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Demonstration of real-time monitoring in smart graded-water supply grid: an institutional case study

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ABSTRACT

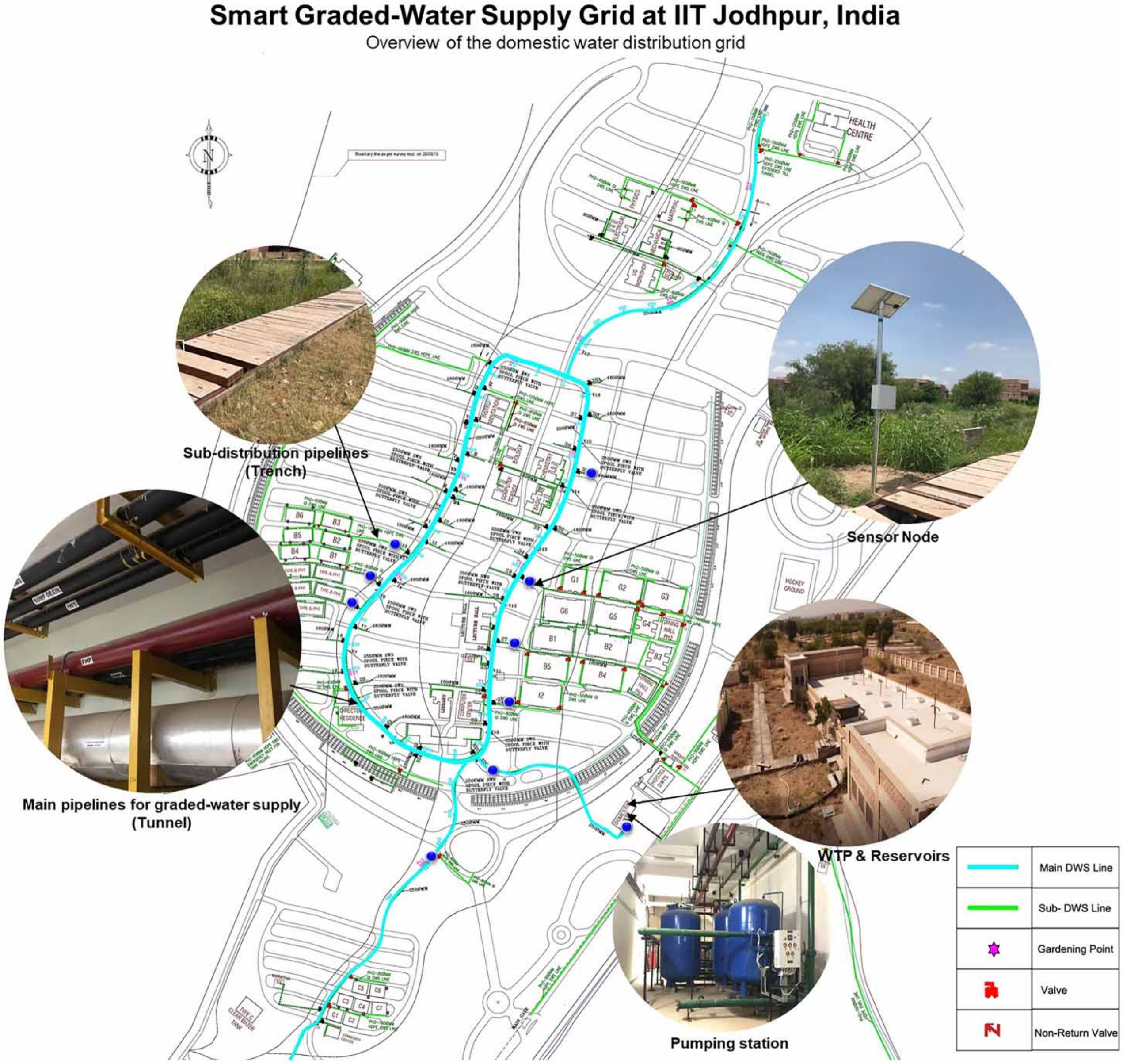
Real-time information on water supply and quality is a crucial asset for planning and managing water resources, infrastructure, and scientific research for sustainable development. In this direction, the innovative concept of smart water infrastructure is progressing. The present paper reports a case study on the demonstration of a `smart graded-water supply grid' on the campus of the Indian Institute of Technology Jodhpur, India. The paper describes the transformation of ~13 km long water distribution network that supplies drinking water to ~5,000 inhabitants into smart supply grid by deploying sensors and establishing an IoT-enabled real-time monitoring platform. The data sets of water flow and pressure collected from sensor nodes are analyzed to understand the characteristic diurnal water usage profiles unique to student hostels on the campus. The data show a distinctive consumption profile of student hostels over the weekdays with a maximum peak consumption of 16.38 m^3/h. Monitoring of vital quality parameters such as chlorine, pH, and temperature demonstrate acceptable levels thereby ensuring compliance with safety standards. The purpose of the paper is to provide insights from a real-world case and close the knowledge gap between general awareness and the potential of smart water grid in sustainable management of graded-water services.

Key words: real-time monitoring, smart water grid, sustainability, water flow and pressure, water quality

HIGHLIGHTS

- An institutional case study of the smart graded-water supply grid in India is presented.
- Deployment of sensor nodes and IoT architecture for remote monitoring is reported.
- Real-time monitoring of pressure, flow, and quality in the water supply grid is demonstrated.
- Temporal variations in water hydraulics and quality are presented and discussed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

An adequate water supply is requisite for the sustainable development of both urban and rural areas. Rapid climate change, population growth, urbanization, unsustainable water extraction, and improper wastewater handling have threatened the clean water supply across the globe (Li *et al.* 2020). It is projected that over 50% of the world's population will be under extreme water scarcity by 2050 (Koncagül *et al.* 2020). India is one of the water-scarce countries with only 4% of world water resources, therefore, at a high risk of a water crisis (He *et al.* 2021). Increasing demand and limited supply of water have raised big challenges for both the government and consumers to manage water resources and supply. Most conventional water distribution systems (WDSs) are either not fully equipped to measure, control, and reduce the loss of water or aging. The disparity between the amount of water supplied into the distribution system and the amount of water utilized by the end user is another key concern plaguing water utilities in the country. A significant fraction of the water supplied to a region is lost owing to water leakage during distribution in network pipes, metering mistakes, or malpractices in consumption. Manual handling and lack of real-time analysis of water network monitoring data further exacerbate water losses in the water distribution grids. To mitigate these water-related issues, the United Nations is promoting the digital transformation of WDSs to ensure the availability and sustainable management of water and sanitation for all primarily in developing countries under Sustainable Development Goal (SDG) no. 6 (United Nations 2023). Advanced technologies like artificial intelligence (AI), the Internet of things (IoT) (Mohanty *et al.* 2016), and new-generation information communication technology (ICT) (Ahad *et al.* 2020) are playing important roles in resolving urgent water-related problems. Some recent reviews (Zaman *et al.* 2020; Oberascher *et al.* 2022a) provide a comprehensive analysis of potential applications of ICT in urban water infrastructures to enhance sustainability and increase the quality of life for citizens. Therefore, adopting advanced technologies is paramount in wiser decision-making and achieving SDG-related metrics as society transitions to a more sustainable future. In addition, many countries around the world are adopting integrated water resource management to address area-specific water challenges with varying degrees of success (Cacal & Taboada 2022; Tayyab *et al.* 2022). Understanding the interactions between ground and surface water resources, agriculture, environment, and society helps access the water needs, policies and required action plans for long-term water management.

A smart water grid (SWG) is an emerging paradigm for long-term sustainable water sources and services (Fabbiano *et al.* 2020; Baanu & Babu 2022). The concept of SWG combines advanced tools with ICT as an integral part of the solution for water distribution and management challenges (Lalle *et al.* 2021). It improves the accessibility and quality of water while simultaneously alleviating water-related issues such as leaks, pressure, flow, and demand in a sustainable manner. Access to robust and actionable data is required for water supply management, planning water resources, designing water infrastructure, and conducting scientific research. Therefore, gathering precise and useful water data is crucial. The deployment of smart IoT sensors to generate real-time data is one of the novel technologies that should become particularly crucial for data collection (Oberascher *et al.* 2022a). Monitoring and analyzing real-time water consumption facilitate systematic and intelligent decision-making in managing water distribution and treatment with minimum use of energy and waste of water in the entire water distribution grid. Although technological information on the smart water grids is accessible, but the path to their deployment is dubious. The key impediments include insufficient integrated and open solutions, difficulties in meeting user's needs, lack of case studies with verified solutions, general awareness, and a lack of regulatory aid. Case studies are useful in learning and adapting solutions to problems associated with real-world scenarios.

During the last decade, several case studies and projects have been reported in the literature to demonstrate the impact of advanced technologies on water distribution (Savić *et al.* 2014; Kouroupetroglou *et al.* 2015; Abbas *et al.* 2017; Rizzoli *et al.* 2018; Antzoulatos *et al.* 2020; Koo *et al.* 2021). However, demonstration studies on smart water distribution networks (WDNs) in universities and academic campuses, particularly in arid or semi-arid climates are quite scarce. Universities are considered to be major water consumers with a large number of users and diverse activities (EPA 2012; Almeida *et al.* 2021). Studies have reported that water consumption per capita is typically higher in university campuses (Yagoub *et al.* 2019; Adams & Jokonya 2022). Management of water supply in large university campuses requires real-time access and visualization of water quantity and quality data. Information on heterogeneous water use by students, faculties, staff, and building types in different time domains allows operators to distribute water with reduced cost. For example, the United Arab Emirates University carried out a study on indoor water use to an understanding of the broad pattern of water consumption on the campus (Yagoub *et al.* 2019). The findings revealed that 47.5% of water use occurred in residential buildings compared to academic buildings based on activity-driven consumption. Among the most recent, the campus of the University of Innsbruck is reported as a Smart Water Campus with a range of sensors including 12 water meters and 6 pressure sensors for monitoring the WDN, and weather stations installed on the ground (Oberascher *et al.* 2022b). The infrastructure offers an innovative testbed for smart and data-driven applications in the field of urban water infrastructure.

In India, the state of Rajasthan is a physically and economically water-scarce region thus under a significant water risk (Niti Ayog 2018). Water contamination due to suspended solids, turbidity, fluoride, and salinity is very common in rural and remote regions (Swami *et al.* 2018). The western region of Rajasthan is mainly occupied by the Thar Desert and, therefore, has a number of drought-prone districts. In addition, the availability of potable water per person is declining steadily due to depleting water sources, population growth, and urbanization. Jodhpur is one of the second largest cities in the state that experiences severe water-related issues such as contamination of water resources by industry (namely, textile and steel industries) wastes. Being in the western part of the state, it also suffers from geogenic climate effects, surface water inaccessibility, water loss, and over-exploitation. Since water is subjected to treatment before it can be used for many useful purposes the overhead in terms of energy consumption varies across different treatment procedures depending on the available sources of water. Over the past two decades, the city has expanded its suburban areas to the northern and southern regions including the settlement of several governmental institutions and organizations. High water demand with limited infrastructure potential for an augmented supply of water has become a common scenario in the region including public and educational institutions. Due to the expansion of higher education in the past few decades, it has become imperative to plan and manage water efficiently at higher educational institutions and other university campuses in an efficient manner. Yet, many institutions, such as the Indian Institute of Technology Jodhpur (IIT Jodhpur), currently operate their WDSs manually. The campuses require water for variety of purposes such as drinking, cleaning, cooling, landscaping, and more. Typical operation is based on water supply from the treated source and emerging conditions to start and stop the pumps and gather data. The water flow and quality information are disruptive, imprecise, uncoordinated, and sometimes come too late to be useful. Moreover, single-source water and original water infrastructure do not take into account the high demands for water posed by the current scale of use. Furthermore, the Government of India is encouraging higher educational institutions in India to transform their campus infrastructure to green and carbon-neutral by 2030 (World Economic Forum 2021). It is, therefore, necessary to upgrade the water infrastructure with advanced monitoring and management intelligence to meet the future demand of increasing student-centric needs with reliable supply and real-time response toward water-related issues. Moreover, the treatment of wastewater and greywater is important in closing the loop by water reuse and recycling to cope with the varying demand and limited supply of water.

This paper reports a case study of the demonstration of the 'smart graded-water supply grid' to sustainably cater to the growing water supply needs of an academic institution in India. A smart graded-water supply grid of capacity 1 MLD (million litres per day) is developed to maximize water use by sustainable management of graded-water distribution inside the institute. The system can distribute bulk water based on graded-water requirements using smart sensors and an ICT network in combination with IoT. Water quantity and quality are continuously monitored in real-time to monitor water consumption, leakages, and quality parameters. Water supply and consumption data are crucial for the system operators to implement water and energy management plans for achieving net-zero sustainability goals within the campus. Real-time data is useful to optimize the water pressure in the distribution network according to the demand pattern. Demand-driven operation cuts down the pumping energy, while still meeting minimum pressure and water quality requirements. The demonstration of a smart graded-water supply system will raise awareness regarding the potential of similar innovative projects at university campuses or municipality scale to reduce water demand while ensuring quality standards. The aim of this study is to share knowledge and disseminate meaningful data essential for developing an SWG for an Indian community. The focus of the work stands on operational as well as future-ready water distribution solutions in India, which need an integration of the water grid to create mutual benefits with respect to reliability and energy savings.

The structure of the paper is organized as follows: Section 2 describes the methodology followed during the implementation of the smart graded-water supply grid and its components. It includes a detailed description of the site, and water supply system under study; the deployment of sensors, and monitoring system is also explained in this section. Section 3 presents the data set collected from the sensors to understand the water use patterns and demand over diurnal and weekly time periods. Section 4 discloses the lessons learned and future work direction. Finally, the paper is summarized and concluded in Section 5.

2. METHODOLOGY

2.1. Site description

The permanent campus of the Indian Institute of Technology Jodhpur (IIT Jodhpur) is located at longitudes 26.37°N and 73.06°E, 25 km north of Jodhpur. The main campus spans over a total area of 852 acres with its three sites A, B and C situated alongside the National Highway (NH62) toward Nagaur. The location of the campus in the Jodhpur district and its three sites are shown in Figure 1. Geologically, the campus area is planar at an average altitude of 200 m above sea level characterized by a hot and semi-arid climate. The groundwater condition is highly variable with a general depth of water level below 40 m bgl.

2.2. Smart graded-water supply grid at IIT Jodhpur

The campus has a well-designed state-of-the-art distribution network for graded-water supply. Separate distribution pipelines for domestic water, irrigation, flush, fire hazard, sump drain, and soft water supply are present to deliver potable water and alternative non-potable water services. This type of graded-water system minimizes potable water use and the risk of potential

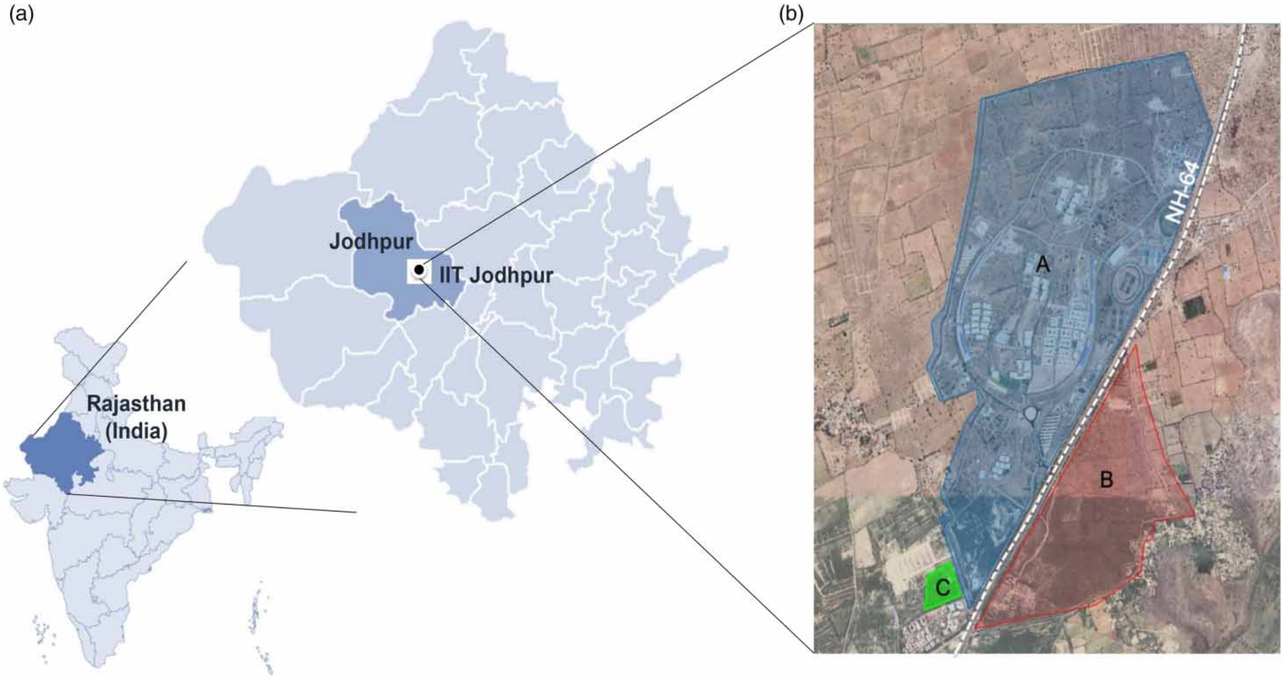


Figure 1 | (a) Location of the IIT Jodhpur in the Jodhpur district of Rajasthan, India. (b) The campus sitemap.

contamination ensuring that the right quality of water is delivered to the intended delivery zone at any time. The main supply line is made of an HDPE pipe of diameter 250 mm that spans the entire campus inside an underground tunnel of about 13 km is laid inside a tunnel built underneath the inner ring-road of the campus. The sub-distribution pipelines of diameter 160 mm branch out of the main pipeline through trenches to supply graded water to different service areas. Figure 2 illustrates the domestic water supply grid of the IIT Jodhpur campus. The tunnel with mains and the trenches with sub-distribution pipelines can be seen in the insets (on the left) in Figure 2. The physical characteristics and data of the domestic WDN are listed in Table 1.

The existing pipeline system has the capacity to supply approximately 1 MLD daily. The primary source of water supply to the institute is operated by the Public Health Engineering Department (PHED), Jodhpur. The source water is fetched through the Indira Canal from the Manaklao pumping station through the trunk main, which is approximately 10 km from the campus. The pre-treated water is first collected in the reservoirs for further treatment at the water treatment plant (WTP) inside the campus. The water is graded and treated before distributing it on the campus from the pumping station (as seen in the inset on the right in Figure 2) for graded water services. The domestic water is treated at the treatment plant through a process consisting of sedimentation, filtration, and final disinfection with liquid chlorine. In addition, responsible and sustainable strategies are adopted by the campus to save local water, and energy. The greywater produced on the campus is treated through four decentralized anaerobic wastewater treatment systems and recycled for non-potable uses like irrigation using pop-up irrigation systems and drip irrigation. It ensures efficient use of water and reduces the institute's water demand. The campus also has rainwater harvesting systems where the rainwater is collected on building roofs, and is then channeled through swales to the rainwater retention pool/pond. However, in the current scenario, the recycled water and the harvested rainwater are not fed to the distribution grid. The campus also has artificial ponds to accommodate reserve water for wildlife on the campus during the dry season.

The WDS of the campus is operated by the Office of Infrastructure Engineering of the institute and supplies graded water services within the campus. The campus has 17 student hostels, 3 faculty and staff residential complexes (Types B, C, and transit), 12 academic units (departments, centers, and schools), 1 administration building, 1 lecture hall building, and a library, 1 club, 1 sports complex, 1 health center, 2 shopping and food complexes, and other academic and non-academic units. Several other academic, research, sports, and cultural activities over the year are also catered by the same supply grid. Approximately 5,000 users, including students, faculties, staff, and visitors, are currently meeting their domestic water

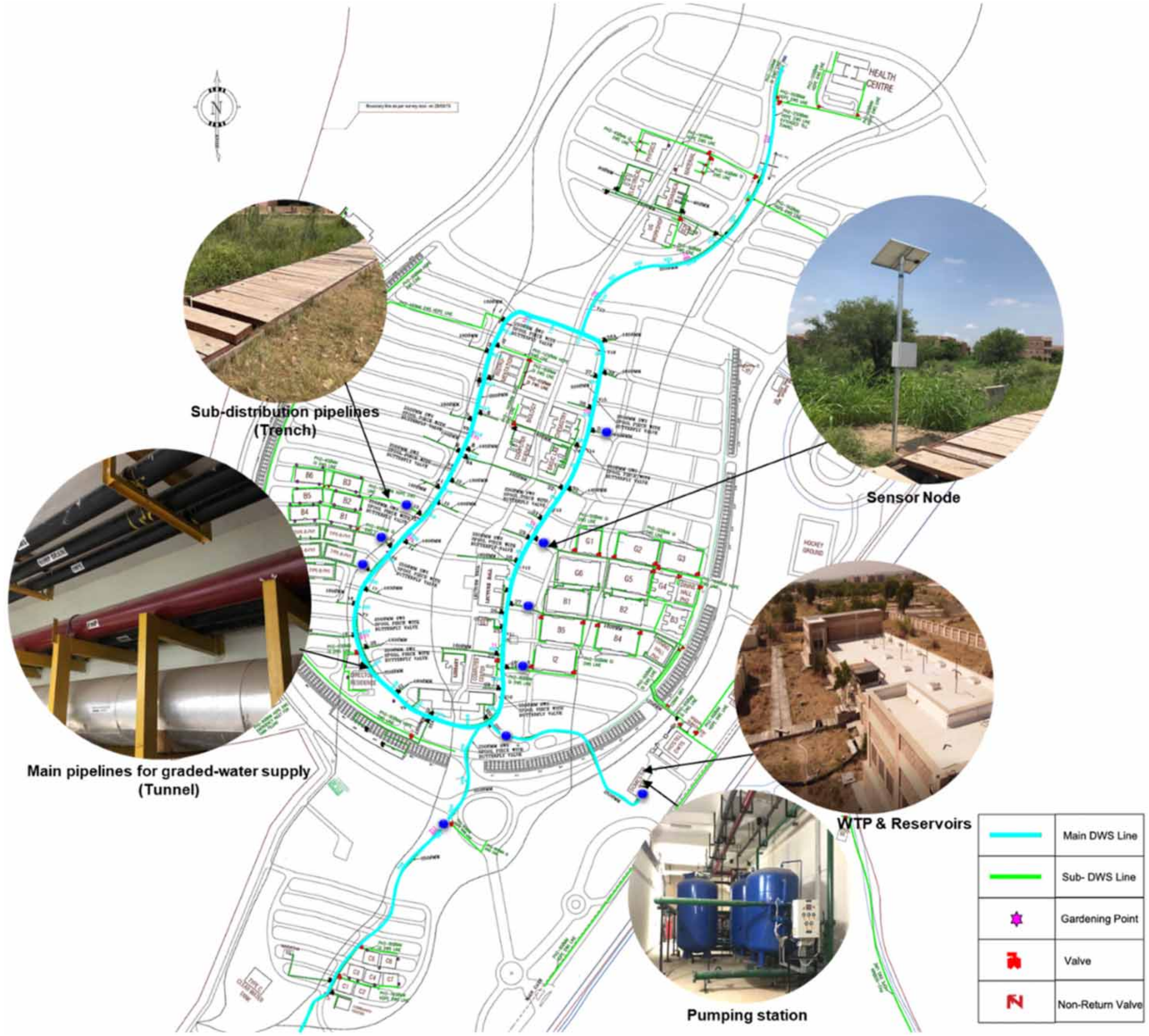


Figure 2 | Domestic water supply distribution network at IIT Jodhpur campus. The main distribution pipeline is highlighted with a cyan colored solid line (—), and sub-distribution pipelines are highlighted with a green colored solid line (—).

requirements from the grid. It was estimated that students' hostel water demand is over 30–35% of the total water consumption on the campus. Therefore, the focus of this paper will be on the domestic water supply grid. However, the system is functioning remarkably close to its maximum capacity, and often due to limited supply from the source unable to deliver water with sufficient pressure heads. The Smart Graded-Water Supply project aims to fulfill the rising demand for domestic water supply is growing fast due to the development of the institute's infrastructure and population. It will enable efficient management of the existing water supply by reclaiming water for potable and non-potable uses. The students of IIT Jodhpur are the true beneficiaries of the project.

2.3. IoT-enabled monitoring architecture

In the present work, an IoT-enabled framework to achieve intelligent automation in sensing, and monitoring at distinct levels is designed. An illustration of the IoT-enabled real-time monitoring architecture is shown in Figure 3. The key elements are represented by the architecture, which includes IoT devices that are in connection with the physical infrastructure of graded

Table 1 | Domestic water network data

Network data and study area	Type/value
Configuration	Hybrid (ring and branched combined)
Area coverage	Approx. 276 ha (Total campus area 352 ha)
Population served	Approx. 5,000
Total pipe length	Approx. 13 km
Junctions	Approx. 1,100
Maximum ground level difference	0.5 m
Pipe diameter	90–250 mm
Pipe length	0.04–36.7 m
Pipe material	High-density polyethylene (HDPE)
Total supply of water capacity	Up to 1 MLD
Average daily pressure	1.5 to 2 bar

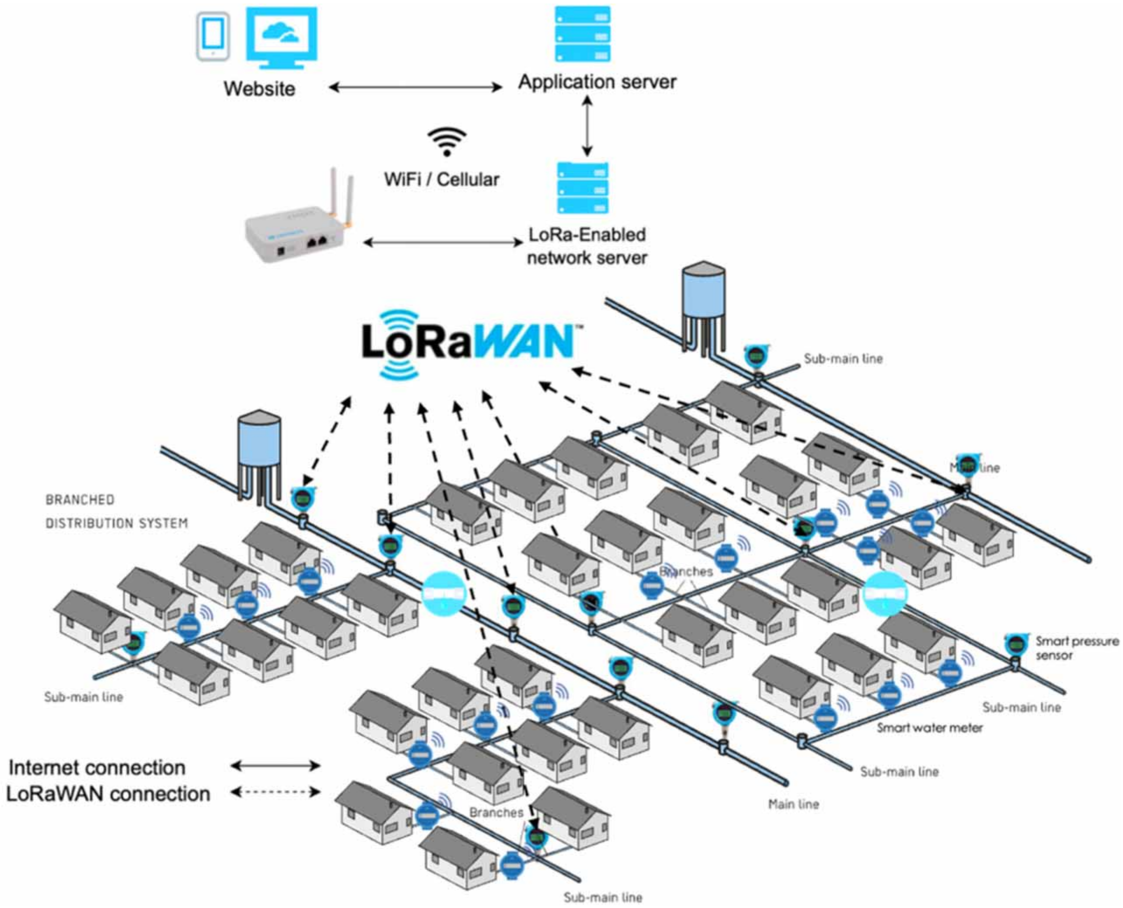


Figure 3 | IoT-enabled real-time monitoring architecture.

water distribution. A typical IoT device is equipped with different sensors designed to sense the pressure, flow, the quality of water, and transducers to transmit the signals. IoT devices are connected to wireless fidelity (Wi-Fi) gateways/routers that communicate to the cloud to enable internet connectivity to the IoT device layer. Devices remain connected using networking or communication technologies. Previous studies have reported that the desired applications are influenced by the communication technology choice, which in turn affects the quality of service (Lalle *et al.* 2021; Oberascher *et al.* 2022b). In the first phase of implementation, Wi-Fi and 4G cellular communication are utilized at the first few nodes due to fast data transfer speed, wide coverage area, low latency, and ease of interfacing between hardware and software (Baanu & Babu 2022). However, later remaining nodes are deployed with a long-range wide-area network (LoRaWAN) for data transmission.

2.4. Sensor node deployment

Sensor nodes allow continuous monitoring of the distribution network and record pressure, flow rate, and important quality parameters in real-time or near real-time, which are crucial in early warning systems. Suitable monitoring location helps detect leaks (Zaman *et al.* 2020) and contaminants (Adedoja *et al.* 2018), therefore, permitting better diagnosis of the supply system. However, owing to the provision and the maintenance cost of the sensor nodes, limited yet strategic nodes were prudently deployed.

Criteria adopted for the selection of locations for sensor placement in the study are driven by cost, user's density, good network coverage, prone to leakage or quality deterioration, and infrastructure availability. Although the optimization-based approach is more suitable for the placement of sensor nodes, it will remain in the scope for second-phase implementation due to the significant data requirement. Figure 4 depicts the locations of sensor nodes installed in the campus during the first phase of implementation. Each hydraulic node comprises the flow and pressure sensor units installed on the pipelines inside the trench. The nodes are deployed at 10 distinct locations of the domestic water supply pipes. Off-the-shelf, commercially available sensors are installed to monitor the flow, pressure, and quality of the domestic water supply. Careful evaluation of sensors was exercised to ensure that the sensors do not significantly affect the hydrodynamic phenomena inside the distribution pipes. Online water quality monitoring often includes key parameters, e.g., pH, residual chlorine, turbidity, conductivity, and dissolved oxygen (Baanu & Babu 2022). These parameters are crucial for pinpointing water

Figure 4 | Google Earth view of sensor node locations (indicated by colored marker) deployed in the study area.

contamination incidents and spotting water mixing from various sources. However, the non-availability of suitable sensors for certain chemical and biological parameters such as *Escherichia coli*, chemical oxygen demand, and others still requires traditional laboratory testing. Therefore, in the first phase of deployment, a combination of the most common quality parameters, namely, residual chlorine, pH, and temperature are measured by deploying a water quality node at the outlet of the WTP. Table 2 lists the specifications of the deployed sensors.

The sensor nodes are designed to continuously gather data at high rates and transmit it in real-time to the server. For wireless communication, a wireless data logger and a USB Wi-Fi modem are connected to the main processing board enabling the collection of comprehensive data sets that can be analyzed centrally. Continuous monitoring also requires a constant power supply, which can be a challenging task. Therefore, each node is equipped with a solar panel that serves as the main power source for the sensors and the data logging system. A 12 V (14 Ah) battery is used as a backup source when the solar panel fails to power the system during cloudy weather. All the devices are enclosed in an IP-67 enclosure to withstand harsh environmental conditions and security. Field images of the deployed hydraulic and quality nodes are shown in Figures 5 and 6.

Table 2 | Specifications of the hydraulic and quality sensors and instruments

Parameters	Sensor type/method	Range	Accuracy	Resolution	Working conditions
Flow rate	Non-invasive, non-intrusive, ultrasonic clamp-on meter	1–100 m^3/s	1%	0.001 m/s	−30 to 60 °C; DN15 to DN6000 mm
Pressure	Non-intrusive, invasive, probe type transmitter	0–6 bar	1% FS	NA	−20 to 70 °C; DN50 –DN700 mm
pH	Electrode	0.00–14.00 pH	±0.02% pH	0.01 pH	0 to 60 °C
Residual chlorine	Electrode	0–20 mg/l	±2%	0.01 mg/l	0 to 60 °C

Figure 5 | Hydraulic Node 27 and its components. (a) Above the ground unit with solar panel. (b) Ultrasonic flow and pressure sensor mounted on supply pipeline control panel. (c) IP67 enclosure for housing IoT devices. (d) Flow meter display screen.

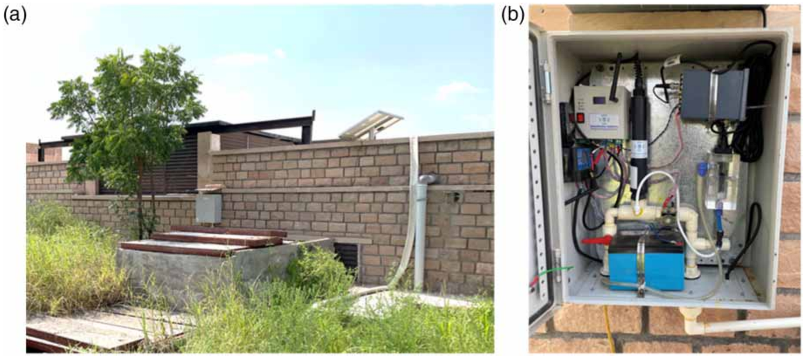


Figure 6 | Quality node and its components. (a) Above the ground unit with solar panel. (b) IP67 enclosure for housing IoT devices and other components.

2.5. Real-time monitoring

Monitoring WDN at various service levels is important to ensure the effective functioning of the system. The water quantity and quality sensors operate via an IoT node-based 4G cellular communication standard. The block diagrams of the on-site smart water flow and quality monitoring system designed in the study can be seen in Figure 7. The sensor transmits the measured data to a centralized server in the cloud providing real-time data for analytics. Hydraulic data is typically sampled

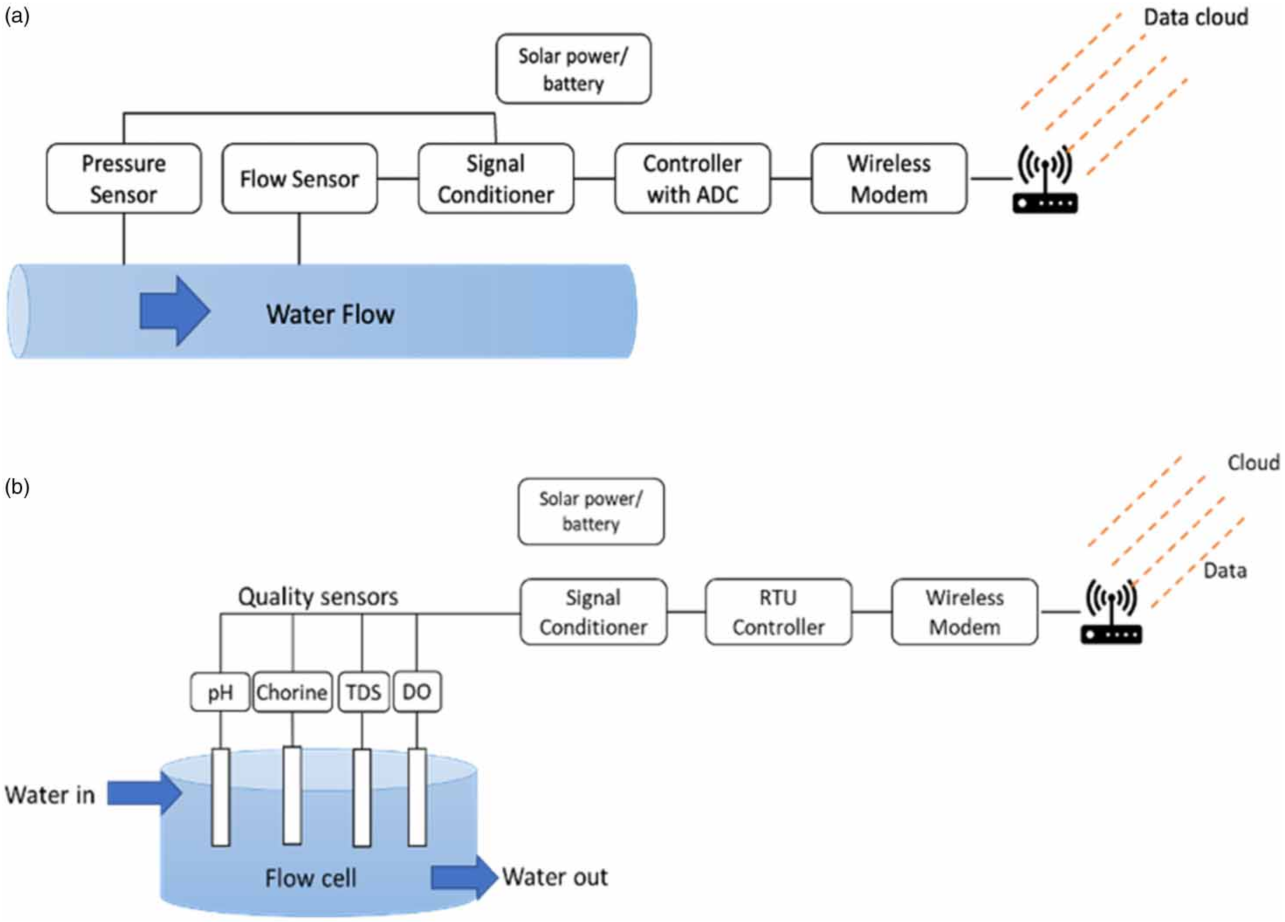


Figure 7 | System architecture of wireless. (a) Flow and pressure monitoring and (b) quality monitoring system adopted in the present work.

and transmitted wirelessly at the 1-min interval, while the quality of water is sampled at a 4-h interval. Minute scale logging is sufficient to offer detailed insights into different user-specific water consumption (Oberascher *et al.* 2022a). The inaccuracies in the data are neglected in the study considering the sensors deployed are new and of high accuracy. Furthermore, sensors were tested to verify their functionality and performance after installation.

A web-based, configurable dashboard, accessible to authorized users, is designed to visualize the data. It serves as a powerful tool to continuously monitor and capture useful data for identifying recurring patterns and enabling the information available in a timely manner for action in unfavorable scenarios like pipe leakages, pipe bursts/faults, contamination, outage, and inequitable distribution. The deployed system generates alerts during abnormal water supply and quality conditions. Figure 8 shows a screenshot of the interactive dashboard designed for real-time data visualization and analysis.

2.6. Time series data and analysis

Real-time monitoring and data analysis are important for decision-making related to adequate water supply, water treatment, regulatory problems, and public safety, thus improving the resilience of the water infrastructure (Baanu & Babu 2022). Hydraulic and quality sensors periodically gather high-resolution data from the predetermined locations in the grid, which is helpful in defining average water demand, diurnal trends, supply status, etc. The data set comprised of data points with timestamps over a period where each data point corresponds to a meter/sensor reading collected between 01 June 2022 and 30 September 2022. In the present study, the sensor logs water flow rate, pressure, and selected quality parameters at regular intervals. The values of water flow rate and pressure at a time instance represent the state of water supply to a distribution zone. Due to high student-centric water consumption, raw data sets from DMA01 (hostel zone) are chosen to be presented in this study. The map of DMA01 with the distribution pipeline and location of flow meters is shown in Figure 9. There are flow meters at every inlet of the DMA01, however, this paper only presents the analysis of water flow rate and pressure at Node 24 and Node 27 in the subsequent section.

3. RESULTS AND DISCUSSION

3.1. Water hydraulics

Time series of flow and pressure on a minute scale, hereafter referred to as the monthly data, are presented in this section. Figure 10(a) depicts the spatiotemporal variation of water flow and pressure at Nodes 22C, 24, and 27 of the supply grid.

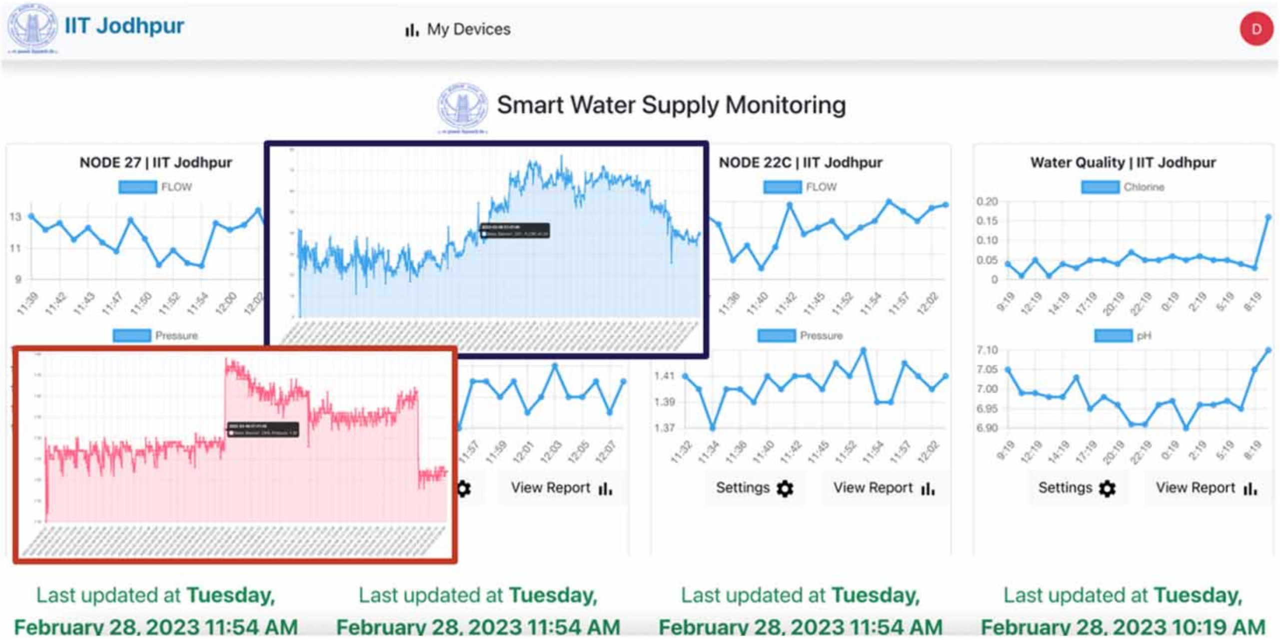


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Figure 8 | Screenshot of the configurable interface taken on 28 February 2023. The insets are the exemplary graphs showing the 24-h flow (—) and pressure (—) pattern at Node 27.

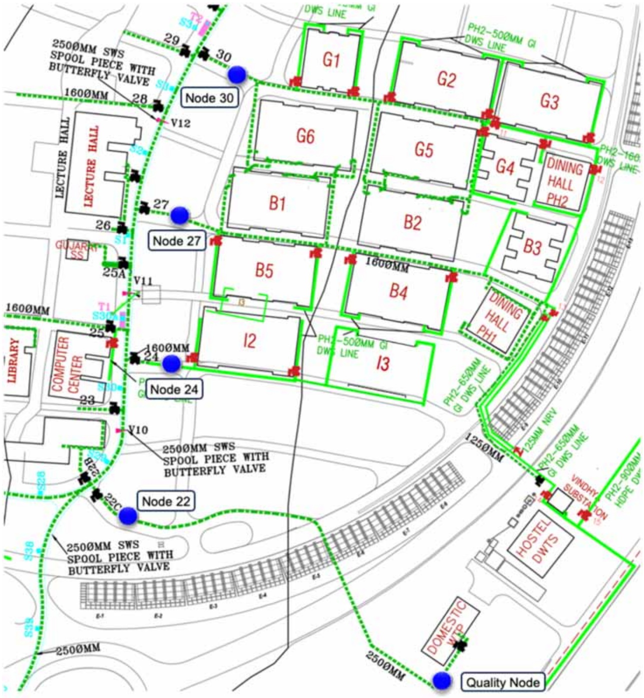

Figure 9 | Map of DMA01 with distribution pipeline and location of sensor nodes 22, 24, and 27 under the study.

Node 22C (data in the blue solid line —) corresponds to the main distribution line, which delivers potable quality water to the entire campus. Nodes 24 (data in the red solid line —) and 27 (data in the cyan solid line —) distribute water to DMA No. 1 supplying water to seven student hostels and two student dining buildings. As expected, a higher flow rate is recorded at Node 22C accounting for the total domestic water consumption in the campus, while Nodes 24 and 27 in the downstream supply to DMA01 have lower water flow rates. Based on the data, the flow rate at Node 22C fluctuates between 0 and 147 m^3/h, which is expected as it indicates the supply to the entire campus but on a higher side. The flow rates at Node 24 and Node 27 are ranging from 0–25 m^3/h and 0–10 m^3/h, respectively. Since the analysis is performed on the raw data set, the water flow and pressure data are characterized by recurring oscillatory patterns, typical in real-time monitoring of WDNs (Kara *et al.* 2016; Oberascher *et al.* 2022b), which is attributed to the combined effect of changes in water consumption, water pump activation or deactivation, and leaks. The flow rate dropping to zero may be due to pump deactivation or communication lag. Several peaks are observed, which could either be physical or owed to anomalous data points; the discussion of which is not in the scope of the present analysis. Nevertheless, the flow pattern observed at each node is distinct owing to the water consumption at each node.

The corresponding pressure variations can be seen in Figure 10(b). The pressure variation at each node is similar with most values close to the nominal network pressure of 1.5 bar. The figure demonstrates spiked patterns consisting of pressure transients that are caused by rapid water consumption changes and recurring pump operation. Similar patterns are detected in the time-series pressure data of a sensor in the WDS of a Dutch drinking water company, Vitens (Geelen *et al.* 2019). It is critical to monitor pressure in the supply networks to avoid degradation of the pipes or valves caused by high water pressure.

To further understand the change in the 24-h consumption profile, typical data of Node 24 over an arbitrarily chosen week, for a period from 15 June 2022 to 24 June 2022, is analyzed. The data are considered sufficient to serve as an adequate representative of typical water consumption patterns in terms of both time and difficulty of analysis. Figure 11 shows the variation in water flow rate (data in the orange solid line —) and pressure (data in the blue solid line —) at Node 24. Node 24 monitors the water supply to two student hostel buildings – I2 and I3 (as can be seen from the map in Figure 9). The diurnal flow rate patterns in the figure show some variation in the water consumption for different days but nearly similar dynamics are observed on all weekdays. The consistency in the diurnal pattern of the water flow rate also demonstrates the factual performance of the sensors deployed. The flow rate starts increasing from 7:00 am with maximum water flow at around 9:00 am,

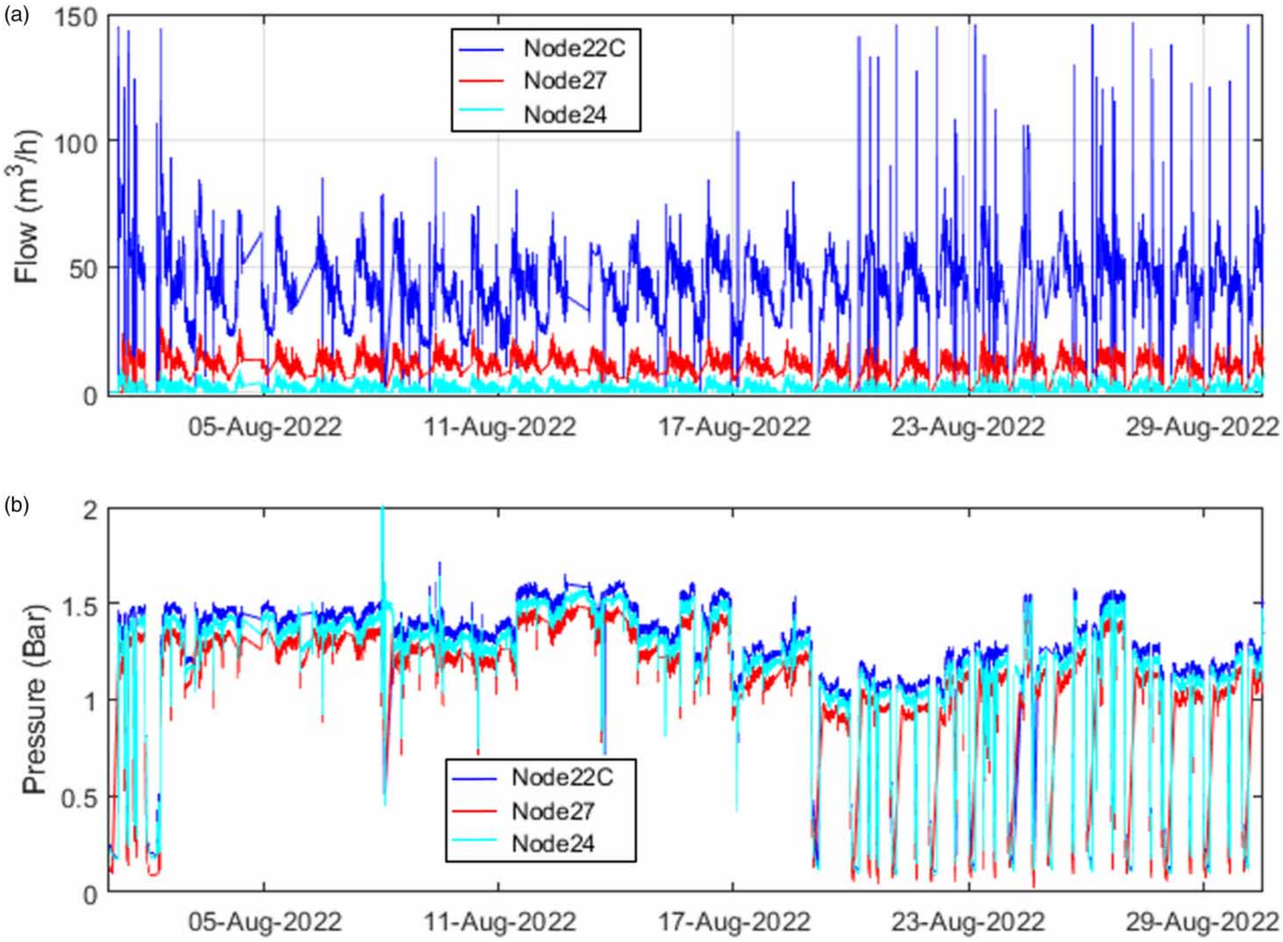

Figure 10 | Temporal variation of (a) water flow rate and (b) pressure.

which corresponds to the peak consumption hour when students use water to get ready for their daily routine. However, the peak is more pronounced on weekdays than on weekends. A slight increment is noticed in the late evening during dinner hours, typically between 8:00 pm to 10:00 pm followed by minimal consumption toward the end of the day.

It is worth mentioning that the institute practices various ways possible to secure the continuous supply of water and to meet the demands of the residents. Pump scheduling minimizes the night flow and ensures adequate supply in the campus during limited supply days. After midnight, the pump is shut down until early morning to conserve water otherwise wasted as night flow. The event is characterized by a gradual decrease and sloped pattern in pressure and zero flow rate during the period. For example, the weekdays data set except the one collected on Thursday displays no flow in the pipeline from midnight until the early morning hour (as seen in Figure 11). In contrast, a minimum night flow of approximately 5 m^3/h can be observed on Thursday when a continuous water supply is maintained. In addition, an event of sudden spike (framed in a rectangle in Figure 11) in water flow rate occurs during early morning hours, which demonstrates pump activation causing the pressure to rise sharply before resuming the normal supply pressure. Besides oscillations, spikes, and slopes, a valley pattern is also seen (encircled in Figure 11). It is characterized by a brief but considerable drop in pressure displaying a sudden and momentary increase in water consumption. The features in the pressure data are consistent with the recurring events found in Viten's WDN data (Geelen *et al.* 2019) useful in locating abnormal events from the usual.

For the same period, the average and maximum flow rate of daily water consumption are estimated for each day and are shown in Figure 12. It can be observed that the average daily water flow to hostels varies marginally between 4.02 and 5.51 m^3/h with a maximum varying from 14.75 to 16.38 m^3/h. The maximum on weekends has declined due to reduced consumption at the typical time of the peak water consumption and comparatively more consumption during non-peak hours than on weekdays.

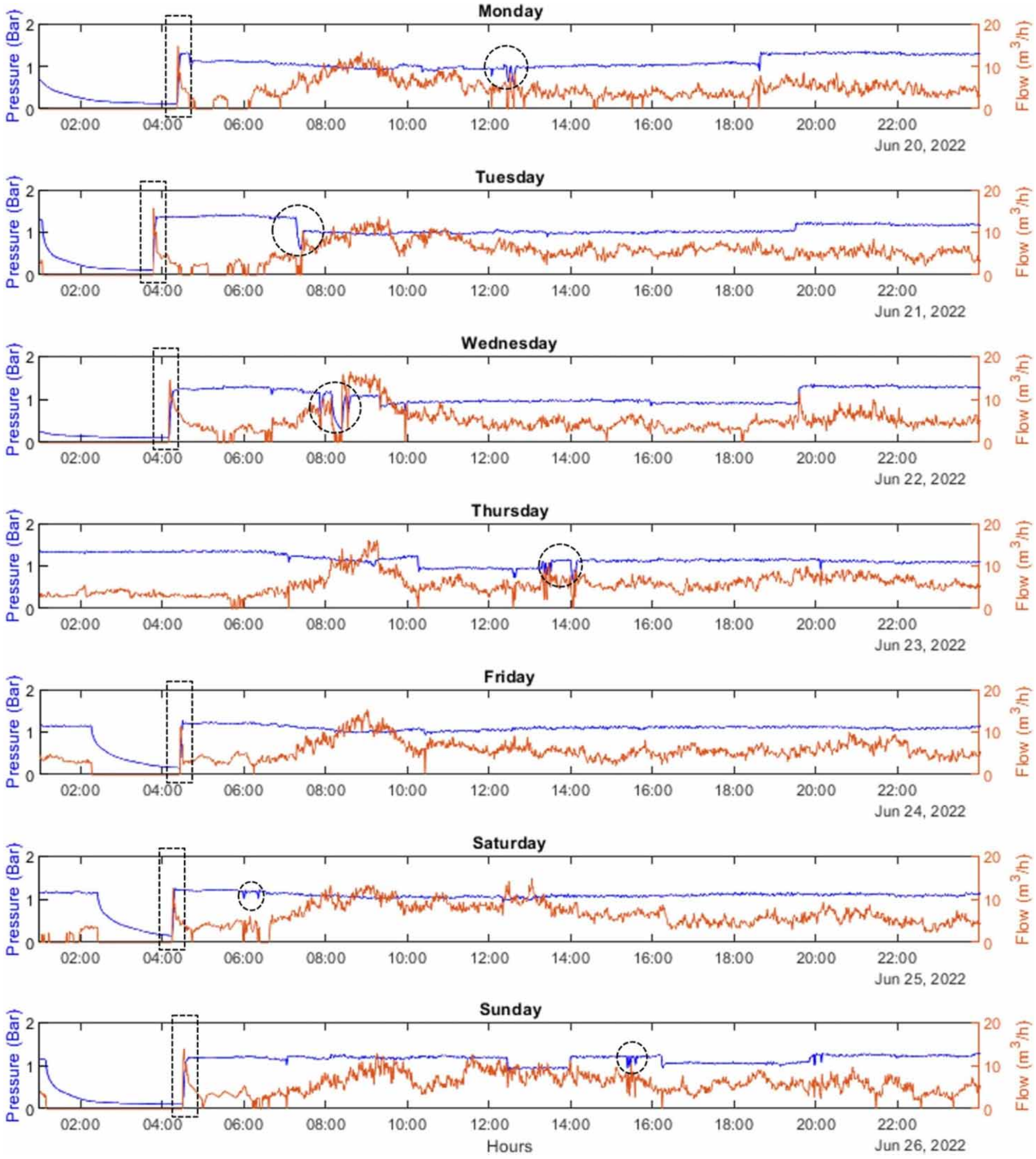

Figure 11 | Temporal variation of water flow rate and pressure at Node 24 over a period of a week from 20 June 2022 to 26 June 2022.

3.2. Water quality

Figure 13 shows the temporal variation of key water quality parameters monitored at a selected node over a period of a month from 01 August 2022 to 31 August 2022. Water quality parameters frequently sampled in the present study include pH, chlorine concentration, and temperature. The main purpose of monitoring these parameters is to continuously assess the quality of the treated water, whether the quality is within the recommended thresholds or not, in turn ensuring the health of the

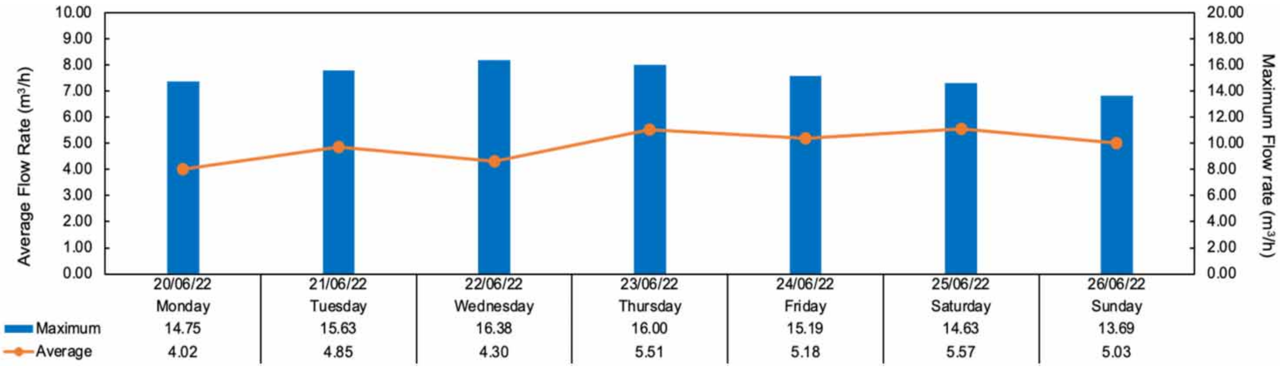

Figure 12 | Data of water flow rate for a week period, from 20 June 2022 to 26 June 2022.

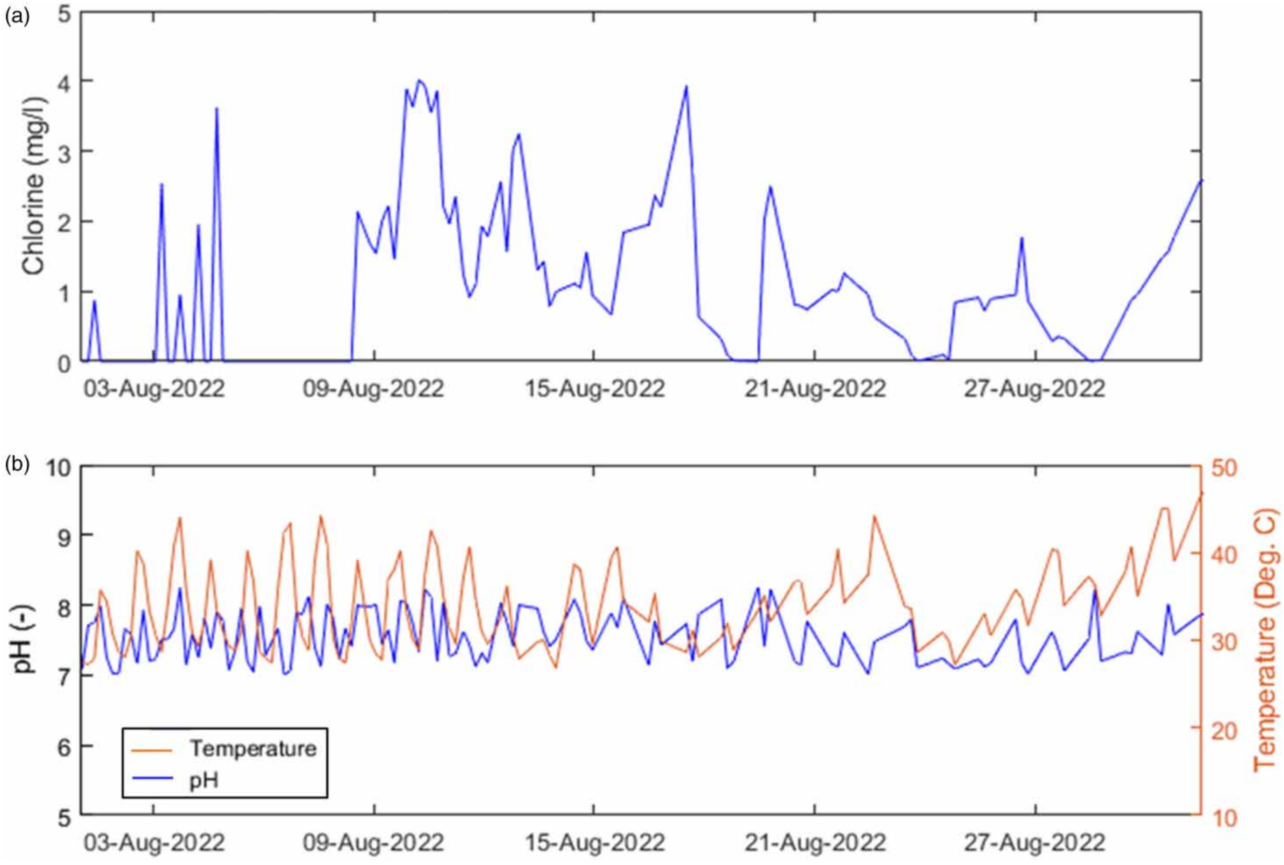

Figure 13 | Temporal variation of (a) chlorine and (b) pH and temperature of the water.

pipeline. Chlorine is a versatile and low-cost drinking water disinfectant appropriate for any size water system, whether it serves a remote rural village or a large modern city. Since the water quality changes with time and space, varied doses of chlorine are used to disinfect the water before distribution. Chlorination at the WTP helps maintain adequate residual chlorine in the distribution system. Drinking water could become contaminated without adequate dosing and adversely affects water taste, odor, and appearance. Figure 13(a) shows the varying concentration of chlorine in the water, wherein peaks of high concentration depicts the time of manual chlorination at the treatment plant. Instances of zero or sharp decrease in free chlorine concentration are also observed, which suggests inadequate disinfection of the supply water at times, an unwanted condition. In general, the data show an acceptable range of chlorine concentrations during the studied time, which is below the World Health Organization (WHO) standard limit of 5 mg/l for free chlorine in drinking water suitable for human consumption (World Health Organization 2022). It should be noted that water quality is measured at the outlet of the treatment plant close to the reservoir, which explains the relatively higher concentrations. The concentration would gradually decrease during distribution and storage till it reaches the users and network endpoints.

Regulating the pH of the water in the distribution system is also necessary. For effective disinfection with chlorine, water pH should preferably be less than 8.0. Failure to do so can result in the contamination of drinking water. The pH of water monitored during the study period is displayed in Figure 13(b). The data show that the pH variation is within a permissible range of WHO, i.e., between 6.5 and 8.5. The lowest and highest pH values exhibited are 8.27 and 7.24, respectively. The relationship of pH with water temperature can also be simultaneously observed where the latter has fluctuated between 26.5 and 47.5 °C. The high water temperature may be a result of water pipes being exposed to the direct sun at the water quality sampling location. In the second phase implementation, the amount of unwanted biological and chemical processes will be measured at various nodes in the grid.

4. LESSON LEARNED AND FUTURE DIRECTION

Real-time monitoring of graded-water is essential for a reliable and sustainable water supply. Yet a number of practical implications during the first phase of the project were realized and are discussed in this section. Although no one solution fits all the lessons learnt might be useful in the deployment of monitoring systems or similar solutions in smart water grids. Time series flow and pressure data offer detailed insights and conclusions with respect to the water consumption pattern by different inhabitants. However, in the present study, only a simple analysis of a selected sample of raw water distribution data is presented. In order to enhance the data interpretation, other techniques should be utilized that are suitable for monitored variables or validation of not only the raw data but metadata. In addition, factors causing redundancies in the data must be eluded in future implementation for better robustness and performance of the supply system. In the first phase of the implementation, network coverage problems were occasionally experienced, which resulted in delayed installation, interrupted sensing, and data logging. One potential future work direction may tackle coverage problems while considering several metrics and issues such as connectivity, energy management, topology, and realistic sensing. The inclusion of stakeholders covering technology partners, regulators, financial agencies, local governance, and line-ministries is critical to help ease the development as well as rapid adoption, hence must be guaranteed. Therefore, as a scope for future development, the framework demonstrated in the present work will consider the following:

i. Steady scaled up by including more robust sensor nodes to improve the efficiency and security of the entire supply system to understand water users' behavior and how hydraulics impacts the quality of the grid.
ii. Installation of more water quality nodes to monitor and regulate the graded-water quality standards and to provide feedback on the treatment process and its performance thereby improving the reclaimed and reuse water quality.
iii. Data modeling to validate, evaluate, and analyze data from each district metered area with a capability of determining anomalies.
iv. Hydraulic modeling of the network to predict systems performance in various scenarios and for developing the digital twin of the supply grid for the future implementation of smart graded-water management.
v. Cybersecurity, data privacy, and governance requirements for the security and success of the future-ready smart graded-water supply grid at all application levels.

5. CONCLUSION

Continuous real-time monitoring of water supply grids is essential for the efficient management of water resources and supply by enabling analysis of data collected. This paper reports insights from a case study, where a framework for the smart graded-water supply grid is developed and demonstrated in an academic institution in the semi-arid region of India. The framework takes graded-water supply as well as quality assurance into consideration, which can be replicated in other university innovation projects or smart cities. The primary focus of the paper implicates the deployment of sensory nodes, and real-time monitoring framework, which provides valuable data on water flow and network pressure. Results present the time-series data monitored and interpreted to understand the student-centric water consumption pattern, status of domestic water supply, leaks and anomalies and to disseminate effective strategies for water conservation and energy in the system. Near real-time monitoring of pH and chlorine concentration in the water supply ensures satisfactory disinfection to the standardized level. The high-resolution hydraulic data provided by sensors has potential not only in terms of its usefulness to assist timely decisions but also in developing and calibrating the hydraulic network model and comparison with the real-time network simulations. Moreover, the accessibility of data informs users about their water use and its effects on present and future generations. The developed framework of the smart graded-water supply grid will serve as a testbed network allowing researchers and practitioners to test and validate core technologies for future Smart Water Grids in Smart Cities with great societal and economic impact.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abbas, O., Abou Rjeily, Y., Sadek, M. & Shahrour, I. 2017 A large-scale experimentation of the smart sewage system. *Water and Environment Journal* **31**, 515–521.

Adams, M. N. & Jokonya, O. 2022 An investigation of smart water meter adoption factors at universities. *Procedia Computer Science* **196**, 324–331.

Adedoja, O. S., Hamam, Y., Khalaf, B. & Sadiku, R. 2018 A state-of-the-art review of an optimal sensor placement for contaminant warning system in a water distribution network. *Urban Water Journal* **15**, 985–1000.

Ahad, M. A., Paiva, S., Tripathi, G. & Feroz, N. 2020 Enabling technologies and sustainable smart cities. *Sustainable Cities and Society* **61**, 102301.

Almeida, A. P., Sousa, V. & Silva, C. M. 2021 Methodology for estimating energy and water consumption patterns in university buildings: Case study, Federal University of Roraima (UFRR). *Heliyon* **7** (12), e08642.

Antzoulatos, G., Mourtzios, C., Stournara, P., Kouloglou, I. O., Papadimitriou, N., Spyrou, D., Mentes, A., Nikolaidis, E., Karakostas, A., Kourtesis, D., Vrochidis, S. & Kompatsiaris, I. 2020 Making urban water smart: The SMART-WATER solution. *Water Science and Technology* **82**, 2691–2710.

Baanu, B. B. & Babu, K. S. J. 2022 Smart water grid: A review and a suggestion for water quality monitoring. *Water Supply* **22** (2), 1434.

Cacal, J. C. & Taboada, E. B. 2022 Assessment and evaluation of IWRM implementation in Palawan, Philippines. *Civil Engineering Journal* **8** (2), 290–307.

EPA, U.S. Environmental Protection Agency 2012 *Saving Water in Educational Facilities*. Available from: https://www.epa.gov/sites/default/files/2017-01/documents/ws-commercial-factsheet-educational-facilities.pdf (accessed 23 September 2023).

Fabbiano, L., Vacca, G. & Dinardo, G. 2020 Smart water grid: A smart methodology to detect leaks in water distribution networks. *Measurement* **151**, 107260.

Geelen, C. V. C., Yntema, D. R., Molenaar, J. & Keesman, K. J. 2019 Monitoring support for water distribution systems based on pressure sensor data. *Water Resources Management* **33** (10), 3339–3353.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. & Bryan, B. 2021 Future global urban water scarcity and potential solutions. *Nature Communications* **12**, 4667.

Kara, S., Karadirek, I. E., Muhammetoglu, A. & Muhammetoglu, H. 2016 Real time monitoring and control in water distribution systems for improving operational efficiency. *Desalination and Water Treatment* **57** (25), 11506–11519.

Koncagül, E., Tran, M. & Connor, R. 2020 *The United Nations World Water Development Report 2020: Water and Climate Change, Facts and Figures*. UNESCO. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en (accessed 23 July 2023).

Koo, K. M., Han, K. H., Jun, K. S., Lee, G. & Yum, K-T. 2021 Smart water grid research group project: An introduction to the smart water grid living-lab demonstrative operation in YeongJong Island, Korea. *Sustainability* **13** (9), 5325.

Kouroupetroglou, C., Curry, E., Smit, S., Tutusaus, M., Mink, J., Koole, W., Messervey, T., Reforgiato, D. & Perfido, D. 2015 Waternomics: ICT for water resource management. In: *The 12th European Semantic Web Conference (ESWC)* (accessed 23 July 2023).

Lalle, Y., Fourati, M., Fourati, L. C. & Barraca, J. P. 2021 Communication technologies for smart water grid applications: Overview, opportunities, and research directions. *Computer Networks* **190**, 107940.

Li, J., Yang, X. & Sitzenfrei, R. 2020 Rethinking the framework of smart water system: A review. *Water* **12** (2), 412.

Mohanty, S. P., Choppali, U. & Kougianos, E. 2016 Everything you wanted to know about smart cities: The Internet of things is the backbone. *IEEE Consumer Electronics Magazine* **5**, 60–70.

Niti Ayog, G. O. I. 2018 *Composite Water Management Index: A Tool for Water Management*. Available from: http://social.niti.gov.in/uploads/sample/water_index_report.pdf (accessed 23 July 2023).

Oberascher, M., Rauch, W. & Sitzenfrei, R. 2022a Towards a smart water city: A comprehensive review of applications, data requirements, and communication technologies for integrated management. *Sustainable Cities and Society* **76**, 103442.

Oberascher, M., Kinzel, C., Kastlunger, U., Schöpf, M., Grimm, K., Plaiasu, D., Rauch, W. & Sitzenfrei, R. 2022b Smart water campus – A testbed for smart water applications. *Water Science and Technology* **86**, 2834–2847.

Rizzoli, A. E., Castelletti, A., Fraternali, P. & Novak, J. 2018 Demo abstract: SmartH2O, demonstrating the impact of gamification technologies for saving water. *Computer Science-Research and Development* **33**, 275–276.

Savić, D., Vamvakeridou-Lyroudia, L. & Kapelan, Z. 2014 Smart meters, smart water, smart societies: The iWIDGET project. *Procedia Engineering* **89**, 1105–1112.

Swami, V. A., Kulkarni, S. S., Thorvat, A. R. & Varur, S. S. 2018 Identification of sustainable option in water conservation for rural India. https://doi.org/10.20897/awet/86714 (accessed 23 July 2023).

Tayyab, M., Abbas, Y. & Hussain, M. W. 2022 Management options for large metropolitans on the verge of a water stress. *Journal of Human, Earth, and Future* **3** (3), 333–344.

United Nations 2023 *Sustainable Development Goals*. Available from: https://www.un.org/sustainabledevelopment/water-and-sanitation/ (accessed 23 July 2023).

World Economic Forum 2021 Mission 2070: A Green New Deal for a Net Zero India. White Paper. Available from: https://gcpcenvis.nic.in/PDF/Mission_2070_A_Green_New_Deal_for_a_Net_Zero_India.pdf (accessed 23 September 2023).

World Health Organization 2022 *Guidelines for Drinking-Water Quality*. Available from: https://www.who.int/publications/i/item/9789240045064 (accessed 23 July 2023).

Yagoub, M. M., AlSumaiti, T. S., Ebrahim, L., Ahmed, Y. & Abdulla, R. 2019 Pattern of water use at the United Arab Emirates University. *Water* **11** (12), 2652.

Zaman, D., Tiwari, M. K., Gupta, A. K. & Sen, D. 2020 A review of leakage detection strategies for pressurised pipeline in steady-state. *Engineering Failure Analysis* **109**, 104264.

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