Software Architecture to Monitor Handpump Performance in Rural Kenya

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Abstract:

The Smart Handpump project is now generating the world's first real-time transmission of hourly handpump water use using mobile technology in rural Kenya. The software architecture that underpins this flow of smart handpump data is discussed and evaluated. Smart handpumps have a GSM-enabled unit securely inserted in the handle with an accelerometer to measure the movement of the handle and calculate water pumped. These data are periodically and automatically transmitted to enable (a) more timely and efficient repairs to be made when pumps break down, (b) greater accountability by enabling central government, donors and other stakeholders to monitor the performance of the handpump network, and (c) a detailed source of water usage data to inform future planning and investment decisions. The data are transmitted to a central server which is accessible through a web interface that displays and maps water consumption data over time. Technical progress is assessed and future opportunities discussed to contribute to the global development priority of accelerating and maintaining reliable water supplies to the 276 million rural Africans without safe water.

Keywords: databases, GSM modems, handpumps, mobile communication

INTRODUCTION

Handpumps are a key technology for obtaining safe drinking water in rural Africa. Despite their importance, it is estimated that one third of all handpumps are non-functioning at any one time (RWSN, 2010). Communities must then resort to alternative sources of water which are potentially distant or unsafe, leading to negative health and welfare consequences. Rosen and Vincent (1999) estimate that 1.4 million person-years of effort are wasted as a result of rural populations not having access to improved water supplies, with much of this effort being shouldered by women (Carincross, et al., 2010). Every year in Africa inadequate water supplies and sanitation cause almost one million deaths and 7.6% of the continent's disease burden (WHO 2009a, WHO 2009b). African women spend 40 billion hours annually collecting water from distant sources, and an estimated 350 million school days are lost annually to water-related illness (CAP-NET and GWA 2006, Hutton and Haller 2004). The number of rural Africans without access to safe water has increased by 38 million between 1990 and 2010 (WHO/UNICEF, 2012). Despite billions of dollars of capital investment in handpumps since the 1980s, knowing where and when handpumps fail on a systematic basis has, to date, not been possible (Hope, et al., 2012).

Utilising the expanding global mobile network, the Smart Handpumps project aims to develop a low cost and scalable system to make usage data from handpumps available to maintenance services and decisions makers (Thomson et al., 2012). More timely and consistent maintenance provision would reduce downtimes and thereby improve access to water for the people in rural areas who rely on these pumps.

In recent years, mobile networks have been used as a means of automated communication for improved decision making in several other fields. The mWASH report from the Pacific Institute (Hutchinson, et al., 2012) provides an excellent overview of various projects using SMS and other mobile technologies in the water and sanitation sector.

Within the greater context of water supply and management, SMS communication has also been employed to aid in irrigation management in other countries with scarce water supply, such as Australia and India (Hornbuckle, et al., 2009 and Galgalikar, et al., 2010) In the former system, SMS is used to send processed data to the farmers to allow them to make a better informed decision on crop watering, however it also serves as a feedback channel from the irrigators. The latter system instead envisages SMS communication to serve as the primary means of data transfer between the soil-moisture sensors in the fields and the processing units that make a decision as to how much and when to irrigate them.

The Smart Handpumps system consists of a GSM-enabled Waterpoint Data Transmitter (WDT), housed within the handle of the pump so as to monitor its movement. The transmitter is programmed to send periodic SMS messages detailing pump usage over the GSM network. Pump usage is calculated from an on-board accelerometer, further details of which can be found in Thomson, et al. (2012).

Technical development and laboratory testing of the WDT commenced in May 2011. A prototype WDT was successfully tested on four handpumps in Zambia in July 2011 (Thomson, et al. 2012). A small-scale field trial in rural Kenya is currently being deployed by the UK Department for International Development (DFID). It has three major aims: (a) to make a technical evaluation of the system in an operational environment; (b) to understand what information is required by stakeholders, e.g. the District Water Officer (DWO), the Water Services Regulatory Board (WASREB), and the water users themselves and (c) assess whether real-time monitoring of handpumps can improve accountability, transparency and performance in the rural water sector.

This paper introduces the software architecture designed for this project and preliminary results of its implementation in Kenya during August 2012 – January 2013.

METHODS

The engineering goal of the project is to automate the monitoring of handpumps by taking advantage of GSM communication networks. Hourly usage data are transmitted from the WDT unit through the GSM network to a server every six hours and entered into a database. Figure 1 presents a flowchart that represents the process of the WDT data flow in addition to the interaction between the system and the different stakeholders.

For the software architecture we have relied primarily on Linux-compatible, open-source software, which can then be compiled on any CPU architecture. The rationale for this is to enable our solution to run efficiently on older hardware and inexpensive single-board computers. This makes it ideal for economical large-scale deployment with little requirements for changes in infrastructure. As the main SMS gateway (Figure 1) we have chosen FrontlineSMS, which is provided as open-source software. It does not require an internet connection, meaning SMS messages can be processed offline, and it is not resource intensive, making it suitable for the intended hardware.

For the interface, we rely on a 'LAMP' stack (Linux Operating System - Apache Webserver - MySQL database server - *PHP* server-side scripting), which is an industry standard. We opted for a web-interface, such that the data could be accessed or forwarded online; however, it should be noted that the web-interface can be accessed locally even when the workstation is offline.

The data must be presented to stakeholders in the format that best suits their needs. There are broadly two categories of users who require the information, but with quite differing needs. Those responsible for administrating and maintaining a network of handpumps (system administrator and maintenance providers on Figure 1), for example a District Water Office or subcontracted mechanic, need immediate data that shows daily usage and most importantly variations in daily usage that might indicate that there is a problem with a pump. They will use this information for the day-to-day upkeep of the pumps and thus presentation of data in an easy-to-use visual format is required. The second category of users (policy makers on Figure 1) requires data that is less immediate and less granular, but which can be analysed to determine long-term usage trends and outage rates. These may be central government bodies or researchers who wish to understand water use patterns or the aggregated information on pump reliability and downtimes. This knowledge will allow them to make better informed choices and future investments and resource allocations as well as giving them oversight of those tasked with providing maintenance services. In addition to these two actors the R&D team (Figure 1) is in charge of maintaining and updating the software solution.

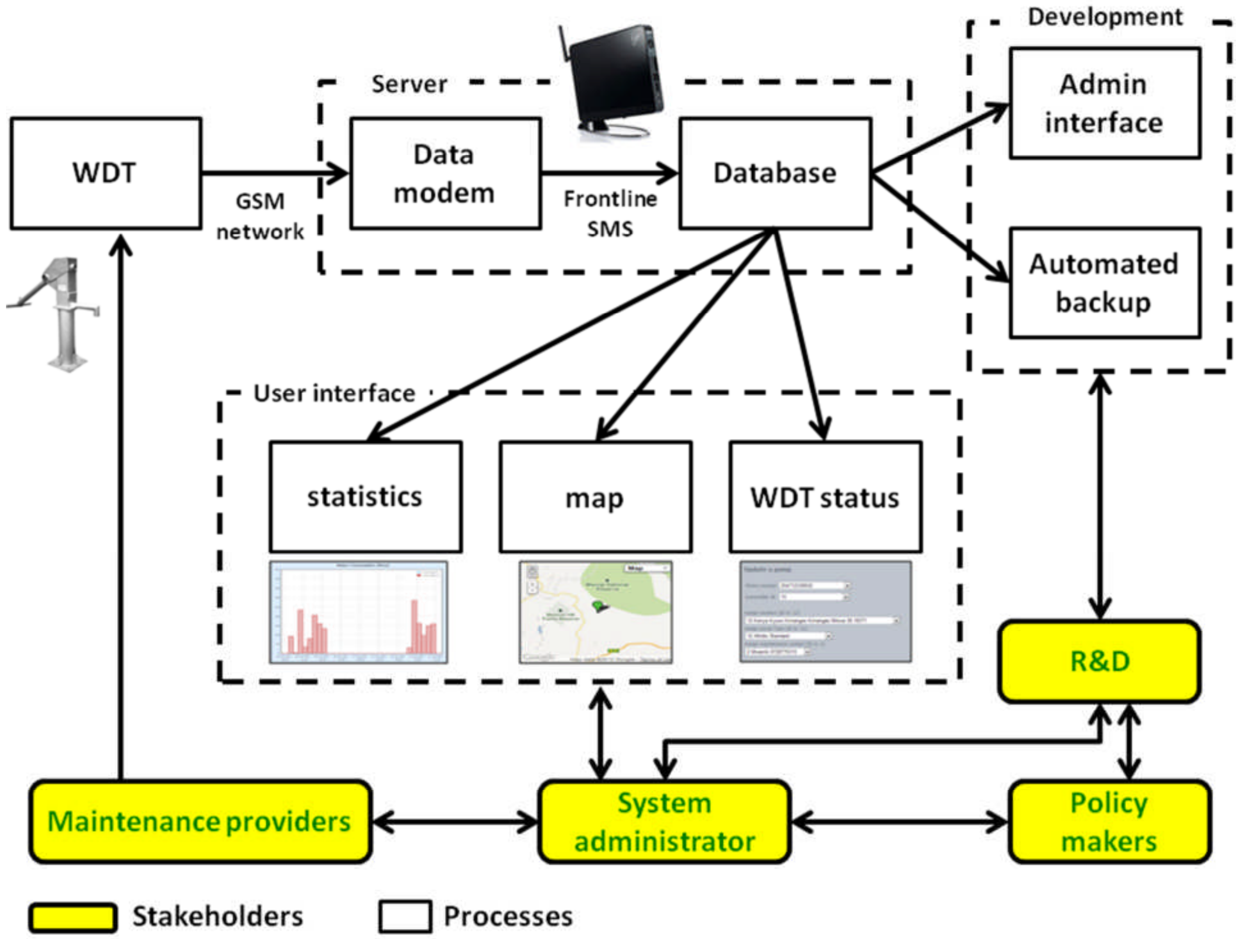

Figure 1. Architecture design of the system: information about pump usage is acquired via the Waterpoint Data Transmitter (WDT) and transmitted via GSM to a centralised SMS server where information is stored in a database. Stakeholders can access the data via a web interface and manage the monitored pumps via a project-tailored user interface. The research and development (R&D) team has access to its own administration interface.

In the remainder of this section, data management and the user interface are discussed. Firstly, we detail the protocols implemented for sending SMS over the existing GSM network, the SMS's structure and how they are stored in the database. This is followed by an overview of how the database is structured, and lastly the graphical interface to suit the different user needs is described.

Incoming data management

The format of the data sent by the transmitters is structured as shown in Figure 2. This consists of (a) the time at which the message was sent, (b) the phone number of the transmitter and (c) the different measurements related to pump usage. The water consumption is obtained by a weighted sum of the measurements. The weights are pump-specific coefficients derived through calibration on different pump models (Thomson *et al*. 2012).

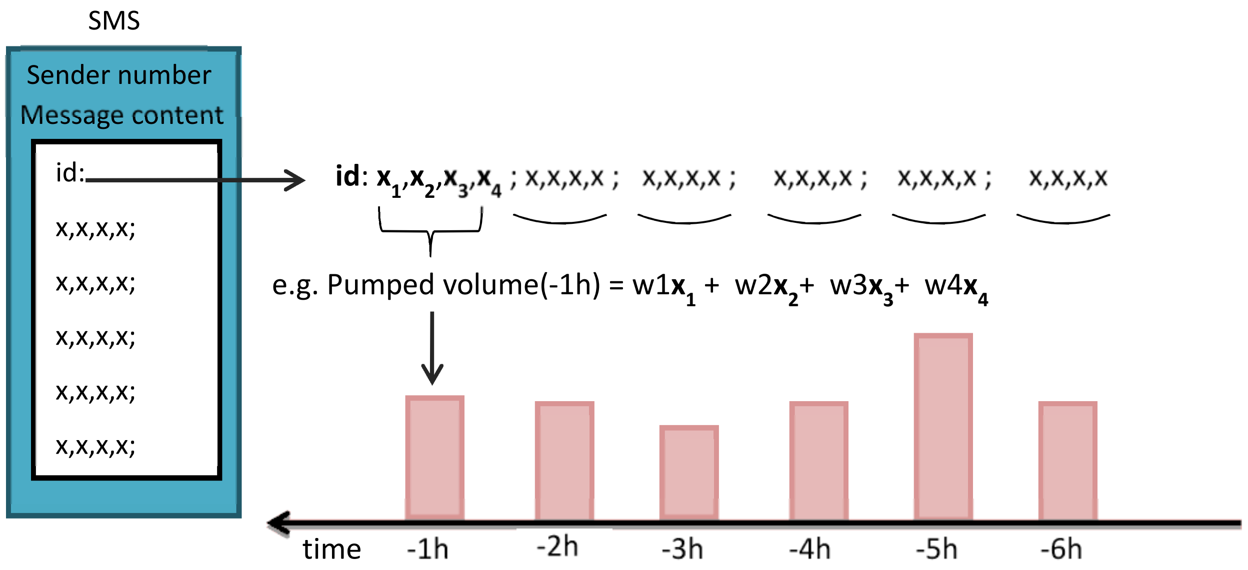

Figure 2: SMS structure and its relation to water consumption. Each SMS contains a timestamp, sender number, message number and a series of measurements (x). Water consumption is obtained when the latter are multiplied by pump specific weights (w). Note that the w coefficients are stored in the central database and not in the individual SMS.

Each text is given an order number ("id" in Figure 2) which together with the time when the WDT is first activated allows the system to generate the water volumes with an hourly precision. A duplicate of each text is send three hours after the original one in order to minimise the amount of lost data. The SMS messages are received by the central server via a GSM modem and stored in a database (described in the Appendix). Frontline SMS (Banks, K., 2005) in combination with *PHP* code are used to receive, format and transfer the SMS information to the database. The *PHP* command includes logical tests to ensure that all data are entered into the database with no duplicates or irregularities (i.e. SMS with missing parameters, SMS out of order, repeated SMS, etc.).

Database and User Interface

A relational database was designed and implemented using the open source MySQL relational database management system (RDBMS) platform, with MySQL client version 4.1 and server version 5.0. The database schema can be found in appendix A. The database is built in a modular fashion so that the system can easily be expanded. This database provides the information for the front-end user interface which has three parts.

Mapping of Transmitter Location

The location of the pumps was identified as the key feature enabling a user to identify a particular pump. During installation the latitude and longitude of each pump was recorded by GPS. An interactive map with markers representing the pumps was integrated into the website using the Google API (version 3) which is compatible with popular browsers (Firefox, Chrome, IE8). Each pump location is represented by a marker on the map (Figure 4). While the status of the pump - fully operational, needing checking, broken, or historical - is represented by the colour of the marker.

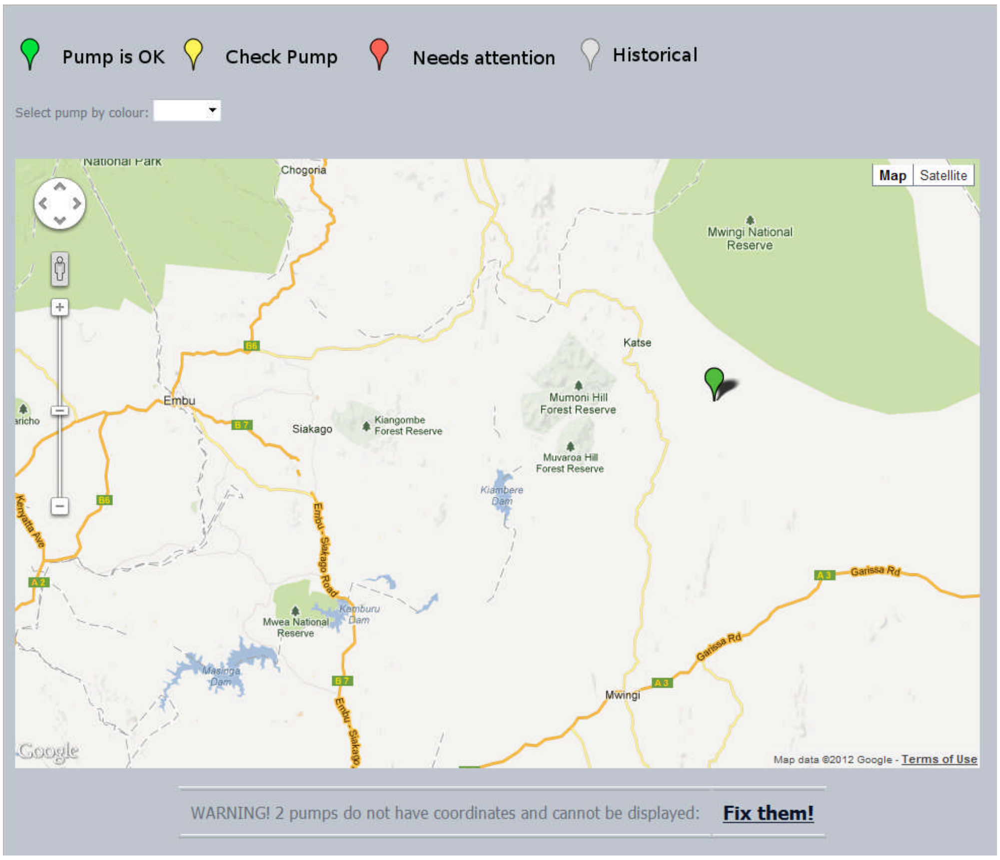

Figure 4: Transmitter locations interface using Google Maps with colour coding to indicate pump status. Transmitters can be filtered by their status to identify issues rapidly. A dialogue box at the bottom of the map ensures that the user is aware of transmitters with missing geographical information.

Visualisation of Pump Use Data

The graphs page is a convenient interface to monitor a pump's output and transmitter history throughout its lifetime as well as other relevant information about the pump on a single webpage (Figure 5). The graph data are extracted directly from the MySQL database via a PHP interface based on the selection made, and a graph is generated dynamically, ensuring the data are always up-to-date. The graphing engine used is the lightweight Flot javascript graphing library (Laursen, 2012); apart from its rich features, it is also a pure javascript-based library, thereby avoiding the need for an online connection or resource-hungry plugin-based frameworks.

Update of Transmitter Information

This module allows management of the transmitters. Users can input all descriptive information pertaining to the pump and the installed WDT unit. All input types (e.g. string, date or integer) are tested in order to ensure data integrity. The pump status can also be changed via a drop menu in which case the transmitter will be displayed with the corresponding colour status on the Google Maps interface.

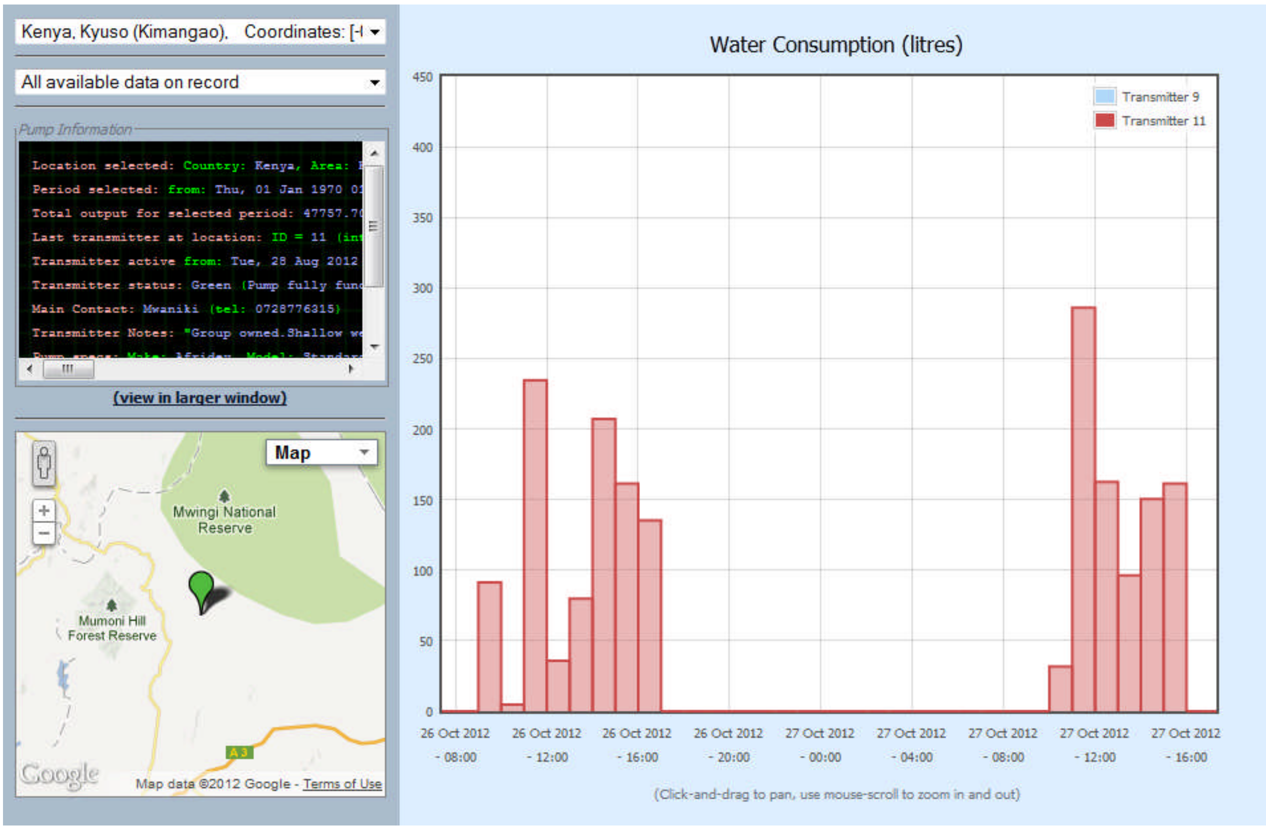

Figure 5: User interface for visualising estimated water consumption and other useful statistics processed from incoming WDT data. Top left panel: pump and time period selection menus. Middle left panel: useful information is displayed for the given pump. Bottom left panel: mini-map interface showing the location of the pump selected. Right panel: Graphs of water consumption in litres as estimated from WDT data with hourly resolution.

RESULTS

The system was deployed in Kenya as a first stage of an on-going trial involving the monitoring of pump usage in eastern Kenya. The present implementation of the system consists of 23 transmitting WDT units in Afridev pumps Kyuso district (Figure 6), and a webserver and modem located in Nairobi. The hardware and software setup outlined in section 2 were installed in Nairobi and a local team was briefed on how to operate the user interface. Building on input from local experts, a WDT installation protocol was defined in order to streamline the data input process by the local team and ensure completeness of the database.

The handpumps were fitted with a WDT unit inserted inside the existing pump handle (one pump required a replacement handle). The simple installation process enabled the team to install between five and eight units each day. The first SMS sent by each unit initialized a new account on the database. The first WDT installation took place on Mikwa, Kimangao on 28th August 2012, whereas all the remaining WDT units were fitted in December 2012. The necessary pump details were later updated on the server using the developed interface. Figure 7 summarises our findings for the measured variable (volume of water abstracted/day) for a pump located in Mikwa village in Kimangao, derived from hourly data for a 5-month period.

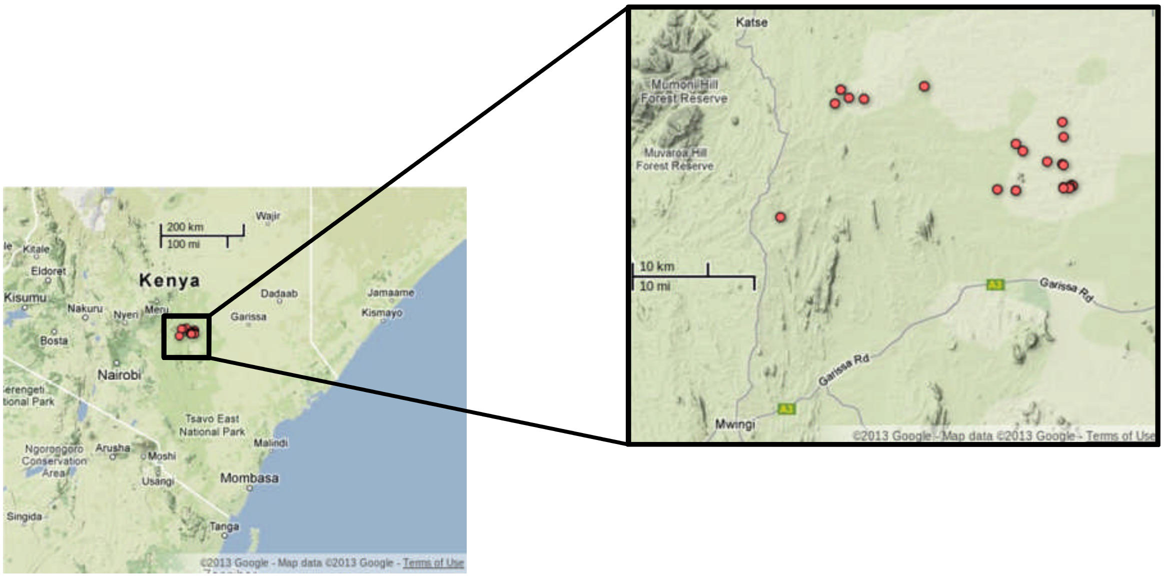

Figure 6: Left: map displaying the location of the WDT currently deployed in Kenya. Right: detailed map of pump locations in the Kyuso province.

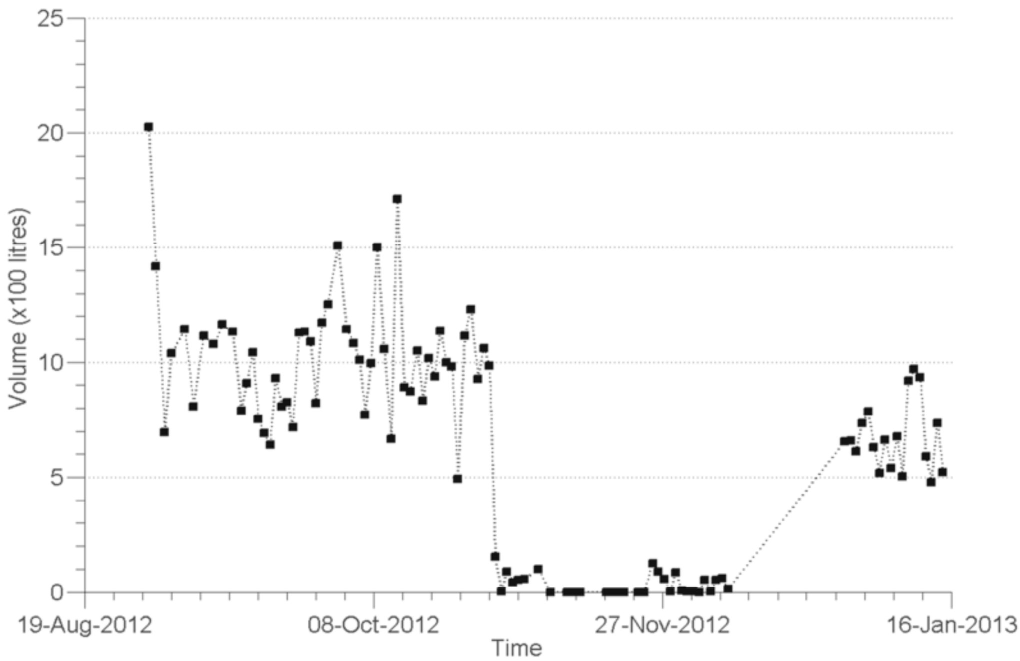

Figure 7 – Daily average volumes of water abstracted as estimated by the WDT unit for the pump located in Mikwa village in Kimangao from the 28th August 2012 to 16th January 2013.

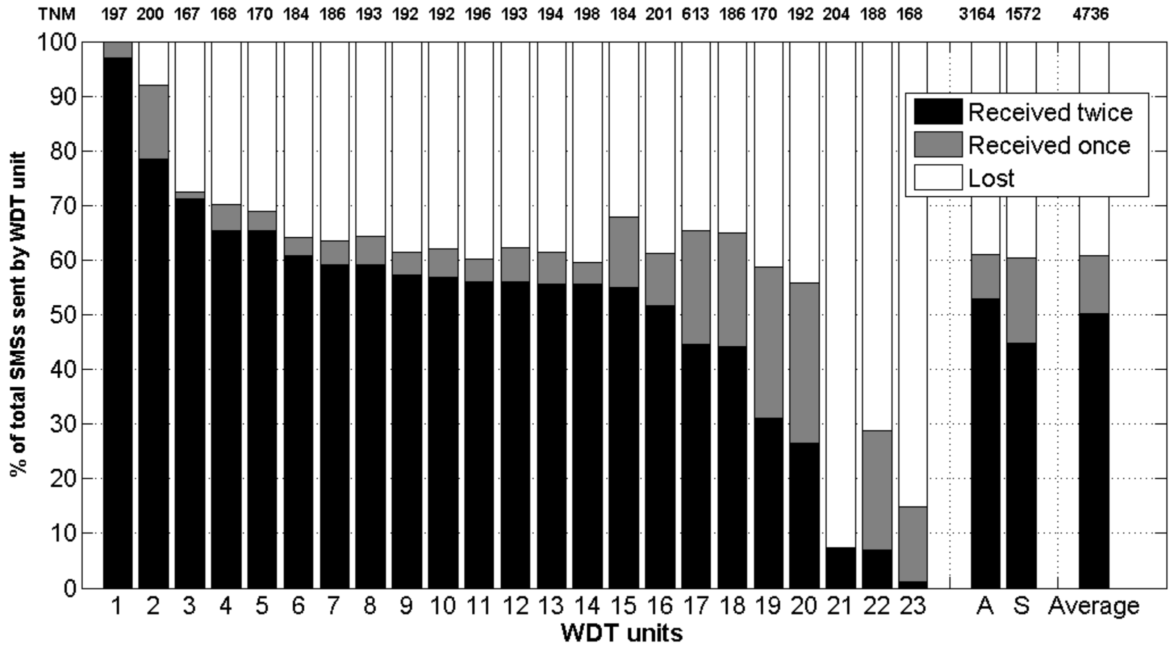

Figure 8: Percentage of data packets received once, twice and lost by WDT units (1-23). Data packets received once, twice and lost by WDT units equipped with a SIM card from two mobile networks (A-S) and average over all WDT units (Average). TNM: Total Number of distinct Messages (for each individual WDT unit).

DISCUSSION

The developed system allows for hourly abstraction volumes from individual handpumps to be estimated from the WDT data stream. The derived volumes can be analysed over different time frames. On the one hand, short time analysis can reveal acute pump failures and offer a valuable insight on the water pumping habits of the study populations. On the other hand, long-term studies allow for seasonal trends to be distinguished, and they also have the potential to reveal pumps on a route to breakage. For illustration, an example of the estimates can be seen in Figure 7, where daily averages are shown over the course of five months for one of handpumps of the ensemble of currently monitored sites. Here the WDT data stream reveals that pump usage markedly falls during the rainy season (from end of October through November) as the population relies less on groundwater during the later period, collecting rainwater instead for daily consumption and picking up again after rains have abated. (The data gap from late November to early December was a result of network coverage being permanently lost – in December the WDT SIM card was replaced with that of a different network provider.)

The development of a GSM-based monitoring technology relies on constant and working network coverage. However, Figure 8 illustrates how unreliable this service can be. Overall, 40% of messages went missing entirely (i.e. they were not received once), although the success rate of each transmitter varies considerably; For the WDT in Twaathi village in Kalwa, Ngomeni (WDT unit 1 on Figure 8) all the messages have been received at least once as opposed to the pump in Makulikya, Kimangao (WDT unit 21 on Figure 8) where most SMSs are missing.

One potential reason for the loss of messages has to do with mobile phone masts. They constitute the main source of coverage and relay our messages from the transmitter to the GSM modem. However, they have questionable reliability since they are often powered by diesel generators that are susceptible to break-downs or fuel shortages. Ensuing power outages lead to a local loss of signal that prevents the messages from being received. Nonetheless, local power outages cannot account for all losses, as can be observed from the output of the Ikime pumps (WDT unit 9, 10, 12-16 and 18, 19 on Figure 8). These pumps are all within several hundred meters from one another. One amongst them has a much lower success rate with respect to the rest of the group. Further analysis will be made of the reasons for message losses in order to reduce missing data, although some message loss is inevitable due to the relative positions of the masts and handpumps, which are often low-lying, and changing in environmental conditions that affect signal propagation.

It should be highlighted that the data stream can be fully reconstructed if all SMS messages sent from a given pump are received at least once. If messages are lost then the missing data could be estimated from previous days' consumption for the same time interval. This consideration becomes more problematic when a large number of consecutive messages are missing. In summary, a robust mobile telecommunications network is a critical factor in the success of the system. Although network coverage is widespread, the service reliability in rural areas is still not at the levels found in urban areas. As a result, on average, Figure 8 (rightmost column) shows that effective monitoring time, i.e. time during which water abstraction volumes are known, is about 60% of total time. This may seem low, but is still an order of magnitude better compared to existing methods of capturing this data.

The local communities in Kyuso District have been very receptive and positive about the WDTs in the trials so far, and locals were happy to be involved. Pump users and committees where fully briefed on the system and the project and transmitters were only installed with their consent. This is important, as the sense of community involvement it brings to the project has been shown to be an important factor for success of development projects in the past (Ngugi, et al., 2010). The long-term success of such an initiative, during the research phase and beyond, relies on local consent, benefits accruing to the local community, and the demonstrating that these benefits are being delivered.

FUTURE WORK

The initial trial (Thomson, et al., 2012) suggested that certain pump-failure modes could be identified from the data stream, as the data generated by a failing pump can be different from that of one that is fully functional. In this case where a pump failure has a slow onset rather than a sudden catastrophic breakage, analysis of certain characteristics allows for certain failure modes to be recognized from the data generated by the system before the pump ceases to produce any water. Currently the system is designed to allow rapid response to pump failures that have just occurred, thereby reducing pump downtimes. If failures can be predicted and pumps can be repaired before they cease functioning, downtimes can potentially be eliminated. A more advanced iteration of the technology would be able to automatically generate alert flags notifying those responsible for maintenance of imminent pump failures.

Currently the focus for the interface has been on providing information in a format that is of use to those responsible for day-to-day maintenance. The system has been designed in collaboration with Rural Focus Ltd. and the District Water Office who are partners in the DFID-funded trial in Kyuso. However, as information like this has never been available before, the system currently presents information based on sector knowledge and experience. As the system is used operationally and the users can see what it can and cannot do, the interface will be refined to better serve their needs. In addition there is interest in the system from central government level in Kenya, in particular the Water Services Regulatory Board (WASREB). Once there is sufficient data to make analysis of usage patterns across wet and dry periods, the team will work with WASREB to see develop outputs that serve its needs.

In addition the possibility of using an SMS gateway rather than a stand-alone modem is being investigated. At the current scale, using a server with a modem located in an office in Nairobi was the most effective way of configuring the system. However as the scale increases, with multiple locations and more stakeholders, a cloud-based system may be more appropriate.

CONCLUSION

The introduced system and software architecture demonstrates SMS-based monitoring of handpumps that is currently deployed in eastern Kenya. The system provides an unprecedented level of data on rural water use, which can be used to detect pumps subject to failure and provide decision makers with information on handpump usage. To date no other system has been able to provide users with this information, let alone in near real-time.

This project has fostered novel research across a wide spectrum of disciplines, linking electronic systems engineering to environmental and social sciences. On-going work in Kenya includes refinements in the system based on what has been learnt to date. These include developing a better strategy for dealing with variable mobile phone reception and developing the interface to better present data to a range of stakeholders.

Such a system providing this level of data can lead to a step-change in the way that rural water services are delivered, improving sustainability and reliability and thereby delivering improved health, economic and social outcomes for rural populations.

Further project information can be found at www.oxwater.co.uk.

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APPENDIX

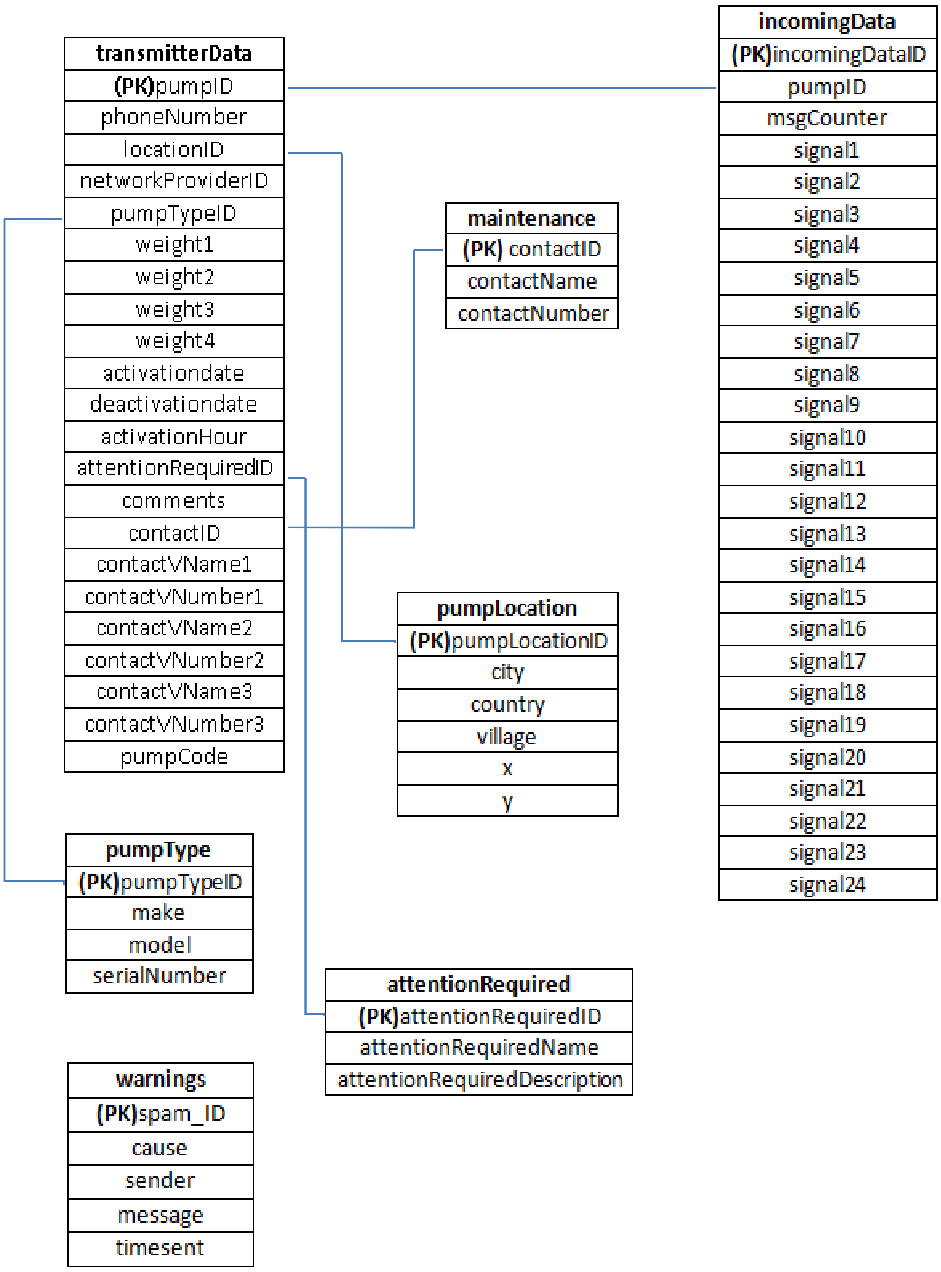

Figure 9: Relational database structure used to store the incoming data transmitted by SMS from the pump to the server. The database holds additional information relative to the individual pumps.

The database consists of seven tables: *transmitterData*, *maintenance*, *incomingData*, *pumpLocation*, *pumpType*, *attentionRequired* and *warnings*. Information regarding the transmitters is stored under the transmitterData table with the following attributes; a unique ID, the phone number associated with the transmitter, a location ID that is linked to the *pumpLocation*. This table also has a *pumpTypeID* attribute which is associated with the *pumpType* table and holds information specific to the pump to which the transmitter is connected. The table also includes an activation date and hour corresponding to the time the WDT unit was switched on and started sending messages. This is to ensure the data can be tracked in time and displayed correctly. The remaining fields in the *transmitterData* table hold details pertaining to the four weights assigned to each pump that allow for the conversion between transmitter data into litres, the village contact names and numbers and the pump maintenance contact details. In addition a code referred to as *pumpCode* is assigned to each pump in order to uniquely define the pump.