Reviewing the use of Monitoring Tools for Rural Water Pumps in the Global South

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Abstract

The establishment of improved water supplies is one of the United Nation's Sustainable Development Goals (SDGs). Many water schemes have provided wells and pumps to enhance the life of local communities across Africa. However, in numerous cases these schemes fail over time due to a lack of established maintenance regimes and trained staff. One of the ways that resilience might be improved is the introduction of remote monitoring systems to allow detection of not only failed pumps but to enable predictions of when a pump might fail without intervention, thus allowing the associated loss of service to be minimised, ensuring that the community is not without safe drinking water for extended periods. This paper pulls together the knowledge and details of the remote monitoring systems that are available in the field today and provides a coherent knowledge base of the work that is being done. The paper also reviews how each of the systems are compiled, their strengths and weaknesses and provides background knowledge that should encourage future research and development in the field. It also queries whether such systems, with their reliance on microprocessors are appropriate for the Global South.

1. Introduction

The United Nations (ESCAP, 2013) defines water security as *"the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."* Many African nations experience poor levels of water security. The World Health Organisation (WHO) indicates that whilst progress has been made towards achieving safely managed drinking water, sanitation, and hygiene services (WASH) over the last 5 years, without urgent ongoing investment "*only 81% of the world's population will have access to safe drinking water at home, leaving 1.6 billion without*" with "*Sub-Saharan Africa experiencing the slowest rate of progress in the world. Only 54 per cent of people used safe drinking water, and only 25 per cent in fragile contexts*" (WHO, 2021).

Improving water security is one of the key aims of the United Nations Sustainable Development Goals (UN, 2015). SDG target 6.1 specifically seeks 'to achieve universal and equitable access to safe and affordable drinking water for all by 2030'. Maintaining progress towards the SDGs is key, and as such maintenance regimes and remote monitoring, that both inform and predict pump performance and potential failure could reinforce those advances that have been made to date.

2 Remote monitoring of hand water pumps

The SDG framework defines a handpump as being a limited, basic, or safely managed service, depending on its location relative to users. Whilst the pump systems are relatively simple and robust, they are subject to fatigue and corrosion from daily use. When they fail, it often means a protracted period where safe drinking water is not available whilst suitable parts are sourced, and technicians are made available to effect repairs, so effective maintenance and repair regimes are required to sustain the systems that have been installed.

The problems associated with broken water infrastructure are well-documented (RWSN, 2010; Chowns, 2015; MacArthur, 2015). For example, Foster et al. (2019) estimate that 25% of water pumps in sub-Saharan Africa are non-functional. This represents an improvement upon prior studies that have reported the rates of non-functioning hand pumps as between 20% to 65% in various African countries (RWSN 2010, USAid 2016). The impacts of broken water infrastructure are significant, affecting an estimated 62 million people in the region (Swan et al. 2017) and threatening to undermine the progress made towards achieving the SDG targets. Broken pumps not only have social implications but also result in a significant financial loss in infrastructure investment. In Africa alone, it has been estimated that broken hand pumps have resulted in between $1.2 billion to $1.5 billion in ineffective investments over the last 20 years (IRC, 2009; USAid, 2016).

The poor performance of hand water pumps has been attributed to a range of factors, such as insufficient local financial resources to fund repairs, limited access to spare parts, inadequate technical capacity within the user community, inappropriate technology implementation, and insufficient post-construction monitoring and support from external agencies (Moriarty et al. 2004; Whittington et al. 2009; Chowns 2015). Post-construction monitoring and support are considered as particularly critical, but reports indicate that less than 5% of WASH (water, sanitation, and hygiene) projects are visited after installation, which means that broken infrastructure often goes unnoticed or unaddressed by relevant stakeholders (USAid 2016).

To help address this problem, several organisations have developed simple robust monitoring systems that can be attached to pumps. These systems detect if the pumps are operational and provide data via cellular or satellite networks to monitoring locations. The data received from these systems is then used to target maintenance activities.
This paper looks at the key monitoring systems that are currently available worldwide and reviews their modes of operation. The main features of these systems are presented in Table 1 and discussed within the ensuing sections.

***Note** - Most information in this paper is available in the public domain. Permission has been sought wherever other information is presented.*

Table 1: Overview of Remote Monitoring Technologies for Hand Pumps

Monitoring Technology	Compatible water pump models	Monitoring technique/s employed	Data transmission	Responsible Organisation/s (Organisation type)	Open access technology & support systems
Dispatch monitor	Afridev, India Mark II	Water levels in headworks	Universal SIM. Data transmitted via GPRS	Charity:Water (Non-profit)	Yes
DOXA Smart Pump	Afridev, LifePump.	Water levels in headworks	Data transmitted via satellite modem	DOXA Wells (Company)	?
e-pump	Compatible with multiple pump types	Flow through Spout	Unknown	Odial Solutions (Company)	?
EyeOneer	India Mark II	Pump handle movement	Unknown	CAYA Constructs Ltd (Company)	No
IWP	Afridev, India Mark II	Pump handle movement & Water levels in headworks	Daily SMS	Messiah College, Desert Research Institute (DRI) & World Vision (Academic / NGO)	?
MANTIS	Afridev, India Mk II	Pump handle movement	Daily SMS	EMS Ltd & Leeds Beckett University (Collaborative: Industrial/ Academic)	No

MoMo	Compatible with multiple pump types	Flow through Spout & Water levels in headworks	Quad-band GSM module supports GPRS and SMS, auto fallback and retry. Two-way communications	Welldone (Non-profit)	Yes
SWEETSense	Afridev, India Mark II, Consallen	Flow through Spout & Pump handle movement	Logged data relayed via GSM or Wi-Fi, at least daily. Two-way communications.	SweetSense Inc (Spin-off Company - from Portland State University)	No
WDT	Compatible with multiple pump types	Pump handle movement	SMS	OxWater Ltd (Spin-off Company from Oxford University)	No
SonSetLink	Afridev, India Mk II, Life Pump	Variety of sensors	Data transmitted via satellite modem	SonSetSolutions (Non-profit)	?

3 Review

The monitoring systems in Table 1 generally seek to achieve the same goal, but they all employ slightly different technologies, physical components, and methodologies. The following parameters were explored in relation to each system:

- *Unit security – i.e., how systems are installed and protected.*
- *Sensor Technology – i.e., what sensors are used and how do they record data.*
- *Operational Life span – i.e., battery life and system resilience.*
- *Data collection and transmission/Network availability – i.e., how is data processed and transmitted.*
- *Cost – i.e., system cost where known and running costs.*

3.1 Unit security

All systems highlighted in Table 1 appear to have been designed to minimise against accidental and malicious damage. To help achieve this, some systems are housed externally of the pump headworks (i.e., in waterproof and dustproof enclosures that are mounted in locations that do not impede the pump operation). Mounting the controller externally allows easy access to the unit (e.g., for battery replacement/etc), but potentially exposes it to a higher risk of damage, hence the range of rugged enclosures used. Furthermore, there is still the need to run connecting cables to the sensors/solar panels/etc. This may complicate the mounting position of the systems as the cables need to be carefully and securely routed away from any moving parts within the pump mechanism and/or protected from damage if they are run externally to the pump head.

Several of the smaller units, adopt a different approach, and locate the controller within the pump head for additional protection. For example, the DOXA smart pump combines a low-profile external head unit with an internal array of six capacitance sensors to measure the water level within the pump head (DOXA, 2022). Similarly, the WDT device is mounted within the pump handle (Thomson, 2021). Mounting the controllers within either the pump architecture or internal to the pump head in general provides mechanical protection and removes the unit from plain sight, reducing the risk of interference. The negative aspect is that the pump head needs to be opened to access the unit or indeed removed completely to access the internals of the device, although in practice this is relatively easy and can in most cases be achieved with local labour. Furthermore, there is the possibility that the some internally mounted systems may become detached within the pump head under operation, causing failure and damage to the pump mechanism.

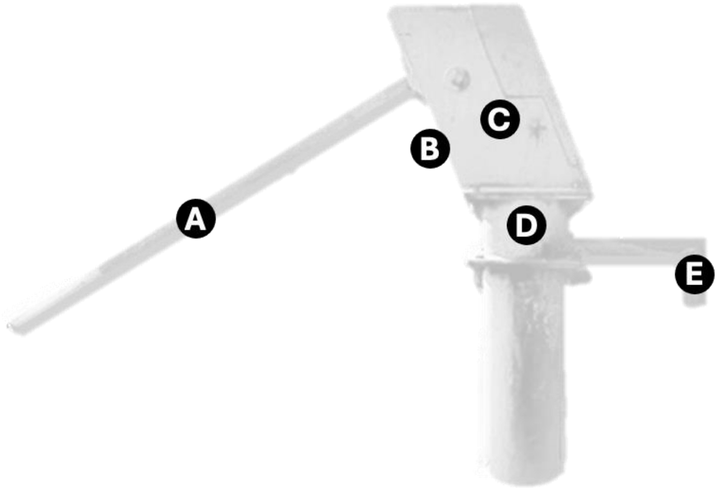

Figure 1 – Remote Monitoring Technologies for Hand Pumps – Unit housing arrangements
A (i) Location of SMART pump WDT device (accelerometer); A (ii) Alternative location of Caya's EyeOneer device; B (i) Presumed location of Caya's EyeOneer device; B (ii) Location of IWP device; C (i) Location of MANTIS device; C (ii) Location of SWEETSense device; D (i) Location of MoMo internal sensor; D (ii) Location of Dispatch Monitor device; D (iii) Location of DOXA sensor; E (i) Location of SonSetLink monitor; E (ii) Location of e-pump flowmeter sensor; E (iii) Location of MoMo flowmeter sensor; E (iv) Location of SWEETSense flowmeter device

There is no right or wrong solution. Out of the systems outlined in Figure 1, six are mounted externally (SonSetLink, e-pump, EyeOneer, SWEETsense, MANTIS and IWP), two appear to have both internal and external configurations (DOXA and WDT) and two are installed within the architecture of the pump (Dispatch Monitor and MoMo).

3.2 Sensor Technology

Most of the reviewed systems (Table 1) capture operational data via the use of discreet sensors. These may take the form of flow sensors, capacitance sensors, pressure transducers, accelerometers, or simple vibration detectors. The location of these sensors varies across each of the reviewed systems. For example, the MoMo and e-pump systems appear to have water flow sensors positioned on the pump delivery pipe (MoMo, 2014; UDUMA, 2017). An alternative approach, employed by DOXA (2022) and Charity:Water's Dispatch monitor (Charity:Water, 2021) is to measure the water level within the pump headworks using capacitance sensors. Other systems, such as the WDT, utilise accelerometers placed externally on the pump handle. Some units appear to restrict functionality to reduce cost and power requirements. The simplest systems (MANTIS, EyeOneer, SWEETsense and WDT) employ a range of different techniques to detect pump handle movements. To some extent the SonSetLink unit can also be classified in this category (i.e., as its sensor package can be configured to be as simple or complex as required). The IWP system uses a combination of handle movement and water pressure to give operation detection and a measurement, there are two pressure transducers with a sensor housing mounted to the rising main with the pump housing. The DOXA Smart Pump uses a combination of handle movement and water presence at the spout entrance to detect pump operations and water delivery.

3.3 Operational life span

The lifespan of electronic systems will obviously vary due to external and internal influences, but in broad terms electronic circuits in a protected environment can operate successfully for

20+ years. The failure rate of such systems against time is often illustrated using "the Bathtub curve" (Lienig and Bruemmer, 2017). Common causes of failure can often be attributed to a small number of critical factors: Heat; Humidity; Dust; Vibration.

3.3.1 Power:

The power supply is also of great importance, most systems rely on simple batteries as their energy consumption has been designed to be extremely low. Battery replacement is simple and, in most cases, can be undertaken by local labour without recourse to specific maintenance support – although caution should be taken to reduce dust ingress during the process, some system manufacturers/operators such as DOXA, provide bulk supplies of batteries that are kept and fitted locally (Peacock. S, 2021). Systems that are solar powered or a mixture of internal battery and solar power have minimal maintenance other than keeping the solar panels clean and free of damage as well as any connecting cabling.

3.3.2 System Failures:

The ability to operate over a considerable time span is a complex mix of protection, hardware, environmental and power supply elements. Lower levels of maintenance intervention are desirable, since minimal intrusion into the systems environment means less chance of introducing dust, moisture etc. (i.e., that could ultimately lead to degradation of the system).

At this stage, it is unclear whether any specific systems highlighted in Table 1 outperform the others in terms of their operational reliability. The publicly available data on unit performance/failure is relatively limited as most manufacturers do not publish sufficient data to determine cause and effect of either good performance or failure of any one system. That said, the IWP team have reported that there have been some cable failures during development. The 2017 update report (Messiah College 2018) highlights "broken accelerometer wires" (the accelerometer is mounted directly to the handle inside the pump casing and hard wired to the control unit, so it is subject to cyclical strain) instigating a "phase of product evaluation to determine the cause of system malfunctions". By 2019 they reported that most of the issues had been addressed and are "continuing to improve upon allowing them to meet future goals of creating a sustainable and reliable product in the field". It should also be noted the SWEETSense team also highlighted a number of operational challenges in the field. For example, some SWEETSense units struggled with extended exposure to fluctuating temperature, humidity, and wet/dry cycles. It was reported that the unit's water-proof seal occasionally leaked, resulting in more sensor failures than had originally been anticipated. Similarly, the device's battery life was also observed as being shorter than originally hoped (Nagel, et al., 2015). Finally, similar issues were reported with respect to field trials of the WDT system. Early trials of this system relied on good GSM network coverage. But it was reported that during these trials the local GSM service was unreliable, to the extent that 40% of SMS messages were lost. The same study also reported that the success rate of the different transmitters varied significantly and speculated that this may be due to reliability issues associated with the local diesel-powered GSM masts (Behar et al., 2013).

3.4 Data collection and transmission

As outlined in Table 1, the field data collected by these various monitoring units is either transmitted via satellite or cellular mobile networks. Most, but not all, units appear to transmit data on a daily basis. Reducing the frequency of data transmissions is a key factor in maintaining good battery life.

However, these different monitoring systems have been designed for a range of differing purposes and as such, adopt a variety of data collection approaches. Where more frequent data transmission is required, the use of rechargeable (e.g., solar powered) systems can help ensure that excessive power drain stops being an issue – which in turn can enable a more complex picture of pump performance to be formed. Ultimately, stakeholders must evaluate such issues against the additional cost and decide in balance if the extra cost justifies the benefits.

3.5 Cost

Cost is a critical factor in making this type of technology viable for widespread application in sub-Saharan Africa. It is considered that monitoring systems will not be viable in this context unless they are affordable, easily mass produced, easy to roll out, install and require minimal maintenance whilst in service. Any deployment must also have the support of key stakeholders (e.g., NGOs, governments, local authorities, and other support groups). All the reviewed monitoring systems claim to be low cost/affordable, but there is very little information in the public domain. Section 5.3 provides some further details of the limited costing data that has been published on these technologies.

4. Status of operation

Limited information is available regarding the previous deployments of the monitoring systems considered within this paper. Some of this information can be gleaned from associated websites or previously published papers. The remainder of this section examines the previous field-trials that have been conducted for each of the monitoring technologies outlined in Table 1.

4.1 Dispatch Monitor (Charity:Water)

It is reported that the Charity:Water NGO have monitored the largest number of hand water pumps (Thomson, 2021). Charity:Water appear to have monitored over 7300 water pumps (AWS, 2020) in rural parts of Ethiopia; Ghana; Malawi; China and Nepal (Thomson, 2021). The NGO's online portal presents pump functionality statistics (e.g. data related to downtimes/repairs) and recently reported that their pumps had a functionality rate of 94% with the median downtimes of between 15 and 30 days (Thomson, 2021).

4.2 E-Pump (Odial Solutions)

The UDUMA project team had reportedly installed 244 monitored water pumps in Burkina Faso and a further 30 in Mali by February 2020 (GSMA, 2020). This field-trial involved the installation of water meters and data loggers onto hand operated water pumps, in order to effectively turn them into E-PUMPS. These E-PUMPS were then trialled as part of a service provision business/management scheme that applied a fixed rate water tariff of 10 CFA francs (€0.015) per 20 litres (Odial Solutions, 2020). The water tariffs were paid via digital payments. For this service charge UDUMA sought to provide continuous servicing for these E-PUMPs, with the intention of limiting pump downtimes to below 72 hours (Odial Solutions, 2020).

4.3. EyeOneer (CAYA Constructs)

The EyeOneer system has reportedly been piloted on 112 water pumps in Himachal Pradesh and West Bengal (YourStory, 2019). But results from these field-trials do not appear to have been made available within the public domain.

4.4 Intelligent Water Project (IWP)

The IWP system has reportedly undergone several design iterations, including lab tests conducted in the USA and pilot trials that were undertaken in northern Ghana during 2014 and 2015 (Weaver *et al*., 2016). However, it is unclear how many IWP devices are currently in operation.

4.5 MANTIS

The MANTIS system (Figure 2) was initially piloted on eleven India Mark II hand pumps in Sierra Leone (Figure 3) and a further twelve pumps in The Gambia (Swan *et al.*, 2018). These pilots were supported by local NGOs (i.e. the Rural Youth Development Organisation in Sierra Leone and the Glove Project NGO in Gambia). These prototype MANTIS units monitored the operational status of the pumps and conveyed this data via SMS messages to a web-based platform. Field data was converted to graphically represent the location and usage pattern of the pumps. During the field trials in Gambia, the MANTIS system correctly identified a water pump failure event and alerted the relevant local stakeholders. In this regard, these pilot studies effectively demonstrated that MANTIS had achieved Technology Readiness Level 7 (i.e. a prototype demonstration in an operational environment).

Figure 2 – Installation of MANTIS monitoring unit on India MkII handpump in The Gambia

4.6 MoMo (Welldone)

It is reported that pilot trials of the MoMo system have been conducted in Cambodia, Ethiopia, Uganda, Rwanda, and Tanzania (TS, 2019). The Mo-Mo project team appears to have deployed a few different strategies to monitor the operational performance of a variety of hand water pumps. An early prototype appears to have been used to directly measure flowrates delivered by a rope pump in Tanzania (MoMo, 2014); whilst later Mo-Mo pilots have monitored water levels within the headworks of an India Mark II model (Welldone, 2021).

4.7 SWEETSense

The SWEETSense system has reportedly been piloted on 181 hand water pumps in Rwanda (Nagel et al., 2015). These investigations evaluated the deployment of a sensor-based maintenance approach against two traditional maintenance schemes using a representative set of pumps. In the case of the sensor-based approach (termed the ‘ambulance’ maintenance model) – the information collected by the SweetSense sensors were used to initiate maintenance visits by pump technicians. Regarding the other strategies: the next approach, described as representing 'Best Practice,' aimed to carry out regular preventative maintenance activities. Whilst, the final maintenance strategy, labelled as 'nominal' maintenance, relied solely on addressing pump problems when they were reported by pump users or other local stakeholders.

Figure 3 – Location of MANTIS pilot trial sites in Sierra Leone denoted by starred markers (Google Maps, 2024)

Over the course of the pilot study, the levels of 'pump functionality' linked to each maintenance regime was evaluated. The 'nominal' maintenance strategy generated a pump functionality rate (mean per pump) of 68%, in contrast to 73% for the 'Best practice' model and 91% for the sensor-informed 'Ambulance model' (Figure 4). In terms of the pump downtimes linked to these three maintenance strategies: the 'nominal' approach yielded an average (median) time to repair of 152 days, whereas for the 'best practice' and 'ambulance' models, this stood at 57 and 21 days respectively. Thomson (2020) describes these functionality rates and downtimes as being largely similar to those reported via Charity:Water's open-access web-portal.

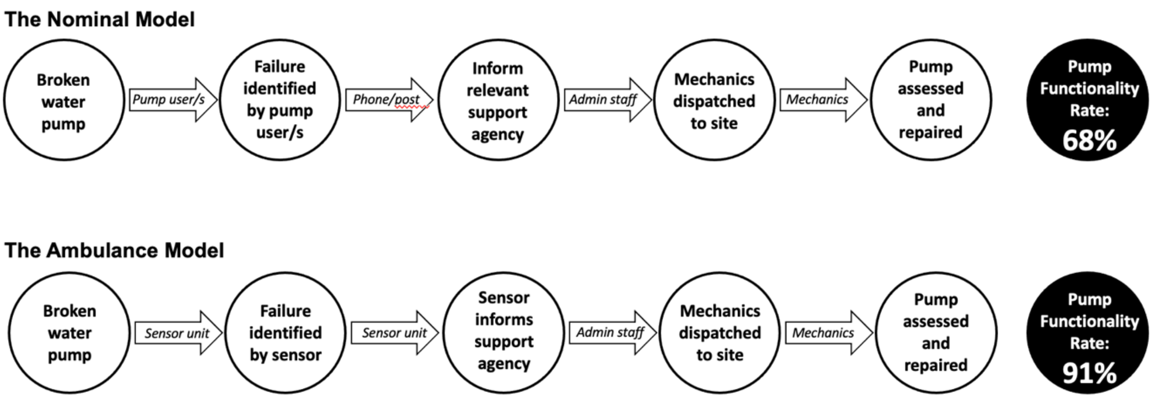

Figure 4 – Comparison of the maintenance strategies employed in SWEETSense trial (adapted from Nagel et al., 2015)

4.8 Waterpoint Data Transmitter (Ox Water Ltd.)

The Waterpoint Data Transmitter (WDT) system has reportedly been piloted on over 300 hand pumps in Kenya (GSMA, 2014). This monitor collected hourly pump usage data, which was then transmitted ever six-hours. Field-data was sent via SMS to a hub database in Nairobi. Results were graphically presented on a map layer, which highlighted those pumps in frequent use. Those pumps not being regularly use were considered to be malfunctioning, and a mechanic sent to resolve the problem (GSMA, 2014). This scheme reportedly reduced the average pump downtime (i.e., time to implement a repair) from 27 days to 2.6 days (Nagel, et al., 2015). Thomson (2020) reported that this system was also trialled via a second pilot study in Kenya – which yielded similar results (e.g. reducing the average time to repair from 37 days to 3 days).

4.9 DOXA Smart Pump

It appears that the DOXA system has been deployed on AfriDev pumps in Malawi since 2015 (DOXA, 2022). However, very few additional details appear to be available in the public domain.

4.10 SonSetLink

In early 2022, there appeared to be 1733 monitored pump sites linked to SonSetLink's online dashboard (Sonsetlink, 2022) – these appeared to correspond to AfriDev, India Mark II and LifePumps located in a variety of locations across Africa, Asia, and the Americas.

5. Discussion

This paper has reviewed ten remote monitoring systems with respect to: methods of installation upon hand pump infrastructure; modes of operation; data collection and transmission; cost; potential physical vulnerability; and life spans. It is clear that a simple, low cost, easy to install monitoring system is a highly desirable tool in the struggle to achieve water security. However, it is not a panacea that will fix pump failures as there are many contributory factors – and as such sustainable solutions need to be multifaceted with the potential to address the complex issues outlined in this and other publications.

5.1 Mechanical failures are still the most prominent issues with hand pumps and many organisations are looking to adopt a combined regime of pump improvement and monitoring to give better long-term solutions. For example, the simple replacement of plastic components with more durable metal items that can prolong the pump life span. In terms of the supportive role of monitoring technologies, some system developers are exploring the use of data to build predictive models that will alert the data centre when a pump is working outside of what could be considered its normal operational range.

5.2 Maintenance regime

Monitoring units that are "fit and forget" have the key benefit that they don't require any maintenance other than very occasional battery replacement but, still rely on a support network to replace batteries/etc. Those that require some attention throughout their service lives, for simple tasks such as, cleaning solar panels, rely on the local user or other organisations such as NGO's or charities to provide ongoing labour to carry out these tasks and therefore could attract more cost in service. However, none of the units that have been reviewed, would create a significant maintenance burden for local users (e.g., local authorities, NGOs). In most cases, simple battery replacement is easily achieved, and some manufacturers/NGOs/charity organisations may provide an upfront cache of batteries, so that the end user can directly replace when necessary. If this does not happen the data stream will cease and alert those monitoring the system of the failure, prompting direct action.

5.3 Cost

It is feasible that remote monitoring technologies for water pumps could reduce both the labour and travel costs associated with conventional monitoring strategies. However, it is likely that these technologies will themselves incur a range of financial costs (e.g. linked to hardware, energy, software, data transmission, repairs, maintenance, and replacement). Additionally, there may be further training costs incurred to enable operatives to use both the hardware and software components of these monitoring systems. Several previous publications have reported on the costs of the sensors and the associated maintenance regimes (Danert and Carter, 2023; Thomson, 2021; Nagel et al., 2015). Some of these studies have estimated the possible economic benefits of applying these technologies:

For example, the Oxford study (2014) reported on the reoccurring operational costs of maintaining 66 handpumps in Kyuso, Kenya. The annual recurring cost per repair in this trial was reported as being USD 62. This resulted in a total cost of USD 8,368 (i.e. for 2013) with an average cost of USD 127 per handpump. The annual unit cost of water production for each pump was calculated by estimating the water pumped per handpump and the associated repair costs (that ranged from less than 0.5 to over 18 USD/m^3). The higher costs were associated with low volume pumps, while lower unit costs were linked to more heavily used handpumps.

The SweetSense system employed in the Rwandan trial (Nagel et al., 2015) had an estimated hardware cost of USD 500 over two years, with maintenance costs of USD 115 per pump per year. The respective servicing costs of the ambulance, circuit rider and nominal models were USD 39.4, USD 30.0 and USD 15.4 per site per month. With additional costs of USD 9.5 per site for sensor servicing. Nagel et al. (2015) then estimated an annual capital expenditure of USD 1,500 based on an assumed capital cost of USD 15,000 for handpump and borehole, with a linear depreciation trend over ten years. Using the model-based estimates for mean pump functionality for the three service models, they calculated the annual capital expenditure (CapEx) and operating expenditure (OpEx) per functional year. The cost per pump per functional year was almost the same for all three models at USD 2,561, 2,611, and 2,508, respectively. A follow-up SweetSense trial focusing on 42 hand pumps in Kenya (Wilson et al., 2017) sought to explore the merits of adopting machine learning techniques. This trial assumed capital costs for each pump of USD 360 and annual costs of USD 410 for the associated sensors. Additional annual admin costs per pump of USD 300 were assumed for Kenya and USD 820 for the USA. The study estimated that the 'machine learner model' would cost USD 2,240/pump/year, compared to USD 2,387 for a circuit rider model (i.e. with no use of sensors/etc) - representing a cost savings of 7%.

Lastly, according to (AWS, 2020) Charity: water's 3rd generation sensor has a cost of approximately USD 250 (i.e. including 10 years of data costs).

Danert and Carter (2023) highlight that the different cost measurements (e.g. cost per pump/functional year and cost per m^3) used across these studies means that meaningful comparisons are hard to derive. However, they argue that these studies do provide some basis for the future derivation of more comprehensive costing methodologies. Thomas et al. (2020) suggest that the key question to consider when comparing the costs against the benefits of sensor technologies to support pump repairs relates to whether the sensors might be replaced with a pump operator, caretaker or other stakeholders phoning a service provider.

5.4 Potential benefits

Despite these previous concerns, the authors still consider that remote monitoring systems have the potential to provide added value in this context. Thomson (2021) supports this viewpoint and describes how "these technologies must be used as a tool to rethink how rural water is managed, not just an additional layer to help monitoring and evaluation". This perspective is reinforced by Carter (2021), who reflects that "Technology is rarely transformational on its own, but it can be part of the solution to intractable problems in rural water service delivery".

Ideally, key stakeholders (Governments, NGO's, funding organisations and rural communities) should work together to develop holistic solutions for safe rural water provision that best utilise remote monitoring tools to help improve operational performance. To date, progress in this area has been somewhat piecemeal, as reflected by the emergence of the ten different systems highlighted in this paper. The systems employed in different regions are sometimes chosen to suit the predominant pump types in use, but the choice may also be subject to other factors such as funding schemes, institutional relationships, etc. These choices might not always deliver the best available service, which, unfortunately, may in turn degrade the argument for the funding and use of remote monitoring systems.

In terms of the ten systems reviewed in this paper, all have been designed to detect when a pump is operating normally and hence delivering water to the community. Judging by the available data there is not enough evidence to say whether this is universally achieved. However, the recent studies (Thomson, 2021) do indicate that the systems work as described and do provide valuable data, which can assist the overall management regime of the hand pumps deployed across Sub-Saharan Africa.

5.5 Potential vulnerabilities

The potential vulnerabilities of each system to damage/misuse/component failure is generally linked to the complexity of the system (e.g., more components equal more failure points; similarly, more exposed infrastructure equates to more risk of damage). Choosing a system format that promotes ease of installation and operation at the expense of functionality is a trade-off in terms of system flexibility and is similar to the debate over the benefits of simple data transmission vs complex measurements / data transmission. Given this context, Swan *et al.* (2018) have previously advocated that a system should ideally be, simple, low cost, easy to deploy, have longevity and have an appropriate minimal level of data collection. Despite the obvious merits in this position, in practice the level of complexity employed may often be dependent upon the level of system functionality required by the developer / management organisation. Where real-time data, or a wide array of field parameters, are required then simple may not always be the appropriate solution. However, simple data does equate to lower power requirements (less maintenance interventions). Whereas complex data equates to more system flexibility / higher power drain. To mitigate this some systems employ solar panels to recharge batteries, which are then subject to potential damage and require regular cleaning.

6 Conclusions

Despite the significant progress that has been made, the goal to achieve water security and deliver Sustainable Development Goal 6 (SD6) is unlikely to be met by the target date of 2030 (WHO, 2021). In this context, remote monitoring systems for hand water pumps could play a role in supporting efforts to achieve this goal. The authors consider that all the systems reviewed in this paper could make a real difference if managed well.

It is fair to say that many of the organisations involved in developing these systems have similar visions but have diversified in their approach to solving the problem. They have all gone through long development journeys, and constant efforts are being made to interpret performance data, and continuously improve for the future. In conclusion there does not appear to be one single perfect configuration as external factors will require a system to be tailored to the users' requirements, obtaining an agreement from all stakeholders, for a universal configuration for deployment across the globe will be highly unlikely, and there is by no means a consensus that the "one size fits all" approach is the right solution.

In conclusion, it is considered that success over the longer term will not solely relate to the technology itself, but also to its interactions with a wider range of factors (i.e. as outlined in Figure 5). One of these is cost. Traditional project costs relate to the expense of purchasing the pump, digging a well or drilling the borehole and the associated costs of installation and pump maintenance. Any additional costs associated with providing and operating a remote monitoring device will hence need to be justified. In this regard any additional expenditure such as unit cost, installation, maintenance requirements and associated labour requirements, data transmission, data sorting and monitoring, response actions (phone calls, emails, text messages) will all need to be evaluated within a context of limited stakeholder budgets.

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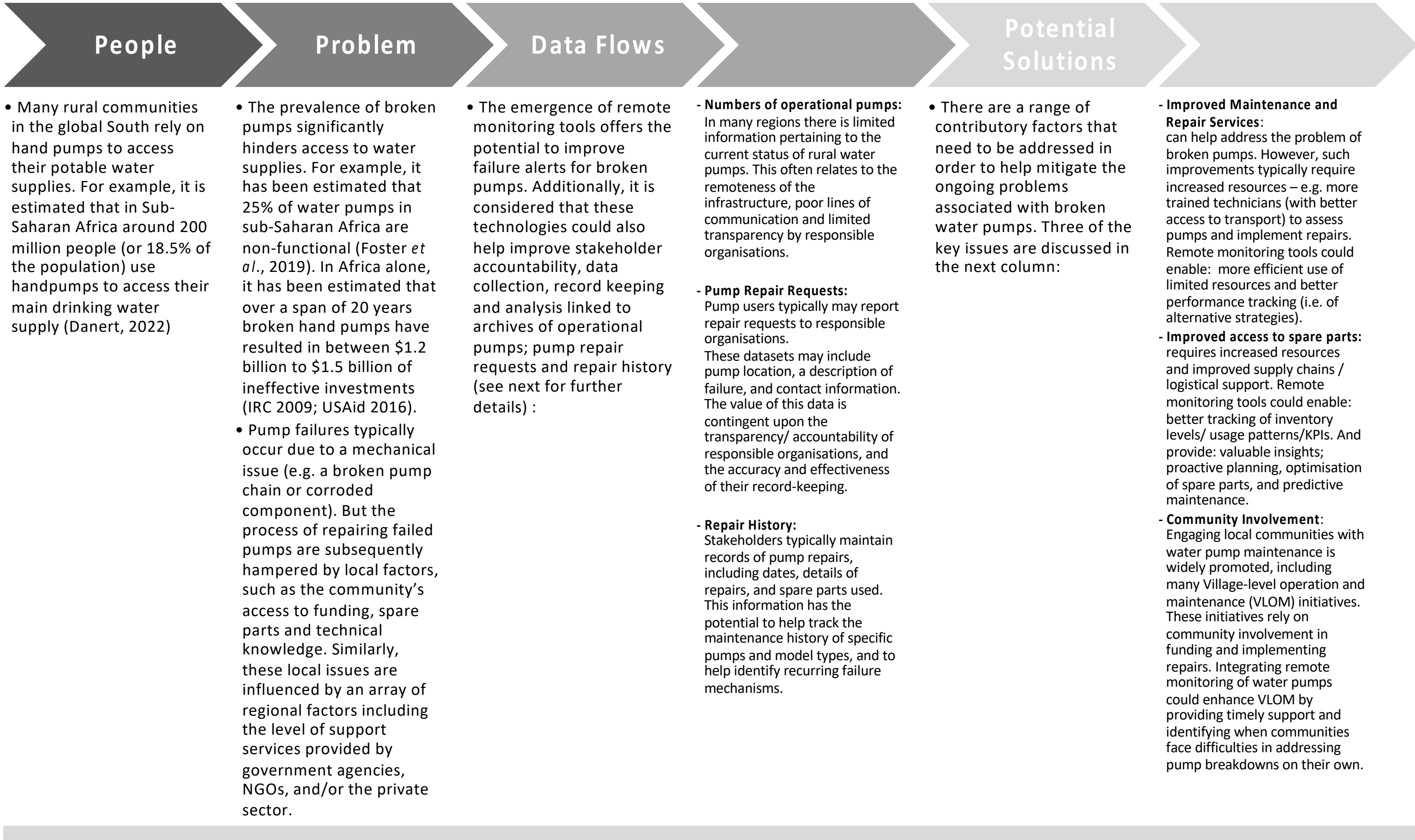

Figure 5 – Contextualisation of remote monitoring systems for water pumps in terms of people, problems, data flows and solutions