The Intelligent Water Project: Bringing Understanding to Water Pumps in Africa

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Abstract: The Intelligent Water Project (IWP), born out of an effort to increase handpump reliability, measures and reports the functionality of handpumps and volume of water extracted on two-hour intervals daily. Additionally, IWP will measure groundwater levels which can be used to evaluate well yields. Data from handpumps is automatically collected and transmitted to a remote database. Once in the database, the data is analyzed and distributed to stakeholders via web and mobile applications and customizable alerts. Besides monitoring water extraction, handpump performance, and borehole health, the IWP system processes data to alert stakeholders of failure or degrading conditions (imminent failure). Coupled with appropriate field management processes, this information can lead to improved handpump availability and lowered cost of ownership. The key goal is to dramatically increase the reliability of handpumps. A secondary goal is the collection of handpump data from all IWP enabled pump sources providing a rich resource of data to enabling WASH practitioners, managers, hydrologist and donors to make more informed decisions.

1 INTRODUCTION

Wells and handpumps in Africa fail at alarming rates within the first two years of installation ((RWSN), 2009). Much of this failure can be attributed to a lack of transparency into the performance of handpumps. Existing manual methods of handpump monitoring require manual field inspection by personnel which is costly, untimely and superficial. Furthermore, traveling long distances to reach handpumps results in infrequent inspections.

The advent of low cost, reliable sensor technology coupled with the ubiquitous GSM network has the potential to bring unprecedented levels of transparency to handpump performance in rural Africa. Our project has refined a fully automated wireless, sensor-based mobile and web application suite to provide significant remote transparency of the overall handpump performance.

Initial concept development of the Intelligent Water Project (IWP) sensor technology and the software suite began in 2012 with internal funding from the Messiah College Collaboratory and the Department of Computer and Information Science (CIS) with subsequent funding from World Vision. This project is being done by a coordinated group of faculty members and students across various engineering and computer science disciplines at Messiah College, a Christian college based in the United States. The software for this project has been developed using the Agile Scrum method(Nejmeh and Weaver, 2014) in two service-learning computer science classes (database applications, senior capstone course in CIS). Given the Christian-faith tradition of Messiah College, we often use Biblical references to help motivate our work. Work on the IWP project has been inspired by the following passage: "*The poor and needy seek water, but there is none, their tongues fail for thirst. I, the Lord, will hear them; I, the God of Israel, will not forsake them. I will open rivers in desolate heights, and fountains in the midst of the valleys; I will make the wilderness a pool of water, and the dry land springs of water.*" Isaiah 41:17-18 (NKJ)

1.1 Related Work

Broadly speaking, there are two different types of solutions to monitoring handpumps: non-sensor based approaches and sensor based approaches. Non-sensor based approaches use mobile apps into which humans input data for subsequent machine analysis. This includes generic (non-water specific) mobile

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app toolkits such as iFormBuilder® (Zerion Software, 2015), Open Data Kit (ODK) (OpenDataKit, 2015), FrontLineSMS (FrontlineSMS, 2015), devicemagic (Inc., 2015), and Magpi (Magpi, 2015) (formerly EpiSurveyor). Water specific mobile apps include aquaya (Institute, 2015), Mwater.co (mWater, 2015), and Akvo FLOW (Akvo, 2015).

There are a few sensor-based approaches to automate handpump data collection. Among them are the Sweetlab project (Thomas, 2013) and the Oxford University Smart Water project (Rob Hope, 2011). The Oxford project performed a proof of concept study to determine the feasibility of using low cost accelerometers to estimate handpump extractions. Our work expands on this work to develop a sophisticated system that monitors not only handle movement but water flow and well water level. Our system is differentiated by the following attributes:

- it provides support for automated, sensor-based handpump data collection over the ubiquitous GSM network,
- it provides full transparency and access to all of the underlying sensor data via the website,
- it supports configurable, periodic status alerts on user defined events of interest,
- it leverages the work of the Messiah College India MKII and Afridev Sustainability Studies that gives unique insight and focus to the sensor design (Anthony Q. Beers, 2013),
- it provides full integration with Google Maps® and ESRI (GIS cloud environment) systems,
- it is a cloud-based application suite which runs on desktops and mobile devices,
- it is being developed by an interdisciplinary team of hydrologists, mechanical engineers, electrical engineers and computer scientists.

2 PROBLEM STATEMENT

Approximately 184 million people living in Africa depend on handpumps for their daily water supply (MacArthur, 2015) with an estimated 50,000 new handpumps shipped to Africa each year (Sansom and Koestler, 2009). Despite efforts to improve rural water service delivery, handpumps serving rural communities often fall into disrepair. According to data compiled by Rural Water Supply Network (RWSN) ((RWSN), 2009) from 20 African nations covering 345,071 wells in 2009, 36% of handpumps are non-operational. This results in a loss of capital investment in infrastructure and a negative impact on rural communities. When a community handpump breaks down, families are forced to find alternative water sources. Alternative sources may include carrying water a greater distance from a handpump in a neighboring community, or less protected sources such as hand dug scoops or surface water. The latter sources carry increased risk of water born disease. The increased time and energy spent collecting water and the potential for illness detract from more economically empowering activities.

Logistical challenges and costs hamper effective and efficient handpump monitoring and evaluation efforts in rural areas. To determine the condition of a handpump, water authority representatives must travel to each handpump location and perform a manual inspection. This process can result in lengthy down-times and high labor and transportation costs incurred by the community and/or sponsoring NGO or government organization. As a consequence, handpumps may go weeks without necessary repairs and Water and Sanitation Hygiene (WASH) managers are forced to make critical program decisions on incomplete data.

Given the critical importance of clean water, it follows that an accurate, reliable and low-cost tool to assess handpump performance efficiency and effectiveness would be valuable to many stakeholders. Improved handpump transparency can lead to better visibility and early warning of handpump problems. This will enable timely handpump remediation, thereby leading to improvements in overall pump efficiency and effectiveness in service to rural African communities.

3 SOLUTION OVERVIEW

The primary goal of IWP is to develop a system to automatically capture and organize data about handpump functionality and performance from both sensor and human sources. This allows the IWP to alert stakeholders via web and mobile applications, email, and text messaging of pump failure or degrading conditions. Coupled with appropriate field response processes, the information the system provides can lead to improved handpump availability with a lower cost of ownership. A secondary goal is the collection of handpump data from all IWP enabled pump sources providing a rich resource of data to enabling WASH practitioners, managers, hydrologists and donors to make more informed decisions.

The IWP team decided on the following design goals and desired outcomes to drive our process:

3.1 Design Goals

- Design a solar-powered, GSM-enabled, pump monitor with a network of sensors to communicate with a cloud-based database application,
- Design a web-based application suite to produce actionable information about handpumps,
- Design a mobile application that exploits location-aware and other mobile capabilities for local field technology workers.

3.2 Desired Outcomes

- Improved visibility of handpump performance and ease of maintenance and reporting,
- Improved understanding of water extraction for each handpump (how much and when),
- Improved understanding of well water level fluctuations,
- Single, unified source for storage, access, and analyses of handpump related data.

3.3 System Overview

The IWP remotely monitors handpumps, including the Afridev and India MKII, through the use of an embedded monitor installed in the handpump. The monitor, connected to and collecting data from concurrently installed sensors, is equipped with a GSM modem to communicate with the cloud-based database application via text messaging through an SMS receiver service. The cloud-based database application parses the transmitted data, populates the database and determines the performance and status of the handpump (See Figure 1).

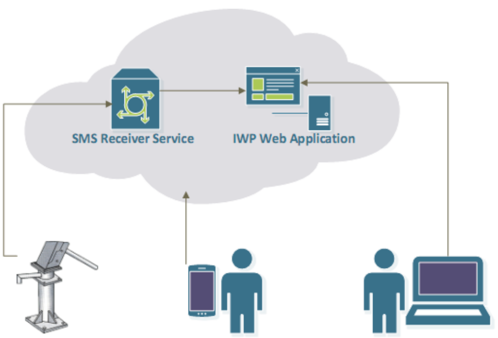

Figure 1: The Conceptual Overview of IWP.

Each day the IWP embedded monitor measures and records the volume of water extracted by the handpump in two hour intervals, the amount of effort required to prime the pump, and the largest recorded leakage rate. This automatically collected data is transmitted daily to the remote database where the information is analyzed and made available to stakeholders via a web or mobile application. In addition to monitoring water extraction, handpump performance, and borehole health, the IWP system processes this data to predict certain degrading conditions before failure occurs and notifies stakeholders via customizable alerts. For instance, an increasing amount of effort required to prime the handpump may indicate degradation of handpump parts while decreasing yield may indicate silting at the screened interval.

In the event of an immediate handpump failure or degrading condition, the system automatically generates email and text message notifications to community members and area handpump mechanics, mobilizing them to inspect the handpump and make repairs. Certain known failure modes are detected and reported by IWP, enabling repair teams to carry the needed parts, supplies, and tools to the site. Community members and area handpump mechanics will also have the ability to report data such as cost of repairs or other visible handpump problems using the mobile app. Once a handpump is repaired, sensor data will verify handpump performance and close the failure reporting loop.

4 FUNCTIONAL OVERVIEW

The main subsystems of IWP include the monitor hardware, database, data transport, mobile app, and web interface.

4.1 Monitor Hardware

The IWP system hardware consists of a solar-powered, GSM cellular-enabled sensor node that mounts inside of India MKII and Afridev handpumps. See Figure 2 for the mechanical layout of IWP on the India MKII platform. The system monitors the motion of the handpump handle and the presence or absence of water in the mouth of the rising main to (a) ascertain the amount of upstroke required to prime the pump, (b) the amount of water extracted from the pump and (c) the rate of leakage in the rising mains. This information is summarized and sent daily to the IWP database.

Since characteristics of handpumps such as the India MKII and Afridev include an open channel, a non-steady flow and low flow rates, standard off-the-shelf

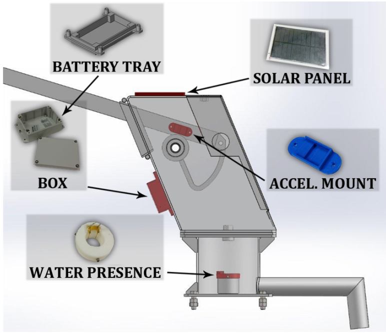

Figure 2: Mechanical Layout of IWP on the India MKII Handpump.

flow meters were found to be unsuitable for our application. Instead, we employ an indirect system of measurement that takes advantage of the mechanics of positive displacement pumps. Knowing the amount of upstroke experienced by the pump rod and the volumetric efficiency of the pump, the amount of water that would have been extracted from the well under ideal conditions can be calculated. For the India MKII handpump this is given by the equation:

$$\text{Volume} = 0.0075\Delta\theta \times \text{Volumetric Efficiency} \quad (1)$$

Where volume is in Liters, 0.0075 is a constant derived from the geometry of the India MKII handpump, θ is the angular displacement of the handle, and the volumetric efficiency is the ratio of the volume of water extracted per stroke to the volume of water swept by the piston (Beyer and Bryan, 1984).

By monitoring the angle of the handle with a low cost accelerometer and performing a numerical integration in software, the total upstroke for each phase of a pumping event can be determined and converted into the theoretical volume of water extracted.

Real handpumps are more complicated than this model suggests due to leakage, therefore, a second sensor is employed. This sensor, located in the throat of the rising main with probes protruding into the riser pipe, relies on the difference in resistivity between air and ground water to sense water flowing in the pump. It transforms IWP from a system calculating theoretical yields to one producing realistic data regarding handpump performance and yield.

To compute the actual volume of water extracted, the priming effort is first assessed by recording the amount of upstroke measured in meters from the start of the pumping event until the water presence sensor detects water. This is stored as another indicator of overall pump health. The theoretical volume of water is then determined using the volume calculation (See Equation 1) from the time the water was sensed until the pumping event is complete. At the end of the pumping event, the monitor starts a timer to determine how long it takes for the water presence sensor to cease detecting water. The time, in conjunction with the cross sectional area of the riser pipe, is used to calculate the current leakage rate of the pump. This leakage rate is then used to deduct the appropriate amount of volume from the theoretical yield, producing a more realistic volume of water extracted. The monitor records water extracted in two-hour intervals, the maximum priming effort, and the leakage rate each day.

While the sensor suite described in detail above is application specific, the rest of the IWP system is applicable to the needs of any solar powered, GSM-enabled monitoring application. As a result it was possible to incorporate several open source and off-the-shelf solutions to decrease development time. GSM Cellular communications and solar battery charging are handled by open source hardware from Adafruit Industries while system power regulation is managed by a commercial boost/buck regulator circuit from Pololu Robotics (See Figure 3).

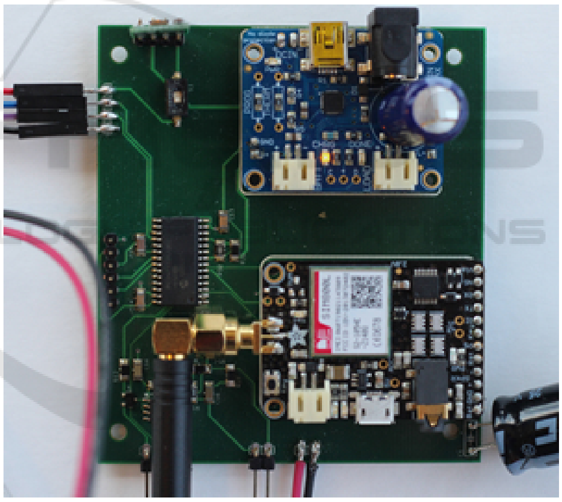

Figure 3: Current Working Prototype Monitor.

4.2 Database and Analytics

The IWP data is housed in a secure, cloud-based database. The main components of the database are depicted in Figure 4.

When an organization installs an IWP Monitor in a handpump within a community, the information necessary to track that handpump is stored in **Organization**, **Pump**, **Community**, and **Part**. The system administrator is then able to link that handpump to authorized **User**s who then have the ability to view information about that pump anywhere in the world. As soon as the Monitor is installed and operational, it begins its collection and transmission of sensor data to be stored in **Sensor Data** (the process of collection and transport is discussed later).

The insertion of sensor data into the database triggers a process that calculates health indicators, such as leakage rate and, based on configurable parameters, determines the current status of the handpump. If the status of the pump changes, the system creates an **Incident** report (SIR), which in turn generates an **Alert**. The user, having the capability to indicate how he/she would like to be notified, will receive the alert on login to the web or mobile application, email, or via text message.

Any authorized user may also create an **Incident** report based on their observation of the handpump. These human-generated incident reports (HIRs) are included in the calculation of the pump status. **Alert**s are generated based on the worse of the two types of incident reports (HIRs or SIRs).

IWP provides a mechanism for grouping handpumps together using **Pump Group**s. Pump groups allow for aggregate analysis, reporting, and searching across pumps in that group. Pumps can belong to more than one group. A pump group has a unique name and a brief description and allows pumps to be grouped by location, field technician, type of pump, or any user-define grouping. There are groups that are automatically formed by IWP based on defined attribute-pair configuration parameters. For example, the system may be instructed to create a group containing all handpumps within an x-kilometer radius on a given GPS location, or those assigned to a given field technician, or within a certain geographic boundary such as a country. The system also allows users to define their own pump groups, or to add groups within groups.

When handpump technicians perform maintenance on a handpump, they complete a **Maintenance Report**, identifying their incurred travel, part, and labor costs.

4.3 Data Transport

The Sensor data collected by the monitor is stored on both an SD Card, installed in the monitor, and resident memory. Every twenty-four hours the monitor packages the collected data as a JSON formatted string and creates an SMS message. The system transmits the SMS message over a GSM (voice grade) wireless network to an SMS Receiver Service. It is commonly known and field studies in Africa have shown (Nejmeh and Dean, 2010) that voice grade GSM network service is much more widely available than 3G network service. Given the desire to field IWP in remote

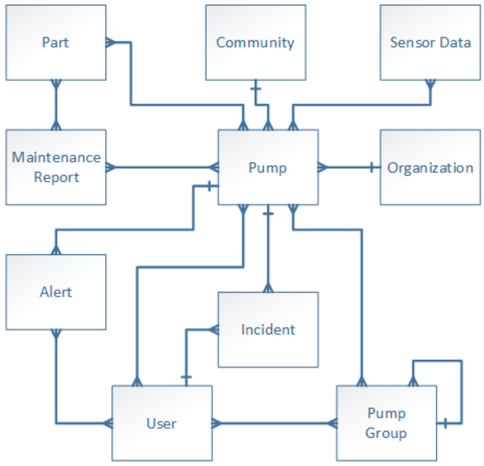

Figure 4: Database Conceptual Model.

areas of Africa, the decision was made to only assume a voice-grade GSM network in our design.

The SMS Receiver Service forwards the message to the parser module in the cloud-resident database application. The parser module posts the raw message in the database, parses the message and (if error-free) stores the parsed sensor data in the database.

These SMS messages are equipped with unique sequence identifiers (USI). Once a message has been successfully processed and added to the database, an ACK message is sent to the monitor. Once received, the monitor will remove the message from its queue based on the USI.

If a message is missing data or the data does not conform to the defined data format, an ERR message is sent to the monitor. The monitor will then attempt to re-transmit the message.

When a duplicate message is encountered, a DUP message is sent to the monitor. In response, the monitor deletes the message from the queue.

The insertion of the data into the database triggers a process that determines the current status of the handpump based on the current sensor data and stores the status in the database. A handpump will have the status of Green (running fine), Yellow (concerns exist about the handpump), Orange (significant problems exist with the handpump), Red (pump failure), or Grey (handpump has not been heard from). This status will be displayed on an authorized user's dashboard and the handpump location depicted on Google Maps®. If the status of the handpump changes, the alert system notifies the appropriate authorized users of the change. Handpump status is a configurable function defined for a given set of handpumps based on the values of daily volume extraction, leakage rate and maximum well level.

4.4 Mobile App

A mobile app is an important element of the overall IWP system. It serves as a lightweight tool for workers to use while in the field, thereby enabling them to take advantage of mobile services such as location awareness and offline modes.

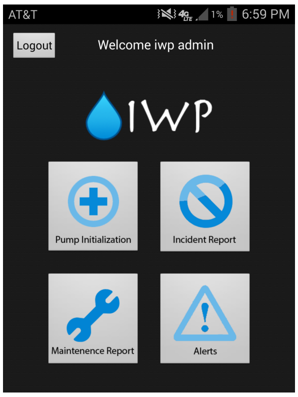

Figure 5: IWP Mobile App.

User Authentication: Mobile app users login to the mobile app using the same user name and password credenials of the web application. The mobile app authenticates users using the same web backend system that authenticates web users. Furthermore, the mobile app limits user access to handpump data and functionality identical to the security and access model imposed by the web application.

Mobile App Interface: Figure 5 displays the main screen of the mobile app. The core IWP mobile app functions are handpump initialization, filing maintenance reports, filing incident reports and viewing handpump alerts.

Handpump Initialization: This function allows a user to initialize a handpump into the IWP system. The function records the field technican assigned to the handpump, the GPS coordinates of the handpump (either automatically recorded (default) or inputted by the user), the phone number on the SIM card installed in the handpump monitor, the date/time of the initialization and other descriptive information about the handpump.

Maintenance Reports: This function allows a user to create and submit handpump maintenance reports (as previously described), including the identity of the handpump, the user filing the maintenance report, date and time of the maintenance report, a brief description of the maintenance performed on the handpump and the total cost of the maintenance report broken down by travel costs, part costs and labor costs.

Incident Reports: This function allows a user to create and submit handpump incident reports (as previously described), including the identity of the handpump, the user filing the incident report, date and time of the incident report, a brief description of the incident being reported on the handpump and the nature of the incident.

Alerts: This function allows a user to view the alerts (as previously described) associated with the handpumps for which the user has been granted access.

Offline and Synchronization Modes: The mobile app requires a data grade connection to transmit data, and since there will be times when such a connection is not available, an offline and synchronization mode is necessary. In such cases, the mobile app will locally persist the data (i.e. yet to be filed maintenance reports and incident reports) on the mobile device. Upon the mobile app sensing a data grade connection, the persisted data will be transmitted to the IWP system.

4.5 Web Interface

The data from the monitor is collected and stored automatically in the database which can be accessed by authorized users via a secure web application or mobile app. The status of individual handpumps can be viewed on a map interface powered by Google Maps®. Each handpump on the map is represented by the pump status indicator (green, yellow, orange, red, or grey) depending on the level of functionality of the handpump.

The reporting module allows users to select a time period, single or multiple handpumps, or pump groups for further investigation, and provides either detailed or aggregated information. Selection can be accomplished via the map interface by selecting individual handpumps or pump groups. The IWP web application can export these queries as printable PDF reports or MS Excel Spreadsheets for further investigation or reporting purposes.

Notifications are handled automatically by the IWP software in the event of a change in a handpump status indicator. These are sent to appropriate stakeholders via email or text message depending on their preferences. The notifications are sent in the case of degradation, such as a status change from green to yellow or red, and in the case of an improvement, such as a status change from red to yellow or green. This allows stakeholders to know not only when a pump is broken, but also when and to what extent it has been repaired.

5 RESULTS TO DATE

Throughout the development of the IWP hardware, intimate knowledge of the inner working of handpumps and their failure modes and frequent field deployment of prototypes have been crucial to the design of a functional system. The IWP project was born out of a prior project (Anthony Q. Beers, 2013) that identified the most common failures in India MKII handpumps in West Africa which resulted in a redesign of several failure prone components. This initial study provided the mechanical understanding necessary to develop a sensor suite tailored to monitoring positive displacement handpumps. IWP also benefited from the availability of complete blueprints and 3D models of both the India MKII and Afridev handpumps and full knowledge that the handpumps in the field are rarely within the tolerances in the specification drawings.

The prototype IWP system has been through four design iterations, including laboratory testing in the US and field testing in northern Ghana. The field trials occurred throughout 2014 and 2015. In our early trials, we discovered that several key dimensions on the MKII often fell well outside MKII design specifications. The IWP geometry and installation procedures were modified to facilitate installation in actual field conditions. Our early field trials also revealed that noise effected the accelerometer data so that deviation between actual and measured water extracted was unacceptable. Our most recent field trial completed in October 2015. This iteration incorporates more robust sensor housings, a theft resistant solar installation design, a software filtering solution for noise in the accelerometer data, and a few minor changes to the printed circuit board design. The water presence sensor was moved out of the throat of the rising main to avoid any proximity with the handpump rod. This sensor is now in a T fitting attached to the top of the rising main. A ten-point moving average algorithm has also proven an effective low pass filter for accelerometer noise. Testing to date indicates water extraction measurements are within ten percent of actual.

The IWP software is managed in a Cloud environment at the domain www.intelligentwater.net. Initially, the data transport software layer had been extensively tested in a simulated environment with representative sensor test data imported from a spreadsheet. Initial smartphone tests in Africa demonstrated successfully sent test messages through an SMS Receiver Service. The web application has been developed and tested using representative sensor test data and is functioning properly. Finally, the mobile app is running on the Android Operating System and includes support for handpump initialization and submission of maintenance reports. The mobile app has been used in Africa to successfully initialize a handpump. The October 2015 field trial has demonstrated that the monitor successfully communicates with the server, sending sensor data in JSON format. In turn, the sensor data has been successfully parsed and populated the database appropriately. Through a series of three successive field trials in Africa over an 18 month period ending October 2015, we have learned a great deal. The IWP has accomplished significant progress toward demonstrating proof of concept. The design of the sensors, solar panel, charging circuit, and printed circuit card are stable, as is their integration with the microprocessor and cell phone modules selected for IWP.

6 FUTURE WORK

Significant opportunities exist for advancing our work. Sensor data collected over time will validate assumptions and features such as alerts, change in handpump status, etc. Ideally, we would like to see the system deployed through the status cycle of a handpump to insure that the system correctly senses the deterioration of the handpump, issues the appropriate alerts and senses the handpump performance improving upon being repaired by a field technician.

The IWP software will evolve based on lessons learned from field trials. It is expected that significant advances will be made in handpump data analytics based on feedback from handpump field technicians. There are a number of future directions envisioned for the mobile app, including:

- improved support for offline functionality and auto-synchronization upon network access,
- Geo-location tracking for locating and navigating to handpumps,
- multi-language support for French, Spanish and other languages,
- 3G wireless network data transport support for the embedded monitor unit mounted within a handpump.

In addition, processes and training need to be developed for local African technicians to utilize the web/mobile app as they fix handpumps. Feedback from theses sources will be used to enhance both the web and mobile applications.

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