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Review of remote monitoring systems for the delivery of sustainable and resilient water infrastructure

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ABSTRACT

Purpose: This paper presents a literature review of remote monitoring systems for water infrastructure in the Global South.

Design/methodology/approach: Following initial scoping searches, further examination was made of key remote monitoring technologies for water infrastructure in the Global South. A standard literature search methodology was adopted to examine these monitoring technologies and their respective deployments. This hierarchical approach prioritised 'peer-reviewed' articles, followed by 'scholarly' publications, then 'credible' information sources, and finally, 'other' relevant materials. The first two search phases were conducted using academic search services (e.g. Scopus and Google Scholar). In the third and fourth phases, web searches were carried out on various stakeholders, including manufacturers, governmental agencies, and NGOs/charities associated with Water, Sanitation, and Hygiene (WASH) in the Global South.

Findings: This exercise expands the number of monitoring technologies considered in comparison to earlier review publications. Similarly, preceding reviews have largely focused upon monitoring applications in sub-Saharan Africa (SSA). This paper explores opportunities in other geographical regions and highlights India as a significant potential market for these tools.

Research limitations/implications: This review predominantly focuses upon information/data currently available in the public domain.

Practical implications: Remote monitoring technologies enable the rapid detection of broken water pumps. Broken water infrastructure significantly impacts many vulnerable communities, often leading to the use of less protected water-sources, and increased exposure to water-related diseases. Further to these public health impacts there are additional economic disadvantages for these user communities.

Originality/value: This literature review has sought to address some key technological omissions and to widen the geographical scope associated with previous investigations.

Key words:
Broken water pumps, Remote monitoring system, Sustainable and Resilient Infrastructure

1. INTRODUCTION

The problem of broken water infrastructure in the Global South is well-documented (Smith *et al*., 2023; Martínez-Santos, 2017; Chowns, 2015). For example, previous studies have suggested that anything between 20% and 65% of hand water pumps installed in sub-Saharan Africa are broken, or out of use (Smith *et al*., 2023; USAid, 2016). It has been highlighted that 62 million people in this region are disadvantaged by broken water infrastructure (Swan *et al*., 2017). Broken pumps also represent a financial loss in infra-structural investment. In this regard, broken hand pumps in Africa may have represented between $1.2 and $1.5 billion of ineffective investment over the last 20 years (Foster *et al*., 2020; USAid, 2016). However, this problem is not just confined to Africa. For example, in India, it is reported that 54% of the population faces high or extremely high-water stress, whilst 6% of the country's hand pumps are out of service at any one time (Foster *et al.*, 2020). The contributory causes of water infrastructural failures are complex, but even new handpumps are often abandoned, provide only intermittent, poor-quality services, or are seasonally dependent (Smith *et al*., 2023; Mkandawire, 2019; Chowns, 2015).

The United Nations (UN) Sustainable Development Goals (SDGs) promote a shift in emphasis from infrastructure provision to service delivery and as such it has been argued that enhanced maintenance provision is required (Thomson 2021). Improved monitoring tools could therefore improve the monitoring/maintenance of water infrastructure that serves vulnerable communities across the Global South, and subsequently help deliver more Sustainable and Resilient Infrastructure (SRI) within this context.

Broken water pumps have significant implications for SRI in terms of the delivery of the UN's Sustainable Development Goals (UN, 2015). Firstly, broken water infrastructure adversely impacts progress towards SDG target 6.1 (i.e. to achieve universal and equitable access to safe and affordable drinking water for all by 2030). Remote monitoring technologies could therefore offer the potential to help deliver SDG 6 (i.e., to ensure availability and sustainable management of water and sanitation for all). Under the SDG framework, a handpump constitutes a limited, basic or safely managed service, depending on its location relative to users. Remote monitoring systems have the potential to reduce water pump breakdown times which could save vulnerable communities many hours of work associated with the collection and conveyance of water supplies (i.e. from unnecessarily remote alternative sources). This could free time for more productive activities with the potential for boosting local economies and in turn helping achieve SDG target 1.1 (i.e. to eradicate extreme poverty by 2030, for all people everywhere currently measured as people living on less than $1.25 a day). Remote monitoring systems also offer the potential for monitoring/management of local water tables and assist progress towards the UN's SDG target 6.4 which aims to "substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" (UN, 2015). Furthermore, under the SDG framework, the rural water sector is beginning to adopt the premise that its key role is actually 'the delivering of services rather than building infrastructure'. From this revised viewpoint the commissioning of new water infrastructure no longer represents the end of a project, but the moment when service provision begins.

This paper presents a literature review focusing on the application of remote sensing technologies to enhance water provision for rural communities in the Global South. Building on established foundations from prior review articles (e.g., Thomson, 2021; Danert K. and Carter R. 2023), our investigations have sought to further this area of research through consideration of a wider range of monitoring technologies and their geographical coverage. Previous reviews have predominantly concentrated on monitoring applications within sub-Saharan Africa (SSA). This paper, however, investigates prospects in different geographical regions and highlights the potential significance of India as a substantial market for these tools.

2. LITERATURE REVIEW OF REMOTE SENSING TOOLS FOR WATER HAND PUMPS

2.1 Background

Remote sensing systems are now used for numerous monitoring activities around the globe. Many remote monitoring systems utilise satellite or mobile-phone networks to transfer field-data from remote locations to a central database and/or web-based dashboard interface (Thomson, 2021). In practice, such field-data may be conveyed via different communication protocols (e.g. SMS and GPRS) – depending upon a number of determining factors such as the size and frequency of data packages to be sent. The key advantages of remote monitoring tools relate to their comparatively low costs and the broad coverage offered by mobile phone networks. There has been rapid growth in terms of both mobile phone services and mobile subscribers throughout Africa (Mitullah, Samson, Wambua, & Balongo, 2016). Between 2008 and 2015 mobile phone penetration (i.e. access to the network, not necessarily owning a phone) rose from 70 to 93%. In contrast, it is interesting to note that access to piped water in this region only grew from 53 to 63% over the same period.

The timeliness of these remote sensing tools is closely linked to the expansion of mobile phone network coverage and the availability of affordable monitoring equipment (Thomson, 2020). This significance is further amplified by evolving cultural shifts within the global water sector, driven by the transition from a focus on 'infrastructural provision' to a greater emphasis on 'service delivery,' as outlined in the SDGs. For example, the lack of maintenance funding for water infrastructure in many developing regions is seen as an important contributory factor that has been discussed in several previous publications (Harvey and Mukanga, 2020; Foster *et al.*, 2020; Thomson and Koehler, 2016; Janus and Keijzer, 2015; Yorke *et al*., 2022; Pories *et al.*, 2019).

In this context it has been suggested that remote monitoring technologies may offer added potential to attract extra funding into the rural water sector (Thomson, 2020). The data employed by service providers for water infrastructure upkeep might also serve the purpose of validating this maintenance process (Thomson, 2020). In addition to representing a cheaper form of project monitoring, cost-conscious NGOs/donors might also employ these datasets to enable the development of performance-driven contracts (Thomson & Koehler, 2016;). These contracts could be financed through emerging Results-Based Aid programs (Janus & Keijzer, 2015).

2.2 Methodology

This review exercise utilised a range of search tools to identify research papers and other relevant information sources. Given that remote sensing within the Global South appears to be a rapidly growing topic area, the emphasis of this literature review exercise was to broaden the search focus to maximise the identification of relevant studies. To this end, a standard literature search methodology was adopted to examine these monitoring technologies and their respective deployments. This hierarchical approach prioritised 'peer-reviewed' articles, followed by 'scholarly' publications, then 'credible' information sources, and finally, 'other' relevant materials. The first two search phases were conducted using academic search services (e.g. Scopus and Google Scholar). In the third and fourth phases, web searches were conducted in relation to various stakeholders, including manufacturers, governmental agencies, and NGOs/charities associated with Water, Sanitation, and Hygiene (WASH) in the Global South.

To ensure relevance and consistency in the selected publications, search keywords were organised into two broad groupings. The first group comprised strings linked to the technological function and application such as " ‘remote sensor*’ AND ‘water’”, “‘remote monitoring’ AND ‘water’”. The second group related to searches focused on the names/titles of specific technologies such as ‘MANTIS’ or ‘SWEETSense’. These search strings and their combinations were initially applied to titles, abstracts, and author-supplied keywords. Google Scholar was used as supplementary source to enhance information gathered from other databases, enabling a comprehensive full-text search across a large volume of documents that are not usually present in conventional scientific databases such as Scopus. Although Google Scholar lacks the capability for abstract or author's keyword searches using combinations of keywords, its extensive coverage and inclusion of scholarly publishers' archives contribute to its value in conducting systematic reviews.

The authors identified ten technologies which have been specifically developed for monitoring hand water pumps in the Global South. A review of the main features of nine of these systems is presented in Table 1 and discussed within the ensuing sections. The authors are aware of a tenth technology, called the UpPump system which was developed by Jordan Seven. This organisation’s website previously reported that the UpPump system captured a number of parameters – including counting the number of pump handle strokes and flow at time intervals (Jordan Seven, 2017). However, this website now appears to be defunct, and the current status of the UpPump system is unknown. Due to these uncertainties the system has not been included within this technological review.

Whilst the field-data dispatched by the remaining nine systems may differ, each of these technologies reportedly employs at least one of three broader monitoring strategies (Thomson, 2020). The first group monitors the movement of the pump handle. The second group monitors water levels within the pump headworks. The third group directly measures flow from the spout of the pump. Most of the technologies highlighted in Table 1 employ just one of the aforementioned monitoring strategies – but some technologies appear to utilise two of these. Table 1 highlights which remote monitoring systems fall within each of these three groupings. This table also highlights which of these technologies, and the data they generate, are open-access – this is generally linked to whether the responsible organisation is a non-profit entity.

Table 1: Overview of Remote Monitoring Technologies for Hand Pumps

Monitoring Technology	Monitoring Techniques Employed			Responsible Organisation/s	Type of Organisation	Open access technology and support systems
	Pump Handle Movement	Water Level in Headworks	Flow Through Spout			
Dispatch monitor		X		Charity:Water	Non-profit	Yes
e-pump			X	Odial Solutions	Company	?
EyeOneer	X			CAYA Constructs Ltd	Company	No
IWP	X	X		Messiah College, Desert Research Institute (DRI) & World Vision	Collaborative: Academic/NGO	?
MANTIS	X			EMS Ltd & Leeds Beckett University	Collaborative: Company/Academic	No
MoMo		X	X	Welldone	Non-profit	Yes
SonSetLink monitor			X	SonSet Solutions	Non-profit	Yes
SWEETSense	X		X	SweetSense Inc	Spin-off Company from Portland State University	No
WDT	X			OxWater Ltd	Spin-off Company from Oxford University	No

These nine systems employ a diverse range of remote measurement approaches and techniques to monitor and evaluate hand pump usage. Figure 1 illustrates how each of these different hardware monitoring technologies attaches to the hand pump. In the case of three of these systems (i.e. SweetSense, Eyeoneer and MoMo), it would appear that alternative installation configurations have been developed. For example, some photos of the EyeOneer system display the monitoring unit attached to the pump handle, whilst other photos show the monitoring unit installed on the pump headworks. These alternative installation arrangements would indicate that two different sensors/sensing methodologies have been employed. As limited technical information appears to be available within the public domain, the authors are unclear whether in these cases – two alternative sensor configurations are currently available, or whether these differing installations just reflect the changes that have been made as prototype units have been updated and refined.

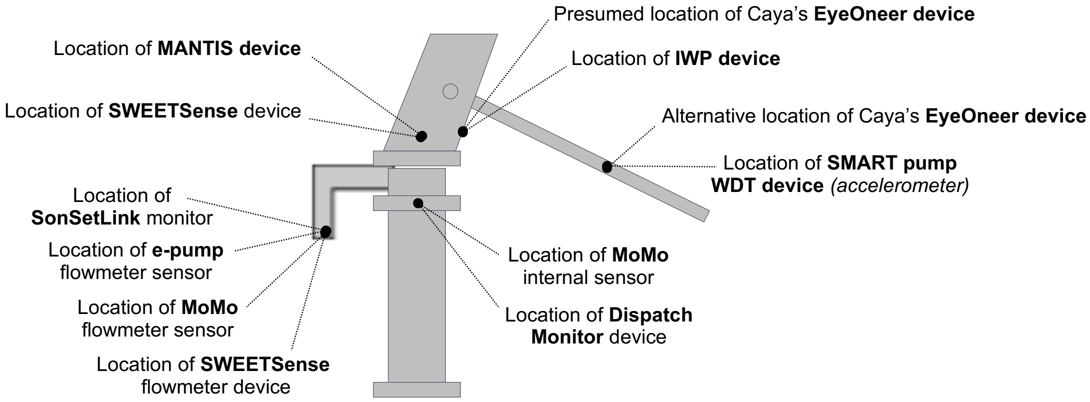

Figure 1 – Remote Monitoring Technologies for Hand Pumps – Unit installation arrangements.

The following sections briefly reviews both the hardware and software interfaces associated with each of the nine systems highlighted in Table 1. This review is largely based on a desktop research exercise and draws on secondary literature and organisational information available in the public domain.

2.3 Dispatch Monitor (Charity:Water)

2.3.1 Hardware

This system comprises of a remote sensor unit and software system that processes data from the field and graphically represents this information upon a user interface. Charity:Water's Dispatch Monitor unit and dashboard are both open-access with technical details available via the Github platform (Charity:Water, 2015*)*. It is reported that the device consists of a stack of six capacitance sensors that measure the physical level of water (Charity:Water, 2021) within the pump's head works (i.e. twice every second). This hardware unit is now manufactured at scale (Charity:Water, 2015) by an industrial partner. This data is converted into the corresponding flow rate (litres per hour) through the pump Charity:Water, 2021). The Dispatch Monitor automatically geo-locates, simplifying the installation process.

2.3.2 Dashboard

Charity:Water's dispatch monitor is served by an open-access dashboard that graphically represents water pump usage data (Charity:Water, 2020b). Field data from the Dispatch Monitor sensor is conveyed via the cloud and processed by a cloud-based Application Programming Interface (API), and presented via an Amazon Web Services (AWS) powered dashboard and a mobile app. The system can generate user alerts to report pump failures – hence enabling maintenance teams to be deployed to address pump issues and restore water flow. The dashboard graphically represents pump locations on a navigable map layer. Clicking on specific pump assets displays operational performance data such as hourly pumped flow (litres/hour). It is also reported that this system employs AI techniques to schedule proactive and predictive maintenance for water pumps (TT, 2020). These outputs are shared with local governments and water bureaus to equip decision makers with valuable knowledge about water usage in their communities to help enhance the management of local water services (Charity:Water, 2021).

2.4 E-Pump (Odial Solutions)

2.4.1 Hardware

It is reported that the e-pump employs a flow-meter based approach to monitor the pump discharge (FWP, 2018). The approach utilises water meters and data loggers. It appears that the e-pump technology was originally developed for the Vergnet Hydro footpump but has subsequently been adapted to work in conjunction with the hand-operated India Mark II model (UDUMA, 2017).

2.4.2 Dashboard

It is reported that Odial's e-pumps convey data to a 'web observatory' developed by AquaSys (Odial Solutions, 2020). This web portal appears to be able to handle real time data about the operational status of pumps from either the e-pump remote monitoring units or manually entered field data inputted by pump users.

2.5. EyeOneer (CAYA Constructs)

2.5.1 Hardware

To date, information in the public domain about the EyeOneer system is somewhat limited and not particularly detailed. However, a report of recent field trials (YourStory, 2019) indicates two different variants in terms of the system's sensor location: one with a monitoring device attached to the pump handle; and the second with a monitoring unit attached to the pump headworks. The locations of both these sensors, would seem to indicate that this system monitors pump handle movement.

2.5.2 Dashboard

There are very limited details about the EyeOneer's dashboard and its functionality in the public domain However, it is reported (YourStory, 2019) that this system is capable of detecting failures and predicting mechanical failures using Artificial Intelligence (AI) and Machine Learning (ML). It is reported that alerts from this system are then automatically sent to government agencies who can ensure that appropriate repairs are implemented.

2.6 Intelligent Water Project (IWP)

2.6.1 Hardware

It is reported that the Intelligent Water Project (IWP) hardware unit monitors pump handle movement using an accelerometer attached to the pump handle and a conductivity sensor to detect the presence of water within the pump headworks (Weaver *et al*., 2016). The system reportedly captures a number of field parameters (e.g. priming effort, volume extracted, leakage rate). It is also reported that an optional groundwater level sensor is planned for future prototype units that will provide daily maximum and minimum well water levels (WVI, 2020).

2.6.2 Dashboard

The data generated from the remote IWP monitoring units is stored on a secure, cloud-based database. This data can then be accessed by users via a secure web application or mobile app (WVI, 2020). The operational status of pump assets can be viewed on a map-based interface, which graphically presents the status of each handpump (WVI, 2020). Each pump is colour coded on the map to reflect operational status (i.e. Green indicates a fully functional pump with no significant leakage or priming issues; Yellow shows that a pump is in a satisfactory condition, with minor leakage or priming issues; Orange indicates that the pump is still working, but is in need of immediate maintenance; and Red represents a non-operational pump). The system sends alerts via SMS or email to stakeholders when the pump status changes – enabling an appropriate response/repair to be implemented.

2.7 MANTIS

2.7.1 Hardware

The MANTIS (Monitoring and Analytics to Improve Service) remote monitoring unit detects whether a pump's handle is in regular use and monitors patterns of usage (Swan *et al*., 2018a). Its simplicity enables it to have a long lifespan. The technology has been designed to function for five years without the need for maintenance or battery change, sending back daily data to stakeholders which can be monitored to ensure repairs are made swiftly.

2.7.2 Dashboard

The MANTIS hardware units relay monitored field data from each pump site, via SMS messages, to an online geo-referenced user interface. This web tool provides a platform for water stakeholders, such as government agencies or NGOs (non-governmental organisations), to observe both the operational status and performance of monitored pump sites. The tool is intended to provide alerts when pumps malfunction and to improve the prioritisation of pump maintenance and rehabilitation interventions.

2.8 MoMo (Welldone)

2.8.1 Hardware

The WellDone project has produced an open-source monitoring platform called MoMo (Mobile Monitor), which allows stakeholders, such as governments and NGOs, to collect sensor data from infrastructure in remote developing world contexts (GMSA, 2014). The approach appears to use local GSM enabled hub units that can compile data from small local monitoring units that can be attached to hand pumps, pipes, and power systems (MoMo, 2014). In terms of hand pump monitoring there appear to be two options: an internal device that sits within the pump headworks (the authors speculate that this device monitors water depth via conductivity or pressure) and a flow sensor that can be attached to the nozzle of the hand-pump. As with many of the other system, field data is sent back via SMS messages to a central database. This database can be monitored for daily service/usage levels for both water and energy infrastructure.

2.8.2 Dashboard

The Stato Dashboard has been developed to compile and present pump performance data from MoMo units in the field. The dashboard is not currently publicly available. But it is reported that this dashboard provides an interface to manage and analyse historical data that is conveyed from field-based MoMo sensors monitoring water pumps (TS, 2019). The dashboard apparently supports trigger alerts which can be sent via SMS and email to key stakeholders when specific operational thresholds are broken. For example, automatic alerts can be sent to a pump's assigned mechanic when the pump's sensor fails to detect water flow for a set period.

2.9 SonSetLink Monitor

2.9.1 Hardware

The SonSetLink unit contains a microprocessor and sensor (SonSet, 2021a) which attaches to the spout (delivery pipe) of a number of different hand pump models (e.g. India MkII, LifePumpLink, AfriDev). This system monitors the operational status of the pump by assessing the presence (or absence) of water in the pump's spout. The unit compiles daily reports containing a number of operational parameters (e.g. Pump time-in-Use; Wet time – time with water in the spout; Dry time –time with no water in the spout; Longest dry time – longest dry period each day). The unit is powered by AA lithium batteries, which are reported to deliver between 3 to 5 years of power.

2.9.2 Dashboard

It is reported that the field data collected by the SonSetLink monitor is relayed to an interactive online dashboard via satellite modem (SonSet, 2021b). This dashboard, which is supported on the ArcGiS platform, presents pump functionality reports, including statistics related to the pump operation performance both with, and without, water in the spout (delivery pipe). It is also reported (SonSet, 2021b) that the SonSet system offers predictive analytics (i.e. to help predict pump failures before they occur).

2.10 **SWEETSense**

2.10.1 Hardware

The SWEETSense company have generated a range of remote-sensing technologies for WASH (Water, Sanitation and Hygiene) projects (GSMA, 2014). In terms of hand water pumps, there appear to be two sensors: an accelerometer and a differential water pressure transducer - to record water level in the pump's overflow basin as pressure (Nagel, et al., 2015). These devices are reportedly compatible with the Afridev, India Mark 2 and Consallen pump models.

2.10.2 Dashboard

The SweetSense system is served by a dashboard that presents a graphical view of water pump status (SweetSense, 2020b). This cloud-based analytics and machine learning platform utilises the IBM Cloud. The dashboard presents a range of different field/operational parameters including the status of pumps (i.e. with pumps grouped as being offline, needing repair, no use, low use and normal use) and average rainfall per month. Whilst some data from the SweetSense dashboard can be accessed via the public domain (SweetSense, 2020b) – it would appear that the dashboard is primarily intended for water service providers to monitor functionality and water volume. At the county-level governance stakeholders can also monitor service provider performance.

It is reported that in Kenya, this platform has enabled local service providers to implement preventative maintenance for the borehole wells to ensure there is water available during drought (Agrilinks, 2020). This monitored data feeds into the Famine Early Warning System Net (FEWSN), which analyses the relationship between rainfall data and monitored groundwater pumping activity to provide an early warning signal for potential drought-related shocks, enabling better planning for water shortage and more resilient recovery.

2.11 Waterpoint Data Transmitter (Ox Water Ltd.)

2.11.1 Hardware

The Waterpoint Data Transmitter (WDT) system developed by Ox Water Ltd appears to employ an accelerometer to monitor pump handle movement. This device can be installed on or within the pump handle and monitors pump usage via the handle's movements, which are detected by the accelerometer (Thomson, 2020). Since the device only attaches to the pump handle – the unit should not interfere with pump maintenance; and could also be easily adapted for use on different pump types.

It is reported that previous field trials of this system have been deployed in Kenya, Uganda, Zambia. In Kenya, the system has been trailed in conjunction with the FundiFix service model (REACH, 2021), which focuses on a performance-based approach for existing water infrastructure serving communities and institutions.

2.11.2 Dashboards / User Interfaces

It is reported that the field data collected by the Waterpoint Data Transmitter unit is relayed via SMS to an operational database (TReNDS, 2018). Operational data is then represented graphically on a map layer, which indicates those pumps that are in frequent use. Further details regarding this dashboard and its functionality are unclear as this platform does not currently appear to be in the public domain.

3. OVERVIEW OF PREVIOUS FIELD DEPLOYMENT

The following section briefly reviews the previous field deployments associated with each of the nine monitoring technologies highlighted in Table 1. Again, the information below is largely based on secondary sources with the exception of MANTIS. Here, a series of semi-structured interviews were carried out with professional stakeholders involved in trials in two West African countries.

3.1 Dispatch Monitor (Charity:Water)

It is reported that Charity:Water is currently the organisation with the largest number of monitored hand-operated water pumps (Thomson, 2020) and as such their open-access web-portal (Charity:Water, 2020b) appears to contain the most comprehensive set of remote operational performance data from such pumps. It was recently reported that Charity:Water is actively monitoring 7300 water pumps in remote areas across various countries such as Ethiopia, Ghana, Malawi, China, and Nepal (AWS, 2020; Thomson, 2021). The NGO's online portal provides statistics on pump functionality, including details about downtimes and repairs. It was noted that in September 2020, the pump assets achieved an impressive functionality rate of 94%, with median downtimes lasting between 15 and 30 days (Thomson, 2021).

3.2 E-Pump (Odial Solutions)

It is reported that by February 2020, the UDUMA project team, which forms part of the Odial Solution group, had installed 244 monitored water points in Burkina Faso and a further 30 in Mali (GSMA, 2020). These assets include both standpipes and manual handpumps. This UDUMA pilot study involved installing water meters and data loggers onto manual pumps, to convert them into E-PUMPS. These E-PUMPS have been deployed as part of a service provision business/management model, which includes a fixed rate water tariff of 10 CFA francs (€0.015) per 20 litres (Odial Solutions, 2020). These water tariffs can be collected as digital payments. In return UDUMA seeks to continuously service these E-PUMP assets, aiming at limiting its pump downtimes to less than 72 hours (Odial Solutions, 2020). Although this still represents an early-stage pilot, one of the key reported benefits is that the digital prepayment records and the associated water point data provided by the E-PUMPS have provided UDUMA with key information to better manage and plan their services.

3.3. EyeOneer (CAYA Constructs)

It is reported that the EyeOneer system has been piloted on 112 devices across remote areas in West Bengal and Himachal Pradesh (YourStory, 2019). However, the results from this exercise do not appear to be in the public domain. The company is now reportedly targeting the installation of 5 million devices across India.

3.4 Intelligent Water Project (IWP)

It has been reported that the prototype IWP system has been through a number of design iterations, including lab testing conducted in the United States and field trials that were undertaken in northern Ghana during 2014 and 2015 (Weaver et al., 2016).

3.5 MANTIS

MANTIS units were field trialed on India Mark II hand pumps at eleven locations in Sierra Leone and twelve locations in The Gambia. These field trials were supported by local representatives from the Rural Youth Development Organisation in the Bumpe Ngoa Chiefdom in Sierra Leone and the Glove Project NGO in the Gambia. The remote MANTIS units reported the operational status of hand pumps via SMS text message to an online platform. Messages were converted to an easily understandable visual representation of the location and usage pattern of the pumps. In Gambia, the MANTIS system successfully detected a water pump failure event and informed the relevant local stakeholders. In this regard, these trials demonstrated that the MANTIS system has achieved Technology Readiness Level 7 (i.e. a prototype demonstration in an operational environment).

Based on a series of semi-structured interviews with stakeholders that had been involved in West African trials, a recent analysis also highlighted the need to understand the wider social context in which they took place. This is necessary to inform the design of the MANTIS unit as well as how it operates as part of wider repair and maintenance service provision. For example, a number of assumptions were made including "that all India Mark II pumps are the same" and that there was a substantial risk of vandalism and theft. In turn, this led to a design that was mounted inside the head pump. However, theft was later found not to pose a major challenge while the decision to use an internal design had a number of knock-on effects. This included difficulties in installing the unit on what turned out to be non-standard pumps including those that had been modified for previous repairs. The internal design of the unit also struggled with signal strength which posed a barrier to data transmission. Furthermore, assumptions were made regarding limited mobile phone infrastructure available which resulted in the requirement for only 2G networks despite The Gambian context moving towards 4G.

The field trials enabled limited engagement with local people due to the focus on installing the MANTIS units and ensuring they were operational. As such they gained limited insight into local water consumption practices and for example how they change throughout the year. Limited observations that did take place on the site of handpumps did however feed into how the MANTIS units were configured, demonstrating the value of such insight.

Finally, evaluation of field trials in West Africa also highlighted the need to build and maintain relationships with wider stakeholders involved to understand and respond to current maintenance and repair regimes, ownerships structures and responsibilities. In Sierra Leone what was described as a 'fit and forget' approach was observed whereby handpumps are installed by a large array of small non-governmental organisations but where subsequent ownership and mechanisms for maintenance and repair remain vague and unsupported. This encouraged a paradigm shift from technology to service provision.

3.6 MoMo (Welldone)

A series of MoMo field trials appear to have been conducted in Cambodia as well as Ethiopia, Uganda, Rwanda and Tanzania in sub-Saharan Africa (TS, 2019). It appears that the Mo-Mo project team has employed a number of alternative monitoring approaches to observe the operational performance of different types of hand-pump. For example, it is reported that an early prototype was used to directly measure the flowrate from a rope pump in Tanzania (MoMo, 2014b); whilst alternative Mo-Mo deployments appear to measure water levels within the headworks of an India Mark II model (Welldone, 2021).

3.7 SonSetLink Monitor

In early 2021, there were 1377 monitored pump sites linked to SonSet's online dashboard. These monitored sites included locations in Sub-Saharan Africa (Central African Republic, Ethiopia, Kenya, Liberia, Mali, Republic of Congo, South Sudan, and Uganda); Asia (Bangladesh, Indonesia, Kyrgyzstan and Nepal); Central America and the Caribbean (Haiti, Honduras, Guatemala, Mexico and Puerto Rico).

3.8 SWEETSense

The SWEETSense system for water pumps has been field trialled on 181 monitored hand water pumps in Rwanda (Nagel et al., 2015). This study explored the merits of a sensor-based maintenance regime against two conventional maintenance strategies using representative groups of pumps. For the sensor-based approach (described as being an 'ambulance' maintenance model) – the remote field data dispatched by the SweetSense units were used to trigger maintenance visits by pump mechanics. In terms of the other strategies: the next approach (described as representing 'Best Practice') sought to undertake regular preventative maintenance activities; whilst the last maintenance strategy (labelled 'nominal' maintenance) only sought to carry out repairs when pump problems were reported by pump users or other local stakeholders. Over the study period, the levels of 'pump functionality' associated with each maintenance regime were evaluated. The 'nominal' maintenance strategy yielded a pump functionality rate (mean per pump) of 68%, compared to 73% for the 'Best practice' model and 91% for the sensor-informed 'Ambulance model'. In terms of the average (median) pump downtimes associated with these three maintenance strategies: the 'nominal' approach achieved an average (median) time to repair of 152 days; whilst for the 'best practice' and 'ambulance' models this was 57 and 21 days respectively. Thomson (2020) highlights that these functionality rates and downtimes are largely similar to those associated with the operational data presented on Charity:Water's open-access web-portal.

It should be noted the SWEETSense field trials also highlighted a number of operational challenges. 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).

3.9 Waterpoint Data Transmitter (Ox Water Ltd.)

The Waterpoint Data Transmitter (WDT) system has been trialled on over 300 hand pumps in Kenya (GSMA, 2014). This system compiled hourly pump usage data, dispatched on a six-hourly basis. Data was relayed via SMS to an operational database in Nairobi. Outputs were graphically represented on a map layer, which indicated those pumps in frequent use. Any pumps not in regular use were assumed to be malfunctioning, and a technician dispatched to them in order to address the problem (GSMA, 2014). This system reportedly improved the average pump downtime (i.e. time until a repair was successfully implemented) from 27 days to 2.6 days (Nagel, et al., 2015). Thomson (2020) reports that the WDT system was trialled in a second similar study in Kenya, which yielded a similar set of results – for example reducing the average time to repair down to 3 days from a pretrial level of 37 days.

These field trials, like those undertaken for the SWEETSense units identified a number of operational challenges. For example, this system relied on good GSM network coverage - but Behar et al. (2013) 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).

Monitoring Technology	**Previous deployments by Region**			
	Sub-Saharan Africa	**Central America**	**Asia (not India)**	**India**
Dispatch monitor	X		X	X
e-pump	X			
EyeOneer				X
IWP	X			
MANTIS	X			
MoMo	X		X	
SonSetLink monitor	X	X	X	X
SWEETSense	X			
WDT	X			

Figure 2 – Previous deployments of remote hand pump monitoring technologies (by Region)

4. DISCUSSION

This section outlines some key reflections from this review exercise.

4.1 India – a new market?

Upon reflection, it appears that previous studies have predominately focused upon the application of these monitoring tools within sub-Saharan Africa (SSA). For example, eight of the nine remote monitoring technologies (reviewed in Sections 3 and 4) were deployed or field-trialled within the SSA region. However, the authors consider that there are significant opportunities to apply these monitoring tools within other geographical regions.

In terms of scale, perhaps the largest potential market for such monitoring technologies is India. This is highlighted by a recent study (Foster *et al*., 2020) which reports over 8.5 times more community hand pumps in India than in the SSA region - 5.8 million in India, compared with 0.68 million in SSA. It is worth noting that this estimate omits a further 29 million domestic hand pumps located on private land across the country. The Indian market also appears to offer better mobile phone network coverage than the SSA region, with around 1% of its population living beyond mobile broadband coverage compared to 25% in SSA (GSMA, 2020b). In terms of background context, 54% of India's population faces high or extremely high-water stress, whilst 6% of the country's hand pumps are out of service at any one time (Foster *et al*., 2020). Even where other water sources are available hand pumps may provide the main source for clean drinking water at household levels.

This review has highlighted that the application of remote monitoring for hand-water pumps in India is still relatively limited compared to other regions. For example, only three of the nine systems reviewed in Section 4 appear to have been deployed in the Indian market. These systems are the SonSetLink monitor, Charity:Water's Dispatch Monitor and Caya's Eyeoneer device. It appears that Charity:Water's Dispatch Monitor has only been deployed on a single monitored hand pump in India. This was an AfriDev model pump which is located near Koeregaon, to the North-East of the city of Pune. Although the dashboard contained the geo-referencing data for this site – there did not appear to be any field data (neither 'live' or historical) linked to this asset. Similarly, the SonSetLink monitor only appears to have been deployed on two pump sites in India. Whilst it is reported that Caya's Eyeoneer device has been trialled on 112 devices across remote areas in West Bengal and Himachal Pradesh. However, the results from this exercise do not appear to have been published. Even within the wider region, only three systems (Charity:Water's Dispatch Monitor, the SonSetLink monitor and MoMo) have been deployed in other parts of Asia.

Furthermore, the authors consider that India offers more economic opportunities to develop/support much of the associated supply chain. This could deliver much lower manufacturing costs than are possible in the USA or Europe (i.e. the places of origin of most technologies highlighted in Table 1). IT skills are abundant in India, meaning the dashboards could be developed/hosted there. Furthermore, many of the world's hand pumps are currently manufactured in India, meaning there are further potential synergies that could be attained by developing the associated remote monitoring systems within this same region.

4.2 Wider social and economic factors

The lessons from the field trials outlined in Section 4 do however highlight the importance of gaining additional understanding of the wider social and economic dimensions. For example, how the technology operates as part of wider repair and maintenance service provision (Section 4.5). Furthermore, it is also important to gain greater insight into local water consumption practices. Questions related to how and for what purpose water is consumed may include temporal dimensions such as seasonal changes that may influence changing practices throughout the year. Contextual insights including how infrastructure is implemented and currently maintained will support physical design adaptations whilst supporting the necessary shift of these remote monitoring tools from being stand-alone technologies to being part of a wider service provision. Lastly, a number of previous publications (Moa *et al*., 2018; Moa *et al.*, 2020) have highlighted that there an array of other social-economic factors that may impact the potential viability of these monitoring systems. One of these articles (Moa *et al.*, 2020) sought to develop a socio-technical roadmap for the application of low-cost water sensor applications in the context of the Global South. This methodology focused across 3 areas of interest: (1) technologies, (2) user contexts and scenarios, and (3) society and communities. The study concluded that these monitoring technologies offer significant potential to assist communities in becoming more resilient and sustainable. However, in order to achieve this, it was considered that closer collaboration amongst key stakeholders (e.g. pump users, governmental agencies, NGOs, etc) and better stakeholder integration is needed in relation to the planning process. Encouraging wider participation and fostering collaborative design methods was also considered as important, along with the identification of the most appropriate governance models and incentive strategies. Adopting such approaches should help ensure that the chosen technologies align more effectively with the needs and expectations of the end-users. To this end it would appear that further research would be beneficial to better define these mechanisms.

5. CONCLUSIONS

In conclusion, this paper has reviewed the application of remote monitoring technologies for water infrastructure, particularly hand pumps, with a focus on their potential to improve water provision to vulnerable communities. This review has largely focused upon the *modus operandi* of these technologies and the geographical reach of their previous deployments. In the context of Sustainable and Resilient Infrastructure (SRI) for water provision, this paper has highlighted several successful field trials. These trials have highlighted that many of these monitoring tools are technically proven and offer strong potential to enhance maintenance regimes – which in turn can improve water supplies to vulnerable communities. However, the review also indicated that consideration of the broader social and economic factors is crucial for effective implementation of such monitoring tools. To this end, collaboration with key stakeholders is considered essential to effectively meet end-users' needs and encourage wider participation.

Lastly, it should be noted that this review exercise has sought to build upon the foundations laid within a number of previous publications (Thomson, 2021; Swan *et al*., 2018b). Whilst the authors acknowledge both the significance and accuracy of these preceding articles – this paper has sought to identify additional monitoring technologies that have been omitted from previous reviews. It has also attempted to broaden the geographical scope of these investigations. This study has highlighted India as a significant potential market for these technologies, with a much larger number of hand pumps and better mobile network coverage compared to Sub-Saharan Africa. By refocusing on India, the authors are not suggesting that remote monitoring stakeholders neglect the SSA market, where we believe such technology still offers the potential to deliver many positive impacts regarding SRI and SDG 6. Rather, the authors consider that India should be viewed as a more of a launch pad for these products to be developed, mass-produced and exported with skills and service designs adapted in SSA and South America, where hand pumps are also common.

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