Blockchain Applications and Opportunities for Water Resources and Hydrology: A Systematic Review

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Abstract

Although blockchain technology was first applied for peer-to-peer financial transactions, it has been used for the digitalization of physical asset management and data management processes in many areas in the industry and academia, including the water domain. Its potential as an immutable data storage system and smart contract integration has provided a plethora of use cases and utility in the domain of hydrology and water resources. In this article, a comprehensive systematic literature review on blockchain applications, opportunities and challenges for the water sector is conducted. The study provides the examination of academic publications, technical reports, whitepapers, hackathon projects, non-academic content and evaluation of the published year, focused hydrology sub-domain, utilized blockchain networks, tools, and development level of application of reviewed content. The current status of blockchain technology in the hydrology literature, potential application areas in the water sector, research gaps, and challenges are discussed from different perspectives, and future study areas are recommended.

Keywords: blockchain, distributed ledger, smart contract, hydrology, water resources

1. Introduction

The life of modern societies in the 21st century depends on the compatibility of artificial and natural complex systems such as the hydrological cycle and urban water systems (Beck et al., 2010), natural energy sources and renewable energy systems, climate extremes and disaster mitigation (Ewing and Demir, 2021), and the agricultural supply chain and resilient infrastructures (Alabbad et al., 2021). More compatible natural and artificial system integration is possible by making more measurements about natural systems, obtaining more data (Muste et al., 2017), and using these data for the development of artificial systems (Omatu et al., 2015) and digital twin environments (Sermet and Demir, 2020). This need has increased the importance of reliable data and accelerated data processing technology (Hu and Demir, 2021). As a result of the rapidly developing information and communication technology approaches in the last two decades, digital transformation has accelerated in nearly all sectors (Knell, 2021). Societies' perspectives on issues such as planning, production, and implementation have evolved in parallel (Savic, 2021). Hydrology and water resources domain followed the same trend with developments in hydroinformatics (Demir et al., 2022). The most notable developments can be listed as novel applications of deep learning in image synthesis and communication (Gautam et al., 2022; Sermet and Demir, 2021), large scale modeling and analysis on client-side systems (Ewing et al., 2022; Li et al., 2022), virtual and augmented reality for hydrological education and modeling purposes (Sermet and Demir, 2022), and novel programming libraries and data standards (Ramirez et al., 2022; Xiang and Demir, 2022). As a natural outcome of this rapid digital transformation, the water sector has started to generate, process, and store more data (Haltas et al., 2021). However, this process has necessitated the reliability, security, and standardization of hydrological data because reliable data is essential for more accurate hydrological forecasts. Similarly, data standardization and security are crucial for water systems stakeholder engagement in a secure and trustworthy way (Voogd et al., 2022). Addressing trust-related concerns has accelerated with the realization of the potential of blockchain technology.

Blockchain technology is an advanced database mechanism that allows transparent information sharing within a network (Nakamoto, 2008). A blockchain database stores data in blocks linked together on a chain. The data is chronologically consistent, as it cannot be deleted or changed in the chain without consensus on the network. As a result, blockchain technology can be used to create an immutable ledger to track orders, payments, accounts, and other transactions. There are built-in mechanisms in the system that prevent unauthorized transaction entries and create consistency in the common viewing of these transactions.

Blockchain is a newly emerging technology that has been adopted by various sectors in innovative ways and is the subject of research and development activities for the last decade. Blockchain-based energy companies can create a trading platform for the sale of electricity between individuals, or homeowners with solar panels can use a similar platform to sell excess solar electricity to their neighbors. This process is largely automated as smart meters generate transactions, the blockchain records them. Likewise, traditional financial systems such as banks and stock exchanges can use blockchain services to manage online payments, accounts, and stock market trading. Also, companies in the media and entertainment industries can use blockchain technology to manage copyrighted data. Similarly, retail companies can use the blockchain to track movements of good between suppliers and buyers (Akinbi et al., 2022; Hu et al., 2022; Jing et al., 2021; Li et al., 2022a). Blockchain technology has the potential to expand a long-term vision in water resource management and has the undeniable promise of decentralized water systems as water becomes a sensitive issue around the world.

Although there are systematic reviews about the applications of blockchain technology in energy markets (Gad et al., 2022), food supply chain (Castellini et al., 2022), the health sector (Merlo et al., 2023), and the effects of blockchain on business in general, there is no comprehensive literature review study on applications of the blockchain technology in water resources and hydrology.

This paper presents a systematic review and analysis of hydrological applications within the scope of blockchain-based technologies. The literature review, which includes journal papers, conference papers, technical websites, technical project documents, and hackathon projects, was conducted in detail. Each study is classified and evaluated according to the area of hydrology it focuses on, its purpose, the level of development of the blockchain application, and the technical details it uses when applying blockchain technology. The study aims to explore real-time and potential application areas of blockchain technology in hydrology and water resources management. At the same time, it aims to create technical guidance on blockchain for all water sector stakeholders, examine how blockchain technology will provide efficiency and benefits for water resources management, and draw the attention of hydroinformatics professionals to new generation data storage and processing algorithms.

1.1. Background on Blockchain Technology

Storing data in distributed ledgers, deciding which data to store with a consensus algorithm, defining preconditions with a smart contract, and being able to track the recorded data transparently, have been discussed theoretically in financial applications since the 1990s, due to the disadvantages of traditional data storage systems and the need for reliable third parties in financial transactions (Szabo, 1998). As mentioned before, Bitcoin was the first real-time application to record financial transaction data. Although the words "block" and "chain" are always mentioned as separate terms in the original bitcoin whitepaper, the name of the technology was shaped to "blockchain" after a while (Nakamoto, 2008). The second milestone of blockchain technology and first example of the application of recording transaction data to a database only if both parties meet a certain prerequisite, was announced with the Ethereum whitepaper (Buterin, 2014) where the predetermined conditions are called smart contracts or chain code.

There are four main types of decentralized or distributed networks in the blockchain. Public blockchain networks are permissionless networks that allow anyone to join. All members of the blockchain have equal rights to read, edit, and verify the blockchain. Public blockchain networks are mainly used for trading and mining cryptocurrencies such as Bitcoin, Ethereum, and Litecoin (Wang et al., 2022). Private blockchains are controlled by a single entity. This authority decides who can become a member and what rights the members have in the network. Private blockchains are only partially decentralized because they contain access restrictions. Hybrid blockchains combine some features of both private and public networks. Companies can set up private, permission-based systems as well as a common system. Thus, they control access to certain data stored on the blockchain while keeping the rest of the data public. They use smart contracts to allow members of the partner system to check whether private transactions have been completed. For example, hybrid blockchains can allow shared access to digital currency, while keeping bank-owned currency private. Consortium blockchain networks are managed by a group of organizations. Pre-selected organizations share responsibility for maintaining the continuity of the blockchain and determining data access rights. Consortium blockchain networks are generally preferred in sectors where many organizations have a common goal and can benefit from responsibility sharing (Arooj et al., 2022).

The blockchain protocol refers to different types of blockchain platforms that can be used for application development purposes. Each blockchain protocol adapts fundamental blockchain principles to suit specific industries or applications. The most famous blockchain protocols are Hyperledger, Ethereum, Corda, and Quorum. Hyperledger Fabric is an open-source project with a set of tools and libraries. In that way, it is possible to customize blockchain applications. Hyperledger Fabric is a modular, general-purpose framework that offers unique identity management and access control features. Due to these features, it is suitable for various usage areas such as tracking and monitoring of supply chains, trade finance, loyalty and reward programs, and reconciliation of financial assets (Hang and Kim, 2021). Ethereum is a decentralized blockchain platform that is useful to build public blockchain applications (Estevam et al., 2021). Corda is an open-source blockchain project designed for business. Quorum is an open-source blockchain protocol derived from Ethereum. It was specifically designed for use in a private blockchain network where all nodes are owned by only one member or in a consortium blockchain network where multiple members each own a portion of the network (Singh et al., 2022).

In summary, the main features of blockchain technology that make a difference are described as follows: Decentralization in blockchain involves the transfer of control and decision-making powers from a central legal entity (i.e., an individual, organization, or group) to a distributed network. Decentralized blockchain networks use the principle of transparency to reduce the need for trust between participants. These networks discourage participants from exercising authority or control over one another, which reduces the functionality of the network. Another main feature is immutability, which means that data cannot be changed or tampered with once it is stored in the blockchain. If a log contains an error, you need to add a new transaction to reverse the error, and both transactions will be visible on the network. Finally, the consensus mechanism is prominent aspect of a blockchain system, which sets the rules for the consent of the participants regarding the recording of transactions. New transactions may be recorded only after the majority of the participants in the network have approved them.

The blockchain architecture, on the other hand, includes several technical components, which are listed as follows: (a) the distributed ledger is the shared database used to record transactions in the blockchain network; (b) smart contracts are programs that are automatically executed and stored in the blockchain system when predetermined conditions are met. They run "if-then" checks so that transactions can be completed safely; and (c) public key encryption is a security feature that uniquely identifies participants in the blockchain network. This mechanism generates two sets of keys for network members. One of the keys is a public key that everyone on the network uses together. The other key is a private key that is unique to each member. Private and public keys work together to unlock the data in the ledger (Figure 1). The first generation of blockchain is bitcoin and cryptocurrencies; the second generation blockchain is smart contracts or chain code; and the third generation, or future, of blockchain will continue to evolve and grow as companies discover and implement new application areas. The ongoing blockchain revolution continues to offer limitless potential.

Like many other industries, the initial ideas for the implementation of blockchain in hydrology and water resources management are mainly focused on the advantages of storing data most reliably. Water-related data reliability has a key role in water management in all dimensions. Since water is a multidimensional natural resource, water resources can be managed most effectively by optimizing the interests of stakeholders with many different priorities. In addition to having different priorities regarding the quantity and quality of water, there is a social dimension for the water as well. Reliable data about shared water resources is essential for the establishment of trust. (Pahl-Wostl, 2015; Stern and Coleman, 2015). The straightforward guarantee of socio-hydrological trust and data reliability is made possible by a simply distributed digital architecture built on blockchain and smart contracts.

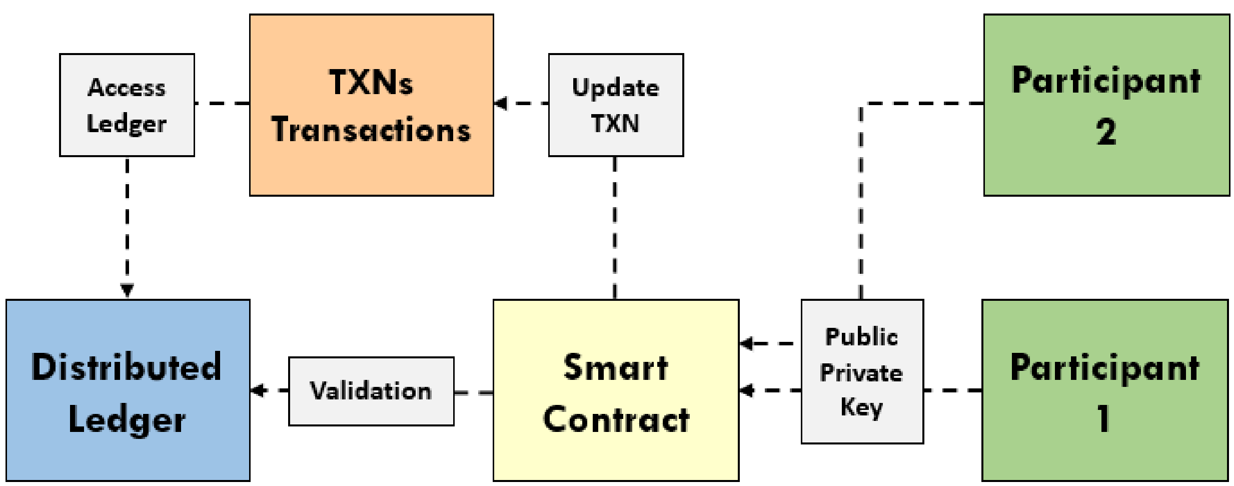

Figure 1. Illustration of basic blockchain architecture

Uncertainty in multi-stakeholder hydrological systems can be reduced with the assistance of immutably recorded data. Likewise, blockchain technology is very suitable for applications in the finance of water. Application areas may be the water market, where water rights are exchanged, or any investment in water management and donations to improve water infrastructure or sanitation in developing countries. In short, it provides the most transparent follow-up of all financial transactions in terms of investors or market stakeholders (Wheeler et al., 2014). Similarly, when there is a necessity for the traceability of water, blockchain may provide effective solutions. Water-related traceability will be critical for agricultural water management (Yildirim and Demir, 2022), water quality and control (Demir et al., 2009), urban water systems, and the water footprint of a special product.

2. Research Methodology

A systematic literature review on blockchain applications in hydrology and water resources was performed for this study (Bramer et al., 2018). The literature review was initially divided into two areas including academic and non-academic use cases. The academic literature review includes journal and conference papers, book chapters, and technical reports. The non-academic literature review includes whitepapers, web documents, reports of official institutions, and hackathon projects.

Google Scholar, Scopus, Web of Science, Crossref, Open Alex, Jisc Library Hub, and the Library of Congress were used as academic databases, and 25 different keyword combinations were used as a systematic search approach (Table A1 in Appendix). After the initial search, the results published before 2008 (before the Bitcoin whitepaper) in the database search results were eliminated. Later on, results that are indexed in more than one database were ultimately removed, so that no duplicates remained. There were 5,330 articles as a result of the research from these stages. These papers were examined according to their titles, abstracts, and the content of the paper, and classified according to their scope of the application. Especially the collections of conference proceedings with a wide scope were caught by keyword combinations, although they did not contain any useful content on blockchain and hydrology. Moreover, results containing only one or two sentences about "blockchain and water" were also excluded from the review. It was expected that there would be at least a few paragraphs or a section that included useful comments or analysis on the subject matter.

For the review of non-academic use cases, hackathon projects were retrieved following the same search approach described above, using the public projects repository of Devpost (Wang et al., 2018). The web pages that detail technological content and official reports with digital transformation content were manually examined, and a non-academic content list that falls under the subject of this study was prepared. Finally, 103 academic and 57 non-academic pieces of content were found directly relevant, and subjected to a detailed review. Tables for a detailed review are given as an appendix.

For the reviewed academic content, several variables and categorization parameters were selected to evaluate the current maturation process of blockchain technology for hydrological applications as follows:

Publication Type: Indicates where and in what format academic content is published including journal paper, conference paper, book, book chapter, thesis, and technical report.

Focus Area: Classification of reviewed studies based on their focus on the sub-field of hydrology and water resources. Although most studies focus on more than one area, as a result of detailed analysis, it was assumed that the study was primarily focused on a single subject area. These subject areas are classified as follows: urban water management, water quality management, water economics, water governance, agricultural water management, water and sustainable development goals (SDG)

Purpose: Indicates the main use cases the study or product is designed to address.

Development Level of Blockchain Application: Indicates the degree to which the blockchain technology was used in the study.

Explore: Studies highlight the potential of blockchain applications in water resources management and hydrology and evaluate research and application gaps. Studies classified in this field are just for exploration and do not include blockchain parameters. Therefore, these studies were not examined for the following fields.

Conceptual: Studies that propose a digital system architecture without a tested application or code list.

Simulation: Studies in which a system is designed, coded, and tested mostly in virtual machines but not converted into a real-world application.

Decentralized Application (DApp): Studies in which the system created can be used with a mobile or web-based application by designing a special interface. The current activity of the application created in the studies or whether it is currently at the service of the users has not been examined.

Pilot Project: Studies where any stage of the project is tested with real-time data.

Blockchain Type: It is a classification made according to which type of blockchain infrastructure the study proposes or uses. Since the studies are divided into blockchain types at a very general level, they are categorized as Public, Private, and Hybrid Blockchain, which contains the features of both types to a certain extent.

Blockchain Technology: It is a categorization made according to which blockchain technology provider the study proposes to use or uses. Studies were classified as Ethereum, Hyperledger, and Other as a result of the review.

Smart Contract/Chain Code Enabled: A Boolean field specifying if the study includes a smart contract or chain code.

Reproducibility: It determines if the blockchain application of the study could be reproduced by using the information provided. The classification is carried out according to sharing level of data and codebase as "Yes", "No", and "Partly".

Cybersecurity Test: Evaluation of studies according to whether they were subjected to cyber security tests or not.

On-Chain Data: Blockchain-based stored data is specified.

Off-Chain Data: Data stored in the standard database are specified.

Consensus Algorithm: Evaluation of the consensus algorithm used by the blockchain infrastructure used in the study.

Feasibility Analysis: Provides a feasibility analysis for the blockchain-based system components involved in the studies.

3. Results

3.1. Summary of Findings

This section presents and examines graphical summaries of the reviewed papers and non-academic content. The summarized graphical demonstration includes the distribution of papers and non-academic content by year and publication type. Moreover, graphs about reviewed papers provide technical details about blockchain use cases such as the application in the sub-field of hydrology, the development level of a blockchain application, the type of blockchain, and the blockchain network.

A table showing the summarized information of 103 papers and 57 non-academic content is included in the appendix (Table A2 and A3). Considering the distribution of papers by years, an approximately linear increase is observed. This trend can be explained by the increase in the application areas of blockchain technology and the increase in the exploration and adoption of modern technologies in hydrological processes. The number of papers in 2022 seems not to have exceeded the previous two years yet. Considering that the papers reviewed cover the period before October 15, 2022, this number may support the continuing linear increase. In addition, sharp fluctuations in cryptocurrency exchanges may have limited the applications of blockchain technology in different areas. Non-academic content production appears to follow a steady uptrend, with the exception of a drastic dive in 2020. (Figure 2).

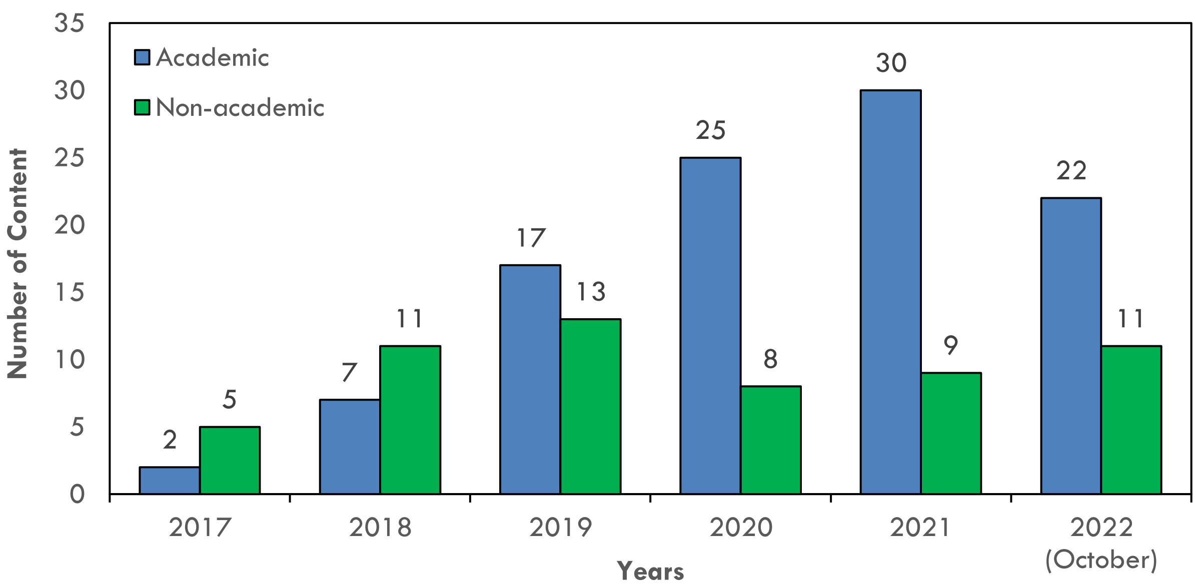

Figure 2. Distribution of academic and non-academic content by years

Reviewed papers are classified as "journal papers," "conference papers," "book chapters," "books," "theses," "working papers," and "technical reports". If outputs from different phases of the same project were presented at different conferences, both conference papers were considered. Contents published as technical reports were evaluated as academic content if the publisher was a governmental entity, or as non-academic content if it was published by a non-governmental organization for the purpose of informing the public. While there is a dominance of journal and conference papers in the reviewed papers, the number of postgraduate theses can be considered very low. The reason for this can be interpreted as the immature level of integration between the academic blockchain ecosystem and the hydroinformatics community, and as a result, the difficulty of finding a suitable use case to support a thesis contribution as well as advisors experienced in this interdisciplinary area. Reviewed non-academic content is divided into three publication types including web documents, whitepapers, and hackathon projects (Figure 3). Projects that published whitepaper emphasize the potential applications instead of providing real-time hydrological application. Hackathon projects are the output of hackathon events that directly focus on hydrological processes.

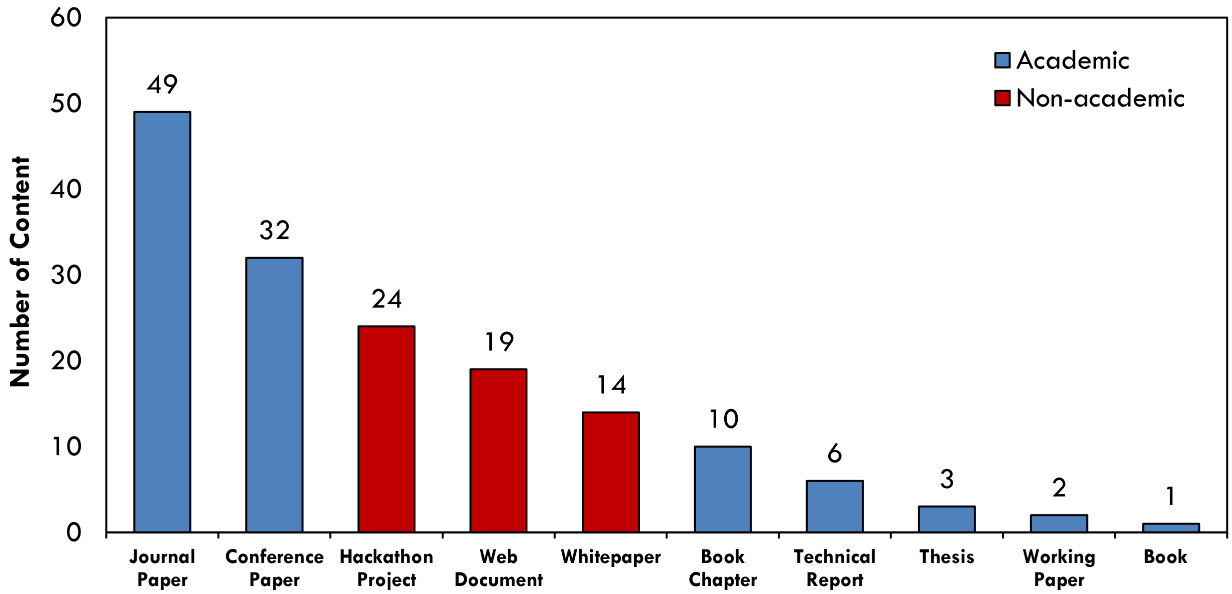

Figure 3. Distribution of academic and non-academic content by publication type

Another classification of reviewed papers is carried out according to their major contribution to sub-fields of hydrology. Although most papers focused on more than one sub-field, they were categorized in the hydrology sub-field that was considered to be the most focused area (Figure 4).

Water Governance: These papers generally anticipate using blockchain as a database and focus on solving administrative problems and building trust among stakeholders. Papers providing a literature review are also categorized here.

Water Quality Management: These papers focus on problems related to water quality, such as monitoring, analysis, wastewater management, and a more transparent demonstration of water quality standards being met.

Water Economics: These papers focus on approaches to water markets at different scales for water trading, water rights, water claims, and water economy applications.

Agricultural Water Management: These papers focus on agriculture-related water problems such as irrigation and agricultural water quality.

Urban Water Management: These papers focus on urban water applications such as drinking water and stormwater systems.

Water SDG: These papers focus on blockchain applications in hydrology and their contribution to achieving Sustainable Development Goals.

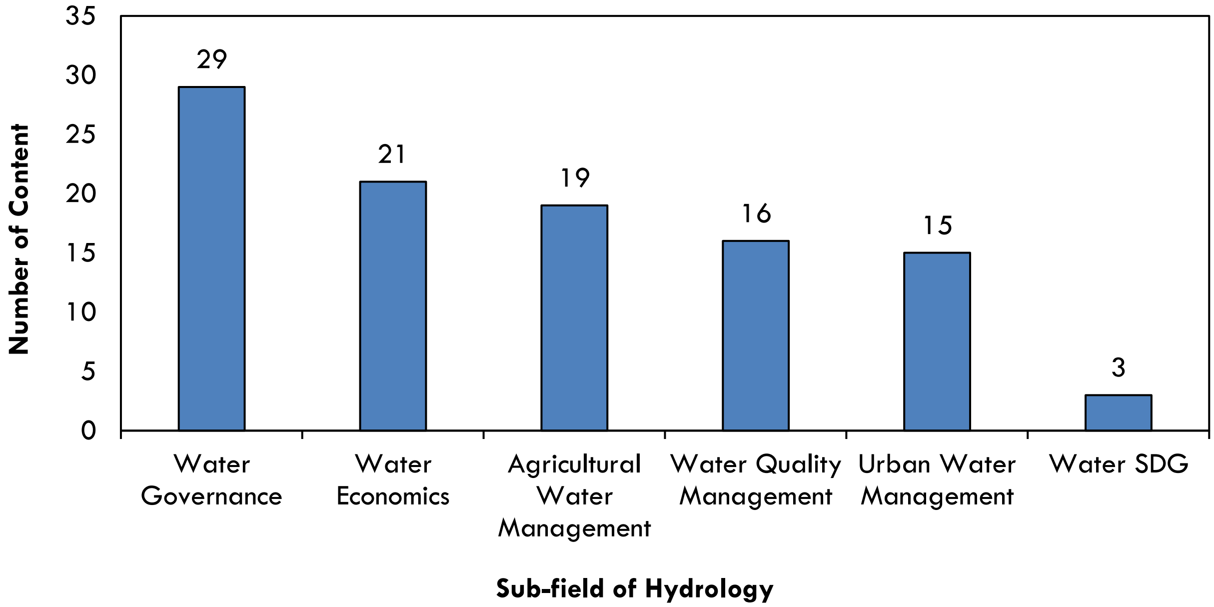

Figure 4. Distribution of academic content by sub-field of hydrology

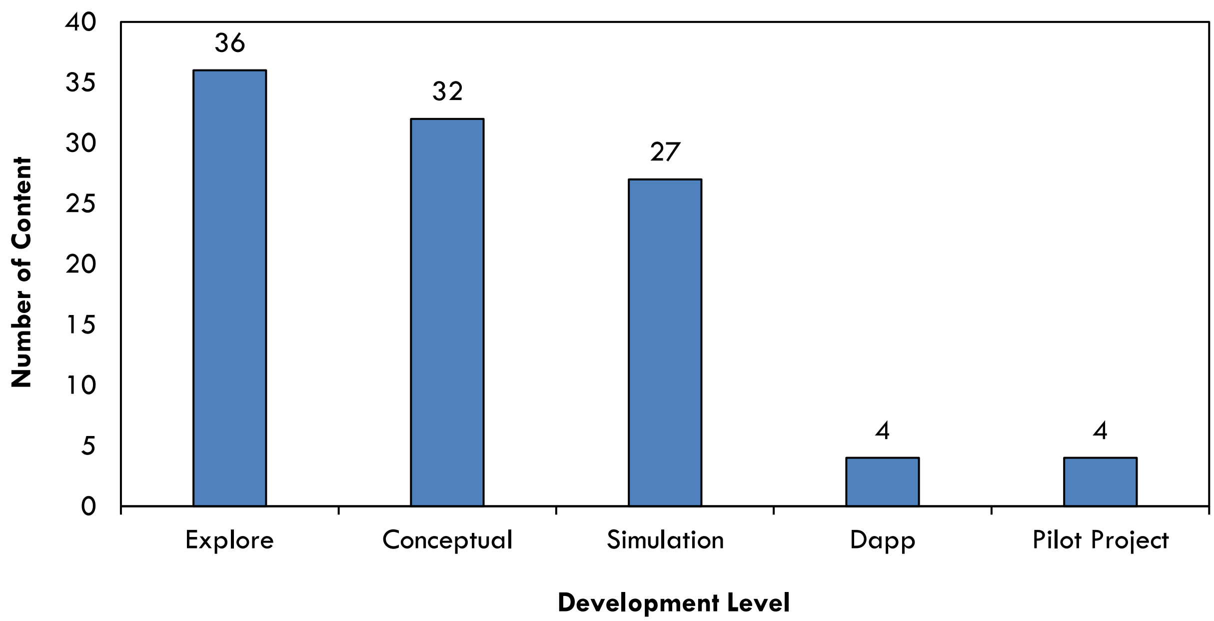

Figure 5. Distribution of academic content by development level of blockchain application

Water Economics is ranked second because decentralized finance applications are the first application of blockchain technology in many other areas, and there is more knowledge on this subject. The distribution of the development level of blockchain applications shows that the hydrology applications are still in the maturation stage (Figure 5). It is noteworthy that few studies include an application as an end product or a pilot project with a real-world active use case. The number of studies in the Water SDG category would have been greater if other studies had been focused on their potential contribution to sustainable development goals.

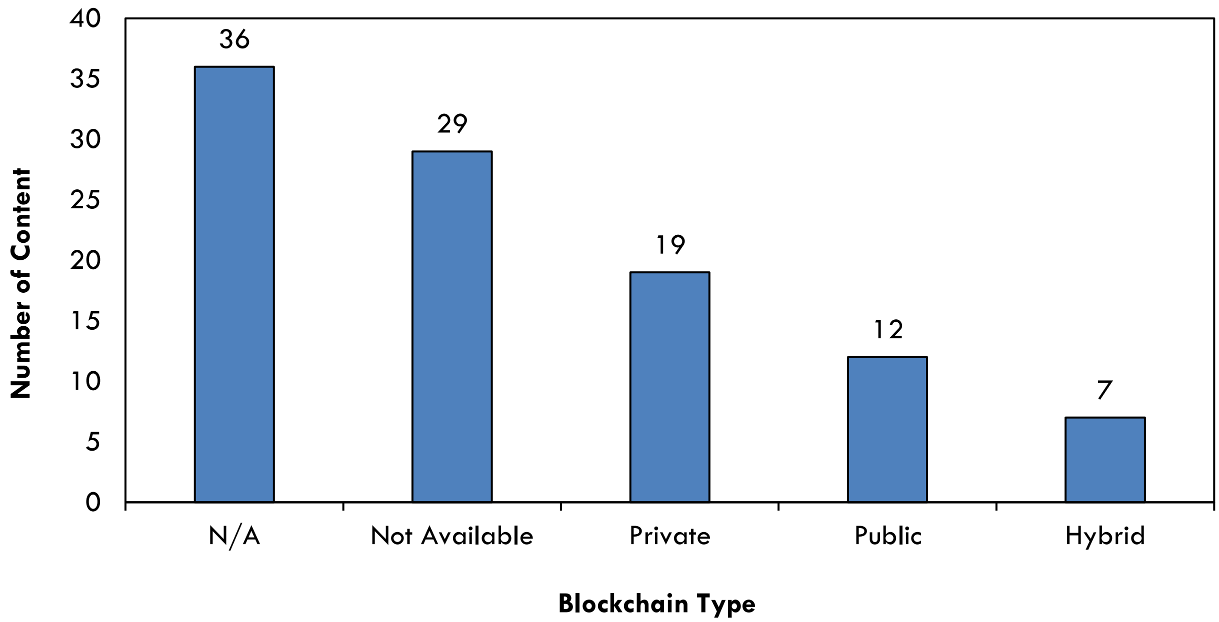

Figure 6. Distribution of academic content by blockchain type

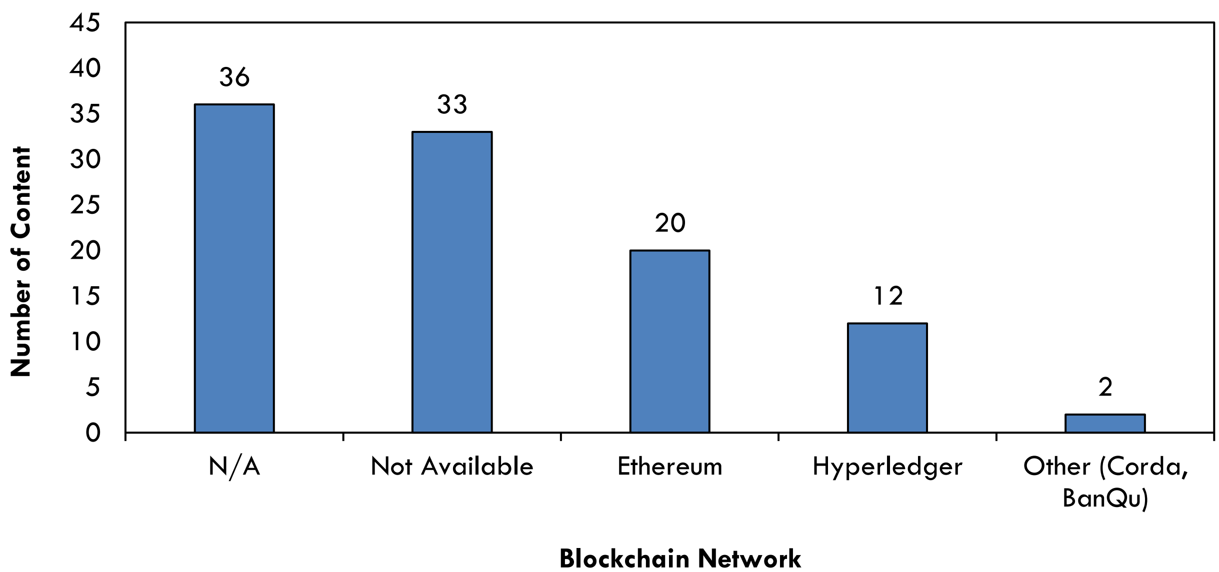

Figure 7. Distribution of academic content by blockchain network

The "N/A" column in Figure 6 and Figure 7; represents the same articles as the "Explore" column, which does not suggest an architecture or system but simply explores potential applications of blockchain technology. Therefore, a blockchain type or a blockchain network is out of the question, as the study only explores potential applications. If a system or architecture is suggested but no blockchain network or blockchain type is specified in the paper, it is categorized as "Not Available." The reason why private blockchains are preferred more may be that the water-related data in the use case is not intended to be shared transparently even if the identities are cryptographically secure because most of the papers contain conceptual and simulation studies. Moreover, fluctuating cryptocurrency markets may be creating concerns about transaction fees to be paid on public blockchains. Ethereum and Hyperledger dominate the field of hydrology as well as other application fields due to smart contract and private blockchain compatibility. Other private blockchains represented in the review were Corda and BanQu.

3.2. Analysis of Academic Content

In this section, the reviewed academic content is briefly summarized. These summaries highlight the papers' approach to blockchain and hydrology integration.

3.2.1. Water Governance

The common consensus is that trust is a critical enabler in water governance. Reliable data and coordination are essential to establishing and maintaining the trust layer. Blockchain provides an immutable database to store water-related data securely. This key feature of blockchain technology provides a straightforward framework for water governance stakeholder coordination. Moreover, smart contracts can contribute to sustainable water governance by codifying environmental and economic conditions. Sobrinho et al. (2019) describe how blockchain technology can help to enhance financial transparency and trust while also helping to improve water governance. Such an enhancement might be made possible, for example, by the development of cryptocurrencies and the use of smart contracts to encourage actions aimed at water resource conservation. Sriyono (2020) investigates the potential of blockchain technology to aid in the efficient management of water resources and offers a framework and architecture for blockchain and water management. The paper also discusses a potential blockchain-based solution for the water quality problems in Puerto Rico. Scozzari et al. (2021) examine how IoT, AI, and blockchain are used to digitally transform smart water networks and blockchain-enabled water rights trading.

Dogo et al. (2019) examine the effects of combining blockchain technologies with intelligent water management and assert that blockchain has the potential to revolutionize water and sanitation governance to achieve SDG 6 as envisioned by the United Nations in 2035, through creative, effective, and scalable solutions, based on these two technologies in African cities. Poonia et al. (2021) examine the spatiotemporal distribution of several drought types, separately and simultaneously, in India. A blockchain-based framework is suggested to enhance the current drought risk-management system to make it easier for those who have died from drought to receive help and aid as soon as possible. Linjing et al. (2020) explain the benefits and standout characteristics of blockchain-enabled IoT applications and contrast them with centralized, more established IoT-based smart water systems. Hangan et al. (2022) examine the potential applications of big data and blockchain in the field of water resources and argue that blockchain can act as a link between a locally used solution and a global infrastructure that is accessible globally and is controlled by a coalition of international organizations using consensus mechanisms.

Iyer and Giri (2020) evaluate water-related issues that may be solved by blockchain, which will be important in the area of ethical pricing and highlight data transparency as data is exchanged across networks for water reuse. Wu et al. (2022) thoroughly examine the properties of blockchain technology, as well as the scenarios and applications that blockchain has in the field of protecting water resources, including the storage of data about water bodies, cross-sectoral collaboration, and increased public involvement level. According to Ragghianti (2021), blockchain allows for the integration of watershed monitoring and direct management of water usage for all system users, maintaining flexibility and guaranteeing all socio-environmental constraints that apply in that basin. Xia et al. (2022) consider a distributed and decentralized water data management system for the whole supply, consumption, and discharge processes. The system includes two conceptual hybrid blockchain-based application scenarios: permits for water abstraction and water quality tracking. Singh and Goel (2020) examine how blockchain might be used to notify authorities of any emergency flood events.

Yasuno et al. (2020) integrate upstream monitoring, dam inflow prediction, a smart contract enabled blockchain framework to reimagine the dam watershed as a smart dam and organize the technologies for flood prediction. Study aims to facilitate real-time coordination among stakeholders and real-time broadcast of disaster prevention information. Lin and Wang (2021) claim that SPOF and DDOS attacks have the potential to exploit the authentication and key agreement in intelligent water conservation systems, thus suggesting a blockchain-based authentication key agreement system for smart water devices. The selected network for blockchain is Ethereum, and to participate in the Ethereum network, smart devices serve as light nodes. The light node does not engage in mining and merely downloads a small bit of the blockchain network. It is appropriate for conditions where there are more smart devices. The consensus algorithm for the blockchain system is Practical Byzantine Fault Tolerance (PBFT).

Asgari and Nemati (2022) investigate the literature based on the three primary Distributed Ledger Technology (DLT) application areas of Smart Water Systems, Water Quality Monitoring, and Storm Water Management. Additionally, they address the legislative, social, administrative, and practical difficulties which can be an obstacle to the use of blockchain technology. Stankovic et al. (2020) provide an overview of possible blockchain-enabled applications in water and sanitation services for Latin America and the Caribbean. Li et al. (2021) provide a peer-to-peer blockchain system based on data to forecast water consumption. There are four layers in the framework: i) the storage layer; ii) the network layer; iii) the smart contract layer; and iv) the application layer.

Zhang et al. (2020) establish a platform with four decentralized participants, such as government agencies, water conservation private sector actors, the general public, and third-party maintenance. The study also provides the design of “dual chain” smart contracts that are "alliance chain and private chain." Additionally, the many possibilities of blockchain-enabled platform applications for smart water conservation are examined. Next, a novel development route including consensus mechanisms, smart contracts, asymmetric encryption, and information source tracing is suggested using the water rights trading market as an example. Chinese Smart Water Conservancy Platform Data is the main on-chain data in the proposed system. Youssef et al. (2019) suggest an unmanned aerial vehicle (UAV), cloud-based solution for dam site monitoring. The UAVs periodically provide meteorological data, water quality and level information, and the condition of dam structures. Blockchain, which offers identification, a database system, and traceability of the UAV cloud's data transmission, ensures a distributed and long-term security solution. The effectiveness of the solution is simulated by assessing the data delivery delay ratio.

Majia (2021) creates a blockchain-based system that maintains the privacy of operational hydropower plant data. The proposed system stores the homomorphic encrypted operational data on chain. Sukrutha et al. (2021) establish a unique blockchain architecture with double hashing as a data storage system that is more secure for groundwater management data. The water level and water quality data of aquifers are stored off-chain, but the hash of the same data is stored on-chain. The simulation is carried out, and the transactional cost is examined. Simulation results show that storing the hash of data is cost-effective. Mohammadi et al. (2022) create a hypothetical blockchain-based system to securely exchange data gathered in real-time from a variety of sensors for monitoring and controlling water consumption. The proposed consensus algorithm is proof of work, and smart water meter data is supposed to be directly stored on-chain.

Dramski et al. (2019) describe a system for gathering environmental data from meteorological sensors and then storing it in a blockchain application. The application is powered by a private Hyperledger blockchain network and a sensor prototype developed on a Raspberry Pi. Tiwari et al. (2020) suggest a public Ethereum-based blockchain system designed to preserve water consumption that satisfies the supply-demand processes of all customers in a peer-to-peer network. Vernekar (2020) outlines a fully decentralized, blockchain-based approach for managing water supply that uses IoT devices to collect data along the configuration and add it to the Ethereum public blockchain.

Sapra et al. (2021) provide a methodology for creating an intelligent water management system that determines and calculates a consumer's water use within a certain area and also detects leaks in the plumbing system. A private blockchain network is designed based on Ethereum, and water quality, pressure, and location data for components of the water distribution system are stored on the block. The California Blockchain Working Group (2020) investigates the potential for blockchain-based technology to assist in the development of a more effective framework that builds on the momentum of recent California water-related data initiatives. There are two pilot project-level studies in this category in the reviewed literature. Mughal et al. (2022) conduct a pilot project emphasizing blockchain-enabled solutions for enhancing Pakistan's data-intensive decision-support systems. The consistency, immutability, and dependability of streamflow time series data were maintained using a private blockchain that was built on the Hyperledger Fabric platform. The model evaluated the use of Hyperledger fabric, employing the distributed autonomous administrative authority of Pakistan's irrigation network. In addition to collecting sensor data for streamflow prediction, the nodes also maintain permanent data storage on the streamflow record and aggregate and approve compliance with the distribution system via chaincode (smart contracts). The proof of authority protocol allows the designated nodes with authorization to create new blocks of streamflow data monitoring irrigation networks, thus maintaining the chain's overall security.

Another pilot project is carried out by Coli et al. (2021). The pilot project in Peru aims to demonstrate the viability of integrating blockchain technology into the microfinance industry for water and sanitation to increase the effectiveness of the current microfinance model and support the inclusion of unbanked people in the financial system. Pilot study also allows for more discovery through first-hand experiences with local microfinance organizations and borrowers. The private blockchain network of BanQu is preferred for the project, and a feasibility analysis is conducted to show operationally cost-effective scenarios as a result of blockchain implementation.

3.2.2. Water Economics

Water economics is the consideration of the economic value of water as a natural resource and the added value it creates in the areas where it is used within the framework of microeconomic theories. The focus of these theories is to maintain the quality and quantity of water under economic and financial constraints and to make water-related investment, cost and water markets efficient. The water economics has been a substantial area of research for exploring blockchain applications due to its intrinsic need for and obvious utility of adopting trustworthy data and currency sharing mechanisms. Bhaduri et al. (2021) investigate the opportunities for potential water market implementation in Los Angeles, USA, and Bengaluru, India. Poberezhna (2018) explores how blockchain-based tools could assist the water sector's businesses and governing bodies in gaining access to real-time data about market shares, consumption trends, consumer bill management, and other possibilities. Ikeda and Liffiton (2019) introduce two possible use cases for blockchain-based water management: i) blockchain-based water and sanitation subsidies, and ii) using blockchain tools to manage water pricing and consumption.

Bou Abdo and Zeadally (2020) create a commercially and economically viable peer-to-peer trading platform for water and energy that supports rainwater gathering and trade of the captured water. The rainwater harvested data is directly stored on-chain. Thomason et al. (2018) examine the relationship between blockchain technology and climate finance as both relate to the problem of water scarcity in poor nations and propose blockchain-based water trading applications as a potential solution. Zhao et al. (2019) underline the significance of creating a peer-to-peer trading network with blockchain capabilities that would enable more irrigators to take part in the platform that secures and transparently allocates water, increasing the total efficiency of water resources. Zecchini (2019) investigates the potential application scenarios for blockchain-enabled water quality credit systems. Grigoras et al. (2018) introduce blockchain and smart contracts integrated into a theoretical water rights trading platform. Angara and Saripalle (2022) review the virtual water literature systematically and provide a conceptual virtual water currency and blockchain-enabled virtual water trade system. Sivaramakrishnan (2020) proposes a blockchain-enabled architecture for water trading platforms between agricultural stakeholders. The Ethereum public network is preferred to perform regulatory requirements as smart contracts. Belliera et al. (2019) create a flood insurance system powered by blockchain.

Vannucci et al. (2021) extend this study and aim to contribute to the analysis and management of flood events from an economic and financial perspective from a public administration viewpoint. The study also entends the unique and robust blockchain-based insurance systems. Zhang (2022) provides a design of a conceptual blockchain-based supply chain financial system model for water resources businesses, and a model to analyze the financial condition of seven water businesses for their potential blockchain-based digital transformation in China. Their conceptual blockchain-based architecture is designed to store the financial supply chain of water resources data directly. Miller (2021) and Ramsey et al. (2020) describe and evaluate the application of blockchain capabilities to the water rights trading ecosystem and design a variety of services that leverage blockchain features and business value. Pee et al. (2018) and Alcarria et al. (2018) examine the potential for a simple peer-to-peer water market based on smart contracts with water trading data stored on the Ethereum private network. Liu and Shang (2022) propose hybrid blockchain approach for trading water rights and Li et al. (2022b) use chain code to enable transactional water rights data storage in a private Hyperledger Fabric network for the same purpose.

This category contains one study at the DApp level and one study at the pilot project level. Abu-Amara et al. (2022) develop a blockchain-based application to manage the supply of water and energy transactions. The application records water and energy use data on a private Hyperledger network and allows consumers to view and pay bills online. CRCNA (2020) provides a pilot project with Civic Ledger, an Australian start-up, in Mareeba-Dimbulah Water Supply Scheme (MDWSS), Northern Australia. Water Ledger, which is Civic Ledger's water trading platform built on Ethereum, is customized to the MDWSS business and operational standards to examine how blockchain technology can minimize trading costs, boost the effectiveness of trade processes, and raise water market transparency. The pilot project highlights that blockchain-enabled systems have the potential to codify regulatory rules, reduce transaction costs, and avoid asymmetric information about actual water prices. The main challenge for the next phases of the project is that the existing water market and the water delivery infrastructure are not interoperable.

3.2.3. Water Quality Management

Water quality management is the entire process of monitoring the water quality from the source to the user, taking measures to protect the water quality, and treating the water if necessary. In this whole process, reliable data and real-time monitoring are vital for the detection of possible contamination and the efficiency of the treatment process. Kassou et al. (2020) propose a blockchain-enabled conceptual system design to control and track medical wastewater infrastructure. Damania et al. (2019) consider the blockchain as a next-generation data storage system and discuss potential integration in terms of water quality management. Ortiz (2018) points out the capabilities of blockchain applications to improve public awareness and governmental accountability about water quality at all scales in Puerto Rico. Yan et al. (2019) present a conceptual blockchain-enabled environmental monitoring system architecture that data analysis, stakeholder authentication and water quality data are synchronized. Wan et al. 2020) deliver an AI-supported management system for wastewater treatment facilities and investigate blockchain as a data storage system.

Hakak et al. (2020) conceptualize a blockchain-enabled smart contract-supported industrial wastewater management system. Quist-Aphetsi and Blankson (2019) explores the cryptographic features of Secure Hash Function 256, which is the most popular hash function in blockchain applications, and examine a potential hybrid data logging system that store cryptographically the quality of water delivered to consumers from the water treatment plant. Kaur and Oza (2020) document the Ethereum Request for Comment Standards 20 (ERC20) from a smart city perspective that Ethereum-based tokens must comply with. The paper simulates the Water Reprocessing Coins (WRC) to create a business environment where everyone has an equal chance of obtaining credits based on recycled wastewater to remove inequalities between different-scale enterprises. Iyer et al. (2019) propose a private blockchain network based on Hyperledger to maximize the effectiveness of wastewater recycling systems for industries. The study's simulation process includes anomaly detection algorithms to apply chaincode rules for possible penalties to industries attempting to tamper with water quality sensors.

Lin et al. (2020) simulate an integrated system based on IoT and blockchain that is structured as a directed acyclic graph and uses geographic information system tools for source tracking of river water quality problems. Berman et al. (2020) provide an implementation of a blockchain-enabled framework for sample identification and logging together with small autonomous boats that can navigate to measure chemical water quality parameters automatically. Niya et al. (2018) propose an IoT-enabled LoRa-based system for monitoring water pollution that is completely decentralized by storing and retrieving data from IoT sensors on the Ethereum blockchain network. Crawford et al. (2021) create an R3 Corda-based DLT system for oil and gas underground injection control (UIC) operations to maintain the water quality of freshwater aquifers. Gudmundsson and Hougaard (2021) create a model that explicitly demonstrates the influence of water quality on production profits and offer a plan for distributing the profits of the best possible pollution abatement. In order to automate negotiations, the paper offers a decentralized solution using smart contracts.

The DApp level categorized in this section is conducted by Alharbi et al. (2021). Initially, the study focuses on measuring the water quality parameters in industrial tanks and looking for any violations using IoT (Internet of Things). Afterward, Hyperledger's private application is used to enforce the necessary penalties on the violating industrial facility and sustain the accuracy, dependability, and transparency of the records of violations. The technology will be able to measure the quality of the water in real time and enable the immediate identification of any violation to apply the appropriate penalties. The administration can access the decentralized web application to track the status of water measures for registered industrial facilities and evaluate the data linked to water violations with easy-to-read illustrations. Shi et al. (2019) present a cutting-edge IoT solution that uses a Hyperledger private network to preserve healthy drinking water consumption in schools. It is mentioned that 39 schools have already implemented the project in Hangzhou's Shangcheng District, China. The project reduces the workload of health professionals and encourages the transformation from conventional site-based inspection to automated remote monitoring.

3.2.4. Agricultural Water Management

Agricultural water management aims to provide the optimum amount and quality of water for agricultural products by considering the continuity of ecosystem services. This optimization is possible by prioritizing data security related to agricultural water management processes, Dong and Fu (2021), Liu et al. (2020) and Kumar et al. (2021) examine possible applications for blockchain-based digital solutions in the agricultural industry and assess the transformation process of traditional agriculture to blockchain-based digitalized smart agriculture systems. Liu et al. (2021) and Ferrag et al. (2020) provide a systematic review of information communication technologies (ICT) and blockchain-enabled agricultural applications.

Dragulinescu et al. (2021) propose a blockchain-enabled conceptual system to maximize smart irrigation by storing the water quality, air quality, and weather data on chain. Dragulinescu et al. (2021) extend the conceptualized framework and perform simulation studies to store and monitor some physical and chemical water quality parameters for irrigation networks, such as temperature, dissolved oxygen, pH, and turbidity. Chang et al. (2021) offer a conceptual Ethereum-based irrigation system that stores agricultural supply and demand data on-chain. Krishna et al. (2021) provide a smart agricultural system architecture that stores soil moisture and temperature on blockchain to protect agricultural data security. Sakthi and DafniRose (2022) propose a Hyperledger private network to provide data transparency and reliability for agricultural stakeholders to encourage them to reduce pesticide and fertilizer-based water and soil pollution. Lin et al. (2017) discuss the potential blockchain applications and propose an architecture based on ICT and hybrid Ethereum network integration.

RajaRajeswari et al. (2022) provide a blockchain-enabled conceptualized framework for smart gardening as a component of the smart city concept. Munir et al. (2019) and Ting et al. (2022) propose a smart irrigation system that uses fuzzy logic-based algorithms for decision-support processes and blockchain for data reliability. Zeng et al. (2021) simulate a system for managing and coordinating the usage of high-quality seeds and water resources between communities; an effective tracking system for seed quality and a smart irrigation management system are designed using IoT and blockchain integration. Giaffreda et al. (2019), Bordel et al. (2019) and Pincheira et al. (2021) provide Ethereum-based agricultural water management systems which include private, hybrid, and public networks respectively. These three studies provide a system that encourages and rewards ethical behavior in agriculture activities for specific multi-stakeholder ecosystems. The main aim of these studies is to create more sustainable and environmentally friendly irrigation water consumption system.

Enescu et al. (2020) describe a DApp that is centered on bringing together small farming communities for effective solar panel-based agricultural management. The DApp is suggested for managing both energy and water. The system uses the Ethereum public network and smart contracts, which enable customers to trade energy and water. ERC20 is implemented for transactions, and two cryptocurrencies are introduced including SIST (Small Irrigation System Token) and Solar Coin.

3.2.5. Urban Water Management

Urban water management aims to perform urban water services in an integrated manner. The main elements of urban water management are water supply, drainage and treatment facilities. The accountability of the urban water authority can become more sustainable within the framework of blockchain. Alnahari and Ariaratnam (2022), Lukić et al. (2022), Makani et al. (2022), Kim et al. (2022) and Kumar et al. (2022) investigate the possible blockchain application for smart cities. It is summarized that blockchain has the potential to enhance water security and accountability through the distribution of transparent, secure ledger accounts. In addition, water quantity and quality can be tracked for whole water supply and demand processes including storage, transmission, treatment, and consumption. Public awareness and trust layer between citizens are the main contributions of blockchain and smart city integration.

Mahmoud et al., (2019) examine the viability of combining Blockchain with intelligent water networks through case studies. Additionally, identity anonymity methods that could be integrated with the system and the customer's data are explored, and a distributed ledger and blockchain-based data aggregation mechanism for the smart meters are suggested. They extend this study and design a MATLAB toolbox that can simulate blockchain-enabled water distribution systems. Different algorithms for consensus mechanisms in blockchain are compared according to their mining time and giving the user the option to select the desired one (Mahmoud et al. 2021). Lalle et al. (2020) present the use of blockchain technology with the machine learning algorithm k-means to preserve user privacy. Users are grouped into clusters, and every cluster has a permissioned blockchain to store the data of its members.

Zecchini et al. (2020) introduce particular fields in their description, and they describe the use of Solidity design patterns applied to urban water management scenarios to provide blockchain developers with greater assistance in making important decisions to create effective decentralized applications. Sundaresan et al. (2021) propose a blockchain-enabled system that stores the quantitative and qualitative data of water distribution systems. Thakur et al. (2021) provide an incentive-based architecture for smart water distribution and saving that combines blockchain technology with edge computing. In the framework, houses are designed as nodes of the Ethereum-based network. The computation operates at the network's edge and offers a quick water-saving incentive system. Arsene et al. (2020) and Pahontu et al. (2020) are similar studies that provide a water supply system integrated with Hyperledger to manage customer demand more effectively. Rottondi and Verticale (2017) propose a public blockchain-enabled smart water metering architecture and a serious gaming platform to incentivize sustainable urban water consumption. Predescu et al. (2021) develop a system at the application level that provides a serious gaming approach for urban water management from the standpoint of mobile crowd sensing. Each crowdsensing task includes a chaincode-based incentive mechanism, and the trust layer of the system is secured by Hyperledger Fabric.

3.2.6. Water and SDGs

SDG-6 aims at sustainable water and sanitation services for all. Mora et al. (2021) outline the key sustainability concerns that cryptocurrency and blockchain technologies are addressing in terms of SDG-6 Clean Water and Sanitation. Le Sève et al. (2018) and Parmentola et al. (2021) provide a literature review about the potential of blockchain for improvements in environmental sustainability. Mattila et al. (2022) investigate the potential of blockchain-enabled data storage systems for their contribution to reaching SDG targets such as climate change, biodiversity loss, and water scarcity.

3.3. Analysis of Non-Academic Content

In this section, the reviewed non-academic content is briefly summarized. Web documents generally focus on the potential of blockchain for hydrological applications and underline the beneficial outputs. The most emphasized issue is that the blockchain-based storage of hydrological data creates a layer of trust between the stakeholders who depend on the quantity and quality of the same water resource. Another issue is the advantages of blockchain-based digitalization of traditional water markets, which are currently traded, such as accountability, easier access to instant market information, and low transaction fees.

Water Services Regulation Authority, a non-ministerial government department of the UK, published a report about customer data reliability and recommended blockchain to UK water companies in 2017 (Ofwat, 2017). A digital asset platform BANKEX introduces a pilot initiative called “water coin” that aims to generate direct investments for clean water provision safely by cutting out any intermediaries or other parties that could taint the process in Kenya (Bankex, 2018). Fujitsu launches a new blockchain water trading system that enables the safe use of botanical water. The botanical water harvesting process is the transformation of food waste into drinking water. Companies that want to use botanical water can purchase it from a suitable refinery by using a blockchain-enabled mechanism provided by Fujitsu (Fujitsu, 2021).

The aims of the projects that publish whitepapers or hackathon projects focus on to provide blockchain-based storage of data on water distribution systems, detection, management, and prevention of water pollution sources; ensure more reliable traceability of water-related investments; create wastewater management layers for both treatment and environmental discharge processes; create micro water trading system for smart cities; and create more accountable water supply-chain processes.

4. Discussion

Blockchain-enabled hydrological applications are unique to each use case and difficult to standardize but the literature has agreed on four fundamental benefits of blockchain-based hydrological applications, which are described below.

Water Trust**:** Since the blockchain has a decentralized structure, none of the stakeholders are directly the owners of the system. In addition, it is certain, thanks to smart contracts, that hydrological and administrative rules are followed by all parties. This creates a trust layer between parties that depend on the same water source, even if they are not aware of each other.

Water Data Security**:** In the blockchain, the data is distributed among the nodes that support the system in a completely distributed manner. This makes the system safe from traditional cyberattacks and power outages. Since the data is stored cryptographically, even if the data is captured in some way, it cannot be disclosed unless the user wants it. It provides data security for natural and legal persons.

Immutable Water Transaction Ledgers**:** Data recorded in distributed ledgers cannot be deleted. It provides a single and common database for stakeholders.

Water Accountability**:** Transactional data records on the blockchain are publicly available for anyone to view and verify. There is no need for a third-party verification system or trusted data provider to verify the data.

Theoretically, the potential benefits of blockchain-based hydrological applications are discussed in detail, but real-time simulation and application stage studies are scarce in the literature. Moreover, there is no blockchain-based hydrological application where the environmental, economic, and regulatory rules are coded as smart contracts and real-time data is processed. Although 34% of academic content includes simulation, application, or a pilot project, the data shared about the process is very limited. The simulation results are mostly graphical representation for the measured water quantity and quality. This can be explained by the fluctuations in cryptocurrency exchanges affecting trust in blockchain technology and prolonging the maturation process of blockchain technology. Blockchain technologies are currently immature for large scale operational and regulatory applications and difficult to justify for long-term investment and commitment.

Another notable point in the review is that a detailed smart contract-oriented feasibility, or optimization study on blockchain transaction fees related to the simulation, application, and pilot project-level studies is very limited. The efficient design of codes in the rules determined by smart contracts has a great impact on transaction fees and can make the whole system feasible. Moreover, while the data recorded on the blockchain is immutable, coding the smart contract is critical. A vulnerability in smart contract codes could lead to incorrect recording or manipulation of data (Nelaturu et al., 2021). A smart contract can only be as smart as the developer who codes it.

Another important issue is the blockchain oracle problem. Blockchains are isolated from physical systems, so they need blockchain oracles that enable data exchange with physical systems (Lo et al. 2020). IoTs that send water-related data to the blockchain must send reliable data. Otherwise, the blockchain system will store incorrect data even if the smart contract is coded perfectly. In the literature, there is a lack of blockchain oracle research focused on flowmeters and water quality sensors that record water-related data and send it to the blockchain system. Although the use of Ethereum and Hyperledger dominates the literature, due to the block structures that allow smart contract design, their hydrological advantages and disadvantages against each other are not evaluated in the literature. Similarly, the hydrological evaluation of the advantages of private and public blockchain applications against each other is not included in the literature.

5. Recommendations for Future Work

Extensive research and case studies is needed with a real-time application focus to directly observe and evaluate the theoretical benefits of the blockchain technology. Research involving more real-time applications will encourage more water authorities to test the blockchain-based performance of their existing systems. It is necessary to analyze the economic and financial feasibility of the blockchain-based digital transformation, which includes the optimization of the blockchain system itself and the digital connection with the physical water systems. In addition, hydrology-focused smart contract optimization and blockchain oracle framework development research are essential. Generalized architectures and blockchain systems that can serve as a plug-and-play technology to many use cases and organizations are essential for realizing the potential in hydrological applications such as water rights trading or urban water supply-chain. Water authorities or companies may want to enjoy the benefits of blockchain applications without needing to learn the cryptographic background.

Private and public blockchain-enabled networks have advantages and disadvantages for a water system, but there is no study in the literature focusing on this comparison. While public blockchain networks provide greater accountability, there are higher transaction fees. This issue should be discussed in particular within applications of water systems. Similarly, different consensus algorithms provide different features, however, there is a lack of hydrology-focused comparison studies about the issue.

Transboundary water systems management is one of the most important areas of hydrology where stakeholders have a problem of trust, reliable data are needed, and a common water management approach should be adopted (Albrecht and Gerlak, 2022). Transboundary water systems are an important field of study with great potential, considering the theoretical benefits of blockchain such as accountability, transparency, and immutability. Virtual water trade and water footprint, which are other sub-branches of hydrology, also have the potential to be digitalized with a blockchain-oriented perspective. The international trade of products brings with it the international flow of virtual water (Delpasand et al., 2023). The supply chains of products can be managed on a blockchain basis by adding water footprint and virtual water trade data.

The last point to be underlined about blockchain-based applications is the Non-Fungible Tokens (NFT). An NFT is a type of cryptocurrency; however, in this definition, the money in question can be any asset that has value (Flick, 2022). Assets that can be considered NFTs include any piece of art, video, tweet, a website, images, and stories that are created on social media. NFTs cannot be exchanged for another identical token, as NFTs are unique and no two are alike. This property is called "non-fungibility," that is, "unchangeable." Public blockchains provide these tokens with provable rarity, while smart contracts ensure that they are non-reproducible and unique. In water resources management, any product's water footprint certificate or water quality credits can be stored as NFTs. Similarly, any investment, water-related bill, or tax payment can be stored as NFTs with the limits drawn by the smart contract, making it immutable who pays when and how much.

6. Conclusions

This paper provides a systematic literature review of applications to address hydrological challenges using blockchain technology. A total of 104 academic publications and 37 non-academic studies dealing with hydrology and water resources were analyzed in detail. During the period of analysis covered, between 2017 and October 15, 2022, it was observed that the number of publications for blockchain-based hydrological applications has increased linearly since 2017, with an observable drop in 2020, only to continue following an uptrend. This study evaluates the potential for existing application areas to be enhanced with a more sophisticated use of blockchain technology as well as the realization of potential new hydrological applications.

Detailed review results demonstrate that the blockchain-enabled hydrological applications have not reached maturity. However, there is a gap in research on hydrological applications and the implementation of water resources management projects that process and use real-time data. With more research and development to address the identified gaps, blockchain technology holds great potential and may provide sustainable utility in the field of hydroinformatics.

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8. Appendix

Table A1. List of Academic Database and Keyword Combination

Database	Keywords	Years	Results
Google Scholar	"blockchain" and "water"	All times	39,000
		Since 2018	19,200
		Since 2019	18,500
		Since 2020	17,500
		Since 2021	16,900
		Since 2022	7,220
	"blockchain" and "water management"	All times	4,230
	"blockchain" and "water rights"	All times	186
	"blockchain" and "water trading"	All times	99
	"blockchain" and "water quality"	All times	3,120
	"blockchain" and "water market"	All times	93
	"blockchain" and "urban water management"	All times	171
	"blockchain" and "transboundary water"	All times	76
	"blockchain" and "wastewater management"	All times	92
	"blockchain" and "water finance"	All times	25
	"blockchain" and "water economics"	All times	25
	"blockchain" and "virtual water"	All times	121
	allintitle: "blockchain" and "water"	All times	61
	"distributed ledger" and "water management"	All times	538
	"distributed ledger" and "water resources management"	All times	50
	"blockchain" and "water resources management"	All times	484
	"blockchain" and "industrial water"	All times	110
	"blockchain" and "basin management"	All times	97
	"smart contract" and "blockchain" and "water management"	All times	351
	"smart contract" and "blockchain" and "water quality"	All times	298
	"smart contract" and "blockchain" and "water rights"	All times	42
	"smart contract" and "blockchain" and "water trading"	All times	51
	"smart contract" and "blockchain" and "urban water"	All times	52
	"smart contract" and "blockchain" and "flood management"	All times	26
	"blockchain" and "water distribution systems"	All times	709
Scopus	"blockchain" and "water"	All times	257
	"blockchain" and "water management"	All times	34
	"blockchain" and "water rights"	All times	13
	"blockchain" and "water trading"	All times	26
	"blockchain" and "water quality"	All times	30
	"blockchain" and "water market"	All times	1
	"blockchain" and "urban water management"	All times	2
	"blockchain" and "transboundary water"	All times	-
	"blockchain" and "waste water management"	All times	1
	"blockchain" and "water finance"	All times	1

	"blockchain" and "water economics"	All times	-
	"blockchain" and "virtual water"	All times	3
	allintitle: "blockchain" and "water"	All times	33
	"distributed ledger" and "water management"	All times	5
	"distributed ledger" and "water resources management"	All times	2
	"blockchain" and "water resources management"	All times	8
	"blockchain" and "industrial water"	All times	1
	"blockchain" and "basin management"	All times	-
	"smart contract" and "blockchain" and "water management"	All times	7
	"smart contract" and "blockchain" and "water quality"	All times	1
	"smart contract" and "blockchain" and "water rights"	All times	2
	"smart contract" and "blockchain" and "water trading"	All times	1
	"smart contract" and "blockchain" and "urban water"	All times	1
	"smart contract" and "blockchain" and "flood management"	All times	5
Web of Science	"blockchain" and "water management"	All times	118
Crossref	"blockchain" and "water management"	All times	1000
Open Alex	"blockchain" and "water"	All times	3
Jisc Library Hub	"blockchain" and "water management"	All times	101
Library of Congress	"blockchain" and "water management"	All times	3

Table A2. List of Reviewed Academic Content

Authors	**Source Type**	**Focus Area**	**Development Level**	**Blockchain Type**	**Blockchain Technology**	**Smart Contract / Chain Code**
A B Belliera, 2019	Journal Paper	Water Economics	Explore	-	-	-
A Bhaduri et al., 2021	Book Chapter	Water Economics	Conceptual	Not Available	Not Available	Yes
A G Vernekar, 2020	Journal Paper	Water Governance	Conceptual	Not Available	Ethereum	Yes
A Hangan et al., 2022	Journal Paper	Water Governance	Explore	-	-	-
A M Dragulinescu et al., 2021	Conference Paper	Agricultural Water Management	Simulation	Not Available	Hyperledger	No
A M Drăgulinescu et al., 2021	Conference Paper	Agricultural Water Management	Conceptual	Not Available	Not Available	No
A Parmentola et al., 2021	Journal Paper	Water - SDG	Explore	-	-	-
A Poberezhna, 2018	Book Chapter	Water Economics	Explore	-	-	-
A Predescu et al., 2021	Journal Paper	Urban Water Management	DApp	Private	Hyperledger	Yes
A Scozzaret al., 2021	Book Chapter	Water Governance	Explore	-	-	-

B Bordel et al., 2019	Conference Paper	Agricultural Water Management	Simulation	Hybrid	Ethereum	Yes
B Miller, 2021	Technical Report	Water Economics	Conceptual	Not Available	Not Available	Yes
B Pahonțu et al., 2020	Conference Paper	Urban Water Management	Simulation	Private	Hyperledger	Yes
C Rottondi, G Verticale, 2017	Journal Paper	Urban Water Management	Simulation	Public	Not Available	No
California Blockchain Working Group, 2020	Technical Report	Water Governance	Explore	-	-	-
CRCNA, Civic Ledger, 2020	Technical Report	Water Economics	Pilot Project	Public	Ethereum	Yes
D Arsene et al., 2020	Conference Paper	Urban Water Management	Simulation	Private	Hyperledger	Yes
E Kaur, A Oza, 2020	Journal Paper	Water Quality Management	Simulation	Private	Ethereum	Yes
E M Dogo et al., 2019	Book Chapter	Water Governance	Explore	-	-	-
E Ramsey et al., 2020	Journal Paper	Water Economics	Explore	-	-	-
E Sriyono, 2020	Journal Paper	Water Governance	Conceptual	Not Available	Not Available	No
E Vannucci et al., 2021	Journal Paper	Water Economics	Explore	-	-	-
F Abu-Amara et al., 2022	Journal Paper	Water Economics	DApp	Private	Hyperledger	Yes
F M Enescu et al., 2020	Journal Paper	Agricultural Water Management	DApp	Public	Ethereum	Yes
F Mohammadi et al., 2022	Conference Paper	Water Governance	Conceptual	Not Available	Not Available	Yes
G Grigoras et al., 2018	Conference Paper	Water Economics	Conceptual	Not Available	Not Available	Yes
G Wu et al., 2022	Conference Paper	Water Governance	Explore	-	-	-
G Zhao et al., 2019	Journal Paper	Water Economics	Explore	-	-	-
H H Mahmoud et al., 2019	Conference Paper	Urban Water Management	Conceptual	Not Available	Not Available	No
H H Mahmoud et al., 2021	Journal Paper	Urban Water Management	Simulation	Not Available	Not Available	No
H Li et al., 2021	Journal Paper	Water Governance	Conceptual	Not Available	Not Available	Yes
H Mora et al., 2021	Journal Paper	Water - SDG	Explore	-	-	-

H Zeng et al., 2021	Journal Paper	Agricultural Water Management	Simulation	Not Available	Not Available	No
I Lukić et al., 2022	Journal Paper	Urban Water Management	Explore	-	-	-
J B Abdo, S Zeadally, 2020	Journal Paper	Water Economics	Conceptual	Not Available	Not Available	Yes
J Crawford et al., 2021	Conference Paper	Water Quality Management	Simulation	-	Other (Corda)	Yes
J Gudmundsson, J L Hougaard, 2021	Technical Report	Water Quality Management	Conceptual	Not Available	Not Available	Yes
J Ikeda, K Liffiton, 2019	Technical Report	Water Economics	Explore	-	-	-
J S V Angara, R S Saripalle, 2022	Journal Paper	Water Economics	Conceptual	Public	Not Available	Yes
J Thomason et al., 2018	Book Chapter	Water Economics	Explore	-	-	-
J Yan et al., 2019	Journal Paper	Water Quality Management	Conceptual	Not Available	Not Available	No
J Yan et al., 2020	Journal Paper	Water Quality Management	Simulation	-	Ethereum	Yes
K M Krishna et al., 2021	Conference Paper	Agricultural Water Management	Conceptual	Not Available	Not Available	No
K Quist-Aphetsi, H Blankson, 2019	Conference Paper	Water Quality Management	Explore	-	-	-
K Wan et al., 2020	Journal Paper	Water Quality Management	Explore	-	-	-
L Lin et al., 2021	Conference Paper	Water Governance	Conceptual	Public	Ethereum	Yes
L Majia, 2021	Conference Paper	Water Governance	Simulation	Not Available	Not Available	No
L S Iyer et al., 2020	Conference Paper	Water Governance	Explore	-	-	-
L Ting et al., 2022	Journal Paper	Agricultural Water Management	Conceptual	Not Available	Not Available	No
M A Ferrag et al., 2020	Journal Paper	Agricultural Water Management	Explore	-	-	-
M Asgari et al., 2022	Journal Paper	Water Governance	Explore	-	-	-
M Dramski et al., 2019	Conference Paper	Water Governance	Simulation	Private	Hyperledger	No
M H Mughal et al., 2022	Journal Paper	Water Governance	Pilot Project	Private	Hyperledger	Yes
M Kassou et al., 2021	Conference Paper	Water Quality Management	Conceptual	Not Available	Not Available	Yes
M Pincheira et al., 2021	Journal Paper	Agricultural Water Management	Simulation	Public	Ethereum	Yes

M S Alnahari, S T Ariaratnam, 2022	Journal Paper	Urban Water Management	Explore	-	-	-
M S Kumar e al., 2021	Book Chapter	Agricultural Water Management	Explore	-	-	-
M S Munir et al., 2019	Journal Paper	Agricultural Water Management	Conceptual	Not Available	Not Available	No
M Singh et al., 2020	Journal Paper	Water Governance	Explore	-	-	-
M Stankovic et al., 2020	Technical Report	Water Governance	Explore	-	-	-
M Zecchini et al., 2019	Journal Paper	Urban Water Management	Conceptual	Public	Ethereum	Yes
M Zecchini, 2019	Thesis	Water Economics	Explore	-	-	-
N Alharbi et al., 2021	Conference Paper	Water Quality Management	DApp	Private	Hyperledger	Yes
N Dong, J Fu, 2021	Conference Paper	Agricultural Water Management	Explore	-	-	-
P Coli et al., 2021	Technical Report	Water Governance	Pilot Project		Ethereum	Yes
P Sapra et al., 2022	Book Chapter	Water Governance	Simulation	Private	Ethereum	Yes
R Alcarria et al., 2018	Journal Paper	Water Economics	Simulation	Private	Ethereum	Yes
R Damania e al., 2019	Book	Water Quality Management	Explore	-	-	-
R Giaffreda, 2019	Conference Paper	Agricultural Water Management	Experimental	Private	Ethereum	Yes
R P Sobrinho et al., 2022	Journal Paper	Water Governance	Explore	-	-	-
R Zhang, 2022	Journal Paper	Water Economics	Conceptual	Not Available	Not Available	No
S B H Youssef et al., 2019	Conference Paper	Water Governance	Simulation	Hybrid	Not Available	No
S Hakak et al., 2020	Journal Paper	Water Quality Management	Conceptual	Not Available	Not Available	Yes
S Iyer et al., 2019	Conference Paper	Water Quality Management	Simulation	Private	Hyperledger	Yes
S J Pee et al., 2018	Conference Paper	Water Economics	Simulation	Private	Ethereum	Yes
S Kim et al., 2022	Journal Paper	Urban Water Management	Explore	-	-	-
S Makani et al., 2022	Journal Paper	Urban Water Management	Explore	-	-	-
S R Niya et al., 2018	Conference Paper	Water Quality Management	Simulation	Public	Ethereum	Yes

S Sundaresan et al., 2021	Book Chapter	Urban Water Management	Simulation	Not Available	Not Available	No
S Tiwari et al., 2020	Journal Paper	Water Governance	Simulation	Public	Ethereum	Yes
T S RajaRajeswari et al., 2022	Conference Paper	Agricultural Water Management	Conceptual	Hybrid	Not Available	No
T Thakur et al., 2021	Journal Paper	Urban Water Management	Simulation	Public	Ethereum	Yes
T Yasuno et al., 2020	Conference Paper	Water Governance	Conceptual	Not Available	Not Available	No
U Sakthi, J DafniRose, 2022	Journal Paper	Agricultural Water Management	Conceptual	Private	Hyperledger	Yes
V Kumar et al., 2022	Book Chapter	Urban Water Management	Explore	-	-	-
V Mattila et al., 2022	Journal Paper	Water - SDG	Explore	-	-	-
V Poonia et a., 2021	Journal Paper	Water Governance	Conceptual	Not Available	Not Available	No
V Sivaramakrishnan, 2020	Thesis	Water Economics	Simulation	Public	Ethereum	Yes
V Sukrutha et al., 2021	Conference Paper	Water Governance	Simulation	Public	Ethereum	Yes
V T Ragghianti, 2021	Other	Water Governance	Conceptual	Not Available	Not Available	No
W Linjing et al., 2020	Book Chapter	Water Governance	Explore	Not Available	Not Available	No
W Liu et al., 2021	Journal Paper	Agricultural Water Management	Explore	-	-	-
W Xia., 2022	Journal Paper	Water Governance	Conceptual	Hybrid	Not Available	Yes
Y Chang et al., 2021	Journal Paper	Agricultural Water Management	Conceptual	Not Available	Ethereum	Yes
Y Lalle et al., 2020	Conference Paper	Urban Water Management	Conceptual	Private	Not Available	No
Y Li et al., 2022	Journal Paper	Water Economics	Simulation	Private	Hyperledger	Yes
Y Liu, C Shang, 2022	Journal Paper	Water Economics	Conceptual	Hybrid	-	Yes
Y P Lin et a., 2020	Journal Paper	Water Quality Management	Simulation	Not Available	Not Available	Yes
Y P Lin et al., 2017	Journal Paper	Agricultural Water Management	Conceptual	Hybrid	Ethereum	Yes
Y P Ortiz, 2018	Working Paper	Water Quality Management	Explore	-	-	-

Y Zhang e al., 2020	Journal Paper	Water Governance	Conceptual	Hybrid	Not Available	Yes
Ye Liu et al., 2020	Journal Paper	Agricultural Water Management	Explore	-	-	-
Z Shi et al., 2019	Journal Paper	Water Quality Management	Pilot Project	Private	Hyperledger	Yes

Table A3. List of Reviewed Non-academic Content

Authors & Organization & Project	**Publication Type**	**Year**
Aqua Coin	Hackathon Project	2019
Baarish	Hackathon Project	2018
Basin Logix	Hackathon Project	2020
Block Garden	Hackathon Project	2022
Climeter	Hackathon Project	2017
Decentralized Rainwater Harvesting	Hackathon Project	2020
EnvChain	Hackathon Project	2022
Environment Connect	Hackathon Project	2022
ETH Water Dam	Hackathon Project	2019
Flood Chain	Hackathon Project	2019
H2O Chain	Hackathon Project	2019
How to Save	Hackathon Project	2021
HydroBlock	Hackathon Project	2018
MaximizeWasteWaterRecovery	Hackathon Project	2019
My Water Chain	Hackathon Project	2020
Wastewater Reuse	Hackathon Project	2019
Water Coin - Env. Sensor Data Sharing	Hackathon Project	2018
Water Coin - WRC Trading	Hackathon Project	2019
Water Guardians	Hackathon Project	2018
Water Monitor Plus	Hackathon Project	2022
Water Reuse Booster	Hackathon Project	2020
WaterWizard	Hackathon Project	2020
WeatherChainXM	Hackathon Project	2021
Wyo Flow	Hackathon Project	2018
Aditya K. Kaushik	Web Document	2019
ARUP	Web Document	2019
Atreides	Web Document	2021
BANKEX	Web Document	2018
C Stinson	Web Document	2018
Crypto Water	Web Document	2017
David Barbeler	Web Document	2019
E Weisbord	Web Document	2018
Fujitsu	Web Document	2021

GSI	Web Document	2022
Hypervine	Web Document	2022
O Russell	Web Document	2018
ODI	Web Document	2018
OFWAT	Web Document	2017
Origin Clear	Web Document	2022
Robert Galarza	Web Document	2022
Statecraft Tech	Web Document	2019
Vottun	Web Document	2022
Y Khatri	Web Document	2019
AquaBit	Whitepaper	2018
Baikalika	Whitepaper	2017
Block-Squid	Whitepaper	2020
Bluechain	Whitepaper	2019
G Booman et al.	Whitepaper	2021
Genesis Research & Technology Group	Whitepaper	2017
h20	Whitepaper	2022
HydroChain	Whitepaper	2021
Kojo	Whitepaper	2022
PG Giampietro	Whitepaper	2020
Pipeline System	Whitepaper	2021
TrashTag	Whitepaper	2021
Treelion	Whitepaper	2021
Water Consortium	Whitepaper	2020