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Title	IoT-enabled water distribution systems - a comparative technological review
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Publication date	2022-09-20
Original Citation	Velayudhan, N. K., Pradeep, P., Rao, S. N., Devidas, A. R. and Ramesh, M. V. (2022) 'IoT-enabled water distribution systems - a comparative technological review', IEEE Access, (31 pp). doi: 10.1109/ACCESS.2022.3208142
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://doi.org/10.1109/ACCESS.2022.3208142 - 10.1109/ACCESS.2022.3208142
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Download date	2026-11-06 02:40:29
Item downloaded from	https://hdl.handle.net/10468/13678



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IEEE Access
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Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

IoT-enabled Water Distribution Systems - A Comparative Technological Review

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This research is performed as part of the Project "Fast forward to SDG6: Acceptable and affordable water in secondary Indian cities (4WARD)" supported by Department of Science & Technology (DST), Water Technology Initiative-National Consortia on Urban Water System (UWS) with project no. DST/TM/EWO/WTI/2K19/UWS-03(G2).

ABSTRACT

Water distribution systems are one of the critical infrastructures and major assets of the water utility in a nation. The infrastructure of the distribution systems consists of resources, treatment plants, reservoirs, distribution lines, and consumers. A sustainable water distribution network management has to take care of accessibility, quality, quantity, and reliability of water. As water is becoming a depleting resource for the coming decades, the regulation and accounting of the water in terms of the above four parameters is a critical task. There have been many efforts towards the establishment of a monitoring and controlling framework, capable of automating various stages of the water distribution processes. The current trending technologies such as Information and Communication Technologies (ICT), Internet of Things (IoT), and Artificial Intelligence (AI) have the potential to track this spatially varying network to collect, process, and analyze the water distribution network attributes and events. In this work, we investigate the role and scope of the IoT technologies in different stages of the water distribution systems. Our survey covers the state-of-the-art monitoring and control systems for the water distribution networks, and the status of IoT architectures for water distribution networks. We explore the existing water distribution systems, providing the necessary background information on the current status. This work also presents an IoT Architecture for Intelligent Water Networks - IoTA4IWNet, for real-time monitoring and control of water distribution networks. We believe that to build a robust water distribution network, these components need to be designed and implemented effectively.

INDEX TERMS Internet of things, IoT communication technologies, IoT services, water distribution network

I. INTRODUCTION

AROUND 70% population in this world live in urban areas and 50% of the population is expected to live in water-stressed areas by 2025 [1]. Over two billion population are facing extreme water stress, as they consume more than 80% of their available supply of water [2], [3]. According to the United Nations, "The human right to water entitles everyone without discrimination to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic use [4]." The UN sustainable development goal (SDG) #6 targets improved water availability, sustainable management of water and sanitation for entire population [5]. To achieve this goal, the researchers can approach in various ways as discussed in [6] and [7]. Albeit 70% of the earth contains surface water and 30% groundwater, only 2.5% water is available for consumption [1]. Engineered hydrologic and hydraulic components, such as a water supply network, are used to transport the water. Water distribution system refers to the part of the water supply network that distributes portable water from a centralised treatment plant or a storage system to residential, commercial, industrial, and firefighting purposes [8]. Water distribution systems have always been important for the well-being and development of communities; they grow and

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evolve in tandem with the growth of towns. However, the water supply has been suffering serious issues as a result of population growth, increased demand, infrastructure ageing, and leakage, necessitating long-term solutions for both water supply and consumption. Therefore it is very challenging to achieve an equitable water supply for the water distribution system [9].

A. CHALLENGES IN THE WATER DISTRIBUTION SYSTEMS

Due to the unauthorized and unauthenticated extension of the network without considering the system's capacity, most water distribution systems lack quality and quantity of water supply, topological parameters, cost and energy management, and plant efficiency. The population increase, climate change, and urbanization enhance water depletion. Furthermore, urbanization and population growth are the primary causes of increased water withdrawal. The migration from rural to urban areas, loss of peri urban agriculture and loss of green areas, due to deforestation, urbanization and so on leads to population growth and urbanization. The climate change, i.e, the rainfall intensity, variability in sea level, melting of glaciers, temperature rise, increasing floods, droughts and storm and changing the seasonality are also challenges the WDS. The governance and policies, some of the global policies, institutional frameworks, political regimes makes the WDS functionality and institutional management complex. Even though agriculture uses 70% of freshwater worldwide according to Food and Agriculture Organization (FAO) [10], there is an increasing imbalance in water usage between developed and developing countries. Most developed countries consume a major portion of their water for industries rather than agriculture and domestic purposes. However, in developing countries, agriculture consumes the majority of water, rather than domestic and industry [11]. In addition, the growing number of international water disputes might of considerable concern.

Deterioration in infrastructure system, such as increased water main breaks, decreased freshwater resources, untraceable non-revenue water consumption, physical loss, commercial loss, unbilled authorized users, increased water demands, increased operational costs and water leakage is the another major challenges identified for the water distribution systems [12]–[14]. Non-revenue water (NRW) [15]–[17], also known as physical losses or apparent losses, is a significant concern for most countries' water distribution systems, as illustrated in Table 1. Leakage, evaporation, incorrect metering, inadequate data collection, and theft all contribute to the NRW. Furthermore, leakages can result in considerable financial losses in water transportation as well as additional costs for the consumer (end-user) due to the wastage of energy and chemicals in water treatment plants. The estimated losses due to leakage account for up to 30% of the total amount of extracted water. Water leakage is primarily caused by the aging of the pipeline (corroded), excavation across the road, high pressure across the pipeline, unnoticed underground pipe leakage, extreme weather conditions, material of construction, soil conditions, increased water consumption of systems that are at capacity and/or are already stressed, increased treatment costs due to larger treatment system requirements, capital expenditure, chemical requirements, operational expenditure, and increased power requirements through larger capacity treatments and pumping assets to support the higher demand [16]. To reduce the leakage, a proper monitoring and maintenance of the water distribution system is required. Moreover lack of historic scientific data on distribution system can leads to improper management and maintenance of the resources and consumer connections such as supply deficiency, leakage, higher demand, low pressure. Table 2 depicts various stages of the water distribution system and its parameters to be monitored in each stage to achieve better functioning and equitable supply. Changes in public priorities, emerging technologies, energy costs and increasing complexity are also challenges for the WDS. In this paper, we are interchangeably using the terms water distribution system and water supply systems.

TABLE 1. A summary of per capita usage and non revenue water in various countries.

Country	Water resource	Liter per capita per day (LPCD)	Non Revenue Water (NRW)
Australia [18]	Surface water/ groundwater / desalination	191	7%
Canada [19]	Rivers, lakes, groundwater, ice snow glaciers	343	30%
China [20]	Surface and groundwater	178	21%
Germany [21]	Spring water and bank-filtered water, groundwater	122	8%
India [22]	Surface water/ groundwater	140	38%
Israel [23], [24]	Aquifers and lakes	137	10%
Japan [25]	Surface water and open wells	250	6%
Malaysia [26]	Surface water/ groundwater	211	33%
US [27], [28]	Ground water, streams, rivers, lakes, aquifers, and reservoirs	302-378	18%

B. ROLE OF INTERNET OF THINGS (IOT) IN WATER SECTOR

Based on the aforementioned water distribution network challenges in section I-A, it can be concluded that an effective monitoring and automation system can alleviate such issues. One of the most prominent technologies for efficient monitoring and automation of the water distribution network is IoT, which enables individuals and objects to connect at any time, anywhere, with anything and anybody, preferably via any network (route) and using any service [29]. IoT has evolved in such a way that, it has to deal with tremen-

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TABLE 2. Different stages in water supply systems and the key parameters to be monitored in each stage to understand the system performance.

Resource	Treatment	Distribution	Consumer
Availability	Tank: overflow/empty	Storage: empty/ overflow	Tank: overflow/empty
Conveyance (Pumping/Gravity)	Pumping/energy	Pumping/energy	Pumping/energy
Intake	Reagent	Pressure	Pressure
Leakage	Leakage	Leakage	Leakage
Quality	Different quality parameters	Quality	Quality parameters
Quantity	Flow rate	Velocity	Velocity

dous data, storage, processing, and analytics [30]–[32]. The capabilities of IoT includes data sensing, processing, analyzing, and inferring parameters from natural resources and delicate ecologies to urban environments [33]. Further, it provides network utilization and context awareness to the system [34]. The embracing of Wireless Sensor Networks (WSN), low power communication technology with small embedded devices led to the technical convergence of IoT [35]. IoT offers several refined and ubiquitous solutions in various applications, such as intelligent transportation systems, governance, environment monitoring, smart homes, smart health, and quality of life [36]. Sustainability has become a key issue nowadays for the world population, as the dynamic and progressive advancement in the area of IoT technologies are leading to totally different helpful edges, however this fast growing developments must be rigorously monitored and evaluated from an environmental point of view to limit the presence of harmful impacts and make sure the smart utilization of limited world resources. There should require a significant analysis efforts within the previous sense to rigorously investigate the positives and negatives of IoT technologies [37].

IoT is considered as an important tool for monitoring and automation [38]–[41] applications. IoT allows precise control over water resources data, thus the key players in the water sector proactively innovate and resolve issues of water scarcity and address the aging water infrastructure [42], [43]. The water sector can no longer sustain itself in isolation from the technological shifts happening in other infrastructure industries and at the customer level. Inspection of corroding pipes, enabling predictive maintenance, analyzing data in real-time to identify leaks, and leveraging software to help utilities and consumers track their home water usage are some applications of IoT enabled monitoring systems.

IoT is one of the powerful monitoring tools for water distribution systems that can integrate analytics and intelligence to achieve control and automation features. Sensing systems, communication technologies, networking capabilities, and computing with storage and visualization makes IoT an efficient platform for an intelligent monitoring system.

Introducing IoT into water distribution network can tackles one of the critical challenges in water management; data unavailability/inadequate scientific information on various water distribution network elements such as water reservoirs and network health. The real time data collected by heterogeneous interconnected devices and sensors can analyze and process the application environment information, hence IoT would be a promising solution for the WDN. Moreover, the application of IoT technology can prove valuable in better water collection, storage, distribution, leakage prevention, waste water management, as well as distribution [44].

C. MOTIVATION

Although IoT-based water supply systems are introduced recently, there are several commercial solutions and platforms [45]–[47] available indicating the growing market demand. We found that most of the commercial solutions and platforms are focusing on the data collection, data integration, and data visualization using IoT sensors, while only a few offer predictive analytics of the acquired data [48]. The technological advances in IoT in recent years have fuelled the need for systematic progress of the present commercial systems and solutions in every industry sector. Based on the progress made at the research level, successful commercial solutions are constantly emerging using innovative technologies.

Table 3 summarizes the existing review articles on the methodologies for monitoring technologies in water distribution systems. They provide different orientations, such as these two articles [1], [49] focus on water quality monitoring systems based on WSN and IoT systems, information and communications technology (ICT) in water supply systems in terms of the importance of the network pressure management and stakeholders engagement via social media and gaming [50], [51], and blockchain solutions [52]. However, most of the review articles do not consider IoT solutions for water distribution systems with monitoring, control, and automation.

D. CONTRIBUTIONS

The management of water distribution is critical for the utilities and authorities, as they need to get a thorough analysis of the distribution network with the scope of IoT to embrace the system flawlessly. In this paper, we have explained the water supply/distribution system with the pervasive inclusion of the IoT and presented the applications. This survey endeavors to examine the research carried out to provide a sustainable water distribution system by utilizing the features of IoT. The major contributions of this paper are as follows.

- Presentation of the water supply system taxonomy, its components and parameters, and their different processes at each stage.
- Providing extensive insights into the IoT communication technologies, cloud platforms, and their characteristics applicable to water distribution systems.

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TABLE 3. Summary of some popular survey articles in the area of IoT and water distribution systems.

Reference	Contribution	Summary
[1]	Water quality monitoring (WQM) applications with WSN	WSN based water quality monitoring techniques explained for water resources and also the shortcoming of traditional manual lab-based (TMLB) monitoring approach and traditional manual in situ (TMIS) monitoring approach for WQM over WSN.
[51]	Importance of ICT in urban water management	(i) Smart ICT solutions derived with flow and pressure sensors in the network and providing online visibility and network intelligence (ii) Remote based control for valves based on automatic pressure optimization algorithm value of social networks and gaming via stakeholder involvement.
[52]	Importance of blockchain in various applications in IoT-based water management system, a scenario in Africa	Explains the challenges and security threats in an IoT-enabled water distribution network and introduces the blockchain as the solution for such challenges and provided the conceptual framework for the smart water supply.
[53]	IoT enabled water quality monitoring	Real-time water quality monitoring applications, parameters to be monitored, suitable communication technologies, controllers, sensors, and power consumption issues with an IoT-based hardware and software architecture is presented in this work.
[54]	WSN systems and use cases	The water quality system and water distribution system are presented as the use cases of the WSN monitoring systems. Monitoring the water quality for both in households and industrial processes, in a natural or an artificial environment, and the monitoring of the water distribution system's critical activities such as potential leakages, quantity or efficiency.

TABLE 4. Comparative study of existing surveys in IoT-based WDS from 2019-2022.

Reference	[55]	[56]	[57]	[58]	[59]	[60]	Our survey
Background of WDS	✗	✗	✗	✗	✗	✗	✓
Overview of IoT technology	✓	✓	✗	✗	✗	✗	✓
Role of IoT in WDS Applications	✓	✓	✓	✓	✗	✓	✓
Recommended Architecture for IoT based WDS	✗	✗	✓	✗	✓	✓	✓
Challenges in IoT based WDN	✓	✓	✓	✗	✓	✗	✓

- Analyzing the scope of various real-world IoT applications in water distribution systems.
- Providing a brief overview of IoT-based monitoring, control, and automation strategies for water distribution system applications.
- Presentation of a IoT Architecture for Intelligent Water Network-IoTA4IWNet.
- Presentation of existing challenges, recommendations, and future research directions for IoT-based water distribution network.

We have considered relevant and recent six publications of surveys and reviews conducted in IoT-based water distribution networks, smart water grids, and ICT on WDS from 2019 to 2022. To acquire insights on IoT-based WDN, existing surveys compared to our work based on the following concepts; the background of the water distribution system, an overview of IoT technologies, IoT-based different water supply applications, an architecture based on the study, and challenges and future directions in IoT-based water distribution systems as shown in Table 4. To the best of our knowledge, we have considered all the above aspects together, which provide a holistic approach that turns out to be novel in this review paper. We feel that this paper will help newcomers to understand the role of IoT in developing a sustainable water distribution system.

E. ORGANIZATION

The organization of the paper is as follows. Section II briefly explains the research method used in the study and development of the research questions such as resources for the study, thought process for the research development, and finally presents the research questions. Each research question is addressed and discussed in detail in Section III. Section IV comprises the analysis of IoT characteristics and constraints in the deployments of water distribution network (WDN). Section V recommends and presents an IoT architecture (IoTA4IWNet) capable of monitoring, control and automate WDN systems and Section VII concludes the paper.

II. RESEARCH METHOD

In this section, we introduce the research approach, by conducting a systematic literature review to understand the role of the IoT in the water distribution systems. Four research questions are considered as the first step of the literature review. A comprehensive review analysis conducted based on literature which are focused on IoT systems in water distribution domain. The objective of this study is to synthesize the current knowledge and approaches for monitor, control, and automation strategies for the water distribution systems. Towards this objective, a quantitative review method, based on the systematic approach, is used in this study. Moreover, qualitative analysis of the core area publications i.e. carefully selected journals and conferences presented in this study. This task is performed such that, the identification and presentation of each articles

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is reviewed and categorized based on its research focus and results. Moreover, we considered only the publications written in English. Fig. 1 depicts an overview of the research methodology adopted for this paper. The major resources for the articles discussing in this work are identified via Google Scholar and Scopus. Most of the selected articles are from Elsevier, IEEE, and Springer, and the rest from other scholarly article resources like arXiv, MDPI, and Wiley. Furthermore, the collected articles are categorized as journals, conference proceedings, white papers, and so forth and their further analysis leads to the development of the research questions.

A. THOUGHT PROCESS

To investigate the role of IoT in the water distribution system, the primary step is to review the existing system based on its parameters, attributes, and different events. Therefore the initial research question deals with the identification of the stages and processes in water distribution systems. Next, we surveyed the available literature in IoT technologies for the period 2000 to 2021, to comprehend the importance, specifications, and characteristics of the IoT technologies, which turned out as the second research question. Subsequently, we investigated the literature to discover various applications of IoT in WDN. Finally, the fourth question introduces the importance of an integrated methodology to monitor, control, and automate the water distribution networks with an IoT-based closed-loop system.

B. RESEARCH QUESTIONS

We aim to identify the scope of IoT in the water distribution system and synthesize this research evidence to propose an IoT-based communication architecture for the same. This is achieved by comparing and contrasting the existing approaches and analyzing this in an application framework. Accordingly, this paper attempts to solve the following research questions:

- RQ1: What are the major processes and stages in the supply of water distribution networks?
- RQ2: What are the available IoT technologies applicable to monitor/control/automate various parameters in water distribution networks?
- RQ3: What are the real-world IoT applications in the water distribution network?
- RQ4: What is the scope of IoT-based monitoring, control, and automation in water supply systems?

III. FINDINGS AND DISCUSSIONS

In this section, we will discuss the above-mentioned four research questions and present the findings of each.

A. ADDRESSING RQ1: WHAT ARE THE PROCESSES AND STAGES IN THE SUPPLY OF WATER DISTRIBUTION NETWORKS?

The water supply system is a spatially organized network that ensures safe water access to the people/community, which consists of water resources, intake system, storage system, conveyance systems, treatment plants, distribution networks, and consumers. The water intake from the source is followed by the transmission system in which conveyance of the raw water is carried out from the collection unit to the water treatment plants (WTP). Subsequently, the distribution of the treated water to the consumers through the pipe networks. In a further attempt to provide more insights into the water distribution system, we portrayed the water supply system with stages, processes, and its attributes and parameters in Fig. 2. The water supply system consists of the following seven subsystems.

1) Water resources

The commonly used water sources are rivers, lakes, aquifers, and bore wells. These water sources can be of different types such as surface water sources, groundwater sources, atmospheric water, recycled wastewater, and saline water. One of the biggest challenges concerning the sources is water availability, which depends on climate change, population, and urbanization. Besides, general longevity of the sources (short-term and long-term), water quality, susceptibility to pollution, and ease of access to the water resources are some other challenges [61].

2) Intake structures

The water resources are associated with an intake system. These intake systems are installed to safely withdraw water from the source and to discharge it into the withdrawal (or intake) conduit, through which it reaches the WTP. It can be categorized into three (see Fig. 2), according to the type of source (river, canal, reservoir and lake intakes), water presence in the intake tower (wet and dry intake) and the position of intakes (submerged and exposed intake) [62].

3) Water conveyance/transport system

Conveyance or the transportation system has the following two stages (see Fig. 2).

- Water can be transported by three methods depending on relative elevations of WTP and water supply sources, whether it is by pumping or by gravity/free-flow, or by the combined action of both pumping and gravity flow.
- Water transported either by pumping directly to the water mains or by pumping to an intermediate overhead tank and then supplying to the water mains via gravity for distribution.

4) Water storage systems

Water storage systems can be situated in water distribution networks in the following ways (see Fig. 2):

- Before the intake system to store tapping water streams with the low and inconsistent flow
- After the intake system to store water for consistent supply to the treatment plant

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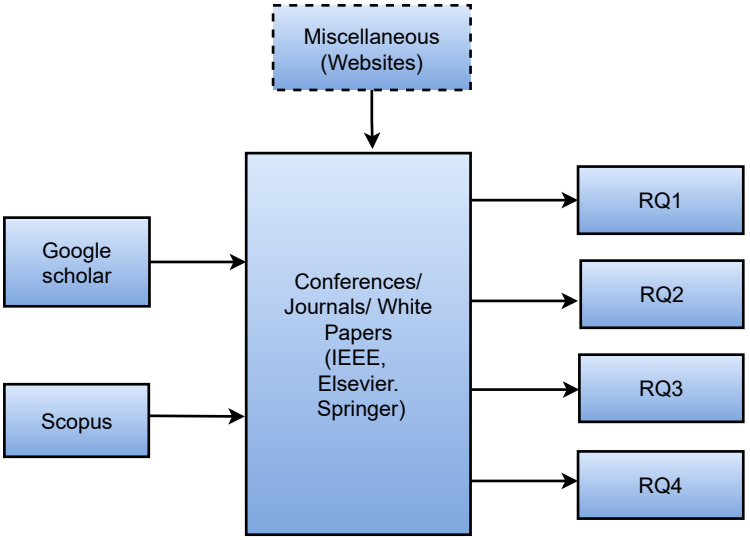


FIGURE 1. Information sources used for the search phase and overview of research methodology.

- Before the treatment system to store water for consistent supply to the treatment plant
- After the treatment plant to safely store the treated water before it reaches the end consumer.

5) Water treatment plant (WTP)

The treatment plant is one of the most vulnerable stages in the supply system. It has the following processes [63].

- *Screening*: Screening refers to the filtration of the coarser floating and suspended materials, and removes impurities like wood, leaves, aquatic plants, papers, polythene, and so forth.
- *Aeration*: An aeration is a unit that brings water and air in close contact and aims at the removal of iron and manganese, dissolved gases, and volatile organic compounds (VOCs).
- *Sedimentation*: Phase separation process to settle down the suspended materials including clay and silt, organic matter, and other associated impurities under the effect of gravity.
- *Coagulation and flocculation*: Respective steps intended to overcome the forces stabilizing the fine suspended or colloidal particles, allowing particle collision and floc development.
- *Filtration*: Water is passed through sand or multimedia filters for the removal of left-over suspended solids and micro-flocs.
- *Disinfection*: Disinfection is the process to remove, deactivate or kill pathogenic microorganisms so that they are not infectious to humans and animals.

6) Water quality

The water abstracted from the source may not be of usable quality in its natural state. Moreover, anthropogenic activities in many regions and the industrial, agriculture, and social pollution [64] compel water quality deterioration. Thus, the quality of the supplied water should ensure public health safety (essentially free of disease-causing microbes and chemicals). Some of the widely used water quality guidelines [65] are the European Union Water Framework Directive, the Clean Water Act in the United States, the World Health Organization (WHO) drinking water quality guidelines, and the Bureau of Investigation Standards (BIS) in India. The valid implementation of these standards depends on the establishment of a robust and verifiable monitoring regime of water supply systems. Systematic and proactive water quality governance and control in the water source management enables earlier identification of the number of quality parameters so that the distribution system can have a reasonable amount of time to act on the quality risk factors. The water quality monitoring parameters can be categorized into three - physical, chemical, and biological [66]. Some of the standard water quality parameters (see Fig. 2) include temperature, color, odor, turbidity, conductivity, solids (total, suspended, dissolved, fixed, volatile) pH, acidity, alkalinity, hardness, nutrients (nitrogen, phosphorous), metals (Fe, Al, As, Cr, Zn, Ni, Co, and so on.), ions (chloride, carbonate, nitrate, sulfate, and so on.), pesticides, radioactive emission, dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and other trace elements, Most Probable Number (MPN), Total and Fecal Coliform.

7) Water distribution network

The water distribution network majorly consists of pipes, valves, appurtenances, pumps and storage structures, and other supporting infrastructure. The water pumping stations can be equipped with pumps, motors, pressure switches, valves and pump on-off valves, and so forth. The energy content in the distribution network employed in this stage, where monitoring, automation, and control together can accomplish the optimized performance of the pumping sys-

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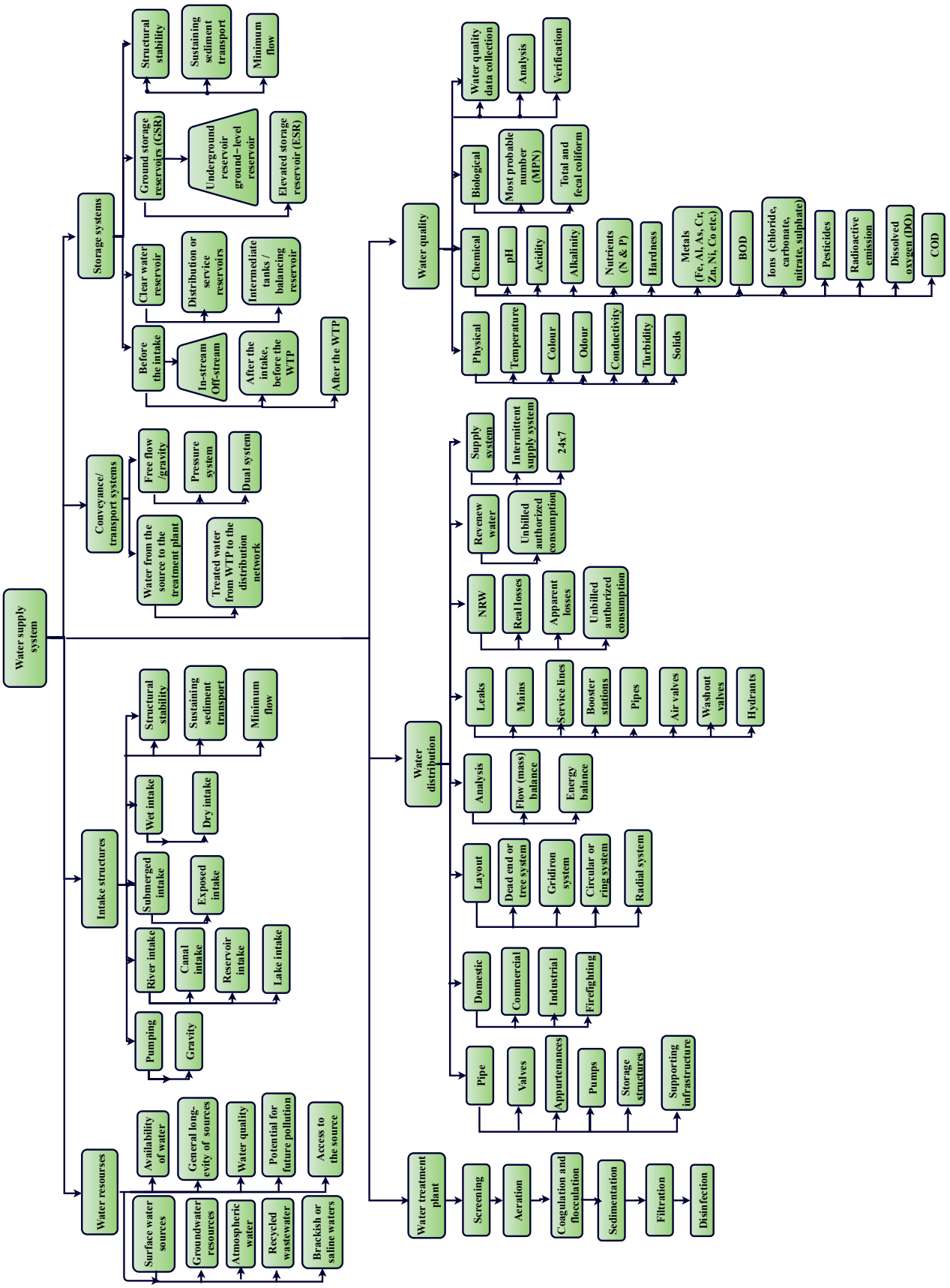


FIGURE 2. Water supply system taxonomy, consisting of different processes in the supply system from the water resources to the stakeholder.

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tem, thereby leading an increase in the performance of the entire supply system. Further, the water quality parameters like pH, chlorine, dissolved oxygen, conductivity, turbidity, and oxidation-reduction potential need to monitor in the water system, before supplied to the customers. In centralized water distribution systems, water treatment is carried out before sending water to consumers. Positively, post-treatment safety is also ensured by eliminating the chances of contamination in distribution systems. Moreover, the treated water is unstored for a long in storage or overhead reservoirs to reduce the chances of contamination due to long storage [67].

As stated in Section I-A, the challenges such as tracking of pipe cracks, pipe bursts, leakage, and water quality are difficult to carry out at frequent time scale, without adequate technical support due to its spatial distribution. Consequently, overall operation and monitoring have been grossly inefficient with traditional practices of monitoring and management, especially with aging infrastructure. Here, some of the critical parameters to monitor are the flow and pressure in mains and consumer end, reservoir level, and valve operations of WDN. In short, both monitoring, control, and automation of the water supply system can enhance the reliability of the entire supply system from the water generation to the consumer. Moreover, a robust water distribution system must be capable of providing the water, without deterioration in the quality in the pipes and deliver with the optimum pressure head for various purposes such as domestic, commercial, industrial, and firefighting. Furthermore, the conventional WDN system can upgrade into three steps as follows: (i) to upgrade the system into an instrumental system with the ability to detect, measure, acquire and record data, (ii) to upgrade the system into an interconnected one with the ability to communicate and interact with system operators, managers, utilities and stakeholders and (iii) to control the system with the feedback from *step (ii)*.

Hence, entire water distribution system management can be divided in to nine applications such as water quality monitoring, leak detection and monitoring, pressure control and monitoring, parameter estimation and monitoring, state estimation and monitoring, demand prediction and monitoring, pipe health monitoring, pump energy consumption monitoring, and water resource management [68].

B. ADDRESSING RQ2: WHAT ARE THE AVAILABLE IOT COMMUNICATION TECHNOLOGIES/INTERFACES APPLICABLE TO MONITOR/CONTROL/ AUTOMATE THE PARAMETERS IN WATER DISTRIBUTION NETWORKS?

IoT deals with billions of devices 'connected to the internet' with the help of various IoT technologies (shown in Table 5), cellular technologies, M2M technologies, and so forth [69]. The growth of the IoT can be identified from various statistical data such as there exist 21.7 billion active connected devices worldwide, from that 11.7 billion (or 54%) is the IoT device connections. By 2025, it is expected to be more than 30 billion IoT connections, which is on an average four IoT devices per person [70], [71]. The total volume of data exceeding 600 ZB per year by 2020, and the global spending on IoT of more than $3.7 trillion in 2018 and projected to grow up to $11.1 trillion per year in 2025 [72]–[74].

Since IoT is a highly advanced technology, it can trigger the development of intelligent devices, smart sensors, actuators, and Machine to Machine (M2M) devices [75], [76] with the coexistence of different IoT technologies like Near Field Communication (NFC) [77], ZigBee [78], Wi-Fi [79], [80], LoRa [81], and NB-IoT [82]. The IoT communication technologies are intend to connect heterogeneous objects or devices within one framework to achieve smart applications and services, with low cost and low power even in adverse communication environments such as in lossy and noisy communication links. To provide more insights into the different IoT technologies and their characteristics, a comparison is shown in Table 5. From different IoT communication technologies, RFID is considered as the first IoT communication technology, which realized the M2M communications via RFID tag and reader concept [83]. NFC is another technology that supports high frequency, low data rate communication with an applicable range up to 10 centimeters [84] which allows the shortest communication distance. The Bluetooth technology is known as the cable replacement technology which is widely used in headphones, mouse, and keyboards while Bluetooth Low Energy (BLE) is used in accessories for smartphone apps and internet-connected devices [85]–[87]. Wi-Fi is the most common communication technology in which used to build smart sensor ad-hoc networks [88], [89]. LTE (Long-Term Evolution) is a standard wireless communication technology for high-speed data transfer between mobile phones based on GSM/UMTS network technologies [90], [91].

Besides the communication technologies, other important aspect of IoT is the cloud platforms and protocols. There are a number of public and private cloud platforms available for IoT applications. Most of the cloud platforms are providing end to end connectivity and services to the edge network and end devices. The major focuses of the cloud platforms are connectivity and normalization, device management, processing and decision making, data visualization and analytic, external interface and database management [95]. The cloud platforms are supported by various data transfer protocols such as Message Queuing Telemetry Transport (MQTT) that handles publish subscribe for message broker, Hypertext Transfer Protocol (HTTP) and so on. Prominent cloud platforms and their supporting protocols are shown in the Table 6.

The IoT system has different functional blocks like identification, sensing, services [48], management [96], security [97], semantics [98] and applications. Moreover, each IoT system needs to accomplish the major IoT characteristics like interoperability, scalability, QoS, reliability, distributive, and security [99]. Furthermore, the steps involved in the

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TABLE 5. Overview of different IoT technologies for water supply system.

Technology	Supported frequency	Range	Data Rate	Standardization	Topology	Security	Modulation
ANT	2.4 GHz ISM band	30m at 0 dBm	12.8 kbps, 20 kbps & 60kbps	Proprietary	P2P, star, tree, mesh	AES-128 and 64-bit key	GFSK
BLE	2.4 GHz	10–600m in air	125 kbps, 250 kbps, 500 kbps, 1 Mbps, & 2 Mbps	Standard	P2P, star, & mesh	AES-128	GFSK
Bluetooth	2.4GHz	1-100m, 20m LoS	1-3 Mbps	Standard ISM band	P2P, scatternet	56-128 bit key	GFSK
Dash 7 (DA7)	Unlicensed ISM band 433.92, 868, 915 MHz	1 - 2 KM (extend using sub-controller)	13, 55, 200 kbps (16, 8, 4 channels)	ISO/IEC 18000-7	Tree, Simple routing two hops	AES-counter with CBC-MAC (CCM)	2-GFSK
EC-GSM-IoT	Cellular GSM bands	154 - 164dB	70-240kbps	3GPP Licensed	Star	3GPP (128-256bit)	GMSK, 8PSK
EnOcean	315 MHz, 868 MHz, 902 MHz	300m Outdoor, 30m Indoors	125 kbps	Standard	Mesh	AES 128-bit key	ASK, FSK
INGENU (RPMA)	2.4GHz	Up to 176 square miles	624 kbps (uplink), 156kbps (downlink)	cellular-based standards	Star	128-bit encryption and two-way authentication	D-BPSK
EnOcean	315 MHz, 868 MHz, 902 MHz	300m Outdoor, 30m Indoors	125 kbps	Standard	Mesh	AES 128-bit key	ASK, FSK
LoRa	Unlicensed ISM band 868, 915 MHz	2 - 5 Km (urban)/15 (rural)	0.3 - 50 (EU) / 0.9 - 100 (US)	LoRa Alliance	Star	128-bit AES encryption	CSS
LTE CAT-M	1.4–20 MHz	Cellular LTE network	1 Mbps	3GPP	Star	128-256bit	16-QAM
MYTHINGS	868 MHz (Europe) or 915 MHz (North America)	1KM-15KM	10 Kbps-100Kbps	Standard	star	Built-in AES-128	Telegram Splitting
NB-IoT	Cellular Band	Greater than 15 Km	250 kbps	3GPP Licensed Star Military grade	LTE cellular framework	256 bit encryption	QPSK, BPSK
NFC	13.56 MHz	Less than 0.2 m	106 kbps to 424 kbps	Standard-ISO-18000-6C	P2P	symmetric cryptography	ASK
RFID	120–150 kHz (LF), 13.56 MHz (HF), 433 MHz (UHF), 865-868/902-928 MHz UHF, 2450-5800 MHz (microwave)	10cm - 200m	40 kbps - 640 kbps	ISO 14443, 15693, 18000 EPC global	P2P & P2M	ISO/IEC 18000 ISO/IEC 29167 use on-chip cryptography	ASK, 2 FSK, 2 PSK
SigFox	868, 902 MHZ ISM	24 Km	100 bps	Proprietary	Star	AES-128 encryption	DBPSK +GFSK
Symphony Link	915-MHz ISM	2312.47 m	200 bps to 100 kbps	Proprietary	Mesh	PKI based Diffie Hellman AES	CSS
Weightless	Varies with legislation (470 – 790MHz)	Up to 10km	1 kbps - 10 Mbps	Weightless SIG	Open Star	AES-128/256 encryption	GMSK, +PSK
Wi-Fi	2.4 GHz, 3.6 GHz and 4.9/5.0 GHz bands.2.4 GHz ISM (g) 5 GHz U-NII (a)	100m+	54 Mbps	IEEE 802.11	Star	Optional- RC4 (AES in 802.11i)	BPSK, QPSK, 16-, 64-QAM
Wi-FI Hallow	Sub-1-GHz	Over 1 KM	150 kbps-86.7 Mbps	802.11 standard unlicensed	star-network	WPA3	OFDM
WiMAX	Licensed/Unlicensed 2 G to 11 GHz	50 Km	100 Mbps	IEEE 802.16	Mesh	Mandatory-3DES Optional-AES	BPSK, QPSK, 16-64-256-QAM
Zigbee	2.4 GHz (+ sub-GHz for ZigBee PRO)	10–100 m	250 kbps (at 2.4 GHz)	Standard	Mesh	AES-128	QPSK
Z-WAVE	2.4 GHz and 900 MHz	10-100 metres	100 kbps	Proprietary	Mesh	AES-128	FSK
3G	850/900/1800/1900 MHz	50-150 KM	2 MB	3GPP licensed	Cellular framework	SNOW3G	CDMA
4G/LTE	2-8GHz	50-150 KM	200Mbps-1 Gbps	3GPP licensed	Cellular framework	128-bit AES and SNOW3G algorithms	CDMA
5G	Low/Mid/mm Wave bands 100/400 MHZ	50-80 KM	Gbps	3GPP licensed	Cellular framework	LTE encription	OFDM, BDMA

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TABLE 6. IoT Cloud Platforms and supported protocols

IoT Cloud Platforms	Protocols	Contribution
AWS IoT CORE [92]	MQTT3.1.1 HTTP(S)	Performanace analysis of three cloud platforms based on cloud service time
MICROSOFT AZURE FOR IoT [92]	MQTT3.1.1 HTTP(S)	Simulation of point to point, fan in and fan out scenarios
GOOGLE CLOUD IoT CORE [92]	MQTT3.1.1 HTTP(S)	Devices send one message per minute of 1kB.
IBM WATSON IoT [93]	MQTT, HTTP(S), AMQP, and CoAP	Twenty one features of five IoT platforms being compared
Oracle IoT [93]	MQTT, HTTP	Theoretical framework design for selection IoT platform
DigiOcean [94]	MQTT, HTTP	Machine learning algorithms for various cloud computing services
Alibaba Cloud [94]	MQTT, HTTP	

IoT system development are understanding the necessities and requirements of IoT users (consumer/utility/stakeholder) and their appliances and devices, pervasive communication networks, and software architectures to transmit, process and compute the sensor data to where it is relevant, and analytic tools for autonomous and intelligent behavior in IoT systems [100], [101].

C. ADDRESSING RQ3: WHAT ARE THE REAL-WORLD IOT APPLICATIONS IN THE WATER DISTRIBUTION NETWORK?

The advanced technological shifts are happening to all infrastructure industries at the customer level, and the water sector can no longer sustain itself from this advanced technological isolation. IoT is considered as a tool for monitoring and automation [38]–[40] that allows precise control over water resources data thereby proactively innovates and resolves the water scarcity problems and address the water infrastructure aging [41]–[43]. Additionally, IoT can integrate analytic and intelligence to achieve control and automation features in a water distribution system. Moreover, the sensing systems, communication technologies, networking capabilities, and computing with storage and visualization makes IoT an efficient platform for an intelligent monitoring system. Some of the main applications of IoT-enabled monitoring systems are inspection of pipes (e.g. corroding and crack), enable maintenance prediction, real-time analysis of sensor data to identify leaks and cracks, and software leverage to help utilities and consumers to track their water usage pattern for the better water management.

In this section, our aim is to provide a brief summary of existing literature in IoT-enabled water distribution system, which are as follows.

- A Low Power Wide Area Network (LPWAN) based IoT system for real-time water quality, availability, and quantity monitoring system is a smart water grid solution [102]. This system incorporated five quality parameters such as oxidation reduction potential (ORP), pH, salinity, turbidity, and temperature along with water level and water flow meter. Furthermore, it addressed the challenges in a distribution grid such as clean water and sewage water mixing, incomplete water treatment, intermittent water supply, and inefficient flow control gate management. LoRa communication technology is used for long communication range and to support small data rates and long communication range. Moreover, the system can overcome the power consumption and computational power efficiency constraints.
- A water usage control and equipment management system with an integrated approach of WSN, IoT, and cloud computing presents various IoT applications in WDS [103]. The water flow meters are used to get consumption and leakage data and the system monitors the intermittent supply, availability, leakage localization, billing, and consumption pattern of the user. The architecture of the smart water distribution system consists of a source (tanks/reservoirs), pumping stations, valves, and pipes. Continuous level sensors, water flow meters, and valves are in the WSN layer. IoT layer occupies 2G/3G communication techniques and it also acts as an adaption layer for both WSN and cloud in this architecture. User awareness, control, and management application and data analytics have been done in the cloud layer. The system is costly and interdisciplinary, hence challenging for the real-world deployment of the system. IoT layer occupies 2G/3G communication techniques and acts as an adaption layer for both WSN and cloud in this architecture. User awareness, control, management application, and data analytics have been made in the cloud. The system is costly and interdisciplinary, hence challenging for the real-world deployment of the system.
- A water quality monitoring system in a single-chip solution interfaces transducers to sensor networks using Field Programmable Gate Arrays (FPGA) with the help of a wireless XBee module [104]. This system incorporates four water quality parameters like pH, turbidity, temperature, and carbon dioxide with an ultrasonic water level sensor. The research focused on developing a number of energy-constrained sensor nodes in an unnoticed environment. Therefore they used low-power, low-cost single-chip fully-integrated autonomous System-on-Chip (SoC) wireless sensor nodes, which use VHSIC Hardware Description Language (VHDL) and C programming for SoC data computation. Further, they used ZigBee wireless nodes for information transfer.
- A sustainable water distribution system for utilities and consumers to save water resources and energy is integrates the technologies Big data and IoT. In this

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system, Wi-Fi-enabled IoT devices are installed on the consumer side, and the accumulated data is transmitted via the Global System for Mobile Communications (GSM) to the utility. The Big-data analytic platform has automated water audits, billing, and hydraulic performance analyses. Moreover, analyzing these data utilities controls the network performance optimization that includes the monitoring, control, pressure, and overflow of the consumer home network.

- Integrating ICT into traditional water management systems can develop Smart Water Management (SWM). SWM can monitor the water resources, diagnose problems, improve efficacy, and coordinate and manage a sustainable water supply. Furthermore, SWM takes care of the whole water management cycle from source to consumer, including withdrawal, treatment, conveyance, distribution, and reuse of water [105].
- The IoT-based water quality monitoring system comprised of three subsystems, a central measurement node, a control node, tiny notification nodes, and a central measurement node through an interconnected ZigBee-Radio Frequency (RF) transceiver. This system provides near-tap notifications locally to the user through interfaced peripherals such as LED and LCD displays and buzzer. This setup has six water quality sensors that can determine water flow, conductivity, ORP, pH, temperature, and turbidity. Since the water distribution system is rapidly polluted with hazardous pollutants, there is an urgent need for such rapid quality detection systems [106], [107].

To provide more insights into IoT-enabled water distribution systems, we reviewed the literature and present the analysis of various IoT technologies and their applications in the WDN in Table 7. Further, we listed the types of sensors required to capture different processes or events of the WDN in Table 8. An effective water distribution system can be built by effective usage and implementation of proper devices, components, and communication technologies.

D. ADDRESSING RQ4: WHAT IS THE SCOPE OF IOT-BASED MONITORING, CONTROL, AND AUTOMATION IN WDN

The water supply system is a complex distributed network that is being converted to networked control systems deployed to monitor, control, and automate in response of physical infrastructure. With the integration of the compatible IoT devices the deprecated infrastructure can be changed into supervisory systems, which enables remote monitoring and control for the infrastructures. These upgraded infrastructures help the utilities to get higher reliability and existability of the deployed systems [141]. Moreover, to promptly detect the defects and deficiencies of water distribution network novel water management procedures are necessary to carefully control the system.

The primary objectives of IoT, which will helps to construct a proper monitoring system, sensor and device integration, sensed information security, information analysis and real-time decision making. Therefore the main steps in the IoT-based water distribution system operation are as follows. The initial step is to facilitate a visualization schematically to gather sufficient information of water supply network components such as, pipes, pumps, air valves, tanks, and stabilizers, to group them in the next step in the geographic information framework [142]. Next, to continuously monitor the various water supply system parameters such as water flow, pressure, and quality a set of sensors are deployed. Finally, the sensed parameters are transmitted via communication channels to an information system for the analysis and to take suitable action [100]. Fig. 3 presents the closed-loop strategy for an IoT network to attain the automatic control features for the the system. An automated real-time control systems can be achieved by the closed-loop strategy with the feedback system. Further, the analysis of monitored results, the hydraulic simulation strategies and the prediction of the control variables according to the control factors can enhance the efficiency of automated real-time water distribution systems.

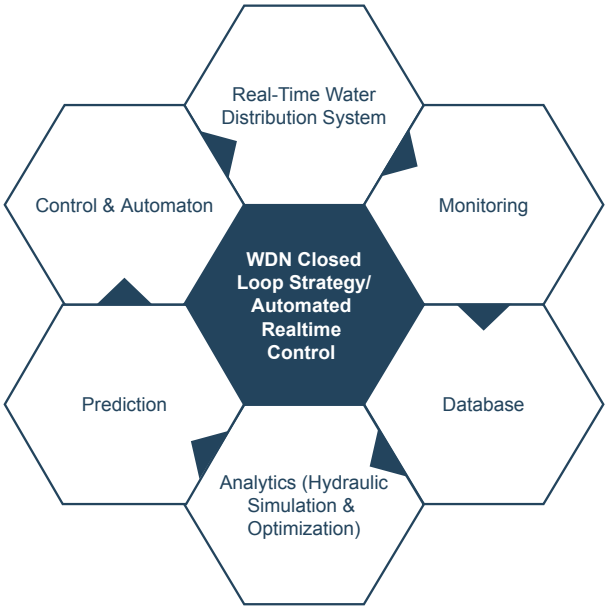


FIGURE 3. Closed-loop strategy for water supply system.

The hydraulic simulation and optimization strategies in water distribution system, deals with demand prediction, network design, pump operation, and real-time processes. Although, major advances were made in this area, these are still unexplored (or poorly explored) methodologies that can be tested and applied in a considerable number of water systems. Furthermore, AI models are powerful tools in hydrology that can facilitate reliability, cost-effectiveness, problem-solving, decision-making, efficiency, and effectiveness.

The use of IoT and AI technologies [147]–[149] are capable to result in the progressive transformation of moni-

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TABLE 7. The role of IoT technologies in various applications of water distribution system.

Technology	Application 1	Application 2	Application 3	Application 4	Application 5	Application 6	Application 7
Bluetooth	EARNPIPE: Energy Aware Reconfigurable sensor Node for water PIPEline monitoring *Role* Sensor node communication [108]	water environment remote monitoring system *Role*: Network connection between routing node to monitoring service center [109]	Smart water meter via Smart App *Role*: Meters with EIM transmitting data to Smartphone [110]	Mobile Phone wireless bacteria sensing system *Role*: Communication between wireless bacteria sensor to mobile phone app [111]	Wireless water flow monitoring based on android smartphone *Role*: Wireless technology for data transmission of water flow [112]	Flows sensor to the mobile app network HydroNet ASV - Autonomous Water Monitoring and Sampling System for Small-Sized ASV *Role*: Sensor probe to the vessel [113]	Autonomous real-time water quality sensing *Role*: Multiple sensor nodes to the base station [114]
LoRa	Campus water management system monitoring of the over head tanks and ground level reservoir *Role*: Network connection for gateway to upload the data [115]	Monitoring and control of water distribution network *Role*: Connection the over head tank and underground tank updates to the gateway [116]	Adige: An efficient smart-water network monitoring and control system *Role*: Connectivity between the sensors to the gateway [117]	Smart water quality monitoring and metering *Role*: Connectivity between the sensors to the gateway and gateways to cloud [118]	Water quality monitoring system for soft-shell crab farming *Role*: Sensor node to the gateway communication [119]	Smart water management system in urban areas *Role*: Transceiver for smart water meter data to the cloud-based server [120]	Water quality monitoring system *Role*: Sensor node to the IoT cloud communication [121]
NFC	Ubiquitous mobile Water quality Reporting system (u-WQR) *Role*: To give access to API [122]	Automated flow monitoring based on android smartphone *Role*: Identification of flow meter sensor [112]	Water purification tracking *Role*: Identification of bucket (Module) [123]	Underwater smart poster *Role*: Service Initiation modality and Peer-to-Peer modality [124]	-	-	-
RFID	IoT Network for monitoring the water loss *Role*: Unique identifier [125]	Bristol Is Open (BIO) platform for water quality monitoring *Role*: Network connectivity [126]	Groundwater level measurement *Role*: Leveling Package Transmission of data [127]	Water level detection with chipless RFID *Role*: Detector power transmitter [128]	Water quality monitoring *Role*: Data transmitter [129]	Smart Water monitoring *Role*: Communication network [130]	Water level monitoring *Role*: Data acquisition [131]
Wi-Fi	Automatic water level checking at the dam gate with moisture sensor and servo motors in arduino *Role*: Arduino to the remote server [132]	Water quality (TDS & pH) monitoring *Role*: Raspberry pi to the cloud [133]	Smart water meter via Smart App *Role*: Meters with EIM transmitting data to Smartphone [110]	Real time water quality monitoring and controlling system *Role*: Connectivity between Raspberry pi to the cloud server [134]	Real time monitoring of water quality in IoT environment *Role*: Wi-Fi module connects the embedded device to internet [135]	Critical water infrastructure monitoring and protection against cyber and physical attacks *Role*: Human intrusion detection via wireless signal reflection [136]	Water quality monitoring system for water tanks *Role*: Sensor data (ESP 8266) to raspberry pi [137]
ZigBee	Water quality monitoring system *Role*: Communication between sensor node to the microcontroller [111]	Real time monitoring of water pressure distribution *Role*: Intra cluster of node's communication [138]	Smart sensors for real-time water quality monitoring*Role*: Sensor data transmission and reception from sensors to microcontroller [139]	Smart Water Quality Monitoring *Role*: FPGA to monitoring module [104]	Water quality Monitoring System *Role*: Network layer (connectivity) Data transmission [140]	-	-

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TABLE 8. Sensors used in different stages of water distribution network.

Parameter	Location/Network equipment	Sensor
Asset management	Transmission network	Video camera
Consumption	Consumer mains	Water meters, flow sensors, pressure sensors
Leakage	Pumps, valves & Transmission mains	Acoustic sensors
Quality	Sources, reservoir, treatment plant	pH meter, TDS and conductivity meter, temperature meter, turbidity meter, ORP meter, dissolved oxygen probes, ion-selective electrodes, total dissolved gases sensors, chlorophyll content sensors
Water level	Reservoirs, storage systems, water towers, and tanks	water level gauges such as floating hydrometers, bubblers, pressure inductive gauges and sonic gauge
Fault detection	Transmission mains, reservoir, treatment plant, and storage structures	pressure sensors, such as piezoresistive, capacitive, electro-magnetic, piezoelectric and optical gauges, normally installed at demand nodes, control valve inlet/outlet, and pump suction/discharge to monitor pressure heads

TABLE 9. Real-world water supply system monitoring platform.

Water management system	Country	Features
HydroIQ [52], [143]	Kenya	A smart and automated meter device known as Water virtual network operator (WNVO), which has the analytic tools, IoT communications, and automatic payment technique. It also monitors the following parameters in real-time, i.e. leaks/faults, water pressure, and water quality and also control domestic water consumption of the of water distribution system. The water bill can be paid via pay-as-you-go (PAYG) feature, which is an electronic channel for online mobile payment.
South East Queensland (SEQ) water grid [144], [145]	Australia	Physical measurement of water use via smart meters with subsequent remote transfer of high resolution data and Water demand forecasting platform Waterhub. Waterhub is a critical system for regulatory compliance in bulk metering management and reporting
Water Supply Network (WSN) of the Public Utilities Board (PUB) [146]	Singapore	The system consists of real time monitoring using smart sensors, and analytic tools for decision support system. It has also other features such as, water quality real-time monitoring, event prediction, demand forecasting, automated meter reading (real-time water utility information/updates), and asset/infrastructure management (risk management platform development, data mining, and database integration).

toring, control, and automation of water distribution network [150], including (a) smart sensor data usage improvement [151], [152], (b) management and governance of the internal functions within the smart water distribution environment which includes the management of the source, storage, and distribution of water [47], [153], [160], (c) detection and limiting of the leakage and cost-saving [161], (d) increase the business efficacy via automating the traditional processes and functions [162], [163] and, (e) the water quality improvement [164]. A major challenge that the water distribution system has to conquer is to provide the utility with the required information in a rapid manner. Therefore AI possesses significant potential to address the urgent challenges encountered by the water distribution network. Over previous decades, there has been a considerable of research and applications of IoT, including in (a) intelligent distribution network [165], (b) robotics [166], [167], (c) water distribution network optimization management [168], [169], (d) automation [170], [171], and (e) knowledge-based systems and decision support systems [172]–[174]. The list of various WDN applications, their monitoring parameters and used ML/AI techniques listed in Table 10. Further, we list the real-world water supply system monitoring platforms in Table 9.

IV. ANALYSIS OF IOT CHARACTERISTICS AND CONSTRAINTS IN THE DEPLOYMENT OF WDN

The IoT system suffers with inherent constrains such as updates, heterogeneity, standardization, security and resources [175]. This section explains the predominant IoT characteristics and the major constrains in implementing an IoT system for water distribution network.

- The non-linear and non-stationary features and vague properties due to the unpredictable natural processes, interdependent relationship, and human interference make the water-related data difficult to design [176].
- To avoid the poor quality of data, advanced tools and technologies like AI and machine learning are used to achieve reliability [177].
- A standardized architecture for IoT is not proposed yet, and is customized according to the applications in order to achieve the IoT system characteristics [178]. Greater standardization can improve the compatibility among different vendors and ensure sufficient network connectivity, data management, and security measures across devices, actuators, and sensors cloud servers and end-user interfaces in the system. This also reduces the gaps between the protocols, hence improves the security as well as reduce the overall cost of data [179].
- Another limiting factor of IoT deployment is energy depletion [180]. The life span of the IoT network deployments can be improved by better power management using alternative power storage mechanisms.
- Sophisticated design and development for various modular hardware and software exclusively for the water distribution system are required. The high-quality sen-

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TABLE 10. Monitor-automation-control applications in WDN based on AI.

WDN Application	Monitor-control-automate parameters	ML/AI Techniques
Real time control of WDN mains [154]	Pressure, flow & power	Artificial Neural Networks (ANN)
Water quality [155]	temperature , pH, specific conductivity, bicarbonate, sulfates, chlorides, total dissolved solids, sodium, magnesium, calcium	Multilayer perceptron (MLP), Support Vector Machine (SVM), and group method of data handling (GMDH)
Water resource management [156]	Global and regional climate, regional hydrology, land use, water withdrawal	Adaptive Intelligent Dynamic Water Resource Planning (AIDWRP)-Markov's Decision Process (MDP)
Water Demand Forecasting [157], [158]	Previous water demands, average temperature, solar radiation, and reference evapotranspiration	Neural Network-Based Methods-support vector regression (SVR), extreme learning machine (ELM), multiple linear regression (MLR), particle swarm optimisation–ANN (PSO-ANN), hybrid backtracking search algorithm ANN (BSA-ANN), deep learning (DL), Random forest, Multivariate Adaptive Regression Splines (MARS) and Projection Pursuit Regression (PPR), Long Short Term Memory (LSTM), auto-regressive integrated moving average (ARIMA), seasonal auto-regressive integrated moving average (SARIMA), Bayesian additive regression trees (BART), gradient boosting machines (GBM), and Bayesian framework & Genetic Algorithms (GA)
Leak Localization [159]	Leak location, leak size, and base node demand uncertainty	Random forest classifier

sors and actuators for water distribution systems are costlier compared to the low-cost embedded computing platforms. IoT solutions require huge number of nodes (may be hundreds and thousands in number), and hence the overall cost for hardware components, internet communication, and data roaming have to be reduced [181].

- There exists compatibility between the water supply infrastructure which is a legacy system to the specialized devices, field equipment, and software, and so forth. As data synchronization and data reliability are more important, the scaling of the IoT networks and IoT devices are critical [182]. Therefore a systematic design and development of the software can standardize the analysis of the generated data, code refining, and feature introduction and upgrading [183].
- The water supply infrastructure is spatially distributed and the whole supply process is temporally distributed. Hence, to improve efficiency for field deployments the commercial IoT solution must handle basic environmental parameters such as temperature variations, humidity, and illumination to deal with seasonal variations and infrastructure-wide climatic variability.
- The security for the IoT realization in the water distribution system is necessary [184], since the water networks are spatially distributed networks, it requires IoT systems to address the end-to-end data security and integrity of the field-deployed devices. IoT security is a major constraint in IoT system deployment where the vulnerabilities include clone attack, network hacking, jamming, eavesdropping, distributed denial-of-service (DDoS), and untrusted communication between devices [52], [185], [186]. The cloud server downtime and inaccessibility of services can influence trust and manipulation of data residing in a central location architecture [141], [187], [188]. Moreover, the industries are introducing external internet access to the existing infrastructure which can increase the vulnerabilities of the cyber-attacks.
- The system design for water supply can be divided into three-levels: user-centric, utility-centric, and infrastructure-centric. User-centric design and sustainable practices are also important in the field of IoT implementation for water distribution systems [189].

Therefore we can conclude capacity, cost and exponential growth of IoT devices, vulnerabilities in IoT architecture and data theft are the major challenges for IoT deployments.

V. SERVICES AND TECHNIQUES FACILITATES WDN

The realization of an IoT based water distribution system includes, the type of IoT network architectures (edge/fog/cloud), underlying protocols, appropriate communication technologies etc. Based on the survey conducted in this paper, Table 11 summarizes these details with existing platforms for various water distribution system applications.

A. IOT ENABLED FRAMEWORK FOR WDN

To summarize the findings of this study, we propose an IoT-based water distribution network framework for monitoring, control and automation of the system, as illustrated in Fig. 4. The service architecture includes sensors, hardware, software, communications, visualization modules and controllers, data management software, data mining software, customer systems, and business systems. The layered framework intend to classify the components and interfaces into various categories according to their features and functionalities. It has four main layers: physical layer, communication layer, service layer, and application layer.

1) Physical layer

Physical layer includes the sensors, actuators, preprocessors, interfaces and other devices to intelligently capture and connect the valuable data on the functioning of the water distribution network while sensing field variables using an IoT communication network. The sensors (see Table.8) are to monitor the stimuli and respond to events in the water supply systems. The sensors or actuators can

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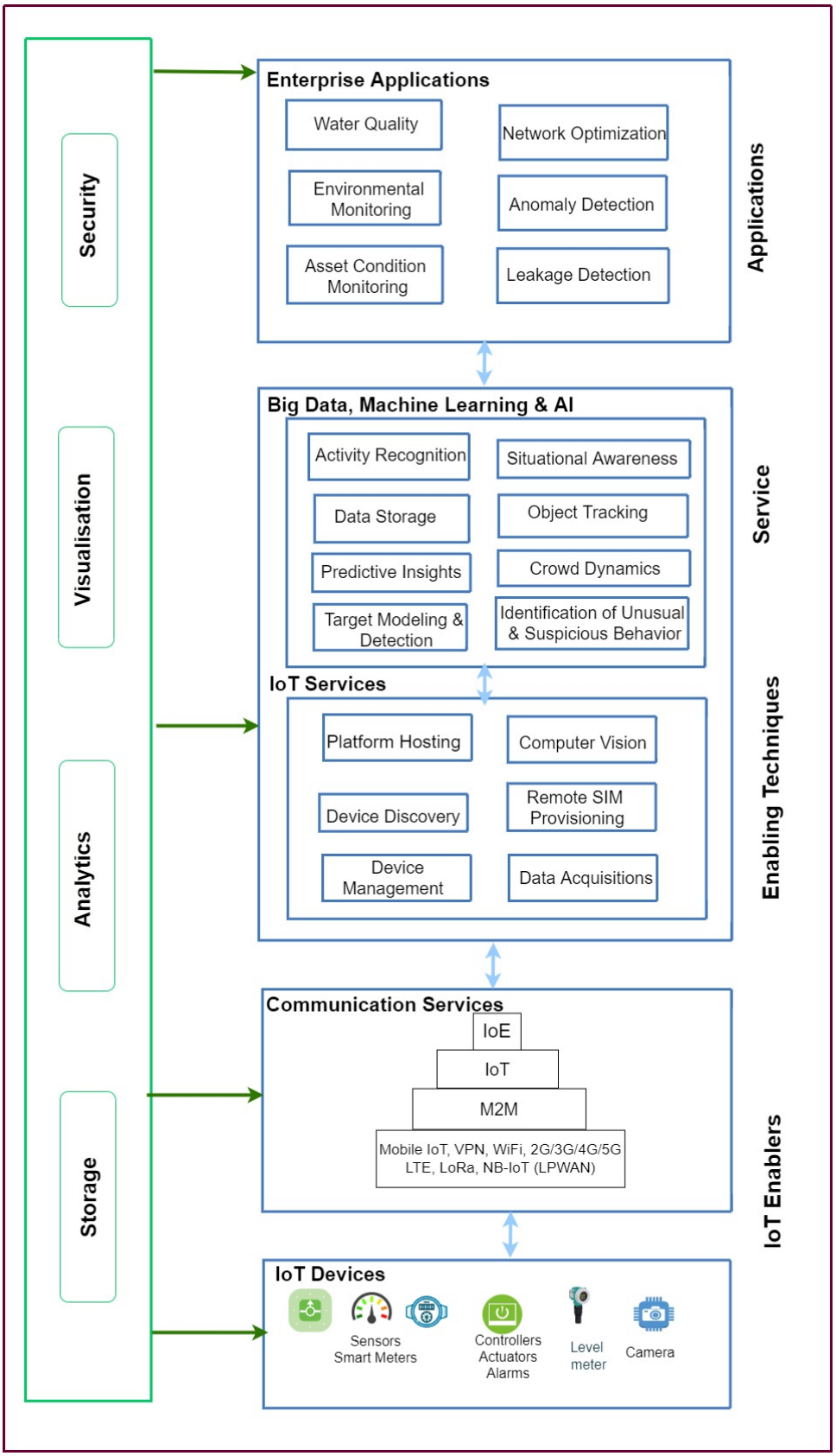


FIGURE 4. Services and techniques facilitates water distribution system.

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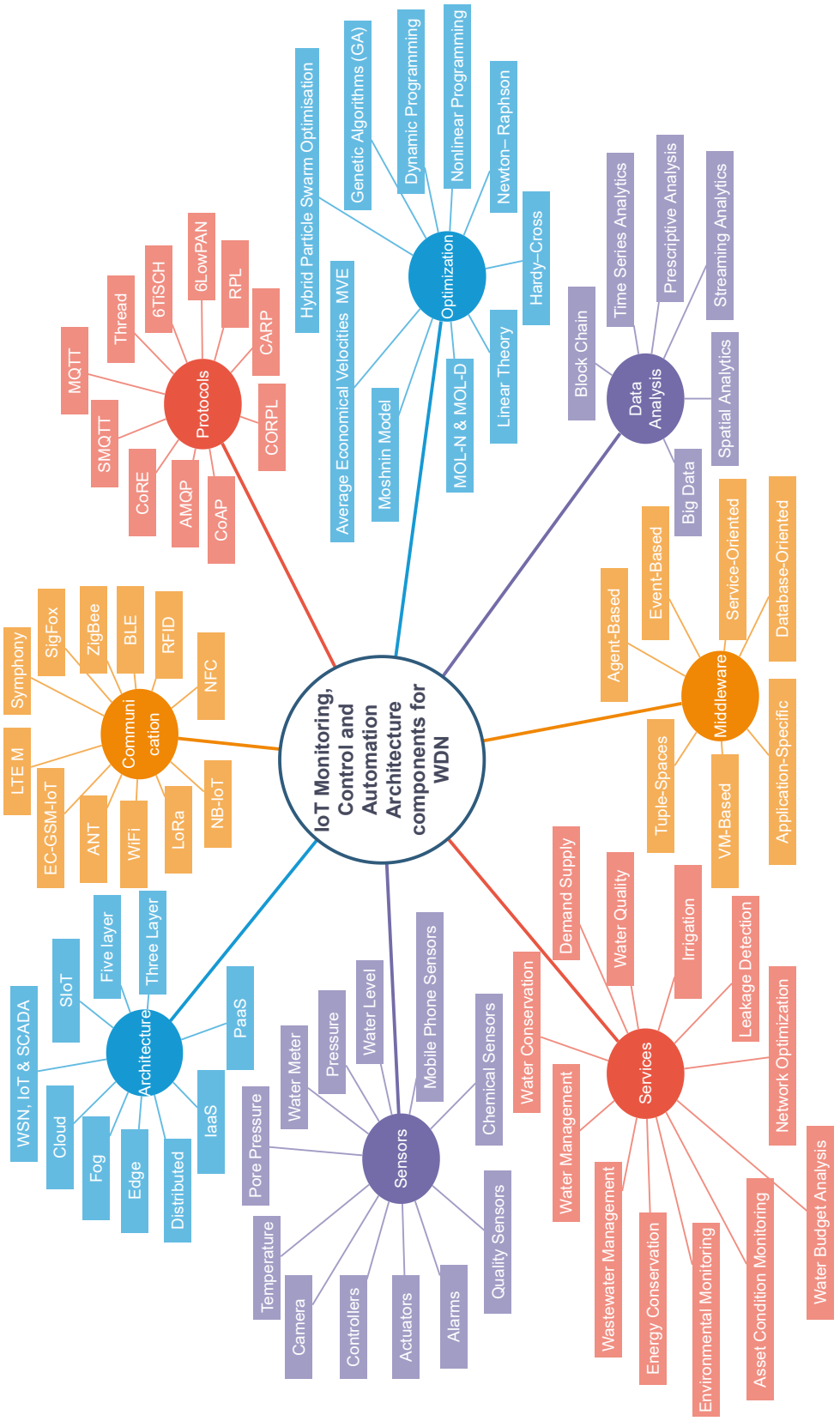


FIGURE 5. The components required to build an IoT-based architecture for monitoring, control and automation of WDN.

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TABLE 11. Real-world application platforms for IoT based water distribution systems

Application platform	Cloud	Fog	Edge	Technology	Protocols	Applications
AgriSens [190]	✓	-	✓	ZigBee, GPRS	Time Division Multiple Access	Water management in fields
AQMS [191]	✓	✓	✓	IEEE 802.15.4, Bluetooth 4.0, ZigBee-IP/ZigBee, and WirelessHART, Wi-Fi, LiDR, LoRAWAN,	MQTT, secure MQTT (SMQTT), CoAP,	Water quality monitoring
Fiware4Water [192], [193]	✓	✓	✓	LoRa, SigFox, Next Generation Service Interfaces	HTTP, MQTT, AMQP	Tank monitoring
ICeWater [194]	✓	-	-	ZigBee, 6LoWPAN, ISA100.11, Bluetooth, Z-Wave, ENOCEAN, IEEE 802.15.4k, WI-SUN, Wireless MBus, SigFox, LoRa, Weightless, Wavenis, Dash7, LTEM, LTN ETSI	-	Water Loss Management (WLM), Water Operation Support (WOS), Water Supply System Planning (WSSP), Water Demand Management (WDM), Water Asset Management (WAM)
MASP [195]	✓	-	✓	USB/WiFi, SENSIBUS	proprietary SENSIBUS serial protocol	Automated recognition of water contaminants
Smart Water Grid [196]	✓	-	-	LoRaWAN, SigFox, NB-IoT	-	Water infrastructure monitoring
SWSDF Framework [197]	✓	✓	-	Wi-Fi	HTTP	Water consumption abnormalities such as leaks or excessive consumption and alerts
Smart Solutions based on IoT Technologies [198]	✓	-	-	LoRa	HTTP(S), WebSocket, MQTT	Water metering and consumption
SENSIPLUS [199]	-	-	-	Wi-Fi, Bluetooth Low Energy (BLE) and USB/BLE/Wi-Fi, SENSIBUS	TCP/IP, Advanced Message Queuing Protocol (AMQP)	Water quality
SWDS [103]	✓	✓	-	Bluetooth, 3G,4G	-	Water level
UIoT [200]	✓	✓	✓	-	-	Underwater IoT communication
WaCoMo [201]	✓	-	-	Wi-Fi	MQTT	Water Consumption
Wastewater management [202]	✓	✓	✓	Bluetooth, WiFi, 3G, 4G, and 5G	-	water storage level, water consumption rate, wastewater generation, and industrial wastewater treated by WWTP
Water Demand Prediction System [203]	✓	-	-	Wi-Fi	MQTT	Water Demand prediction
WQMS [121]	✓	-	-	LoRa	-	Water quality

achieve two-way communications within the network by providing commands to be sent from the water utility to the smart sensors for various functionalities, including real-time monitoring of parameters such as water flow at the pipes, pressure at the nodes and changing the frequency sampling of readings. Furthermore, short-term deployments of devices/sensors powered by batteries, and long term deployments can be powered by solar panels due to their low-power consumption characteristics in the sensing layer. Moreover, the control part of the sensing layer can acts as a data sink, transceiving data from the communication layer. The data/information received to the control layer can alter the actuators state. The communication network between the sensors and the utility center intends to collect and distribute the relevant information to consumers, suppliers, stakeholders, utility companies, and service providers. Each sensor has a specific communication technology, which is dependent on the climatic and geographic (spatial and temporal) conditions, and multi-criteria decision methods. Therefore to choose the most appropriate and reliable communication technology, both the quantitative and qualitative variables are taken into the consideration. Furthermore, the sensor location and distribution, the distances to the edge device, the communication costs, the urban context, restrictions and governance, and the scalability are the parameters that need to be considered for choosing the best communication technology.

2) Communication layer

The communication layer which is contextually known as network layer, is responsible for the IoT system connectivity to the network technologies for a secure and robust data communication to other layers. Therefore, the communication layer reciprocate the communication between the data collected from the sensing layer and send the data via field gateways. The primary objective of the communication layer is to establish a communication channel for data transfer from the physical layer to the internet and receive data from the IoT gateway based either on Ethernet or other communication technologies (see Table.5) Wi-Fi, WiMAX, Zigbee, mobile communications, LoRa, RFID, and Bluetooth Low

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Energy (BLE), NB-IoT, 5G etc [204]–[207]. This layer has the field gateways which interfaces IoT gateways or edge nodes with transceivers using ZigBee, Bluetooth, NFC, Wi-Fi, LoRa, or Sigfox.

3) Service layer

The service layer serves as the interface for both the consumer and the IoT system. The service layer has two sub-layers, IoT services sub-layer and analytical services sub-layer. The IoT services sub-layer handles data ingestion from the communication layer and the analytical services sub-layer handles data processing (digestion) and perform various analytics. The IoT services sub-layer provide services for the system to achieve device management [208], data acquisition [209], device discovery [210], [211], remote sim provisioning [212], [213], platform hosting [33], [214], [215], and computer vision [216], [217] which are closely accessible for the physical layer, i.e., data and device interaction (middleware layer) [218]–[220]. The analytics services sub-layer handles data processing such as target modeling and detection, identification of suspicious behavior in the network, data storage and situational awareness, crowd dynamics, object tracking, and activity recognition. The services of Big-data [221], [222], Machine learning and AI [223]–[225] analytic tools are taken in this layer in order for the water distribution network modeling, hydraulic simulation, and optimization [226] to form useful insight to which the real-time data can accommodate, validate and predict the system behavior, as shown in Fig.3. The storage, security, data analytic tools, and visualization modules are needed to process and compute the data and data models. These modules intend to provide services for both the service layer and the application layer.

Since the service layer shares and analyze the information of the consumers and the IoT system, this layer is highly vulnerable and affects the authentication and security of the system. To rectify the issue some robust and flexible security protocols are widely used. The following are the specifically proposed IoT protocols (see Fig.5): Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (COAP), Secure Message Queue Telemetry Transport (SMQTT), IPv6 over Low -Power Wireless Personal Area Networks (6LoWPAN) and Routing Protocol for Low-Power and Lossy Networks (RPL). Since these communication protocols are modifiable, the user can define the desired functionalities according to the applications without compromising the protocol performance. Therefore the factors influencing the selection of the most appropriate protocol for an IoT system are the network range (area of the action), openness, interoperability, and network architecture [227].

4) Application layer

The application layer takes services from the service layer and allows the end-user to handle monitoring, control, prediction, and services. For the water distribution system, there are specific applications [228], [229] such as water quality monitoring, treatment processes monitoring, the data analysis leads to the control measures, and automation of the control process (e.g., Chlorination). Environmental monitoring, water distribution network infrastructure monitoring (asset monitoring), leakage detection, the anomaly detection for the entire network by analyzing both spatial and temporal scale, consumption analysis, and demand prediction are the different application-level functionalities for the water distribution system.

The components required for the implementation of Intelligent IoT based water distribution network shown in Fig 5. This encapsulates most of the studies analyzed in this paper such as IoT sensors, communication technologies, protocols, architectures, optimization techniques, data analysis methods and types of middle-wares. With all these insights we are recommending an architecture for intelligent IoT based water network.

VI. RECOMMENDATIONS BASED ON THE SURVEY

A. RECOMMENDED ARCHITECTURE: IOT ARCHITECTURE FOR INTELLIGENT WATER NETWORK - IOTA4IWNET

The proposed architecture depicted in Fig.6 summarises the studies performed in this survey. The architecture contains the WDN applications for a system's monitoring control and automation. The IoTA4IWNet architecture is split into WDN applications and four planes i.e, IoT edge plane, IoT fog plane, IoT cloud plane and IoT service plane. The IoT service plane further divided into edge services sub-plane, fog services sub-plane and cloud services sub-plane.

1) WDN applications

IoTA4IWNet can monitor, automate and control the water distribution system in applications such as demand (consumer), junctions, water levels, leaks, reservoir, treatment plant, and utility (services). Consumer demand monitoring is beneficial for optimizing the water quantity allocation from various water sources, deriving individual and cumulative water usage patterns, and creating awareness regarding water usage among stakeholders of WDN. In WDN, junctions are one of the vital entities where monitoring is essential since they are prone to various threats. Information on water level variations in each reservoir, storage system, and water tower are significant for planning the water allocation, optimizing the water usage, scheduling the pump on/off, and determining the water overflow. In WDN, water leakages are also one of the significant threats, and their monitoring is tedious (see Table10). Reservoir monitoring is required to determine the quantity, quality, seasonal variations, and optimized water allocation. Treatment plants are one of the essential entities in WDN as the change in water quality can adversity affect the health of consumers as well as WDN infrastructure. The quality and quantity assessment of portable water, usage pattern analysis, water demand profile maintenance and prediction, the discovery of malpractices,

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and automated water meter readings and billing are some of the services that come under utility that are intended for the consumers. For enabling all these services, WDN monitoring, automation, and control are essential.

An example scenario for the IoTA4IWNet architecture is as follows; sensors are deployed to monitor water pressure within a distribution network. A single sensor out of a thousand deployed, sensed the pressure variation in one single node due to a water hammer (single instance), thus raising a false alarm. The edge node closest to that sensor reacts immediate due to proximity, however, a hierarchically higher fog node at the city's observatory office collates all responses from sensors and passed it to the cloud. Thus, a predictive judgment is made based on machine intelligence. This prediction can be used for future occurrences.

2) IoT edge plane

The edge plane consists of four layers; the first layer contains sensors and actuators for sensing water system parameters and state transitions for the parameters. The second layer contains the interface devices such as analog to digital converters, multiplexers, relays, filters, and so on, which will help in data acquisition. The third layer consists of IoT network and processing devices such as base-station, switches, processors, visualization modules, and so on. The fourth layer in the edge plane is the communication interfaces for sensors to edge devices. From the survey (Table 5, 7, 11) the communication technology used in edge planes are BLE, Bluetooth, Zigbee, NB-IoT, LoRa, Wi-Fi and LTE. The communication interface between edge to fog nodes is shown as an overlapping layer between the edge plane and the fog plane. The edge plane contributes resources and voluntarily assists the fog and cloud plane in transmission, communication, and computation, and handles multiple end devices/users. Scheduling and resource provisioning, mobility consideration, security, privacy, and authentication are the tools that help in satisfying the edge plane functioning [230], [231]. Low power wide area networks [232] can be used for the best communication results in this plane as it has the advantage of low power consumption and long-range communication features [233].

IoT edge services: The services provided by the edge plane are sensing and actuation of the system parameters. These services are transferred to routing of the devices in the edge network, caching the data (micro data centers), computing (things/devices), and control of the edge plane devices. Context-aware and location-aware services can be extracted in the edge plane. It also provides communication interfaces for cloud and fog planes. The security service provides a trust relationship between the edge plane to the fog and cloud plane by guaranteeing the required device security, communication security and integrated computing module security. The possible threats and attacks in the edge plane and their mitigation measures are listed in Table 12. Federated edge computing can also be brought into this architecture for computation optimization.

The introduction of edge plane reduces the latency and perform distributed computation and storage in local proximity of the IoT devices, which will reduce delay, improve the security, scalability, and bandwidth for the entire system [234].

3) IoT fog plane

The fog plane is responsible for infrastructure-based computing [235]. It can inter-operate all its connected devices and provide the necessary service support even if the internet connection is intermittent. The fog plane can be considered as the distributed virtualized platform dedicated for intersection of edge services and cloud services. It extends the services and functionalities of the cloud plane to the edge plane such as database operations, storage (mini data centers), computing, integration, security, and device management to the proximity of the edge plane. The benefits of the IoT fog plane are reducing network congestion and end-to-end latency, improving privacy and security, and enhancing scalability and connectivity [236]. The fog network device layer consists of devices that can enable connectivity between edge to fog, fog to cloud and within fog plane. The fog computing devices can get the context-aware computing paradigm by moving the intelligence to LAN level and data processing at fog plane. The communication interface layer enables the communication between fog nodes using LPWAN technologies and communication interface for fog plane to cloud plane using 4G/5G/6G technologies.

IoT fog services: The services provided by the fog plane includes storage (mini data centers) and computation of the data. The data from the edge plane processed in fog plane and enables the services to both edge plane and fog plane. Various computing algorithms run at the fog plane and extract remote intelligence of the data by the analytics. The anatytic service is vital for extracting the insights for future updation of the system. Machine learning and deep learning are some of the tools used for analytics. Furthermore it provides integration services and user interface services. The integration services allow dynamic management and future development of the fog plane. It also provides the communication interfaces services for cloud and edge plane. The security service provides a trust relationship between fog plane to the edge plane and cloud plane by guaranteeing the required network security, communication security and integrated computing modules security. Refer Table 12 for security threats and mitigation measures for fog plane.

4) IoT cloud plane

The IoT cloud plane is introduced to deal with massive data (Big data). It is the most powerful plane in terms of computation, efficacy, storage and other resources. The cloud plane consist of network of data centers which accumulates with various application data. From the survey conducted (see Table.11) COAP, MQTT, AMQP and HTTPS are the communication and application protocols that provide services based on Representational State Transfer Application Pro-

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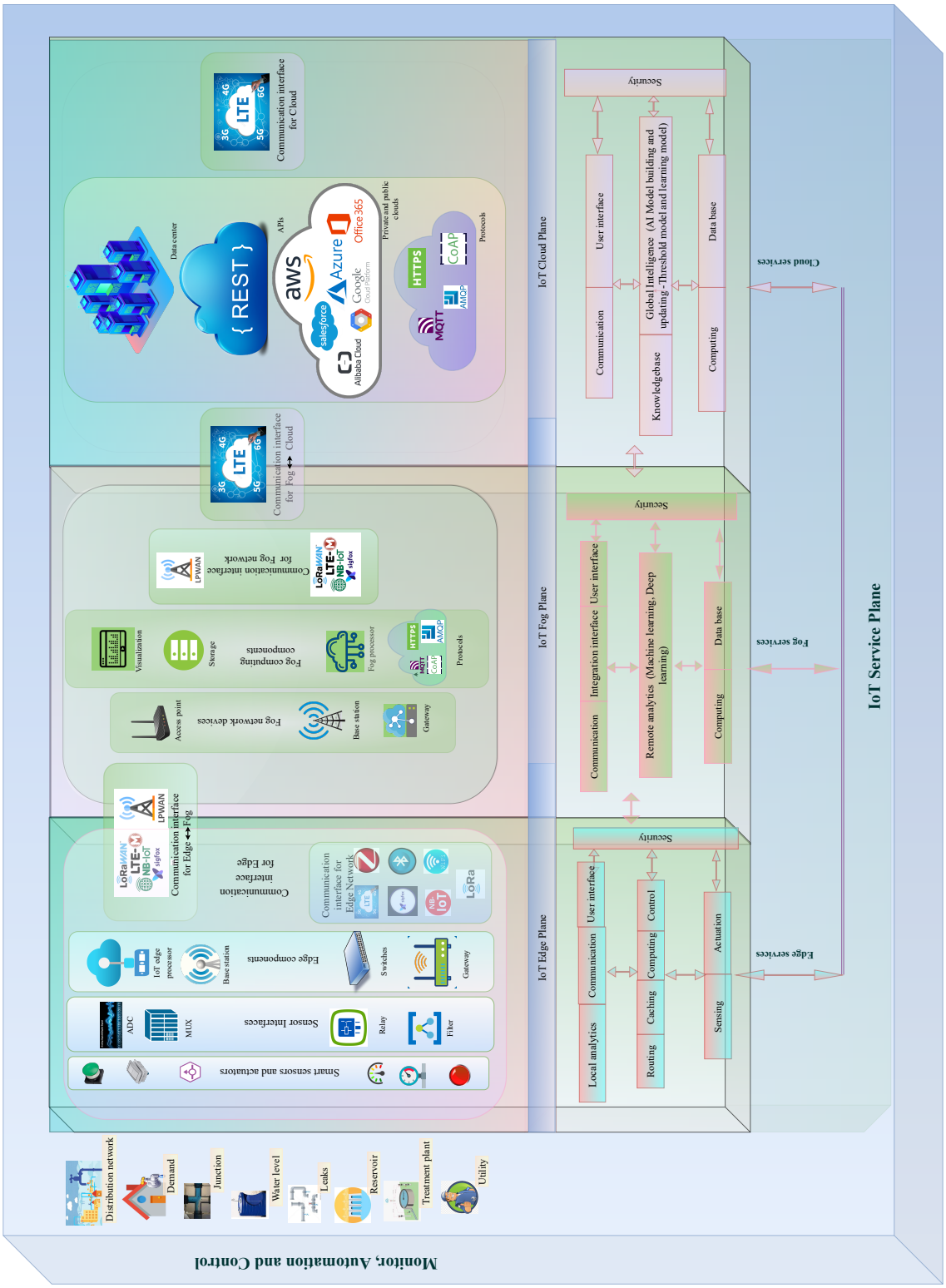


FIGURE 6. IoT Architecture for Intelligent Water distribution Network - IoTA4IWNet

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gramming Interface (REST API) [237]. The communication interface layer for data centers and cloud platforms consist of 3G/4G/5G/6G [238] networks. The IoT cloud platforms widely used for various water system application are given in Table 6. Since the IoT cloud layer deals with Big-data, the analytic techniques can combine with the Big data, which can be structured, semi-structured, or unstructured. The data cleaning and autonomous data quality check are significant roadblocks to the WDN system due to the integration of several heterogeneous data sources/sensors. We can fine-tune the Big data analytics for WDN by including all the influencing parameters, such as physical, chemical, biological, socio-economical, geospatial, and behavioral of the WDN system, to predict short-term to long-term changes. Data-driven decision-making, scientific discovery, and process optimization of WDN can be achieved with the help of Big data analytics [239]. Demand forecasting, water leak predictions, reservoir capacity prediction, reservoir water level predictions, queries, reports, visualization and interpretation, modeling and prediction, service improvement, and auditing and evaluation [240], [241] are the other outcomes of the data analytics for WDN system. The following are the major outcomes of WDN integrated with Big data analytics:

- *Sustainability*: Big data analytics with existing and future water infrastructure represent a significant unexplored opportunity for the operation, maintenance, and rehabilitation of WDN infrastructure to achieve economic and environmental sustainability [242].
- *Responsiveness*: For a failure scenario event, big data analytics can accelerate and improve response and selection of mitigation strategy by elucidating the state of emergency and the effectiveness of alternative scenarios to the decision-makers [243].
- *Durability*: Big data analytics models can help by extending the service life of existing long-term water infrastructure assets through a set of strategies to intensify, maintain, rehabilitate, and replace infrastructure [241], [242].
- *Model-based risk analysis*: With high-resolution, real-time data feed integrated with the hydraulic model, an actual image of the current system conditions and its projections under different possible response and recovery scenarios is provided [243].
- *Resilience*: To gain a critical view of a utility's infrastructure for strategizing recovery efforts by integrating real-time, high-resolution data with their water distribution model. The improved response times during planned and emergency outages by reducing the time spent setting the model boundary conditions. [243].
- *Reliability*: The improved operation, maintenance, and optimal scheduling, rehabilitation, and resilience improve the reliability of the WDN [244].

IoT cloud services: The cloud services are integral part of IoT realization. The services provided by the cloud plane includes storage (macro data centers) and computation of the data. The knowledge-base and global intelligence analytics of the system are performed in the cloud plane. It provisions AI model building and updates, threshold modeling and learning models. It also provides user interface services. Furthermore, it enables the communication interfaces for fog and edge plane and security services.

TABLE 12. Cyber security measurements for an IoT system.

IoT Plane	Security threats/attacks	Existing measures for maintaining cyber-security
Edge plane	Network attack [250], port attack [251], proximity attack [252] and physical attack [253]	Confidentiality, integrity, access control, encryption and authentication, regular security patches and updates, physical security, backdoors and logins, intrusion detection systems (IDS) and IP fast hopping [254], [255]
Fog plane	Man-in-the-middle attack (MITM), data and security access management, reduce delay time, real-time attack detention, and prevention of unauthorized access to information [256]–[258]	Intrusion detection technique in combination with Hellman key exchange, Shibboleth protocol, block chain-based distributed cloud framework, AES and SSL [259], [260]
Cloud plane	Side channel attacks, denial of service attacks, social networking attacks, Mobile device attacks, insider and organized crime threat, cheap data and data analysis, cost-effective defense of availability, increased authentication demands, and mash-up authorization [261]	Information-centric security, high-assurance remote server attestation, privacy-enhanced business intelligence, authentication, authorization, and digital Signatures [262], [263]

Cyber attacks focus on IoT devices, software, and network as device attacks, data attacks, privacy attacks, and network availability attacks. As WDN systems are critical to human lives, the IoT-based WDN infrastructure can be sensitive to/prone to political, military, and terrorist activities [245], [246]. Hence the cyber security for the WDN system should be ensured for the reliable water distribution networks [247]–[249]. The types of attacks on cloud plane and its existing measures for maintaining cyber security in the WDN-enabled IoT system are present in Table 12.

B. EXISTING CHALLENGES AND FUTURE DIRECTIONS

This paper deals with two contexts, water distribution system and impact of Internet of Things in WDS. The challenges for water distribution systems are climate changes, urbanization, population growth, infrastructure deterioration, governance and policies, emerging technologies, energy costs, changing priorities of public, and complexity. The challenges for the IoT in WDS are listed in Table 13.

A sustainable management of water distribution network requires both technical and hydrological dependent system. A water distribution network varies spatially and temporally, i.e, according to seasonal changes, the water availability varies in the case of water network. The water distribution

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network is a complex infrastructure with inter-dependent entities and parameters, hence challenging the IoT integration on top of the network. The non-invasive sensors and control modules preferred over invasive modules as health of the infrastructure is delicate. Most of the real time implementations are pilot set ups and lacking end-to-end real time system. The scalability, security, implementation cost optimization, maximum bandwidth utilization via virtualization are the future directions of this application.

The real-time monitoring and control of the WDN is challenging due to dynamic spatio-temporal variabilities. Health monitoring of each entities in the network such as pipe, valves, pump, nodes, and so on, due to cost effective and lack of appropriate IoT compatible sensors and devices. This can be rectified by design and implementation of a full fledged monitoring system, in a framework of optimized available sensor usage and incorporated software advancement (AI based ML algorithms). Real-time demand monitoring, forecast and the implementation of the algorithms are primitive in WDS area.

Several factors include seasonal variations, climatic changes, types of geographical regions such as urban, suburban, and rural, and user behaviour that affects the variations in water demand. In a year, temporal variations of water demand can experience spatially based on geographical variations. For instance, in India, water usage is 30-40% higher in the summer than in other seasons [264]. However, in some nations like Netherlands, water usage is higher in winter as the heater always works [265]. Likewise, climatic changes influence water demand variations. For example, the water requirements on a rainy day are lesser than on a humid day. Moreover, the daily water demand varies for rural, and urban areas as the water usage is 40 liters per capita per day (lpcd) for rural areas and 140 lpcd in urban areas as per the Ministry of Housing and Urban Affairs [22]. Variations of user behaviors based on social practices, religious practices, and regional practices influence the water demand. Major challenge in designing the IoT architecture for water demand application is comprehending all these dynamically varying factors that affect water demand.

AI-ML enabled data driven operations, predictive algorithms, and digital twin methods can be mitigate the challenges in demand forecasting. The water quantity is one of the influencing factor for sustainable WDS operation. Monitoring the water levels of different kind of storage structures is necessary as its dynamic spatio-temporal variability characteristics. It is also important for planning and regulations of policies for an area. Suitable sensor unavailability due to cost and performance, the sub optimal manual intervention for the pump, valve and motor operations, climatic changes makes monitoring of the application challenging.

Water level monitoring challenging as the sub-optimal decision making due to human intervene, hence automation of the level monitoring has an important role in WDS automation. Real time monitoring of the water level leads to low water wastage, optimized water usage, sensible intake of water from reservoir. The water levels in any storage structure depends on climatic variability. A fully automated system with optimal decision making can overcome the challenges due to manual interventions (pump, motor and valve operations -(dry run, on/off)).

In WDS, junctions plays an important role as it is the most vulnerable entity. Control and monitoring of the junctions enables the WDN to identify the theft, illegal connection, pressure drops, pipe burst and so on. Predictive maintenance and autonomous operation can make the entity self resilient. Security is the one of the key element is automation of junctions. Hence block chain based predictive maintenance and autonomous system can mitigate the challenges.

Water leaks is one of the frequent and unavoidable factor in a distribution network. Since most of the pipes are in underground, the leaks may leads to the wastage of considerable amount of water. Ultrasonic sensors, ground penetrating radar (GPR), sonar, nano/micro robots, radars are some of the techniques used to identify and prevent the leaks. However, it requires an integrated framework for monitoring, control and automation of junctions pipes and appurtenance, as junctions and underground pipes are more prone to leaks. It is also important to analyse the impact of risk assessment due to the pip burst or leakage.

Water system starts with reservoir, hence it is important to monitor the quantity, quality, and health of the reservoirs. The system able to handle the dynamic characteristics of the reservoirs such as spatio-temporal variations climate changes (seasonal variability) and pollution due to waste dumping, industries, agriculture etc. A cost effective sustainable IoT-integrated intake system, which caters all the above parameters can mitigate the challenges.

Water treatment plant monitoring, control and automation is one of the critical and complex task. The input water for the treatment plant depends on seasonal variability and the IoT system has to capture its dynamically varying quality parameters and also the systematic controlling and automation for each treatment process. Since the WDS is an spatial-temporal distributed system, the dynamic nature of the infrastructure makes the system unreliable for the static strategic functionalities.

Table 14 listed the challenges and recommendations required for IoT system design. Advantages of the IoT in WDN are enhanced transparency for the entire system processes, immense response for identifying and predicting the anomalies and damages, optimized use of human resources, optimized cost, and sustainability (reducing water wastage, pollution and carbon footprint).

VII. CONCLUSION

This paper presented a detailed, up-to-date review of the state-of-the-art of the role of IoT in water distribution systems. It presented the taxonomy of the water distribution system and role of IoT technologies, architectures, cloud platforms in various water distribution applications. It proposed an IoT architecture for intelligent water networks

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Application area	Challenges	Why is it a challenge?	State of the art	Future directions
WDN	• Real time monitoring and control of the various WDN parameters • Health monitoring of the entities	• Piece wise applications implemented to monitor specific parameters. • Since most of the pipelines are underground, the real time health monitoring is limited	Refer Table 11	• Design and implementation of end-to-end monitoring system • Control and automation of the WDN by considering IoT characteristics such as scalability, security, data, stability, security, cost, bandwidth, cloud, edge, and analytics
Demand monitoring and forecasting	• Real time monitoring of water demand • Efficient algorithms for ensuring demand-supply balance • Demand forecasting	• Dynamic spatio-temporal variations • Geographic region wise variations (Urban-suburban-rural) • impact of climatic variations in water sources	• Most of the present research works explores on the impact of seasonal variations in different water sources, however demand variations are not fully explored • Site specific variability of water resources • Most of the machine learning algorithms implemented for the demand prediction is using historical data rather than the real time data	• Intelligent algorithms for demand supply balance
Monitoring water level	Real time control and automation of pump operation integrated with water levels and over flow of reservoir/dam/storage-tank/water-tower	• Manual interventions leads to sub-optimal decisions • Fully automated system with multiple control points depended on multiple sensing points makes the design complex	Prototype design and experimentation available in literature	• Fully automated system for optimal decision making with minimal manual interventions • Data analytics platform to incorporate data from multiple sensing and control points • support multi-dimensional analysis for various operational functions
Control and monitoring of Junctions	Real time control and of the junctions Automation of junction valves	• Illegal connections • Theft • Multiple branches inflow and out flow	Authenticated Block chain based IoT system design	• Predictive maintenance and autonomous operation • Enhanced security algorithms
Monitoring and control of water leaks	• Integrated framework for monitoring, control and automation of junction, pipe and appurtenance • Prediction of the water leaks and • Impact and risk assessment of water leakage to the community	• Since WDN is a wide network and most of the pipes are underground, it is challenging to detect, localize and manage the leaks • In most cases WDN running through highly populated regions, this can create risk to the community due to significant water leakage	• Only site specific robotic leakage detection • Sensitivity matrix-based approaches • Optimization-calibration approaches • Error-domain model falsification-based approaches	• Implementation of IoT based system with crack, moisture and leak sensors • GIS integrated control and monitoring system • Integrated digital twin for water networks, communication network and community • Non-invasive sensors for leak detection for the running system
Monitoring reservoir	• Real time monitoring and prediction of both watre quality and quantity of the reservoirs • Quality • Quantity • Health	• Capturing the dynamic characteristics such as spatio-temporal variations, climate changes, and pollution • Unavailability and cost of sensors	Design and prototype experiments only	• Cost effective real time monitoring methods for water quality • Ensure sustainable water intake from the reservoir • Develop algorithms to predict intake quantity, and quality
Treatment plant	• Security • Real time water quality • SCADA system • Optimized automation	• Integrated control system for actuators, valves, pumps and motors in the water treatment plant • sub optimal manual interventions	Semi automation and controlling for treatment plant operations	• Smart Integrated Validation Plant • digital twin for the Plant • Digitization of operations and management of treatment plant with Data-driven tools • Advanced analytics and artificial intelligence for optimising operations and maintenance

TABLE 13. Challenges and recommendations for IoT applications in WDN

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TABLE 14. Challenges and recommendations for IoT system design

Area	Challenges	Recommendations
Edge plane	IoT compatible sensor developments, Lack of built in security in IoT devices, Implementation of AI/ML analytic, cost	Identification of available sensors in market, Design devices with higher RAM and clock frequency
Fog plane	Real time monitoring and prediction of total and sectored demand calculation for a network, cost	Identification of demand for each consumer point
Cloud plane	Public clouds lacks in security, Private clouds are costlier, Lack of visualization from multiple sensing and control systems integrated in a single frame work	Develop own cloud servers

- IoTA4IWNet, for real-time monitoring, control and automation of different water distribution system applications. This work was guided by an exhaustive literature review and based on that, the research questions pertaining to IoT in water distribution networks and applications were formulated and analysed in great detail. During this study, it was discovered that most of the research focused on monitoring applications and did not cover closed-loop control strategy and prediction for water distribution applications using IoT. An efficient and reliable water distribution system can reduce water stress by avoiding the challenges of the water distribution network. An intelligent water distribution system with operational excellence and productivity can be achieved by using automated IoT systems with predictive analytics. The architecture presented in this paper, for the network automation and real-time operation, will make a significant contribution towards meeting the challenges of building an efficient water distribution system.

VIII. ACKNOWLEDGMENT

We are grateful to our Chancellor, Sri (Dr.) Mata Amritanandamayi Devi (Amma), for guidance and providing us the inspiration and motivation to carry out this work. We also thank Dr. Rekha P, Assistant Professor, Amrita Center for Wireless Networks & Applications for her motivation for writing this paper. This research is performed as part of the Project "Fast forward to SDG6: Acceptable and affordable water in secondary Indian cities (4WARD)" supported by Department of Science & Technology (DST), Water Technology Initiative-National Consortia on Urban Water System (UWS) with project no. DST/TM/EWO/WTI/2K19/UWS-03(G2).

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content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3208142

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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3208142



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