



# Application of Distributed Ledger Platforms in Smart Water Systems—A Literature Review

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The application of distributed ledger technologies, including blockchain, is rapidly growing in governance, transport, supply chain, and logistics. Today, blockchain technology is promoted as the heart of Smart Cities. This study reviews the potential of blockchain application in water management systems. We surveyed the literature and organized the previous studies based on three main application topics: Smart Water Systems, Water Quality Monitoring, and Storm Water Management. Also, we addressed technical, organizational, social, and institutional challenges that may hinder the adoption of Blockchain technology. Water management systems need to have a long-term commitment plan, update their organizational policies, and acquire relevant knowledge and expertise before successfully adopting any distributed ledger technology.

**Keywords:** blockchain, IoT, water quality, stormwater, urban, smart cities

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## INTRODUCTION

The expansion of internet access, improved intelligent devices, and the advancement of information and communication technologies (ICT) have created opportunities for even more interconnection of physical and virtual domains (Caragliu et al., 2011; Shahid et al., 2018). Our modern life is entangled with an inter-networking of embedded devices, sensors, and computers known as the Internet of Things (IoT) that collect and distribute a large amount of data (Rose et al., 2015). The development of cloud platforms that use several servers to store data has improved IoT extensively (Tsague and Twala, 2018). This growing system of interconnected smart objects utilizing the Internet and supporting technologies is paving the way to create smart cities that could involve smart homes, connected automotive, digitized healthcare, smart environment control, effective monitoring of the quality of water, and much more (Shahid et al., 2018; Shilpi and Ahad, 2020). Nevertheless, The IoT sector faces data security and privacy challenges leading to device spoofing, false authentication, and less reliability in data sharing (Rose et al., 2015; Kumar and Mallick, 2018; Qatawneh et al., 2020).

Blockchain solutions are among emerging technology that is used to keep track of ownership of assets and record transactions in the form of distributed ledger, hence improving data security and privacy (Teeluck et al., 2021). Blockchain was the steppingstone for the creation of cryptocurrencies (Nakamoto, 2008). However, during the past two decades, the application of blockchains has expanded to manage smart assets and create and manage smart contracts (Christidis and Devetsikiotis, 2016).

In blockchains, all the data is saved into immutable blocks providing a secure peer-to-peer transaction without a third-party authentication (Brotsis et al., 2021). A blockchain is a series of time-stamped batches of information (i.e., blocks). Each block contains a unique string of

alphanumeric characters of fixed length called hash, a hash of the previous block, an index, a time-stamp, the data, and a hash of the data. The hash of each block is calculated using the information from its previous block (Teeluck et al., 2021).

Unlike conventional methods of storing data, blockchain technology is decentralized, which means that the information is stored on a network of participating computers or nodes (Reyna et al., 2018; Teeluck et al., 2021). The blockchain is called public if participating in and contributing to the network's computing power does not require permission from other host members, and all nodes have equal rights. On the other hand, the blockchain is private if a centralized organization act as a certificate authority that can change the rules (including the consensus mechanism) and revert or modify the transactions. A consortium blockchain mixes the previous two types that only preselected trusted nodes participate in the consensus mechanism (Akram et al., 2020).

A new block is processed and added to the chain when a transaction occurs, known as mining (Reyna et al., 2018). Before any new block is added to the chain, it is required that participating nodes form a consensus about the authenticity of the new information. There are 12 different types of consensus mechanisms based on the application, and the Blockchain architecture and each network define its consensus mechanism (Teeluck et al., 2021).

In essence, the four main characteristics of blockchain technology differentiate it from most existing information systems designs (see **Figure 1**). These key characteristics include decentralization (non-localization), security, auditability, and smart execution (Saberi et al., 2019).

Blockchain is implemented in various sectors, some using major platforms such as Ethereum or Hyperledger and others smaller custom-made ones. For instance, the technology is used to store information about ownership, authenticity, and transactions related to high-value assets like diamonds; to trace and certify goods across supply chains (end-to-end tracking of containers and certifying origin of food ingredients and products); to provide a platform for energy trading; and to create smart contracts that facilitate transactions in real estate (Teeluck et al., 2021).

In the context of global water scarcity, the spatial distribution of water resources, and multi-scale water resource management, a distributed network approach like blockchain is advantageous to ensure trust in data reliability, data security, and data verification in public water transactions. Combining IoT, AI, and Blockchain as reinforcing technologies can increase public trust, encourage informed decision-making, and yield efficient optimization and water allocation (Lin et al., 2018). This study reviews the literature highlighting the application of smart systems, including IoT and blockchain technologies, in urban water management. We organized the reviewed publications into three main topics: *Smart Water Systems*, *Water Quality Monitoring*, and *Stormwater Management*. In the end, we provide a summary discussion of the benefits and challenges that water managers may face when implementing blockchain technology.

## SMART WATER SYSTEMS

Depleting resources, complex regulations, and increasing demand for clean and affordable water are challenging current water management systems (Sriyono, 2020). Advanced digital technology is used to collect data on the distribution and consumption of water in urban settings, and IoT can be used to monitor the urban environment (Yang et al., 2015; Eggimann et al., 2017). The impacts of employing smart water systems can go beyond efficient management of resources. Innovative, efficient, and scalable solutions based on the integration of Blockchain and IoT for intelligent water and sanitation management in Africa can help nations achieve Sustainable Development Goals (Dogo et al., 2019b,c).

Smart water systems are often defined within the concept of smart cities (D'amico et al., 2020). In a smart city, the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure are collectively and intelligently connected (Chourabi et al., 2012; Bassoo et al., 2018). Smart water grid systems enhance consumption management, sustainability and compliance, and effective policymaking using integrated Blockchain and IoT technologies (Dogo et al., 2019c; Sriyono, 2020). Furthermore, the adaptation of smart grids helps urban water systems to identify and respond to sustainability and resiliency challenges, including drought and natural disasters, more effectively (Mutchek and Williams, 2014).

### Examples of Implementing Smart Water Technologies

Depending on their needs, communities that use smart water technologies integrate various detecting devices and intelligent systems. In Singapore, the smart water grid is designed to track pressure, flow, and disinfectant levels in the distribution system. The data is transmitted through the cell network to a Computer Center to be analyzed in real-time. In case of detecting a problem, the Center alarms the utility and pinpoints the problem location to within 40 meters (Public Utilities Board Singapore, 2016). The East Bay Municipal Utility District (EBMUD) in San Francisco Bay Area has employed several programs that facilitate issue detection and reduce water use. They have tested and deployed advanced leak detection devices, set up smart irrigation controller rebates for consumers, and installed smart metering in conjunction with web-based tools that help users to detect leaks. Early leak detection and repairs resulted, on average 20% reduction in water use (Mutchek and Williams, 2014).

To successfully integrate water management and ICT, a smart water grid needs to configure a platform in both water and ICT networks; guarantee water resources; control water flows intelligently through bi-directional communication in water infrastructure; better manage assets in the water infrastructure; operate and maintain water infrastructure in an energy-efficient manner (Lee et al., 2014). Although the purpose of this review study initially was to find examples of successful and effective water management systems that had implemented DL platforms, we did not find a system that had all these characteristics. That makes the point that current water systems may have only partially benefitted from IoT and DL technologies. The benefits

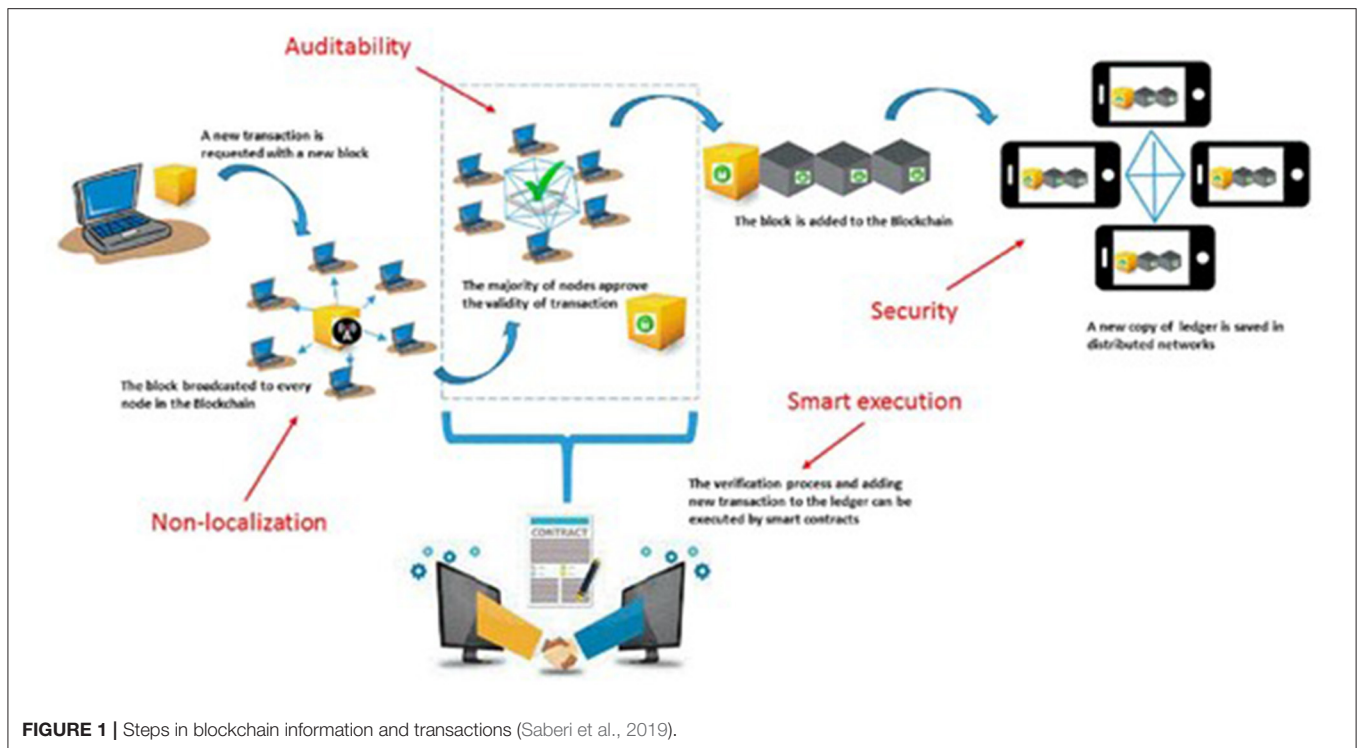


FIGURE 1 | Steps in blockchain information and transactions (Saber et al., 2019).

of Intelligent water management systems that use IoT sensors are described and evaluated in different contexts by various scholars. Managers can constantly manage and control both the operational aspects (asset management, leak management, water quality monitoring) and the customer end (automated meter reading and water conservation) using an integrated end-to-end platform that monitors the water distribution systems in real-time (Allen et al., 2012; Public Utilities Board Singapore, 2016; Rojek and Studzinski, 2019; Abdelhafidh et al., 2020).

## Water Trading and DL Platforms

In the context of water trading, Blockchain technology would increase transparency to auditors and regulators by recording trades and actions on the chain, preventing speculation. Also, implementing blockchain technology in water trading would streamline the counterparty data management process and save millions of dollars by creating a digital identity for organizations, digitizing water assets, and storing the digital assets on a shared ledger (Poberezhna, 2018). From the financial aspect, Blockchain technology facilitates collaboration among counterpart organizations and eliminates manual checks and reconciliation processes (Poberezhna, 2018).

In Australia, for instance, water authorities have partnered with the private sector, Civic Ledger, to improve the transparency and reliability of water market information. A pilot study aiming at assessing the feasibility of blockchain in agricultural water trading markets in Australia revealed that the main barriers to water market participation by irrigators include the complexity of trade process, lack of trust and price transparency in some closed systems, and lack of knowledge (Civic Ledger, 2020). The

study found that implementing Blockchain technology to water trading in their case could immediately solve the issues related to authority, ownership, price, volume, and trade history because the market participants would have access to the essential supply chain information in real-time. The authorization issue would be solved by setting up water accounts in the Water Ledger platform where each water account was assigned an owner ID number, hence solving the ownership issue. Historical pricing data was gathered from the irrigators, and therefore by implementing the smart contracts, transparency in water pricing for the future would be resolved.

Smart contracts are effective tools to capture volume data as well. Combined with the historical volume data, water market volume information would be available in real-time going forward. Finally, access to trade history was solved by implementing smart contracts combined with the longitudinal trade data (Civic Ledger, 2020). Of course, the proposed solution design of Civic Ledger is tailored to the issues relevant to water trading in the agricultural sector.

## Evaluation of DL Platforms

Finding a systematic framework to guide a smart water network's real-world design and deployment is challenging and context-dependent (Li et al., 2020). In addition, evaluating the accuracy and efficiency of the data generated by the IoT and managed by distributed ledger platforms is essential for enhanced, and in some cases autonomous, decision-making in water management. Scientists have proposed various architectural designs to build intelligent water planning and managing systems that fit a specific application. For instance,

Xiang et al. (2021) propose an Adaptive Intelligent Dynamic Water Resource Planning (AIDWRP), an AI technique, to effectively model sustainable water development. The goal is to help sustain urban areas' water environment and optimize systems' resource distribution. This computational model aims to reduce water supply costs subjected to a constraint to water requirement. The evaluation of the performance and accuracy of the model show that AI is an effective tool in managing and decision-making in urban water resources management (Xiang et al., 2021).

As another example, Wu et al. (2020) designed two predictive models for water quality based on integrated smart data-driven technologies. They collected raw water data from the urban water supply systems of Oslo and Bergen in Norway to predict biological water quality indicators in supply sources. Even though water supply systems are integrated with ubiquitous sensing technologies, very few appropriate microbial sensors are developed mainly due to the difficulty of measuring and collecting biological indicators of water quality (Wu et al., 2020).

The proposed models by Wu et al. (2020) both show significant predictive accuracy. Considering that water sources are affected by the seepage from agricultural, residential, and industrial users, effective quality control of water sources is essential to the safety planning of the water supply system. The outcome of Wu et al. (2020) proposed predictive models indicates that the Smart Data-Driven framework is an efficient way for future decision-making support of water quality control and risk management.

Some newly proposed architectural designs integrate IoT, Blockchain, Decision Support Systems, and AI technologies to ensure efficient water management. In a proposed design, Pahontu et al. (2020) create an experimental water distribution network integrated with a distributed architecture based on Blockchain and Hyperledger Fabric framework. They test the capabilities of their solution to evaluate the intervals for reading and writing data, reorganize the format of the data that is saved into the blockchain, and find a solution that fits the network's decision-making needs.

The major challenge regarding the large-scale adaptation of smart water networks is the lack of a standardized framework for designing and constructing such networks (Li et al., 2020). However, the performance of any proposed smart water system can be evaluated using two conceptual metrics of smartness and cyber wellness that measure system efficiency and security, respectively (Li et al., 2020). The smartness of the system is usually quantified by the time lag between the start input and terminal output and measured in minutes (Marchese and Linkov, 2017). Therefore, smartness aims to minimize the time delay between the system input and output, hence perfecting the real-time monitoring, sampling, transporting, processing, simulating, modeling, and controlling. The information security issue arises from the vulnerability of the IoT component where sensors and actuators across the water distribution network communicate data. Based on the International Telecommunication Union's definition, cyber wellness indicates the maximum data stored before a cyberattack while withstanding cyberattacks as long as possible at the same time (Li et al., 2020).

## WATER QUALITY MONITORING

Water quality refers to water's physical, biological, and chemical characteristics. The important measurable water quality parameters include chemical oxygen demand, biochemical oxygen demand, pH, dissolved oxygen, turbidity, electrical conductivity, temperature, oxidation-reduction potential, salinity, total nitrogen, and total phosphorus (Bahadori and Smith, 2016; Kamaludin and Ismail, 2017). IoT framework enables the real-time monitoring of water quality indices facilitated by the speed of internet communication (Das and Jain, 2017; Kumar Jha et al., 2018). Automation of processes through IoT reduces the need for human resources and consequently limits human errors (Wiliem et al., 2006). Smart monitoring systems are adaptive and responsive, alerting users and decision-makers regarding sub-optimal or dangerous conditions in real-time. IoT-based water quality monitoring is cost-effective compared to traditional manual sampling methods (Spandana and Seshagiri Rao, 2018; Ighalo et al., 2021).

An IoT-based platform for water quality monitoring consists of microcontrollers, sensors, and communication units. A microcontroller is the processing unit in the system; the sensor unit is responsible for the actual data collection; and the communication unit transmits the data (Bai et al., 2020; Ighalo et al., 2021). The collected data is transferred to Cloud storage for further analysis or to a user-friendly PC/Smartphone interface through Wi-Fi modules (Lavanya and Raghavendra Babu, 2019; Shanthi et al., 2019). Some framework designs suggest using solar panels to provide the energy for running the system (Arvind et al., 2020). There are extensive proposed designs for an IoT based water quality monitoring system in the literature, focusing on portability (Tripathy et al., 2020), performance efficiency, and data reliability (Zin et al., 2019; Kumar et al., 2020), cost-effectiveness (Sarraf et al., 2020), and communication ability (Sithole et al., 2019a,b) of the module.

The application of IoT in monitoring water quality ranges from observing any chemical or physical change of water in rivers (Cianchi et al., 2000; Wang et al., 2013; Chowdury et al., 2019; Meshal et al., 2020) and watersheds (Hoos et al., 2019) to identify pollution levels in near real-time (Saravanan et al., 2018); to detection of hydrologic variability in estuarine and marine ecosystems used for early warning systems and rapid response to harmful algal bloom events (Glasgow et al., 2004). Developing countries like Nigeria use IoT to test the quality of surface water, groundwater, rainwater, and commercially available water to ensure access to safe drinking water in remote areas (Ighalo and Adeniyi, 2020).

The data generated from IoT integration into the water source management, treatment, and distribution systems can predict water quality, thus playing an important role in future risk control and decision support in urban water supply systems (Wu et al., 2020). The continuous monitoring of the water supply system creates time-series data that can further be examined to identify the impact of climate parameters, like monsoon in summer or wind speed, on the quality of water delivered to a specific geographical location (Tripathy et al., 2020). Some applications improve in-home conservation decision making

where autonomous IoT enabled units can activate various filters used in homes depending on the change in the quality of water delivered to households (Almetwally et al., 2020) or send signals to households if health hazards are detected in the tap water (Sithole et al., 2019b).

Automated water quality monitoring in near real-time generates high-frequency, high-volume data. Anomaly in water quality data is inevitable and can be related to various factors, including sensor malfunction, database failure, and system deviations from its natural behavior (Rodriguez-Perez et al., 2020). Traditional methods of manual data anomaly detection and correction are complemented or replaced by more advanced rule-based, regression-based, and feature-based methods (Rodriguez-Perez et al., 2020). Machine learning (ML) and deep learning (DL) approaches are used in water quality anomaly detection tasks. Through a comprehensive literature review, Dogo et al. (2019a) argue that, in general, DL approaches tend to outperform traditional ML techniques in terms of feature learning accuracy and fewer false-positive rates. They propose a hybrid framework that mixes DL with extreme machine learning as a possible solution to detect anomalies in water quality data (Dogo et al., 2019a). One promising alternative is Artificial Neural Networks (ANNs) which do not require a priori knowledge of the underlying physical and environmental processes (Rodriguez-Perez et al., 2020). ANNs have the flexibility to train models using different learning methods to detect a broad range of anomaly types. For instance, Shi et al. (2018) proposed a wavelet-ANN-based model to detect and warn against water quality anomalies. They applied this approach as a case study to the Potomac River Basin in Virginia, USA, which successfully detected two anomaly events of TP variations from high-frequency online sensors. In Europe, Tinelli and Juran (2019) show how innovative sensing technology solutions, such as ANN, are used in combination with advanced pattern recognizers to ensure a real-time quality control for early chemical and/or bio-contamination detection and pre-emptive risk management purposes.

## STORMWATER MANAGEMENT

Stormwater runoff is the excess water not absorbed by saturated, sealed, or impermeable surfaces such as roads (Bassi et al., 2017). Surface runoff volumes and peak flows are significantly higher in urban areas because of the higher share of impermeable surfaces and the limited capacity of water management infrastructures (Bassi et al., 2017). In cities with combined sewage systems, heavy precipitation events damage physical infrastructure and create environmental and health issues when stormwater is mixed with sewage before heading to treatment facilities (Le Jallé et al., 2013). Furthermore, various non-point sources increasingly pollute urban water bodies. One example is commercial nurseries near urban areas that create a pollution problem during storm events. Experimental studies that measure runoff characteristics from commercial nurseries during typical irrigation events show that, on average, total nitrogen (TN) and phosphorus (TP) levels are like that of urban runoff. In contrast, total sediment (TS)

is 2–4 times greater. However, during storm events, the average loading of TN, TP, and TS is approximately 35, 50, and 900 times higher than those of irrigation events, respectively (Yazdi et al., 2019).

Municipalities worldwide address the urban runoff issue using engineered (or gray) and green stormwater infrastructures. Gray infrastructures are engineered drainage and treatment systems. In contrast, green infrastructures (GI) are natural and artificial elements and processes used to manage wet weather impacts through improving ecological and hydrological functions (Bassi et al., 2017; McPhillips and Matsler, 2018). An integrated approach to managing stormwater runoff uses new GI measures to mitigate the impact of runoff volume, speed, and pollution through natural filtration (Bassi et al., 2017). However, collecting data on the runoff characteristics and field observations during urban flooding are rarely available for model calibration and validation (Guan et al., 2021). In the context of climate change, higher severity and frequency of urban flooding are expected, requiring a new approach in short-term forecasting for emergency response and long-term planning for climate adaptation (Guan et al., 2021).

To improve our understanding of the fundamental urban runoff dynamics and associated processes like pollutant transport, we need to enhance our analytical capability and data support in urban flood modeling, using new approaches like using IoT in water system monitoring and the application of DL/ML in flood prediction (Kabir et al., 2020; Nie et al., 2020; Guan et al., 2021). Digitization can also help improve urban planning processes that aim to reintegrate stormwater into urban water cycles, recognizing stormwater as a resource to increase the supply of water where it is needed the most (Le Jallé et al., 2013; Su et al., 2013).

Successful stormwater governance mechanisms often combine command-and-control regulations with economic instruments to incentivize private property owners to implement effective measures against stormwater runoffs (Bassi et al., 2017). Digital technology, and specifically IoT and blockchain platforms, can be used to facilitate the development of an effective trading and mitigation framework, to help expand access to stormwater credit markets, to identify, measure, and track units of trading like volume and pollution level, and to automate the management of permanent or time-bound credits (Lathrop et al., 2012; Bassi et al., 2017).

## CONCLUDING REMARKS: FEASIBILITY OF BLOCKCHAIN IMPLEMENTATION

IoT enables water systems to execute processes and communicate using a standard interface, orchestrate the management through new coordination applications, and provide tailored information services for a specific water distribution network community (Tadokoro et al., 2011; Robles et al., 2015; Syed et al., 2021). Access to real-time data from sensors and actuators improves the management of water infrastructures and asset utilization, resulting in cost savings (Robles et al., 2015; Napolitano et al., 2021).

Nevertheless, examples of IoT implementation show that it would not eliminate the need for third-party validation and oversight in water systems (Anjana et al., 2015; Perumal et al., 2015; Wadekar et al., 2016; Alabi et al., 2019). A potentially better alternative technology is a distributed ledger blockchain. Considering the novelty of this technology, blockchain is yet to be tested and evaluated in the context of different applications, including urban water management. For instance, Li et al. (2021) recently proposed a data-driven peer-to-peer blockchain to predict water consumption. Effective water consumption forecasts will improve production and supply planning, reduce operating costs, and improve social benefits (Li et al., 2021).

Like any other new technology, different Blockchain applications (e.g., cryptocurrencies, autonomous vehicles, and infrastructure and governance) face different maturity and adoption stages. However, there are common technical, organizational, social, and institutional challenges that any organization should address before it can achieve the objectives and full potential of Blockchain technology (Zhao et al., 2019; Feng et al., 2020; Bagloee et al., 2021). As Bagloee et al. (2021) suggest, the first issue is the scalability of Blockchain networks. As a data-intensive and computationally demanding solution, the requirements for data storage, bandwidth, computational speed, and power highly depend on the number of participating nodes and the quantity of data analyzed.

Cybersecurity is another technical concern. Although the recent incidents of unauthorized penetration to cryptocurrency exchange platforms are rare, the scope of such a threat is yet to be fully understood (Brotsis et al., 2021). Industries willing to adopt this technology need to consider standardization and interoperability across Blockchain platforms, especially if the system requires collaboration between competitors, suppliers, and other stakeholders. Organizations that adopt blockchain should be mindful of the platform's significant electricity use and energy costs due to its power-intensive computing nature. That might put Blockchain participants at odds with sustainability goals. Recent advancements in Blockchain-as-a-service where cloud computing is incorporated might be a solution. Finally, the technological advances have outpaced the sluggish regulation developments. A close collaboration of adopting industry, technology developers, and policymakers can help remove regulatory obstacles to Blockchain adoption (Bagloee et al., 2021).

Once it is decided that blockchain is a suitable and economically viable solution to implement, a distributed ledger system should be designed to improve water management operations, including quality control on water reserves, efficient systemic water management, water leakage detection, water quality, and safety monitoring, transparency of consumption, and prescriptive maintenance on infrastructure (Alabi et al., 2019). In general, the initial investments required for the adoption of blockchain-based water management systems are capital investments in equipment (e.g., computers and blockchain miners, sensors, smart meters, communication devices), service investments (e.g., remote sensing, blockchain

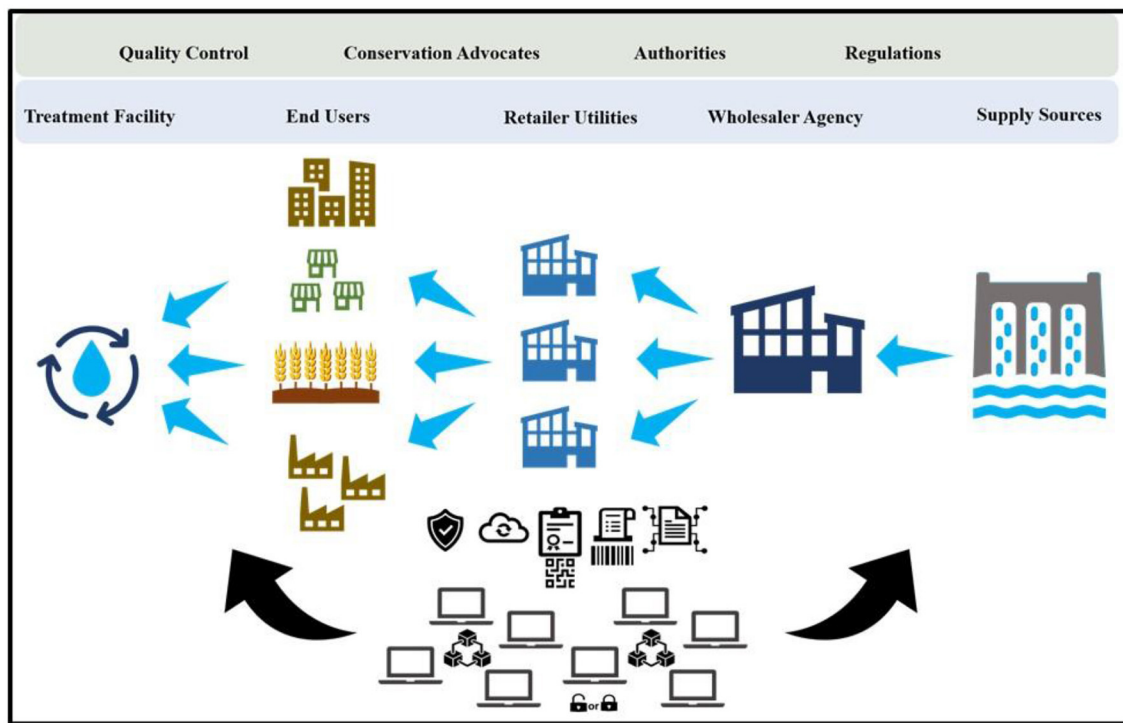
mining services, cloud-based decision models), and knowledge and human capital investments (localized knowledge to monitor and manage the system).

The architectural design, then, includes a network of IoT devices embedded within the distribution system to measure water consumption, a public blockchain infrastructure, and smart contracts that represent the interests of different stakeholders and regulate the distribution of incentives amongst different users (see **Figure 2**). Water managers and end-users at the core of the network who directly benefit from the digitized water distribution system. The direct benefit of IoT and Blockchain in enhancing business processes such as accounting, billing, and distribution is discussed extensively (Pincheira et al., 2021). For instance, the cost of recordkeeping can be significantly reduced if real-time data regarding market shares are managed by smart contracts and saved on a Blockchain platform (Poberezhna, 2018). Digitized quality certificates and consumption information would be easily accessible to authorized participants in the blockchain network.

Participating authorities and regulators can also monitor and audit business practices, transactions, and other financial documents in real-time. Business decisions can be made seamlessly through smart contracts based on predefined rules that govern the blockchain network. Data security is greatly improved compared to conventional centralized systems, and the inherent immutability of blockchain assures data integrity. Access to data can be restricted to authorized participants depending on whether a permission or permissionless architectural design is implemented. In water management systems that promote water savings, permissionless networks are more open and transparent and thus enable any stakeholder to put a value tag on those savings (Pincheira et al., 2021).

There are, however, legal limitations and ethical issues associated with blockchain technology before it reaches mainstream implementation. First, as an immutable and distributed ledger, blockchain does not conform to users' right to rectification and the right to be forgotten imposed by law to data software structures and public platforms (Teeluck et al., 2021). Also, there are problems with smart contracts in terms of conflict and dispute resolution. The legal system yet needs to find a way to assign responsibility in the case of conflict and decide upon the terms and conditions of the contract if disputes arise (Bottoni et al., 2020; Daniel and Ifejika Speranza, 2020; Dudder et al., 2021). In addition, the expansion of blockchain as a resource-intensive power-consuming process should raise concerns about the environmental impacts of the technology (Enescu et al., 2020; Teeluck et al., 2021). Finally, blockchain provides anonymity that could shield criminal activities such as money laundering, human trafficking, and terrorism financing.

Any blockchain application has three general technical and organizational components: the distributed ledger, the governance structure to use the ledger, and the ecosystem (i.e., stakeholders) that form the network (Van Wassenaeer et al., 2021). Any attempt to implement blockchain technology at a large scale should succeed in a careful pilot program in



**FIGURE 2** | Blockchain-based water management system. The graph is developed by authors using icons embedded in Microsoft Office software.

which different technologies are tested, considering the role of interoperable blockchain solutions and standardization of information requirements in the water management industry (Sengupta and Kim, 2021). In this regard, it is important to identify critical information and data elements that have value to stakeholders, including end-user in water supply systems (Van Hilten et al., 2020; Sengupta and Kim, 2021). Managing the access to data and authorization criteria can be addressed via permissioned and permissionless blockchain solutions (Van Hilten et al., 2020).

To prepare for adopting blockchain solutions in water management systems, understanding the potential barriers is critical. Most importantly, successful blockchain implementation depends on overcoming intra-organizational barriers such as management's long-term commitment and support, lack of new organizational policies, and lack of knowledge and expertise (Saber et al., 2019).

Furthermore, differences among partners in terms of organizational culture and information disclosure policies can lead to collaboration, communication, and coordination problems and therefore pose an inter-organizational barrier to adopting blockchain technology (Saber et al., 2019). Access to technology, smart devices, and IT tools can also be challenging to water system stakeholders. Scalability, data storage, and computational power are system-related barriers that should be addressed before the technology is fully adopted (Ahram et al., 2017; Helmbrecht et al., 2017; Saber et al., 2019). Entities that are not directly economically

benefiting from the adoption of blockchain could pose external barriers. A fair distribution of costs and revenues determined by the association of the stakeholders and regulators would facilitate blockchain technology development via a consortium approach. Blockchain technology features like smart contracts can ensure that cost distribution is according to pre-determined rules, increasing transparency and assurance (Sengupta and Kim, 2021). Finally, a robust mechanism that secures information flow along the water supply system is necessary.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## SUPPLEMENTARY MATERIAL

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