ICT-enabled solutions for smart management of water supply in Africa

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***Abstract*—Pervasive and ubiquitous technologies that include mobile device applications, machine to machine communications, and cloud computing, are increasingly used for cost-effective data aggregation and information dissemination. Recently, this trend has started to gain momentum in the water sector and is being used for various management and monitoring tasks, such as remote leakage detection, automated meter reading and enhanced usage feedback to water users. This paper analyses the challenges faced by various stakeholders (consumers, utilities, etc.) in the water supply industry. Application of the said technologies is then proposed to address these unique challenges and the varying data needs of all stakeholders. An example solution, with a mobile device application and supporting cloud computing solution, is developed and presented as a proof-of-concept to further illustrate the potential use of ICT for water supply management.**

I. Introduction

Access to a safe and reliable water supply impacts every aspect of our lives, even if we may not be aware of the consequences. For over 300 million people living in Africa without access to safe water [1], hours are spent every day fetching water from rivers and other potentially unsafe sources of water simply to meet their daily water needs. Additionally, they face the risk of infection from water borne diseases or dehydration from using unsafe and vulnerable water sources.

For those with access to piped water in their homes, it is easy to take this source of water for granted and forget about the water scarcity being experienced around the world. The only usage feedback they receive is a monthly bill that details the user's cumulative consumption at the end of a month, making it difficult to identify the effects of specific events (e.g. how much energy and water a five minute shower uses). Additionally, many water service providers (WSPs) are struggling to recover costs associated with water service provision and the development of infrastructure. For example, in 2010, the World Bank estimated that US$ 17 billion would be required annually for the water supply infrastructure in sub-Saharan Africa to meet the millennium development goals, with around a third of this funding allocated to operation and maintenance costs [2].

By providing consumers and service providers with additional data and enhanced means of information collection, through the use of information and communication technologies (ICTs), many of these challenges can be alleviated. These technologies have been leveraged in other sectors, such as healthcare, education and agriculture, to create unique solutions for the problems faced by these industries [3]. For example, Text to Change (TTC) has utilised basic mobile phones to provide farmers in Africa with daily information on effective agricultural practices, market prices and weather forecasts using text and voice messages [4].

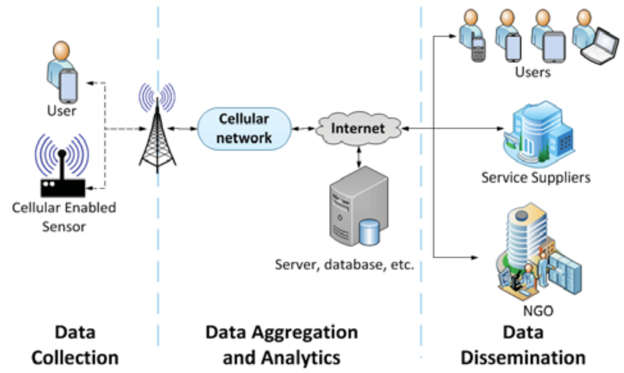

Fig. 1. Typical flow of information in the water supply industry. (Adapted from [5])

Figure 1 shows the typical flow of information for ICT systems in the water supply industry. Data collection can be performed by users (customers or employees of WSPs) with a mobile device through various means, including Short Message Service (SMS), Unstructured Supplementary Service Data (USSD) or data submissions from smartphone devices (e.g. photos or co-ordinates). Alternatively, information can be reported in by automated sensors over cellular networks. The data is then stored in a central server or database where it can be accessed directly or processed further to create useable data (e.g. reports for WSP managers). Data can then be accessed by users (e.g. consumers accessing usage data) or disseminated automatically to relevant stakeholders (e.g. informing users of events).

A. Contribution

This paper presents an analysis of the various implementations of ICTs in the water supply industry in Africa and illustrates how these technologies can be used to empower a wide array of users, with varying economic and physical (i.e. location) circumstances, as well as offering benefits to all the stakeholders in the industry. Additionally, a proof-of-concept

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Android mobile application is also presented, which can be used to view usage data for domestic hot water cylinders.

The rest of this paper is organised as follows: Section II describes the various roles that ICTs can play in the water industry and the challenges they can help to alleviate; Section III presents the proof-of-concept Android mobile application that is used to further illustrate the potential of ICTs as well as the future work for the application; and Section IV concludes the paper.

II. Role of ICTs in the Water Industry

The mobile industry has had a tremendous effect on the African continent. Global System for Mobile Communications (GSM) coverage is estimated to reach 76 percent of the African population and has outgrown access to reliable and affordable electricity and water services over the past 10 years [6]. The rapid growth of mobile network coverage is providing millions of people with first time access to modern infrastructure services. For example, 130 million people in sub-Saharan Africa (SSA) are covered by mobile networks but do not have access to an improved water source [6]. Mobile phones are becoming increasingly ubiquitous, with a unique mobile subscriber penetration of 35 percent in Africa at the end of 2013. Along with the decreasing cost of mobile handsets, these devices are being used as cost-effective tools for collecting and disseminating critical information [5] [7]. **Mention penetration and growth rates of smartphones in Africa.

Coupled with the growth in machine-to-machine (M2M) communications, mobile banking and other ICTs, there are many opportunities to enhance the lives of everyone in Africa. The following sections present examples of using ICTs for various stakeholders and applications in the water industry in Africa, ranging from cellular enabled handpumps to increase reliable service provision for the rural poor, to smart meter enabled systems to aid middle- and high-income groups in urban areas in using their energy and water more efficiently.

A. Crowdsourcing Data

Water quality is a problem that affects all stakeholders in water supply industry: WSPs are required to monitor the quality of the water they provide; and end users face the health risks associated with consuming contaminated water. In crowdsourcing systems, data is collected and submitted by members of the community via mobile devices [8]. The aim of these systems is to allow end-users to directly communicate information to relevant stakeholders in order to benefit both parties [5]. For example, the Mobile 4 Water application allows members of the community, in Uganda, to report a fault at a water point via SMS [9]. Over 15 000 water points are being monitored by this system, which allows WSPs to obtain additional information which would not have been possible through costly field visits [9]. End-users, on the other hand, are incentivised with the promise of better service provision for communities by prompting WSPs to take corrective action [8], as well as being able to view the status of water points in their area and, therefore, avoid consuming water from contaminated sources [9].

Another example of such as system is the m-Maji mobile phone-based water information system in Kenya. Water vendors, who resell water from the utility network or a private source, play a crucial part of service provision in many African countries [10]. For example, mobile vendors serve an estimated 32 percent of the urban population in Mauritania [11]. This is because private piped water supply access is limited and, in areas where it is available, service provision is often intermittent or insufficient [10] [11] [12]. The m-Maji mobile application allows water vendors to advertise their services using USSD. This includes: the selling price of their water; their location; and, optionally, whether or not the water has been purified. This data is stored in a central database which water buyers can use to search for suitable vendors, also using USSD. The system also caters for quality management by allowing buyers to report vendors who are fraudulent (e.g. lied about quality or price) to alert future buyers [13]. Additionally, the quality of water being advertised as purified is monitored by M-Maji staff through random monthly water quality tests [13].

B. Data Capturing

In addition to using crowdsourcing as a means of collecting data, mobile phones can also be used to facilitate the process of data capture by WSPs' field staff. In [14] the design of a mobile phone-based information system is presented for water quality management by municipalities in rural and under-resourced areas. The system was implemented in four rural municipalities in South Africa and employed two mobile applications: the water quality reporter (WQR); and the water quality manager (WQM). The WQR application is used for data collection and was installed on the phone of a water supply caretaker (e.g. borehole operator). The caretaker could collect and insert the required data into a form that is then submitted to a server for verification and storage purposes. The server would return a message that informs the caretaker of the success or failure of the submission. In the event that the caretaker submits any erroneous data (i.e. invalid values), the information would have to be recaptured and resubmitted.

Additionally, a message is sent to the responsible manager if the results are outside of suitable bounds. The WQM application is intended to support management functions, such as analysis of collected data, and was thus installed on four Android phones which were supplied to a manager at each municipality. Managers could review water quality testing for any of the water sources under their authority in real-time. The WQR system automatically provided the relevant managers with weekly reports of raw data in spreadsheets. The reporting of water quality standards of all four municipalities increased with the introduction of this system. Additionally, managers and water supply caretakers stated an increased awareness and appreciation for collecting data used in monitoring and diagnostics.

C. Remote Asset Monitoring

In Africa, handpumps are installed in remote rural locations as a means of improving the access to safe drinking water and to decrease the distance the rural population must travel to satisfy their water needs. The operation and maintenance (e.g. spare parts for repairs) of these assets is a complex challenge

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[15] as there is insufficient data on their usage and status. Often the spare parts required for repairs are not always rapidly available [15] and it has been estimated that a third of installed handpumps are out of service at any given time [16]. GSM coverage is expanding into areas that rely on handpumps for their water supply, allowing ICTs to facilitate the management of these assets [8].

The design, building and testing of a prototype Waterpoint Data Transmitter (WDT) that provides real-time usage data for handpumps is presented in [15]. A field test was conducted on three India Mark 2 handpumps (installed two years prior to the test) over a period of four days in Valley View, north-west Lusaka (Zambia). The WDT is attached to the handle of a handpump and consists of: a simple microprocessor; an integrated circuit (IC) based accelerometer; and a Global Systems for Mobile communications (GSM) modem. The device monitors the number of strokes made during operation of the handpump and transmits this data in one minute intervals via SMS using the GSM network. Analysis of this data can lead to: estimates of the usage (volumetric output) and performance of handpumps; the detection of faults and possibly insight into the nature of the failure when compared to historical data [15]; better infrastructure management by identifying areas requiring additional assets; and increased accountability of service suppliers, as the upkeep and usage of assets can be recorded to determine the efficiency of service delivery. Additionally, all of these functions can be performed remotely which implies that less field visits are required to collect the relevant data (e.g. determining usage of a specific asset), resulting in substantial cost reductions for WSPs.

D. Information Dissemination

Another challenge faced in Africa is water-borne diseases, which kill millions of people each year. This section presents the mHealth E.coli smartphone application. This application is used in conjunction with a Mobile Water Kit (MWK) to act as a low-cost water monitoring system for the rapid detection of certain harmful bacteria (i.e. E.coli and total coliform) in water samples [17]. To assess the quality of water, the user is required to collect a sample of water to be tested using a syringe and filtering the sample through a syringe filter unit. The user must then add the formulated chemical reagents sequentially onto the syringe filter unit. The presence of harmful bacteria is indicated by the appearance of a red colour on the surface of the syringe filter unit.

This data can then be submitted via the mHealth E.coli application, which runs on an Android smartphone. Users first select the type of source that the water sample was collected from (e.g. river, well, etc.) and then proceed to take a photo of the tested syringe filter unit. The photo is analysed by the application and the results are shown to the user. Thereafter, the photo and the Global Positioning System (GPS) location of the smartphone are uploaded to a server via SMS to provide a unique location identifier for contaminated water sources. These results are then used to send SMS notifications to issue water quality alerts to subscribed users. Although this system was trial-tested in Canada and India, it is also applicable to the African context. This system can create an early warning system to detect outbreak of water-borne diseases in communities and users of contaminated sources.

E. Consumer Data Access

Eco-feedback is based on the theory that the majority of users are unaware of or don't understand the impact of their daily activities on the environment [18]. This lack of knowledge can be mitigated using ICTs to help consumers better understand their usage by accessing higher resolution data through timeous feedback channels. In [19], a wireless M2M network was used in several regions of South Africa to remotely monitor and control the hot water cylinders (HWCs) of residential households in near real-time. The HWCs are equipped with sensors (e.g. thermocouple) and actuators (e.g. dump valve) that are used to collect data and perform control operations, such as monitoring temperature or safely emptying the HWC in case of a failure. A cellular modem allows these devices to connect to a remote server with general packet radio service (GPRS) using cellular connections. Data can then be reported to the server at a set interval and is stored in a database where it can be used in its raw form (e.g. current temperature of water in HWC) or processed further to create useful results (e.g. cumulative energy usage for a day). Users can access this stored data via an Internet portal which performs queries on the database and relays relevant data to corresponding users and also allows them to issue control commands, such as manually turning a HWC on or off. Commands are received by the assets from ther server using the cellular modems and are performed by the hardware (e.g. microprocessor and actuators) situated at the HWC asset. This system therefore allows consumers to view their usage, such as temperature and energy graphs, and control aspects of the system from any remote location with Internet access.

Feedback of usage data to consumers in near real-time can allow them to make informed decisions regarding their future resource use, resulting in reductions in water and energy demand from residential households [20]. This type of system is better suited to middle- and high-income users as it requires users to live in a household with electricity and private piped water access, as well as requiring users to have Internet access to interact with the systems online interface. However, this system illustrates how ICTs can be leveraged to create a wide array of solutions for all types of consumers. Additionally, this type of system is beneficial to WSPs as they can better understand consumers usage (on a local, provincial or national level) and improve management of infrastructure and other management tasks with higher resolution data [20]. For example, they could use a smart metering system to determine if users are complying with water restrictions, which is of particular importance to drought stricken areas. This data can further support management tasks for WSPs by allowing them to cater education programs (aimed at promoting water conservation) towards specific usage patterns in different areas (e.g. a program could focus on a specific end-use of water, such as outdoor use for gardening activities).

III. Proof-of-concept Smartphone Application

The interface used to control assets, mentioned in the previous section, is not particularly well suited for access by mobile phones or tablets. The proof-of-concept mobile application presented in this section, therefore, builds upon the functionality of the aforementioned system by allowing users to monitor their usage through an Android smartphone by interacting with easy to use native Android elements, such as spinners (i.e. dropdown menus).

This section presents a proof-of-concept smartphone application that is aimed at aiding demand-side management of residential household energy and water usage (i.e. reduction in water demand of residential consumers), which, in turn, allows for the deferral of additional water supply infrastructure asset construction [20] and the conservation of precious water resources. Although HWCs make use of both water and electricity and only includes hot water usage (not total household water usage), the application constitutes as a eco-feedback implementation. This mobile application runs on an Android smartphone and allows users to monitor the current status of their HWC as well as graph historical usage data. Data is requested from the central server through the system's representational state transfer (REST) application programming interface (API) and suitable Hypertext Transfer Protocol (HTTP) GET requests, based on the task the user is performing. The server can either convey the raw data to users (e.g. instantaneous thermostat temperature) for graphing purposes or it can provide users with metric values, which have been processed by the server to create a useful data value (e.g. average internal HWC pressure) for asset status updates or monitoring purposes. The application is divided into three main tabs that are described in further detail in the following sections.

A. *Usage Tab*

The Usage tab, shown on the right in Figure 2, can be used to view the most recent data reported by the HWC asset. It provides the user with an overview of the asset's daily resource consumption and the associated cost thereof (in Rands). The data is also timestamped so that users are able to determine when last these values were updated. Users are also able to manually refresh this data by clicking the refresh icon in the action bar. If the application attempts to obtain data from the server and is unsuccessful (due to lack of network access, etc.) a relevant error message is displayed to the user. The system is not yet able to provide usage statistics for user water consumption and thus the values shown for water consumption and flow are included to provide a preview of future work and to illustrate the complete appearance of the user interface.

The data summarised by this tab can help users to better understand their daily usage patterns without providing excessive amounts of data that would overwhelm and confuse users. Additionally, the tab provides both a usage value (either kWh or litres), for those users who are perhaps more technical or interested on the environmental impact of their usage, as well as a monetary value, for users who may be non-technical users or interested in financial incentives for reducing their energy and water consumption.

B. *Status Tab*

Users are able to view the status and present settings for the control unit that manages the HWC asset on the Status tab shown on the left in Figure 2. This includes: the present water temperature value; the temperature set point, which is only enforced when the control unit is enabled; the present on or off state of the HWC element; the present energy usage of the asset; the status of the timer control unit (i.e. whether or not control unit is enabled); and the on/off schedule that is implemented by the control unit (which is an expandable table that can be minimised to save space). However, due to API restrictions, users must login separately on the Internet platform, through a browser window, to edit any of the settings of the controller unit (such as the schedule or temperature set point). The dials used in the usage and status tabs were created by editing a custom library, called SpeedometerView [21].

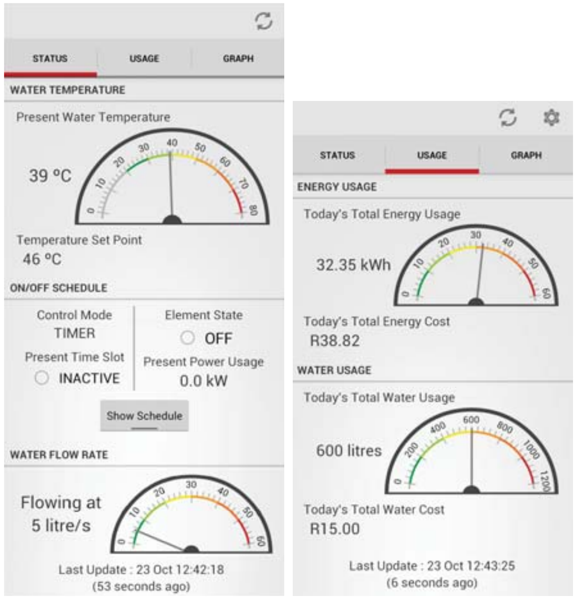

Fig. 2. Status (Left) and Usage (Right) tab of smartphone application

C. *Graph Tab*

The application also allows users to graph various types of daily usage data on the Graph Tab, shown in Figure 3, in order to better understand their usage. This functionality was created with the use of AChartEngine, an open source graphing library for Android [22]. The user can choose the type (e.g. energy consumption) and date of the data they wish to view. The data for an entire day is obtained from the server and displayed in time intervals of one minute. Users are also able touch anywhere on the graph to obtain the time and data values for a particular point (the annotation and vertical line in Figure 3).

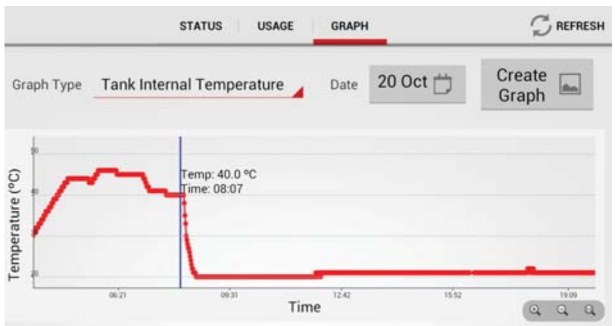

Fig. 3. Graph tab of smartphone application

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D. Future Work

Future development of the mobile application will involve several enhancements to the functionality. Firstly, the application will include the feedback of water usage to consumers as this is important in understanding their overall resource consumption. Secondly, control capabilities will be added to the application to allow users to control the various aspects of their HWC (such as the temperature set point and on/off schedule) from the mobile application interface. Additionally, the analytics of the system will be greatly improved. The system will access users' current settings and analyse their daily usage patterns to make recommendations on optimising their HWC's settings in order to reduce their energy usage. Coupled with the control functionality, this has the potential to significantly reduce consumer usage by disabling the HWC when not in use while maintaining the temperature of the user's hot water at a comfortable level that suits their schedule. Furthermore, an audit function will allow users to enter information about their household (e.g. the number of bathrooms, showers, etc.). This information will then provide users with a typical usage value that would be expected for such a household. Users could then compare their usage to these values (i.e. normative comparisons) and become aware of how much water they use in comparison to other similar households, which helps to contextualise a user's consumption by providing a benchmark for resource usage.

IV. Conclusion

This paper presented several ICT-based solutions to challenges faced by the water supply industry in Africa. The proposed solutions cater for a variety of stakeholders with varying information needs and circumstances, ranging from low-income water consumers in remote rural areas to WSPs serving middle- to high-income consumers in an urban setting. A proof-of-concept smartphone application was also presented to illustrate how these technologies can be leveraged to create unique solutions. This mobile application was aimed at increasing consumer awareness and reducing water and electricity demand, as well as providing WSPs with additional data for management tasks.

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