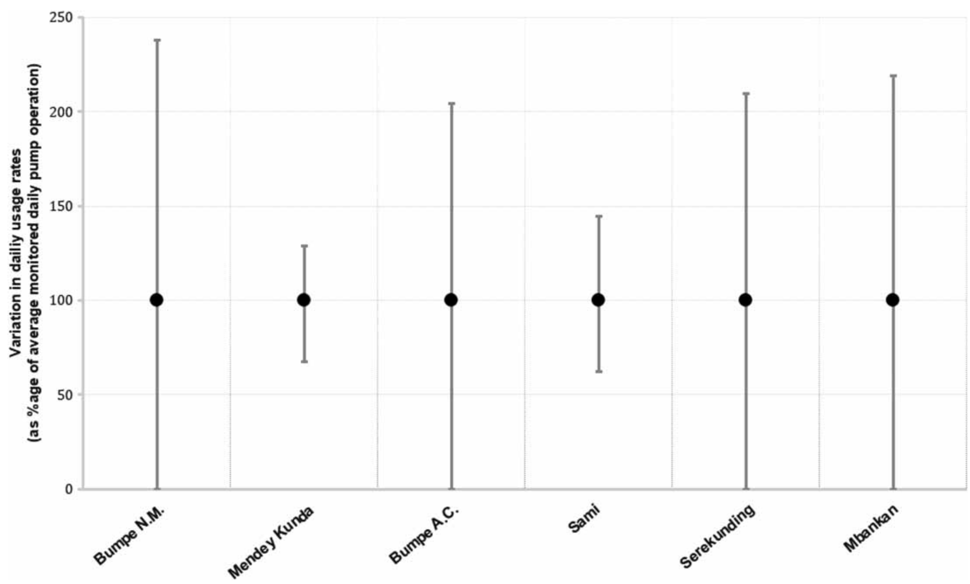

Figure 7 | Operational ranges for six hand pumps in Gambia and Sierra Leone.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

to the local population; the impact of agricultural and farming activities; climatic conditions; the age and operational reliability of the pump; the proximity of alternative water points, etc. To this end, it is worth reflecting upon the operational variations observed at different pumps included in this field exercise. Figure 7 compares the operational range of six hand pumps that were monitored for more than 20 days by FP units in Gambia and Sierra Leone. This graph expresses the daily maximum and minimum observed for each pump as a percentage of a pump's averaged daily number of pump operations. Further descriptive statistics for these hand pumps are also presented in Table 1.

It is evident that these pumps exhibit differing operational ranges in terms of their daily usage patterns, but this data does not explain why the observed usage ranges of these pumps are so different, or whether these patterns will remain relatively stable or change with time (both throughout the year and over the longer-term). Further investigation of the various contributory factors would normally be required to better understand these issues.

Table 1 | Descriptive statistics for six hand pumps in Gambia and Sierra Leone

		s		Range		Min		Max		
Pump site	$\bar{x}$	#	% of $\bar{x}$	#	% of $\bar{x}$	#	% of $\bar{x}$	#	% of $\bar{x}$	**Count**
Bumpe N.M.	5,054	3,899	*77*	12,014	*238*	0	*0*	12,014	*238*	36
Mendey Kunda	18,932	2,956	*16*	11,697	*62*	12,733	*67*	24,430	*129*	31
Bumpe A.C.	7,750	4,493	*58*	15,834	*204*	0	*0*	15,834	*204*	25
Sami	18,414	4,460	*24*	15,205	*83*	11,427	*62*	26,632	*145*	23
Serekunding	15,080	14,783	*98*	31,570	*209*	0	*0*	31,570	*209*	24
Mbankan	4,850	3,895	*80*	10,620	*219*	0	*0*	10,620	*219*	23

However, this exercise highlights another potential benefit of the MANTIS system, and other similar technologies. Prior to the emergence of such systems, there was a limited amount of historical data relating to the operational patterns of remote hand pumps. It is envisaged that the growing pool of historical data generated by these tools should begin to help answer some of the aforementioned questions. For example, these growing datasets could be analysed using fuzzy logic or other AI techniques to establish normal operational patterns for each pump. This in turn will enable the 'near real time' analysis of field data received by the UI, to indicate whether a specific pump is being operated within its normal range, or exhibiting a divergent pattern that might be associated with an impending failure. As the collected data sets increase in duration, and a wider range of temporal events are observed, it should become easier to distinguish an 'unusual pattern' caused by a mechanical problem from other changes that may be associated with temporal, environmental and climatic conditions.

CONCLUSIONS

1. In summary, this paper has outlined that fewer than 5% of WASH projects are visited by supervisory bodies after construction, and that subsequently broken infrastructure is frequently not detected or addressed by relevant agencies. As such, broken hand pumps may go undetected for a significant period of time (i.e., until a physical site visit is made to the local community and their pump installation).
2. The authors consider that remote-sensing applications, such as MANTIS, have significant potential to improve both monitoring and maintenance strategies, and ultimately to increase the longevity of water pumps.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.093

3. The paper has successfully demonstrated the primary aim of the MANTIS system in the field (i.e., to indicate whether monitored hand pumps are operational). This has been achieved by monitoring the pump usage pattern. This simplistic approach seeks to reduce both the monitoring unit's production costs and power requirements. Reducing power demand in turn increases the unit's operational life span.
4. It is envisaged that in future the simplistic information (pump usage patterns) collected from individual and proximate pumps will be analysed to indicate pump wear, increasing use, falling water tables, and inaction due to a completely receded water table.
5. The paper has highlighted some of the associated challenges that need to be addressed in order for MANTIS to fulfil its potential as an invaluable monitoring tool for remote hand pumps. The paper has demonstrated that the MANTIS system has already achieved Technology Readiness Level 7 (i.e., a prototype demonstration in an operational environment). However, the authors consider that further product development is required towards a market-readied product and further demonstration activities. These should enable MANTIS to reach TRL8 (i.e., the actual technology completed and qualified through test and demonstration) and ultimately to achieve TRL9 (i.e., the actual system has been thoroughly demonstrated and tested in its operational environment).

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