

ADVANCED REVIEW

Remote monitoring of rural water systems: A pathway to improved performance and sustainability?

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Abstract

The presence of the mobile phone network in rural areas where there is little other infrastructure has opened up the prospect of automatically monitoring rural water systems, something previously possible only in person and perhaps only on foot. The technology to monitor these systems continues to develop: basic systems are now leaving research and being implemented in operational WASH programs; machine learning is making pump failure prediction possible. With the move from the previous infrastructure-focused community management paradigm, to a service-delivery approach to rural water, remote monitoring has salience with its potential to inform professional maintenance services. This is not without cost. To justify its use in rural water service delivery remote monitoring must generate benefits for service providers: (1) it must be integrated into management systems, and help redesign them; (2) it must contribute to increases in performance that produce real improvement in outcomes for water users; (3) it must open up new transparent sources of funding previously unavailable to the rural water sector. If remote monitoring can do these three things it has a role to play in achieving SDG 6.1; if not it will join the list of development techno-fixes that failed to make an impact despite the best of intentions.

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1 | INTRODUCTION

Understanding and improving the sustainability of rural water supplies has been the subject of academic study for decades. Since the 1960s and spurred on by the International Drinking Water Supply and Sanitation Decade (1981–1990) donor governments, NGOs, and international agencies spent heavily on water supply projects. Iyer, Davis, and Yavuz (2006) estimated that in the quarter of a century between in 1978 and 2003, the World Bank lent US\$5.5 billion to the rural water supply and sanitation sector, and it was estimated that by the late 1980s external agencies were

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spending US\$4.5 billion a year on water supply and sanitation programs in developing countries (United Nations, 1990). During this time the focus was on building infrastructure, what came to be known as “improved” water sources, the humble handpump being the archetypal improved source that could provide a rural community with groundwater for their daily needs. These water systems were usually handed over to communities who then had the responsibility for managing them, this “community management” model becoming the default approach. The Joint Monitoring Programme (JMP) stated that MDG target 7c of “reduc[ing] by half the proportion of people without sustainable access to safe water” was met in 2010, with an estimated 89% of the world’s population having access to “improved” water sources compared to 76% in 1990. Despite this apparent achievement and the vast quantities of money and effort expended over the previous 30 years, the Rural Water Supply Network estimated a decade ago that globally one in three handpumps were broken (RWSN, 2010). As the MDG era progressed there was increasing skepticism about community management, and the role of enterprise in rural water service provision began to be re-evaluated. Harvey and Reed (2006) contend that a private sector model has the advantage that responsibility and incentives for O&M are more clearly defined than under a community-managed model. Kleemeier’s (2010) review of private sector involvement in the rural water sector cited a number of examples, ranging from full private ownership, to pump leasing and private O&M contracts. While there are examples of effective private sector involvement, as there were—and still are—with community management, Foster et al. (2019) estimated a mere one-in-four handpumps broken at any one time. This represents a slight improvement from a decade earlier but hardly evidence to suggest that we are on track to deliver “universal and equitable access to safe and affordable drinking water for all” by 2030, the Sustainable Development Goal for water set in 2015. In fact, many of the problems described a generation earlier (Blum & Feachem, 1983; Blum, Feachem, Huttly, Kirkwood, & Emeh, 1987; Esrey, Feachem, & Hughes, 1985; White, Bradley, & White, 1972) still persist to this day. Against this backdrop of sluggish progress in the sector, this review looks at recent developments in remote monitoring of rural water systems, and asks what role they may have in improving the sustainability of these systems, and by extension increasing the water security of those who rely on them. The focus of this review is on handpumps, the archetypal manifestation of rural water infrastructure in low- and middle- income countries, and the subject of much of the research to date on rural water supply. But the issues around remote monitoring, and whether it is part of the solution or a technological distraction, can apply to any form of water supply infrastructure.

2 | BACKGROUND

2.1 | Rural water supply

In rural areas with no grid electricity or insufficient funds to run diesel generators, handpumps are a key means for obtaining drinking water. A well-sited and installed handpump accessing groundwater can provide reasonable quantities of drinking water at low cost (MacDonald & Calow, 2009). A lack of bacteriological contamination comparable to piped systems (Bain et al., 2014) means that this simple form of water supply can reduce the burden of disease, in particular diarrhoeal disease associated with drinking unsafe water (Hunter, MacDonald, & Carter, 2010; Prüss-Ustün et al., 2019; Wolf et al., 2018). In 1987, the World Bank conducted an exhaustive study on handpump technology. This assessed the technical aspects of 70 different pump models as well as providing guidance for the design and implementation of the entire system, identifying six key elements that must be addressed to assure the long-term success of a handpump project: “the community, the aquifer, the well, the maintenance system, the pump, and the finance” (Arlosoroff et al., 1987, p. 31). Ensuring community participation in rural water project design became a major factor in globally policy design, investment, and implementation activities (Narayan, 1994; Sara & Katz, 1998).

The Community Management approach became the sanctioned discourse for rural water supply from the late 1970s onward. It was assumed that an increase in community participation could solve the problems of sustainability associated with previous top-down approaches. Kleemeier (2000) explains that this emphasis on community participation and management in rural water supply was part of a general trend toward a bottom-up, basic needs strategy of development, adopted in response to the perceived failure of centralized grand plans. Practitioners with bitter experience of failed government projects and neo-liberal funders’ views on reducing the role of government could be reconciled with the ideas of community empowerment prevalent—and sometimes romanticized—within NGOs from the Global North (Harvey & Reed, 2006; Mamdani, 1996).

The Community Management model for rural water services has not achieved the results we would have hoped: It is estimated that one in four handpumps in sub-Saharan Africa are still nonfunctioning at any given point in time (Foster et al., 2019), a slight improvement on estimates from a decade earlier suggesting one in three (RWSN, 2010). Conservative projections from work done by Sansom and Koestler (2009) suggest that there are likely to be between half a million and a million handpumps in Africa, potentially serving over 100 million people (Thomson et al., 2019). One cannot infer that the consequence of a quarter of handpumps being nonfunctional is that 25 million people are unserved, but at the very least this equates to a significant proportion of the approximately US\$8 billion invested by communities, governments, and aid agencies in handpumps (Hope, Thomson, Koehler, & Foster, 2020) that is not generating any benefit.

Some of these broken pumps may be caused by a mismatch between the pump technology chosen and management system put in place, as emphasized in the 1987 World Bank report (Arlosoroff et al., 1987), but the causes of this lack of sustainability are various and complex. They have been examined with a more critical and nuanced analysis of the role of the community management model than was provided when some of these projects were first conceived. On one side, studies showed the benefits of community managed water projects (Isham & Kahkonen, 2001; Narayan, 1994; Sara & Katz, 1998). Sounding a more skeptical note, Iyer et al. (2006) noted improvements related to the shift away from government ownership of World Bank funded projects, but that no causal link had been identified. Mansuri (2004) cautioned that the evidence is weak for the benefit of community-driven projects as outcomes are often measured with respect to the baseline situation rather than with respect to a project run on a different basis. Chowns (2015) is blunt in concluding from a study in Malawi that “community management does not work well for communities,” and a study in Kenya (Hope, 2015) suggests that communities would not choose community management if other choices were available.

2.2 | Impacts of poor performance

This poor performance and lack of sustainability has a substantive impact on the communities and households relying on these systems. It impacts their health, their livelihoods, and their life chances. Inadequate water supplies affect physical health, most notably through diarrhoeal diseases. Diarrhoeal diseases cause 1.31 million deaths worldwide. For children under five in sub-Saharan Africa it causes 303,045 deaths and 27 million DALYs (Troeger et al., 2017), which corresponds to around one in every seven DALYs for that demographic. Drinking poor quality water can lead to Environmental Enteric Dysfunction (Desai, Borkar, Pathare, Dighe, & Jeejeebhoy, 1969; Lindenbaum, Harmon, & Gerson, 1972; Schenk, Samloff, & Klipstein, 1968) and interact with nutrition, reducing nutrient absorption (Lindsay, 1997; Schlaudecker, Steinhoff, & Moore, 2011). This is especially egregious in children as undernutrition can have long-term nonrecoverable negative impacts on physical and cognitive development (Crookston et al., 2011; Lorntz et al., 2006; MacIntyre, McTaggart, Guerrant, & Goldfarb, 2014; Patrick et al., 2016). Troeger et al. (2018) estimated the long term impacts of this interaction, finding that the DALYs in under-fives attributable to diarrhea were potentially underestimated by 39% as a consequence of not taking these long-term effects into account.

Of particular relevance to the discussion of sustainability of these rural water systems, of the impact of their failure rates and downtimes, is that the onset and recovery of illnesses related to drinking poor quality water are not symmetrical and are nonlinear. Modeling suggests that drinking contaminated water for even the briefest of periods can have a disproportionately long term impacts (Brown & Clasen, 2012; Hunter, Zmirou-Navier, & Hartemann, 2009), echoing the finding decades earlier that recovery from EED is measured in months and years (Lindenbaum, Gerson, & Kent, 1971). A merely “good” water supply will not guarantee good health outcomes.

It is these adverse health impacts associated with poor water supply that still motivate both research and programmatic efforts to improve WASH. But there are many impacts, aside from those related to physical health, from poor water supply and sanitation. The economic benefits of improving water and sanitation, quantified as potential time saved (Whittington, Xinming, & Roche, 1990) or reduced mortality (Jeuland, Fuente, Ozdemir, Allaire, & Whittington, 2013) are also significant. Households and individuals often heavily discount the costs of their own poor health. Time spent collecting water has a clearer opportunity cost: that of time lost that could be spent on other activities. In a number of countries time cost may soon be greater than the health costs (Fuente, Allaire, Jeuland, & Whittington, 2020). Water insecurity, both in terms of the poor quality of service and the uncertainty around that service can result in psychosocial stresses (Bisung & Elliott, 2017), mental health issues (Wutich, Brewis, & Tsai, 2020), and adversely impact family relations (Zolnikov & Salafia, 2016). This burden of water

insecurity disproportionately falls on women (Sweetman & Medland, 2017). That some of these have yet to be more formally quantified, either as economic impacts or into the Global Burden of Disease does not diminish their importance.

2.3 | The SDGs and delivering water services

The definitions used for the MDGs were understood across the sector to have severe limitations, overstating success by implicitly equating the presence of water supply infrastructure with there being something potable coming out of it (Bradley & Bartram, 2013; Clasen, 2012; Shaheed, Orgill, Montgomery, Jeuland, & Brown, 2014). Unlike the MDG for water which referred to the existence of the source of water, the water supply target 6.1 beneath SDG 6 of “ensur[ing] access to water and sanitation for all” is to “by 2030, achieve universal and equitable access to safe and affordable drinking water for all.” The service ladder in the JMP’s methodological note, which further articulates what is meant by these goals, refers to “safely managed water”. Thus the SDG explicitly considers the water itself and the way it is managed, and so implicitly views the delivery of this water a service. Debate about how to achieve the SDGs and how to monitor progress continues, with an acknowledgement that the two interact, making scrutiny of targets—and the data needed to track progress—an important part of achieving actual results (Bartram, Brocklehurst, Bradley, Muller, & Evans, 2018).

The fundamental change from the MDGs to the SDGs has been to move thinking away from focusing on waterpoints to considering the water itself; a shift from building infrastructure to providing services. This has two consequences, both of which pull in the same direction. The first is that “handing over” a pump and borehole to a community does not empower that community, as the borehole itself is not a thing of inherent value. The second is that a water service starts the day the borehole is commissioned, the day a traditional water project would be completed and written up as a success. How the pump over the borehole keeps working and delivering water is the key question. Who owns the pump, pipes or taps is largely moot if there is nothing coming out of them. This viewing of rural water supply as a service delivery challenge (Moriarty, Smits, Butterworth, & Franceys, 2013) both leads to discussion of professionalization within the sector (Hope, Foster, Koehler, & Thomson, 2019; Le Gouais, 2011; Thomson & Koehler, 2016) and the increasing acceptance of the role enterprise can play in rural water service delivery.

The role of the private sector in rural water service provision, and whether or not enterprise and markets will lead to greater sustainability, has been a subject of increasing interest for the last two decades. Harvey and Reed (2006) contend that a private sector model has the advantage that responsibility and incentives for O&M are more clearly defined than under a community-managed model and that private involvement in service provision as well as parts supply will allow for greater revenue generation and thus be a more sustainable business than spare parts provision alone. Kleemeier’s (2010) review of private sector involvement in the rural water sector show that the community management paradigm is being challenged. In recent years, this interest has strengthened further (Kumasi, Agbemor, & Burr, 2019; Lockwood, 2019; McNicholl et al., 2019; Obeta, 2019), with evidence that an enterprise approach can bring higher performance, whether delivered by civil society (Chindarkar, Chen, & Wichelns, 2018) or private ownership (Cronk & Bartram, 2017).

2.4 | Expanding mobile phone coverage

As the apparently intractable problem of providing rural communities with safe water to drink was lurching from the MDG era into the SDG era, the apparently unrelated expansion of the mobile phone network coverage across Africa was well underway. Afrobarometer (Mitullah, Samson, Wambua, & Balongo, 2016) mapped the rapid penetration of mobile phone services and increase in mobile subscribers throughout Africa. Between 2008 and 2015 mobile phone penetration (access to the network, not necessarily owning a phone) rose from 70 to 93%. This is in contrast to piped water, which moved from 53 to 63% over the same period. GSMA Intelligence (2017) puts the number of unique subscribers at the end of 2016 at 420 million, a penetration of 43%. Irrespective of the appropriate metric for coverage, the economic impact of mobile telephony across Africa has been significant (Aker & Mbiti, 2010; Suri & Jack, 2016). As saturation approaches for urban residents, mobile operators are focusing more attention on the untapped market remaining in rural areas. Despite the less favorable cost–benefit ratio for rural cell towers (GSM Association, 2019), coverage in rural areas is still high, at 89% against 99% for urban areas (Mitullah et al., 2016). Villages that lack certain basic infrastructure elements, such as electricity and sewerage, now have mobile phone coverage, providing the rural

BOX 1 MOBILE MONEY

The transfer of phone credit between friends and family became prevalent across Africa shortly after the introduction of mobile phones in the 2000s, creating de-facto mobile banking. This was subsequently formalized—and regulated—as mobile banking services, the most successful being Safaricom's M-PESA system in Kenya. This has enabled remittances and low-value, noncash transfers. As well as convenience this also brings transparency. Water users can make a payment quickly for their contribution to maintaining or repairing their water supply infrastructure, but they can also now easily prove that the payment has been made. Recognizing the importance of M-PESA Safaricom reduced its low-value transaction fees by two thirds in 2014. By 2016, just under 10 years since its launch in 2007, M-PESA has been used by 96% of Kenyan households and in doing so contributed to reducing poverty (Suri & Jack, 2016).

population with new opportunities for communication and commerce. A significant aspect of the mobile phone network reaching less wealthy rural areas is the fact that individuals and families have found the means to acquire mobile phones and the benefits they provide. Information generates value and those on low incomes, and even those who might have limited access to cash at all, will pay for a service if that service generates value for them, including mobile banking services (Box 1 describes the origins of mobile money). A study of the fish markets on the Indian coast as the mobile phone network was introduced found that fishermen were able to tailor their catch to current market demand, which both reduced wastage and got a better price for their catch (Abraham, 2006; Jensen, 2007; Srinivasan & Burrell, 2015). In this case mobile phones reduced information asymmetry, benefiting those at the base of the supply chain. The mobile phone network is also being used opportunistically in disparate applications such as disease surveillance (Lee et al., 2016; Wesolowski et al., 2015) and measuring rainfall (Chwala & Kunstmann, 2019; Uijlenhoet, Overeem, & Leijnse, 2018).

2.5 | Mobile phones and WASH

The mobile phone network now reaches into areas currently reliant on handpumps for their water supply, the same areas currently struggling to maintain those handpumps on sustainable basis. As well as the existing benefits mobile coverage brings to these areas it also has the potential to be the means by which the “objective, reliable and detailed information about water access” called for by Jiménez and Pérez-Foguet (2010) can be transmitted and distributed. In Senegal Manobi harnesses the increasing mobile coverage to provide monitoring of small scale urban water systems (Karim, 2018). This uses a dedicated mobile phone application, which allows an operator to send information about water output and system availability to a central management system. Similar systems have been set up in Mali, Niger, and Rwanda and more recently moved into supporting rural Water Service Providers in Benin (Karim, 2018). FLOW (Field Level Operations Watch) developed by Water for People, a US nonprofit, but now run by AKVO in the Netherlands, uses an application on a smartphone that enables users to complete a survey, take pictures and GPS references of, for example, a gravity-fed stand-pipe. This provides geo-referenced information about the functioning of the system, giving the body responsible for it a snapshot of its status. Finally, mWater (www.mwater.co) provides a similar app to FLOW, combining it with a data portal. If widely adopted, these systems can generate information, which has the potential to improve sector performance through increased monitoring and transparency.

These systems generate snapshots of system functionality, whether at a specific point post-implementation, or in the assessment of average performance a large system or network. These systems are essentially using the mobile era's newly available data transfer architecture to make an existing tool—paper surveys—faster, more efficient, and lower cost. These data collection apps are hugely beneficial, with information that is instantly uploaded using the mobile data network much more likely to get into the hands of those who can use it than paper surveys that have to be physically transported and manually transcribed before becoming useful.

3 | AUTOMATED REMOTE MONITORING

3.1 | Approaches to automated monitoring

Automated monitoring “may overcome some of the shortcomings inherent in crowdsourced approaches” (Thomson, Hope, & Foster, 2012b), and by linking rural water infrastructure directly to the information-transfer infrastructure of the mobile phone network—and so into the internet of things—it may be truly transformative. While not without shortcomings, automatic data can be generated and distributed fast enough to inform more effective maintenance repair services (Hope, Foster, Money, & Rouse, 2012), enabling new models for rural water management and in doing so contribute to dissolving the distinction between the rural and urban contexts (Bradley & Bartram, 2013). Alongside the ubiquity of the mobile phone network, three other inter-related factors linked to mobile communications make the development of devices that can link rural water infrastructure to the mobile data network, and their use in areas where there is no grid electricity, both possible and feasible: (1) Technological advances have made electronic components smaller and in consequence more energy efficient; (2) Solar power and battery technology have become more efficient, generating and storing more energy for a given size than previously possible; (3) Economies of scale generated by the huge numbers of mobile devices now produced have made these technologies cheaper.

A number of studies and projects have developed remote monitoring technology and trialed it. These systems process these data and transmit it over the mobile phone network to databases and dashboards that present the data to users. These systems have the ability to generate real-time data on the status of pumps, and to present this information in a structured and objective way. The raw data generated by these technologies varies, with three main approaches: measuring the movement of the handle (Swan, Skipworth, et al., 2017; Thomson, Hope, & Foster, 2012a); sensing water in the body of the pump (Charitywater, 2015; Nagel, Beach, Iribagiza, & Thomas, 2015) using capacitive and pressure sensors, respectively; measuring water flow using a rotating flow meter attached to the pump spout/outflow (Susteq, 2016; Uduma, 2015; Welldone, 2014). While these systems have been implemented on differently types of handpump, there is nothing in the fundamental approach that ties them to a particular type; with some mechanical adaptation and calibration they can all be used on different pump types.

I will briefly address the advantages and disadvantages of these different approaches to generating the raw data that are used in these different sensors. This is not to provide a detailed engineering analysis, but to illustrate that all of these require calculations to produce the top level metric of volume pumped or pump usage, that are ultimately proxies or estimations to a greater or lesser extent. In some aspects the limitations—and possibilities—of the system as a whole turn on the characteristics of the fundamental sensor technology.

Direct flow measurement using a rotating impeller is the way that standard piped water meters measure flow. These have been adapted for handpumps and would seem to give the most direct measurement of water flow and use. But a flow meter designed to measure flow rate within a piped water system assumes a “full pipe” and have a certain minimum pressure or flow rate below which it will not be accurate. In the case of a piped water system pressure below a certain level or the pipe not being full would indicate a failure in the system, and in that situation an erroneous flow measurement is not the main problem at hand. For a handpump the flow at the outflow is inevitably intermittent and the outflow pipe is rarely full. Adapting the system to make the reading correct requires creating back pressure that will at the very least result in more effort being needed by the users to pump the same volume of water; at worst it will severely impact the pump's functioning as the pressures created are at odds with the inherent design of the pump. If a volumetric reading is needed—as opposed to a flow vs. no flow indications—a specific calibration would be required which may be error-prone given variations between pumps. Uduma/Vergnet Hydro use a flow-meter based system in their “e-pump.” As a vertically integrated supplier with control over the design and manufacturer of the pump and the monitoring device, and its deployment and management, Vergnet Hydro has integrated the flow meter into a design variant of their own pump, so it is likely to be more accurate and less likely to compromise operation and user experience than retrofitting a flow meter to an existing pump.

The second approach to monitoring, adopted by Sweetsense and charity: water, senses the presence of water in the pump head. A calibration/conversion factor will be needed to translate that into a volumetric output, which is likely to be susceptible to errors if the pump is experiencing mechanical problems, but it does represent a direct measurement of the presence of water. The main risk of this method is that of putting electronics in close proximity to water. Charity: water have addressed this issue by housing their system in a unit that fits between the head and base of the pump. This effectively isolates the electronics from exposure to water, but does subject the system to large mechanical stresses as

TABLE 1 Advantages and disadvantages of different technological approaches to remote monitoring

Technology	Organization(s)	Pros	Cons
Traditional flow sensor on pump outflow.	<ul style="list-style-type: none"> • Vergent-Hydro /Uduma • Welldone. • Susteq. 	Direct flow measurement.	Creates back pressure that interferes with user experience; may show error as not designed for intermittent flow.
Sensing of water in the pump head.	<ul style="list-style-type: none"> • Sweetsense • charity: water 	Measures presence of water directly.	Electronics in proximity to water.
Sensing movement of pump parts.	<ul style="list-style-type: none"> • Oxford University • Leeds Beckett University 	Generates information on pump itself.	Indirect measure of volume susceptible to error as pump condition changes.

the force of pumping is channeled through their unit. The main benefit of this approach is that the presence of the device will have no negative impact on the users' experience of the pump. It will not require more effort to get water.

Measuring the movement of the pump mechanism, the approach taken by Oxford University's "Smart Handpump" and the MANTIS system developed by Environmental Monitoring Solutions and Leeds Beckett University, changes the device from one that is primarily attempting to measure the volume of water being pumped, in the same way that a water meter does, to one that is monitoring the pump itself. Again, this will require calibration to convert pump use into a volume, and as an even less direct measure, this will vary between pump of the same type that are in different conditions or pumping water from different depths, as well as between pump types. The accuracy of this type of system may be liable to drift over time as pump components wear, the most extreme instance of this being when there is a fault with the pump such as a leaky foot valve or rising main (Thomson et al., 2012a). This variability will limit the ability to make precise pump-to-pump comparisons of the volume of water abstracted, and to use the device to set precise volumetric tariffs, the latter being arguably an advantage rather than a disadvantage.

These systems do not interfere with user experience or maintenance: Oxford University's accelerometer-based system is connected solely to the pump handle and the MANTIS system to the pump head cover, both parts that are easily removed and set aside during maintenance. The main advantage of monitoring the pump itself is that, while knowing the volume of water pumped is certainly useful and an intuitive way to present pump use patterns, the main reason for remote monitoring is to support pump maintenance (Swan, Cooper, et al., 2017; Thomson et al., 2012a). A direct measure of pump use—or lack of use—may better inform a mechanic than the volume of water being pumped. A pump that is not being used out of choice is likely to show a slow reduction in use before reaching zero, whereas pump that is not producing any water but is in demand, is likely to show some activity as users try to pump it, but in a pattern and at a level that is very different to that which is exhibited when it is functioning normally. Triangulating this remote monitoring information with reports of breakdowns from mechanics and the experience of pump users will allow rural water managers to recognize patterns and adapt maintenance regimes accordingly. Table 1 summarizes the advantages and disadvantage of each system.

3.2 | Does remote monitoring improve performance?

These monitoring systems generate information for rural water managers and mechanics, but does this information help them improve the performance of rural water services? Two of the university-led projects described above conducted trials to assess the effectiveness of their systems in helping reduce pump downtimes.

In 2014 and 2015, the Sweetsense team, installed 181 sensors on handpumps in three provinces of Rwanda (Nagel et al., 2015). This study had three arms, two of which were blinded to the data being generated by the sensors. One arm was a "best practice" circuit rider model, based on preventative maintenance. A second was an "ambulance" service model that used the sensor data to inform the dispatch of mechanics. The final control arm was a "nominal" maintenance model that approximated typical pump servicing conducted by an NGO for which pump maintenance is only one of their activities, with repairs triggered by requests from communities or local officials. The nominal arm group achieved a mean per pump functionality level of 68% and a median time to repair of 152 days. The circuit rider arm had a functionality level of 73% and time to successful repair of 57 days. Finally, the ambulance arm achieved a

successful repair interval was 21 days with a functionality mean of 91%. All these three arms showed an improvement on the baseline pre-trial performance. The improvement between a status-quo model and the best-practice circuit rider model was significant, but what is of interest here is the benefit of the data-assisted ambulance model over the circuit rider. This was also significant, with time-to-repair dropping from around 8 to 3 weeks with a corresponding increase in average functionality/uptime.

Oxford University conducted two studies in Kenya which also demonstrated a reduction in pump down time. The first study in Kitui County had two arms in the same geographical area, which it compared to pretrial baseline data collected in the same area (Smith School Water Programme, 2014). The “active monitoring” arm involved mechanics being dispatched based on the data generated by the system, the “crowd-sourcing” arm involved the same mechanics, but they were only dispatched when a request was made by the community. Average days-to-repair dropped from 27 days pretrial to 2 days for pumps transmitting automated data and 4 days for pumps where faults were called in by the community. A second study in Kwale County showed similar results with an average time-to-repair of less than 3 days, down from a pretrial average of 37 days (Thomson & Koehler, 2016).

While there are no formal publications to review, with the largest number of pumps under monitoring of any organization, it is important to include charity: water in this review as it is currently the best example of a system operating at scale. Charity: water presents functionality statistics from their system on their website, providing information about downtimes and repairs.¹ This operational data reported 3,065 systems under active monitoring in Ethiopia and Malawi as of the end of September 2020. These systems have a functionality rate of 94%. Of those nonfunctional (184) the median downtime is between 15 and 30 days with 61% of pumps (113) nonfunctional for more than a year. The charity: water figures do not have a comparator, either in the form of another study arm or preintervention data, but the functionality rates and downtimes are broadly similar to those achieved in Rwanda as described by Nagel et al. (2015).

3.3 | Costs of remote monitoring

The Oxford trial reported an annual “recurring maintenance cost” per handpump of \$127 in their smaller trial, with 27% of that reported as “information,” implicitly the additional cost of remote monitoring over and above running the maintenance service (Smith School Water Programme, 2014). The \$127 figure is stated as “recurring maintenance costs,” so does not include annualized capital costs. This figure will not be indicative of the full cost of running a repair service, but is likely to be close to the marginal cost of providing the service, of relevance if the economic efficiency of water allocation is considered important.

Charity: water’s work on remote monitoring was funded by a 2012 Google Global Impact Award of \$5M. Charity: water’s financial accounts separately report the Google Remote Monitoring project, enabling examination of the cost of their remote monitoring program (charity: water 2020). Over the 5 years 2013–2017 charity: water spent \$3.1M on remote monitoring, which included the development of their sensor and manufacture of around 3,000 units. Over the same period, they spent \$4.4M on repairs and maintenance. The total expenditure on “water project funding” (excluding the repairs and maintenance, and remote monitoring elements) which corresponds to the funds disbursed to implementing partners over the same 5 year period, was \$134M. This equates to 5.3% if total project costs being spent on O&M with 42% of this spent on remote monitoring (this may be an underestimate of the total cost of this project as some of the Google funding was unrestricted and included in charity:water’s “operations” budget lines). For 2018 and 2019, the percentage spent on O&M remains at 5.3% but remote monitoring is subsumed into the same budget as repairs. Taking the figures 2016 and 2017, when upfront development costs are unlikely to be a factor so the figures are more likely to represent the ongoing cost, remote monitoring adds an additional 22% to the O&M budget. The Rwanda study also broke down the cost of providing the service, and put the additional cost of monitoring at 18% of operational cost, excluding the capital cost of sensors.

The three cases cited are very different and calculated the additional cost of monitoring in different ways, but came up with broadly similar figures. The additional cost associate with monitoring is considerable; the cost is sufficiently large that remote monitoring must pay its way. Do the benefits of remote monitoring warrant these additional costs? The additional cost of running a repair service with remote monitoring is not only the cost of the monitoring itself. A responsive service that uses the real-time information about pump failures to dispatch mechanics to fix specific pumps without delay will almost certainly increase transport costs, is likely to use more spare parts, and may also have higher labor costs from employing mechanics who can provide a responsive service. Oxford University and charity: water do

not have premonitoring costs to make comparisons against, but Nagel et al. (2015) compared the costs of running the three different types of repair service. The “circuit rider” service was almost twice as expensive to run as the “nominal” service, with the data-driven “ambulance” service 30% more costly again. However, once the costs were normalized to account for the pump uptime, the costs for all three services were the effectively same.

The Rwanda trial suggest that remote monitoring was cost-neutral in term of system availability; the Oxford trial's “crowd-sourced” arm showed an improvement in performance almost as good as the remote monitoring arm, apparently without the added cost and complication of monitoring. If remote monitoring of handpumps is assessed simply by the raw metric of days of reduced downtimes, or percentage increase in uptime, it might seem that that the cost of monitoring does not generate a commensurate return. Does this indicate that remote monitoring of rural water systems is just a flash-in-the-pan techno-fix? I would suggest not, for three inter-related reasons: the complex and nonlinear relationship between pump uptime and the benefits of that uptime; the potential for the transparency afforded by remote monitoring to bring additional finance into the sector; the role remote automated monitoring can play in rethinking how rural water services are delivered.

4 | IS REMOTE MONITORING A PATHWAY TO SUSTAINABILITY?

4.1 | Nonlinearity of health benefits

The studies described in this review achieved large improvements in system uptime when measured against their comparator arms or baseline data. Some benefits of this increased performance, such as reduced collection time from other sources further away, will be increase broadly in proportion to the improvement in uptime as fewer days broken directly translate into few days walking to an alternate source. Modeling of the health impacts of consuming poor quality water suggest that even a few days without access to a pump providing uncontaminated groundwater, that would push users to switch to alternative sources, will have disproportionate health impacts (Brown & Clasen, 2012; Hunter et al., 2009). This is consistent with comparable empirical evidence from piped water contexts (Majuru, Michael Mokoena, Jagals, & Hunter, 2011; Pickering, Yoshika, Sultana, & Swarhout, 2019). None of the trials described in this article consistently achieved the level of performance that these studies indicate would lead to a significant reduction in diarrhoeal disease. Even the best run reactive maintenance models triggered by remote monitoring will struggle to guarantee same-day repairs to randomly occurring failures without increasing the number of mechanics available to respond to these breakdowns. This would inevitably drive up costs and even then be limited by the logistical and geographical challenges associated with sparsely populated rural areas.

The only way to consistently close the gap from days to hours is to repair handpumps before they break (Thomson et al., 2012b). Two studies, both using real (albeit postprocessed) data, have shown that applying machine learning to the data generated by existing remote monitoring systems creates the possibility of failure prediction (Greeff, Manandhar, Thomson, Hope, & Clifton, 2019; Wilson, Coyle, & Thomas, 2017). While such methods will not predict every pump failure in advance, this additional information can enable hybrid “preventative, predictive, reactive” models. In such a PPR system the bulk of maintenance will be preventative maintenance informed by failure prediction, reducing the proportion that is reactive, reactive being the most costly to operate and being the most costly in terms of the negative outcomes for the water users.

4.2 | Remote monitoring and rural water finance

Remote monitoring has the potential to bring much-needed additional funding into the rural water sector. The same data that are used by service providers to maintain water systems can be used to verify this maintenance (Thomson et al., 2012b). In addition to providing a lower cost means of project monitoring for existing donors who may be becoming more discerning about the value their funds are generating, these data can be used to devise performance-based contracts (Thomson & Koehler, 2016) that can be funded through the Results-Based Aid programs that are become more prevalent (Gelb & Hashmi, 2014; Janus & Keijzer, 2015; Klingebiel, 2012). Such programs have been challenging for the rural water sector, as the robust and transparent evaluation that is required for such contracts is necessarily expensive due to rural geographies. Remote monitoring can directly measure outputs in the form of pump failures and repairs, system uptime and the volume of water produced. These output metrics may be the key to unlocking Results-

Based financing for the rural water sector (Hope et al., 2020; McNicholl et al., 2019). They may be a measure of the quality of the service being provided, but these output metrics are proxies for the—less easily measured—outcomes of improved health, livelihoods, and agency of rural households. One risk associated with Results-Based aid is that it creates a strong incentive to optimize operations around the metric against which payment is calculated (a.k.a. Goodhart's law). This makes it all the more important to understand the relationship between the (measurable) outputs and (desired) outcomes as ostensibly reasonable payment-triggering performance criteria based on outputs could lead to services that do not generate the outcomes we wish for.

4.3 | Rethinking the management of rural water services

Finally, these technologies must be used a tool to rethink how rural water is managed, not just an additional data layer to help monitoring and evaluation (Thomson et al., 2012b; Thomson & Koehler, 2016). Irrespective of specific metrics of service performance or improved health outcomes, this is also an issue of equity. Many of us who have treated water piped into our homes, experience a water availability of better than 99.9% (8 hr of outage in a year). That we are now discussing water availability for rural handpump users that is only one order of magnitude worse than what we enjoy—rather than two orders of magnitude—indicates that we are now taking the issue seriously, not that we have solved it. The assumption implicit in how rural water supplies have been managed to date has been is that rural waterpoints are individual; that information about their use and state can only be known locally and cannot be centrally collated. By implication the assumption has been that they can only be managed individually. The existence of real-time, low cost monitoring data has changed that. Waterpoints can now be viewed as a system and managed as accordingly, just as the taps connected to a piped water system are. By way of example, for the two trials in Kenya undertaken by Oxford University a maintenance service was set up, explicitly based on the use of remote monitoring data, rather than adding an information stream to an existing operation. Notwithstanding shorter average pretrial downtimes that might imply an easier operating environment, this maintenance service achieved the lowest downtimes of the trials reviewed here. This technology can enable more innovative and flexible governance models (Koehler, Rayner, Katuva, Thomson, & Hope, 2018), but if technology is to be transformative, and must be integrated into a socio-technical system it is to maximize societal benefit (Mao et al., 2020) and be a tool that provides rather than excludes.

5 | CONCLUSIONS

Remote automatic monitoring of rural water systems may be emerging from its infancy, but has yet to be taken up at significant scale. The very same environmental factors that make delivering clean water to rural communities a challenge make trialing, deploying and maintaining a new technology difficult. Trials to-date have been testing a new technology in a difficult environment while simultaneously attempting to demonstrate the benefits that a mature technology might bring. As reliability, performance, and ease of use of the technology reaches the point where the details of the technology are fading into the background, rural water managers may now be open to incorporating these new data streams into their operations. As the field matures performance and reliability will improve and costs will decrease, we can focus on the information generated and the use we can make of that information.

The additional costs associated with monitoring must be justified by contributing to significantly better outcomes or increased revenues. Efficiency gains from monitoring can reduce costs, but under current management practices this is likely only to do this at the margin. Likewise, under current assumptions about acceptable performance in the rural water sector and the metrics used to measure that performance, the additional gains from remote monitoring seem slight. Under the SDGs, the rural water sector is now embracing the idea that it is in the business of delivering services rather than building infrastructure. With the commissioning of a new water system is no longer when the project ends, but the point when the service starts, remote automated monitoring has new salience. But the SDGs may also be a hindrance to the uptake of remote monitoring despite the benefits it may bring, as there may be reluctance to invest in improving the performance of “improved” source that are an explicitly interim measure, arguably incapable of providing “safely managed water” under definitions of SDG 6.1.

Remote monitoring must prove its worth to the rural water sector in two ways. Two studies described here have shown the technological possibility of predicting pump failures. There is now a need for empirical evidence that this failure prediction can reduce costs by improving operational efficiencies, and deliver better health outcomes by

eliminating pump downtimes. Remote monitoring can validate the performance of professional service providers. With data on usage level, speed of repairs and system uptimes made public, sources of finance that may have previously been reluctant to be involved—on account of the lack of performance transparency—may now be enticed into the rural water sector. With these data readily available, performance-related contracts that incentivize sustainable service delivery over short-term infrastructure investment can become the norm.

Both are possible and are the two are complementary, but they require those responsible for delivering rural water services to rethink how they manage their operations around an assumption that data on the system they are managing exists and is that their fingertips. Remote monitoring of rural water systems can be the means to put this at their fingertips, enabling them to deliver high quality, sustainable services to rural water users.

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CONFLICT OF INTEREST

The author is an unpaid director of a spin-out company set up to operationalize remote monitoring of rural water systems.

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ENDNOTE

¹ <https://www.charitywater.org/our-work/sensors>

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REFERENCES

- Abraham, R. (2006). *Mobile Phones and Economic Development: Evidence from the Fishing Industry in India*. 2006 International Conference on Information and Communication Technologies and Development. IEEE. pp. 48–56.
- Aker, J. C., & Mbiti, I. M. (2010). Mobile phones and economic development in Africa. *Journal of Economic Perspectives*, 24(3), 207–232.
- Arlosoroff, S., Tschannerl, G., Grey, D., Journey, W., Karp, A., Langeneffer, O., & Roche, R. (1987). *Community water supply: The handpump option*. Washington DC: The World Bank.
- Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., ... Bartram, J. K. (2014). Global assessment of exposure to Faecal contamination through drinking water based on a systematic review. *Tropical Medicine & International Health*, 19(8), 917–927.
- Bartram, J., Brocklehurst, C., Bradley, D., Muller, M., & Evans, B. (2018). Policy review of the means of implementation targets and indicators for the sustainable development goal for water and sanitation. *Npj Clean Water*, 1(1), 3.
- Bisung, E., & Elliott, S. J. (2017). Psychosocial impacts of the lack of access to water and sanitation in low- and middle-income countries: A scoping review. *Journal of Water and Health*, 15(1), 17–30.
- Blum, D., Feachem, R. G., Huttly, S. R. A., Kirkwood, B. R., & Emeh, R. N. (1987). The effects of distance and season on the use of boreholes in northeastern Imo state, Nigeria. *Journal of Tropical Medicine and Hygiene*, 90(1), 45–50.
- Blum, D., & Feachem, R. G. (1983). Measuring the impact of water supply and sanitation investments on Diarrhoeal diseases: Problems of methodology. *International Journal of Epidemiology*, 12(3), 357–365.
- Bradley, D. J., & Bartram, J. K. (2013). Domestic water and sanitation as water security: Monitoring, concepts and strategy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(2002), 20120420.
- Brown, J., & Clasen, T. (2012). High adherence is necessary to realize health gains from water quality interventions.” edited by S. J. Drews. *PloS One*, 7(5), e36735.
- Charity Global. (2020). Charity: Water financial statements. Retrieved from <https://www.charitywater.org/about/financials>.

- Charitywater. (2015). Blog/Charity: Water—Wanna build your own sensor? Retrieved from https://blog.charitywater.org/post/143498518002/wanna-build-your-own-sensor?is_related_post=1.
- Chindarkar, N., Chen, Y. J., & Wichelns, D. (2018). Government-civil society co-management contracts for rural water services: Lessons from India. *Policy Design and Practice*, 1(4), 269–280.
- Chowns, E. (2015). Is community management an efficient and effective model of public service delivery? Lessons from the rural water supply sector in Malawi. *Public Administration and Development*, 35(4), 263–276.
- Chwala, C., & Kunstmann, H. (2019). Commercial microwave link networks for rainfall observation: Assessment of the current status and future challenges. *Wiley Interdisciplinary Reviews: Water*, 6(2), e1337.
- Clasen, T. F. (2012). Millennium development goals water target claim exaggerates achievement. *Tropical Medicine & International Health*, 17(10), 1178–1180.
- Cronk, R., & Bartram, J. (2017). Factors influencing water system functionality in Nigeria and Tanzania: A regression and Bayesian network analysis. *Environmental Science & Technology*, 51(19), 11336–11345.
- Crookston, B. T., Dearden, K. A., Alder, S. C., Porucznik, C. A., Stanford, J. B., Merrill, R. M., ... Penny, M. E. (2011). Impact of early and concurrent stunting on cognition. *Maternal & Child Nutrition*, 7(4), 397–409.
- Desai, H. G., Borkar, A. V., Pathare, S. M., Dighe, P. K., & Jeejeebhoy, K. N. (1969). 'Flat' Jejunal Mucosa in the tropics. *Indian Journal of Medical Sciences*, 23(1), 1–5.
- Esrey, S. A., Feachem, R. G., & Hughes, J. M. (1985). Interventions for the control of diarrhoeal diseases among young children: Improving water supplies and excreta disposal facilities. *Bulletin of the World Health Organization*, 63(4), 757–772.
- Foster, T., Furey, S., Brian Banks, & Willetts, J. (2019). Functionality of handpump water supplies: A review of data from sub-Saharan Africa and the Asia-Pacific region. *International Journal of Water Resources Development*, 36(5), 855–869.
- Fuente, D., Allaire, M., Jeuland, M., & Whittington, D. (2020). Forecasts of mortality and economic losses from poor water and sanitation in sub-Saharan Africa. *PLoS One*, 15(3), e0227611.
- Gelb, A. & Hashmi, N. (2014). "The anatomy of program-for-results: An approach to results-based aid." *SSRN Electronic Journal*.
- Greiff, H., Manandhar, A., Thomson, P., Hope, R., & Clifton, D. A. (2019). Distributed inference condition monitoring system for rural infrastructure in the developing world. *IEEE Sensors Journal*, 19(5), 1820–1828.
- GSM Association. (2019). *The Mobile economy sub-Saharan Africa 2019—The mobile economy*. London: GSM Association.
- Harvey, P. A. & Reed, R. A. (2006). Sustainable supply chains for rural water supplies in Africa. pp. 31–39.
- Hope, R. (2015). Is community water management the community's choice? Implications for water and development policy in Africa. *Water Policy*, 17(4), 664–678.
- Hope, R., Foster, T., Koehler, J., & Thomson, P. (2019). Rural water policy in Africa and Asia. In *Water science, policy, and management* (pp. 159–179). Chichester: Wiley.
- Hope, R., Foster, T., Money, A., & Rouse, M. (2012). Harnessing Mobile communications innovations for water security. *Global Policy*, 3(4), 433–442.
- Hope, R., Thomson, P., Koehler, J., & Foster, T. (2020). Rethinking the economics of rural water in Africa. *Oxford Review of Economic Policy*, 36(1), 171–190.
- Hunter, P. R., MacDonald, A. M., & Carter, R. C. (2010). Water supply and health. *PLoS Medicine*, 7(11), e1000361.
- Hunter, P. R., Zmirou-Navier, D., & Hartemann, P. (2009). Estimating the impact on health of poor reliability of drinking water interventions in developing countries. *Science of the Total Environment*, 407(8), 2621–2624.
- GSMA Intelligence. (2017). *The mobile economy: Sub-Saharan Africa 2017*.
- Isham, Jonathan and Satu Kahkonen. 2001. "Institutional determinants of the impact of community-based water services: Evidence from Sri Lanka and India." *SSRN Electronic Journal*.
- Iyer, P., Davis, J., & Yavuz, E. (2006). Rural water supply, sanitation, and hygiene: A review of 25 years of lending 1978–2003. pp. 1–54.
- Janus, H., & Keijzer, N. (2015). Big results now? Emerging lessons from results-based aid in Tanzania. *SSRN Electronic Journal*, 4, 1–31.
- Jensen, R. (2007). The digital divide: Information (technology), market performance, and welfare in the south Indian fisheries sector. *Quarterly Journal of Economics*, 122(3), 879–924.
- Jeuland, M. A., Fuente, D. E., Ozdemir, S., Allaire, M. C., & Whittington, D. (2013). The long-term dynamics of mortality benefits from improved water and sanitation in less developed countries. *PLoS One*, 8(10), e74804.
- Jiménez, A., & Pérez-Foguet, A. (2010). Challenges for water governance in rural water supply: Lessons learned from Tanzania. *International Journal of Water Resources Development*, 26(2), 235–248.
- Karim, S. F. (2018). Manobi: Deploying mobile payments and tools for rural water utilities in Benin|Mobile for development.
- Kleemeier, E. L. (2000). The impact of participation on sustainability: An analysis of the Malawi rural piped scheme program. *World Development*, 28(5), 929–944.
- Kleemeier, E. L. (2010). Private operators and rural water supplies: Can it work?. pp. 1–5.
- Klingebiel, S. (2012). Results-based aid (RBA): New aid approaches, limitations and the application to promote good governance. *SSRN Electronic Journal*, 14, 1–36.
- Koehler, J., Rayner, S., Katuva, J., Thomson, P., & Hope, R. (2018). A cultural theory of drinking water risks, values and institutional change. *Global Environmental Change*, 50, 268–277.
- Kumasi, T. C., Agbemor, B. D., & Burr, P. (2019). Rural water asset management practices in Ghana: The gaps and needs. *Water and Environment Journal*, 33(2), 252–264.

- Le Gouais, A. (2011). Rural ural water supply in Benin and new service delivery approaches approche. pp. 79–83.
- Lee, E. C., Asher, J. M., Goldlust, S., Kraemer, J. D., Lawson, A. B., & Bansal, S. (2016). Mind the scales: Harnessing spatial big data for infectious disease surveillance and inference. *Journal of Infectious Diseases*, 214(Suppl_4, S409–S413).
- Lindenbaum, J., Gerson, C. D., & Kent, T. H. (1971). Recovery of small-intestinal structure and function after residence in the tropics. I. Studies in peace corps volunteers. *Annals of Internal Medicine*, 74(2), 218–222.
- Lindenbaum, J., Harmon, J. W., & Gerson, C. D. (1972). Subclinical Malabsorption in developing countries. *The American Journal of Clinical Nutrition*, 25(10), 1056–1061.
- Lindsay, J. A. (1997). Chronic sequelae of foodborne disease. *Emerging Infectious Diseases*, 3(4), 443–452.
- Lockwood, H. (2019). Sustaining rural water—A comparative study of maintenance models for community-managed schemes.
- Lorntz, B., Soares, A. M., Moore, S. R., Pinkerton, R., Gansneder, B., Bovbjerg, V. E., ... Guerrant, R. L. (2006). Early childhood diarrhea predicts impaired school performance. *The Pediatric Infectious Disease Journal*, 25(6), 513–520.
- MacDonald, A. M., & Calow, R. C. (2009). Developing groundwater for secure rural water supplies in Africa. *Desalination*, 248(1–3), 546–556.
- MacIntyre, J., McTaggart, J., Guerrant, R. L., & Goldfarb, D. M. (2014). Early childhood diarrhoeal diseases and cognition: Are we missing the rest of the iceberg? *Paediatrics and International Child Health*, 34(4), 295–307.
- Majuru, B., Michael Mokoena, M., Jagals, P., & Hunter, P. R. (2011). Health impact of small-community water supply reliability. *International Journal of Hygiene and Environmental Health*, 214(2), 162–166.
- Mamdani, M. (1996). *Citizen and subject: Contemporary Africa and the legacy of late colonialism*. Princeton: Princeton University Press.
- Mansuri, G. (2004). Community-based and -driven development: A critical review. *The World Bank Research Observer*, 19(1), 1–39.
- Mao, F., Khamis, K., Clark, J., Krause, S., Buytaert, W., Ochoa-Tocachi, B. F., & Hannah, D. M. (2020). Moving beyond the technology: A socio-technical roadmap for low-cost water sensor network applications. *Environmental Science & Technology*, 54(15), 9145–9158.
- McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., van der Wilk, N., ... Koehler, J. (2019). Performance-based funding for reliable rural water services in Africa.
- Mitullah, W. V., Samson, R., Wambua, P. M., & Balongo, S. (2016). Afrobarometer dispatch no. 69.
- Moriarty, P., Smits, S., Butterworth, J., & Franceys, R. (2013). Trends in rural water supply: Towards a service delivery approach. *Water Alternatives*, 6(3), 329–349.
- Nagel, C., Beach, J., Iribagiza, C., & Thomas, E. A. (2015). Evaluating cellular instrumentation on rural Handpumps to improve service delivery—A longitudinal study in rural Rwanda. *Environmental Science & Technology*, 49(24), 14292–14300.
- Narayan, D. (1994). *Contribution of people's participation: Evidence from 121 rural water supply projects*. Environmentally Sustainable Development Occasional Paper Series No. 1.
- Obeta, M. C. (2019). Private for-profit rural water supply in Nigeria: Policy constraints and options for improved performance. *Journal of Water and Land Development*, 41(1), 101–110.
- Patrick, P. D., Moore, S. R., Wiseman, B. L., Niehaus, M. D., Oriá, R. B., Guerrant, R. L., ... Oriá, M. O. B. (2016). Early childhood diarrhea predicts cognitive delays in later childhood independently of malnutrition. *The American Journal of Tropical Medicine and Hygiene*, 95(5), 1004–1010.
- Pickering, A. J., Yoshika, C., Sultana, S., Swarhout, J., Goddard, F. G. B., Islam, S. A., ... Luby, S. P. (2019). Effect of in-line drinking water chlorination at the point of collection on child Diarrhoea in urban Bangladesh: A double-blind, cluster-randomised controlled trial. *The Lancet Global Health*, 7(9), e1247–e1256.
- Smith School Water Programme. (2014). *From rights to results in rural water services-evidence from Kyuso, Kenya Smith School Water Programme*. Smith School Working Paper.
- Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M. C., ... Johnston, R. (2019). Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low- and middle-income countries. *International Journal of Hygiene and Environmental Health*, 222(5), 765–777.
- RWSN. (2010). Myths of the Rural Water Supply Sector. *Rural Water Supply Network Perspectives No. 4*.
- Sansom, K. & Koestler, L. (2009). African handpump market mapping study: Summary report for UNICEF WASH Section and Supply Division.
- Sara, J. & Katz, T. (1998). Making rural water supply sustainable: Report on the impact of project rules supply sustainable: Report on the Impact of Project rules.
- Schenk, E. A., Samloff, I. M., & Klipstein, F. A. (1968). Morphology of small bowel biopsies. *The American Journal of Clinical Nutrition*, 21(9), 944–961.
- Schlaudecker, E. P., Steinhoff, M. C., & Moore, S. R. (2011). Interactions of diarrhea, pneumonia, and malnutrition in childhood. *Current Opinion in Infectious Diseases*, 24(5), 496–502.
- Shaheed, A., Orgill, J., Montgomery, M. A., Jeuland, M. A., & Brown, J. (2014). Why ‘improved’ water sources are not always safe. *Bulletin of the World Health Organization*, 92, 283–289.
- Srinivasan, J., & Burrell, J. (2015). On the importance of price information to fishers and to economists: Revisiting mobile phone use among fishers in Kerala. *Information Technologies & International Development*, 11(1), 57–70.
- Suri, T., & Jack, W. (2016). The long-run poverty and gender impacts of mobile money. *Science*, 354(6317), 1288–1292.
- Susteq. 2016. *Rural water services through pre-paid handpump technology*. RWSN Forum 7.

- Swan, A., Cooper, N., Gamble, W., & Pritchard, M. (2018). Using smart pumps to help deliver universal access to safe and affordable drinking water. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 171(6), 277–285.
- Swan, A., Skipworth, P., Walker, L., & Thursfield, G. (2018). Field trials of a new monitoring system for water pumps in Sierra Leone and The Gambia. *Proceedings of the Institution of Civil Engineers - Water Management*, 171(3), 173–176.
- Sweetman, C., & Medland, L. (2017). Introduction: Gender and water, sanitation and hygiene. *Gender and Development*, 25(2), 153–166.
- Thomson, P., Bradley, D., Katilu, A., Katuva, J., Lanzoni, M., Koehler, J., & Hope, R. (2019). Rainfall and groundwater use in rural Kenya. *Science of the Total Environment*, 649, 722–730.
- Thomson, P., Hope, R., & Foster, T. (2012a). GSM-enabled remote monitoring of rural Handpumps: A proof-of-concept study. *Journal of Hydroinformatics*, 14(4), 829–839.
- Thomson, P., Hope, R., & Foster, T. (2012b). Is silence Golden? Of mobiles, monitoring, and rural water supplies. *Waterlines*, 31(4), 280–292.
- Thomson, P., & Koehler, J. (2016). Performance-oriented monitoring for the water SDG – Challenges, tensions and opportunities. *Aquatic Procedia*, 6, 87–95.
- Troeger, C., Colombara, D. V., Rao, P. C., Khalil, I. A., Brown, A., Brewer, T. G., ... Mokdad, A. H. (2018). Global disability-adjusted life-year estimates of long-term health burden and Undernutrition attributable to Diarrhoeal diseases in children younger than 5 years. *The Lancet. Global Health*, 6(3), e255–e269.
- Troeger, C., Forouzanfar, M., Rao, P. C., Khalil, I., Brown, A., Reiner, R. C., ... Mokdad, A. H. (2017). Estimates of global, regional, and National Morbidity, mortality, and Aetiologies of Diarrhoeal diseases: A systematic analysis for the global burden of disease study 2015. *The Lancet Infectious Diseases*, 17(9), 909–948.
- Uduma. (2015). Retrieved from <https://www.uduma.net/en/our-innovations/>.
- Uijlenhoet, R., Overeem, A., & Leijnse, H. (2018). Opportunistic remote sensing of rainfall using microwave links from cellular communication networks. *Wiley Interdisciplinary Reviews: Water*, 5(4), e1289.
- United Nations. (1990). *Achievements of the International Drinking Water Supply and Sanitation Decade*. General Assembly 45 Session 15931.
- WellDone. (2014). MoMo (mobile monitor)|WellDone MoMo. Retrieved from <https://momo.welldone.org/>.
- Wesolowski, A., Qureshi, T., Boni, M. F., Sundsøy, P. R., Johansson, M. A., Rasheed, S. B., ... Singer, B. H. (2015). Impact of human mobility on the emergence of dengue epidemics in Pakistan. *Proceedings of the National Academy of Sciences of the United States of America*, 112(38), 11887–11892.
- White, G. F., Bradley, D. J., & White, A. U. (1972). *Drawers of water: Domestic water use in East Africa*. Chicago: University of Chicago.
- Whittington, D., Xinming, M., & Roche, R. (1990). Calculating the value of time spent collecting water: Some estimates for Ukunda, Kenya. *World Development*, 18(2), 269–280.
- Wilson, D. L., Coyle, J. R., & Thomas, E. A. (2017). Ensemble machine learning and forecasting can achieve 99% uptime for rural Handpumps” edited by J. P. van Wouwe. *PLoS One*, 12(11), e0188808.
- Wolf, J., Hunter, P. R., Freeman, M. C., Cumming, O., Clasen, T., Bartram, J., ... Prüss-Ustün, A. (2018). Impact of drinking water, sanitation and Handwashing with soap on childhood Diarrhoeal disease: Updated meta-analysis and meta-regression. *Tropical Medicine & International Health*, 23(5), 508–525.
- Wutich, A., Brewis, A., & Tsai, A. (2020). Water and mental health. *WIREs Water*, 7(5), e1461.
- Zolnikov, T. R., & Salafia, E. B. (2016). Improved relationships in eastern Kenya from water interventions and access to water. *Health Psychology*, 35(3), 273–280.

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