frontiers in Environmental Science

POLICY AND PRACTICE REVIEWS
published: 24 March 2022
doi: 10.3389/fenvs.2022.816824

Digitalization in Urban Water Governance: Case Study of Bengaluru and Singapore

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Urban water governance aims to ensure equitable access to adequate quality water and related services to rapidly growing urban population while protecting the environment. Rapid urbanization and changing climate are posing challenges to the formal and informal institutions responsible for governing and managing water resources. Complexities existing due to the interaction between societal and environmental subsystems of urban water cycle adds pressure on institutional capabilities to cope up with various uncertainties. Emergence of digital technologies has provided the necessary tools in urban water governance to strengthen capabilities through effective monitoring, decision making, and forecasting. The paper examines how sequencing and leveraging the synergies of different digital technologies can help mitigate various problems and challenges faced in urban water governance. The paper analyses three digital technologies, Smart Water Metering Supervisory Control and Data Acquisition and Flood Alert System (FAS) using the case studies of Bengaluru and Singapore to understand the transformative capabilities of digitalization in urban water governance. It is assumed that the learnings from this study can be generalized to a large extent. The paper indicates that to unlock the full potential and derive best returns of investment, digitalization needs to have broader objectives. Multi-purpose use of digital tools can contribute effectively to the implementation of Integrated Urban Water Management. The results highlighted that societal acceptability of digitalization depends majorly on the mode of implementation and not so much on the technology.

Keywords: water governance, digitalization, urban water, urban water management, digital water

Edited by:
Sharad Kumar Jain, Indian Institute of Technology Roorkee, India

Reviewed by:
Daphne Gondhalekar, Technical University of Munich, Germany
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *17 November 2021*
Accepted: *01 March 2022*
Published: *24 March 2022*

Citation:
Banerjee C, Bhaduri A and Saraswat C (2022) Digitalization in Urban Water Governance: Case Study of Bengaluru and Singapore. Front. Environ. Sci. 10:816824. doi: 10.3389/fenvs.2022.816824

1 INTRODUCTION

Many countries in the Asia Pacific region face urban water governance challenges and weak institutional capacity, especially in regions prone to human water insecurity (Panella et al., 2020). The governance challenges are multifaceted and extend across social, technological, environmental, and economic boundaries, as well as administrative systems (Tortajada 2010; Azhoni et al., 2017; Yasmin et al., 2018; Chadha and Pandya 2019; Machado et al., 2019). Interrelated societal challenges includes urbanization and population growth that contribute to increase in water demand and directly impact the water provisioning services in urban regions (Mukhtarov et al., 2018; Chadha and Pandya 2019; Balogun et al., 2020). Furthermore, the changes in lifestyle and low awareness of efficient water use causes mounting pressure on water provisioning systems (Hubacek et al., 2009). As urbanization has become a widely adopted global development strategy, many cities in the Asia Pacific region are the drivers of economic growth in these countries (Chen et al., 2014). Industrial growth and economic development are essential for urban regions to thrive, but growing urbanization leads to complex governance challenges. Climate change impacts are worsening the status quo of water regimes widely characterized by inadequate and ineffective water management systems. This in turn leads to greater consequences, especially during floods and droughts (Chadha and Pandya 2019).

Water governance is key to water sustainability and is about how to govern the system appropriately to deal with too little, too much, too polluted water (Romano and Akhmouch 2019). Urban water governance can be defined as institutional arrangements interacting with multiple stakeholders and performing functions related to water services. Water utilities are the entities through which urban water service provisions and governance functions are performed. It functions under the institutional arrangement and interacts with a variety of stakeholders. It is also considered as the entry point for water-related innovations (Lieberherr and Truffer 2015). Water utilities in urban regions provide multiple water-related services which can be broadly categorized into three types 1) providing water for domestic, industrial, commercial, and other purposes, 2) collecting, treating, and disposing wastewater, and 3) managing stormwater and floods. Other important activities that water utilities with national, state and local municipal bodies need to carry out are development, operation and maintenance of water infrastructure which includes dams and reservoirs from where the water is sourced, pipelines, pumps and storage tanks for water distribution, sewers for collecting wastewater, water and wastewater treatment plants, and stormwater drains to collect and carry stormwater.

One of the inherent functions of the utilities include maintaining and improving the water quality standards based on occurrence and use of water. For example, various water uses would have different water quality requirements and it is necessary to maintain the required water quality standards. Similarly, when wastewater is returned to the natural environment, either from the wastewater treatment plants or from stormwater drains, the quality and entropy of water discharged needs to be assessed to not only protect the natural environment but also to maintain ambient water quality of natural water resources. With increase in water demand, water utilities try to increase water use efficiency and hence water demand management is also becoming a key function to deliver quality water services. Due to climate change and other above-mentioned pressures the water utilities need transformation towards sustainability practices, and digitalization provides a pathway towards it.

Previous research showed that digitalization of the water sector presents a new pathway to effectively address many of water governance challenges (Pahl-Wostl et al., 2020). Digitalization in urban water sector, supporting a wide range of processes, services and functions ranging from daily operations to designing integrated smart infrastructure, is necessary (Yasmin et al., 2018; Grigg 2019). Its major role is towards reduction of water demand, increased recycled water use and reducing pressure on existing water sources. However, there exist multiple challenges in the adoption and implementation of digital technology in the urban water sector. The study aims to evaluate the adoption and implementation and explore how digitalization can help water managers in urban water governance under different conditions of growth, enabling conditions and institutional capacity. Our study focuses on three important digitization processes, namely, Smart Water Metering (SWM), Supervisory Control and Data Acquisition (SCADA) system, and Flood Alert System (FAS), in a comparative structure between the two cities of Bengaluru and Singapore. The case studies have been selected purposely to compare different water challenges and growth potential under varying institutional conditions. Bengaluru represents the city from an emerging economy, and Singapore represents a developed city. Both the cities have public water governance systems where the decision powers exist with the local/national government institutions or organizations derived based on societal needs and aspirations.

The study focuses on the adoption and implementation of digital technology i.e., the process of digitalization and not on the technologies themselves. A digitalization process can consist of a single digital technology such as the SCADA system or a combination of different technologies as in case of FAS or SWM, details of which are provided in the subsequent sections. Digital technologies in themselves are neutral by design and can be operative with full efficiency under requisite conditions and assumptions stipulated for maximum outputs. However, often digital technologies functions below the full efficiency level due to the challenges in the adoption and implementation of the technology. Adoption is the phase where it is decided to use a particular technology to solve a set of problems, outlining the desired outcomes. Implementation in the phase that follows when the technology is introduced in the system on ground by creating new infrastructure and capacity or by making modifications in the existing infrastructure and enhancing capacity to support the system. The paper assesses four aspects of digitalization: 1) the target problems that are expected to get resolved through digitization, 2) enabling conditions that prevail in terms of physical and digital infrastructure, management structure, capacity of human resources and stakeholder awareness, 3) implementation process of the technology adopted in terms of features and specifications and 4) the desired outcomes that the water managers expected to obtain after digitalization. The first two aspects, i.e., identification of target problems and recognizing enabling conditions constitute the adoption phase. The digital technology to be adopted is based on these two criteria. The methodology adopted for conducting this research are literature review, document analysis and quantitative analysis of secondary data collected from official government reports, official government websites, news articles, journal papers, etc. The underlying assumption of the research is that the lessons learnt, and conclusions drawn based on the study of the three digitalization processes across the two cities of Bengaluru and Singapore could be generalized to larger extent and apply to city across the world of similar scale like Bengaluru and Singapore. The paper is structured as follows. First, the paper provides a brief background of digital technologies used in water sector, the

TABLE 1 | List of the various digital technologies that are used in urban water management along with their appropriate definitions.

Sl. No	Technology	Acronym	Details
1	Supervisory Control and Data Acquisition	SCADA	"is a computer-based system for gathering and analyzing real-time data to monitor and control equipment that deals with critical and time-sensitive materials or events." (OleumTech 2021)
2	Geographical Information System	GIS	"is a system that creates, manages, analyzes, and maps all types of data. GIS connects data to a map, integrating location data with all types of descriptive information." (ESRI, 2022)
3	Computer Models	--	"consists of writing a computer program version of a mathematical model for a physical or biological system. Computer simulations that are run according to such programs can produce knowledge out of reach of mathematical analysis or natural experimentation." (Nature, 2022)
4	Decision Support System	DSS	"is a computerized program used to support determinations, judgments, and courses of action in an organization or a business. A DSS sifts through and analyzes massive amounts of data, compiling comprehensive information that can be used to solve problems and in decision-making." (Segal 2021)
5	Internet of Things	Iot	"describes the network of physical objects—"things"—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet." (Oracle, 2022)
6	Artificial Intelligence	AI	"is a field, which combines computer science and robust datasets, to enable problem-solving. It also encompasses sub-fields of machine learning and deep learning, which are frequently mentioned in conjunction with artificial intelligence. These disciplines are comprised of AI algorithms which seek to create expert systems which make predictions or classifications based on input data." (IBM 2020)
7	Information and Communication Technology	ICT	"is an umbrella term that includes any communication device or application, encompassing: radio, television, cellular phones, computer and network hardware and software, satellite systems, and so on, as well as the various services and applications associated with them, such as videoconferencing and distance learning." (Huth et al., 2017)
8	Big Data Analytics	--	"is the use of advanced analytic techniques against very large, diverse data sets that include structured, semi-structured and unstructured data, from different sources, and in different sizes from terabytes to zettabytes." (IBM, 2022)

framework, and the study areas in **Sections 2**, **3**, and **4**. In **Section 5** the analysis of SWM, SCADA system and FAS is presented, and results are indicated. Finally, the paper discusses the learnings from the case studies in **Section 6** and conclusions at the end in **Section 7**.

2 BACKGROUND OF DIGITALIZATION IN URBAN WATER

Digitalization plays a major role in the delivery of the water services and the performance of many underlying functions. Water supply, one of the fundamental roles of water utilities, is becoming increasingly digitalized and providing real-time information regarding water quantity and quality for consumers. Large water distribution networks with pipes, valves, pumps, and reservoirs are connected to the sources of water and consumption points, and numerous consumer connections are monitored, operated, and managed using digital technology. Various Control Systems are used to operate valves and pumps (Manohar and Kumar 2014) and a combination of Geographic Information System (GIS), Computer Models of water supply networks, Internet of Thing (IoT) devices such as smart water meters and SCADA systems are used to detect leakages and potential contamination in the water supply networks (Taylor and Richter 2017; Rojek and Studzinski 2019; Nie et al., 2020). Various Artificial Intelligence (AI) Methods are becoming increasingly popular in developing Decision Support Systems (DSS) of Urban Water Systems (Hadjimichael et al., 2016). As discussed earlier, urban water asset management is an important function and various AI techniques could be used as DSS for urban water distribution networks for maintenance prioritization based on readily available information, for instance, about pipe-breakage history, pipe material and age (Christodoulou et al., 2009; Christodoulou and Deligianni 2010). Similar digital tools and techniques such as Information and Communication Technology (ICT), AI and Big Data could be used for providing wastewater services which includes operation and maintenance of wastewater infrastructure–sewers and wastewater treatment plants (WWTPs) and their life cycle assessment (Sousa et al., 2014; Du et al., 2019; Rebello et al., 2021). Digital technology comes very handy even when it comes to water demand management or analysing and improving public perception for using recycled water (Jayarathna et al., 2017; Fu et al., 2018). ICT solutions can be used to provide integrated solutions for water supply, water demand management and asset management (Kulkarni and Farnham 2016).

Water quality monitoring of the water resource for a city or surface water bodies within the city boundary is of vital importance for the resource and ecosystem services that they provide. Digital tools such as IoT devices - wireless sensor networks and ICT coupled with AI and Big Data Analytics are being proposed to be used for surface water quality monitoring (Chen et al., 2018). Management of urban stormwater is essential as stormwater acts as a source of water for cities either through direct use or by recharging various surface water and groundwater resources. Moreover, under adverse circumstances, stormwater may cause urban flooding of different scales and magnitudes, disrupting life and damaging property. Use of digital technology immensely improve urban stormwater management by integrating flood risk and city planning on GIS platforms, AI based DSS, and flood alert system coupled with ICT technology for dissemination of information and use of computer modelling for planning the use of green infrastructure for stormwater management (Price and Vojinovic 2008; Yang et al., 2015; Bertram et al., 2017; De Paola et al., 2018). Thus, the host of digital technology available including IoTs, AI, Big Data Analytics, ICT, GIS and computer models can help build Smart Cities of the future where all the activities of water management starting from data generation and collection to decision making would be automated (Rathore et al., 2018; Antzoulatos et al., 2020). A summary of these digital technologies is provided in **Table 1**.

3 FRAMEWORK

Figure 1 shows the accelerated pathways digitalization provides (shown in green) to complement traditional governance and development pathways (indicated in dark blue). Following a systems approach, the paper configures the linkages between state of urban water system, Influences, Assets and Outcomes and how actions influence the changes. Any anthropogenic modification of the state of urban water system influences the ecological and hydrological systems and processes within an urban area, identified here as influence. For example, increase in urban population can exhaust existing available water resources and cause water scarcity. Such influences inspire action that can either be in the form of a feedback or creation of assets. The positive actions can minimize the disruption on the system through multiple ways. It can directly control the influence through direct water demand management. Further, there are over indirect ways to influence the state through building physical and natural assets, and human capital building that will minimize the risk and ensure higher water supply through better function of the system. Such responses to influences are direct or indirect changes that takes time though systemic learning in the adaptation process. Digitalization could fast track the process to instill changes in the system through better understanding of feedbacks, predict functionalities, and assess vulnerability. Digitalization can provide accelerated pathways or accelerate the traditional pathways by providing quick information of investment opportunities and priorities in the creation of physical assets or infrastructure.

4 STUDY AREA

The two cities - Bengaluru and Singapore were selected to study the adoption and implementation of digital technology. Singapore has made considerable advancement towards achieving water security and sustainability, with adoption and utilization of digital technology for water management. Bengaluru, also known as the Silicon Valley of India, has embarked on its journey in the path of digitalization to improve water management and governance in the city. The comparison of adoption of digital technology and its mode of implementation between the two cities will provide a comprehensive understanding of the challenges and pitfalls in the path of achieving an efficient water management system.

4.1 Bengaluru

Bengaluru is the capital city of the state of Karnataka in India with a population of 12.9 million and a land area of around 800 square kilometers. The city is situated on a hillock at an elevation of 900 m above msl and has a semi-arid climate with an average annual rainfall of about 900 mm, most of which occurs during the

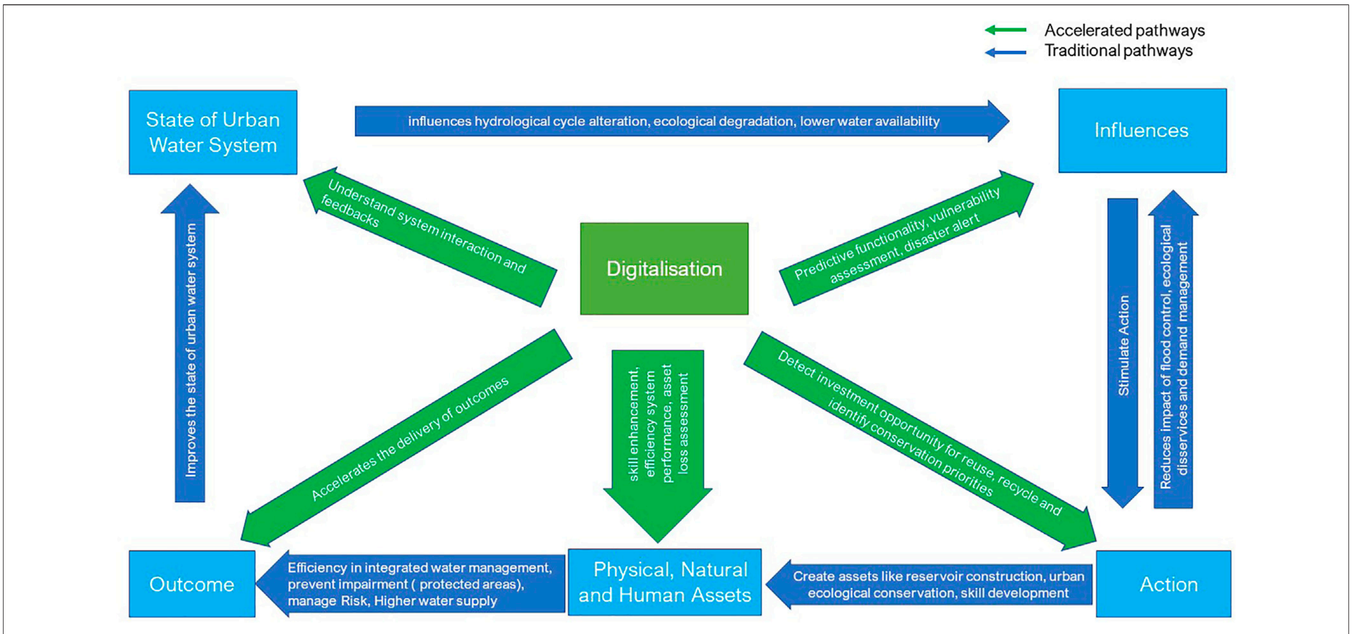

FIGURE 1 | A conceptual framework showing how digitalization can provide alternate accelerated pathways to the traditional development pathways.

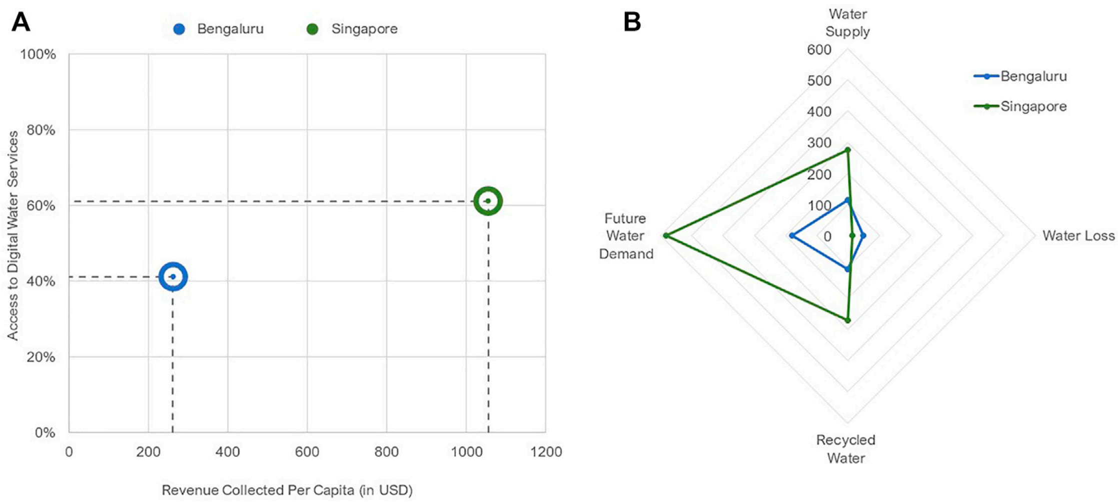

FIGURE 2 | The figure shows a comparison of the current situation in Bengaluru and Singapore. Part **(A)** shows the access to digital water services in the two cities plotted versus the revenue collected per person per year by the water utilities. Part **(B)** shows how the quantities of water supply, water loss, water recycled, and future water demands compare across the two cities. The unit of the quantities in part (b) are in liter per capita per day. All the data has been sourced from the official websites of the water utilities (JICA, 2017; Cag, 2018; Tortajada 2019).

summer monsoon. Until early 1900, the city sourced its water from the river Arkavathy, one that runs adjacent to the eastern periphery of the city. With development of government and private industries, and the consequent migration of people to the city, water demand grew rapidly. In the year 1964, the Bangalore Water Supply and Sewerage Board (BWSSB) was established to procure and supply water to the city. BWSSB developed the Cauvery Water Supply Scheme (CWSS) to draw water from the river Cauvery, one of the major rivers of southern India. Over the years, four stages have been developed, which now brings about 1,450 million liters daily of water daily from a distance of 100 km. However, water drawn from Cauvery is not sufficient in meeting the city's water demand, and groundwater is extensively utilized, especially in the peripheral areas of the city where BWSSB has yet not been able to provide piped water (Sekhar et al., 2018). Other than the rapid growth in water demand, large percentage (more than 30%) of water loss due to leakages and unauthorized consumption is a major challenge for Bengaluru (Paul et al., 2018). Stormwater is not seen as a source of water in the city and systematic management of stormwater is mostly lacking.

4.2 Singapore

Singapore is a city-state in Southeast Asia with a population of 5.2 million and a land area of 714 square kilometers. The country receives good annual rainfall of about 2,500 mm but has a small catchment area to collect and store rainwater. Considering its geographical location, which has neither natural aquifer nor underground water, Singapore faces a serious challenge of freshwater scarcity as its population grows rapidly. In 1965, when Singapore's population was 1.9 million, the domestic demand for potable water was around 32 million gallons per day (MGD). By 2011, the domestic demand rose to around 175 MGD. The total demand in 2011 including domestic, non-domestic potable water and non-potable water was around 380 MGD. To tackle this and become self-sufficient in water needs, Singapore adopted an integrated and innovative approach, which, together with careful planning and hard work of more than 40 years, enabled it to overcome water supply constraints thus attaining sustainable and cost-effective water management. Public Utility Board (Pub, 2022) is the national water agency, responsible for the collection, production, distribution, and reclamation of water in Singapore. Earlier till 2001, PUB managed potable water, electricity, and gas but later responsibilities of sewerage and drainage were also transferred from the Ministry of Environment. Today, its entire population enjoys continuous access to high-quality piped water. Singapore has a daily water requirement of 430 million gallons, 45% of which is domestic water demand and 55% is non-domestic sector demand. The water is sourced from the "Four National Taps" which are Local Water, Imported Water, NEWater (high grade reclaimed water) and Desalinated Water. PUB has estimated that by 2060 the water demand could double, owing to population and economic growth, 30% of which is estimated to be domestic water demand and the rest non-domestic.

5 APPLICATION OF DIGITALIZATION AND CROSS CITY COMPARISON

An initial comparison of the two cities is presented in **Figure 2**. The present coverage of digital water services in Singapore is 61% higher as compared to that in Bengaluru, where it is 41%. These are estimates based on the coverage of SCADA and SWM across the two cities. However, the revenue collected in Singapore is 1056 USD per person per year, which is quite high as compared to 261 USD collected by the water utility in Bengaluru per person per year. The higher revenue collected in Singapore plays a key role in enabling the water utility to provide better water services which is done by larger and fast expanding coverage and sophistication of the digital water services. Part (b) of the figure shows that water supply, recycled water and future water demand of Singapore is larger than those of Bengaluru. On the other hand, the water loss in Singapore is much lesser than that in Bengaluru due to greater coverage and utilization of SCADA system. Moreover, future water demand in Singapore is comparatively much larger as compared to the current water supply. Thus, the predicted future water demands in Singapore are huge and the city state is adopting various measures including a large leap in digitalization to deal with the future water demand scenarios. One of the major focus areas of Singapore's digitalization is water demand management and SWM is being used as a tool to achieve it.

5.1 Smart Water Metering

Measuring water consumption in cities is not only necessary for billing purposes but also to understand consumption patterns for better management and increased operational efficiency of the water supply systems. Smart Water Metering (SWM) is considered here as a digitalization process that combines an automatic water meter (AWM), recording data at a high frequency, typically every 15 min, with a short-term data storage to store data of 1–2 months and a transmission system to transfer the data to a central server for storage, management, and analysis of the data. This not only cuts down a lot of human labour and associated errors but also provides large quantities of data that can be used to understand variations in water demand even within a day and accordingly optimize water supply network systems and operations, finally resulting in reduced operation, maintenance and energy costs and conservation of water. However, AWM is a high-end technology that has a very high cost of individual meters as compared to mechanical water meters. Moreover, there is a need for an automatic metering infrastructure to support the smart meters in terms of data transmission, and storage.

The full potential of AWM can be harnessed only if it is coupled with extensive analysis of data gathered based on which policy decisions can be taken as well as a mobile application that each customer can use. The mobile application not only provides customers to monitor the real time water usage but also creates an interface for the water agencies to interact with them and implement policy decisions taken based on data analysis. Therefore, SWM requires high initial investment and has a long payback time contingent on large-scale adoption and/or implementation within a city, preferably the whole urban area, and policy decisions made based on Big Data Analytics of the large volumes of data generated by these IoT devices.

The two cities adopted two different strategies for implementation of SWM for two different objectives. Bengaluru aims to meet the revenue gap and recover water losses in the system while in Singapore the main objective is to attain service efficiency and sustainability to face major challenges such as rising future water demand, high labour cost, increasing operational cost and climate change. The adoption of SWM in Singapore started with two pilot projects by PUB, one in 2016 at Punggol and the other in 2018 at Yuhua across a total of 800 households. The households reported an average of 5% water saving owing to early detection of leaks and by employing water saving habits after tracking real time water consumption through their mobile app.

In Bengaluru, BWSSB mandated the installation of SWM for all new bulk water connections for domestic and non-domestic premises, starting from 2013. As of March 2017, only 2,261 connections adopted the technology of which only 133 connections were billed based on data collected by AWMs. Thus, it is evident that SWM has become successful in Singapore which is rolling out the first phase of its SWM project that will cover a total of 300,000 customers. It plans to provide real time water consumption information to customers to incentivize and facilitate water conservation efforts at homes and company premises. In addition, it also anticipates increase in operation efficiency of the water supply network through precise and real time demand prediction. On the other hand, Bengaluru has faced major hurdles on its way towards large scale adoption of this technology.

The major hurdles in the implementation of SWM in Bengaluru includes high cost and sluggish implementation strategy. Successful adoption of SWM is determined by the ability to cover the cost of installation, operation, and maintenance of AWMs by the revenue generated from its implementation. According to the financial model adopted by BWSSB, customers are charged for the cost of AWMs. The incremental benefits obtained by consumers from installing AWM is much lesser than the average cost of AWM they must bear. Hence the simple payback time is longer for the consumers in Bengaluru, leading to extremely limited adoption of the technology. On the other hand, SWM leads to lower usage of water with higher efficiency; as a result, consumer demand for water decreases and leads to lower revenue generation for BWSSB. Moreover, the social benefits, for example, increase in system efficiency, reduction of water loss, could have been directly realized by BWSSB and thereafter translated to the society is not realized due to poor coverage.

In Singapore, the objective behind SWM is resource efficiency and realization of social benefit rather than revenue generation. To realize the overall societal gain, SWM is completely subsidized, and it covers the deadweight loss (DWL), which is the loss of economic efficiency in terms of utility for consumers such that optimal or allocative efficiency is not achieved. DWL can be defined as a loss of total welfare or social surplus. In Singapore, efforts to reduce per unit cost was also observed and it leads to higher adoption of SWM.

Thus, the two major findings related to SWM can be summarized as follows. Firstly, subsidy is required to cover the DWL and increase the adoption rate of SWM. The burden of subsidy can be reduced through innovations, for example, selection or design of low complexity AWM with low power requirement for a stable and reliable system, shared and/or low-cost infrastructure networks for data transmission, storage and analysis, utilization of water consumption data generated to improve system efficiency and reduce power usage, etc. Secondly, SWM may not help in covering the revenue loss as the initial implementation costs are high and the payback time is longer. SWM can only work with the objective of resource efficiency and sustainability.

5.2 Supervisory Control and Data Acquisition System

Supervisory Control and Data Acquisition (SCADA)[1] plays an important role in water system management, for instance, in the operation of pumps, valves, switches, based on algorithms that ensure optimal use of the water distribution and treatment systems and monitor key parameters such as water pressure, flow rate, levels, and energy consumption. SCADA systems can also produce alert signals in case of system failure when any of the parameters breach safe limits. Implementing a SCADA system helps to alleviate significant problems related to water and wastewater management and operations. This helps in detection of any sub system inconsistency problem-solving capabilities through real-time data acquisition and reduces the response time necessary in decision making.

In Bengaluru, SCADA system was introduced in 1995 for the automatic control of its water supply systems. The main objective of establishing SCADA system was to automatize the control and monitoring of the water treatment and supply and wastewater collection and treatment processes using programmable logic controllers (PLCs), an integral component of SCADA system. The major expansion of SCADA system in Bengaluru, however, took place in 2012 to support the water supply network and related infrastructures including water treatment plants (WTPs), pumping stations, ground level reservoirs (GLRs), sewage treatment plants (STPs), intermediate sewage pumping stations (ISPSs) and terminal sewage pumping stations (TSPSs). A centralized SCADA is currently in implementation that provides a holistic view of the entire water treatment and distribution network along with the sewerage network. It facilitates monitoring of the individual water treatment and distribution facilities, as well as the sewage treatment plants and the intermediate sewage pump stations.

Bangalore also faces a big challenge in terms non-revenue water (NRW). This included physical leakages in the water distribution system as well as unlicensed consumptions in informal settlements or slums. Nearly 41% of the water supply accounted for NRW in 2017. SCADA in Bengaluru has three different functionalities towards reducing such losses in NRW. First, it identifies physical leakages in terms of unaccounted water (UFW) in the supply to the district metering areas (DMAs). Second, it monitors the water supplied in informal settlements and integrates the information with the centralized SCADA centers. The third functionality includes the tracking of bulk water consumptions. The primary variables monitored are water flow rates and water pressure. The quantity of water supplied are then compared with the revenue from water consumption at different supply points (or nodes) to identify leakages and potential points of water or revenue loss.

There is complementarity in the value of investment between SCADA and SWM for Bengaluru. Both SCADA and SWM, in conjunction improve monitoring capability reducing water losses and reducing unaccounted water in the system. However, both the technologies are from water supply perspectives with the objective to increase net water availability rather than to induce water use efficiency.

In Singapore, the adoption of SCADA follows a different path compared to that of Bengaluru, with the overall objective of facilitating effective management of water resources and efficient delivery of services instead of standalone objectives of decreasing water losses or NRW in the system. The SCADA system in Singapore provides the basis for an effective management of water and monitors not only water quantity parameters such as water levels, flow rate, pressure, and rainfall but also water quality parameters such as pH, turbidity, dissolved oxygen, and chlorine residual. Moreover, as part of the integrated system, the SCADA system also tracks the energy costs of operating the water systems by monitoring supply voltage, current and energy consumption.

Singapore has adopted the newest digital technologies available to make SCADA more efficient and better monitor the health of its assets. One of the examples is the digitalization of the daily decision making of quantities of water to be procured from the four national taps of Singapore based on weather forecasts, demand projections, system constraints, capacities of water treatment plants and financial costs. It utilizes AI-based programmes that analyse data gathered by IoT devices to consider various conditions, constraints, and possible scenarios to reduce decision making time on water allocation and repair of critical infrastructures and in providing real-time future predictions.

5.3 Flood Alert System

Urban flooding is a reality in many cities across the world. Instances of flooding caused due to the sudden surge of stormwater in cities disrupt daily life, which includes transport, electricity and water supply and may cause loss of life and property in extreme conditions. There are two parts to the problem, firstly high intensity of rainfall propels flooding, and the other is the tremendous modification of urban geomorphology and land use that disrupts the natural water flow pathways. In addition to stormwater management and flood risk management plans, cities are now adopting flood alert systems (FAS) to reduce the risk of exposure to flooding. FAS in urban areas

[1]SCADA was introduced first emerged in the 1970s using newly developed computer systems for application in industrial processes and electrical systems Anton et al. (2017) focused on supervisory or automatic control of various processes and collecting data of the system's performance. An important component of a SCADA system is Programmable Logic Controllers (PLCs) which are used to control the various industrial processes. One of the first scientific literature that reports the use of SCADA in water supply and wastewater treatment in 1986 described it as "control of processes, the monitoring of data and the transmission, displaying and logging of this information in a form which can be utilized in various ways in the water industry" (Taylor, 1986).

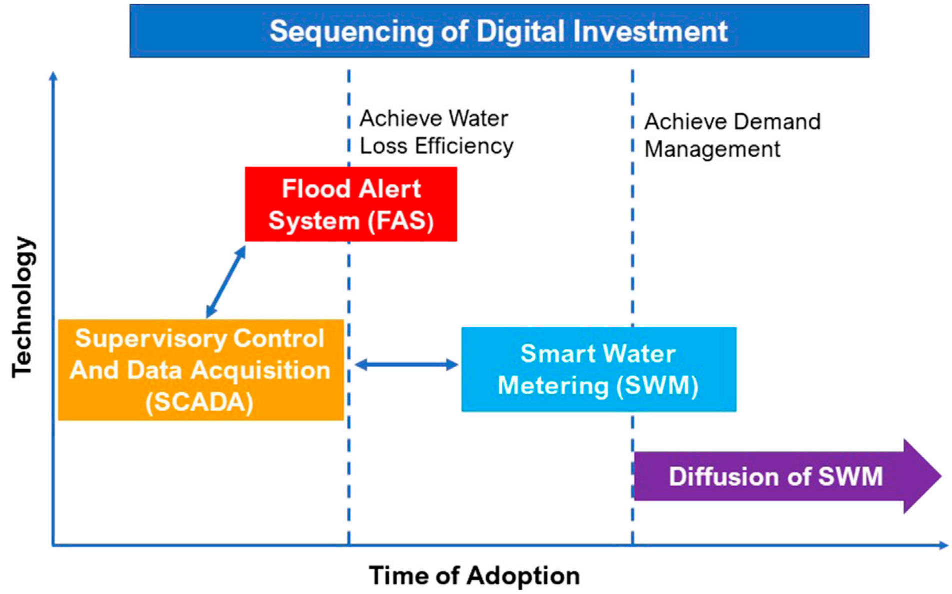

FIGURE 3 | Illustration showing the recommended sequence of adoption and implementation of digital technologies studies here, viz., smart water metering, SCADA system and flood alert system.

generally consists of two aspects - 1) rainfall forecasting and 2) assessment of stormwater surge due to the forecasted rainfall. Thus, a FAS can comprise of set of digital technologies implemented together, consisting of IoT devices, GIS systems, computer models, ICT, etc.

In recent years, Bengaluru has seen multiple instances of flooding in various low-lying areas of the city, mostly attributed to faulty and poor land management practices. The rapid population growth and urbanization have resulted in unplanned development in the city, encroaching many lakes and wetlands. These low-lying areas now get flooded during heavy rains. The problem is compounded by higher stormwater generation due to increasing areas of impervious surfaces, encroachment of stormwater drains by slums, and clogging of drains due to the dumping of solid waste and untreated sewage. Recognizing the increasing flood risk exposure to its population, Bangalore devised a real-time warning and information system on floods.

The mobile application "Megha Sandesha" provides forecasts of rainfall and real-time flood inundation information for the city of Bengaluru and displays a safe route for commuting or for evacuation during floods to avoid inundated areas. With more than 100 Telemetric Rain Gauges (TRG) in the city and weather sensors at vulnerable points, FAS provides information on real-time amount and intensity of rainfall and its impact based on temperature, relative humidity, wind speed, wind direction and real-time data on stormwater drainage.

On the other hand, Singapore is also prone to flooding due to flash floods caused by short-duration high intensity rainfall events and prolonged periods of rainfall during the monsoon season. Urbanization has increased the flood risk due to higher and faster stormwater generation in developed areas. Stormwater is a primary source of water supply for the city and thus it needs to balance between flood risk and water requirements. Under these circumstances Singapore strived effectively to bring down the flood-prone areas from 3,200 ha in 1970 to 49 ha in 2012. Decreased Public tolerance of flooding triggered the implementation flood alert system that provides personalized information to people who are expected to face flood and related troubles in their premises or neighbourhoods. It provides information about the location and time of expected heavy rainfall over Singapore and information about high tide if there were possibilities that they would coincide. SMS alert is also sent when the water levels recede. The FAS utilizes the hydrometric network of PUB consisting of 260 water level sensors and 80 flow sensors in key canals and drains, and a network of 142 closed circuited television (CCTV) cameras for real-time monitoring, out of which 49 camera feeds are available for public viewing.

Interestingly, the FAS of Singapore is a digitally integrated system as opposed to the standalone system of Bengaluru. In 2017, PUB deployed the Catchment and Waterways Operations System (CWOS) in the Marina Catchment, the largest catchment in Singapore. The data generated by the hydrometric network within the catchment, including the rain gauges of the National Environmental Agency (NEA), is used as inputs for analytics and predictive models to achieve three objectives simultaneously. First, optimizing the operation of Marina Barrage to maximize freshwater storage, a major source of water for Singapore. Second, minimizing flood risk in the low-lying areas within the city and third, monitoring the water quality in the reservoirs and waterways within the catchment.

In Singapore, the flood alert system has been extended to the flood management system and is part of the integrated water management system. The solutions in the flood management system are part of the circular water economy as stormwater is considered an important local source of water. This broader focus of the flood management

TABLE 2 | Comparison of the adoption and implementation of the three technologies between the two cities of Bengaluru and Singapore across four key aspects.

	Smart water metering		Urban flood alert		SCADA system	
	Bengaluru	**Singapore**	**Bengaluru**	**Singapore**	**Bengaluru**	**Singapore**
Actions	Monitor Water Usage and Control Pilferage	Water Conservation, Demand Management and Operational Efficiency	Identify in real-time areas of potential flood risk	Stormwater Management	Water Quality Monitoring	Water Quality and Quantity Monitoring
Physical Assets	Water Supply Infrastructure and Pilot Project between 2003 and 2005	Pilot Projects in 2016 and 2018 and Advanced Metering Infrastructure	State Disaster Monitoring Centre	Drastic Reduction in number of flood events, Flood Risk Maps	Water and Wastewater Infrastructure, Bulk and Household Water Meters	Water, wastewater and Digital infrastructure, competent human resources
Digital Assets	Automatic Meter Reading with GSM Communication	Automatic Meter Readers with wireless communication and mobile application	100 rain gauges, 8 weather stations, RADAR, Hydrological modelling	210 flow sensors, 142 CCTV cameras Inputs from Meteorological Services of Singapore	Programmable Logical Controller based SCADA System	Continuously upgraded technology with Cyber Security
Outcomes	Reduce Non-Revenue Water and Billing Inaccuracies	Water Sustainability under changing climate through water conservation	Prevent the loss of life and property	Cater to reduced tolerance of citizens to floods	Reduce Water Leakage and increase Tarif Collection	Reduce reliance on manual labour, minimize human errors and improve efficiency

system coupled with other digital water management systems such as SCADA aims to optimize water productivity and minimize energy consumption and maximize reuse.

6 DISCUSSION

In addition to understanding the modes of adoption and implementation of individual digital technologies, it is important to realise the complementarities and synergies that exists between technologies. For instance, the implementation of high-end technology, for instance, SWM requires identification and elimination of all major sources of physical water loss using efficient real-time monitoring through the SCADA system. Unless the losses are minimized, water availability and loss of revenue remain the major concerns for the water utilities, limiting them from focusing on other aspects of urban water management. This was evident from the poor adoption of SWM in Bengaluru, where water losses still account for 35–40% of the total water supply. On the other hand, in Singapore, where water loss is just 5%, SWM pilot projects yielded promising results and are currently being implemented across a larger population. The study has revealed that sequencing, shown in **Figure 3**, is necessary to maximize not only the social benefits and economic returns but also achieve the long-term goals of urban water security and sustainability. The study finds that there exists complementarity between digital technologies, and optimal sequencing[2] is required to realize the co-benefits of digital technologies. The premise here is that the measurement and identification of losses are prerequisite before tools are employed to manage the loss and bring distributional efficiency, and it forms the basis of sequencing of implementation of digital tools and technologies in urban water governance. The value of such sequencing depends on the volume of losses in an urban water system.

A step forward for Bengaluru in the direction of more efficient water governance would be to first use SCADA system to pinpoint all the leakages in the water supply and distribution system. This would include identification of physical leakage points in the distribution system and unauthorized consumption. Subsequently, infrastructural changes as well as policy changes are needed to reduce physical wastage and recover cost accounting for the much-needed benefits provided to the marginalized sections of the society. SCADA can also be used to reduce physical wastage of water in operations of the water distribution system. These coherent actions will pave the way towards SWM at consumer premises to further increase water use efficiency and reduce the wastage of water at consumption points. However, it is important to note here that implementation of SCADA system is not a prerequisite of SWM, but minimum water loss is. The recovery of the water lost due to physical leakages in Bengaluru can be further utilized to meet the growing water demand in the city. Thus, digitalization has the capability to positively accelerate problem solving in the urban water sector resulting into accelerated pathways for sustainable development.

Moreover, the implementation of high-end technologies such as SWM or FAS needs advanced infrastructural support. Thus, implementation of SCADA system before SWM and FAS can provide the platform through the creation of a large network of digital infrastructure and technical capabilities in the workforce along with system efficiencies that facilitate greater adoption of digitalization. System efficiencies can lead to low water loss, higher revenue generation and low risk of failure. They can also be social and institutional efficiencies such that the

[2]Optimal sequencing here indicates a particular ordering of implementations of digital technologies with respect to time which will yield maximum value to the society and environment

acceptability of digitalization increases, and institutional rules and mechanisms become akin to new technologies and innovations. **Table 2** shows a comparison between the two cities of Bengaluru and Singapore, showing how the actions, existing physical assets, digital assets, and desired outcomes of the digitalization process differs. These are listed for all the three-digitalization process studied in this paper.

Affordability to cover the high cost of digitization is another issue could influence, and delay the adoption, implementation as well as acceleration in the digitization process. The study finds that foresight in planning including appropriate sequencing and optimal time of adoption of digital technology, leveraging the synergies of different technology can reduce the cost burden to a large extent. On the other hand, digitalization can also improve cost effectiveness and affordability of water related services. For, example utilization of SCADA system in Bengaluru can bring down the water lost due to physical leakages which could then be utilized to provide adequate quantity of water to the weaker sections of the society. Moreover, early warnings provided by FAS can increase preparedness within the society and reduce damages caused due to flooding thus reducing the severity of the shocks to the growing economy.

Urban water governance is intrinsically related to urban planning including land management. For example, in Bengaluru, inappropriate land management practices have resulted in increased flood risk in a city which is neither close to the sea nor any river. The rainwater that used to flow through the natural streams and was harvested in a cascading system of manmade lakes was completely overlooked in urban planning when the city started growing thus leading to flood like situations in Bengaluru. On the other hand, Singapore that experiences more than double the annual rainfall that of Bengaluru connected its land management practices with urban water governance. Urban planning made room for natural streams and even being an island, Singapore managed to significantly reduce the area within the city susceptible to flooding. Essentially, Singapore utilized the concept of Integrated Urban Water Management (IUWM) that recognizes the entire urban water cycle and approached urban water management in a holistic manner, as demonstrated by the deployment of CWOS in Marina catchment. CWOS integrates three distinct urban water management operations, viz drainage operations during high water levels due to downpour, water quality management and modelling and the operations of the Marina Barrage which a primary source of water for Singapore. IUWM is often regarded a robust strategy towards achieving urban water security with sensitivity and resilience to changes including the impact of land use on the natural water cycle. It is based on the premise that by managing the urban and natural water cycle as a whole; resources can be used efficiently, with higher economic benefits and improved social and environmental outcomes.

A successful integration of digital technologies embedded in IUWM for instance, IoT, AI and data economy can significantly reduce the adverse impacts of information asymmetry and uncertainty regarding unsustainable practices and land use change and thus help to attain cost efficiency in wastewater treatment and water supply and improve environmental outcomes. For instance, the integration of SCADA system at water treatment plants that monitors both the quality and quantity of recycled water produced, with the water distribution SCADA can simplify the allocation and use of recycled water for demands where it can be used. Similarly, integration of SWM with SCADA can help optimize the water supply and distribution systems through preprogrammed modes of operation of pumps and valves by utilizing the water consumption data produced by SWM. Such integrations not only remove information asymmetry though information exchange between different urban water systems but also helps optimize water resource and energy utilization leading to cost efficiency.

7 CONCLUSION

Digital technologies are multifaceted and multi-purpose tools and need to have a broad rather than narrow goals to unlock the full potential and derive the best returns of investments. For instance, SWM in Bengaluru was implemented to reduce water loss and improve revenue generation. This is an extremely narrow objective producing a very low return of investment which severely restricted the wider adoption and implementation of the technology. On the other hand, in Singapore, SWM is being implemented with the wider objectives of efficient resource utilization and conservation. This goal consists of multiple inherent objectives such as reduction of human labour for meter reading, optimization of water supply system operation for reduction of losses and power consumption, water demand management, eliminating water loss at consumer premises, encouraging water conservation practices such as the use of water-efficient fixtures, etc. These objectives would be achieved through maximum utilization of data generated from SWM devices using AI and Big Data Analytics. For example, these datasets can be utilized to predict future water demand, which in turn could be utilized to optimize the water supply network functioning, reducing water losses and energy consumption. Moreover, SWM in Singapore is used for demand management, where it is implemented along with a mobile application to provide real-time water consumption data to the respective consumers. The mobile application is an excellent platform that can be utilized to incentivize water conservation efforts.

The integration of digital technologies for multi-purpose use leads to a more significant application of IUWM. Laying out wider objectives of digital technologies leads to the identification of complementarities between different digital technology assets and tools. It will help to realize the co-benefits, unlocks the actual potential of digital technology for IUWM. For example, the large volumes of data generated by IoT devices such as SWM have huge potential when used in conjunction with SCADA system to optimize the function of the water supply system that can reduce water losses and energy consumption and increase system efficiency. Another example, the FAS in Singapore, where the hydrometric infrastructure used for FAS is used in conjunction with the SCADA and AI-based monitoring and decision-making systems are utilized for integrated water management. The combined digital system can maximize the surface water source of the city, maintaining water quality in the reservoirs and waterways within the catchment and avoiding flood situations within the city.

Another important aspect of the digitalization of urban water is the social acceptability of technology. The study shows that the social acceptability of digitalization depends majorly on the mode of implementation and not so much on the technology. For example, the SWM implementation in Bengaluru puts the financial burden on the consumers leading to poor adoption of the technology, whereas in Singapore, where financial subsidy is provided, the adoption is much higher. Moreover, it is learnt from the study that social response to digitalization is better when the final product or service provided is personalized for customers or users. For example, the FAS in Singapore is a more personalized service that provides alerts only when there is a risk of flooding in the subscribers' locality. In Bengaluru, FAS mobile application is a platform with general information available to users.

Policy Implications

The urban water governance in Singapore though digitalization is truly exemplary in terms of its performance, transparency, and accountability with respect to water supply and wastewater management systems. The paper draws insights from the Singapore case studies and create a common conceptual framework to effectively integrate digitalization in urban water governance, which can be replicated in other cities.

Rules and regulations differ greatly between cities, but the study finds that there are almost no legal or regulatory constraints on digitalization in urban water sector. SCADA system is more of an internal digitalization process for water utilities to make it more efficient. FAS is kind of an information service provided to the citizens, without any compliance requirements and is utilized by people purely based on their own discretion. Only in case of SWM, some compliance issue is noticed. In Singapore, SWM is implemented mandatorily for all consumer connections but there is no resistance faced for two reasons. First, the financial burden of the technology implementation is not put on consumers and second, consumers are brought on board by providing a linked mobile application that consumers can use to track their own water use and reduce wastage, thus bringing down the water bills. As mentioned earlier, the financial model of SWM in Bengaluru is very different but there are no regulatory bindings put on consumers to adopt the technology as the consumers themselves need to take the financial burden. Digitalization is meant to improve the urban water system and benefit society at large. Successful model of digitalization, as seen in Singapore, should include transferring financial and social benefits to the society to ensure greater adoption of digital technology.

In 2015, India initiated the Smart Cities mission to promote sustainable and inclusive cities with infrastructure and application of smart solutions for higher human wellbeing, clean and sustainable environment. Adequate water supply, digitalization, and good governance are some of the key features of the multibillion-dollar Smart Cities mission. The Smart Cities could become hubs of economic development and social inclusion with system resilience through digitalization and IUWM. The findings of the paper, including the understanding the complementarities between smart solutions or digital solutions and their proper sequencing to realize the digital co-benefits could be of great value to the adoption and implementation of digital solutions for cities in India in the ambit of the Smart Cities Mission.

AUTHOR CONTRIBUTIONS

CB, AB and CS conceived the idea for the study. CB and CS gathered the documents required for analysis. AB, CB and CS conducted the analysis. CB wrote the first draft of the paper. CS contributed to the introduction section. AB conceptualized the framework and the sequencing diagrams. CB conducted data analysis to create the context diagram. AB, CB and CS wrote the discussion and conclusion sections. AB edited the drafts to create the final form of the manuscript.

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