IoT innovation in rural water supply in sub-Saharan Africa: a critical assessment of emerging ICT

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Abstract

Internet of Things (IoT) technologies are beginning to transform rural water supply in sub-Saharan Africa. Such Information Communication Technologies (ICTs) can facilitate change away from current unsustainable approaches that fail communities. Fast-moving developments in this area are under-researched, and sustainability of the innovations themselves and their place in the complex operating system require fuller consideration and presentation to the practitioner community. First, rural water supply in sub-Saharan Africa is critically contextualised as a 'wicked problem'. Second, specific challenges to rural water supply in Tanzania are quantitatively assessed using expert interviews. Analysis of these coupled with academic and practitioner-oriented literature demonstrates the need to move towards a 'service delivery approach'. Third, existing novel ICT and IoT technologies are categorised and critically evaluated, presenting the landscape of innovation to practitioners within the above context. Current research gaps are outlined. With a focus on research in the context of rapid technological innovation, the paper shows policy makers and practitioners how IoT innovations will support a service delivery approach. Longer-term planning using the enhanced data collection, and more integrated collection-to-use information flows, will advance service delivery further and increase sustainability. Practitioners must contextualise this with an appreciation of the complex operating system.

Keywords

Internet of Things, Rural Water Supply, sub-Saharan Africa, Wicked Problem, Tanzania

1. Introduction

Failing rural water supply in sub-Saharan Africa is a well-documented challenge, with characteristics of a 'wicked problem' (Rittel and Webber, 1973). The challenge can be conceptualised as part of a complex adaptive system with multiple levels of: actors (e.g. water users), pressures (e.g. population growth), and shifting uncertainties (e.g. climate change). An estimated 42% of sub-Saharan Africa's population remain without basic drinking water service (WHO, 2017a, 2017b), largely due to unsustainability of rural water supply systems.

ICT (Information and Communications Technology) innovations can address a number of the challenges to system sustainability (GSMA, 2018a). Such innovations can facilitate enhanced data collection, reporting, and decision-making. IoT (Internet of Things) innovations can automate this process in real-time, increasing timeliness and accuracy, and provide tools for practitioners wanting to improve service provision.

Sustainability of such innovations and their longer-term impact need fuller consideration. It remains uncertain if they will facilitate short-term solutions, or go further and underpin fundamental systemic change. An academic scoping exercise is needed that contextualises ICT, specifically IoT, innovations within this complex rural water supply system and trends in management models.

This paper will:

1. Establish the context for rural water supply in sub-Saharan Africa and a basis for systems thinking, using specific examples from Tanzania,
2. In this context, highlight gaps evident in current research on ICT innovations (specifically IoT) and inform suitable directions for new research, and present a range of such ICT innovations for practitioners along with considerations for their effective use.

2. Methodology

- Stage 1 - Review of the complex context of rural water supply in sub-Saharan Africa, including current theory of rural water supply management models. This frames understandings of ICT solutions in terms of systems thinking.
- Stage 2 - Review of how rural water supply failures manifest in a specific country, to avoid regional generalisations. Tanzania was selected because of the availability of published studies and its rural water supply context. An estimated 63% of the rural

population lack basic drinking water service compared to the rural sub-Saharan national average of 57%, and roughly 40% of rural water points are non-functional at any one time (WHO, 2017b; Impact Tanzania, 2017).

Findings were combined with semi-structured expert interviews (Tanzanians = 5, Europeans = 3), designed to uncover additional information or emphasis (Noxolo, 2017; Drescher et al., 2013; Voinov et al., 2016; FitzGibbon and Mensah, 2012; FAO, 1990; Oppenheim, 2000).

- Stage 3 - Review of developments of ICT innovations for rural water supply in sub-Saharan Africa. Current evaluations of successes (and challenges) to ICT and IoT innovations were critically assessed. ICT innovations that are operational, recently operational, or partly developed in rural water supply in sub-Saharan Africa were included, categorised and evaluated within the context established in Stages 1 and regarding specific challenges from Stage 2. The emphasis and categorisations of ICT in existing grey literature overviews were incorporated.

Inclusion of practitioner research and project reports add necessary breadth (e.g. Whaley and Cleaver, 2017). Interviewees in Stage 2 are sector experts, not rural water users, however ethical principles were still adhered to. Permission for each interview was obtained beforehand, where each respondent was made aware that responses are personal and not organisational viewpoints. Each gave permission for publication of responses. Each were informed that personal details will be kept confidential and destroyed following research completion, and that information from responses would be aggregated and averaged to maintain anonymity, with names deleted for analysis onwards. University of Exeter ethical guidelines were consulted and no further possible ethical implications were found. Since the ethical considerations were addressed as above, further formal review was not pursued.

3. Rural water supply in sub-Saharan Africa

Contextualisation of rural water supply as a 'wicked problem'

Supply of water in rural sub-Saharan Africa is complex (Huston and Moriarty, 2018). Combined demographic changes, economic inequalities, urbanisation, and entrenched poverty restrain progress towards SDG 6.1. Furthermore, water is considered the primary medium where the impacts of climate change are being felt (UN-Water, 2010). Heterogeneous management processes and entities do not aggregate, and interact with the system in non-linear ways. There are significant uncertainties of information.

Complexity extends into both technical and social realms. Simple solutions such as building more water points are ineffective. Working at a systemic level can directly address the holistic web of factors (Liddle and Fenner, 2017).

An understanding of rural water supply in sub-Saharan Africa using the definition of a 'wicked problem' has not been developed. The link is suggested in grey literature (Casella et al., 2015) and applied in other relevant research areas (e.g. FitzGibbon and Mensah, 2012). Here (Table 1), the above context is critically tested against Rittel and Webber's (1973) properties of 'wicked problems'. This illustrates why systems thinking is required for any potential solution to this challenge, including ICT.

Table 1. Rural water supply in sub-Saharan Africa as a 'wicked problem'

Properties of a wicked problem (Rittel and Webber, 1973)	*Explanation*	*Does this apply to rural water supply in sub-Saharan Africa?*
There is no definitive formulation of a wicked problem	Problem understanding and problem resolution are concomitant	Yes. Diversity and uncertainty of stakeholder understandings over different scales and timeframes. It is a complex adaptive system (Butterworth et al., 2010).
Wicked problems have no stopping rule	There can always be better solutions	Yes. Underpinning development/environment trends will keep changing rural water supply requirements and pressures.
Solutions to wicked problems are not true or false but good or bad	Judgements and needs vary between stakeholders	Yes. Positives for some may be negatives for others, or may influence factors beyond the system.
There is no immediate and no ultimate test of a solution to a wicked problem	Any solution will have consequences beyond the present	Yes. System complexity, pace of progress and length of time scales means a solution would alter future system dynamics.
Every solution to a wicked problem is a "one-shot operation" because there is no opportunity to learn by trial and error; every attempt counts significantly	Every implemented solution is irreversible and makes a difference	Yes. Solutions would directly influence water users' lives, the environment and future planning, as shown with previous attempted solutions.

Wicked problems do not have an enumerable (or exhaustively describable) set of potential solutions, and there is no well-described set of permissible operations that may be incorporated into the plan	No solution may be found, or more potential solutions arise following one	Yes. Varying situations and influence of rural water supply stakeholders keeps potential solutions re-emerging.
Every wicked problem is essentially unique	Always an additional distinguishing property	Yes. Changing developmental trends, unprecedented environmental change and unique global setting.
Every wicked problem can be considered to be a symptom of another problem	Can be linked to a higher level	Yes. Demographics, poverty, environmental change or previous rural water supply management could be examples.
The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution	The choice of explanation is arbitrary	Yes. There is no single correct explanation out of the multiple interconnected factors influencing rural water supply.
The planner has no right to be wrong (Planners are liable for the consequences of the actions they generate)	The aim is directly to improve the world where people live	Yes. Solutions would have fundamental impact on rural water users in sub-Saharan Africa across different time-scales.

Why Rural Water Supply is Being Delivered Ineffectively in sub-Saharan Africa: Different Models of Management

Debate around why 'community management' became the dominant management model for rural water supply in developing countries is ongoing (Hutchings, P, 2018). The model is based on donation of water infrastructure to rural communities who take on the responsibility of operation and maintenance (O&M), which is purchased from a service provider using revenue that is collected from water users (Harvey and Reed, 2004; Schouten and Moriarty, 2003). Revenue collection is well-established as crucial to sustainability (Harvey and Reed, 2006).

The limitations of community management are now well-addressed and reviewed elsewhere (Chowns, 2015; Whaley and Cleaver, 2017; Behnke et al., 2017), and are exemplified by long-term failings and unsustainability of rural water supply systems. Researchers have recognised this is because of institutional reasons more than technical (Tincani et al., 2015; Jones, 2011; Jiménez and Pérez-Foguet, 2010a). Neglected O&M has resulted in a reported range of 10% to 67% non-functionality of water points in the region (RWSN, 2009; Baumann, 2006; Harvey and Reed, 2006; Andrés et al. 2018a). There is general agreement throughout the academic literature that communities' lack of capacity and finance (i.e. revenue collection) to undertake O&M is a fundamental cause. Other factors include access to information (Hope et al., 2012).

'Community management plus' (CM+) has more recently been theorised as a successor management model based on a shared O&M responsibility between communities, local authorities and central government (Baumann, 2006). There is no strong evidence, however, that it offers solutions dramatically beyond community management. Community management was adopted by governments largely because they could reduce capital expenditure and abdicate responsibility. The dependency of project success on national levels of wealth and favourable socio-economic factors (Hutchings, P, et al., 2015) suggests that CM+ does not fundamentally go beyond a homogenous community management approach.

The 'service delivery approach' (Lockwood and Smits, 2011; Moriarty et al., 2013; IRC 2015) offers a heterogeneous, adaptive and 'professionalised' model that can move beyond reliance on communities themselves. Key features are a move away from voluntary arrangements, promotion of alternative service provision, monitoring of service delivery, and stakeholder harmonisation. This follows from reasoning that external encouragement, motivation, capacity building and specialist technical assistance are required. A resultant virtuous cycle (Figure 1) has been hypothesised by practitioners (WSP, 2010). This may be initiated once progress is made in only one or two of the 'ten building blocks' of the service delivery approach. ICT innovations are directly relevant to most of these, as described below.

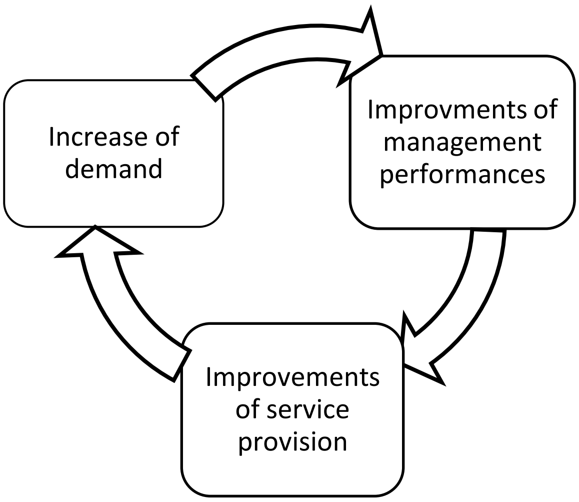

Figure 1. Positive feedback loop resulting from the service delivery approach (adapted from WSP, 2010)

As part of this, strong interest by governments to promote private or public-private partnership involvement has been noted (Lockwood and Smits, 2011; WSP, 2010; van der Byl and Carter, 2018). Potential limitations include financial infeasibility with demand and supply variability, lack of regulation, and service inequalities (Brikké and Bredero, 2003; Hope, 2015; Chowns, 2015). Regardless, flexibility, openness to alternative service providers, harmonisation amongst stakeholders, and adaptive management make the service delivery approach more compatible with the complex system outlined above.

How rural water supply failure is shown to manifest in Tanzania

An estimated US$ 2 billion has been spent on rural water supply in Tanzania by the government and development partners since 2006 (Twaweza, 2017). 63% of the rural population do not have at least basic water services (WHO, 2017b). Rapid population growth is outpacing investment.

As with much of sub-Saharan Africa, non-functionality of water points is high. Approximations of non-functionality of the 65,000–77,000 water points stand at 40%, 45.2% and 39.6% (Impact Tanzania, 2017; Klug et al., 2017; World Bank, 2017). These nationwide estimations are supplemented by a regionalised study covering 15% of the total rural population, showing that in the first five years of operation about 30% of water points become non-functional; after 15 years only 35%–47% of water points remained functioning (Jiménez and Pérez-Foguet, 2010b; 2011). There is no fee collection in an estimated 61.6% of water systems in Tanzania, 85.6% of which are under community management (Klug et al., 2017; Foster and Hope, 2016).

Approximately 75% of expenditure on rural water supply between 2012 and 2015 went to construction of new water systems rather than support for O&M (Kwezi and Fonseca, 2017). The community management model has resulted in neglected O&M and has put the sustainability of rural water supply in jeopardy (Mandara et al., 2013).

Good data is vital for effective decision-making and O&M (Dickinson et al., 2017; Kwezi, 2017). Questionnaire-based surveys or interviews with rural water users are typically used for sub-national assessments (e.g. Kyamani, 2013; Toyna, 2015; Haysom, 2006; Twaweza, 2017). While these approaches can examine specific areas in depth and encapsulate viewpoints of communities, reporting biases, periodicity, overestimation and subjectivity decrease reliability (Thomas et al., 2013). The ICT innovations discussed below are largely designed to address these limitations to revenue collection and monitoring exemplified in Tanzania.

For a more comprehensive and holistic understanding, the present study used additional expert knowledge generation. Results are presented in Table 3. The expert viewpoints collected (N = 8) correlate with many findings in the literature. They also add emphasis to certain factors and show disagreements and uncertainties not previously obvious:

- Constraints to access of water points for rural Tanzanian communities is evidenced by significance of the long distance of travel to water points and low overall number of water points ascribed (factors B1.1 and B1.2). While there is variation across Tanzania (B1.4), generally there are not enough water points to serve the needs of communities. This is supported by the common viewpoint among respondents that more water infrastructure should be constructed (B1.6). The evident emphasis of this over O&M of existing infrastructure (B1.5) suggest a disregard for sustainability, which is common across sub-Saharan Africa as discussed above.
- Some respondents suggest that there is an overall lack of capital investment (B1.7) in rural water supply in Tanzania. However, most of the respondents suggest that funds with donors and other partners are not the limiting factor, which is instead inefficiency of spending and low value for money.
- There is strong agreement among respondents that community management remains the predominant model in Tanzania (B1.9). Variance of opinion around whether it works (B1.10) is the highest amongst the factors, emphasising the relevance of the on-going debate around community management across sub-Saharan Africa outlined above. This arises from different opinions on what constitutes community management. For instance, respondents who suggest it can work caveat with reasons that correlate with more support or professionalisation. No counter evidence to the limitations of community management outlined above was provided.

- General agreement that global environmental change is reducing available water resources (B1.13) is added to by some respondents' suggestions that human-induced factors such as over-grazing of cattle and local deforestation are equally (if not more) significant for water resource protection. Observed changes to local precipitation were highlighted.
- The strongest agreement among factors is from inefficiencies in the political and bureaucratic process (B1.11). Sustainability is suggested to have strong emphasis at higher levels of the governance hierarchy (B1.12), but takes time to filter down to the district level. To this end, the potential benefits to sustainability of public-private partnerships were emphasised by some of the respondents, and such partnerships of relevant for ICT technology providers. High agreement and awareness around willingness to pay (B1.14) aligns with the literature findings that revenue collection leads to sustainability (Foster, 2013).
- Agreement across respondents that multiple factors are important (B1.15) further demonstrates the complexity of the challenge. Each respondent emphasised different factors as more important. The complex context of rural water supply in sub-Saharan Africa outlined above is therefore manifest in Tanzania, as recognised by experts who interact with the complexity of the system through their work. However, some factors emerged as more significant overall. These include political will, community payment and revenue collection, accountability of payment, the variability of circumstances different local authorities operate within, and lack of funds.
- These same key factors in Tanzania have the potential to be addressed by ICT/IoT innovations, as shown below. One respondent suggests that technological innovation (B1.16) should precede change in social and management structures, while another suggests that change in management must come before technological innovation otherwise technology will not address the root causes. In reality, iterative and symbiotic development of both is required (Kranzberg, 1986), while being considerate of the complex system that these new technologies operate within, as emphasised here.

A major conclusion from these results from Tanzania and the literature on both Tanzania and sub-Saharan Africa is that there is dramatic complexity amongst different factors, and uncertainty about extents, explanations and impacts of these individual factors. This further evidences the 'wicked problem' nature of rural water supply sustainability outlined at the start of the paper. Research has remained focused around individual factors, which risks missing the cross-factor potential that novel ICT innovations bring. This is discussed below.

Table 3. Ratings from experts (N = 8) of different factors (1 = strongly disagree, 5 = strongly agree)

Potential factor	*How true is this statement? (1-5)*					*How aware are you of this factor? (1-5)*				
	Number of respondents who selected each rating is represented by the area of each circle									
Access to rural water sources:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.1. The average distance of travel for users from households to water sources is too long			●	•	⬤		•			⬤
B1.2. The overall number of water sources in rural Tanzania is too low		•	●	•	●	•		•	●	●
B1.3. Water points are too densely concentrated within communities	●	●	●					•	⬤	●
B1.4. There is significant variation across Tanzania of the effectiveness of rural water supply			●	•	⬤	•			⬤	•
Infrastructure:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.5. The focus on building new infrastructure outweighs focus on maintenance of existing infrastructure	•			•	⬤				●	⬤
B1.6. More new water infrastructure should be constructed in rural communities	•			●	⬤			●		⬤
B1.7. Not enough capital investment is available for rural water supply	●	•		●	●			●	●	●
B1.8. There are not enough trained technicians with sufficient capacity to sustain the rural water supply system		●	●	•	●			●	●	●
Management of rural water supply:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.9. 'Community management' remains the predominant model			•	⬤	●			•	⬤	●
B1.10. 'Community management' does not always work	●	•	•		●			•	●	⬤

B1.11. Inefficiencies in political and bureaucratic processes make progress more difficult		
B1.12. Sustainability of rural water supply is suitably considered in new or existing projects		
B1.13. Climate change and environmental change is reducing available water resources in rural Tanzania		
B1.14. More willingness of rural communities to pay for rural water supply would result in more sustainable rural water supply		
B1.15. The effectiveness of rural water supply is defined by a combination of multiple factors more than it is by specific individual factors		
B1.16. Technical innovation within the rural water supply system will add nothing; progress lies in addressing the above factors more effectively		

ICT innovations for rural water supply in sub-Saharan Africa

The use of ICT for development purposes and its benefits for service provision and decision-making has already been widely explored (UNESCO, 2016; Hellström, 2010; Pepper and Garrity, 2014). The Internet of Things (IoT) is a globally connected information infrastructure featuring machine-produced data, usually using specific sensors, and its automated communication. In sub-Saharan Africa, Global System for Mobile Communications (GSM) population coverage was reported as 60% in 2012, while electrification rate remained at 49% (Nique and Arab, 2012).

ICT (including IoT) is promising to remotely record higher resolution and more useful data on rural water supply that is more accurate, accountable, timely, cost-effective and higher resolution (Dickinson et al., 2017; Andrés et al. 2018b; Stuart et al., 2015). This can move beyond the limitations to understanding that have been outlined here (Kumpel et al., 2015), and address many of the specific and general limitations to rural water supply raised by the expert respondents above. Information on water withdrawal and water point/system non-functionality, alongside socio-economic and environmental data, can be obtained in real time.

This is directly and indirectly beneficial to the service delivery approach and its practitioners. Such monitoring can alert service providers to problems allowing for rapid and consistent O&M. For users, this can increase financial accountability and improve communication with service providers (Koehler et al., 2015). There are also benefits for decision and policy makers who aim to streamline data management (e.g. GoT, 2012). Revenue collection, asset management, and relationships with users can be improved, along with providing communities a voice and enhancing accountability and trust between stakeholders (Welle et al., 2015; Schaub-Jones, 2013).

Scope of existing reviews and studies has stayed broad with no exclusive focus on IoT, and limited to practice-oriented overviews. Critically, the extent to which novel innovations are presented within the complex system of rural water supply in sub-Saharan Africa is limited. Hutchings, M, et al. (2012) examined over 40 mobile phone-based WASH innovations worldwide, showing SMS (Short Message Service) to be the most common data collection method. Pearce et al. (2014; Dickinson and Bostoen, 2013) demonstrate that ICT innovations fit into five different steps of data/information flow: 1) collection, 2) transfer and communication, 3) data management, 4) analysis and reporting, and 5) use. The authors show that individual projects do not tend to include all of these steps, therefore ICT innovations are limited to 'islands of success'. Both reviews emphasise the joint importance of social design, technical design and programme design for success, cognisant of the need for systems thinking outlined above. Welle et al. (2015) shows that success is more likely if: 1) the data reporting is service provider-led rather than crowdsourced from the community, and 2) when users prefer the data reporting system to previous methods. These points are compatible with the service delivery approach (Williams et al., 2016). McGee and Carlitz (2013) and Wesselink et al. (2015) also further emphasise the social context.

Some assessments have focused on improvements to revenue collection systems. Pay-as-you-fetch water management models, as opposed to e.g. semi-regular payments, have been shown to increase service levels (Foster and Hope, 2017). ICT can facilitate this, for example through pre-payment (termed a "game changer" by Heymans et al., 2014). Mobile money has the potential to allow direct, accountable financial flows to the service provider. Nique and Arab (2012) outline some benefits of when mobile money payments are coupled with ICT data reporting innovations: 1) improved payment and collection, 2) leak and theft detection, 3) improved monitoring and 4) higher payment transparency. For consumers, benefits include saved time and money and more reliable infrastructure. Increased revenue collection can positively feedback with enhanced service delivery.

Table 4 presents ICT innovations that are operational, recently operational, or in pilot phases. Innovations are categorised into mobile phone-based and IoT enabled (Pearce et al., 2014).

Table 4. ICT innovations in rural water supply

Name of innovation	*Overview of aim and operation*
Mobile phone based innovations	
Akvo Flow	Data collection and mapping software using mobile-based surveys allows users to take GPS coordinates, take pictures and videos, and fill out questionnaires. This information is then mapped, and can be tracked over time. Community members and partners from 258 different organisations are currently using Akvo Flow *https://akvo.org/products/akvoflow/ [last accessed 23.01.2019]*
Human Sensor Web	Water users and local water authority staff report functionality or water quality information via SMS. On non-functionality, a mass-SMS is delivered to registered community users, and data is disclosed on a dedicated website interface. Limits to upscaling were cost of SMS for community members, capacity of the data processing, and community uptake. Verbal or phone call reporting was preferred over the specific SMS codes required (Jürrens et al., 2009). A limited research endeavour on Zanzibar with 50 water points no longer operational.
Maji Matone	SMS input from water users about non-functioning water points in Tanzania sent to district water engineers and local radio and newspapers to publicise reports, inform users and pressure water service providers. Only 53 SMS messages were received, and only 20 water points were repaired and the project closed. Users likely had low expectations of what O&M would be done and the SMS format was inappropriate for the users. *http://mtega.com/tag/maji-matone/ [last accessed 23.01.2019]*
Mobile 4 Water	SMS input from water users about non-functioning water points in Uganda sent to district water engineers. Message transmitted to the Mobile 4 Water system, managed by the District Water Management Office. Water service provider alerted about the non-functionality who then dispatches a technician to conduct O&M. 400 previously unknown water points were identified but the project worked slowly and is no longer operational. Not well tailored for the local context and users tended to phone technicians rather than text. Managers neglected checking for updates and data was not integrated with the national reporting system *https://www.ircwash.org/news/experiment-overview-2 [last accessed 23.01.2019]*
mWater	Customisable app-based mobile technology for data collection from field assessments.

	Provides cloud-based data and survey management platform allowing real-time assessment. An interactive map using the online Water Point Mapper tool allows users to customise exportable maps. This processing of data can highlight functionality, sustainability, equity and planning factors. Other sources of data with GPS information can also be uploaded to Water Point Mapper. Used by over 13,000 users in 130 countries to map and monitor water and sanitation sites. Over 350,000 water sites are included in the online database using data from the global Water Point Data Exchange and mWater users. *http://www.mwater.co/ [last accessed 23.01.2019]*
Pump for Life MSABI	Subscription based water point O&M service in Tanzania. Payment of US$ 5 monthly subscription per water point via mobile money. Improved revenue collection allows for rapid O&M. Focuses on rope-pumps with cheaper O&M costs. Water point data tracked using mobile phone inputs from technicians, and used to monitor distribution and functionality of water points and payments. Currently relies on community reporting of non-functioning water points but plans to integrate sensors for remote detection of non-functionality and near field communication tags for water point identification. 190 water points included, with 48 schools and 38,000 clients. Over 7,000 O&M visits have been tracked. *http://msabi.org/pump-for-life-1/ [last accessed 23.01.2019]*
IoT enabled innovations	
Charity: Water Remote sensors	Sensors monitor flow from Afridev handpumps at regular time intervals. Consists of a stack of six capacitance sensors that measure physical water level in the wellhead to calculate flow rate. Sensors can be installed with minimal tools. Data is mapped on a dashboard for analysis. Aims to monitor effectiveness of water projects that *Charity: Water* is undertaking and improve response times for O&M, with successful pilots in Ethiopia *https://www.charitywater.org/our-projects/completed-projects/ [last accessed 23.01.2019]*
eWATERpay	Rural community standpipes of water distribution systems fitted with eWATER tap that is operated with NFC-enabled tag. Water users load their tag with credit using a dedicated app, via mobile money, or at a pre-loaded tap. Access to water point throughout 24 hours. Usage data on functionality, flow rates and revenue collection per individual user and tap is reported remotely to cloud-based online dashboard and data management system. Service provider assesses non-functionality and usage patterns. Low-power requirements run by battery and small solar array. Operational in villages in The Gambia, Tanzania and Ghana serving 20,000 users. *www.ewaterpay.com [last accessed 23.01.2019]*
MoMo (Welldone)	'Mobile monitor' with integrated physical sensor and GSM connection. Sensors collect flow data from pilot rural handpumps in Tanzania every 10 seconds. Data is aggregated and sent

	daily via GSM to a central server using a microSIM, or directly to stakeholders. Low-power requirements and solar power designed for long-term deployment. Modular platform design can be used with range of sensors and communication media and is open source. Data is collected and managed using an online interface, which allows analysis over time. Strong mobile phone reception is required, and one early pilot failed to transmit data because installation was in an area without adequate reception. http://momo.welldone.org/ [last accessed 23.01.2019]
Smart Handpumps	Accelerometer attached to the handle of a rural handpump records pumping velocity and frequency, which is automatically transmitted via GSM to the project operators. Non-functionality is recorded when low or no pumping is recorded over a set time, and O&M is triggered. Data is shared with the service provider, local government and the regulator using a web-interface. In Kenya this has led to 10-fold reduction in 'downtime' to three days, five times higher revenue collection, and fairer usage and payment. Strong links with local government and service providers have contributed to on-going success. The innovation has also been successfully coupled with a 'clustered' handpump management solution (Hope et al., 2014).
Susteq	Rural standpipes and water kiosks fitted with pre-payment meters operated using RFID-enabled tag. Water users load the tag with credit, purchased using mobile money from a nearby water kiosk. Usage data is recorded and reported remotely and can be monitored using an online dashboard. Successful pilot projects in both rural and urban Kenya, Uganda and Tanzania. http://www.susteq.nl/ [last accessed 23.01.2019]
SweetSense	Sensors continuously collect handpump performance and water flow data and communicate it back to stakeholders. Attaches to the pump head. Data can be communicated using Wi-Fi or GSM with a SIM card, with distributed processing between hardware and the cloud. Data are then integrated into an online database and dashboard for analysis. Notifications sent to stakeholders via SMS and email. 200 sensors installed on rural Rwandan handpumps in a pilot project demonstrating improved O&M response time by 86% relative to existing management model (Nagel et al., 2015).

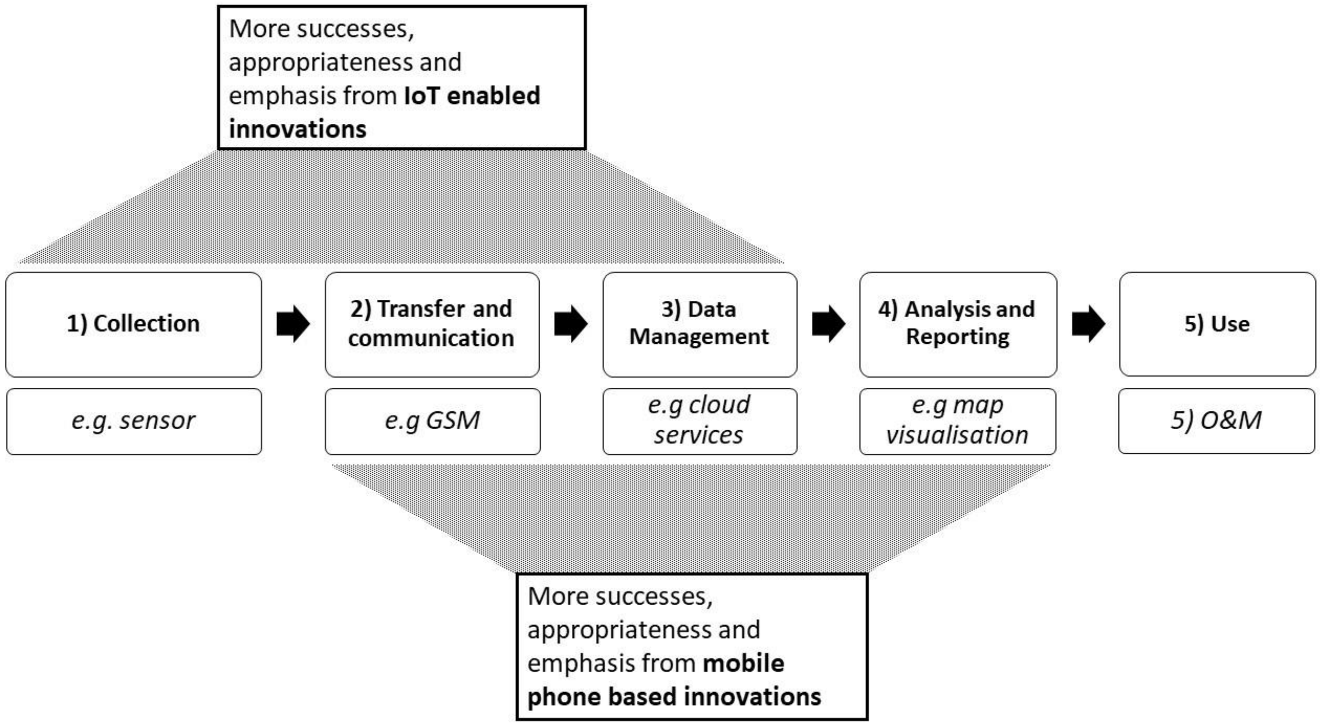

Figure 2. Different categories of ICT innovation show different areas of success, appropriateness and emphasis, based on the five steps of data/information (Pearce et al., 2014; Dickinson and Bostoen, 2013).

Mobile phone-based innovations are shown to suitably address the 'transfer and communication', 'data management', and 'analysis and reporting' of data (Figure 2). Such innovations are more established. In general, mapping of data collected from mobile phone reporting is shown to be an effective method for 'analysis and reporting' of data. However, they are more limited in 'collection' and 'use'. For instance, community mobile phone reporting is limited by the requirement and inaccuracies of volunteer-based manual input, as opposed to professional service providers. For examples, as seen with Mobile 4 Water and Human Sensor Web, users show a general preference to phone calls rather than the required SMS messaging. This group appears to be limited to facilitating existing management structures rather than bringing fundamental transformation.

IoT enabled innovations have greater potential for the 'collection' of data, along with 'transfer and communication', as automated sensing and reporting removes those limitations outlined for mobile phone-based innovations. In the above innovations, considering they have been designed more with 'collection' in mind, IoT is so far demonstrating limited emphasis on 'analysis and reporting' and 'use'. These innovations are typically newer than mobile phone-based innovations, and therefore have had less time to integrate with stakeholders relevant for these steps. Combinations of successful aspects from both categories of ICT innovation could allow for enhanced project success, for example automated mapping of IoT collected data and metadata for service providers, with available access for all stakeholders. In practice, the collection-to-use steps become indistinguishable with a successful service.

Pearce et al. (2014) point out that there remain a limited number of cases where increased availability of data from ICT innovations has directly improved rural water supply. 'Use' of data appears to be the limiting step for both categories (Adank, 2017; Dickinson et al., 2017). This is unlike with successful modern utilities and service providers elsewhere where data 'use' methods such as automation of processes have long been effective. Multiple factors influence this limitation, such as uncertainty over stakeholder responsibilities for putting the data to use. In practice, the lack of professional support services and the management system have meant such solutions have not been able to develop.

Research Gaps

As this analysis shows, the majority of emphasis for both mobile phone-based and IoT enabled innovations focuses on shorter-term benefits such as real-time monitoring. Application of longer-term benefits such as baseline data generated by continual collection and analysis of patterns remain largely untapped. A move towards these could further benefit sustainability of rural water supply and improvement of service delivery overall in a manner that is considerate of the complex operating system. Automated collection of technical and metadata from IoT enabled innovations to repositories such as the Water Point Data Exchange (waterpointdata.org) could benefit multiple stakeholders. Reporting of more detailed data (e.g. flow rate, user profiles, financing, revenue collection, maintenance history, water resources, installation) would be compatible with recent suggestions of new metrics of water point 'functionality' (Carter and Ross, 2015; Bonsor et al., 2018).

Longer-term mobile phone-based innovations are examined more comprehensively elsewhere (GSMA, 2016; Hellström, 2010).

New research on IoT enabled innovations can therefore be based on:

- Novel IoT enabled innovations can provide a new method for data collection and reporting to replace or supplement the limitations of surveys and water point mapping.

- Such data should be used to evaluate, visualise and plan for long-term trends and patterns in rural water use and supply, and enhance understanding of factors influencing sustainability.
- Successful 'collection' steps of IoT enabled innovations should be considered alongside successful 'analysis and reporting' used with mobile phone based innovations (Figure 2).
- Understanding must develop on what flows of information are necessary for effective 'use' of data to occur, and what information is required by decision makers to do this.

Two research projects have evaluated IoT innovations designed to decrease non-functionality of water point: *Smart Handpumps* (Hope et al., 2014; Koehler et al., 2015), and *SweetSense* (Nagel et al., 2015). Methods and results are critically compared in Table 5. (Shorter evaluations of other IoT innovations exist in the grey literature and presentations, e.g. GSMA 2018b).

Both studies evaluate reduced non-functionality time by a comparison of the innovation outcomes against baseline maintenance models. Reduction of maintenance times are similar, proportional to baseline maintenance models (11.1% and 13.8%). Both innovations operated with free maintenance models, which is not representative of the needs of rural water supply systems considering the above findings and is unaddressed in either. Detail is lacking on available water resources and some other contextual factors. An analysis of the longer-term sustainable implementation of the innovations themselves would have assessed their actual potential for fundamental change to the research and practitioner communities.

Table 5. Existing academic evaluations of IoT enabled innovations

	Smart Handpumps	*SweetSense*
Study design	Survey of use of 21 *Smart Handpu*mps in rural Kenya, to demonstrate failure rate and maintenance time, and payment level. Effectiveness of two maintenance models concurrently assessed over 12 months: 1) 'Crowdsourced' community reporting of non-functionality 2) Non-functionality alerts from Smart	Sensors installed in 181 handpumps in rural Rwanda evaluated. Effectiveness of three maintenance models concurrently assessed over 7 months: 1) Community contacts service provider on non-functionality 2) Service provider makes periodic visits to handpumps 3) Real-time *SweetSense* data available

	Handpumps used to coordinate maintenance. Time assessed between non-functionality alerts and maintenance times (relative to the baseline).	to service providers used to coordinate O&M. Cost of different models also assessed.
Reported sensor and communication	Microprocessor, batteries, GSM modem sending SMS messages. Accelerometer measuring handle movement. Hourly data reporting (Colchester et al., 2017).	Batteries, cellular radio chip, SIM card, accelerometer. Daily identification of non-functionality based on data collected every 60 s.
Results	Twice as many repairs were conducted on Model 2 than Model 1. Model 2 reduced mean non-functionality 'downtime' from a baseline of 27 days to under 3 (11.1%), resulting in 98% functionality of handpumps over the study period.	Model 3 reduced median non-functionality 'downtime' to 21 days, compared to the first model's 152 days (13.8%), and second model's 57 days (36.8%). Financial cost was approximately similar between the three models.

Ensemble machine learning and failure forecasting has already been successfully applied to *SweetSense* data (Wilson et al., 2017). Depths of groundwater and groundwater use with seasonality have been estimated with *Smart Handpumps* using waveforms collected from the accelerometers and machine learning techniques, with significant policy implications (Colchester et al., 2017; Thomson et al., 2018). These considerations of systemic factors fits with the requirements outlined above. Additionally, this demonstrates the high potential such innovations have for impactful research outcomes, e.g. regarding seasonality. While the innovations are rigorously demonstrated as effective, further work could now incorporate 'analysis and reporting' and 'use' of data elements, and build this useful information into long-term system planning.

IoT innovations on non-handpump water points (e.g. standpipe taps) remain unevaluated, yet have potential for higher resolution data from even flow patterns, and individual user identification. 'Predictive maintenance' of water points based on alerts of impending non-functionality, derived through machine learning techniques using existing water point breakdown data, can theoretically bring non-functionality times to zero. This requires coupling with responsive maintenance teams (Brocklehurst, 2018) and professional support services. In practice, such IoT innovations must be developed simultaneously with management models that account for the whole system.

4. Discussion

Many practitioners see the service delivery approach as an appropriate direction of travel away from community management in sub-Saharan Africa. This agenda presents a good context in which to consider the place of ICT innovations in future rural water supply in this complex system.

One implication of this trend is that the landscape of rural water supply is open for application and research of ICT innovations. These innovations facilitate certain building blocks of the service delivery approach, which in turn can kick-start positive feedback. In this sense, ICT innovations possess catalytic potential for more general transformation.

This is specifically the case for IoT enabled innovations. Early research on such innovations for rural handpumps has demonstrated impressive success rates. More research into different contexts, types of water infrastructures and implications for management are required.

One uncertainty in current literature is the extent to which IoT innovations (and ICT in general) will merely build on existing management models, or how much they will create disruptive systemic change. ICT innovation in other sectors in this context e.g. mobile money (Suri and Jack, 2016) demonstrate the potential for the later.

Another major lesson drawn from the broader literature is that any ICT innovation must be fully considerate of the system in which it operates. Indeed, it adds another level of complexity to this system. In general, understanding rural water supply as part of a complex system and moving away from linear thinking has been limited. Unsustainability has been the outcome. Systems thinking is increasingly promoted and is beginning to develop within the practitioner community (Moriarty, 2018). As ICT innovations develop and upscale, systems thinking must underpin their development (Wesselink et al., 2015). Understanding rural water supply in the sub-Saharan African context as a ‘wicked problem’ further frames this assertion. Interactions with institutions, socio-economic user context, and policy are important, and systems analysis methods can be employed to these ends (Liddle and Fenner, 2017).

5. Conclusions

Rural water supply in sub-Saharan Africa can be more effective and sustainable if it uses the enhanced capacity of the technological innovations outlined here. Energy, communication, health, finance and other sectors have amply demonstrated their benefits to development outcomes. IoT innovations can facilitate change away from outdated management models towards an effective service delivery approach.

To do this, research must go beyond current evaluations of innovation effectiveness. The potential for long-term planning and sustainability of the innovations, combining effective 'collection' of data with 'analysis and reporting' and appropriate 'use' of data all require fuller consideration.

Practitioners cannot ignore the complex system of rural water supply in which IoT innovations operate and be sustainable. Otherwise, novel innovations risk making the mistakes of previous 'solutions', resulting in limited development outcomes for the world's poorest communities.

6. References

1. Adank, M. (2017) 'Data collection, data use and (monitoring) systems building: the SMARTerWASH experience' [blog]. IRC. <https://www.ircwash.org/blog/data-collection-data-use-and-monitoring-systems-building-smarterwash-experience> (posted 8 May 2017) [last accessed 23.01.2019].
2. Andrés, L. A., Chellarai, G., Gupta, B. D., Grabinsky, J. and Joseph, G. (2018a) *Why Are So Many Water Points in Nigeria Non-Functional? An Empirical Analysis of Contributing Factors*. Policy Research Working Paper 8388, March 2018. Washington DC., USA: The World Bank Group, Water Global Practice.
3. Andrés, L. A., Borja-Vega, C. and Thomas E. A. (2018b) 'A review of In-Situ and Remote Sensing Technologies to Monitor Water and Sanitation Interventions', *Water* 10(6): 756-769 <https://doi.org/10.3390/w10060756>.
4. Baumann, E. (2006) 'Do operation and maintenance pay?', *Waterlines* 25(1): 10-12 <https://doi.org/10.3362/0262-8104.2006.033>.
5. Behnke, N. L., Klug, T., Cronk, R., Shields, K. F., Lee, K., Kelly, E. R., Allgood, G. and Bartram, J. (2017) 'Resource mobilization for community-managed rural water systems: Evidence from Ghana, Kenya, and Zambia', *Journal of Cleaner Production* 156: 437-444 <https://doi.org/10.1016/j.jclepro.2017.04.016>.
6. Bonsor, H., MacDonald, A., Casey, V, Carter, R and Wilson, P. (2018) 'The need for a standard approach to assessing the functionality of rural community water supplies', *Hydrogeology Journal* 26(1): 360-370 <https://doi.org/10.1007/s10040-017-1711-0>.
7. Brikké, F. and Bredero, M. (2003) *Linking technology choice with operation and maintenance in the context of community water supply and sanitation: A reference document for planners and project staff.* Geneva, Switzerland: World Health Organisation and IRC Water and Sanitation Centre.
8. Brocklehurst C. (2018) *Remote Monitoring of Handpump Functionality*, WaSH Policy Research Digest Issue 8. May 2018. Chapel Hill, North Carolina, USA: UNC Water Institute.

9. Butterworth, J., Warner, J. F., Moriarty, P., Smits, S., & Batchelor, C. (2010) 'Finding practical approaches to integrated water resources management', *Water Alternatives* 3(1): 68-81.

10. Carter, R. C. and Ross, I. (2016) 'Beyond 'functionality' of handpump-supplied rural water services in developing countries', *Waterlines* 35(1): 94-110 <http://dx.doi.org/10.3362/1756-3488.2016.008>.

11. Casella D., van Tongeren, S. and Nikolic I. (2015) *Change in complex adaptive systems: A review of concepts, theory and approaches for tackling 'wicked' problems in achieving sustainable rural water services.* IRC Working Paper. Geneva, Switzerland: IRC Water and Sanitation Centre.

12. 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 <http//doi.org/10.1002/pad.1737>.

13. Colchester, F. E., Marais, H. G., Thomson, P., Hope, R. and Clifton, D. A. (2017) 'Accidental infrastructure for groundwater monitoring in Africa', *Environmental Modelling & Software* 91: 241-250 <https://doi.org/10.1016/j.envsoft.2017.01.026>.

14. Dickinson, N., Knipschild, F., Magara, P., and Kwizera, G. (2017) *Harnessing water point data to improve drinking water services.* WASHNote, USAID, Coca Cola, WADA, IRC.

15. Dickinson, N. and Bostoen, K. (2013) *Using ICT for monitoring rural water services: from data to action,* Triple-S Working Paper 4*.* Geneva, Switzerland: IRC Water and Sanitation Centre.

16. Drescher, M., Perera, A., Johnson, C., Buse, L., Drew, C., and Burgman M. (2013) 'Toward rigorous use of expert knowledge in ecological research', *Ecosphere* 4(7): 83 < https://doi.org/10.1890/ES12-00415.1>.

17. FAO (1990) *The communities toolbox: the idea, methods and tools for participatory assessment, monitoring and evaluation in community forestry.* Corporate document repository*.* Rome, Italy: United Nations Food and Agriculture Organisation.

18. FitzGibbon, J. and Mensah K. O. (2012) 'Climate Change as a Wicked Problem: An Evaluation of the Institutional Context for Rural Water Management in Ghana', *SAGE Open Access* <https://doi.org:10.1177/2158244012448487>

19. Foster, T. (2013) 'Predictors of sustainability for community-managed handpumps in sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda', *Environmental Science & Technology* 47(21): 12037-12046 <https://doi.org:10.1021/es402086n>.

20. Foster, T. and Hope, R. (2016) 'A multi-decadal and social-ecological systems analysis of community waterpoint payment behaviours in rural Kenya', *Journal of Rural Studies* 47: 85-96 <https://doi.org/10.1016/j.jrurstud.2016.07.026>.

21. Foster, T., and Hope, R. (2017) 'Evaluating waterpoint sustainability and access implications of revenue collection approaches in rural Kenya', *Water Resources Research*, 53(2): 1473-1490 <https://doi.org/10.1002/2016WR019634>.

22. Government of Tanzania (GoT) (2012) *National Key Result Area Water 2013/14 – 2015/16. Tanzania Development Visions 2025 Big Results Now Roadmap*. Dar es Salaam, Tanzania: Government of Tanzania.

23. Global System for Mobile Communications (GSMA) (2018a) *Key trends in mobile-enabled water services: What's working and what's next*, GSMA, London, UK.

24. Global System for Mobile Communications (GSMA) (2018b) *Africa Water Enterprises: Using IoT to monitor and introduce pre-payment for remote water stands in The Gambia*, GSMA, London, UK.

25. Global System for Mobile Communications (GSMA) (2016) *Mobile for Development Utilities. Unlocking access to utility services: the transformational value of mobile*, *GSMA*, London, UK.
26. Harvey P. and Reed B. (2004) 'Rural Water Supply in Africa: Building Blocks for Handpump Sustainability', *Water, Engineering and Development Centre*, Loughborough University, UK.
27. Harvey, P.A. and Reed, R.A. (2006) 'Community-managed water supplies in Africa: Sustainable or dispensable?', *Community Development Journal* 42(3): 365-378 < https://doi.org/10.1093/cdj/bsl001>.
28. Haysom, A. (2006) 'A Study of the Factors Affecting Sustainability of Rural Water Supplies in Tanzania', *Masters Thesis*, Cranfield University/WaterAid.
29. Hellström, J. (2010) *The innovative use of mobile applications in East Africa*. SIDA Review. Swedish International Development Cooperation, Stockholm, Sweden.
30. Heymans, C., Eales, K. and Franceys, R. (2014) *The Limits and Possibilities of Prepaid Water in Urban Africa.* World Bank Group and Water and Sanitation Programme report. Washington DC, USA: World Bank Group.
31. Hope, R., Foster, T., Money, A. and Rouse, M. (2012) 'Harnessing mobile communications innovations for water security', *Global Policy* 3(4): 433-442 <https://doi.org/10.1111/j.1758-5899.2011.00164.x>.
32. Hope, R., Thomson, P., Koehler, J., Foster, T. and Thomas, M. (2014) *From Rights to Results in Rural Water Services – Evidence from Kyuso, Kenya.* Working Paper 1. Smith School of Enterprise and the Environment, Water Programme. Oxford University, UK.
33. 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 <https://doi.org/10.2166/wp.2014.170>.
34. Huston, A. and Moriarty, P. (2018) *Building strong WASH systems for the SDGs: Understanding the WASH system and its building blocks*. IRC Working paper. The Hague, Netherlands: IRC.
35. Hutchings M., Dev A., Palaniappan M., Srinivasan V., Ramanathan N. and Taylor J. (2012) *mWASH: Mobile Phone Applications for the Water, Sanitation, and Hygiene Sector.* Oakland, CA, USA: Nexleaf Analytics and Pacific Institute.
36. Hutchings, P., Chan M. Y., Cuadrado L., Ezbakhe F., Mesa B., Tamekawa C. and Franceys R. (2015) 'A systematic review of success factors in the community management of rural water supplies over the past 30 years', *Water Policy* 17(5): 963-983 <https://doi.org/10.2166/wp.2015.128>.
37. Hutchings, P. (2018) 'Community Management or Coproduction? The Role of State and Citizens in Rural Water Service Delivery in India', *Water Alternatives* 11(2):357-374.
38. Impact Tanzania (2017) *What Local Factors Explain the Sustainability of Rural Water Points?: Understanding the drivers of rural water maintenance in Tanzania*. Note 1. Dar es Salaam, Tanzania: DfID and World Bank Group.
39. IRC (2015) *Reimagining rural water services: the future agenda. An introduction to ten building blocks to support sustainable service delivery.* Briefing note for Triple-S. The Hague, Netherlands: IRC.
40. Jiménez, A. and Pérez-Foguet, A. (2010a) 'Challenges for water governance in rural water supply: lessons learned from Tanzania', *International Journal of Water*

Resources Development 26(2): 235-248 <https://doi.org/10.1080/07900621003775763>.

41. Jiménez, A. and Pérez-Foguet, A. (2010b) 'Water point mapping for the analysis of rural water supply plans: case study from Tanzania', *Journal of Water Resources Planning and Manage*ment 137(5): 439-447 <https://doi.org/10.1061/(ASCE)WR.1943-5452.0000135>.

42. Jiménez, A. and Pérez-Foguet, A. (2011) 'The relationship between technology and functionality of rural water points: evidence from Tanzania', *Water science and technology* 63(5): 948-955 <https://doi.org/10.2166/wst.2011.274>.

43. Jones S. (2011) 'Participation as citizenship or payment? A case study of rural drinking water governance in Mali', *Water Alternatives* 4(1): 54-71.

44. Jürrens, E. H., Bröring, A. and Jirka, S. (2009) 'A human sensor web for water availability monitoring', *Proceedings of OneSpace* <http://arne-broering.de/Juerrens%20(OneSpace2009)%20-%20A%20human%20sensor%20web%20for%20water%20availability%20monitoring.pdf> [last accessed 23.01.2019].

45. Klug, T., Cronk, R., Shields, K. F., and Bartram, J. (2018) 'A categorization of water system breakdowns: Evidence from Liberia, Nigeria, Tanzania, and Uganda', *Science of The Total Environment* 619: 1126-1132 <https://doi.org/10.1016/j.scitotenv.2017.11.183>.

46. Koehler, J., Thomson, P. and Hope, R. (2015) 'Pump-priming payments for sustainable water services in rural Africa', *World Development* 74: 397-411 <https://doi.org/10.1016/j.worlddev.2015.05.020>.

47. Kranzberg, M. (1986) 'Technology and History: "Kranzberg's Laws"', *Technology and culture*, 27(3), 544-560 <https://doi.org/10.2307/3105385>.

48. Kumpel, E., Peletz R., Bonham M., Fay A., Cock-Esteb A. and Khush R. (2015) 'When are mobile phones useful for water quality data collection? An analysis of data flows and ICT applications among regulated monitoring institutions in Sub-Saharan Africa', *International journal of environmental research and public health* 12(9): 10846-10860 <https://doi.org/10.3390/ijerph120910846>.

49. Kwezi L. (2017) Understanding what drives maintenance of rural water infrastructure in Tanzania (and it's not what you think!) [blog] IRC. <https://www.ircwash.org/blog/understanding-what-drives-maintenance-rural-water-infrastructure-tanzania-and-it%E2%80%99s-not-what-you> (posted 1 June 2017) [last accessed 23.01.2019].

50. Kwezi L. and Fonseca C. (2017) Rural water supply access in Tanzania: why has it stagnated? [blog] IRC. <https://www.ircwash.org/blog/rural-water-supply-access-tanzania-why-has-it-stagnated> (posted 2 February 2017) [last accessed 23.01.2019]

51. Kyamani, W.A. (2013) Determinants of rural water project sustainability: a case of Rufiji district, Pwani region, Tanzania. *Masters dissertation*. Sokoine University of Agriculture, Tanzania.

52. Liddle, E. S., and Fenner, R. (2017) 'Water point failure in sub-Saharan Africa: the value of a systems thinking approach', *Waterlines* 36(2): 140-166 < http://dx.doi.org/10.3362/1756-3488.16-00022>.

53. Lockwood, H. and Smits, S. (2011) *Supporting rural water supply: Moving towards a service delivery approach.* Practical Action Publishing, Rugby, UK.

54. Mandara, C.G., Butijn, C. and Niehof, A. (2013) 'Community management and sustainability of rural water facilities in Tanzania', *Water Policy* 15: 79-100 <https://doi.org/10.2166/wp.2013.014>.

55. McGee, R. and Carlitz, R. (2013) *Learning Study on the 'users' in technology for transparency and accountability initiatives: Assumptions and realities.* The Knowledge Programme. Brighton, UK: IDS.

56. Moriarty P. (2018. Can we make 2018 the year of the WASH System? [blog] IRC. <https://www.ircwash.org/blog/can-we-make-2018-year-wash-system?utm_source=Amplify&utm_campaign=04ac76364a-Amplify_December_2017&utm_medium=email&utm_term=0_d60e6862b4-04ac76364a-57613593> (posted 25 January 2018) [last accessed 23.01.2019].

57. Moriarty, P., Smits, S., Butterworth, J. and Franceys, R. (2013) 'Trends in rural water supply: towards a service delivery approach', *Water Alternatives* 6(3): 329–349.

58. Nagel, C., Beach, J., Iribagiza, C., and 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 < https://doi.org/10.1021/acs.est.5b04077>.

59. Nique M. and Arab F. (2012) *Sustainable Energy & Water Access through M2M Connectivity. GSMA Mobile Enabled Community Services.* GSMA White Paper. London, UK: GSMA.

60. Noxolo, P. (2017) 'Introduction: Decolonising geographical knowledge in a colonised and re-colonising postcolonial world', *Area* 49(3): 317–319 <https://doi.org/10.1111/area.12370>.

61. Oppenheim, A. N. (2000) *Questionnaire design, interviewing and attitude measurement*, pp. 81. Bloomsbury Publishing, London, UK.

62. Pearce, J., Dickinson, N. and Welle, K. (2014) 'Technology, data, and people: opportunities and pitfalls of using ICT to monitor sustainable WASH service delivery', in Shouten T. and Smits S. (eds.), *Infrastructure to Services: Trends in Monitoring Sustainable Water, Sanitation and Hygiene Services,* pp.85-108*,* Practical Action Publishing, Rugby, UK.

63. Pepper, R. and Garrity, J. (2014) *The Internet of Everything: How the Network Unleashes the Benefits of Big Data*. Global IT Report 2014. Switzerland: WEF.

64. Rittel, H. W., and Webber, M. M. (1973) 'Dilemmas in a general theory of planning', *Policy sciences* 4(2): 155-169.

65. Rural Water Supply Network (RWSN) (2009) *Myths of the Rural Water Supply Sector, Perspectives No. 4, RWSN Executive Steering Committee*. St Gallen, Switzerland: Rural Water Supply Network.

66. Schaub-Jones, D. (2013) 'Considerations for the successful design & implementation of ICT systems in the WASH sector', *Proceedings of IRC Symposium 2013: Monitoring sustainable WASH service delivery. Addis Ababa, Ethiopia.*

67. Schouten, T. and Moriarty, P. (2003) *Community Water, Community Management. From System to Service in Rural Areas.* ITDG Publishing, London, UK.

68. Stuart E., Samman E., Avis W. and Berliner T. (2015) *The Data Revolution: finding the missing millions.* Overseas Development Institute. Research Report. London, UK: ODI.

69. Thomas, E. A., Zumr, Z., Graf, J., Wick, C. A., McCellan, J. H., Imam, Z., Barstow, C., Spiller K., and Fleming, M. (2013) 'Remotely accessible instrumented monitoring of

global development programs: Technology development and validation', *Sustainability* 5(8): 3288-3301 <http://dx.doi.org/10.3390/su5083288>.

70. Thomson, P., Bradley, D., Katilu, A., Katuva, J., Lanzoni, M., Koehler, J., & Hope, R. (2018) 'Rainfall and groundwater use in rural Kenya', *Science of The Total Environment*. 649(2019): 722-730 <https://doi.org/10.1016/j.scitotenv.2018.08.330>.
71. Tincani, L., Ross, I., Zaman, R., Burr, P., Mujica, A., Ensink, J. and Evans, B. (2015) *Improving value for money and sustainability in WASH programmes (VFM-WASH). Regional assessment of the operational sustainability of water and sanitation services in Sub-Saharan Africa.* Oxford, UK: Oxford Policy Management.
72. Tonya, E.M. (2015) 'Assessing the Implications of Water Supply Technology on the Sustainability of Rural Water Supply in Dodoma Region, Tanzania', Masters dissertation, The Open University Of Tanzania, Tanzania.
73. Twaweza (2017) *Clean and Safe? Water, Sanitation and Hygiene*. Brief no. 40. Dar es Salaam, Tanzania: Twaweza East Africa.
74. UNESCO (2016) *Harnessing the Internet of Things for Global Development. A Contribution to the UN Broadband Commission for Sustainable Development. ITU/UNESCO Broadband Commission for Sustainable Development & Cisco.* Geneva, Switzerland: UNESCO and Cisco.
75. UN-Water (2010) *Climate Change Adaptation: The Pivotal Role of Water.* Policy Brief. Geneva, Switzerland: UN-Water.
76. van der Byl, W. and Carter, R. C. (2018) 'An investigation of private operator models for the management of rural water supply in sub-Saharan Africa', *Waterlines*, 37(2), 155-174 <https://doi.org/10.3362/1756-3488.18-00005>.
77. Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., and Ramu, P. (2016) 'Modelling with stakeholders – Next generation', *Environmental Modelling & Software* 77: 196-220 < https://doi.org/10.1016/j.envsoft.2015.11.016>.
78. Welle, K., Williams, J., Pearce, J. and Befani, B. (2015) *Testing the Waters: A Qualitative Comparative Analysis of the Factors Affecting Success in Rendering Water Services Sustainable Based on ICT Reporting.* Brighton, UK: IDS and WaterAid.
79. Wesselink, A., Hoppe, R. and Lemmens, R. (2015) 'Not just a tool. Taking context into account in the development of a mobile app for rural water supply in Tanzania', *Water alternatives* 8(2): 57-76.
80. Whaley, L. and Cleaver, F. (2017) 'Can 'functionality' save the community management model of rural water supply?' *Water resources and rural development* 9: 56-66 < https://doi.org/10.1016/j.wrr.2017.04.001>.
81. Water and Sanitation Programme (WSP) (2010) *A Practitioners' Workshop Report: Sustainable Management of Small Water Supply Systems in Africa.* Maputo, 6-8 October 2010. Nairobi, Kenya: Water and Sanitation Program.
82. World Health Organisation (WHO) (2017a) *Safely managed drinking water: thematic report on drinking water 2017.* Geneva, Switzerland: World Health Organization.
83. World Health Organisation (WHO) (2017b) *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. Geneva, Switzerland: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF).
84. Williams, J., Welle, K., and Pearce, J. (2016) *How can ICT initiatives be designed to improve rural water supply?* Brighton, UK: IDS and WaterAid.

85. Wilson, D. L., Coyle, J. R. and Thomas, E. A. (2017) ‘Ensemble machine learning and forecasting can achieve 99% uptime for rural handpumps’, *PLoS ONE* 12(11): 1-13 <https://doi.org/10.1371/journal.pone.0188808>.

86. World Bank (2017) *Sustainability Assessment of Rural Water Service Delivery Models: Findings of a Multi-Country Review*. Washington, DC, USA: World Bank.