www.water-alternatives.org Volume 14 | Issue 2

Amankwaa, G.; Heeks, R. and Browne, A.L. 2021. Digital innovations
and water services in cities of the global South: A systematic literature review.
Water Alternatives 14(2): 619-644

Digital Innovations and Water Services in Cities of the Global South: A Systematic Literature Review

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ABSTRACT: Increasing implementation of digital water innovations in cities of the Global South has been accompanied by a growth in research on this topic. This paper presents a first systematic literature review of this domain, analysing a total of 43 papers using a range of thematic categorisations. Overall profiling finds literature to be recent, limited in its engagement with theorisation or methodology, and with some disciplinary, geographic and method gaps. Research has been conservative with regards to the technologies covered, with a provider-centric, rather than a user- or government-centric leaning. Impact findings are skewed towards benefits more than disbenefits, and towards impacts on providers and users rather than towards the broader socio-environmental impacts. The paper ends by laying out a future research agenda that particularly emphasises the value of more contextualised sociotechnical and sociopolitical research.

KEYWORDS: Digital technologies, digital water innovations, urban water, Global South, systematic literature review

INTRODUCTION

Water security is foundational to all human lives and livelihoods and to global development. There are, however, serious concerns that water-related development goals will not be achieved, being hampered by pressures that include population growth, climate change, poor funding, and urbanisation (Dos Santos et al., 2017; Kingdom et al., 2018; WWAP, 2019). For example, despite the global commitment – captured within United Nations Sustainable Development Goal (SDG) target 6.1 – to achieving universal access to safe and affordable water by 2030, only one in five countries with water coverage of less than 95% is on track to achieve this target (UN, 2018). Lack of access to safe water is a particular, and growing challenge in urban areas of the Global South,[1] which are home to more than 3.2 billion people (Ray and Shaw, 2019; Rouse, 2013; UNDESA, 2018). The main water sector problems of these cities – which impact both water service providers (WSPs) and the general public – include large off-grid populations, billing and payment inefficiencies, weak physical and institutional infrastructure, and poor water quality coupled with low investments (Adams et al., 2019; Cardone and Fonseca, 2003; Danilenko et al., 2014; Hope and Rouse, 2013; Rouse, 2013; World Bank, 2016a).

[1] This refers to countries that are classified by the World Bank as low- or middle-income and are located in Africa, Asia, Oceania, Latin America and the Caribbean (Clarke, 2018).

Digital systems (data and technologies) are increasingly seen as a priority in addressing the many social and environmental challenges faced in water management and service provision (Daigger et al., 2019; Sarni et al., 2019). Digital water innovations are also seen as being integral to 'smart city' visions across the world (Joss et al., 2019). Typically first deployed in the Global North, these technologies are increasingly being implemented in cities of the Global South (Amankwaa et al., 2020; GSMA, 2018; Heymans et al., 2014; Waldron et al., 2019), and it is predicted that by 2025, about 80% of water service providers in large cities of the Global North and half of the utilities in large cities of the Global South will have water supply systems that incorporate digital technologies such as advanced metering infrastructure (McKinsey, 2018).

Recognising the many challenges in the water sector, a whole series of reforms and innovations has been developed. These include innovations based around digital technologies which have come with a variety of terminologies and emphases including digital water, smart water, water 4.0, water informatics, information and communication technologies (ICT) for water, and internet of things (IoT) for water, etc. (Geetha and Gouthami, 2016; Owen, 2018; Sarni et al., 2019). In this paper, we refer to all digital systems (data and technologies) for water services collectively as digital water innovations, or DWIs. An illustration of the coverage of this term is provided in Table 1 which uses two main dimensions derived from the literature to categorise DWIs. First, a particular feature of the urban Global South context is the presence of many citizens – typically living in informal settlements – who are 'off-grid'; that is, they have no connection to the formal water infrastructure (Kjellen and McGranahan, 2006). DWIs in Table 1 are thus divided into those serving on-grid markets and those serving off-grid markets. Second, a ready way to understand the water sector is via a water services value chain that starts with water sources, then distribution and delivery of water, then consumption by end users such as individual households or businesses (Wehn and Montalvo, 2018). DWIs can thus be further subdivided into these three stages. Using this 2 x 3 categorisation schema, the specific DWIs mentioned in Table 1 were identified from a review of literature on the digital systems applied to drinking water services in urban contexts.

The growth in technology roll-out has been accompanied by a related growth in the number of research papers being written on this topic, though these are still relatively small compared to the literature on other aspects of water management. The growth in research on DWIs has in turn led to reviews of research which, for example, identified the actual and potential financial, operational and environmental benefits of digital water innovations (Beal and Flynn, 2015; Cominola et al., 2015; Liu and Mukheibir, 2018; Monks et al., 2019). They have also identified the challenges to DWI implementation, including the financial, human, technical and institutional barriers (Beal and Flynn, 2015; Stewart et al., 2018), and the challenges faced by implemented DWIs, such as data management, privacy breaches and cyber-attacks (Boyle et al., 2013; Cominola et al., 2015).

The focus of these reviews has been the actual or planned DWI implementations in the Global North; however, as described in relation to the urban water sector more generally, there are significant differences between the Global South and the Global North in terms of context, innovation priorities, implementation issues, and impacts of digital systems (Bediako et al., 2018; Guma, 2019). We identified only two literature reviews relating to digital and water in the Global South, those by Champanis et al. (2013) and Ndaw (2015). These both focus on digital applications in WASH (water, sanitation and hygiene) overall, rather than having a particular focus on either drinking water or urban locations. They also, given the time at which they were written, found only pilot applications of digital technology in WASH and therefore draw their evidence not even from this sector specifically, but from all applications of information and communication technologies for development.

Table 1. Digital water innovations for urban drinking water services in the global South.

Stage of water value chain	Activities	On-grid water networks		Off-grid water networks	
		Physical technologies	Digital water innovations	Physical technologies	Digital water innovations
Source	- Sourcing water from natural or formal sources - Water collection, conveyance and purification - Water treatment and monitoring	- Reservoirs - 'Headworks' - Water mains - Pumps - Turbines - Sensors - Buoys - Bulk meters - Valves - Aerators	- Sensors (supervisory control and data acquisition, or SCADA; loggers; etc) - Telemetry systems - Hydraulic modelling - Digitised service plans - Augmented and virtual reality tools - Other monitoring tools and algorithms	- Water extraction systems (from wells, lakes, etc) - Hydrants and other parts of formal water systems - Water purification technologies	- Portable digital water purification systems
Distribution and delivery	- Water distribution and monitoring	- Water mains - Distribution pipelines and other network connections - Sensors - Pumps - Valves - Pipe joins	- Geographic information systems (GIS) - Data mining and machine learning techniques - Internet of things (IoT) applications including sensors (flow loggers, leak detectors, data loggers, etc) - Remote sensing - Hydrologic and system modelling - Network monitoring and management systems - Forecast and demand planning	- Tanker trucks - Packaged water (sachets or bottled) - Water-dispensing systems - Water vending/reseller kiosks and systems - Standpipes	- Mobile phones - Water ATMs - Prepaid community water meters
End use	- Water consumption - Consumption monitoring and revenue collection - Service feedback - Water resale	- Meters - Valves - Pipes - Taps	- Smart meters and meter data management - Billing and payment systems - Customer information systems including customer apps - Customer engagement channels including call systems	As for 'Distribution and Delivery'	- Digital (mobile) payment systems - Prepaid water payment systems

Source: Authors, based on cases of DWIs presented by GSMA (2018), Gurung et al. (2016), Heymans et al. (2014), Laspidou (2014), Liu and Mukheibir (2018), Nguyen et al. (2018), Sarni et al. (2019), Stewart et al. (2018) and Waldron et al. (2019).

Thus, to date, there has been no systematic review of the specific and burgeoning evidence base addressing actual digital water applications for urban contexts in developing countries. Filling this gap provides the aim of this paper and its focal question: what research evidence exists about digital water innovations in cities of the Global South, and what remains to be researched?

The paper will undertake the filling of this gap by investigating three thematic subdomains: the profile of the literature to date, the nature and implementation of digital technologies used in cities in the Global South, and the impacts of these technologies so far. We believe the paper will be of particular value to water researchers; summarising for them what is already known about DWIs in developing country urban contexts and providing an agenda for future research. In addition, agencies such as the International Water Association and the World Bank have endorsed and encouraged a global programme of water service digitisation which is particularly linked to the drive to achieve the water-related SDGs. This means that water practitioners and policy makers in international development agencies and national governments, as well as water service providers in the Global South, are increasingly seeking evidence-based guidance regarding the role of digital systems. We hope this paper can help towards such guidance.

The remainder of this paper is structured as follows. The next section discusses the systematic literature review methodology adopted here. This is followed by a presentation of the results of that review. The paper ends with a discussion of the future research agenda.

METHODOLOGY

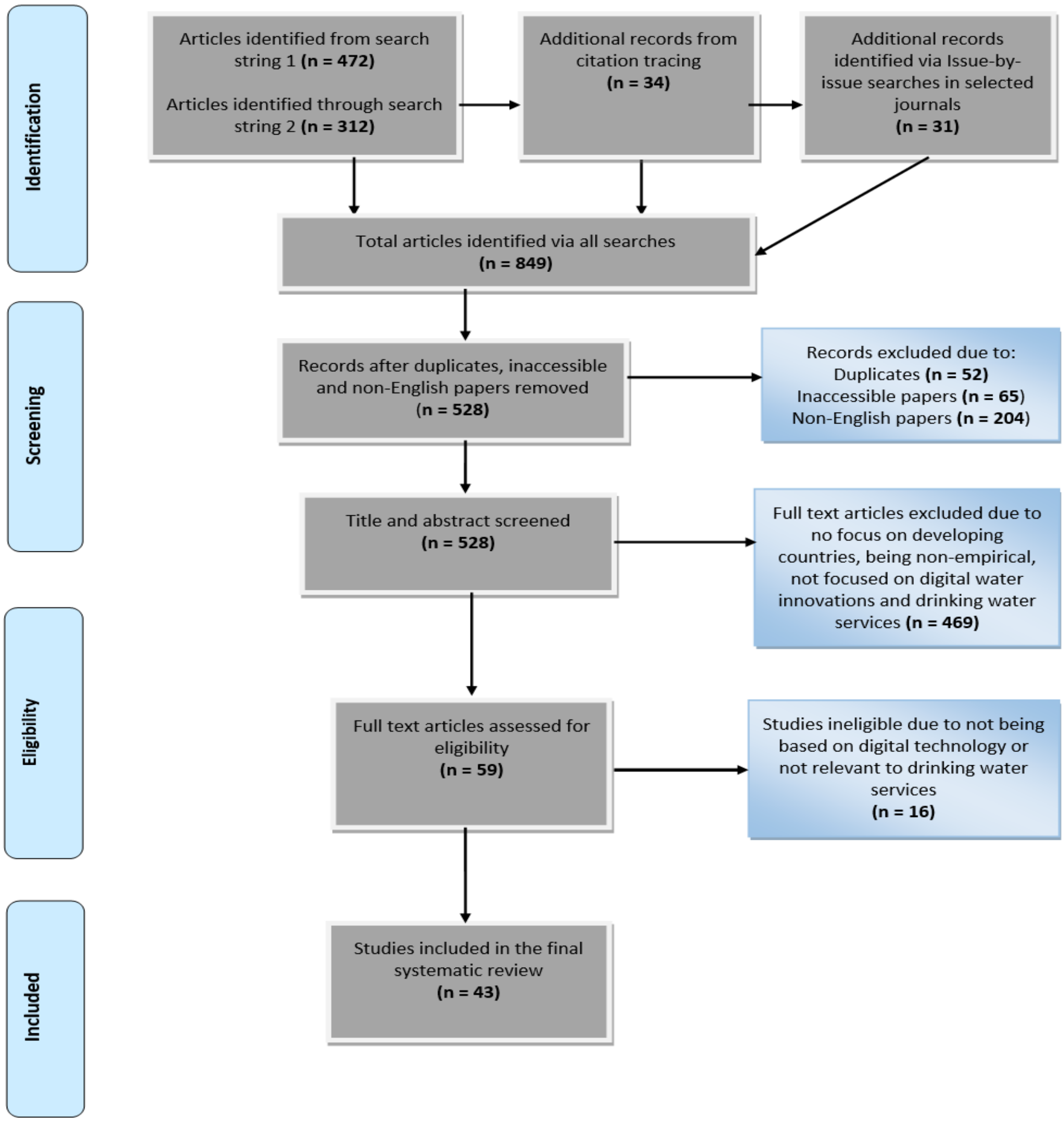
The first author led a systematic review to identify and screen for relevant cases from academic journals and policy reports; the review was guided by the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach (see Figure 1) (Moher et al., 2009). Given the interdisciplinary nature of the study topic, two search methods were used.

First, we conducted an automatic search in Google Scholar using 'allintitle' plus Boolean operators to retrieve articles which had key terms in their texts. Google Scholar was used to implement the search strategy because it has the widest coverage of academic documents compared to other academic literature databases and because it includes grey literature such as organisational reports; further, as it is freely accessible, searches can readily be reproduced (Khabsa and Giles, 2014). As a cross-check, we made initial searches on other databases – Scopus, Web of Science, and Engineering Village – and found only a subset of those papers already identified via Google Scholar. The review domain represented the intersection of four topics from which two search strings were developed (see the Annex for details). As indicated in Figure 1, the first produced 472 initial citations and the second produced 312.

Second, we conducted a two-part manual search. This consisted, first, of backward and forward citation tracing from the articles identified by the Google Scholar search, looking through the reference lists of these papers and also using Google Scholar's 'cited by' facility. This produced 34 additional sources. The manual search also consisted of an issue-by-issue search of selected journals which we had found – from prior reading and from the Google Scholar search – to contain relevant papers on DWI in cities of the Global South. These were *Smart Water*, *Urban Water*, *Water Alternatives*, *Water Policy*, and *World Development*, which together provided coverage of urban, political/policy, development, and technological aspects of the topic. Given the relative recency of DWI implementation in the Global South, this search was restricted to the 10-year period of 2009 and 2019, and it led to the identification of a further 31 papers.

In our next step (see Figure 1) we screened the identified literature at the level of titles and abstracts, based on the inclusion criteria (see the Annex for details). This ensured that the papers focused on drinking water services rather than on other water sector applications; that they focused on urban, Global South locations; and that they focused on digital water innovations. Papers were only included if they were in English with the full text available and if they reflected primary research based on empirical results. The full text of the papers was then assessed, with 16 papers deemed ineligible because they did not focus on urban locations in the Global South, on drinking water, or on digital innovations. Ultimately, a total of 43 articles was included in the final corpus of analysis: 19 from the direct Google Scholar search, 19 from citation tracing, and 5 from the issue-by-issue search.

Figure 1. Flow diagram for the identification and selection protocol.



Source: Adapted from the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol by Moher et al. (2009).

As is typical in some systematic literature reviews, this review adopted an iterative approach in order to develop thematic categories for analysis of the literature. While there were no other reviews looking specifically at our chosen topic, we examined categorisations used in other water-related reviews (Boyle et al., 2013; Liu and Mukheibir, 2018; Ndaw, 2015; Wehn and Montalvo, 2018) and in syntheses of evidence on digital technologies and development (Heeks, 2006, 2018). These formed the deductive starting point for analysis; they were then developed into a coding schema by the first author and then were discussed among the authors. The revised schema was then iteratively applied, first by the first author and then through co-coding of the first ten papers by the author team. This then led to further revisions and a finalisation of the categories and codes. Qualitative and quantitative analysis of the content of the 43 selected papers was then undertaken based on the coding schema, alongside mapping of study locations. The finalised thematic categorisation was divided into three main domains, as previously identified in the introduction to this paper: characterisation of literature, DWI implementation, and impacts (see the Annex for details).

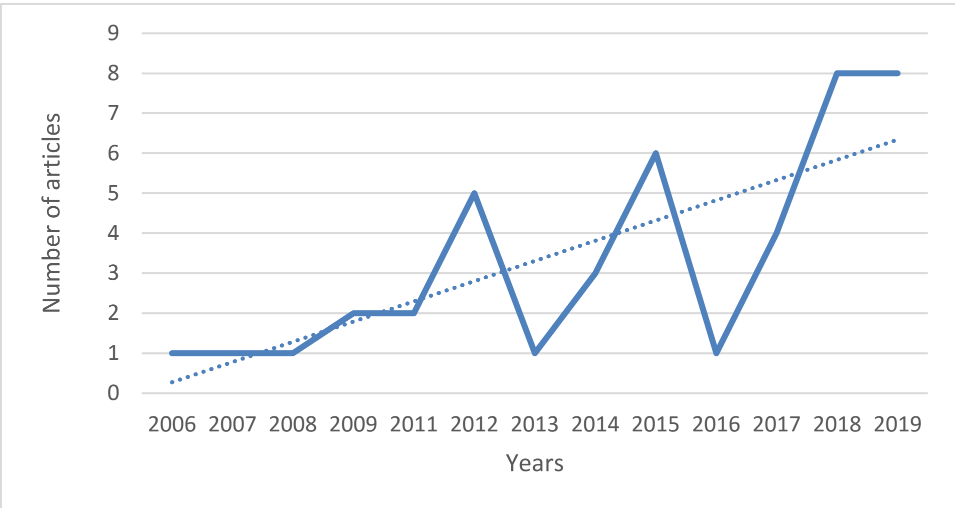
FINDINGS

Profile of literature on digital water innovations in Global South urban contexts

Timeline and outlets

Figure 2 shows the publication dates of the reviewed literature. The pattern reflects a number of features of literature on DWI in the Global South. First, the relative recency of work – first paper published in 2006, roughly two-thirds of papers published in the last five years of the review, and more than one-third in the last two years – reflecting the relative recency of digital technologies being deployed in developing countries. Second, the volatility of publication, reflecting the immaturity of the field and the lack so far of critical mass and momentum. However, as the trend line in Figure 2 indicates and mirroring the growth in DWI investment and implementation, this is a growing research field, making it an appropriate moment for this review.

Figure 2. Publication timeline of reviewed papers.



Source: Authors.

Of the 43 papers, 30 were published in journals, 7 in conference proceedings, and 6 were grey literature made up of organisational reports. There was little aggregation of material: only four outlets were represented multiple times: the journals *Urban Water Journal* (three papers) and *Water Alternatives* (two papers), and publications from the Smart Water Systems project of the University of Oxford (two papers), and the Water and Sanitation Program of the World Bank (three papers). The reports are all from reputable sources (the sixth paper coming from the Pacific Institute) but the outlet reputation – and hence potentially their quality – of other papers was mixed. Only four of the conference proceedings were based on conferences from formal professional associations. The quality of the journal outlets was also mixed and was judged using the ranking produced by Scimago, which categorises journals into disciplinary quartiles based on citation evidence, which can be taken as a proxy of quality. Journals not listed on Scimago can be very new but are more often of limited quality and influence (Falagas et al., 2008; Delgado-López-Cózar and Cabezas-Clavijo, 2013). As Table 2 shows, there was a bimodal distribution of papers, with just under one-quarter published in top-ranked journals and just over a quarter published in unlisted journals. At the least, this suggests opportunities for greater publication of research in high-quality outlets.

Table 2. Journal and papers distribution according to Scimago ranking.

Scimago rank	Number of journals	Number of papers
Q1	7	10
Q2	7	7
Q3	1	1
Q4	1	1
Unlisted	11	11

Source: Authors.

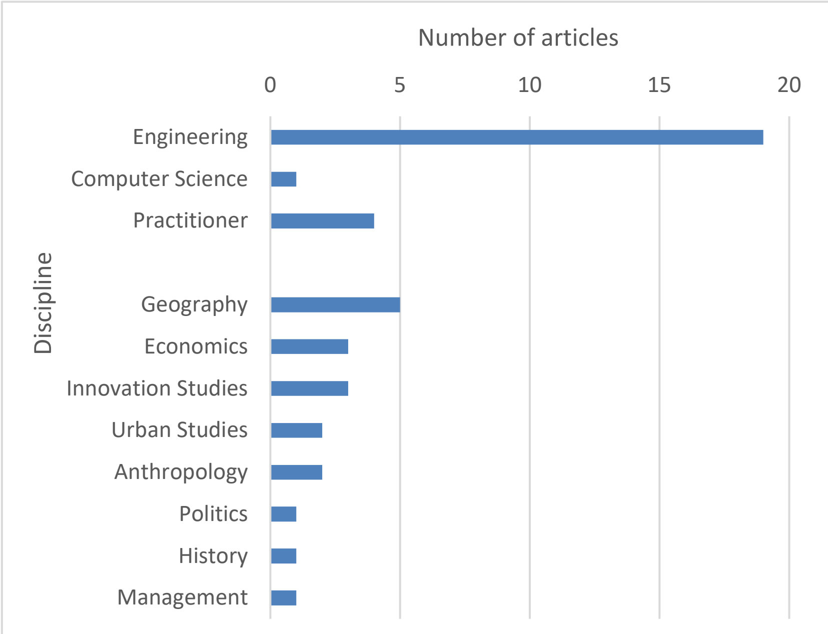
Three-quarters of the papers appeared to be the only domain-relevant output from their authors. Four papers were authored by members of the University of Oxford group and three from those working mainly at Jiangsu University. In two other cases, authors were part of two papers. Given the relative recency of papers, this picture may change over time, with authors repeat-publishing in the field and perhaps undertaking research over a sustained period. At present, though, most work appears to be researchers' sole foray into the field.

Discipline and theory

Analysis of academic discipline, summarised in Figure 3, shows a strong domination of engineering; nearly half of all papers were published by science and engineering authors who were academics and – once technical practitioner authors are added in – this came to more than half. A variety of social sciences are represented, which conveys the interdisciplinary potential for research on the topic; conversely, however, one may see the field as fragmented with no sense of critical mass within any individual social science discipline. This disciplinary leaning towards science and engineering has meant that there is a proportionately large volume of work on technical topics, a skew that is amplified because some urban and innovation studies authors write technically oriented papers. Not only are sociopolitical perspectives in shorter supply; there was also little evidence of interdisciplinary work, and thus a notable absence of a rounded sociotechnical conceptualisation.

The disciplinary profile is echoed in our analysis of the use of theories and frameworks. Sixteen of the papers – nearly 40% – had no discernible conceptualisation or framing, something that could be of concern if this field is to produce work of high academic quality that allows ready comparison and aggregation of knowledge. A further 13 – just under one-third – used some form of mathematical or technical model. Five papers focused on the adoption of digital technologies using particularly Rogers' Diffusion of Innovation model or the Unified Theory of Acceptance and Use of Technology, but they made no cross-citation to one another. The remainder used a mix of inductively derived frames and individual models such as principal-agent theory, or technological frames with no creation of any critical mass of conceptualisation.

Figure 3. Disciplinary focus for reviewed papers



Source: Authors.

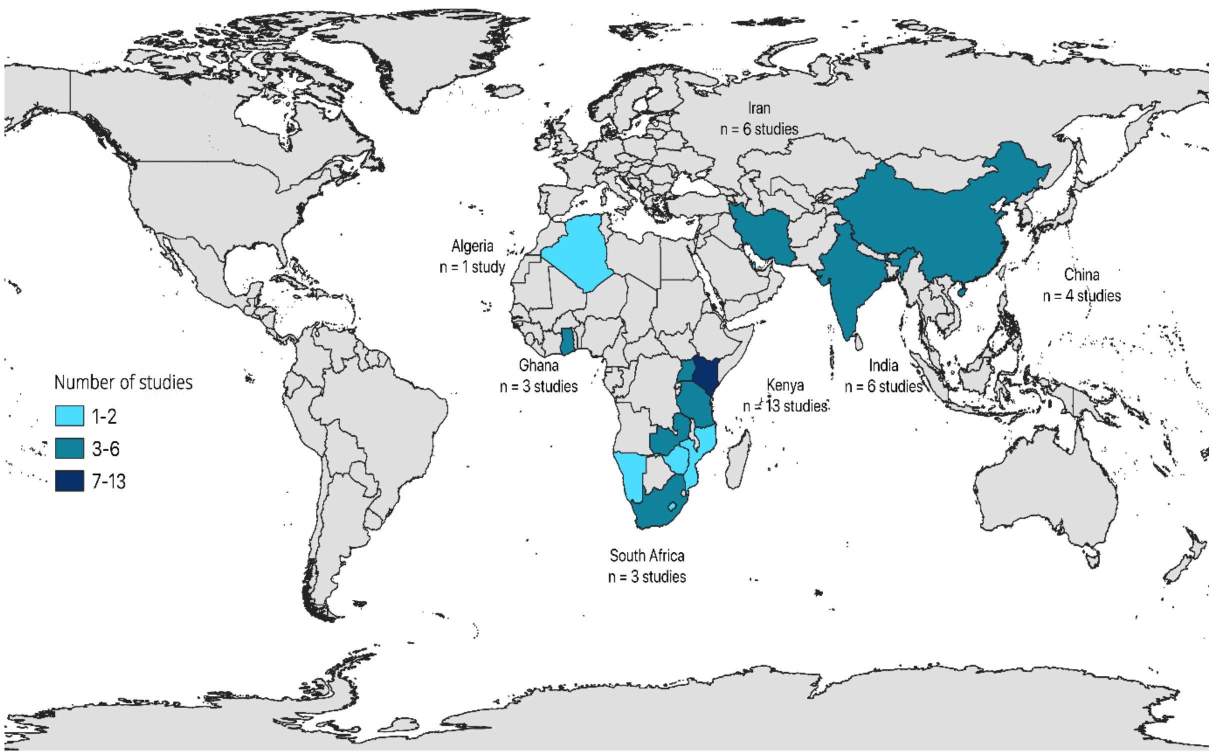
Geographic coverage

In terms of geographic focus (see Figure 4), just over half of the studies included a focus on Africa (58%) and just under half on Asia (44%). Two of the studies were cross-continental, focusing on Africa, Asia and Latin America. Regionally, there were no studies on Oceania, Southeast Asia or Central Africa and few on West and North Africa. Nationally, there were also skews: 13 studies encompassed Kenya, 6 each covered India and Iran, and only 10 other countries were specifically included. There may be explanations for this, including a leaning in paper selection towards Anglophone countries given the review language criterion and a leaning in research towards countries with more well-developed research and water innovation infrastructures. This does mean, however, that current literature and knowledge on digital and water in cities of the Global South are highly skewed in geographic terms and that whole continents, regions and the great majority of developing countries are still missing from our understanding.

Research philosophy, strategy and methods

None of the reviewed papers explicitly stated their underpinning philosophical perspective, which might again manifest the relative immaturity of the field and its relative lack of academic depth. Interpretation of research philosophy based on ontological or epistemological statements or practices within the papers suggests that a majority (59%) of those that could be interpreted were following a positivist paradigm, with a further 21% adopting some form of realist position; only one-fifth could be said to be interpretive and none were critical realist in approach. This skew away from interpretive and critical realist work derives in part from the strong presence of engineering and wider technical disciplinary authorship among the corpus of literature reviewed; it also means, however, that a significant proportion of the social-science-based research (for example, all of that within economics, innovation studies, politics and management) was positivist or took some other variant of realist ontology.

Figure 4. Focal locations for literature.



Source: Authors.

Note: Some studies included multiple countries.

The disciplinary and philosophical slants in the reviewed work were also seen in research strategies and methods. Research strategies were not often explicitly identified, but 42% of papers used survey strategies and a further 19% used others forms of field study strategy that investigated digital water innovations in their context of implementation or use. Just under one-quarter of studies used a technical research strategy, either piloting some software or testing a mathematical or engineering model, and the small remainder used case study or archival research strategies. As would be expected from this profile, there was a dominance of quantitative methods; used in three-quarters of the studies that had a clear method and used in 56% of papers as the only type of method. Only one-quarter of the papers used qualitative methods alone, and only 17% used a mixed methods approach. Data sources used with these methods included primary sources (surveys, questionnaires, key informant interviews) and secondary sources (particularly water-use data from institutions within the respective countries).

Looking overall at the literature then, at present, the research domain is in danger of 'falling between two stools': it is not particularly diverse with a domination of technical, positivist/realist and quantitative research. Yet at the same time it has not been able to aggregate knowledge or create a critical mass of ideas or debate around particular issues. These are atomised, fragmented efforts in terms of authorship, discipline, publication outlets, use of theory, etc. Reusing a metaphor from another immature field, "The image is of random rocks being thrown into a pool rather than building cairns of knowledge" (Heeks and Bailur, 2007: 256).

DWI implementation research

Categorising on the basis of the digital life cycle model (see the Annex for details), every paper discussed some aspect of implementation, but these were further categorised by implementation stage. Just under half of the papers (19 of 43, or 44%) discussed design and development of digital water innovations, just over a quarter (12 papers, or 28%) discussed adoption and uptake, and just over one-third (16 papers, or 37%) discussed use of DWIs.

Digital technology type

This theme analysed the different functionalities of digital technologies discussed in the literature, using the information value chain-based categorisation (see the Annex for details). Six of the papers were not specific in focusing on particular types of digital water innovation, while three discussed a broad variety of technologies, covering multiple examples within all four of the categories. In reporting below, these are excluded in order to hone in on those papers discussing particular types of DWI, though a number of the remaining 34 papers discussed more than one category of technology.

1. *Data capture technology* provides data and can act as a source of real-time data on water quality, flows, pressures and levels among other parameters in the water value chain. This was discussed by just over one-quarter of the technology-specific papers (9 of 34, or 26%). Particularly represented was a discussion of sensors for monitoring water flow and distribution networks. Remote sensing was discussed as the basis for capturing data, but only for foundational maps that would then be used for visualisation, rather than as the basis for capturing data related to water systems. Two papers discussed smart meters as a source of data (Abdallah and Shahrour, 2019; Hope et al., 2012): a small number compared – say – to the extent to which this issue arises in literature on DWI in the Global North (see, for example Gurung et al., 2014; Beal and Flynn, 2014). Use of supervisory control and data acquisition (SCADA)-based systems has likewise been growing worldwide for some years, especially in higher-income countries (see, for example, Dobriceanu et al., 2008); however, it was discussed in only one paper (Yan et al., 2009). Use of telemetry systems to communicate captured water data was not the basis for discussion in any of the papers.
2. *Data processing technology* takes captured data, processes it, and then allows it to be visualised, potentially providing information to recipients. Half of the papers (17 of 34) discussed this category of technology of which a majority (10 of 17) included geographic information systems as the means to process and visualise. Just over one-third discussed development of an algorithm through which data could be analysed; for example, in order to identify likelihood of pipes bursting or forecast demand. Most likely reflecting the more limited extent of big data and related capabilities in the Global South, only one paper discussed data mining and machine learning (Dikshit and Krishnarao, 2006), despite their demonstrated value in the Global North (Cominola et al., 2019; Duerr et al., 2018). None discussed the formal application of artificial intelligence, blockchain, virtual reality or augmented reality though all have been shown – for example via laboratory prototypes developed in the Global North – to have potential in urban water supply (Mahmoud et al., 2019; Mirauda et al., 2020; Rojek and Studzinski, 2019; Sarni et al., 2019).
3. As the name suggests, the main role of *decision-support technology* is to produce information that will feed into specific types of water sector decisions. Just under one-third (10 of 34) of the papers incorporated coverage of this type of innovation, broken into two main types; i) Management information systems which monitor data streams to produce alerts and summaries for water sector managers, for example monitoring water quality or pipeline leaks and blockages; and ii)Planning support systems which use existing data to make forecasts about the future from the relatively micro level (such as which valves to close if a pipe bursts, or how to direct pipeline maintenance to those

pipes most likely to burst or leak), to the relatively macro level (the extent and timelines for water demand). Half of the papers dealt with modelling of the water distribution network.

4. *Action support technology* either undertakes or facilitates water-related actions or transactions. As with data processing, half of the papers (17 of 34) included discussion of this technology. The majority of these (10 of 17) researched mobile payment systems; which is not surprising given their growing use in cities of the Global South. Seven papers, all with a focus on Africa, discussed adoption or emergent impact of prepaid smart water meters, installed for either household or communal use. Mobile is the dominant lens through which individual user experience of digital in developing countries is understood (Heeks, 2018). However, four of the papers did see the web as a focal technology; particularly for payment or for communication between water service providers and consumers (Guma et al., 2019; Hellstrom and Jacobson, 2014; Kumar et al., 2018; Mwangi et al., 2015). Despite interest in their potential and implementation in some countries, only one paper focused on water ATMs (Sarkar, 2019). Though increasingly incorporating digital technology, none of the papers discussed ICT-based water purification technologies.

Overall, then, the literature has dealt rather more with data processing/visualisation and action support technologies than it has with data capture and decision-support technologies. Field research will lean towards analysis of technologies already deployed: sensors and meters, geographic and other types of traditional information systems, and mobile payment systems. However, even field prototyping or adoption surveys have been relatively conservative, so far showing little or no coverage of a number of the technologies that have already been implemented or demonstrated to have potential in the Global North. The specific context of the Global South is also reflected in the relatively strong presence of mobile-based innovations; they were a topic in one-third of the papers.

Technology locus

Table 3 summarises the stage of the water value chain on which literature focused. As can be seen, there was relatively little research on DWIs applied at the upstream end of the value chain, including water sources, headworks and treatment. In fact, only one paper was dedicated to this topic (Chen et al., 2012), while eight others also covered other parts of the value chain, often looking quite broadly at different types of digital water innovation. This could reflect the more limited implementation of DWIs in water sourcing and treatment and/or the greater physical, geographic and social scope of the distribution and use stages of the drinking water value chain. We hypothesised that the research profile might also relate to barriers to undertaking research with water service providers compared, say, to end-user research that would not need provider permission. However, this was not the case in practice: for example, most end-user-focused research did also involve the water service provider.

Indeed, analysing those identified in each paper as key stakeholders of relevance to the focal digital water innovations and research, almost all papers (93%) discussed water service providers. Just under one-quarter discussed end users/consumers, only three papers discussed government, and four discussed other agencies such as NGOs helping implement innovations. This pattern may reflect the fact that providers are generally the ones funding and leading the innovation process; particularly given the process of WSP privatisation, with privatised utilities seen as notably keen on using DWIs for cost reduction or revenue maximisation (Bakker, 2010). The research reflects a provider-centric view of innovation. There were, for example, no instances of user-driven or government-driven innovation or even co-design or participative approaches to implementation involving users or government, and there were few examples of partnership arrangements for innovation development and implementation.

Table 3. Classification of studies by water value chain stage.

Focal stage of operation	Number of articles	Percentage of all papers
Source	9	21
Distribution and delivery	25	58
End use	27	63

Source: Authors.

Of the world's urban population, 15% – around 650 million people – live without access to safely managed piped water (UNICEF/WHO, 2019). There are, however, sharp global divides within this overall figure, as shown in Table 4. We cannot perform an exact calculation but, based on the UNICEF/WHO (2019) data, we estimate that approximately one-quarter of the urban populations in the countries covered by the systematic literature review are 'off-grid' – that is, without access to piped water. Yet only one of the papers looked specifically at digital water innovations for this population, such as water ATMs (Sarkar, 2019). A further seven papers (16%) looked at mobile-phone – based innovations that could have some application to off-grid populations, but even for those papers, this was not the main focus. This lack of attention exists despite the fact that, this is the group in cities of the Global South that is hardest hit by water insecurities; compared to on-grid consumers, they experience higher prices, poorer and less-certain supply, and lower water quality (Ablo and Yekple, 2018; Adams, 2018; Braimah et al., 2018).

The formal water infrastructure has been the overriding concern of DWI research to date. Within that, low-income consumers were not ignored: one-third of papers, such as some on mobile applications and prepaid meters, included this group among others. Only 14% of papers, however, looked specifically at digital technologies of relevance to on-grid, low-income users; this was the case despite their forming a much larger proportion of urban populations in developing countries (at a very rough estimate around 50% of the urban population in countries studied earned less than US$ 5.50 per day (World Bank, 2020)) and the fact that their lives are characterised by higher water insecurities (Bakker et al., 2008).

Table 4. Percentage of urban population without access to piped water, 2017.

Region	Percentage of urban population
Sub-Saharan Africa	36
Central and Southern Asia	30
Oceania	22
East and Southeast Asia	15
Northern Africa and Western Asia	10
Australia and New Zealand	6
Latin America and the Caribbean	3
Europe and North America	1

Source: UNICEF/WHO (2019).

There has thus, to date, been a mismatch between urban population profiles and research, especially in terms of those who are off- grid. This likely also reflects a wider orientation for digital water innovations towards the piped water grid and the formal water sector (Daigger et al., 2019; Sarni et al., 2019). Of course opportunities to apply DWIs are lower for those – for example in informal settlements – who lack access to piped water, and barriers to successful implementation are higher. However, their water-related problems are by far the greatest (for example, reflected in the SDG 6 targets) and hence their need for water innovations is arguably the highest. To a somewhat lesser degree, the same research mismatch, innovation issues and needs apply more broadly to lower-income groups in cities of the Global South. But DWI researchers and their research do not just focus on the innovations of others – given its technical emphasis, much of the research reported here is action research that forms part of an innovation process producing a technical DWI artefact. Indeed, such research may in part set the agenda and direction for innovation. So skews in research away from off-grid are not just a detached reflection of innovation biases, they are also a cause of those biases as well.

Implementation findings

Where identified, there were three main types of DWI implementation challenges discussed. There were technical issues either internal to the digital system such as problems with data or software quality (Tabesh and Dini, 2009; Kattan and Alrawi, 2018); or more related to external infrastructure such as limited penetration of mobile phones or internet connectivity or frequent power/telecommunication breakdowns (see, for example, Gambe, 2015; Hope et al., 2011a; Magoma, 2018). For example, though prepaid smart water meters have potential to improve water provider revenues, their implementation has faced "rampant power outages" in some locations (Gambe, 2015: 245).

There were adoption problems with users or service providers unable to afford to implement or use the technologies (Bediako et al., 2017a; Hope et al., 2011a; Ndaw, 2015), with a lack of necessary skills (Bediako et al., 2018), or more general resistance among user groups to change their existing methods of water access or payment (Guma et al., 2019; Magoma, 2018; Ndaw, 2015). One paper suggested that this could be understood in terms of the "conceptual gap" between the design of DWIs and the social realities into which they were introduced, including the complexity of those realities that were not necessarily understood by innovation designers (Guma et al., 2019). That conceptual gap may originate from the top-down way in which DWIs are being designed and implemented. The absence of co-production and participative approaches was identified above, and in more than three-quarters of the papers, decision-making was associated with strategic, high-level management. Given, as just noted, the core role of water service providers in the surveyed papers, those high-level decisions – and hence DWI design and implementation – would be guided by strategic WSP goals such as revenue generation and cost recovery. These goals, rather than the specific interests and goals and contexts of users, may therefore be key drivers and motivations for digitisation, though there was little overt exploration of this theme in the literature reviewed.

Third, and more related to impact, four studies noted the limited impact of introducing an individual technological innovation alone (Heymans et al., 2014; Hope et al., 2011a; Kimorop et al., 2018; Krolikowski, 2014). However, only one paper, (Heymans et al., 2014) was particularly directive about the implications of this, seeing a need for complementary changes to run alongside technology implementation. Looking over the implementation challenges, those complementary changes could potentially cover WSP staff and user capabilities (skills and knowledge), incentives and motivations, and processes of water management or billing or consumption.

DWI impact research

Overall profile of DWI impact research

A little under half of the papers (21 of the 43) reported on impact of the digital systems. Of these, eight used terms such as 'potential' or 'putative' and were thus speculative in their impact findings, rather than having based these directly on primary field data. For the remainder, most reported on pilot implementations of DWIs or, at most, their early stages, which is not surprising given the relatively formative nature of use of the technologies in the Global South. These were analysed using the typology of impacts presented in Table 5, which was iteratively developed from the starting point of categorisation of benefits by Sarni et al. (2019).

Table 5. Typology of digital water innovation impacts.

Impacted stakeholder	Impact category	Specific impacts
Water service provider (WSP) benefits	Financial benefits	- Lower operational costs including water supply and payment administration costs
		- Lower maintenance costs
		- Increased revenue including reduced non-payment
	Operational benefits	- Better decision-making (for example, due to better data)
		- Less operational downtime or failures
	Other benefits	- For example, reduced payment-related corruption
User benefits	Financial benefits	- Lower costs of water supply (including time costs)
		- Lower costs of bill payment process (including time costs)
	Supply benefits	- Greater accessibility to water
		- More certain supply (less chance of disconnection/loss)
		- Higher water quality
	Service benefits	- Greater transparency and responsiveness
	Other benefits	- For example, time savings for women/children
Government benefits	Other benefits	- For example, improved policy-making due to better data
Broader benefits	Environmental benefits	- Less waste of water through leakage reduction
WSP disbenefits	Financial disbenefits	- Costs of implementation
	Other disbenefits	- For example, technology problems (including meter bypassing by users or data hacking/privacy problems)
User disbenefits	Financial disbenefits	- Costs of using digital water innovations
	Other disbenefits	- For example, technology breakdowns
Broader disbenefits	Environmental disbenefits	- Water source depletion
	Sociopolitical disbenefits	- Increased inequality

Source: Authors.

In terms of overall perspective on impact, there was a balance of discussion of both benefits and disbenefits of digital water innovations, though with some orientation towards benefits (see, for example, Krolikowski, 2014; Magoma, 2018; Ndaw, 2015; Sarkar, 2019). While almost every paper discussed both aspects of impact, coverage of disbenefits was much more limited; on average each paper talked about four different types of benefit but fewer than two types of disbenefit. Evidence-based discussion was also skewed; nearly two-thirds of papers discussing benefits did so on the basis of primary evidence, while just over two-thirds of papers discussing disbenefits did so in hypothetical terms without a primary evidence base. We investigated whether any benefit-disbenefit skew might relate to authorial interests. We considered whether authors might be biased towards benefits because, for example, they had themselves developed the DWI that was under investigation or had worked for the organisation that funded the DWI; however, this was not detected. The four papers that did not report any disbenefits were all written by independent authors, and the balance of benefits to disbenefits in a paper did not correlate to presence or absence of authorial interest.

Among the papers, interest was clustered around benefits for users and water service providers; almost every paper discussed both. Discussion of broader societal – mainly environmental – benefits was found in only four papers (Guma et al., 2019; Kumar et al., 2018; Mwangi et al., 2015; von Schnitzler, 2008). While there was generally less discussion of disbenefits, coverage of broader – both environmental and socio-political – disbenefits was found about as often as that on specific disbenefits for users and WSPs. Evidence-based analysis of broader impacts, however, was much more limited; only three papers in the case of sociopolitical impact and two papers in the case of environmental impact discussed that impact on the basis of primary data (Guma, 2019; Guma et al., 2019; Sarkar, 2019; von Schnitzler, 2008, 2013). Mirroring the more general stakeholder pattern, there was minimal focus on the impact on government and policy; no papers explicitly discussed this.

There was a strong skew in terms of the technologies covered; this was seen especially in the impact papers that were based on primary fieldwork, with all of them discussing the impact of action support technologies. Two papers that discussed a variety of technologies also included specific evidence around sensors and management information systems (Hellstrom and Jacobson, 2014; Kumar et al., 2018). Otherwise, though, there was no primary evidence-based impacts research on the great majority of data capture, data data-processing and decision decision-support technologies. Linked to this, papers had not yet engaged with the datafication of water, that is, the growing presence, use and impact of data in the water value chain. This was despite not just the reality of datafication but also the burgeoning literature on datafication in developing countries and on its wider implications for issues such as distribution of value and power (Heeks et al., 2019).

Impact findings

Digging down into the details, we summarise here some of the main findings on the impact of digital water innovations in urban Global South contexts. We restrict our summary to those papers presenting primary research-based findings and again based on the Table 5 typology of DWI impacts.

For water service providers, there was evidence of digital technologies having positive financial impacts in three main ways. Operational costs have been reduced, particularly in relation to reduced administrative costs for bill collection through the introduction of web- and mobile-based payments (Magoma, 2018; Mwangi et al., 2015). There was just one example of lower maintenance costs, via faster identification of faults so that these can be rectified at lower cost before they become more serious (Ndaw, 2015). Water revenues have been increased via water ATMs, prepaid meters and via mobile payments with the latter linked to revenue increases of around 15% (Magoma, 2018; Ndaw, 2015). In only one study was the financial cost of investments in DWIs directly evidenced; this was a finding from a pilot project in India which showed that water ATMs sited near free piped water supplies provided a poor return on investment (Sarkar, 2019).

There was little direct evidence of other impacts on water service providers, despite wider discussion of the potential for DWIs. One study found that digital systems could help improve decision-making within WSPs through improved water supply monitoring (Hellstrom and Jacobson, 2014) and, in a related finding, another study claimed improved service reliability (Hutchings et al., 2012). Despite the repeated assumption that digital billing systems would reduce corruption (see, for example, Krolikowski, 2014; Magoma, 2018; Sherry et al., 2019), no direct evidence on this was presented. On downsides, two sources mentioned users tampering with or bypassing prepaid water meters, thus denying revenue and data for the water company (Guma et al., 2019; von Schnitzler, 2013). Typical implications of the move to digital – loss of physical records and oversight, dangers of data privacy breaches or hacking of water infrastructure – were raised but not directly evidenced.

User benefits were particularly discussed in financial terms though that was mainly understood in terms of time savings. There was little direct evidence of savings in relation to water access: the only detailed survey related just to communal prepaid water meters and reported both cost savings – "After the installation of the meters, instead of paying an average of US$ 0.08, consumers now pay USD 0.01 per jerry can" (Hanjahanja and Omuto, 2018: 8) – and time savings: "before the communal prepaid meters were installed, 67% of beneficiaries spent 1 h or more daily collecting water (…). After the installation, 92% spend less than 15 min collecting water" (ibid: 7). Time savings were seen as particularly being generated for women and children given their responsibility for sourcing water for their households (Foster et al., 2012), though this benefit derives more from the physical infrastructure and presence rather than digital functionality of water meters.

There was a bit more evidence in relation to mobile payments saving transaction costs for payments; again understood mainly in time terms; it is stated, for example, that, "those paying with mobile money spend 82% less time paying bills than those settling their bills at the bank, saving 54 minutes on average" (Foster et al., 2012: 798). Digitally enabled metered billing has also been found to be more accurate than earlier methods; satisfying households that they only pay for what they use (Mwangi et al., 2015). On the other hand, some DWIs were imposing higher costs on users: the Indian water ATM pilot noted above charged a fee whereas piped water was free (Sarkar, 2019), direct costs of using mobile money payments were typically greater than costs of paying water bills via a bank (Foster et al., 2012), reporting a problem via text message imposed a new cost (Hellstrom and Jacobson, 2014), and some users in Kenya had covered costs for prepaid meters by taking out loans that they then found it hard to repay (Guma et al., 2019). One issue raised was that the payment systems associated with digital water innovations had aggregated, formalised and/or financialised costs that households previously paid in small amounts, or that households had previously 'paid' through their own time rather than with money.

Less-quantified user benefits were also reported by a few studies such as reduced stress when households were informed of water availability times in rationed systems (Kumar et al., 2018), faster and better response to complaints and requests when WSPs introduced ICT-based customer relationship management systems (Ndaw, 2015), and improved access to better quality drinking water though this again was more a physical than digital functionality of new water technologies (Hanjahanja and Omuto, 2018; Sarkar, 2019). Less-tangibly, consumer empowerment was identified as an impact, brought on by better access to digitally-based information that allowed consumers greater control over their water use or greater understanding of water service level standards and provision (Hellstrom and Jacobson, 2014; Mwangi et al., 2015). Alongside this, though, ran greater technological vulnerabilities with evidence of breakdown of water meters (Guma et al., 2019) and concerns about greater ease of disconnection of supply (von Schnitzler, 2008).

Evidence of broader impacts was limited and tended to extrapolate from individual studies. The more-efficient use of water associated with some DWIs was seen as environmentally beneficial (Guma et al., 2019; von Schnitzler, 2008). Environmental disbenefits, such as depletion of groundwater supplies, were not the subject of primary research. Several papers discussed potential distributional impacts, but differentials in implementation of DWIs which could exacerbate inequalities were only directly evidenced in one paper: with application to on-grid not off-grid consumers meaning only the former gain the benefits of the technologies, and with user costs associated with the technologies making them harder for lower-income households to afford, adopt and benefit from (Guma et al., 2019).

DWIs were also argued to be forging new relationships; for example changing individuals from citizens to consumers, or water supply relations from moral to financial and technical, demonstrating the way in which the wider socio-political context is shaped by the impact of these technologies (Hutchings et al., 2012; von Schnitzler, 2013). This forms a complementary argument to that advanced in two cases: that the sociopolitical context shapes the impact of DWIs. Echoing the 'conceptual gap' argument noted earlier, this was understood to derive from the top-down nature of innovation and implementation design (Guma, 2019; Nilsson, 2016). As already noted, this was argued to prioritise corporate, technocratic, modernist goals – such as increasing revenue via greater sales and cost recovery – rather than contextual and socio-political realities, with a consequent knock-on into the actual impacts achieved by these innovations.

THE FUTURE RESEARCH AGENDA

Our literature review reveals a field of research at a formative stage, which thus provides a ready opportunity for a future research agenda. In laying out that agenda, we rely largely on the implications of our own analysis as presented above; but that can also be supplemented by those relatively few papers (13 of 43, or 30%) which made explicit suggestions for future research. Those suggestions fell into three categories, including calls for further technical development of models used for monitoring, prediction, etc.; calls for a broader range of factors (psychological, socio-economic, political) to be analysed in understanding DWIs; and, most prevalent, calls for more research on the actual impacts of DWIs.

At the very broadest level, digital water innovations for urban areas in the Global South have the potential to impact the lives of more than 3 billion people currently; more than 4 billion by 2030 (UNDESA, 2018). Despite this – and partly reflecting the limited roll-out of digital systems for water services in these locations – this systematic literature review has found research on this topic to be quite limited at present. As our analysis has shown, there is therefore a need for more – and more-sustained – research on this topic, particularly targeted at higher-quality journals.

Beyond this, the review has identified a variety of gaps. In discussing these, we acknowledge that one cannot simply point to a gap in the current literature and declare that it needs to be filled. Two further things – beyond the scope of this review – also need to be assessed. First, the importance of filling a gap for example in relation to the value of a particular innovation or the size of an impact. Second, and part of this importance assessment, a reality check. Does the relative absence of a topic – a particular country or technology type or implementation issue or impact – reflect a shortcoming in research, or does it reflect reality; for example, is it the case that, in practice, there are currently no DWIs in that country or of that application type etc. Acknowledging this, we will sometimes describe gaps below more as potential opportunities rather than as essential parts of a future research agenda.

Overall research priorities

From analysis of the literature profile, we identify the potential around how research is undertaken for more explicit engagement with all aspects of research methodology, for more interpretive and critical realist research, for more qualitative and mixed methods research, and for more explicit use of theory and conceptual frameworks including reuse of conceptualisations used in earlier papers in order to facilitate accumulation of knowledge. In terms of where research is undertaken, future work can focus on a greater variety of Global South contexts – including the 'blanks on the map' indicated in Figure 4 – and on more multi-country aggregative or comparative research.

In saying this, we recognise this covers two different imperatives that somewhat conflict. Undertaking research using currently absent or under-represented theories, geographies, methodologies, etc. will increase the diversity of work being produced and reduce potential skews in current knowledge; at the same time, research that reuses existing theories, methodologies, countries and cases will also be valuable in helping to create more of an accumulation and critical mass of knowledge. Imperatives of both diversification and concentration thus have value, given the formative nature of the field; the one increases breadth of knowledge and the other increases depth.

In analysing the literature profile, we noted the relative lack of – and hence opportunity for more – social science research, including sociopolitical and interdisciplinary sociotechnical perspectives. This is not to undermine the importance of science and engineering research in design, development and implementation of digital water innovations; however, it does suggest that such work could be enhanced by understanding the deep ever-present interconnections between the technical, the social and the political, which will enable researchers to "think further about the politics and spatialities of the urban nexus of ICTs and socio-technical systems" (Guma, 2019: 2350).

In relation to sociopolitical approaches, some of the studies recognised the important influence of the wider social and political forces on the direction and impact of DWIs. These include, for example, the way in which neoliberal or managerialist agendas are inscribed into innovations, the way in which top-down approaches or informal institutional forces shape implementation and impact, or the impact of DWIs on the distribution of resources and structural relations. All of this suggests that fully rounded research cannot be detached from a broader understanding of water and society. A few of the studies show, for example, the way in which asymmetries and inequalities within a context are reproduced and/or revised by the introduction of digital water innovations. As findings on implementation and impact both indicated, such research should not be solely structural in its approach but must also consider the role of human agency. As Guma and Monstadt (2020: 3) conclude, "artifacts – including plans and technologies – cannot be understood without also understanding their embeddedness in context-specific realities and their shaping by human action".

Related, interdisciplinary perspectives in particular seem appropriate given the obvious interplay of the social and the technical, as reflected in both implementation and impact findings. Interdisciplinary perspectives – for example, combining a technical perspective from computer science or information systems disciplines with a social perspective from sociology or development studies disciplines – allow for a holistic understanding of these innovations which could encompass at least four aspects that have emerged from the review: the underlying digital – physical architecture of infrastructure and applications; the data architecture that sits on top of this; the digital and human processes of data handling, decisions and actions; and the broader context of governance and institutions that shapes operationalisation of the digital systems (Luppicini, 2020).

Specific technology, implementation and impact priorities

There are clear opportunities for more research on particular digital technologies with proven water-related potential: data capture technologies (remote sensing, smart meters, SCADA, telemetry); data processing technologies (big data, data mining, machine learning, artificial intelligence, blockchain, virtual and augmented reality); and action support technologies (water ATMs, digital purification systems). There are opportunities for more research on 'upstream' water value chain technologies and on technologies for off-grid and low-income users. In particular, there seems to be a good case for more emphasis on off-grid applications, given the greater needs of off-grid consumers and also the particular contexts and practices of those users.

Once again, the diversification vs. concentration argument has relevance here, pulling future research towards, respectively, un- or under-represented technologies vs. already-represented technologies. The latter direction may be given added weight by the argument of relevance, in that research into technologies already significantly deployed in urban Global South contexts could be argued more relevant than research into technologies which have yet to find any notable role in those contexts. As noted above, however, even if one accepts this argument, the newer or less-prevalent technologies could still be the subject of field prototyping and adoption surveys.

In relation to implementation processes, there are opportunities for research (including action research) on user- and government-centred or participative innovation processes. While not reported in the current literature, such approaches are seen more generally to improve success rates of projects applying digital technologies in developing countries (Heeks, 2018). There are opportunities for more research on how the context of interests and power shapes DWI design and implementation. This could, for example, use the ideas of technological inscription from science and technology studies to understand how those interests come to be "written in" to digital technologies (Akrich, 1992). There are also opportunities for research into the complementary changes in capabilities, incentives and management processes that successful implementation may require; this could draw on the existing literature on such changes within the field of ICTs-for-development (World Bank, 2016b).

In overall terms of impact, there has been a relatively limited set of work to date – just thirteen papers identified by this review, representing 30% of the total – analysing impact of digital water innovations in urban Global South settings on the basis of primary data. There is a generalised need for more such work providing evidence of impact, including evidence of longer-term impact given that a number of the current papers looked only at relatively early-stage implementations.

In terms of the types of impact, it appears that future research could do more to incorporate evidence on disbenefits, on broader societal (particularly sociopolitical) impacts, and on impacts for government and policy. There are also opportunities to understand more about the impact of data capture, processing and decision-support technologies. That impact can be conceived through sociopolitical and sociotechnical lenses that have been applied to other instances of digitalisation in development such as that of 'data justice', which would address issues of who benefits from processing, ownership and use of the new data being gathered via DWIs (Heeks and Shekhar, 2019).

Looking at specific impact topics, one could highlight as a future priority those topics for which there was no primary evidence within this literature corpus, that is, impacts on corruption, cyber-vulnerabilities and groundwater depletion. Most of the impacts that were summarised above, however, were evidenced by only one, or at most two, studies. There is thus a need for further research into the entire range of impacts – both benefits and disbenefits – on water service providers, users and government, and on even more broad impacts. In undertaking this, there will be a need to differentiate between the types of innovation; for example, sensors on the water infrastructure have a very different impact from mobile payment systems. There will be a need to try to disentangle the causes of the impacts. As can be seen from the summary above, impacts may be more or less associated with any one of the three elements of change that cluster around DWIs: change in physical technology/infrastructure, change in digital systems, and change in operational practices and processes. There also needs to be more insight into the ways in which impacts are mediated by the sociopolitical context of implementation. This therefore re-emphasises the future potential for sociotechnical and sociopolitical approaches.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support for this research provided by the School of Environment, Education and Development at the University of Manchester.

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METHODOLOGICAL ANNEX

This Annex provides further details on the systematic literature review.

Search strategy and data extraction

The review domain represented the intersection of four topics (see also Table A1) namely:

- Service: water, specifically drinking water. Attempting to narrow searches by specifying type of water service artificially excluded relevant items, and so only the term 'water' was used.
- Global location: the Global South. Use of the terms 'Global South' or 'developing countries' was found to artificially exclude relevant items, and so these terms were not used.
- National location: urban areas. The two terms 'urban' and 'city' were both useful in excluding irrelevant items, so both were used.
- Technology: digital systems. While the term 'digital' was helpful, it was found that many relevant items did not use this particular descriptor. An iterative review was therefore used (see also Table 1) to identify key terms used to describe DWIs in the literature, with 11 eventually being used as part of the search string.

On the basis of this intersection, two search strings were used, as shown in Table A2.

Table A1. Key search terms, inclusion and exclusion criteria

Category	Key term(s)	Description
Service	Water	Reviews focused on drinking water services including accessibility, availability and quality of the main source used by households and businesses alike for drinking and other domestic purposes (UNICEF/WHO, 2019); this included urban water supply, water access and delivery, and service provision/delivery, including informal water. Papers focusing on irrigation systems, storm water, wastewater, etc. were excluded.
Location	Urban/city	A city is defined as an urban agglomeration with a population of over 300,000 inhabitants (UNDESA, 2018).
Digital technology	(see 'search strings')	This refers to digital systems, tools, devices and resources that generate, collect and process data.
Paper type	n/a	This refers to empirical research methods rather than reviews and synthesis papers.
Language	n/a	Only studies written in English were considered.
Full text availability	n/a	Only studies that were either open access or were accessible through the University of Manchester library system were considered.

Table A2. Google Scholar search strategy used for literature search

Search string	Str1: allintitle: water urban (digital OR mobile OR smart OR meter OR ICT OR information OR SMS OR data OR technology OR intelligent OR innovation)
	Str2: allintitle: water city (digital OR mobile OR smart OR meter OR ICT OR information OR SMS OR data OR technology OR intelligent OR innovation)
Exclude	Citations and patents
Final search date	8 November 2019

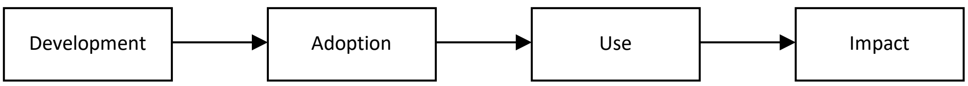
Thematic analysis approach

Details of the three main domains for thematic categorisation of the literature are as follows:

a) Characterisation of literature. Papers were coded according to basic information: either the academic discipline that was explicitly labelled or the department of the first author; year of publication; focal country/countries and continent(s). We also coded the research philosophy reflected in the work and the research strategy and methodology, using standard formulations for these and then modifying as emergent codes arose (Saunders et al., 2016).

b) DWI implementation. In order to understand the extent to which literature has focused on implementation as opposed to other matters such as impact, we classified on the basis of the digital life cycle model (Heeks, 2006), as shown in Figure A1. This analysed whether the main focus of each paper was: the development of the digital water innovation; issues surrounding its adoption and uptake; use of the technology; or the impact of that use.

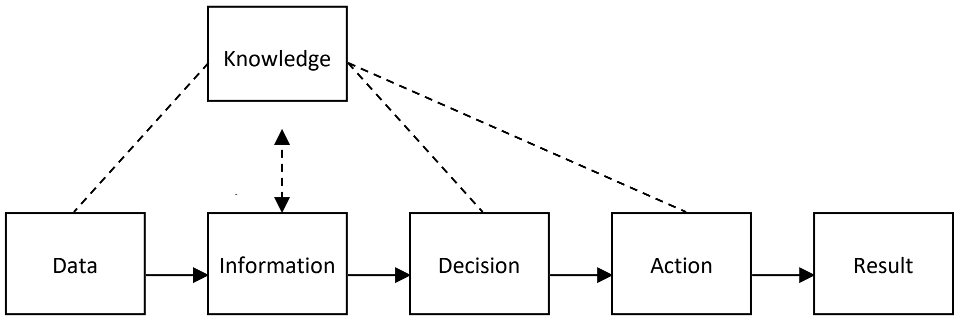
Figure A1. Digital life cycle model.



Source: Heeks (2006).

Two categorisations of implemented innovations were already summarised in Table 1. In terms of markets served, papers were classified on the basis of whether they dealt with on- or off-grid water networks. Seeing a differentiation among the papers, we also added the nature of consumption in markets, whether by higher- or lower-income consumers. In terms of the stage of the water value chain, we coded according to the three water value chain elements of Table 1: water source, distribution/ delivery, and use. While this provided a valuable water-oriented categorisation, we also felt it helpful to add a digital-oriented categorisation; we thus developed one based on the information value chain (Heeks, 2018) as shown in Figure A2. This process model charts the chain of steps linking a digital system to development results: capture of data, its processing and visualisation as information that informs decisions, which lead to actions, and create results. This helped to readily categorise digital technologies into four functional types that arose in the literature: i) data capture technologies such as sensors, loggers and meters; ii) data processing technologies that turn data into information, such as machine learning, data mining, algorithms, modelling, etc.; iii) decision-support technologies such as management information systems or planning systems; and iv) action-related tools such as payment systems. (In the review, no knowledge- or learning-focused systems were identified.)

Figure A2. Information value chain.



Source: Heeks (2018).

Finally, we analysed literature in terms of the focal stakeholders (higher-level authorities such as government, water service providers, or end consumers) and inductively developed a categorisation of implementation issues, albeit sensitised by categories used by earlier literature (as reported in the introduction to this paper).

c) DWI impact. Categories of impact were iteratively derived from the review of literature (see also Table 5) but using as the starting point the categorisation of digital water impacts by Sarni et al. (2019) into community, operational, financial and long-term resiliency benefits.