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PAPER

Blockchain of Things for Securing and Managing Water 4.0 Applications

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ABSTRACT

The design of a smart water monitoring and control system in urban areas plays a pivotal role in providing efficient distribution mechanisms to reduce leakage, especially in regions facing water scarcity and limited resources. The convergence of the Internet of Things (IoT) and blockchain technology to improve the system's performance, enhance its security, and provide a decentralized and tamper-proof environment presents an excellent opportunity to evolve the system further and form a state-of-the-art Water 4.0 ecosystem. The proposed Blockchain of Things (BCoT) water system is introduced as a pilot to explore its potential in delivering and managing Water 4.0 applications. An Ethereum platform formed the heart of the BCoT system, while a Raspberry Pi 4 acted as a node to the blockchain that collected data from various sensors and microcontrollers via MQTT programmed by Node-Red. LabVIEW software also provided supervisory control and data acquisition (SCADA). The BCoT system was tested, and its functionality was verified, showing good promise to take smart water systems to a new level of innovation that may resolve the many challenges faced by countries with limited water resources and address the challenges of the 21st-century "Water 4.0" ecosystem.

KEYWORDS

Blockchain of Things (BCoT), blockchain, Internet of Things (IoT), smart water systems, Water 4.0, LabVIEW

1 INTRODUCTION

The advent of the fourth industrial revolution at the turn of the century has enabled the world to resolve many technological issues. The convergence of emerging technologies such as artificial intelligence, machine learning, robotics, the Internet of Things (IoT), blockchain, and many others has ignited a new wave of innovations and signaled the start of this technical revolution. The emerging technologies considerably influence water management systems by resolving long-standing difficulties and challenges facing many countries worldwide with severe water shortages and limited resources [1]. The new technologies have

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transformed water management systems into smart schemes that provide authorities with real-time data, thus enhancing their operational efficiency and improving water quality and distribution. The new industrial revolution is characterized by its decentralized nature, which may provide water systems with intelligence and decision-making capabilities, thus enabling society to transform supply chains necessary for the efficient operation of smart water management ecosystems in the era of Water 4.0 [2]. However, it also highlights the need for active collaboration among stakeholders to effectively use these technologies and manage their associated risks to create a sustainable and resilient water future [3]. The Water 4.0 concept envisions a proper digital transformation of the water industry to cope with the advancement in Industry 4.0 by merging the physical and virtual worlds into a cyber-physical space, thus improving water management productivity and resource efficiency. The benefits of such an ecosystem may include economic advantages by reducing costs and speeding up the decision-making process [4]. It is also possible to introduce an integrated business model in the Water 4.0 ecosystem capable of resolving problems efficiently and employing data science analytical techniques to make intelligent and informed decisions almost instantly [5].

The convergence of IoT sensors and devices with blockchain platforms in a Blockchain of Things (BCoT) environment represents an opportunity to enhance security and improve the efficiency of controlling and monitoring water systems [6]. Other advantages of this integration include reducing operation and maintenance costs and providing a secure framework that protects data from cyberattacks while creating a decentralized and transparent design for managing and transferring data [7]. The decentralized nature of BCoT offers large networks of interconnected IoT devices the ability to coordinate actions effectively. Additionally, BCoT is considered a progressive evolution of IoT, where unique properties such as distribution, immutability, and decentralization are fundamental to its structural foundation [8]. In essence, BCoT emerges as a revolutionary change in IoT that promises the future of IoT, enabling improved implementation, data immutability, and distributed system deployment.

This paper focuses on developing a BCoT water system monitoring and control solution. An Ethereum platform is used to process the data generated by the system, Node-Red to communicate with and program a Raspberry Pi 4 broker using the MQTT protocol, and LabVIEW with an intuitive graphical interface that enables continuous real-time monitoring of water status, flow, and quality.

2 WATER 4.0 PARADIGM

Water 4.0 is a term first coined by Sedlak in 2014 [9] and has since emerged in the broader Industry 4.0 context. The Water 4.0 concept was pioneered by the German Water Partnership (GWP) to describe the digitization and automation of water management, transforming conventional water systems into 21st-century water infrastructure systems and management [4]. The Water 4.0 framework integrates water systems and real-time monitoring using sensors, computer models, IoT, and services. Critical features of Water 4.0 include machines, processes, storage systems, materials, smart factories, and IoT networks that connect them to achieve systematic water management. The main objectives of Water 4.0 can be achieved by improving the quality, services, and resource efficiency of water management and by developing new business models and innovative solutions. Examples of Water 4.0 applications in different contexts include real-time management of sewage networks, web monitoring of tunnel construction, and intelligent water consumption calculations [4].

Water 4.0 is a transformative approach that integrates technologies from the fourth industrial revolution to revolutionize water resource management. It focuses on four domains: water infrastructure systems and management, diversified sources of supply, redesigned supply chains, and real-time interoperable water data. Each of the four domains of Water 4.0 utilizes one or more emerging technologies to make profound changes that enhance the efficiency of the water system, its security, and sustainability. For example, IoT, robots, blockchain, AI, and augmented reality can help automate maintenance operations, secure data and transactions, optimize decision-making, and provide visualization aids for monitoring and training purposes. While technologies like AI and IoT could oversee resources, efficient logistics, and data-driven decision-making, drones may aid in exploring and transporting new resources. The synergies between these technologies and applications create a proactive, dynamic ecosystem for water sourcing, distribution, and consolidation of water management systems in the 21st century, thus representing a new paradigm shift and a holistic strategy to ensure the sustainability of one of humanity's most valuable global resources.

Blockchain may prove to be one of the most critical technologies for Water 4.0 as it addresses the security issues of smart water systems. Blockchain operates on a decentralized ledger system, ensuring that data is stored across a network of computers rather than on a single centralized server. This decentralized nature makes it inherently resistant to tampering and unauthorized access. In the context of water systems, blockchain provides a secure platform for recording and verifying transactions related to water usage, thereby ensuring the integrity of the data. Blockchain enhances transparency in water management. All transactions recorded on the blockchain are visible to authorized parties, fostering accountability and trust among stakeholders. This transparency is vital in regions facing water scarcity because it allows for a more equitable and accountable distribution of water resources. It also helps track and manage water rights, ensuring that water is allocated fairly and following the established regulations. Integrating IoT and blockchain technologies into intelligent water systems represents a paradigm shift in water management. The real-time monitoring and remote-control capabilities afforded by IoT enhance the efficiency of water distribution, whereas blockchain ensures the security and transparency of the data generated. Together, these technologies offer potent solutions to the challenges faced by resource-scarce regions, paving the way for more sustainable and resilient water systems.

3 IOT-BLOCKCHAIN CONVERGENCE IN THE WATER 4.0 CONTEXT

Blockchain technology is a decentralized ledger system that ensures the secure and tamper-proof recording of transactions. It operates through a chain of blocks containing transaction sets, timestamps, and unique cryptographic hashes, forming an immutable record. Blockchain technology significantly enhances security when applied to IoT on a private Ethereum network. The decentralized nature of blockchain ensures that data records are firm and protected against unauthorized alterations, which is crucial for IoT devices that are often vulnerable to cyberattacks. This level of security is achieved through cryptographic algorithms that authenticate data and restrict access to authorized users only, making it particularly valuable in sensitive areas such as healthcare.

Additionally, the privacy of network transactions is maintained with cryptographic techniques, ensuring that data exchanged between IoT devices remains confidential. Cost is a critical factor when considering the adoption of blockchain for IoT. While initial development and deployment on a private Ethereum blockchain may be costly, this investment can reduce operational costs. The peer-to-peer data transmission facilitated by blockchain eliminates the need for centralized control, which can lower overall costs. Furthermore, the transparency provided by blockchain allows for the efficient sharing of IoT data among stakeholders, streamlining processes such as regulatory compliance and supply chain management, which can also contribute to cost savings. Decentralized nodes verify transactions using consensus mechanisms like proof-of-work or proof-of-stake. Once added to the blockchain, a transaction becomes permanent, providing security for applications like digital currencies and supply chain management. Smart contracts, written directly into blockchain code, automate deal terms, enhancing transaction efficiency. Standard blockchain platforms like Ethereum offer secure and transparent ledgers and address issues that target IoT environments. Ethereum transactions on the Tangle involve creating and attaching transactions, which are pending until confirmed by other users. The feeless system and support for micro-transactions make Ethereum suitable for IoT applications. The Ethereum platform also enables developers to use Solidity, a modern scripting language, for efficient smart contract creation. The Ethereum decentralized security service has been proposed for public blockchains, using blockchain smart contracts for data management and incentivizing IoT users. The system incorporates tamper-proof cryptographic hash functions, demonstrating viability, safety, and scalability. The relationship between blockchain and IoT has been explored to enhance data analytics architecture in smart cities, improving data transmission and security performance. Integrating IoT and blockchain thus combines cutting-edge technologies to address security, privacy, and data reliability issues in IoT devices. Blockchain's distributed and secure nature enhances transparency, latency, and data storage capabilities. Eliminating central authorities and using consensus algorithms and smart contracts speed up communication and ensure data validity. Blockchain's hashing algorithms secure data through cryptography [10].

The choice between Ethereum, Hyperledger, and IOTA for blockchain applications depends on the specific project requirements. Ethereum, known for its smart contract support and decentralized applications (dApps), faces scalability challenges, but ongoing updates like Ethereum 2.0 aim to address these issues. Hyperledger, an open-source collaboration for cross-industry blockchain technologies, offers modularity and customization, making it suitable for private and permissioned enterprise solutions. With its Tangle technology, IOTA is designed for IoT transactions, boasting scalability and feeless transactions. The decision should consider public versus private networks, smart contract functionality, and industry requirements.

Ethereum stands out for its robust and active developer community, which facilitates resource availability and support. Its established position in the blockchain space and transition to Ethereum 2.0 with a proof-of-stake consensus mechanism highlights its commitment to overcoming scalability challenges. The popularity of the Ethereum platform is attributed to its track record of accomplishments, including smart contract capabilities, and its potential utilization in various fields, especially in public decentralized applications.

Several BCoT architectures offer numerous benefits and advantages, including task offloading and resource allocations in applications such as smart homes, factories, and hospitals. The architectures implement fog computing, distributed cloud models, and security protocols to ensure data integrity and transaction viability. The BCoT system includes sub-layers for data, consensus, incentive, backend, and front-end services, providing APIs, data collection, encryption, digital signatures, and hash functions [11]. A typical BCoT system for Water 4.0 application in controlling and monitoring a water distribution system is depicted in Figure 1. Besides the standard

3-layer IoT architecture consisting of the physical, network, and applications layers, a fourth blockchain layer with five sub-layers is incorporated into the architecture. The five sub-layers of the blockchain are data, consensus, incentive, backend service, and finally, front-end service. The BCoT provides services such as application programming interfaces (APIs), data collection from the IoT physical layer, data encryption, digital signatures using a variety of algorithms, and hash functions with the cryptographic hash used in the Ethereum platform. These blockchain sub-layers utilize several tools, such as Firefly Wallet, ReactJS, HTML, and CSS for the user interface, Git, Gitlab, Docker, Docker-compose, and Ansible to install terminal command lines and the docker-compose.yml file, and the infrastructure-as-a-code (IaaC) tool. Ansible was employed to deploy and configure large-scale infrastructures automatically. A smart contract is also designed in Solidity code to store the large amount of data IoT devices generate in the physical layer. The application layer may contain several tools and devices to monitor and control the water distribution system and allow continuous observation of the status of various parts and functions of the ecosystem. An HTML, JavaScript, and CSS front-end application was made to present sensor data to create the user interface (UI) for the proposed system. With HTML providing the structure, CSS handling styling and layout, and JavaScript adding interactivity and responsiveness to user input, these widely used web development technologies enabled the creation of aesthetically pleasing and interactive web pages. A middle layer was created using the JavaScript library Web3 to facilitate communication between the BCoT front-end and back-end components. The front-end application can communicate with smart contracts and other elements using the APIs provided by this library. As a result, the user interface is created by a front-end application made of HTML, JavaScript, and CSS, with the Web3 library acting as a communication link between the front-end and back-end parts. Developing a user-friendly, interactive application that can provide decentralized services and functionality is made possible by integrating HTML, JavaScript, CSS, and Web3 into the BCoT development process. In addition, the LabVIEW human-machine interface (HMI) of the BCoT system may demonstrate the monitoring process of different appliances in the water distribution system.

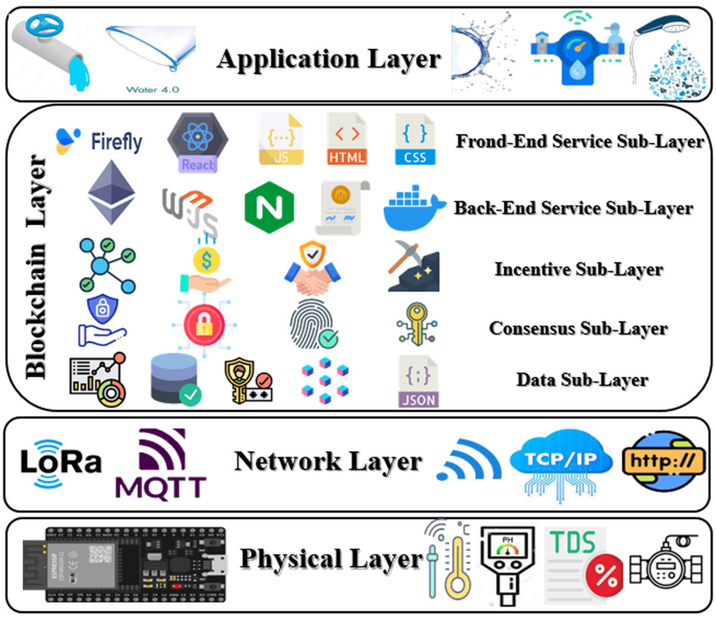


Fig. 1. BCoT 4-layer for the architecture of Water 4 applications

4 PROPOSED BLOCKCHAIN OF THINGS WATER 4.0 ECOSYSTEM

A smart water control and monitoring distribution system was designed, as shown in Figure 2. A ten-gallon main tank feeds three 20-liter auxiliary tanks distributed in a network that represents reservoirs to emulate a natural system designed to spread water to different parts of a city at regular weekly intervals. This is a typical situation in many regions known for their water scarcity. The proposed system can monitor how water is distributed among different neighborhoods of the city or suburb, a process that is often slow and inefficient and suffers from leaks, contamination, and vandalism. Thus, the system serves as a pilot for water distribution to the various city districts to preserve water and save time, speeding up the distribution process. Safety tips were incorporated into the system to ensure smooth water flow. Sensors regularly monitor and analyze water movement to ensure adequate water flow control, including one at the inlet and three above the destination tanks. Another sensor provides a feedback mechanism, detecting surplus water for timely adjustments. The system prioritizes minimizing water loss and optimal resource distribution, employing solenoid valves regulated by relays. Orchestrated by a Raspberry Pi 4 microcomputer programmed by Python, many ESP32 microcontrollers and a Raspberry Pi Pico W were implemented in the design and connected to a set of appropriate sensors. The main ESP32 microcontroller controlled three solenoid valves and monitored five flow meters mounted on the main board of the distribution system. Each auxiliary water tank was observed by one ESP32 microcontroller connected to an ultrasonic sensor to determine the height of the water as it was poured in, in addition to a TDS sensor to measure the quality of the total dissolved solids. The Raspberry Pi Pico W monitored ambient conditions such as temperature, humidity, and pressure through the BME280 sensor. The Raspberry Pi 4 was configured and linked to the network of microcontrollers via Wi-Fi.

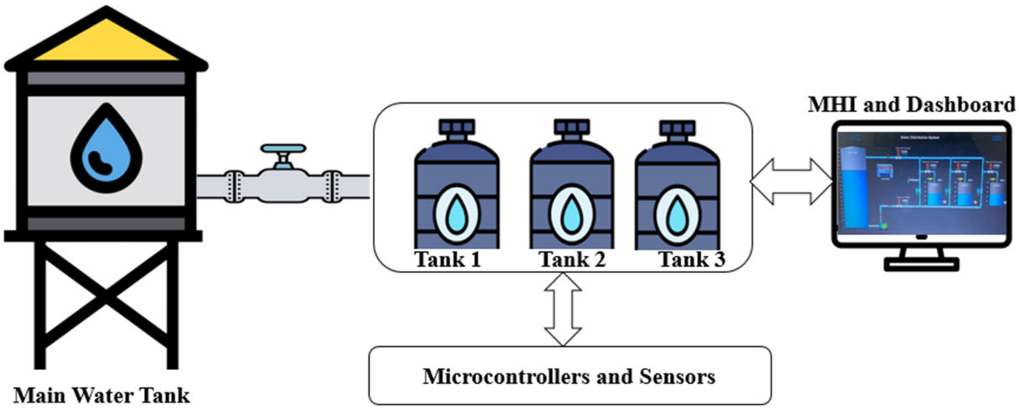


Fig. 2. Water 4.0 control and monitoring distribution system

A Node-RED visual programming development tool was utilized to connect hardware devices, APIs, and online services and provide a web browser-based streaming editor that can be used to generate JavaScript functions. In addition, the water distribution system integrated various components for efficient water management, featuring an adjustable water pump controlled by a potentiometer to limit and control the amount of water flow before entering circulation. The flow sensors periodically measure and publish flow rates to Node-RED using the MQTT protocol. The combination and integration of Datagram Transport Layer Security (DTLS) and MQTT may form a robust alliance for secure and efficient communication within smart water management systems. DTLS, designed for datagram-based communication, excels in IoT scenarios where devices have limited resources and rely on UDP's minimal overhead. MQTT, a lightweight publish-subscribe protocol, is widely embraced in the IoT for its real-time capabilities and streamlined data exchange. Integrating DTLS and MQTT establishes a secure channel for data flow between resource-constrained devices and the blockchain, protecting against unauthorized access and tampering. Additionally, ensuring secure communication with the MQTT broker enhances the overall security and reliability of the system. While considerations such as performance in congested networks and implementation complexity are pertinent, the advantages of DTLS/MQTT make it a compelling choice for constructing secure and efficient smart water management systems [12].

A combination of encryption libraries, mainly wolfSSL on the microcontrollers and uTLS on the Raspberry Pi, addressed the security issues between the physical and network layers. This combination offers an adequate solution for securing the data transfer between these devices. Both wolfSSL and uTLS have been extensively tested to deliver reliable and secure TLS connections.

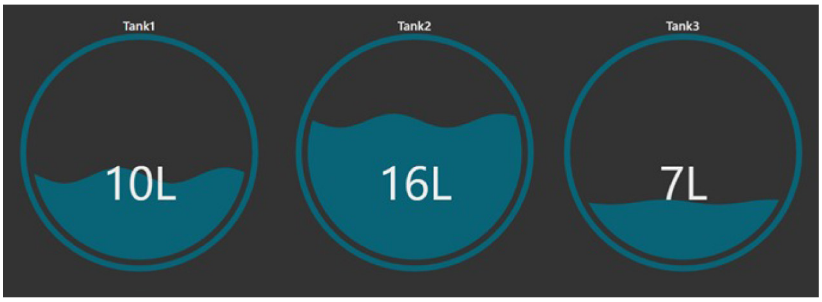
The Node-Red dashboard was configured to display the various data sets generated by the system. The dashboard can be set up to capture and visualize diverse parameters in different formats, such as the rate of water flow, depth, TDS values, and ambient conditions such as temperature, humidity, and pressure. LabVIEW software also offered an engaging real-time SCADA view of the water flow. The interface visually represents the system's various components and current state, including valves and other essential elements for ensuring efficient and proper distribution.

The Ethereum platform was integrated into the system to provide a decentralized and secure environment to ensure transparency and immutability of the system data [13]. The Truffle framework was used for implementing smart contracts, and the Ganache workspace was essential for deploying, compiling, and testing smart contracts. An Ethereum public address was used. HTML, JavaScript, and Web3.js were employed to create the front-end application, enabling the Ethereum smart contracts to communicate with each other from the back end to the front-end users. A JavaScript code (app.js) is also used as part of the web application to integrate the Ethereum smart contracts for managing sensor data. The application utilizes the Bootstrap framework for styling and layout. It incorporates the MetaMask extension as a fallback to connect to the Ethereum blockchain through the Web3.js library. An HTML front-end application was also included in the design to provide an interface for users.

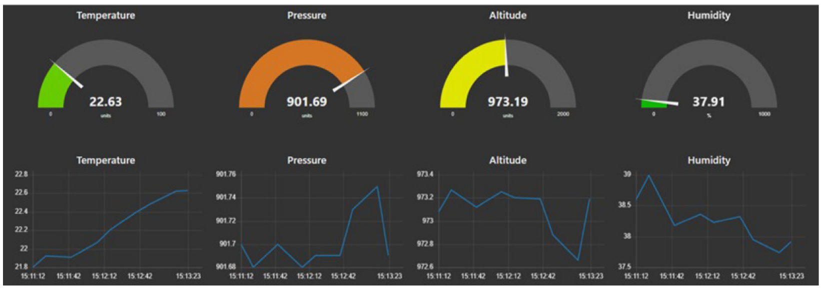
The sandboxing technique was utilized to ensure the security of smart contracts by isolating individual smart contracts from the rest of the network. Virtual machines (VMs) and Docker containers are the two primary approaches to implementing sandboxing for smart contracts. VMs create a separate, isolated VM for each smart contract, providing a robust layer of security by creating a solid barrier between contracts. On the other hand, Docker containers offer a lightweight and isolated environment for each smart contract, preventing contracts from interfering with or modifying each other's files or processes. We have used both techniques but eventually settled for Docker containers since they are more suitable for scenarios where computational power is limited, hence offering a balance between security and resource efficiency. The Ethereum virtual machine (EVM) operates in a sandboxed environment where each smart contract is executed in isolation. Additionally, the EVM incorporates runtime verification mechanisms that detect and prevent issues such as gas exhaustion, stack overflows, and invalid opcodes. This combination of sandboxing and runtime verification within the EVM significantly enhances the security of smart contracts on the Ethereum network.

5 RESULTS AND DISCUSSION

The smart water control and monitoring distribution system prototype was tested and verified. Figure 3 displays the various generated data, providing a snapshot of the Node-Red dashboard showing the water level in the three tanks calibrated and measured in liters, along with ambient conditions such as temperature, humidity, and pressure.



a) Water levels in tanks



b) Ambient conditions

Fig. 3. Snapshots of the Node-Red dashboard showing: a) water level in the three tanks, b) ambient conditions

The LabVIEW front panel of the HMI system was also operated as illustrated in Figure 4, demonstrating the monitoring process of the primary and auxiliary tanks, pipe layout and connections, valves, flow meters, and associated values in units of liter per second. It represents a comprehensive example of the system's outcomes, chosen to showcase the feasibility of the proposed BCoT and its successful implementation.

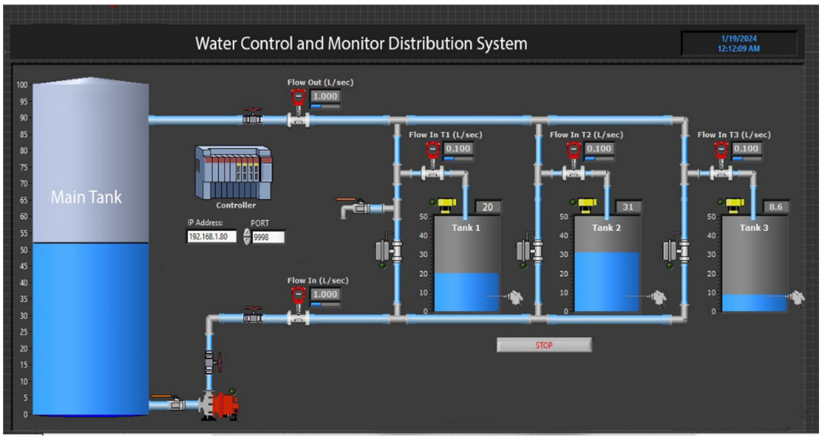


Fig. 4. LabVIEW HMI panel of the water distribution and monitoring system

The big data was subsequently stored on the Ethereum platform for future retrieval and manipulation. Solidity smart contracts were developed to store data and provide a backend for the proposed system. The front-end application was created using HTML, JavaScript, and CSS to establish a user interface (UI) for the proposed system. The Web3 JavaScript library served as an intermediary layer to facilitate communication between the front and back ends of the proposed Dapp. This transaction occurs whenever data generated by IoT sensors is stored and displayed to an end user. The Ganache workspace displays the fee, block number, and timestamp used for each transaction, as illustrated in Figure 5.

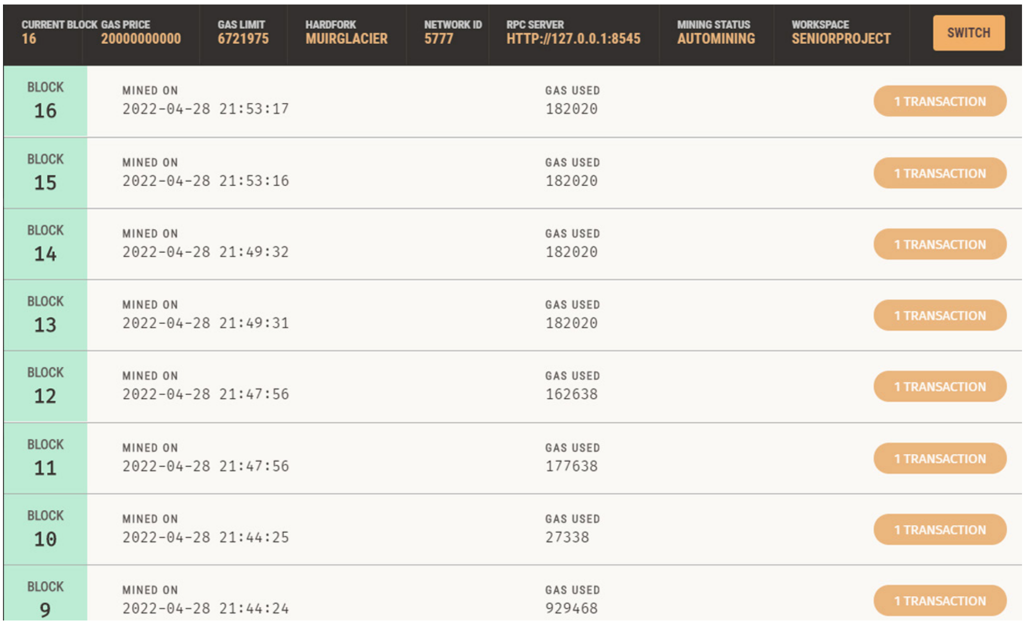


Fig. 5. The blocks of the data transactions mined as displayed on Ganache

The system was configured to receive the data from the text file and display it on the web page, as illustrated in Figure 6, showing the results of flow rates in all three tanks, TDS, and ambient conditions.

Temperature	Humidity	Pressure	Altitude	UV	FlowRate1	FlowRate2	FlowRate3	FlowRate4	FlowRate5	TDS	Distance	Distance1	Distance2
23.5	45	1015	150	3.2	10	15	12	14	13	200	5	10	7
24.0	46	1016	152	3.3	11	16	13	15	14	205	6	11	8
23.8	47	1014	151	3.1	9	14	11	13	12	210	4	9	6
23.7	48	1013	153	3.4	12	17	14	16	15	215	7	12	9
24.1	44	1017	149	3.0	13	18	15	17	16	220	8	13	10
23.4	49	1018	148	2.9	14	19	16	18	17	225	9	14	11
24.2	43	1019	147	2.8	15	20	17	19	18	230	10	15	12
23.3	50	1020	146	2.7	16	21	18	20	19	235	11	16	13
24.3	42	1021	145	2.6	17	22	19	21	20	240	12	17	14
23.2	51	1022	144	2.5	18	23	20	22	21	245	13	18	15

Fig. 6. Snapshot of real-time sensor data displayed from blockchain to the end-user

In the proposed BCoT system, water can be tracked from its source to its destination, ensuring accountability and preventing fraud or unauthorized access. The system can quickly alert operators by detecting leaks or other irregularities, preventing waste, and reducing downtime. These sensors act as the smart water distribution system's surveillance tools, facilitating proactive maintenance and swift response to anomalies.

When the IoT devices are indirectly connected and the Raspberry Pi 4 may be considered a single point of failure, the MQTT protocol may intervene as a broker to address such challenges. In this scenario, the MQTT broker could act as an intermediary entity that enables MQTT clients. The IoT devices could then communicate with one another in a scalable and fault-tolerant fashion. Consequently, the MQTT broker receives messages published by the clients and directs them to appropriate subscribers to ensure accurate and efficient delivery of messages without direct connections between these IoT devices. In addition, several MQTT brokers could interact in a scalable architecture that can tolerate faults and mitigate single points of failure. The brokers can also be utilized in multiple forms and infrastructures, ranging from services managed in the cloud to on-premise hosted solutions. In such cases, considerable flexibility is added to the IoT system. Accordingly, IoT devices may effectively send data to multiple brokers, enabling efficient and reliable communication within IoT systems. Such a solution aids IoT systems in overcoming the limitations of direct device interaction and single points of failure.

In implementing the proposed BCoT water system, utilizing off-chain storage such as the InterPlanetary File System (IPFS) complements the architecture's robustness and scalability. Alongside the Ethereum platform as the system's core and the Raspberry Pi 4 as a blockchain node, IPFS is an integral component for storing and retrieving data generated by various sensors and microcontrollers. By employing IPFS, the system ensures decentralized and tamper-proof data storage, aligning with the overarching goal of enhancing security and reliability within the Water 4.0 ecosystem.

Through the integration of IPFS, the BCoT system facilitates efficient data management while reducing the burden on the blockchain network. Data stored on IPFS remains accessible to authorized parties, ensuring transparency and integrity in water monitoring and control operations. This implementation underscores the system's commitment to innovation and addresses challenges faced by regions with limited water resources. By leveraging IPFS alongside other technologies, the BCoT water system demonstrates its readiness to embrace cutting-edge solutions and contribute to advancing smart water systems in the 21st century.

Furthermore, implementing the BCoT system involves initial setup costs that encompass the development of blockchain infrastructure, integration of IoT devices, deployment of smart contracts, and network configuration. While these upfront expenses may exceed those of non-blockchain solutions, BCoT offers heightened security and transparency benefits. However, ongoing operational costs arise from managing the blockchain network, conducting transactions, and ensuring data integrity. Additionally, as the BCoT system scales up to accommodate more nodes, transactions, and data, additional expenses must be considered for scaling the blockchain network and upgrading infrastructure. Moreover, implementing BCoT may require specialized knowledge and expertise in blockchain technology, smart contracts, and IoT integration. These expertise-related costs, which may involve staff training or hiring skilled professionals, contribute to the overall expense of implementing BCoT. Therefore, while BCoT presents advantages in terms of security and efficiency, it is essential to carefully evaluate the cumulative costs, including initial setup, ongoing operations, scalability, and training and expertise, compared with traditional non-blockchain solutions.

In addition, integrating BCoT with existing water management infrastructure and IoT devices may be complex and require specialized knowledge and expertise. Ensuring seamless integration without disrupting existing systems could be a challenge. Compliance with regulations and data privacy laws in the water sector is essential. Implementing BCoT may raise concerns about data ownership, privacy, and compliance with industry standards and regulations.

6 CONCLUSIONS

A smart water system was introduced to monitor and control water flow, leakage, and quality based on BCoT configuration, forming a Water 4.0 ecosystem. Implementing BCoT in IoT systems offers a novel approach for collecting, storing, manipulating, and retrieving complex data in smart applications. The system is connected to a user application linked to the Ethereum blockchain platform through a Raspberry Pi 4, serving as a gateway and monitoring the smart panel's status using LabVIEW software. Work processes and associated intelligent system parameters are continuously monitored to address unexpected events and emergencies through machine or human actions. The successful prototype showcased secure and distributed data retrieval and processing in IoT applications. A pilot study of BCoT on the Ethereum blockchain platform demonstrated the feasibility of the proposed concept. Integrating blockchain technology into IoT ensures immutability, privacy, transparency, decentralization, authentication, integrity, availability, and data security.

The BCoT could be enhanced by adding more nodes to the blockchain to simulate real-world situations. Several brokers could serve as nodes on the Ethereum platform at various locations. Long-range radio communication techniques (LoRa) could transmit water data from remote areas. Additionally, cutting-edge technologies such as AI, drones, and robotics could be integrated into the system to boost its effectiveness and performance by enhancing its predictive and decision-making abilities, creating a dynamic Water 4.0 ecosystem.

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