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Using smart pumps to help deliver universal access to safe and affordable drinking water

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It is estimated that broken water pumps impact 62 million people in sub-Saharan Africa. Over the last 20 years, broken handpumps have represented US$1·2–1·5 billion of lost investment in this region, with 30–40% of rural water systems failing prematurely. While the contributory factors are complex and multi-faceted, the authors consider that improved post-construction monitoring strategies for remote water projects, which rely on smart pumps to monitor operational performance in place of physical site visits, may address some of these problems and help reduce the heavy time and resource demands on stakeholders associated with traditional monitoring strategies. As such, smart pumps could play a significant role in improving project monitoring and might subsequently help deliver universal access to safe and affordable drinking water by 2030, which constitutes one of the key targets of United Nations sustainable development goal 6 and is embedded in some national constitutions.

1. Background/context

1.1 Access to safe water

Many communities across the globe lack sustainable access to safe drinking water. It has been reported that 768 million people in developing regions do not have access to safe water (WHO and Unicef, 2013). Sadly, this results in a significant amount of preventable diseases and death. For example, diarrhoeal disease, which is often linked to exposure to unsafe water, is the second leading cause of death in children under 5 years old (WHO, 2013a), causing approximately two million deaths per year (WHO, 2013b).

1.2 Sustainable development goal 6

The United Nations (UN) sustainable development goals (SDGs) are a set of goals, targets and indicators that UN member states adopted in 2015 to steer international policies up to 2030. The SDGs cover a range of development issues, including ending poverty and hunger and improving health and education (UN, 2015). Sustainable development goal 6 (SDG 6) – which specifically addresses access to clean water and sanitation – aims to ensure universal access to safe and affordable drinking water by 2030. It also seeks to 'expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programmes' and to 'support and strengthen the participation of local communities in improving water and sanitation management' (UN, 2015).

1.3 Millennium development goal 7

The SDGs seek to build on the UN millennium development goals (MDGs), which were a previous set of developmental targets adopted by the UN in 2000. The MDGs included target 7.C, which aimed to 'halve, by 2015, the proportion of people without sustainable access to safe drinking water' (UN, 2008). It has been widely reported that target 7.C has been achieved (Loyn, 2012). It is claimed that 89% of the world's population now has access to 'improved water' supplies; compared to a reported 76% in 1990 (WHO, 2012). An 'improved water' source is generally defined as one that is constructed such that it protects the supplied water from contamination, in particular faecal matter.

Despite recent progress, including the achievement of MDG target 7.C, many sub-Saharan Africans still do not have access to improved water sources. It has been reported (WHO and Unicef, 2013) that only 63% of the population in this region have access to improved water supplies.

1.4 Broken water infrastructure

Many rural populations served by an improved water source, such as a borehole, may still experience operational challenges. It is evident that all types of water pumps will deteriorate and exhibit worsening performance with age (Jiménez and Pérez-Foguet, 2011). But when such infrastructure malfunctions, local communities will often resort to using less-protected water sources, increasing their exposure to a wide range of water-related diseases.

The problem of broken water pumps (Figure 1) in rural Africa is well documented, with studies reporting that between 20 and 65% of handpumps installed in various African countries are broken or out of use (RWSN, 2010). It is estimated that approximately 61·8 million people across this region are served by broken water pumps. This is derived from a reported total of 823 856 handpumps in sub-Saharan Africa (MacArthur, 2015) and the assumptions that (*a*) each pump serves an approximate user community of 250 people and (*b*) 30% of these pumps are broken. Figure 2 compares the population of sub-Saharan Africa affected by broken pumps with their access levels to other key infrastructure (GSMA, 2014; Tortora, 2014; WHO and Unicef, 2013; World Bank, 2015).

Figure 1. Broken water infrastructure in sub-Saharan Africa

The problem of broken pumps threatens to undermine some of the gains made as a result of the MDG targets (e.g. MDG 7.C). This could represent a regression in people's access to water, contrary to various international agreements towards progressive realisation of the human right to water (as discussed in Section 4.1). Furthermore, broken pumps represent a capital loss of infrastructural investment. It is reported that, over the last 20 years, broken handpumps in this region have represented between US$1·2 and 1·5 billion of lost investment, with 30–40% of rural water systems failing prematurely (Usaid, 2016). The contributory factors associated with the reliability of such pumps are considered to be varied, complex and, in many cases, interconnected. Figure 3 attempts to represent graphically these issues and their interactions.

Cooper *et al*. (2014) previously reviewed the contributory factors that impact pump reliability and maintenance. It is considered that key issues include: insufficient local financial resources to fund necessary repairs; limited access to spare parts; limited technical capacity within the user community; inappropriate project implementation and/or technology choice; and limited post-construction monitoring and support from external agencies. For example, it is widely advocated across much of the developmental sector that local communities should both manage and financially service their own water points, with some degree of external support. For instance, the non-governmental organisation (NGO) WaterAid promotes water 'technologies that can be operated, managed and financed by communities, with assistance from local government and service providers' (WaterAid, 2015). But the

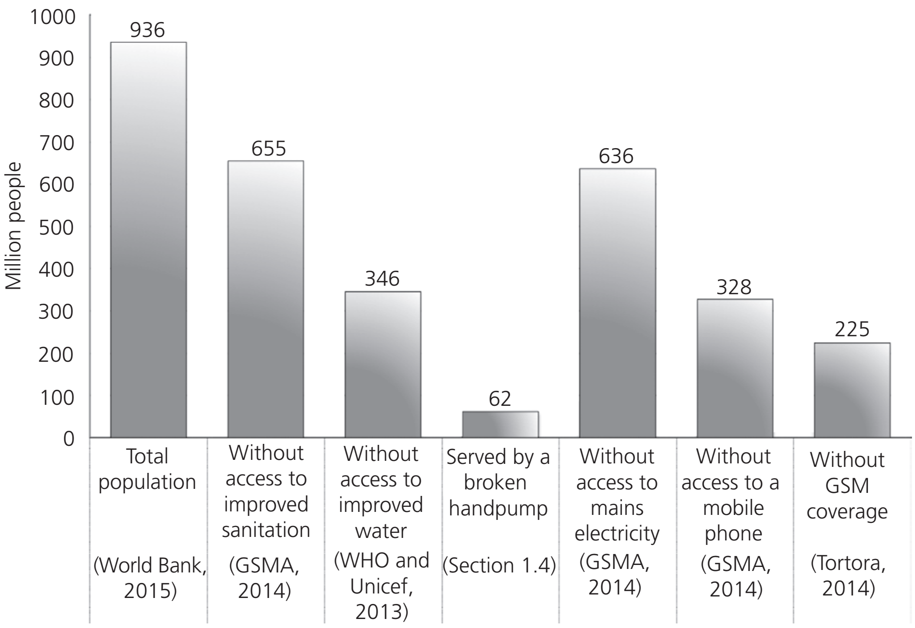

Figure 2. Sub-Saharan Africa – population and access to key infrastructure

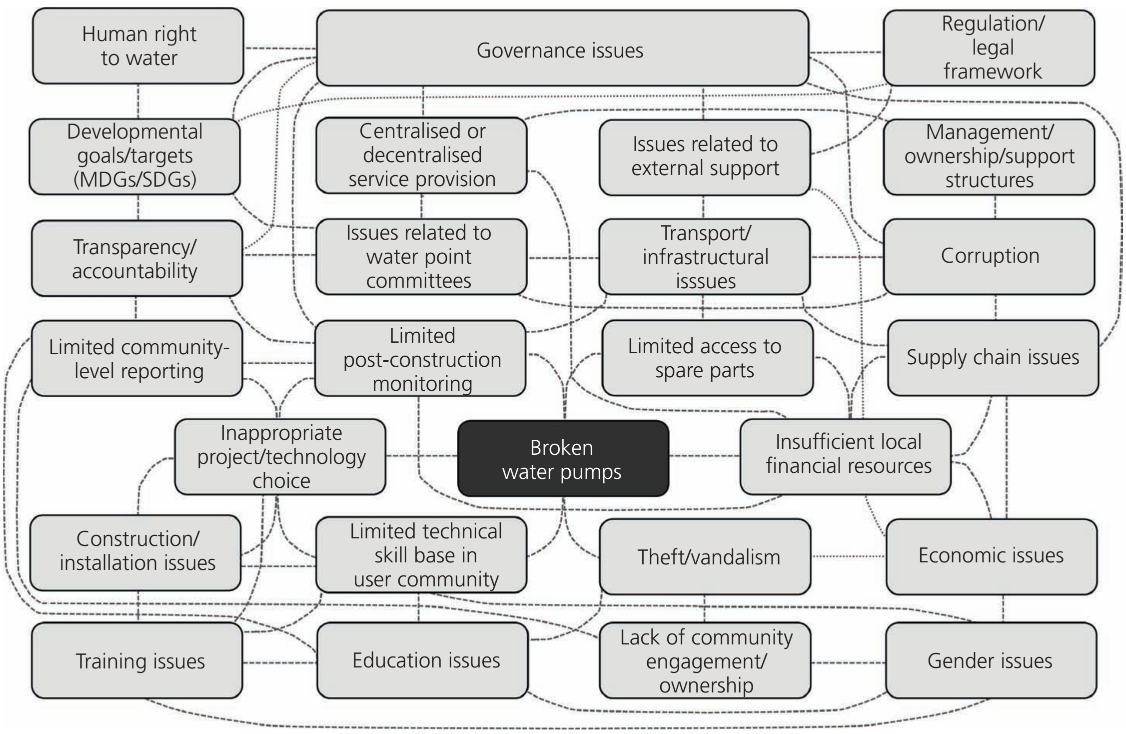

Figure 3. Interconnected contributory factors associated with broken water pumps

success of any maintenance system/strategy can only really be observed, and assessed, by conducting ongoing project monitoring. Without such post-construction monitoring of water points or continued dialogue with local communities, external support agencies are unlikely to detect problems requiring attention, or even to maintain accurate historical records of the levels of operational performance achieved.

1.5 Limited project monitoring

Previous studies from across the global south have reported low levels of post-construction monitoring for rural water projects. For example, Usaid (2016) recently reported that less than 5% of water, sanitation and hygiene (Wash) projects are visited after installation and, as such, broken infrastructure frequently goes undetected or is not addressed by the relevant stakeholders. In relation to water provision, an extensive study of 400 remote water points within Peru, Bolivia and Ghana (Whittington *et al*., 2008) indicated that, over a 3-year period, more than 50% of the surveyed water point communities received no visit, assistance or training from external support agencies. A more recent study conducted at 679 water points across Malawi (Chowns, 2015) reported very low levels of post-construction monitoring: 71% received none from the installer and 57% received none from any source. This study also highlighted that most communities with a broken-down water point had not reported it to anyone outside the village, despite this supposedly being a responsibility of the local government (Chowns, 2015).

In this context, it is considered that improving post-construction monitoring of remote water projects through the use of smart pumps or other forms of telemetry, which can remotely monitor operational performance in place of physical site visits, could potentially help address some of these challenges and reduce some of the heavy time and resource demands on stakeholders that are characteristic of more traditional monitoring strategies.

2. Telemetry and other relevant innovations

2.1 Overview

Telemetry devices that remotely measure operational performance data are widely used for many applications across the globe. Some telemetry systems use short message service (SMS) messages to send operational data from remote locations, providing comparatively low costs and wide coverage offered by mobile phone networks. This is timely, given the rapid growth in mobile phone network coverage that has occurred in recent years, coupled with the emergence of cheap telemetry monitoring systems. For example, a recent survey (Tortora, 2014) conducted in 23 sub-Saharan African countries indicated that two-thirds (65%) of households had at least one mobile phone in 2013. This represents an increase of 27% since 2008 within these countries.

2.2 Review of emerging telemetry technologies

There is a growing interest in the use of mobile phone-based tools and telemetry technologies for monitoring water projects in sub-Saharan Africa. This is demonstrated by the emergence of field trials of a number of new technologies, most notably SweetSense, the smart handpump project and MoMo. Many of these systems are designed to monitor remotely the operational status of handpumps, with problems reported back to local maintenance teams (see Figure 4). These technologies are based on a diverse range of remote measurement, including the use of accelerometers, pressure transducers or flow sensors.

2.2.1 SweetSense project

The SweetSense programme of Portland State University has produced technologies for the developing-world context that are focused on the collection and dissemination of a range of field data over mobile phone networks. These sensor technologies have been used to monitor the operational status and/or performance of key rural infrastructure such as bridges, sanitation and water projects (GSMA, 2014).

A 7-month field trial of 181 monitored water pumps across Rwanda began in November 2014. It is reported that this approach used CellPump monitors, with differential pressure transducers, to measure flow rates. This study explored the merits of different pump management strategies, one of which used CellPump monitors to observe the pumps' operational status and report back to maintenance teams, through a smartphone app, if and when repairs were needed (GSMA, 2014). It is reported (GSMA, 2014) that, during the study period, the monitored group of pumps had a median time to successful repair of approximately 21 d, with a mean per-pump functionality of about 91%. In comparison, a benchmark group of pumps, with a conventional maintenance strategy (i.e. that did not use operational data from the pump monitors), had a successful repair interval of approximately 152 d with a functionality mean of nearly 68% (Nagel *et al*., 2015). It is evident from this study that the prototype system may offer some potential to improve the operational performance of water pumps.

2.2.2 Smart handpump project

The University of Oxford has field-trialled smart handpumps that use a mobile data transmitter and an accelerometer linked to the pump handle. The approach was initially demonstrated as a proof-of-concept prototype in Zambia (Thomson *et al*., 2012). This platform consisted of an integrated circuit-based accelerometer, microprocessor and Global System for Mobile Communications (GSM) modem, attached to India Mark II handpumps. The technology was subsequently trialled on 66 handpumps in Kenya for 12 months between 2013 and 2014. The prototype system compiled hourly pump usage data, which were dispatched on a per 6-h basis. These field data were relayed through SMS messages to an operational database in Nairobi and in turn graphically presented on a map layer, which indicated those pumps that are in frequent use. Pumps that did not appear to be regularly used were assumed to be malfunctioning, and a technician was dispatched to them in order to identify and rectify the problem (GSMA, 2014). It was reported that the use of the water point data transmitter (WDT) system helped improve the average pump downtime (i.e. time until a successful repair was implemented) from 27 to 2·6 d (Nagel *et al*., 2015). The preliminary WDT trial (Thomson *et al*., 2012) also indicated that it might be possible to identify proactively some pump-failure mechanisms from the field data received.

2.2.3 WellDone project

WellDone is seeking to develop an open-source monitoring platform called MoMo (mobile monitor) that will allow key stakeholders, such as governments and NGOs, to compile sensor data from rural infrastructure in remote developing-world contexts (GSMA, 2014). The approach involves the use of GSM-enabled units that can be attached to handpumps, pipes and power systems. As with the smart system, field data are sent back through SMS messages to a central database. This database can be monitored for daily service/usage levels for both water and energy infrastructure. A series of field trials is underway across Africa.

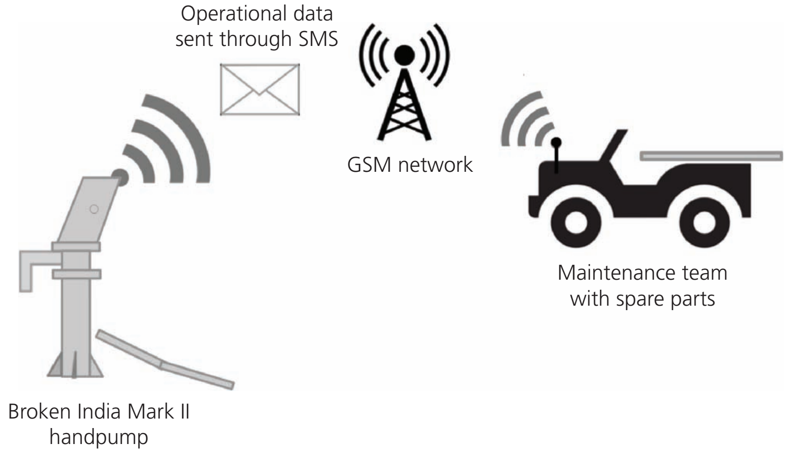

Figure 4. Remote monitoring of operational status of handpumps, with problems reported back to maintenance teams

2.2.4 Dispatch monitor

The NGO charity: water and its partner organisations have developed a dispatch monitor system that comprises a remote sensor unit and software system that processes data from the field and graphically presents this information on a user interface. Field trials of this system are underway in Ethiopia (charity: water, 2015).

2.2.5 Leeds Beckett University and Environmental Monitoring Solutions

Investigations are underway to develop appropriate low-cost telemetry tools for improving the post-construction monitoring of remote water points in developing regions. This is the focus of an ongoing PhD study at Leeds Beckett University as well as the collaborative Mantis (an acronym for 'Monitoring and Analytics to Improve Service') project between the university and Environmental Monitoring Solutions. In addition to the low target cost, these studies aim to develop units that are easily deployable, robust and durable. The Mantis units relay information through an SMS server to an online platform, which can be used to identify repair requirements and schedule timely interventions. The system is intended to identify issues associated with water scarcity, resource demand and long-term operational reliability. The Mantis system is currently being field-trialled in Sierra Leone (see Figure 5); these investigations will be reported within ensuing publications.

In summary, despite the relatively recent emergence of such monitoring technologies, the early field trials described in this section appear to highlight the potential merits of smart pumps in improving operational performance/pump reliability, particularly when they are used as a component of a wider maintenance strategy. For example, the operational reliability of handpumps, and as a result 'access to water', appears to have improved through the application of both the SweetSense and smart handpumps prototype systems in field trials conducted in Rwanda and Kenya, respectively. In both studies, the use of smart pumps to identify failures rapidly to maintenance teams led to significant reductions in pump downtime (or the time taken for a repair to be implemented) in comparison with a 'business-as-normal' benchmark scenario. The SweetSense trials demonstrated that mean pump downtimes dropped to 13·8% of the benchmark level (i.e. reduced from 152 to 21 d), while the smart pump trial reported mean pump downtime as being 9·6% of the benchmark level (i.e. from 27 to 2·6 d). In terms of operational functionality, the introduction of smart monitoring increased the percentage of operational pumps from 68 to 91% in the SweetSense study and from 70 to 98% in the smart pump study.

There are some notable local differences between the two sets of results. For example, the reported downtimes (i.e. both before and during the field trials) were significantly longer in the Rwandan study than in the Kenyan study. This illustrates that, in reality, there are likely to be many local factors that will affect the maintenance regimes/systems applied in different areas (e.g. the available resources, the expertise/skill base of the repairer, the level of external support provided). As highlighted in Figure 3, there appears to be a vast array of interconnected factors that may contribute to the problem of broken pumps. However, despite local differences between these two field study sites, it is interesting to note that the level of operational improvement associated with the introduction of smart monitoring technologies appears remarkably similar in the two cases – that is, with mean pump downtimes at 13·8 and 9·6% of their benchmark levels in the Rwandan and Kenyan studies, respectively, while 33·8 and 40%, improvements in operational functionality were reported in these respective studies.

3. Challenges, obstacles and opportunities

It is evident that several key challenges and logistical obstacles still need to be addressed before monitoring devices are widely applied in this context. The cost, reliability, functionality, security and user acceptability of these technologies have previously been identified as important barriers to uptake (Cooper *et al*., 2014). Similarly, two further technical challenges have been identified

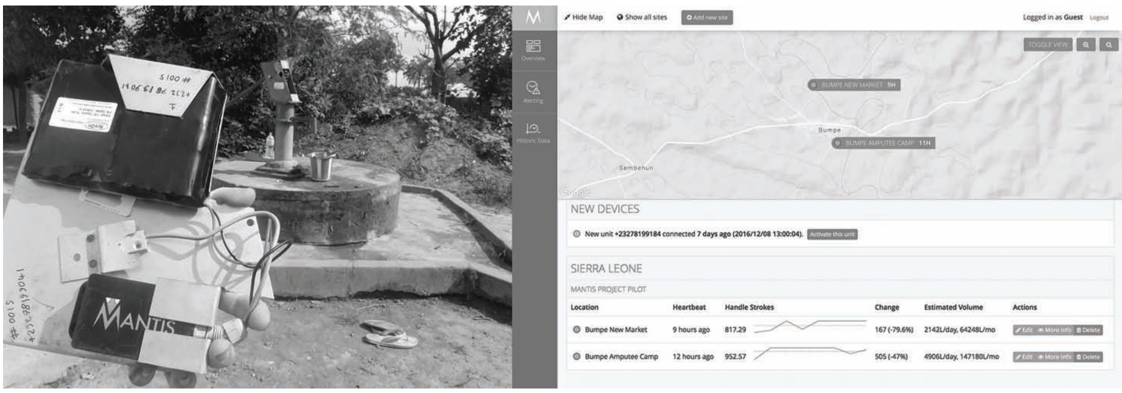

Figure 5. Field trials of the Mantis system in Sierra Leone

through the field trials (described in Section 2); these relate to the provision of reliable power supplies (Section 3.1) and mobile network coverage (Section 3.2).

3.1 Access to electricity

Access to electricity is a significant issue in many developing regions. This is particularly the case in sub-Saharan Africa, where 74% of the population do not have access to a mains electricity supply (El Bassam *et al*., 2013). As such, it is evident that alternative energy sources must be considered for powering remote monitoring applications for the vast majority of rural communities in sub-Saharan Africa. Batteries are a commonly used power source, but when these become depleted the cost of replacement becomes problematic and in many cases replacement may not be economically viable. For example, the SweetSense study (Section 2.2.1) highlighted the importance of battery life – the prototype units used were designed to operate for between 6 and 12 months without maintenance. However, battery consumption was observed to be considerably higher than anticipated and reduced the ‘maintenance-free’ operational lifespan of the units (Nagel *et al*., 2015).

3.2 Mobile network coverage

The telemetry systems discussed in this paper typically rely on GSM networks as their main means of communication. In many rural areas, mobile phone networks have represented the first telecommunication infrastructure to be introduced (Acker and Mbiti, 2010). GSM mobile telephone coverage varies across many developing regions. For example, coverage by area is claimed to be between 1 and 100% depending on the region, with a median of 34·5% (GSMA, 2013a). By population, coverage is between 4 and 100%, with a median of 78% (GSMA, 2013b). There is a trend of coverage increasing over time (GSMA, 2013a). However, it is worth noting that the smart pump trial in Kenya highlighted that the local GSM service was unreliable, to the extent that 40% of SMS messages were lost (Behar *et al*., 2013). The same study also reported that the success rate of the different transmitters varied significantly and speculated that this might be due to reliability issues associated with the local diesel-powered GSM masts, which appeared to be prone to malfunction or fuel shortages (Behar *et al*., 2013). Where mobile network coverage does not exist, alternative ‘low-cost’ systems for creating local networks are emerging; these include wireless long-distance networks (Subramanian *et al*., 2006), and recent proposals to improve Internet coverage include the use of drones and high-altitude balloons (Wakefield, 2014).

The authors suggest that these technical challenges should not be considered as being insurmountable, nor should these barriers necessarily exclude the technologies from being considered as appropriate for this African context. After all, it is worth reflecting that similar technologies are being increasingly used across the globe in a diverse range of contexts and applications (e.g. from remotely monitoring stock levels in vending machines to flow levels within sewers). Furthermore, mobile phones, from which many of these remote monitoring devices have been derived, have proven to be incredibly successful within the sub-Saharan context. As previously highlighted, over two-thirds (65%) of households in this region now have access to at least one mobile phone. It is hoped that the production costs of these devices will continue to fall and their operational performance (e.g. in terms of battery life and reliability) will gradually improve. While the appropriateness, and user acceptance, of these tools may be truly determined only through extended field trials, it is considered that recent experiences from other geographical regions and related technologies indicate that these obstacles may be gradually conquered over time.

3.3 Human (management) systems

The issues associated with underperforming Wash initiatives and investments are complex and multi-faceted. A number of previous studies (Baumann, 2006; Chowns, 2015; Harvey and Reed, 2007; Hope, 2015) have highlighted that the management issues associated with water projects in Africa are diverse and wide ranging. It is beyond the scope of this paper, and the expertise of its authors, to comment in detail on the optimal management structures for water services. Rather, the authors’ focus is the role of these technologies within the context of legal obligations. The purpose of this section is firstly to acknowledge that significant improvements to water services will not be achieved by technological solutions alone and secondly to suggest some of the ways that human management could be positively affected by smart monitoring technologies.

As already highlighted (Section 2), recent advances in low-cost telemetry could facilitate more targeted and, as a result, more appropriate capture and dissemination of information, with the potential to contribute to sustainable and reliable water service provision. This has considerable potential to assist in the management of water services, and to empower key stakeholders, by swiftly providing immediate and relevant performance information. Two questions are crucial to unleashing the full potential of such empowering information: who receives the information and what will they do with it?

Sending information on water performance to those directly involved in, and responsible for, pump maintenance could certainly be beneficial. As highlighted by the preliminary field trials (Section 2), remotely monitoring pump performance can lead to quicker intervention and repairs than relying on periodic physical inspection and/or potentially delayed or unreliable reports from pump users. This may result in a cheaper, more efficient maintenance programme and a more reliable water service. But this application of smart pumps would also create a closed loop of information, which could miss the transformative potential latent in this technology if disseminated to a wider, but targeted, group of stakeholders and interested parties.

This discussion of the empowering potential of smart pumps should contribute to any consideration of the institutional arrangements within which stakeholders might be represented, be that within private sector service provision or in partnership with NGOs, 'commons' or public utility models of ownership and provision. The aforementioned field trials should help to inform this ongoing discussion further. For this reason, it is crucial that the human management of smart pumps (i.e. how people can best interact with and apply this technology) must be observed and 'tested', as well as testing the technology itself.

It is not necessary at this stage to be prescriptive about the particular form(s) that water-related performance information should be presented in (there already exists a host of creative infographic possibilities) or on (whether accessed on mobile phones, smartphones, tablets, computers, etc.). Neither is it wise to restrict imagination about the number of people or groups who could use this information positively, to help pursue the goal of universal access to water. But it is suggested that, in addition to those stakeholders directly responsible for pump maintenance, there is scope for pump performance information to be used by water users themselves, by local community organisations and the wider civil society, by NGOs, by local and national media and even by politicians in ways that focus attention and resources towards greater fulfilment of access to sufficient water. Moves towards greater community management of water resources would be assisted by accurate, accessible information.

For example, in terms of a 'system-minded approach', it is widely advocated across much of the developmental sector that local communities should both manage and financially service their own water points, with some degree of external support. For instance, WaterAid (a well-known NGO) promotes water 'technologies that can be operated, managed and financed by communities, with assistance from local government and service providers' (WaterAid, 2015). However, without adequate ongoing post-construction monitoring of water points or continued dialogue with local communities it is unclear how external support agencies might detect those problems requiring attention, or even maintain accurate historical records of operational performance. Without accurate historical records, it is not easy to assess which maintenance systems/strategies or technologies are effective at addressing these problems.

4. Reflections on the specific undertaking of SDG 6

Provided that the aforementioned challenges can be surmounted, smart pumps look well placed to form part of the response to SDG 6 (e.g. to ensure the availability and sustainable management of water and sanitation for all), which looks set to play a significant guiding role in setting, measuring and facilitating the achievement of international Wash objectives over the next 15 years. Although broader in their scope, the SDGs continue the model chosen for the MDGs, avoiding direct legal obligations in favour of a 'report card' approach to help monitor and improve the performance of the international community regarding the targets set. In this non-binding regulatory context, monitoring tools could offer improved accountability for both governments and other key stakeholders. For example, the levels of water provision/coverage reported by these stakeholders could be verified against historical field data collected from smart pumps. Similarly, the problems of malfunctioning/broken pumps would be clearly demonstrated by the application of remote monitoring.

4.1 Access to water as a human right

The 193 member states that agreed on the SDGs have committed themselves to 'work tirelessly for the full implementation of the Agenda by 2030' (UN, 2015). The obligations undertaken as a result of this commitment are not legally binding. But many of the obligations reflect or overlap with pre-existing obligations with binding legal status. SDG 6 is one such example, reflecting the states' obligations towards recognising the human right to clean water and sanitation, as declared by the UN General Assembly (2010).

The status of the mentioned UN General Assembly resolution is itself non-binding, while doubtless reflecting considerable global consensus. However, the International Covenant on Economic, Social and Cultural Rights has been authoritatively interpreted as including a human right to water (UNCESCR, 2003). To this end, state obligations include the need to take steps to the maximum of their available resources 'with a view to achieving progressively the full realization of the right[s]' (UN General Assembly, 1966). This carries a 'strong presumption that retrogressive measures taken in relation to the right to water are prohibited' under the UN Committee on Economic, Social and Cultural Rights (UNCESCR, 2003).

4.2 Human rights and SDGs

The universal aim of SDG 6 makes it particularly compatible with a human rights approach to access to water. Alongside their shared universality, it would appear that 'soft' (non-binding) development approaches such as the SDGs have a significant role to play in achieving the human right to water. Together, the human rights approach and that of development goals seem to offer a more realistic and multi-layered approach to the right to water in action than does relying on a human rights approach alone. Such a multi-layered conception of the right to water is able to acknowledge the crucial, central role of states in embodying the right through legislative and other means, including embracing non-legislative measures such as improved monitoring strategies to pursue development goals. It is here that the potential of smart pumps to help achieve SDG 6 can be seen most clearly.

5. Conclusions

This paper has outlined that fewer than 5% of Wash projects are currently visited after their construction; as such, broken infrastructure frequently goes undetected or is not addressed by relevant stakeholders. As a consequence, it is estimated that broken water pumps impact the lives of 62 million people in sub-Saharan Africa. In financial terms, this represents between US$1·2 and 1·5 billion of lost investment over the last 20 years. These operational problems obviously hamper efforts to ensure universal access to safe and affordable drinking water, as embodied by SDG 6. These reliability problems have been attributed to a wide range of factors, including limited post-construction monitoring and support from external agencies. The use of smart pumps, or other forms of telemetry, could potentially improve both monitoring and maintenance strategies and ultimately increase the longevity of water projects. As such, these technologies could play a significant role in ensuring universal access to safe and affordable drinking water by 2030, which constitutes one of the key targets associated with SDG 6. However, it is considered that a number of key challenges and logistical obstacles still need to be addressed before such remote monitoring technologies are commonplace in the Wash context. Some of these challenges relate to technical issues (e.g. battery life and network coverage issues), others are financial, while others are societal (e.g. community acceptance of these technologies). Finally, the role of such technologies should be considered within the broader context of the SDGs and the human right to water. Access to sufficient water continues to be emphasised as a human right necessary for dignified existence, as well as a specific international development goal. But by simultaneously acknowledging the practical and legal hurdles that face a human right to water while pursuing the fulfilment of SDG 6, a complementary approach to water governance can be found. Despite their global scope, '[h]uman rights and the human rights movement depend on governments and on the state system' (Henkin, 1999) for their respect, protection and fulfilment. In this landscape, the application of smart pumps, or similar technologies, could significantly improve the monitoring of these states for minimum standards and service violations in the field, helping to ensure against regressions in the realisation of the human right to water.

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