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A Framework of Blockchain Technology in Intelligent Water Management

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At present, water resource information management in China is mainly a centralized model, and there exist some problems such as high cost, low efficiency, and data storage insecurity. Blockchain technology provides a good solution which can create an efficient trust mechanism among the links in the process of water resource utilization. It guarantees the security of the data, avoiding the sudden collapse of the central institutions caused by some normal operations of the entire system. Based on a decentralization blockchain, we propose a decentralized water resource information management system for the whole process of "supply-use-consumption-discharge," which improves the traditional water data storage. Specifically, the monitoring and business data are encrypted by the blockchain and are transmitted using a peer-to-peer network. Moreover, the centralized management mode is changed and part of the management work is dispersed to each node. Thus, decisions and measures can be made and implemented quickly after discovering problems to improve the efficiency of information transmission and management. In addition, two typical blockchain-based application scenarios for water resource management are designed. A blockchain-based approach makes issuing and monitoring water abstraction permits more convenient and obtaining license information more secure and verifiable. A reliable mechanism for tracing water quality ensures the accuracy and reliability of water quality information, enables the detection of locations with inadequate water quality, and clarifies people's responsibility, thus guaranteeing the water safety of the residents.

Keywords: water management, blockchain, decentralization, traceability, information security

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1 INTRODUCTION

Information technologies are developing rapidly. Blockchain is a novel technology that has resulted in new technological breakthroughs. It has attracted wide attention in the industry domestically and internationally since 2013. Blockchain technology is being used in many fields, including finance (Zhu and Wang, 2019; Wang M. et al., 2020; Wang, 2021), intelligent manufacturing (Kim et al., 2020; Zhang et al., 2020; Xu et al., 2021), digital asset trading (Hasan and Salah, 2018), supply chain management (Wang Y. et al., 2020; Della Valle and Oliver, 2021), and other fields. Since the value of the blockchain has been widely recognized, an increasing number of industries are exploring blockchain solutions. However, there are few practical applications of blockchain technology in water resource development and utilization. Thus, it is essential to investigate how the emerging blockchain technology can help optimize present water management systems.

Traditional water management systems in many Chinese cities suffer from some problems. The urban water supply plants and water sources are decentralized, making it challenging to share and deliver information efficiently. The data storage of traditional centralized water information systems is not safe enough. Data can be falsified or distorted, and information access takes a long time and is affected by network congestion. Water utilization is a complex process involving numerous links. Thus, it is difficult to monitor this process accurately, resulting in high data verification costs. Many government departments are involved in water resource management, and a lack of trust among the departments leads to the formation of information islands, adversely affecting business coordination and reducing work efficiency (Sundaresan et al., 2021). Blockchain technology can solve these problems; specifically, it improves data reliability and transmission efficiency because of its reliable network that integrates processes and data (Li et al., 2021). First, the distributed storage network of the blockchain allows each link to query water data rapidly, ensuring a dynamic response and scientific decision-making in case of accidents, preventing one-sided decisions by participants based on their data. Second, encryption technology ensures data security and makes it difficult to tamper with the data. In addition, blockchain technology can also build trust and facilitate secure information sharing at a low cost. Finally, the innovative decentralized information management model improves the work efficiency in water resource management.

Some studies have tried to illustrate the application value of blockchain in water-related fields. Initially, blockchain technology was primarily applied to water trading systems to prevent time delays and reduce transaction costs. For example, Poberezhna (2018) proposed using blockchain technology for water credits and water trade and provided a comprehensive solution to the sustainable development of water resources. Pee et al. (2018) developed a lightweight peer-to-peer (P2P) water trading system using private blockchain smart contracts. The case of water trading in California demonstrates that the blockchain has a good application prospect to build stronger market mechanisms for resource allocation (Chohan, 2019).

Water markets in many areas remain underdeveloped, making it difficult for the application of blockchain technology in water trading systems to move forward in practice. Therefore, it is necessary to investigate the role of blockchain technology in other aspects of water management. Blockchain technology has been used for managing water supply systems (Grigoras et al., 2018; Pahontu et al., 2020). For instance, Mahmoud et al. (2019) discussed the feasibility of using blockchain technology for a water allocation system and proposed a smart meter data aggregation mechanism for water supply systems. Maouriyan and Krishna (2019) presented a blockchain-based Internet of Things (IoT) system for water supply chain management and traceability. This system records the production and consumption data in the water supply chain in real time. Dogo et al. (2019) believed that the integration of blockchain and IoT technologies for urban water supply management has social and economic benefits. As for agricultural water supply, some studies have proposed blockchain-based methods for real-time management of agricultural irrigation systems (Bordel et al., 2019; Miloudi et al., 2019) and pollutant identification in irrigation water (Lin et al., 2020). The blockchain has also attracted attention for water quality monitoring. It has been demonstrated that the adoption of blockchain technology for collecting water data could increase the public's awareness of water quality and achieve traceability of water quality (Pérez Ortiz, 2018; Zecchini et al., 2019). Some studies proposed a blockchain-based industrial wastewater management framework (Hakak et al., 2020) and a wastewater recycling system managed with blockchain technology (Iyer et al., 2019) based on the amount of reused wastewater and wastewater quality indicators.

Most studies have focused on the individual aspects of water resource management, such as water rights trading and water quality monitoring. However, these studies were not comprehensive and systematic and did not combine blockchain technology with water resource management during the entire life cycle of water resources. Therefore, how to combine blockchain and water management effectively needs to be investigated in-depth. Information interaction and business collaboration between each link and object should also be considered. Thus, we construct a decentralized water resource information management system based on a decentralized blockchain network for managing water supply, use, consumption, and discharge. This system provides a timely solution to water resource problems in each link, improving the management efficiency. In addition, we design two application scenarios for managing water abstraction permits and monitoring water quality.

The remainder of this study is organized as follows: **Section 2** describes the conception and component technology of blockchain. **Section 3** presents the architecture and functions of a water resource management system and two typical application scenarios, which are based on blockchain technology. **Section 4** provides the conclusions of this study.

2 BLOCKCHAIN THEORY

2.1 Blockchain Concept

Blockchain technology was first proposed in the article "Bitcoin: A P2P Electronic Cash System" published by Nakamoto (2008). As shown in **Figure 1**, the blockchain is a decentralized, distributed database. Its data structure consists of a combination of data blocks linked in a chain according to the time sequence. Cryptography ensures secure data transmission. The blockchain is a distributed shared general ledger system used for consistent data storage that is tamper-proof. The block consists of a block header and block body. The block header records the metadata of the current block, including the hash of the previous block, timestamp, and Merkle root hash, whereas the block body records the data information.

Three types of blockchains exist, including, a public chain, alliance chain, and private chain. Any individual or group can access the public chain and record transactions, which are validated by the blockchain, and any group or individual can

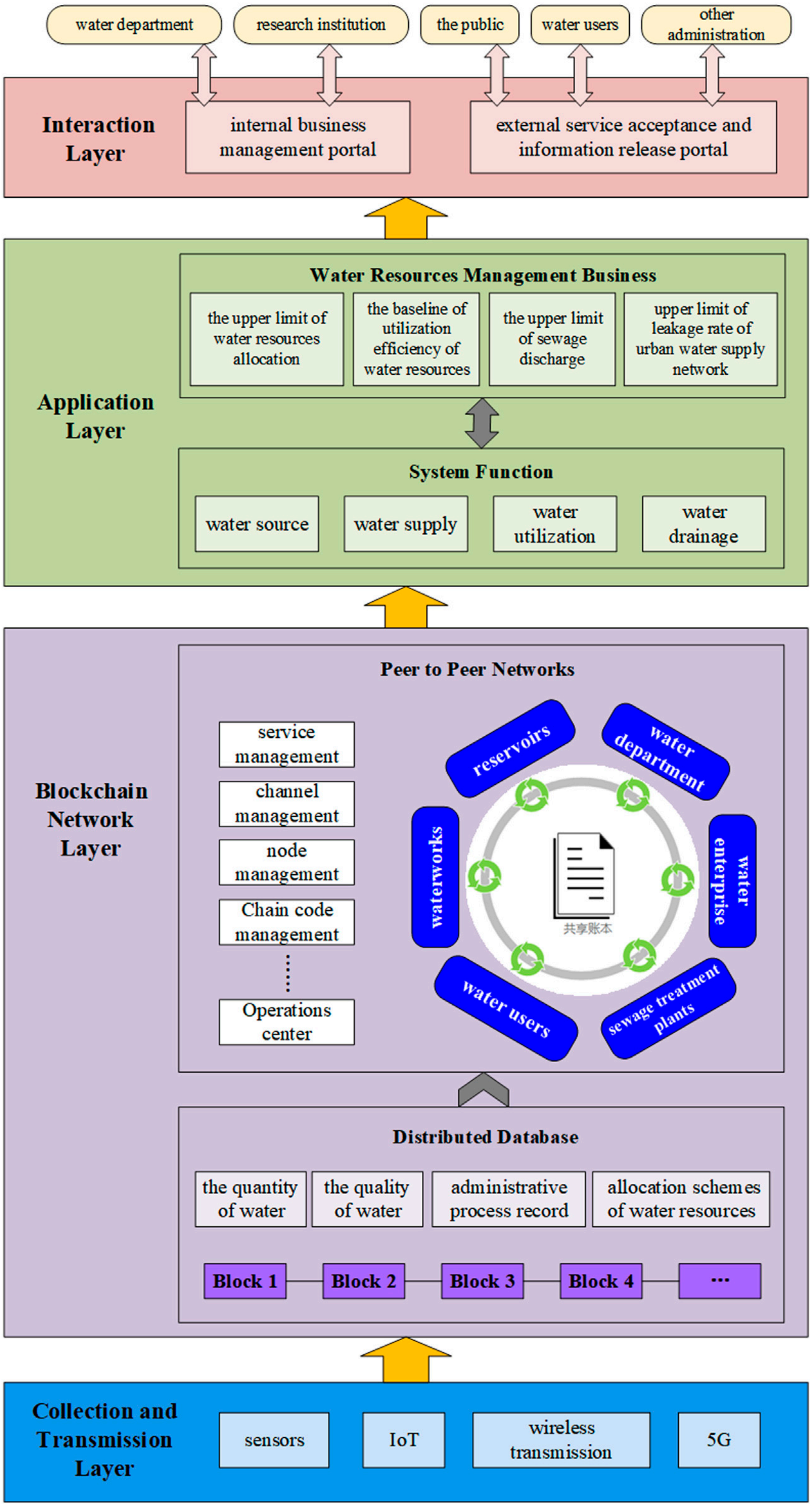

FIGURE 1 | The blockchain framework for water resource management system.

participate in the consensus process. The alliance chain is managed by multiple alliance institutions. In the alliance chain, pre-selected nodes are designated as bookholders and the generation of each block is jointly decided by all pre-selected nodes. Other nodes can only access the blockchain to handle transactions but do not participate in the consensus process. A private chain only uses blockchain technology for billing operations but is not publicly accessible. It is highly restricted in terms of reading, and writes permissions and protects personal privacy. It is generally established by enterprises, governments, and other similar institutions. Alliance chains combine the full openness of a public chain with the high concentration of a private chain. An alliance chain is suitable for water resource information management because of the need for information sharing among water plants, water users, and other nodes and for the unified management of water administration departments to prevent malicious nodes from interfering with data records.

The blockchain has many advantages over traditional distributed databases. In the latter, only one central server node maintains the data and the other nodes store only backups of the data. Each storage node can tamper with the data since there are no accurate records, unlike in the blockchain with a tamper-proof ledger. All nodes of a blockchain participate in data maintenance. The tampering or deletion of data on a single node does not affect the data stored on the blockchain. Thus, the data are stored safely, and each node can trust each other's data. Blockchain technology has the following four characteristics.

2.1.1 Decentralization

A P2P network consists of numerous nodes, and there is no centralized device or management organization. The maintenance of the network depends on all nodes with maintenance functions in the network. All nodes have equal status. Blockchain technology uses a consensus algorithm to share data with the node server timely. When some nodes are attacked or the data on the node are tampered with or maliciously deleted, the normal operation of the entire system is not affected.

2.1.2 No Data Falsification

The distributed storage of the blockchain ensures the decentralization of the data and prevents intervention. In the network, 51% of the nodes must be controlled to tamper with the data in the blockchain. If an attacker wants to hijack the data, tamper with them, and send them, it is extremely difficult to crack the private key in the encrypted transmission. All information in the remaining chain must be modified to modify the information of a node. The data are encrypted with the hash algorithm, and the security and data integrity are guaranteed because the hash algorithm is irreversible.

2.1.3 Traceability

The blockchain uses time-stamped blocks to store data, and each transaction on the block is cryptographically linked to two adjacent blocks so that any transaction is traceable. Given the characteristics of the blockchain, each transaction can be traced and its time is recorded. The completed transaction information is fully recorded and searchable, and any node can query any block information in the blockchain, which greatly improves the transparency of the interaction. All transaction records can be checked at each node, and the data are open and transparent and cannot be tampered with. These characteristics ensure trust and result in reliable cooperation.

2.1.4 Programmability

The blockchain supports the development of on-chain scripting for application-layer services. Users can create smart contracts to ensure automated transactions and operations. They can establish contracts efficiently and with high flexibility. Smart contracts existed before the blockchain but were not widely used, except between third-party intermediaries and users. Blockchain technology supports the wide application of smart contracts, which are equivalent to embedding an optimization algorithm recognized by both parties into the blockchain. Data information of the buyer and the seller is processed to complete the transaction online.

2.2 Component Technologies

Blockchain is not a single innovative technology but an integration of multiple technologies. It utilizes blocks and encryption to store data, P2P networks, and a consensus mechanism to verify the data and communication of distributed nodes. It uses on-chain scripts to achieve complex business functions, resulting in a new method of data recording, storage, and expression.

The critical technologies of the blockchain are cryptography, distributed storage, consensus mechanism, and smart contracts. The hash function, asymmetric encryption, digital signature, and digital certificate ensure that the information source in water resource management can be trusted during transmissions, and the transaction information is safe and reliable. The distributed system ensures that the transaction data are dispersed in the decentralized system, the data are stored securely and consistently, and data tampering is difficult.

2.2.1 Cryptography

The hash algorithm compresses the data into smaller units, which are called hash values. Generally, different data do not have the same hash value after the operation. Each transaction in the block is hashed to a single hash value, and the bottom-up transactions are hashed to a single hash value that represents the Merkle root of the block. Because hash values are unique, changing a transaction will change the root value of the Merkle tree significantly. Thus, it is easy to verify that the data blocks have changed and the system rejects the tampered blocks. Each pair of keys is composed of a public key and a private key. The private key is easier to calculate than the public key, and the public key is almost impossible to calculate compared to the private key. In a blockchain, the public key is visible to all nodes in the network, whereas the private key is kept only by the account holder. The information encrypted by the private key of the blockchain node can only be unlocked by the public key, and the information encrypted by the public key can only be decrypted by the private key. Therefore, the public key is used for encryption, and the private key is used for decryption. As a result, the blockchain has higher security than a system using symmetric encryption.

2.2.2 Distributed Storage

A P2P network is a distributed network architecture in which nodes act as clients and servers. A client/server (C/S) architecture is a centralized architecture, whereas a P2P architecture is an internet system without a central server that relies on user groups to exchange information. A P2P network has the advantages of attack resistance and high fault tolerance because there is no centralized server. In addition, all nodes have equal status, and services are distributed on all nodes. Therefore, attacks on some nodes or networks have negligible impacts on the entire system. P2P transmission in the blockchain allows transfers and transactions directly between users without the need for confirmation or authorization from intermediaries. This architecture has a low cost and high transaction efficiency and ensures data security.

2.2.3 Consensus Mechanism

The purpose of the consensus mechanism is to ensure that an agreement is reached on who has the right to write data and synchronize the data. Nodes in the distributed network can create copies of the data. The nodes selected by the consensus mechanism assemble the data into blocks and broadcast the block data to the blockchain network. All nodes detect these data and decide whether they should be issued by legitimate authorized nodes. If a consensus is reached on the block data and other formatting requirements, the data are appended to the blockchain ledger maintained by each node, and the data are synchronized. By repeating these two processes, the blockchain ledger is updated and synchronized reliably, preventing data chaos and falsification. Common consensus mechanisms in blockchains include proof of work (POW) and proof of stake (POS).

2.2.4 Smart Contracts

A smart contract is a piece of computer code that accepts a transaction request from a user and executes a program to invoke it. Smart contracts allow both parties to trade safely in the absence of a third-party intermediary. Before the advent of the blockchain, smart contracts could not be executed in a credible environment. The blockchain ensures that data related to smart contracts are difficult to tamper with and can be traced.

3 BLOCKCHAIN FRAMEWORK FOR INTELLIGENT WATER MANAGEMENT

3.1 Framework for a Water Resource Management System

As shown in **Figure 1**, the blockchain framework for water resource management can be divided into four parts: an interaction layer, application layer, blockchain network layer, and data collection and transmission layer. Blockchain technology is used in the blockchain network layer, and the application layer, for distributed data storage and data sharing between nodes to prevent data tampering. The smart contract code is used to identify problems automatically and provide rewards or punishments to the persons.

3.1.1 Information Collection Layer

Relying on the monitoring system, this layer provides a variety of services for collecting and transmitting real-time water resource information and integrates them with existing databases.

3.1.2 Blockchain Network Layer

Each node (e.g., water sources, waterworks, water users, and sewage treatment plants) stores data on water resource information and evaluates the results on the block. A blockchain is created in series using time stamps, and a P2P network is established between the nodes. In addition, business operations related to water resource management can also be recorded in the block. Planning schemes and index standards are stored in the block as basic data. The blockchain network layer performs data uploads and exchanges between nodes, data queries, and smart contract rule development. The blockchain operation and maintenance are performed in collaboration with internet providers to implement the blockchain service functions and facilitate the management of the water sector.

3.1.3 Application Layer

According to the needs for information service, business management, responsibility, traceability, scheduling, configuration, emergency management, and other functions, four application modules are established in this layer to manage water sources, water supply, water utilization, and water discharge. This approach supports the three red line management systems (the upper limit of water resource allocation, the baseline of the utilization efficiency of water resources, and the upper limit of sewage discharge).

3.1.4 Interactive Layer

This layer provides a unified integration platform and information portal after the system has been implemented.

3.2 Function Modules of the Water Management Application Platform

The blockchain framework for water resource management has four functional modules: water source management, water supply management, water utilization management, and water discharge management. Each management unit can select the appropriate function module according to its permission settings. **Figure 2** shows that blockchain technology is used for the following aspects. Because of the distributed data storage, each node can share the global data, preventing one-sided decisions. The consensus mechanism ensures the consistency of information. The hash algorithm ensures that information is difficult to tamper with, and asymmetric encryption provides high security. Therefore, trust is created between the nodes and the departments, reducing the cost of supervision. Because of the flexible smart contract script, the water management function of each node is automatic, providing high system efficiency.

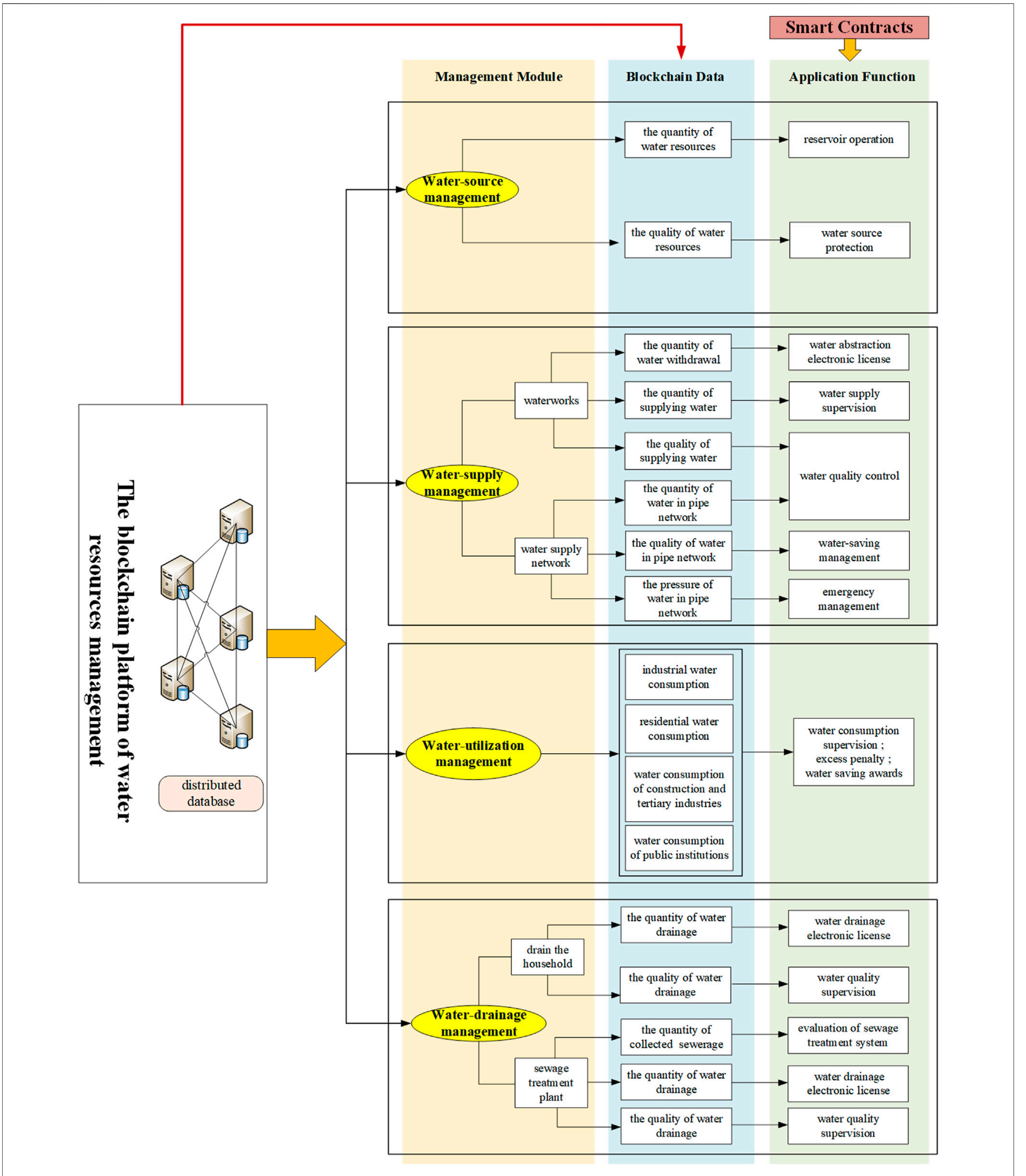

FIGURE 2 | Function modules of the water management application platform based on blockchain.

Each node can access the blockchain network and create an account after verification. The management module of the corresponding link is enabled after the staff logs into the account. Each function module is formulated in the form of code by the smart contract to enable data queries, information retrieval, analysis, and scientific decision-making. The application functions of the four modules are as follows.

3.2.1 Water Source Management Module

The objective of this module is to ensure adequate quantity and quality of water sources. Drinking water is obtained from reservoirs; therefore, the water quantity in reservoirs affects the water supply in cities. Reservoir water–level data are transmitted to the block of the water source node in real-time by the sensors, and each data point is timestamped. An embedded data analysis program compares the water level information of the reservoirs with control indices, such as the drought limit water level, and the results are transmitted to the blockchain for storage. The water source management module also has a decision-making function. Optimization algorithms, knowledge reasoning, and other technologies are used to optimize the water supply plan according to the real-time water level information and evaluation results (Mahmoud et al., 2021).

In addition, the water quality data of the water sources obtained from sensors are transmitted to the block of the node for storage. After comparing the measured data with the water quality objectives using smart contracts, the evaluation results are transmitted to the blockchain. This module also has a decision-making function. The water quality is monitored and the results are transmitted in real-time to detect water pollution incidents in time. The linking of the real-time monitoring data of water quantity and water quality of reservoirs ensures that water supply plans can be adjusted scientifically and quickly.

3.2.2 Water Supply Management Module

The water supply management module includes two parts: waterworks management and water pipe management. The first module monitors the water quantity and water quality, and the real-time data with timestamps are transmitted to the nodes of the waterworks. Smart contracts are used to compare the monitoring data of water withdrawal with the amount in the water abstraction permits to determine whether the permit is exceeded. The results are transmitted to the blockchain for storage. The strict supervision of the water withdrawal amounts ensures water is saved. In addition, the water supply monitoring data are compared with the quantity required in the water supply scheme. Similarly, the water quality monitoring data are compared with the standard values in the “Standard for Drinking Water Quality,” and the results are transmitted to the blockchain for storage. In addition, water quantity and quality of the source water will also affect the water supply dispatching scheme. Hence, in addition to the water supply and water quality of waterworks, the quantity and quality data of the source water are the basic data required by the water supply dispatching function.

For the management of the pipe network, real-time water quality information is transmitted to the blockchain of the waterworks nodes. Then the water quality monitoring data of the pipe network will be compared with the standard values in the “Standard for Drinking Water Quality” to judge whether the water quality meets the requirements. In addition, the water supply management module also monitors pipeline leakage. The leakage rate of the pipe network is compared with the standard values, and the evaluation results are transmitted to the blockchain for storage. A hydraulic model is established based on the real-time water pressure in the pipeline to locate the leakage points in the pipe network and diagnose faults in the water supply network.

Similarly, this module also has a decision-making function and can identify and diagnose water supply problems in time, perform tracing, and provide effective emergency response plans.

3.2.3 Water Utilization Management Module

The water utilization management module focuses on the behavior of water users. An important goal is to improve water efficiency and water-savings. All users can log into the module with their accounts to obtain water-use information and the water quota; thus, users can reduce their water consumption. The real-time water use data obtained from water monitoring devices, such as smart water meters at user ports, are transmitted to the blockchain for storage. Smart contracts in the module compare the water use information with the planned water use target or quota for businesses or communities. The evaluation results are stored in the data block. The difference between the actual and planned water use is classified into three classes (red, yellow, and blue) to provide an early warning system. Users that exceed the limits are subjected to progressive water pricing, and incentive mechanisms are used for water-saving, such as water charges.

The water utilization management module also has a decision-making function so that users can determine anomalous water use in time and determine the cause. The module analyzes water consumption to implement water-saving measures for different users (e.g., technical information on water-saving measures and the installation of water-saving faucets and toilets).

3.2.4 Water Discharge Management Module

The water discharge management module includes drainage system management and sewage system management. The water discharge of each drainage system is monitored, and the timestamped data are transmitted to the blockchain. Smart contracts are used to compare the drainage information with the standards in the urban drainage permit of the system, and the results are also transmitted to the blockchain for storage. The water quality of the drainage system is compared with the water quality indicators in the “Wastewater Quality Standards for Discharge to Municipal Sewers” to determine whether the water quality meets the standards. The results are transmitted to the blockchain for storage. The managers of the drainage systems can manage the water drainage using this module.

In the management module of a sewage treatment system, the sewage volume is monitored at the water inlet of sewage treatment plants, and the timestamped data are transmitted to the blockchain. The amount of sewage is calculated by smart

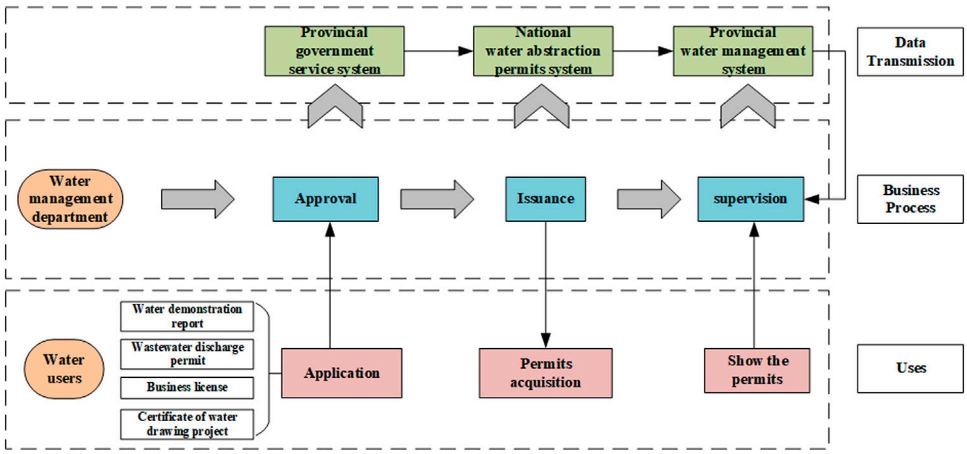

FIGURE 3 | The business process of electronic water abstraction permits in China.

contracts in the module and the results are transmitted to the blockchain for storage. The sewage volume is also monitored at the outlet of sewage treatment plants, and the time-stamped data are transmitted to the blockchain. Smart contracts are used to compare the sewage volume with the volume in the standards and the results are transmitted to the blockchain for storage. Water quality is also monitored at the outlet of the sewage treatment plant. A decision-making function is used to identify and diagnose water resource problems quickly, perform tracing and analysis, and provide optional and effective emergency treatment plans.

Flood control and drainage are crucial aspects of urban water resource management and require comprehensive data information, such as precipitation, water inflow, reservoir level, water flow in drainage pipe networks, water-drainage volume, sewage volume, and water discharge in the sewage treatment plants. The corresponding data on the blockchain are transmitted to the flood control and drainage function. In conjunction with meteorological data, terrain data, traffic planning, and other information, the system uses data analysis and visualization to classify the flood risk, provide early warning, and implement emergency response measures, such as sluice control and pump station scheduling.

3.3 Design of Blockchain-Based Water Abstraction Permits

After the electronic water abstraction permit has been approved by the water department, it is issued through the national electronic license system. As shown in **Figure 3**, the issuance, extension, and change in water abstraction permits are accomplished in this system. After the licenses have been issued, their authenticity has to be verified, and water withdrawals have to be monitored. Blockchain technology can be used to verify information securely, prevent falsification, and optimize water supervision. Therefore, it is necessary to apply blockchain technology to permit verification and water abstraction supervision to determine whether the permit information has been tampered with and whether the electronic seal is genuine. Because of the efficient transmission and safe sharing of data using blockchain technology, water management departments can obtain accurate water intake data in time to perform effective supervision.

3.3.1 Information Verification of Water Abstraction Permit Holders

In water-related project management, enterprise investment approval, water rights transfer, water fee and tax collection, water resource supervision, and other transactions, it is essential for water users to provide water abstraction permits and for departments to verify the information in the permits. Reliable information verification is crucial. However, the traditional data management strategy is prone to license falsification and information tampering. In contrast, blockchain technology ensures the safe storage of electronic license information and verification. Changes in license information are also recorded in the blockchain, enabling traceability.

A digital signature or electronic seal stored on the blockchain confirms the validity of the water abstraction permit because it provides proof of identity and cannot be counterfeit. As shown in **Figure 4**, the online platform of government services or mobile APP can be used by enterprises or individuals to upload relevant materials for online applications. The water management department then issues the permit, and the water license information is encrypted on the chain. When users need proof of the water permit, they can access the electronic version on the government service platform, and audit departments can query the information in the permits by inputting the credit code of the enterprise or scanning the QR code generated by the blockchain encryption algorithm to verify the authenticity of the document. These records are automatically linked in the blockchain for transparent tracing and auditing in the future.

Therefore, adopting blockchain technology for electronic license management ensures the credibility and consistency of

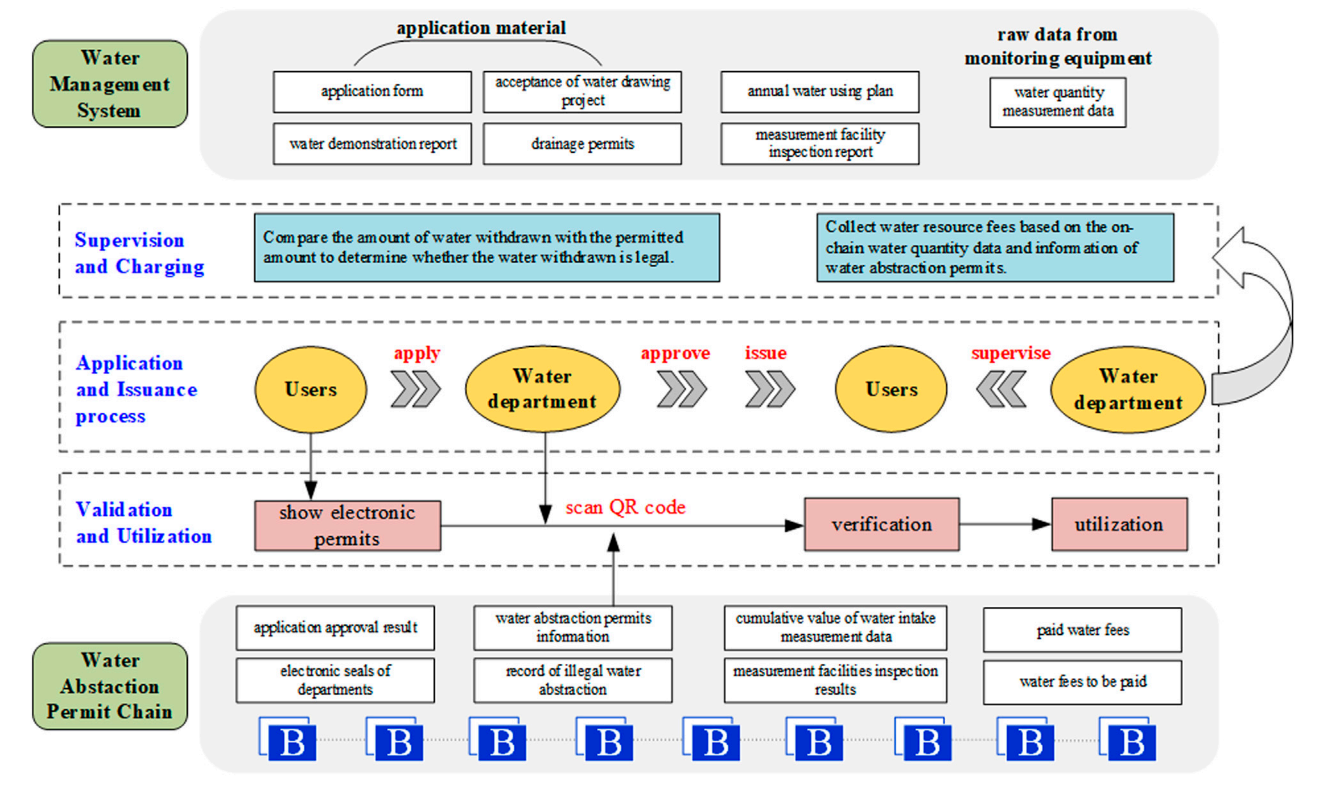

FIGURE 4 | The application scenario of blockchain-based information verification when electronic water abstraction permits is being used.

water abstraction permits, provides storage and verification services, and enhances the security of electronic licenses. Moreover, blockchain technology guarantees that electronic permits and information are stored permanently on the chain to prevent tampering. This approach is convenient and efficient for verifying certificates. In addition, the blockchain retains a complete record of each license authorization to ensure that the information can be traced and to prevent theft. All operations can be traced, eliminating the security concerns of the public.

3.3.2 Supervision of Water Use Based on Water Abstraction Permits

Information asymmetry exists between the government and the water users for supervising the issuance of licenses. Local water conservancy departments experience many difficulties in verifying the water abstraction data submitted by enterprises. For example, water users are scattered, making it difficult to determine their actions. The decentralized blockchain technology and secure data sharing facilitate water abstraction permit management and minimize problems, such as data dispersion, information asymmetry, slow feedback, and difficult supervision, resulting in efficient and low-cost verification of water permits. Furthermore, the water supply and use must be considered when reviewing and issuing water abstraction licenses.

The smart water system and blockchain technology are combined to monitor and encrypt the water use data in real time. Asymmetric encryption is used to ensure safe and confidential data transfer, providing accurate data for supervision and inspection. As shown in **Figure 4**, blockchain technology is used for the application, review, and modification of water permits and information monitoring, data storage, and management of water resources. By combining water resource management and monitoring, data on water intake, flow, and discharge are monitored by sensors and transmitted to the blockchain in real time. Therefore, the department in charge of water abstraction licenses can query the water use data in real-time and determine whether the water users act in accordance with the water permits, improving supervision efficiency. Moreover, the management of water resources is strictly controlled to ensure the appropriate allocation of water for industrial production. For example, agricultural water use would be significantly affected if an irrigation district originally applied for a water permit for agricultural irrigation and then used the water for industrial use without changing the water permit. Blockchain technology utilizes a unique digital ID for the monitoring equipment of water users, ensuring traceability of the water used by enterprises. If water users want to replace their equipment, they must reapply. Therefore, the water management department can strictly supervise water use in accordance with the water abstraction permits.

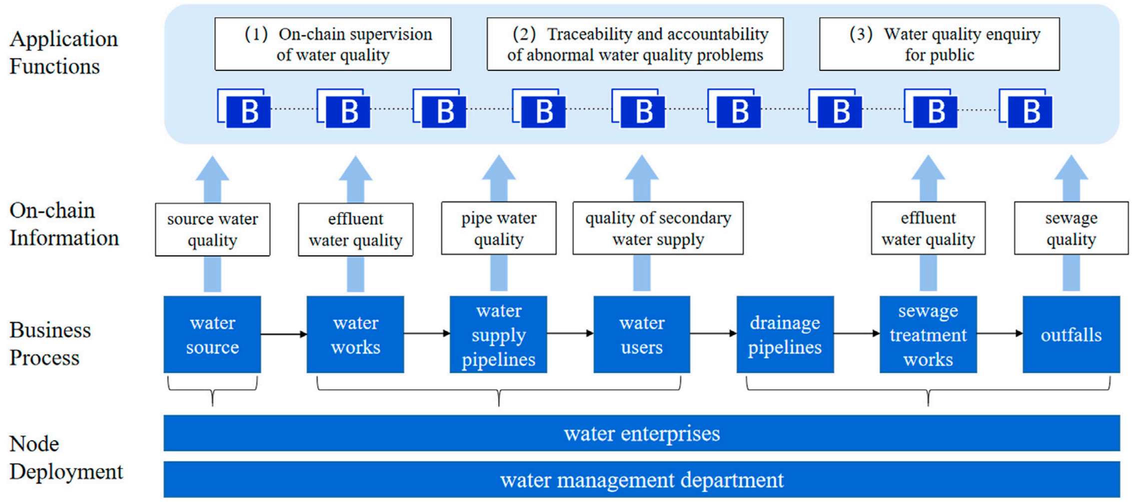

FIGURE 5 | The application scenario of reliable water quality traceability mechanism.

3.4 Design of a Reliable Water Quality Traceability Mechanism

Water quality data are critical and sensitive. Pollutants in the water can rapidly spread to other areas and are difficult to trace. Blockchain technology provides traceability of the water quality. The water quality at different nodes is linked so that the type of pollutant, its source, and the responsible person can be accurately traced without tampering or denial. Since the data are time-stamped, they cannot be altered, ensuring data safety and traceability.

Through whole-chain supervision and traceability of the water quality, the location of a water pollutant or low water quality can be quickly determined, and the responsible people can be identified with high efficiency and credibility, thus ensuring the water quality safety of residents. As shown in **Figure 5**, blockchain technology is used to conduct on-chain monitoring of water quality information, including the water quality of the water source, water supply pipe network, the treatment plant, and the water treatment cycle. The water quality data are authentic and reliable and are shared by all departments in each link of the water supply through the blockchain network nodes. The secondary water supply is also monitored, focusing on whether the water quality and cleaning cycle of residential communities are in compliance. The early warning information is transmitted to all departments to enable a timely response to water quality events, reduce the impact and loss, and strictly protect the water quality of the residences. The monitoring of water pollution incidents should be strengthened. If an incident occurs, evidence should be collected immediately to enable analysis and provide accountability. Anomalous water quality events can be located quickly to determine who is responsible, improving the efficiency and credibility of water quality incidents. The water quality is improved, and the occurrence of water pollution incidents is prevented due to information linking.

In water supply management, in order to help water users obtain water information, the water resources' traceability encoding of the daily water supply is constructed. It can be added to the big data analysis platform of the water resources to encode the daily water supply, enabling the monitoring of water consumption in different geographical locations. Each water user can query the traceability information on the blockchain platform, such as the source of today's water and the water quality of the source and treatment plant. Water providers, sewage treatment plants, and other enterprises and water management departments require comprehensive enterprise records and long time-series water quality data. The data blocks in the blockchain are linked in chronological order. Thus, water enterprises and departments can query water quantity and quality information in a certain period or link the data according to the date.

4 CONCLUSION

In terms of problems in building trust, low management efficiency, and high risk of data storage in traditional centralized water management, this study analyzed the application of blockchain technology for optimizing water management and proposed a decentralized water resource information management system for the entire process of a social water cycle, comprising four functional modules, namely, water-source management, water-supply management, water-utilization management, and water-drainage management. This strategy provides high trust, high management efficiency, and secure data storage. The proposed system comprises four functional modules to manage water sources, water supply, water utilization, and water discharge. The advantages of the system include reliable and secure storage of water resource data, high efficiency of information transmission, and high traceability of water quality problems. We considered two typical blockchain-based application scenarios: water abstraction permits and water quality traceability to exploit the blockchain's advantages of information encryption and traceability.

The integration of blockchain technology into water management systems faces some challenges, such as data sharing between departments, legal aspects related to the blockchain, and the lack of a standard system. It is essential to change traditional thinking and adjust business management according to the blockchain platform. In addition, it is necessary to link with existing information systems and promote the application of blockchain technology to ensure adequate adjustments.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WX and XC conceived the presented idea. WX and CS developed the theory, constructed the system architecture, and conducted in-depth research. All authors discussed the results and WX mainly contributed to the final manuscript.

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