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Re: Promoting Public Involvement in Water Issues and Exploring Opportunities to Use Technological Advancements for Water Supply Management
Final Report

Please find herein the final report titled, *Promoting Public Involvement in Water Issues and Exploring Opportunities to Use Technological Advancements for Water Supply Management*, which investigates the application of IoT and Blockchain technologies in San Diego County. We reviewed 224 articles worldwide and summarized them on five application topics: *Smart Water Systems, Water Quality Monitoring, Storm Water Management, Agricultural and Food Industry, and Supply Chain*. Finally, we addressed technical, organizational, social, and institutional challenges that may hinder the adoption of Blockchain technology.

Sincerely,

M.Nemati

Mehdi Nemati, Ph.D.

Promoting Public Involvement in Water Issues and Exploring Opportunities to Use Technological Advancements for Water Supply Management

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Dr. Mahdi Asgari is a Postdoctoral scholar in the School of Public Policy, University of California-Riverside, where he studies water consumption and management economics. Dr. Asgari is especially interested in investigating regional and legal institutions that form water policy in the Southwest United States. He had published his previous research in journals like AJAE, Agribusiness, and JAAE. Dr. Asgari earned his Ph.D. in agricultural economics from the University of Kentucky. He is completing the Master of Legal Studies program at the University of Arizona while working for UCR.

Executive Summary

The application of distributed ledger technologies, including Blockchain, is rapidly growing in the domains of governance, transport, supply chain, and logistics. Blockchain was first used to create Bitcoin in 2008 as the first cryptocurrency as an emerging and disruptive technology. Today, blockchain technology is promoted as the heart of Smart Cities. In this report, we review the potentials of blockchain application in water management systems.

There are numerous peer-reviewed publications, reports, and general education materials that focus on explaining the IoT and Blockchain technologies, proposing specific architectural designs for a particular application, and reviewing relevant literature. Our search withing Google Scholar with keywords such as “Blockchain,” “IoT,” “Water Management,” and a combination of them resulted in more than a few hundred articles as our initial depository. We set a citation alert and monitored recent publications to add the most relevant work to our references. In total, we reviewed 224 publications and cited 97 articles that we found most relevant to the purpose of this study. We had to forego technical publications, mainly in the field of computer science and information technology which are outside our expertise area. However, we used 13 widely cited technical articles to provide a general background to Blockchain and IoT concepts. We did not include unpublished work, industry briefs, and not peer-reviewed materials in this report.

We surveyed 80 articles and organized the main part of this literature review study based on five application topics: *Smart Water Systems*, *Water Quality Monitoring*, *Storm Water Management*, *Agricultural and Food Industry*, and *Supply Chain*. The first three topics are the most relevant to the purpose of this study and account for 63 percent of our citations in these sections (50 out of 80). To be more specific, we used 21 peer-reviewed articles to highlight the application of IoT and Blockchain in smart water systems, 21 articles in water quality monitoring, and eight articles focusing on stormwater management. We also reviewed the application of Blockchain in the agricultural industry and supply chain using 30 articles.

Finally, we addressed technical, organizational, social, and institutional challenges that may hinder the adoption of Blockchain technology. Successful industry-wide implementation of Blockchain solutions should overcome scalability, cybersecurity, and interoperability issues in an expanded blockchain network while considering the significant energy costs of the computational components. In addition, stakeholders and policymakers should collaborate to update laws and regulations that encourage the adoption of Blockchain technology.

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Introduction

According to recent estimates of the U.S. Census Bureau, the county of San Diego is home to more than 3.34 million residents[1]. It is bordered by Imperial on the east and Riverside and Orange counties on the north (see Figure 1). We have collected information on the 200 water systems serving this population under the San Diego County Water Authority (SDCWA). Most of these local water agencies are small in terms of the population served. In fact, more than 77% of water systems in San Diego County serve communities of less than 500, and almost 93% of the agencies serve communities with less than 50,000 customers (see Table 1, Panel A).

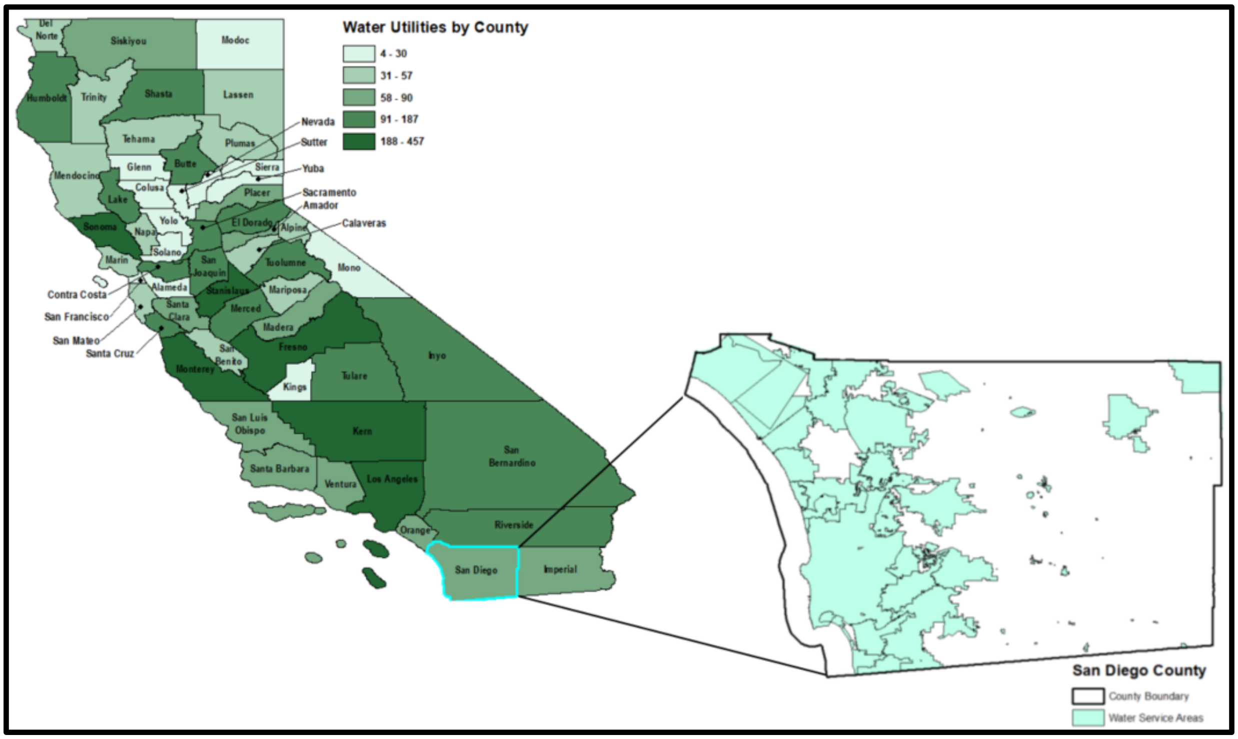

Figure 1. San Diego County map and Water Service locations (*Lee, Nemati, and Dinar 2021b*).

The largest water system in the county is serving the city of San Diego, with more than 1.4 million residents. Groundwater is the primary source for 168 of the 200 water systems in the county (see Table 1, Panel B). However, groundwater accounts for only 5% of water use, while surface water from various sources forms more than 67 percent.[2] The primary source for one agency was not reported, but the other 31 agencies rely on surface water from the Colorado

[1] See U.S. Census Bureau (https://www.census.gov/quickfacts/fact/table/sandiegocountycalifornia,US/PST045219)
[2] See San Diego County Water Authority for detailed current and planned water resource portfolio (https://www.sdcwa.org/your-water/?q=/water-supplies).

River and Northern California water sources. In recent years, SDCWA has developed a supply diversification strategy to build a more robust water system, including investments in desalination and treatment plants to meet the needs of the growing urban population. Water systems in San Diego County primarily provide services to residential and recreational areas (see Table 1, Panel C). Mobile home parks are the other major service area.

Table 1. Water systems in California San Diego County by various characteristics

	Number Water Systems	Share (%)
Panel A: Population Served		
<=100	80	40.00
101-500	75	37.50
501-1,000	15	7.50
1,001-3,300	4	2.00
3,301-10,000	3	1.50
10,001-50,000	10	5.00
50,001-100,000	5	2.50
100,001-250,000	6	3.00
250,001-500,000	1	0.50
500,001-1,000,000	0	0.00
>1,000,000	1	0.50
Total	**200**	**100.00**
Panel B: Primary Water Source		
Groundwater	164	82.00
Groundwater under the influence of surface water	4	2.00
Surface water	12	6.00
Surface water purchased	19	9.50
Unknown primary source	1	0.50
Total	**200**	**100.00**
Panel C: Service Area		
Residential area*	63	31.50
Recreation area	67	33.50
Industrial/Agricultural	1	0.50
Other transient areas	12	6.00
Mobile home park	16	8.00
Restaurant	7	3.50
School	8	4.00
Other**	26	13.00
Total	**200**	**100.00**

Note: *Includes Residential area, Secondary residences, and Other residential. ** Includes Institution, Hotel/Motel, Wholesaler of water, Service station, Highway rest area, Other non-transient areas, Medical facility, and Other areas.
Source: U.S. EPA, Safe Drinking Water Information System (SDWIS) database.

More than 39% of the water systems in San Diego County are community water systems that serve at least 15 service connections used by year-round residents or regularly serve at least 25 year-round residents (see Table 2). Most of the community water systems are privately owned (52 out of 79), while the rest is managed by local (20), federal (6), or state (1) governments. There are 101 transient non-community (e.g., campground or highway rest stop with a water source) and 20 non-transient non-community (e.g., school or office building with a water source) systems in the county as well.

Table 2. Count of water systems in California, San Diego County by ownership type

Ownership Type	Count		Share (%)	
Community water system*		**79**		**39.5**
Federal government	6		7.59	
Local government	20		25.32	
Private	52		65.82	
State government	1		1.27	
Transient non-community system**		**101**		**50.50**
Federal government	11		10.89	
Local government	37		36.63	
Private	36		35.64	
State government	17		16.83	
Non-transient non-community system***		**20**		**10.00**
Federal government	0		0.00	
Local government	1		5.00	
Private	19		95.00	
State government	0		0.00	
Total		**200**		**100**

Note: *Community water systems are defined as a water system that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents (e.g., homes, apartments, and condominiums occupied year-round primary residences). **Transient non-community systems are defined as a non-community water system that does not regularly serve at least 25 of the same persons over six months per year. A typical example is a campground or a highway rest stop with its own water source, such as a drinking water well. ***Non-transient non-community systems are a non-community PWS that regularly serves at least 25 of the same persons over six months per year. A typical example of a non-transient, non-community water system is a school or an office building with its own water source, such as a drinking water well.
Source: U.S. EPA, SDWIS database. For definitions, see Data Download Summary and Data Element Dictionary (https://echo.epa.gov/tools/data-downloads/sdwa-download-summary).

Despite a 35 percent population growth in the region, the total use of potable water in San Diego County was about 30 percent less in 2020 than in 1990. The success of SDCWA's water-use efficiency programs and conservation initiatives is depicted in the declining trend of potable water use since 2007 (See Figure 2). However, a recent study on residential water use in 2019 shows that, on average, the estimated share of outdoor use was 60 percent in California, and in Southern agencies, that share has increased by 56 percent since 1994 (Lee, Nemati, and Dinar 2021a).

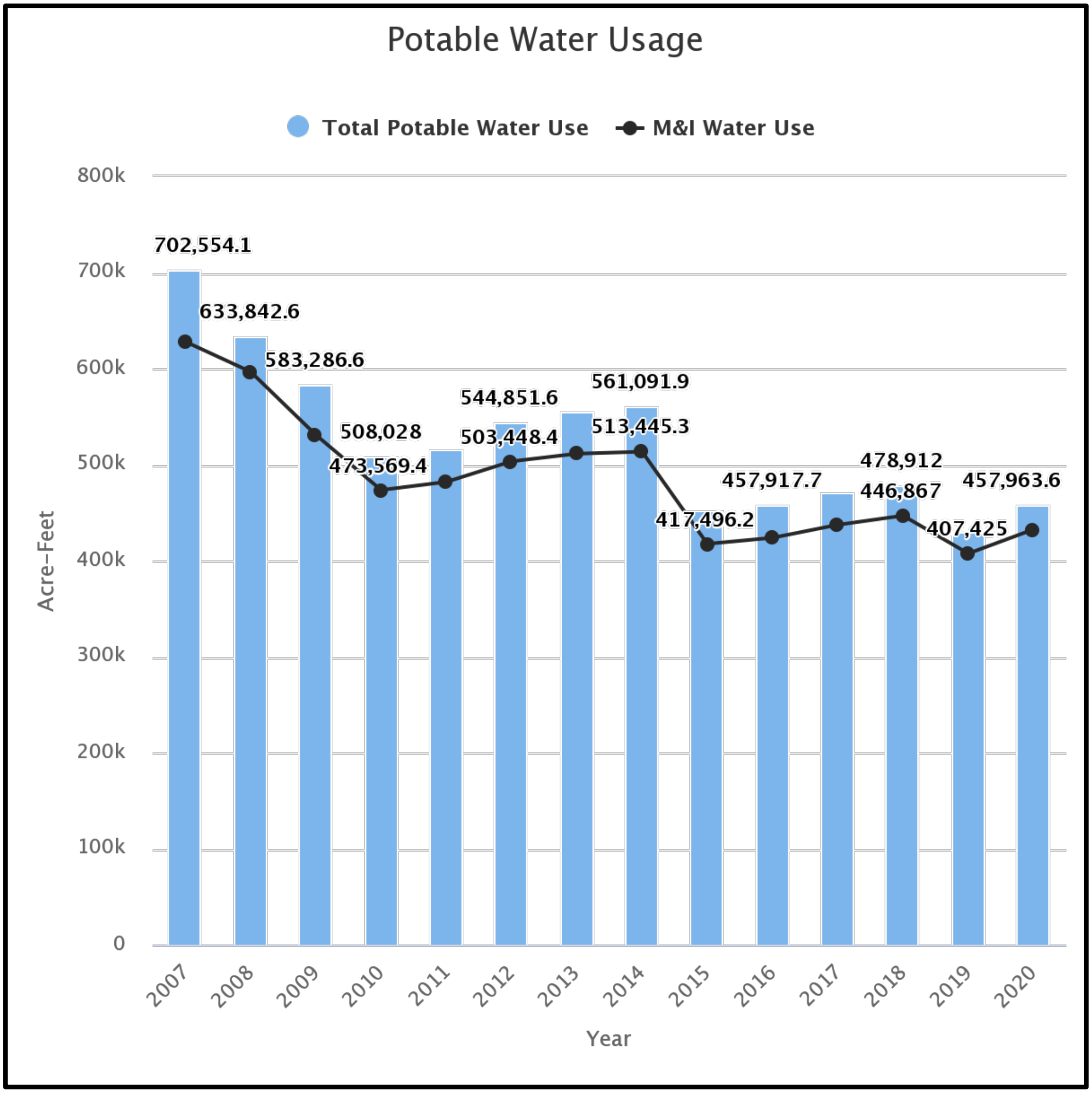

Figure 2. Potable water use trend in San Diego County (2007-2020)
Note: Total potable water use excludes reclaimed water. To provide for a meaningful comparison, 2007 M&I water use was adjusted for 2009-2011 IAWP and SAWR opt-out volumes that convert to M&I water use.
Source: SDCWA (https://www.sdcwa.org/your-water/water-use/).

Water conservation is a priority in urban water management in California. The state had implemented policy measures to improve water saving and introduced technologies to increase water efficiency. Nevertheless, exacerbated climate impacts especially extended drought periods, necessitates further conservation efforts and policy designs that reflect individual communities' perceptions and needs (Lee, Nemati, and Dinar 2021a). State-wide blanket policies to restrict water use while overlooking the heterogeneity of household types, weather conditions, and property sizes throughout the state cannot be effective in saving further water (Lee, Nemati, and Dinar 2021a). On the other hand, tailored policy to specific conditions such as time period, region, and agency characteristics require widespread monitoring of infrastructure, extensive data collection and analysis, and real-time decision making.

In recent years the development of IoT technology as an architectural framework that connects real-world objects, data-collecting sensors, and computational devices via the network, has enabled us to access and transmit the resources through the Internet without manual performance (Mahalakshmi et al. 2020). Smart water systems that combine the use of the Internet of Things (IoT), artificial intelligence (AI), and big data have enhanced addressing urban processes, including waste and water management as well as water conservation (D'Amico et al. 2020). Underwater sensors and smart meters along the water supply system can detect temperature changes, water leakage, chemical leakage, and pressure level and collect and send information to the main server where service engineers can promptly address problems (Nie et al. 2020).

IoT application expands over wearables, smart homes, automation of vehicles, energy engagement, and smart cities, to name a few (Mahalakshmi et al. 2020). These advancements coupled with communication technologies like WIFI and 5G are shaping our future cities where Blockchain, as a decentralized and distributed ledger, has a significant role in a bottom-up approach to city-shaping and design (Bagloee et al. 2021). Integrated Blockchain systems greatly focus on improving flexibility and resilience while enhancing trust and transparency between industry partners (Düdder et al. 2021). Blockchain fundamentally transforms how industries and business structure their interactions and processes (Poberezhna 2018).

The engineering and technical details of blockchain technology are beyond the scope of this study. However, a general overview of the components, architecture, and platforms used in blockchain technology is provided before focusing on the applications. In the water industry, stakeholders would benefit from being real-time participants in the analytical process rather than receiving post hoc reports (Poberezhna 2018). Utilities that plan to issue bonds can share the space with agencies involved in the verification, compliance, and trading processes (Poberezhna 2018). Within the water utility sector, integrated IoT and Blockchain solutions affect back-end, administrative, and legal processes by automating billing and customer relationship management or digitizing water assets and trading (Poberezhna 2018). Regulators and auditors can rely on the immutability, immediacy, and transparency of the information saved on a distributed ledger platform, hence reduce the time and effort required for regulatory reporting.

Blockchain Technology and IoT

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 (Shahid et al. 2018). Our modern life is involved with an inter-networking of embedded devices, sensors, and computers that collect and distribute a large amount of data, known as the Internet of Things (IoT). 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 (Dey et al. 2018, Qatawneh, Almobaideen, and AbuAlghanam 2020, Rose, Eldridge, and Chapin 2015). Blockchain solutions improve data security and privacy (Teeluck, Durjan, and Bassoo 2021).

Blockchain: characteristics, applications, and limitations

Blockchain is an emerging technology that is used to keep track of ownership of assets and record transactions in the form of distributed ledger (Teeluck, Durjan, and Bassoo 2021). All the data is saved into immutable blocks providing a secure peer-to-peer transaction without the need for a third party authentication (Teeluck, Durjan, and Bassoo 2021). Blockchain was the steppingstone for the creation of cryptocurrencies (Nakamoto 2008). During the past two decades, the application of Blockchain was expanded to manage smart assets and to create and manage smart contracts (Teeluck, Durjan, and Bassoo 2021, Akram et al. 2020).

A blockchain is a series of time-stamped batches of information (i.e., blocks) that each 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 (Teeluck, Durjan, and Bassoo 2021). The hash of each block is calculated using the information from its previous block (Teeluck, Durjan, and Bassoo 2021).

When a transaction occurs, a new block is processed and added to the chain which is known as mining (Reyna et al. 2018). Before any new block is added to the chain, a form of consensus among nodes about the authenticity of the new information is required. There are 12 different types of consensus mechanisms based on the application and the Blockchain architecture (Teeluck, Durjan, and Bassoo 2021). Each network defines the consensus mechanism.

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 (Teeluck, Durjan, and Bassoo 2021, Reyna et al. 2018). 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 (Akram et al. 2020). 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 (Akram et al. 2020). A consortium blockchain mixes the previous two types that only preselected trusted nodes participate in the consensus mechanism (Akram et al. 2020).

In essence, the four main characteristics of blockchain technology differentiate it from most existing information systems designs (Saberi et al. 2019). These key characteristics include decentralization (non-localization), security, auditability, and smart execution (see Figure 3).

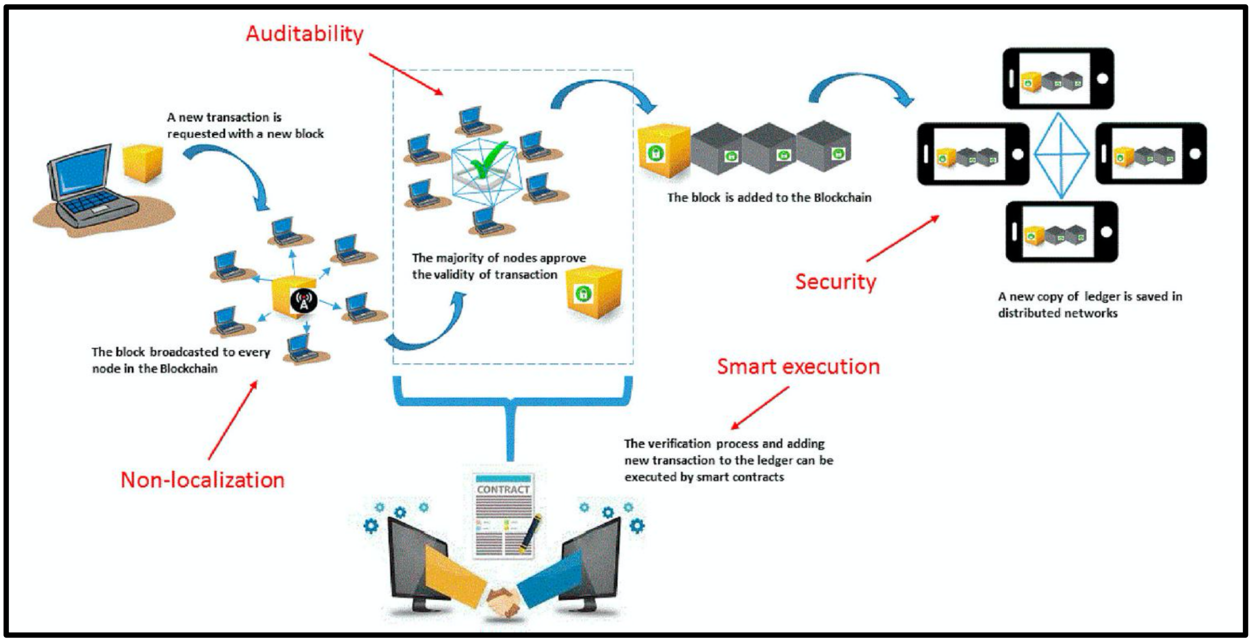

Figure 3. Steps in blockchain information and transactions (*Saberi et al. 2019*).

Blockchain is implemented in various sectors, some using major platforms such as Ethereum or Hyperledger and others smaller custom-made ones. In the healthcare industry, Blockchain has improved anonymity, security, traceability, management, and transparency of data allowing for real-time monitoring of remote patients on wireless sensor networks and adding to data integrity and interoperability of health studies (Teeluck, Durjan, and Bassoo 2021, Ahram et al. 2017). Blockchain networks are also used in asset traceability, logistics, and smart ownership. 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, Durjan, and Bassoo 2021).

Automotive and telecommunication industries implement blockchains to improve transparency and interconnectivity among users, devices, and external institutions (Teeluck, Durjan, and Bassoo 2021). The development of 5G technology would further improve machine-to-machine communications, and Blockchain can be used to secure, authenticate, and privatize personal data (Teeluck, Durjan, and Bassoo 2021). Governments can issue digital identifiers like birth certificates, driving licenses, and passports and use Blockchain to store sensitive personal data securely, deny unauthorized access, and authenticity travelers across borders (Teeluck, Durjan, and Bassoo 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, Durjan, and Bassoo 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 (Teeluck, Durjan, and Bassoo 2021). In addition, the expansion of Blockchain as a resource-intensive power-consuming process should raise concerns with regard to the environmental impacts of the technology (Teeluck, Durjan, and Bassoo 2021). Finally, Blockchain provides anonymity that could shield criminal activities such as money laundering, human trafficking, and terrorism financing.

There is a need for innovative legislation to regulate and certificate distributed ledger technology (DLT) platforms to address these issues. Malta is a pioneering country in legislating DLT platforms and regulating transactions that use cryptocurrencies (Teeluck, Durjan, and Bassoo 2021). The Maltese government has implemented the Malta Digital Innovation Authority (MDIA) Act and the Innovative Technological Arrangement and Services (ITAS) Act, which layout a certification process for DLT platforms. Furthermore, the Virtual Financial Asset (VFA) Act regulates the creation of new Initial Coin Offerings (ICOs), the exchange between crypto-currencies and digital wallet providers. These historical first laws have been widely encouraged by the European Union.[3]

Blockchain and IoT

Integration of Blockchain into the IoT sector would decentralize the network, improve data sharing, and eliminate central failure points (Teeluck, Durjan, and Bassoo 2021). Also, smart devices are uniquely identified on a blockchain network, thus resolving scalability limitations faced by traditional Internet-based protocols (Teeluck, Durjan, and Bassoo 2021). Furthermore,

[3] See Business Matters, Blockchain technology & Malta's regulatory framework, 3 Aug 2018, https://www.bmmagazine.co.uk/business/blockchain-technology-maltas-regulatory-framework/.

blockchains embed smart contracts, digital wallets, and consensus mechanisms into the network so that smart devices can gain higher autonomy in interacting with each other (Teeluck, Durjan, and Bassoo 2021). Finally, since existing data cannot be modified or tampered with on the Blockchain, data reliability and security are significantly improved for IoT when the two technologies are integrated (Teeluck, Durjan, and Bassoo 2021, Christidis and Devetsikiotis 2016).

When integrating Blockchain and IoT, should decide how underlying IoT infrastructure would communicate. These interactions can be designed to take place inside the IoT, through Blockchain, or via a hybrid approach (Reyna et al. 2018). In the IoT-IoT approach, the interactions take place outside the Blockchain network, make it a faster method (see Figure 4a). The IoT-Blockchain approach (Figure 4b) enables an immutable and traceable record of interactions. Finally, in a hybrid design (Figure 4c) the interactions and data partly take place in the Blockchain while the rest are directly shared between the IoT devices.

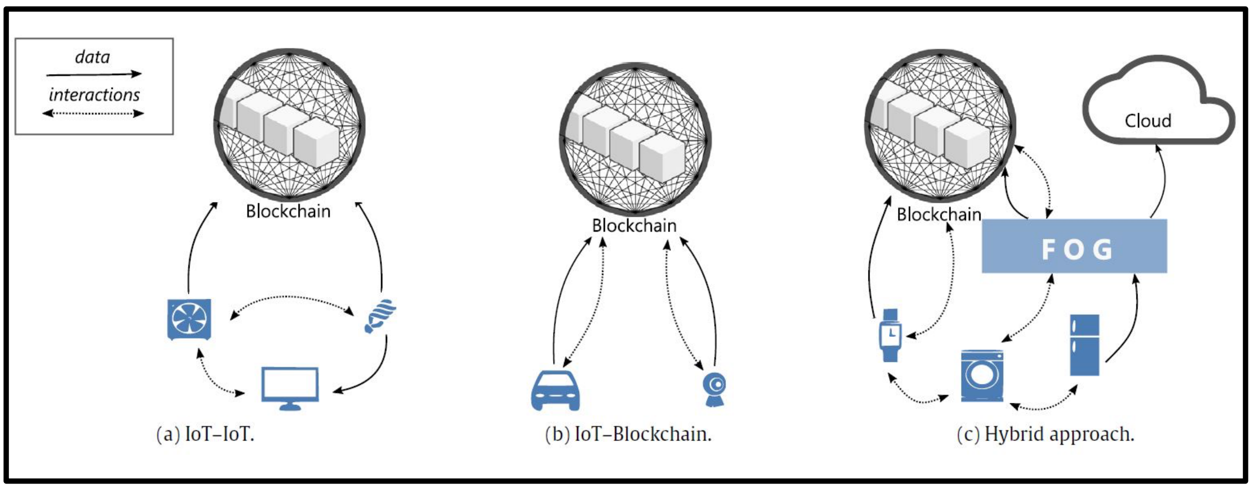

Figure 4. Blockchain IoT interactions (*Reyna et al. 2018*).

The rapid spread of Blockchain applications does not mean that it is always worth using them. Increasing the IoT autonomy through Blockchain can require costly sophisticated hardware for computational purposes. Therefore, implementation of the Blockchain highly depends on the application's requirements (*Reyna et al. 2018*).

Smart Water Systems

Depleting resources, complex regulations, and increasing demand for clean and affordable water challenge current water management systems (Sriyono 2020). Advanced digital technology is used to collect data on the distribution and consumption of water in urban settings (Public Utilities Board Singapore 2016). Smart water grid systems enhance consumption management, sustainability and compliance, and effective policymaking using integrated Blockchain and IoT technologies (Sriyono 2020, Dogo, Salami, et al. 2019).

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 (Lin et al. 2018). 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).

Smart water systems are often defined within the concept of smart cities. 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). In smart cities, IoT can be used to monitor the urban environment. The concept of Environmental Internet of Things (EIoT) refers to the sense, acquire, process, and transfer of environmental information over a large area in real-time (Su et al. 2013). 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).

Communities that use smart water technologies integrate various detecting devices and intelligent systems, depending on their needs. 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 result in water use reduction. 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, and operate and maintain water infrastructure in an energy-efficient manner (Lee et al. 2014).

The benefits of Intelligent water management systems that use IoT sensors are described and evaluated in a different context. By utilizing an integrated end-to-end platform that monitors the water distribution systems in real-time, both the operational aspects (asset management, leak management, water quality monitoring) and customer end (automated meter reading and water conservation) are managed and controlled constantly (Allen et al. 2012, Abdelhafidh, Fourati, and Chaari Fourati 2020, Public Utilities Board Singapore 2016). 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 move toward achieving Sustainable Development Goals (SDG6) as envisioned by the UN in 2035 (Dogo, Salami, et al. 2019).

From the financial aspect, Blockchain technology facilitates collaboration among counterpart organizations and eliminates manual checks and reconciliation processes (Poberezhna 2018). For instance, 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, by creating a digital identity for organizations, digitizing water assets, and storing these on a shared ledger, millions of dollars would be saved through streamlined counterparty data management process (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 the implementation of 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. Finding a systematic framework to guide the real-world design and deployment of a smart water network is challenging and context-dependent (Li, Yang, and Sitzenfrei 2020). In addition, evaluating the accuracy and efficiency of the data generated by the IoT and managed by DLT 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, Wang, and Seidu (2020) designed two predictive models for water quality based on integrated smart data-driven technologies. The focus of their design is on predicting 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 to measure biological indicators of water quality (Wu, Wang, and Seidu 2020). Considering the seepage from agricultural, residential, and industrial users into the water sources, effective quality control of water sources is essential to the safety planning of the water supply system. They collected raw water data from the urban water supply systems of Oslo and

Bergen in Norway. The outcome of their proposed predictive models shows that the Smart Data-Driven framework is an efficient way for future decision-making support of water quality control and risk management. Although biological indicators are difficult to measure and collect, both proposed models result in significant predictive accuracy (Wu, Wang, and Seidu 2020).

Some newly proposed architectural designs integrate IoT, Blockchain, Decision Support Systems, and AI technologies to ensure efficient water management. In a proposed design, Pahonțu 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.

A comprehensive review of the literature shows that 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, Yang, and Sitzenfrei 2020). However, the proposed smart water systems (SWS) performance can be evaluated using two conceptual metrics of smartness and cyber wellness that measure system efficiency and security, respectively (Li, Yang, and Sitzenfrei 2020). The smart performance of SWS 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 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). The information security issue arises from the vulnerability of the IoT component where sensors and actuators across the water distribution network communicate data. Borrowing the International Telecommunication Union's definition, Li, Yang, and Sitzenfrei (2020) introduce cyber wellness as a measure that indicates the maximum data stored before a cyberattack while withstanding cyberattacks as long as possible at the same time.

Water Quality Monitoring

Water quality refers to the physical, biological, and chemical characteristics of water. The important measurable water quality parameters include chemical oxygen demand, biochemical oxygen demand, pH, dissolved oxygen, turbidity, electrical conductivity, temperature, oxidationreduction potential, salinity, total nitrogen, and total phosphorus (Bahadori and Smith 2016). IoT framework enables the real-time monitoring of water quality indices facilitated by the speed of internet communication. Automation of processes through IoT reduces the need for human resources and consequently limits human errors. Smart monitoring systems are adaptive and responsive, which can alert 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 (Ighalo, Adeniyi, and Marques 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 (Ighalo, Adeniyi, and Marques 2021, Bai, Wu, and Jin 2020). The collected data is transferred to Cloud storage for further analysis or to a user-friendly PC/Smartphone interface through Wi-Fi modules (Shanthi, Gopi, and Vidhyesh 2019). Some framework designs suggest the use of solar panels to provide the energy for running the system (Arvind, Paul, and Bhulania 2020). There are extensive proposed designs for an IoT based water quality monitoring system in the literature, focusing on portability (Tripathy, Das, and Chowdhary 2020), performance efficiency, and data reliability (Cho Zin et al. 2019, Kumar, Askarunisa, and Kumar 2020), cost-effectiveness (Sarraf et al. 2020), and communication ability (Sithole, Nwulu, and Dogo 2019) of the module.

The application of IoT in monitoring water quality ranges from observing any chemical or physical change of water in rivers (Meshal, Mikhael, and Mansour 2020, Wang et al. 2013, Cianchi et al. 2000, Chowdury et al. 2019) and watersheds (Hoos, Wang, and Schwarz 2019) to identify pollution levels in near real-time; to detection of hydrologic variability in estuarine and marine ecosystems (Glasgow et al. 2004) used for early warning systems and rapid response to harmful algal bloom events. Developing countries 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 be used to predict water quality, thus playing an important role in future risk control and decision support in urban water supply systems (Wu, Wang, and Seidu 2020). The continuous monitoring of the water supply system creates a time-series data set that can further be analyzed to identify the impact of climate parameters like monsoon or summer on the quality of water delivered to a specific how the quality of water is affected by monsoon or in summer or by wind speed and by different geographical location (Tripathy, Das, and Chowdhary 2020). There is also developing applications for improvement 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, Hassan, and Mourad 2020) and also send signals to households if health hazards are detected in the tap water (Sithole, Nwulu, and Dogo 2019).

Data anomaly detection

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 deviations of the system from its natural behavior (Rodriguez-Perez et al. 2020). Traditional methods of manual data anomaly detection (AD) 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, Nwulu, et al. (2019) 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 an extreme learning machine (ELM) as a possible solution to detect anomalies in water quality data (Dogo, Nwulu, et al. 2019). One promising alternative is Artificial neural networks (ANNs) which do not require a priori knowledge of the underlying physical and environmental processes. ANNs have the flexibility to train models using different learning methods to detect a broad range of anomaly types (Rodriguez-Perez et al. 2020).

Storm Water 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 surface and the limited capacity of water management infrastructures (Bassi et al. 2017). Apart from damage to physical infrastructure, heavy precipitation events create environmental and health issues in cities with combined sewage systems through which stormwater is mixed with sewage before heading to treatment facilities (Bassi et al. 2017). 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. Measuring 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. Nevertheless, the average loading of TN, TP, and TS during storm events is approximately 35, 50, and 900 times higher than those of irrigation events, respectively (Yazdi et al. 2019).

Municipalities worldwide had addressed the urban runoff issue using engineered (or gray) and green stormwater infrastructures. Gray infrastructures are engineered drainage and treatment systems, while green infrastructures (GI) are natural and manmade elements and processes used to manage wet weather impacts through improving ecological and hydrological functions (Bassi et al. 2017). An integrated approach to manage stormwater runoff uses new GI measures to mitigate the impact of runoff volume, speed, and pollution through natural filtration (Bassi et al. 2017).

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). Market-based solutions in the form of tax or fees and incentives or subsidies can create price signals. In contrast, quantity-based allowances create a trading environment that helps private investors to decide which runoff control projects are economical (Bassi et al. 2017). Washington D.C.'s specific stormwater retention credit for property developers is a good example of a credit trading mechanism (Bassi et al. 2017). It is needless to say that the success of incentive-based policies relies on the participation of local economic actors and how technical challenges are addressed (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 expanding 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-bond credits (Bassi et al. 2017, Lathrop et al. 2012).

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, Liang, and Hou 2021). To improve our understanding of the fundamental urban runoff dynamics and associated processes like pollutant transport, we need to we need to enhance our analytical capability and data support in urban flood modeling, including the application of deep/machine learning to support flood prediction (Guan, Liang, and Hou 2021, Kabir et al. 2020). 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, Désille, and Burkhardt 2013).

Other Applications

Agricultural and food Industry

The application of digital technologies to crop and livestock management has increased in recent years. A combination of information technologies, computational decision, and analytical tools, and automation of farm machinery has enabled precise monitoring and detection of variations in crop health, soil fertility, and yields in fields as well as animals' health and barn's climate, using proximal or remote sensing (Khanna 2020, Birner, Daum, and Pray 2021). Combined with real-time information about weather, climate conditions, and soil nutrient needs, "smart farming" aggregates the high-resolution field/farm-level data with other sources of public data and privately-held data for decision making (Khanna 2020).

The advancements in sensing technology and machine learning approaches have enabled the agriculture industry to incorporate IoT and automated real-time decision-making processes into the management of farms. The employment of new devices such as drones and robots is also gaining momentum due to advances in sensor and positioning technologies and computing powers (Birner, Daum, and Pray 2021). Generally, various forms of IoT in agriculture create large data sensing and analysis that require extensive computational power (Kour and Arora 2020).

There is extensive literature documenting IoT and Blockchain technologies in agriculture (Bermeo-Almeida et al. 2018). Farmers now can remotely analyze the water used for crops and the moisture level in the field and schedule automated recurring watering through smart irrigation applications that work based on IoT platforms (Rabadiya Kinjal, Shivangi Patel, and Chintan Bhatt 2018). While IoT is used for data gathering, communication, and computation, blockchain technology is applied to ensure transparency and trust in data-sharing processes (Antonucci et al. 2019). These characteristics are especially important for communities that need to regulate access to scarce resources such as water. In areas that farmers compete over limited water, a blockchain-based control system can manage the irrigation water effectively and transparently while keeping the activities of participants anonymous (Bordel et al. 2019).

Similarly, smart irrigation systems are used in food production under a controlled environment. Experimental studies show that using IoT to monitor and manage temperature, humidity, CO_2, pH, electroconductivity, and water flow in hydroponics can improve production yields (Lakshmiprabha and Govindaraju 2019, Marques, Aleixo, and Pitarma 2019, Mehra et al. 2018, Palande, Zaheer, and George 2018). These smart monitoring systems can also be adopted by urban gardens, urban farms, and green buildings (Ruengittinun, Phongsamsuan, and Sureeratanakorn 2017).

The precision technologies embodied in the physical devices are often complemented by disembodied software tools, including online platforms, management software, and advisory and financial apps (Birner, Daum, and Pray 2021). These software solutions assist farmers, managers, consumers, and other stakeholders across the value chain (Birner, Daum, and Pray 2021). The data generated along these systems can verify standard practices if all participants can access, verify, and modify the data.

The conventional food supply chain system entails complex processes that document the exchange of goods, extensive paperwork, high risks for buyers, and the costly involvement of intermediaries (Kamilaris, Cole, and Prenafeta-Boldú 2021). Digitization has reduced the operational costs of the food supply chain and increased the efficiency and reliability of the system, yet there is much space for improvement (Krzyzanowski Guerra and Boys 2021). The information that is created as the farms and firms produce crops, process crops to food ingredients, transform ingredients to food products, package, transport, and sell products to final consumers can be stored in a common database and managed through a DLT platform (Griffin et al. 2021). DLT technology, encompassing Blockchain and other similar applications, provides trust, traceability, and transparency throughout the agriculture supply chain, facilitates implementing extremely large data sets and furthers the development of farm data communities (Griffin et al. 2021). DLT expedites the validation process for any agricultural product that requires some form of certification and end-to-end tracking in the supply chain (Griffin et al. 2021). The security of DLT is guaranteed through its distributed nature, digital signatures, and its consensus algorithm that could be designed as private, requiring permission to join, or anonymous and permissionless (Griffin et al. 2021).

A digitized food supply chain using blockchain technology (Figure 5) includes a physical layer where the flow of goods occur and a digital layer comprising of several integrated technologies including QR codes, RFID, NFC, trusted online certification and digital signatures, sensors, and actuators, and mobile phones (Kamilaris, Cole, and Prenafeta-Boldú 2021). The information that is accepted and validated by participating business partners, as each transaction takes place, is stored as a permanent record in a block and shared through a distributed ledger.

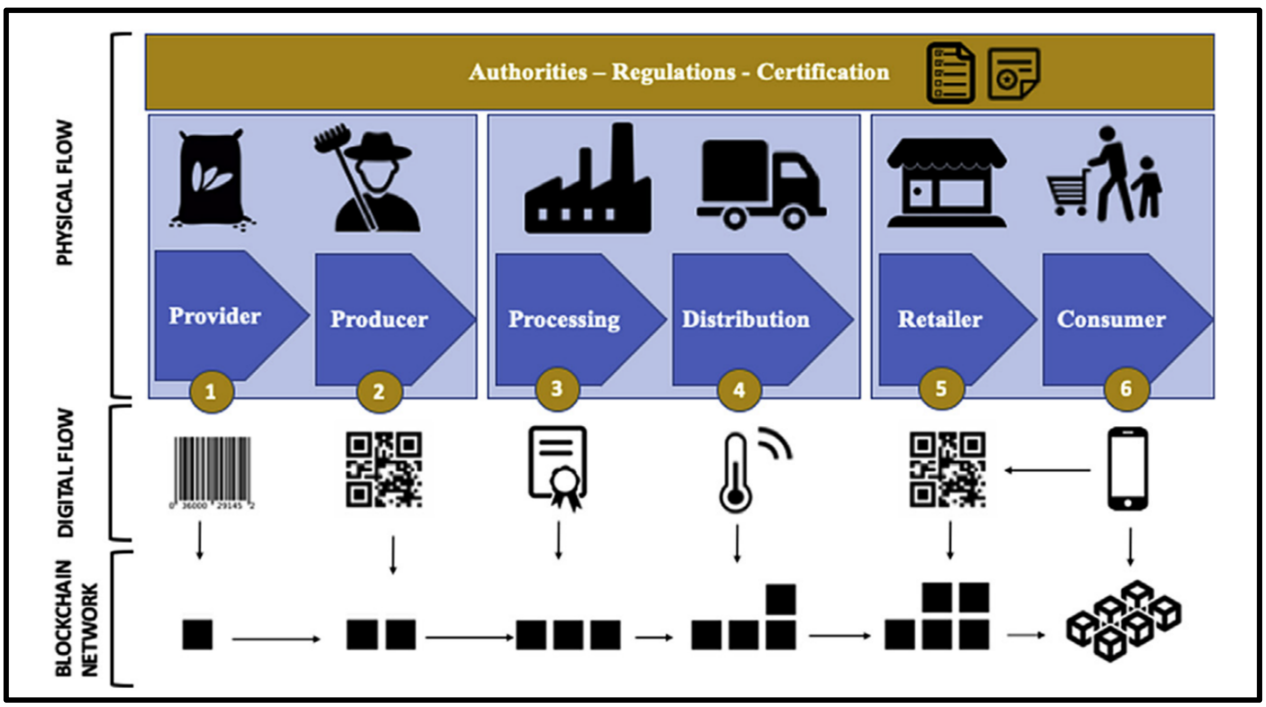

Figure 5. A simplified food system (Kamilaris, Cole, and Prenafeta-Boldú 2021).

For instance, the ***Provider*** can record the information with regard to the seeds, fertilizers, and pesticides supplied; the ***Producer*** may provide data about the farm and the practices employed therein; the ***Processing*** and ***Distribution*** record data about the factory equipment and storage conditions; the ***Retailer*** can create a current and historical data on the quality and quantity of the product; while the ***Consumer*** has access to all the information associated with the product (Kamilaris, Fonts, and Prenafeta-Boldύ 2019).

A systematic review of the literature shows that the agri-food industry has applied blockchain technology to enhance value chain traceability, information security, manufacturing settings through smart contracts, resource allocation, and process, data, and quality management (Zhao et al. 2019). Food safety is a major challenge, and foodborne illnesses impose a significant financial burden on the food industry. An efficient and reliable traceability system can reduce the time needed to identify the issue and help minimize the impact of an outbreak (Collart and Canales 2021). Also, a blockchain-based traceability system can increase confidence in labels and claims about credence attributes such as local, organic, or fair trade by reducing the information gap between consumers and producers (Collart and Canales 2021, Creydt and Fischer 2019).

Empirical studies show that consumers worldwide value food products with blockchain-based traceability at premiums (Shew et al. 2021, Lin et al. 2020, Violino et al. 2019). The benefits of applying Blockchain to supply chain traceability in the food industry, summarized by Sengupta and Kim (2021), varies from the reduction of time, scope, and costs for food product recalls, to the reduction of disputes in quality assurance in the food supply chain, to increase in the size of the market based on the assurance of quality. Furthermore, blockchain-based traceability can increase pricing and value capture based on value for customers and distribute that value to stakeholders in the supply chain through Smart Contracts (Sengupta and Kim 2021). Blockchain traceability is sufficiently flexible for future needs. It provides the ability to connect to additional blockchain solutions such as insurance products and services and to meet increasing consumer demands for information on food origins and processes (Sengupta and Kim 2021).

In commodity crop trading, asymmetric information regarding grain quality, protein level, for instance, could expose sellers and buyers to the risk of shipment rejection by importers and increase the cost of testing (Lakkakula, Bullock, and Wilson 2021). A blockchain framework can mitigate the asymmetric information problem through smart-contract functionality. Buyers and importers who are participating in the network can create a predefined logic that permits the transaction only if the shipment meets the required quality. Participant sellers can upload and share a quality certification to the network. This framework results in substantial premiums in the market and facilitates grain trading by reducing transaction costs, improving efficiency, and prioritizing procurement strategies (Lakkakula, Bullock, and Wilson 2021).

Several major food companies have adopted (or are adopting) blockchain-based traceability, though not all of them share information with consumers (Collart and Canales 2021). The leading platform is the IBM Food Trust, launched in partnership with Walmart, Nestlé, and Unilever that allows permissioned partners to track a food product in real-time, execute smart contracts, analyze inventory, examine the age of the product, and share the records of certifications, licenses, and reports (Collart and Canales 2021). Although small producers and can join this network to upload and share their information, like many other new technologies, the costs associated with the organizational learning curve, continued employee training, and constant technical support limits the full accessibility of this technology to large scale operations (Collart and Canales 2021).

Companies and organizations can face limitations in adopting blockchain technology, including lack of technology literacy, lack of resources to implement the system and collect comprehensive data, lack of a standardized cross-communication system between platforms, as well as lack of trust in the technology among business partners and compatibility of different networks. The cost of improving or creating software integrability is also considerable (Collart and Canales 2021). Companies that handle sensitive data may be concerned about intellectual property ownership, data privacy, and governance (Collart and Canales 2021). One feature of distributed ledger platforms is to allow for creating a private ecosystem to which joining and implementing transactions require prior permission by participants. Also, the accuracy of blockchain-based traceability systems can address concerns about the quality of data uploaded to the network (Collart and Canales 2021).

However, lack of regulatory harmony and regulatory uncertainty is one of the significant or perceived barriers to blockchain adoption in the agri-food sector. The main concern is the differences between state and federal regulations governing this technology. The current approach by the US is to amend existing legislation to include provisions related to Blockchain, but the outdated regulatory frameworks may pose a challenge to the adaptation of the technology. Nevertheless, there are no legal barriers to implementing Blockchain, and, except for cryptocurrencies, the regulatory environment is flexible as to no hinder innovation (Krzyzanowski Guerra and Boys 2021).

Supply chain

Blockchain technology is pervasively used in supply chain management (Kouhizadeh and Sarkis 2018). Reducing the transaction costs and risks motivates the application of blockchain technology to supply chain processes (Saberi et al. 2019). Records on blockchains are time-stamped and secure and, therefore, perfect for providing trust and reliability to supply chain partners (Kouhizadeh and Sarkis 2018). To ensure privacy and protect sensitive data, a closed, private, permissioned blockchain network with multiple, limited players may be more favorable (Saberi et al. 2019). Complex and private business networks can streamline transaction approval using smart contracts that are activated based on a particular regulation and predefined conditions (Bottoni et al. 2020, Kouhizadeh and Sarkis 2018). Recent proposals further the role of smart contracts beyond ordinary deterministic computations by incorporating artificial intelligence in a blockchain to automate planning for optimal returns (Bottoni et al. 2020).

Current supply chain systems are under pressure to verify that products, processes, and practices are certified, meeting certain sustainability criteria (Saberi et al. 2019). Customers in the agri-food sector, pharmaceutical and medical products, and high-value goods are requiring a higher degree of transparency, including the information about the origin and flow of products and processes, the parties involved in transactions, and transportation data (Saberi et al. 2019, Kouhizadeh and Sarkis 2018). There are many ways that blockchain technology can contribute to social and environmental sustainability. For instance, immutability and traceability of data in blockchains can reduce the illegal seizure of assets by corrupt authorities because information can not be modified without consent by all authorized actors in the network (Saberi et al. 2019). Verifying environmentally friendly practices and tracing products' carbon footprint is easier through a blockchain-based supply chain. Also, blockchain-based emission trading schemes improve the system's efficacy due to the fidelity and transparency of Blockchain (Saberi et al. 2019). In Northern Europe, recycling programs are coupled with blockchain technology to motivate people and organizations to participate via cryptographic tokens as a reward (Saberi et al. 2019).

Feasibility of Blockchain implementation

The application of IoT in water management scenarios can provide benefits to water companies and associations. IoT enables real-time operational control and decision-making, increasing efficiency, productivity, and profitability (Robles et al. 2015). 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). In essence, 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 (Robles et al. 2015). Nevertheless, IoT implementation would not eliminate the need for third-party validation and oversight in water systems. A potentially better alternative technology is 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).

To help water managers decide whether to adopt Blockchain in their system, Bagloee et al. (2021) propose a decision support model (see Figure 6) based on the concept of Benefit-Cost ratio (BCR) where the investment is considered viable if the BCR ratio is greater than one.

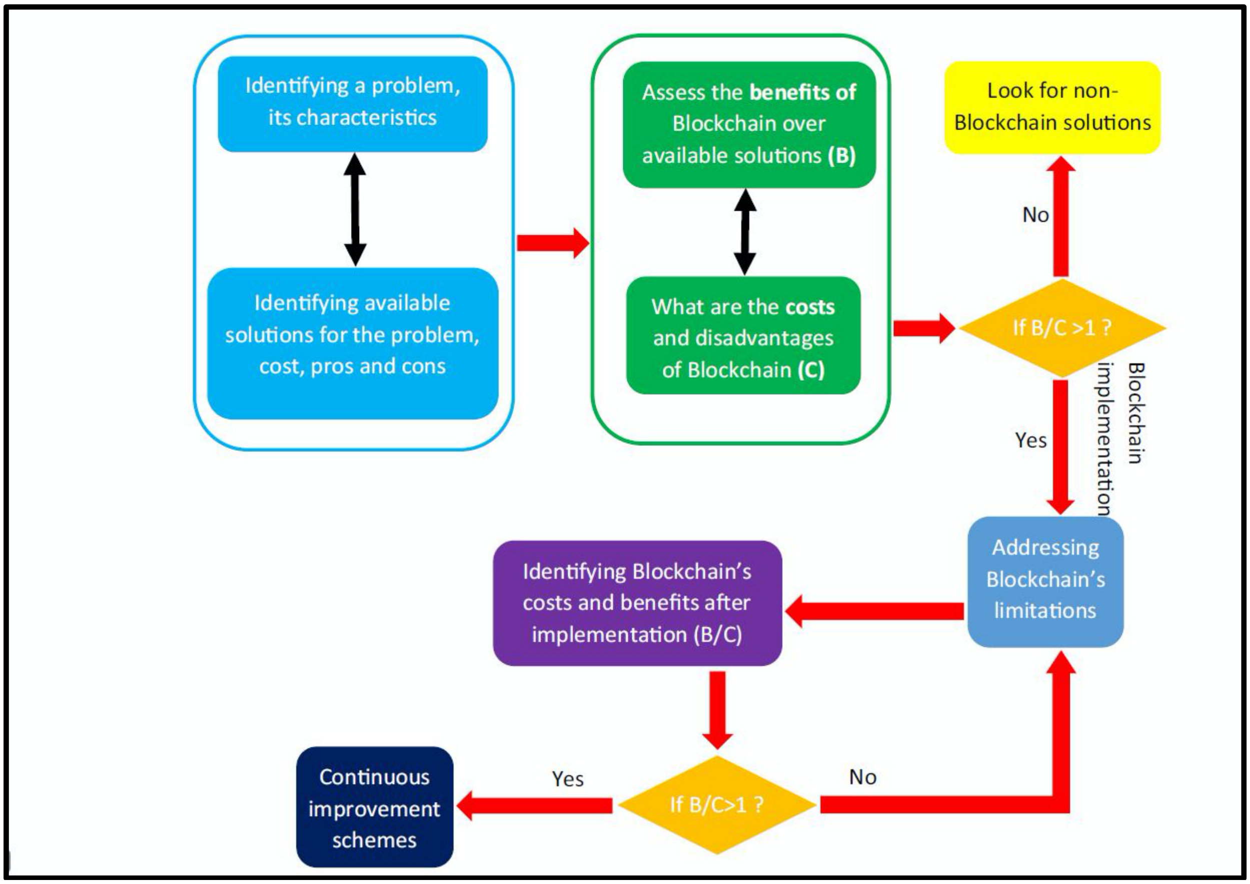

Figure 6. A decision support framework for the adoption of Blockchain (*Bagloee et al. 2021*).

The first step in this set of the sequential decision-making process is to identify the characteristics of the problem in the water system and the available solutions, including Blockchain. Then, the benefits and costs of the blockchain solution over the alternatives should be evaluated. At this stage, the blockchain solution is preferred only if benefits exceed the costs. The next steps are to design and implement a pilot blockchain architecture, followed by identifying and addressing known limitations. After implementation, another BCR analysis is required to verify the costs and benefits to determine the cost-effectiveness of the design. If the costs exceed the benefits, the entity should decide either to modify the pilot design to address the limitations or to seek alternative solutions. It is important to consider that blockchain technology is developing and evolving at an incredibly fast pace. Therefore, future efforts should consider the latest advancements that improve the reliability and security of blockchains (Bagloee 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 should be addressed by any organization before it can achieve the objectives and full potential of Blockchain technology (Bagloee et al. 2021, Feng et al. 2020, Zhao et al. 2019). 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, and 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 that are 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-base 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 7). At the core of the network are water managers and end-users 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.

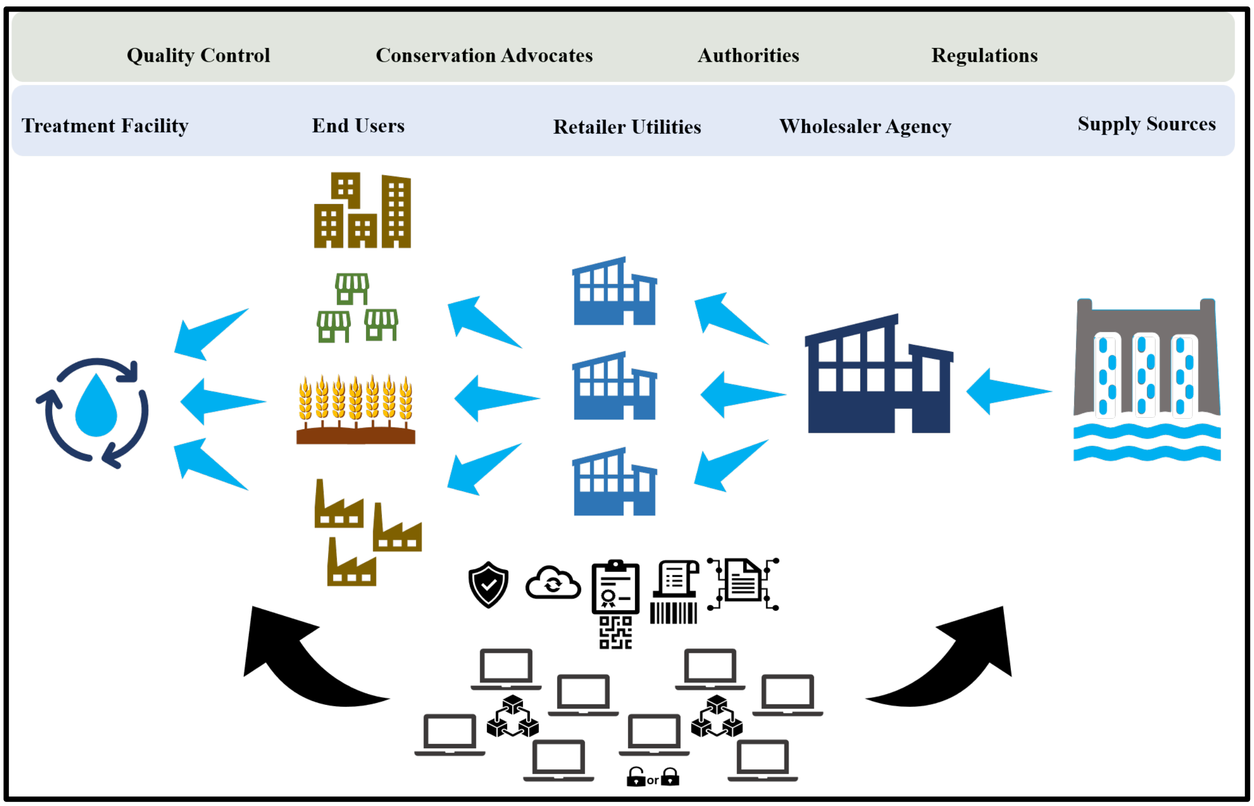

Figure 7. Blockchain-based water management system
Notes: the graph is developed by authors using icons embedded in Microsoft Office software.

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 permissioned 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 to those savings (Pincheira et al. 2021).

Summary of recommendations

Blockchain applications have three different 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 Wassenaer, Verdouw, and Wolfert 2021). To prepare for the adoption of blockchain solutions in water management systems, understanding the potential barriers is critical. As the first step, successful implementation of Blockchain 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 (Saberi et al. 2019).

Furthermore, differences among partners in terms of organizational culture and information disclosure policies can lead to problems in collaboration, communication, and coordination and therefore pose an inter-organizational barrier to adopt blockchain technology (Saberi 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 (Saberi et al. 2019). Entities that are not directly economically benefiting from the adoption of Blockchain could pose external barriers (Saberi et al. 2019). Lack of appropriate and encouraging policies, unclear governmental regulations and laws, and demand uncertainty digitized water systems could hinder the adoption process.

Any attempt to implement blockchain technology at a large scale should succeed in a careful pilot program in 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 (Sengupta and Kim 2021, Van Hilten, Ongena, and Ravesteijn 2020). Managing the access to data and authorization criteria can be addressed via permissioned and permissionless blockchain solutions (Van Hilten, Ongena, and Ravesteijn 2020).

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.

References

Abdelhafidh, Maroua, Mohamed Fourati, and Lamia Chaari Fourati. 2020. "A genetic algorithm‐based intelligent solution for water pipeline monitoring system in a transient state." *Concurrency and Computation: Practice and Experience*. doi: 10.1002/cpe.5959.

Ahram, Tareq, Arman Sargolzaei, Saman Sargolzaei, Jeff Daniels, and Ben Amaba. 2017. "Blockchain Technology Innovations."

Akram, Shaik V., Praveen K. Malik, Rajesh Singh, Gehlot Anita, and Sudeep Tanwar. 2020. Adoption of blockchain technology in various realms: Opportunities and challenges. Wiley.

Alabi, Micheal O, Arnesh Telukdarie, Nickey Van, and Janse Rensburg. 2019. "Industry 4.0: Innovative Solutions for The Water Industry."

Allen, Michael, Ami Preis, Mudasser Iqbal, and Andrew J. Whittle. 2012. "Case study: a smart water grid in Singapore." *Water Practice and Technology* 7 (4). doi: 10.2166/wpt.2012.089.

AlMetwally, Saif Allah H., Mohamed K. Hassan, and Mohamed H. Mourad. 2020. "Real Time Internet of Things (IoT) Based Water Quality Management System." *Procedia CIRP* 91:478-485. doi: 10.1016/j.procir.2020.03.107.

Antonucci, F., S. Figorilli, C. Costa, F. Pallottino, L. Raso, and P. Menesatti. 2019. "A review on blockchain applications in the agri-food sector." *J Sci Food Agric* 99 (14):6129-6138. doi: 10.1002/jsfa.9912.

Arvind, Arnav , Rajtirtha Paul, and Paurush Bhulania. 2020. Implementation of Water Quality Sensing System using Internet of Things.

Bagloee, Saeed Asadi, Mitra Heshmati, Hussein Dia, Hadi Ghaderi, Chris Pettit, and Mohsen Asadi. 2021. "Blockchain: The operating system of smart cities." *Cities* 112. doi: 10.1016/j.cities.2021.103104.

Bahadori, Alireza, and Scott T. Smith. 2016. *Dictionary of Environmental Engineering and Wastewater Treatment*: Springer, Cham.

Bai, Qiuchan, Jiahao Wu, and Chunxia Jin. 2020. "The Water Quality Online Monitoring System Based on Wireless Sensor Network." 2020 13th International Symposium on Computational Intelligence and Design (ISCID).

Bassi, Andrea, Andrés Cuéllar, Georg Pallaske, and Laurin Wuennenberg. 2017. Stormwater Markets: Concepts and applications. International Institute for Sustainable Development.

Bermeo-Almeida, Oscar, Mario Cardenas-Rodriguez, Teresa Samaniego-Cobo, Enrique Ferruzola-Gómez, Roberto Cabezas-Cabezas, and William Bazán-Vera. 2018. "Blockchain in Agriculture: A Systematic Literature Review." In, 44-56. Springer International Publishing.

Birner, Regina, Thomas Daum, and Carl Pray. 2021. "Who drives the digital revolution in agriculture? A review of supply‐side trends, players and challenges." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13145.

Bordel, B. , D. Martin, R. Alcarria, and T. Robles. 2019. "A Blockchain-based Water Control System for the Automatic Management of Irrigation Communities." 2019 IEEE International Conference on Consumer Electronics (ICCE), 11-13 January.

Bottoni, Paolo, Nicola Gessa, Gilda Massa, Remo Pareschi, Hesham Selim, and Enrico Arcuri. 2020. "Intelligent Smart Contracts for Innovative Supply Chain Management." *Frontiers in Blockchain* 3. doi: 10.3389/fbloc.2020.535787.

Brotsis, Sotirios, Konstantinos Limniotis, Gueltoum Bendiab, Nicholas Kolokotronis, and Stavros Shiaeles. 2021. "On the suitability of blockchain platforms for IoT applications: Architectures, security, privacy, and performance." *Computer Networks*. doi: 10.1016/j.comnet.2021.108005.

Cho Zin, M., G. Lenin, L. Huo Chong, and M. V. Prassana. 2019. Real-time water quality system in Internet of things. Institute of Physics Publishing.

Chourabi, Hafedh, Taewoo Nam, Shawn Walker, J Ramon Gil-Garcia, Sehl Mellouli, Karine Nahon, Theresa A Pardo, and Hans Jochen Scholl. 2012. "Understanding smart cities: An integrative framework." 45th Hawaii International Conference on System Sciences, Maui, HI.

Chowdury, Mohammad Salah Uddin, Talha Bin Emran, Subhasish Ghosh, Abhijit Pathak, Mohd Manjur Alam, Nurul Absar, Karl Andersson, and Mohammad Shahadat Hossain. 2019. "IoT Based Real-time River Water Quality Monitoring System." *Procedia Computer Science* 155:161-168. doi: 10.1016/j.procs.2019.08.025.

Christidis, Konstantinos, and Michael Devetsikiotis. 2016. "Blockchains and Smart Contracts for the Internet of Things." *IEEE Access* 4:2292-2303. doi: 10.1109/access.2016.2566339.

Cianchi, P., S. Marsili-Libelli, A Burchi, and S Burchielli. 2000. "Integrated river quality management using internet technologies." WATERMATEX, Gent, Belgium, 8 - 20 Sept.

Civic Ledger. 2020. Improving Water Markets through New Digital Technologies.

Collart, Alba J., and Elizabeth Canales. 2021. "How might broad adoption of blockchain‐based traceability impact the U.S. fresh produce supply chain?" *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13134.

Creydt, M., and M. Fischer. 2019. "Blockchain and more - Algorithm driven food traceability." *Food Control* 105:45-51. doi: 10.1016/j.foodcont.2019.05.019.

D'Amico, Gaspare, Raffaella Taddeo, Lei Shi, Tan Yigitcanlar, and Giuseppe Ioppolo. 2020. "Ecological indicators of smart urban metabolism: A review of the literature on international standards." *Ecological Indicators* 118. doi: 10.1016/j.ecolind.2020.106808.

Dey, Nilanjan, Aboul Ella Hassanien, Chintan Bhatt, Amira Ashour, and Suresh Chandra Satapathy. 2018. *Internet of things and big data analytics toward next-generation intelligence*: Springer.

Dogo, Eustace M, Abdulazeez F Salami, Nnamdi I Nwulu, and Clinton O Aigbavboa. 2019. "Blockchain and Internet of Things-Based Technologies for Intelligent Water Management System." In *Artificial Intelligence in IoT*, edited by Fadi Al-Turjman, 129-150. Cham: Springer International Publishing.

Dogo, Eustace M., Nnamdi I. Nwulu, Bhekisipho Twala, and Clinton Aigbavboa. 2019. "A survey of machine learning methods applied to anomaly detection on drinking-water quality data." *Urban Water Journal* 16 (3):235-248. doi: 10.1080/1573062x.2019.1637002.

Düdder, Boris, Vladislav Fomin, Tan Gürpinar, Michael Henke, Mubashar Iqbal, Viktorija Janavičienė, Raimundas Matulevičius, Natalia Straub, and Haiqin Wu. 2021. "Interdisciplinary Blockchain Education: Utilizing Blockchain Technology From Various Perspectives." *Frontiers in Blockchain* 3. doi: 10.3389/fbloc.2020.578022.

Feng, Huanhuan, Xiang Wang, Yanqing Duan, Jian Zhang, and Xiaoshuan Zhang. 2020. "Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges." *Journal of Cleaner Production* 260:121031. doi: 10.1016/j.jclepro.2020.121031.

Glasgow, Howard B., Joann M. Burkholder, Robert E. Reed, Alan J. Lewitus, and Joseph E. Kleinman. 2004. "Real-time remote monitoring of water quality: a review of current applications, and advancements in sensor, telemetry, and computing technologies." *Journal of Experimental Marine Biology and Ecology* 300 (1-2):409-448. doi: 10.1016/j.jembe.2004.02.022.

Griffin, Terry W., Keith D. Harris, Jason K. Ward, Paul Goeringer, and Jessica A. Richard. 2021. "Three Digital Agriculture Problems in Cotton Solved by Distributed Ledger Technology." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13142.

Guan, Mingfu, Qiuhua Liang, and Jingming Hou. 2021. "Editorial: Smart Approaches to Predict Urban Flooding: Current Advances and Challenges." *Frontiers in Earth Science* 9. doi: 10.3389/feart.2021.681751.

Hoos, Anne B., Sherry H. Wang, and Gregory E. Schwarz. 2019. "Adapting a regional water-quality model for local application: A case study for Tennessee, USA." *Environmental Modelling & Software* 115:187-199. doi: 10.1016/j.envsoft.2019.01.001.

Ighalo, Joshua O., and Adewale G. Adeniyi. 2020. "A comprehensive review of water quality monitoring and assessment in Nigeria." *Chemosphere* 260:127569. doi: 10.1016/j.chemosphere.2020.127569.

Ighalo, Joshua O., Adewale George Adeniyi, and Goncalo Marques. 2021. "Internet of Things for Water Quality Monitoring and Assessment: A Comprehensive Review." In *Artificial Intelligence for Sustainable Development: Theory, Practice and Future Applications*, 245-259.

Kabir, Syed, Sandhya Patidar, Xilin Xia, Qiuhua Liang, Jeffrey Neal, and Gareth Pender. 2020. "A deep convolutional neural network model for rapid prediction of fluvial flood inundation." *Journal of Hydrology* 590. doi: 10.1016/j.jhydrol.2020.125481.

Kamilaris, Andreas, Ian R. Cole, and Francesc X. Prenafeta-Boldú. 2021. "Blockchain in agriculture." In *Food Technology Disruptions*, edited by Charis M. Galanakis, 247-284. Elsevier.

Kamilaris, Andreas, Agusti Fonts, and Francesc X. Prenafeta-Boldύ. 2019. "The rise of blockchain technology in agriculture and food supply chains." *Trends in Food Science & Technology* 91:640-652. doi: 10.1016/j.tifs.2019.07.034.

Khanna, Madhu. 2020. "Digital Transformation of the Agricultural Sector: Pathways, Drivers and Policy Implications." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13103.

Kouhizadeh, Mahtab, and Joseph Sarkis. 2018. "Blockchain Practices, Potentials, and Perspectives in Greening Supply Chains." *Sustainability* 10 (10). doi: 10.3390/su10103652.

Kour, Vippon Preet, and Sakshi Arora. 2020. Recent Developments of the Internet of Things in Agriculture: A Survey. Institute of Electrical and Electronics Engineers Inc.

Krzyzanowski Guerra, Kathleen, and Kathryn A. Boys. 2021. "A new food chain: Adoption and policy implications to blockchain use in agri‐food industries." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13163.

Kumar, D. Senthil , A. Askarunisa, and R. Mohan Kumar. 2020. "Embedded processor based automated assessment of quality of the water in an IoT background." *Microprocessors and Microsystems* 77:103167. doi: 10.1016/j.micpro.2020.103167.

Lakkakula, Prithviraj, David W. Bullock, and William W. Wilson. 2021. "Asymmetric information and blockchains in soybean commodity markets." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13159.

Lakshmiprabha, Kakkanallur Ethirajan, and Chinnathambi Govindaraju. 2019. "Hydroponic-based smart irrigation system using Internet of Things." *International Journal of Communication Systems*. doi: 10.1002/dac.4071.

Lathrop, Richard G., Lisa Auermuller, Scott Haag, and Wansoo Im. 2012. "The StormWater Management and Planning Tool: Coastal Water Quality Enhancement through the Use of an Internet-Based Geospatial Tool." *Coastal Management* 40 (4):339-354. doi: 10.1080/08920753.2012.692309.

Le Jallé, Christophe, Denis Désille, and Gilles Burkhardt. 2013. "Urban stormwater management in developing countries." *NOVATECH*.

Lee, Juhee, Mehdi Nemati, and Ariel Dinar. 2021a. "Historical trends of residential water use in California: Effects of droughts and conservation policies." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13149.

Lee, Juhee, Mehdi Nemati, and Ariel Dinar 2021b. How Has Residential Per Capita Water Consumption in California Changed Between 1994–2019? In *ARE Update*. Giannini Foundation of Agricultural Economics: University of California.

Lee, Seung Won, Sarper Sarp, Dong Jin Jeon, and Joon Ha Kim. 2014. "Smart water grid: the future water management platform." *Desalination and Water Treatment* 55 (2):339-346. doi: 10.1080/19443994.2014.917887.

Li, Huimin, Xinyao Chen, Zhiwei Guo, Junli Xu, Yu Shen, and Xu Gao. 2021. "Data-driven peer-to-peer blockchain framework for water consumption management." *Peer-to-Peer Networking and Applications*. doi: 10.1007/s12083-021-01121-6.

Li, Jiada, Xiafei Yang, and Robert Sitzenfrei. 2020. "Rethinking the Framework of Smart Water System: A Review." *Water* 12 (2). doi: 10.3390/w12020412.

Lin, Wen, David L. Ortega, Danielle Ufer, Vincenzina Caputo, and Titus Awokuse. 2020. "Blockchain‐based traceability and demand for U.S. beef in China." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13135.

Lin, Yu-Pin, Joy Petway, Wan-Yu Lien, and Josef Settele. 2018. "Blockchain with Artificial Intelligence to Efficiently Manage Water Use under Climate Change." *Environments* 5 (3):1-2. doi: 10.3390/environments5030034.

Mahalakshmi, J., K. Kuppusamy, C. Kaleeswari, and P. Maheswari. 2020. "IoT Sensor-Based Smart Agricultural System." In *Emerging Technologies for Agriculture and Environment*, edited by Babu Subramanian, Shiao-Shing Chen and Krishna R. Reddy, 39-52. Springer Singapore.

Marchese, Dayton, and Igor Linkov. 2017. "Can You Be Smart and Resilient at the Same Time?" *Environmental Science & Technology* 51 (11):5867-5868. doi: 10.1021/acs.est.7b01912.

Marques, Gonçalo, Diogo Aleixo, and Rui Pitarma. 2019. "Enhanced Hydroponic Agriculture Environmental Monitoring: An Internet of Things Approach." In, 658-669. Springer International Publishing.

Mehra, Manav, Sameer Saxena, Suresh Sankaranarayanan, Rijo Jackson Tom, and M. Veeramanikandan. 2018. "IoT based hydroponics system using Deep Neural Networks." *Computers and Electronics in Agriculture* 155:473-486. doi: 10.1016/j.compag.2018.10.015.

Meshal, Ahmed, Michael N Mikhael, and Hala A Mansour. 2020. "Water Quality Monitoring system of the Nile River." *ENGINEERING RESEARCH JOURNAL (ERJ)* 1 (43):100-104.

Mutchek, Michele, and Eric Williams. 2014. Moving Towards Sustainable and Resilient Smart Water Grids. MDPI AG.

Nakamoto, Satoshi. 2008. Bitcoin: A Peer-to-Peer Electronic Cash System.

Nie, Xiangtian, Tianyu Fan, Bo Wang, Zhiyong Li, Achyut Shankar, and Adhiyaman Manickam. 2020. "Big Data analytics and IoT in Operation safety management in Under Water Management." *Computer Communications* 154:188-196. doi: 10.1016/j.comcom.2020.02.052.

Pahonțu, Bogdan, Diana Arsene, Alexandru Predescu, and Mariana Mocanu. 2020. "Application and challenges of Blockchain technology for real-time operation in a water distribution system." 24th International Conference on System Theory, Control and Computing.

Palande, Vaibhav, Adam Zaheer, and Kiran George. 2018. "Fully Automated Hydroponic System for Indoor Plant Growth." *Procedia Computer Science* 129:482-488. doi: 10.1016/j.procs.2018.03.028.

Pincheira, Miguel, Massimo Vecchio, Raffaele Giaffreda, and Salil S. Kanhere. 2021. "Cost-effective IoT devices as trustworthy data sources for a blockchain-based water management system in precision agriculture." *Computers and Electronics in Agriculture* 180. doi: 10.1016/j.compag.2020.105889.

Poberezhna, Anna. 2018. "Addressing Water Sustainability With Blockchain Technology and Green Finance." In *Transforming Climate Finance and Green Investment with Blockchains*, edited by Alastair Marke, 189-196. Elsevier Inc.

Public Utilities Board Singapore. 2016. "Managing the water distribution network with a Smart Water Grid." *Smart Water* 1 (4):4. doi: 10.1186/s40713-016-0004-4.

Qatawneh, Mohammad, Wesam Almobaideen, and Orieb AbuAlghanam. 2020. "Challenges of Blockchain Technology in Context Internet of Things: A Survey."

Rabadiya Kinjal, A., B. Shivangi Patel, and C. Chintan Bhatt. 2018. "Smart Irrigation: Towards Next Generation Agriculture." In *Internet of Things and Big Data Analytics Toward Next-Generation Intelligence*, 265-282.

Reyna, Ana, Cristian Martín, Jaime Chen, Enrique Soler, and Manuel Díaz. 2018. "On Blockchain and its integration with IoT. Challenges and opportunities." *Future Generation Computer Systems* 88:173-190. doi: 10.1016/j.future.2018.05.046.

Robles, Tomás , Ramón Alcarria, Diego Martín, Mariano Navarro, Rodrigo Calero, Sofía Iglesias, and Manuel López. 2015. "An IoT based reference architecture for smart water management processes." *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications* 6 (1):4-23. doi: 10.22667/JOWUA.2015.03.31.004.

Rodriguez-Perez, J., C. Leigh, B. Liquet, C. Kermorvant, E. Peterson, D. Sous, and K. Mengersen. 2020. "Detecting Technical Anomalies in High-Frequency Water-Quality Data Using Artificial Neural Networks." *Environ Sci Technol*. doi: 10.1021/acs.est.0c04069.

Rose, K., S. Eldridge, and L. Chapin. 2015. The Internet of Things: An Overview - Understanding the Issues and Challenges of a More Connected World. Internet Society.

Ruengittinun, Somchoke, Sitthidech Phongsamsuan, and Phasawut Sureeratanakorn. 2017. "Applied Internet of Thing for Smart Hydroponic Farming Ecosystem (HFE)." 10th

International Conference on Ubi-media Computing and Workshops, Pattaya, Thailand, 1-4 Aug.

Saberi, Sara, Mahtab Kouhizadeh, Joseph Sarkis, and Lejia Shen. 2019. "Blockchain technology and its relationships to sustainable supply chain management." *International Journal of Production Research* 57 (7):2117-2135. doi: 10.1080/00207543.2018.1533261.

Sarraf, Rajan, Shalini Ojha, Damini Biraris, and Kishor B Bhangale. 2020. "IoT Based Smart Quality Water Management System." *International Journal of Advance Scientific Research and Engineering Trends* 5 (3):12-16.

Sengupta, Ushnish, and Henry Michael Kim. 2021. "Meeting Changing Customer Requirements in Food and Agriculture Through the Application of Blockchain Technology." *Frontiers in Blockchain* 4. doi: 10.3389/fbloc.2021.613346.

Shahid, Arsalan, Bilal Khalid, Shahtaj Shaukat, Hashim Ali, and Muhammad Yasir Qadri. 2018. "Internet of Things Shaping Smart Cities: A Survey." In *Internet of Things and Big Data Analytics Toward Next-Generation Intelligence*, 335-358.

Shanthi, S, T Gopi, and C Vidhyesh. 2019. "IoT Based Water and Air Quality Monitoring System and Analysis." *International Journal of Applied Engineering Research* 14 (6):1405-1409.

Shew, Aaron M., Heather A. Snell, Rodolfo M. Nayga, and Mary C. Lacity. 2021. "Consumer valuation of blockchain traceability for beef in the United States." *Applied Economic Perspectives and Policy*. doi: 10.1002/aepp.13157.

Shilpi, and Mohd Ahad. 2020. "Blockchain Technology and Smart Cities - A Review." *EAI Endorsed Transactions on Smart Cities* 4 (10). doi: 10.4108/eai.13-7-2018.163846.

Sithole, M.P.P., N. I. Nwulu, and E. M. Dogo. 2019. "Development of a Wireless Sensor Network Based Water Quality Monitoring and Notification System." 2019 International Artificial Intelligence and Data Processing Symposium (IDAP), Malatya, Turkey, 21-22 Sept.

Sriyono, Edy. 2020. "Digitizing water management: Toward the innovative use of blockchain technologies to address sustainability." *Cogent Engineering* 7 (1). doi: 10.1080/23311916.2020.1769366.

Su, Xiaodan, Guofan Shao, Jonathan Vause, and Lina Tang. 2013. "An integrated system for urban environmental monitoring and management based on the Environmental Internet of Things." *International Journal of Sustainable Development & World Ecology* 20 (3):205-209. doi: 10.1080/13504509.2013.782580.

Teeluck, R., S. Durjan, and V. Bassoo. 2021. "Blockchain Technology and Emerging Communications Applications." In *Security and Privacy Applications for Smart City Development*, 207-256.

Tripathy, Asis Kumar, Tapan Kumar Das, and Chiranji Lal Chowdhary. 2020. "Monitoring Quality of Tap Water in Cities Using IoT." In *Emerging Technologies for Agriculture and Environment*, edited by Babu Subramanian, Shiao-Shing Chen and Krishna R. Reddy, 107-113. Springer Singapore.

Tsague, Hippolyte Djonon, and Bheki Twala. 2018. "Practical Techniques for Securing the Internet of Things (IoT) Against Side Channel Attacks." In *Internet of Things and Big Data Analytics Toward Next-Generation Intelligence*, 439-481.

Van Hilten, Mireille, Guido Ongena, and Pascal Ravesteijn. 2020. "Blockchain for Organic Food Traceability: Case Studies on Drivers and Challenges." *Frontiers in Blockchain* 3. doi: 10.3389/fbloc.2020.567175.

Van Wassenaer, Lan, Cor Verdouw, and Sjaak Wolfert. 2021. "What Blockchain Are We Talking About? An Analytical Framework for Understanding Blockchain Applications in Agriculture and Food." *Frontiers in Blockchain* 4. doi: 10.3389/fbloc.2021.653128.
Violino, Simona, Federico Pallottino, Giulio Sperandio, Simone Figorilli, Francesca Antonucci, Vanessa Ioannoni, Daniele Fappiano, and Corrado Costa. 2019. "Are the Innovative Electronic Labels for Extra Virgin Olive Oil Sustainable, Traceable, and Accepted by Consumers?" *Foods* 8 (11):529. doi: 10.3390/foods8110529.
Wang, Shumei, Zhaoji Zhang, Zhilong Ye, Xiaojun Wang, Xiangyu Lin, and Shaohua Chen. 2013. "Application of Environmental Internet of Things on water quality management of urban scenic river." *International Journal of Sustainable Development & World Ecology* 20 (3):216-222. doi: 10.1080/13504509.2013.785040.
Wu, Di, Hao Wang, and Razak Seidu. 2020. "Smart data driven quality prediction for urban water source management." *Future Generation Computer Systems* 107:418-432. doi: 10.1016/j.future.2020.02.022.
Xiang, Xiaojun, Qiong Li, Shahnawaz Khan, and Osamah Ibrahim Khalaf. 2021. "Urban water resource management for sustainable environment planning using artificial intelligence techniques." *Environmental Impact Assessment Review* 86. doi: 10.1016/j.eiar.2020.106515.
Yazdi, M. N., D. J. Sample, D. Scott, J. S. Owen, M. Ketabchy, and N. Alamdari. 2019. "Water quality characterization of storm and irrigation runoff from a container nursery." *Sci Total Environ* 667:166-178. doi: 10.1016/j.scitotenv.2019.02.326.
Zhao, Guoqing, Shaofeng Liu, Carmen Lopez, Haiyan Lu, Sebastian Elgueta, Huilan Chen, and Biljana Mileva Boshkoska. 2019. "Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions." *Computers in Industry* 109:83-99. doi: 10.1016/j.compind.2019.04.002.