

## A Trust-Anchored Computational Framework for Real-Time Water Quality Inference with Immutable Consumption Accounting

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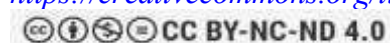
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### ABSTRACT

Water resource management (WMT) has become increasingly important due to rising demand, uneven distribution, and concerns regarding water quality and transparency. Many systems rely on centralized storage and manual monitoring, which lead to inefficiencies, lack of accountability, and vulnerability to data tampering, while also lacking strong authentication mechanisms and real-time validation of water quality. These limitations make allocation and billing processes less reliable and expose sensitive data to unauthorized access. To overcome these issues, there is a need for a secure, intelligent, and automated system that ensures data integrity, controlled access, and accurate decision-making. The proposed system integrates Blockchain Technology, Machine Learning (ML), and a secure login module within a web-based environment. The authentication mechanism ensures that only authorized administrators can access key functionalities such as water allocation, billing, and payment management, thereby enhance security and prevent unauthorized usage. Blockchain technology is utilized to store all resource and billing records in a decentralized and tamper-resistant manner, ensuring transparency, traceability, and trust across operations. Additionally, a ML based model Random Forest Classifier (RFC) is employed to predict water quality using parameters such as pH, conductivity, turbidity, and organic carbon before allocation decisions are made. This enables proactive assessment of water safety and improves resource utilization. The integration of secure authentication, predictive analytics, and immutable storage enhances system reliability and efficiency. The system supports better decision-making, prevents data manipulation, and ensures accurate and transparent water distribution and billing, making it a robust solution for modern water management applications.

**Keywords:** Water resource management (WMT), Blockchain Technology, Machine Learning (ML), Smart Water Allocation, Billing and Payment System.

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### 1. INTRODUCTION

Accelerated industrial growth, urbanization, and agricultural intensification have significantly increased the discharge of complex micropollutants—including heavy metals, pharmaceuticals, and

organic contaminants—into natural water bodies, posing serious risks to ecosystems and human health. Consequently, maintaining water quality has emerged as a fundamental priority in environmental management and sustainable development. Water quality monitoring (WQM) serves as a critical mechanism for collecting, analyzing, and interpreting data necessary for regulatory compliance, pollution control, and environmental protection strategies [1,2]. It enables the identification of contamination sources, evaluation of physicochemical and biological parameters, and early detection of hazardous conditions, thereby supporting timely remediation and policy decisions. However, implementing efficient WQM systems remains challenging due to the heterogeneous and dynamic nature of aquatic environments, where variations in temperature, pH, flow patterns, and external influences complicate accurate monitoring and data interpretation [3]. The overall process and challenges associated with water quality monitoring are illustrated in Fig. 1.

Existing systems frequently rely on manual calibration, periodic sampling, and standalone instrumentation, resulting in delayed responses, high energy consumption, increased operational costs, and limited scalability. Although advanced approaches such as data mining and optimization techniques have been explored to improve parameter selection and system performance, they often lack real-time adaptability and integration capabilities, leaving critical gaps in efficiency and reliability [4].

In addition to monitoring challenges, effective water resource distribution and utilization continue to be major global concerns, particularly in arid regions that depend on alternative water sources. In Saudi Arabia, desalination plants located along coastal regions form the backbone of water supply systems, necessitating precise monitoring and efficient allocation to minimize losses and ensure sustainability. Regions such as Madinah Munawara experience persistent issues related to pressure imbalances, uneven distribution, and water wastage across industrial and commercial users [5].

While flowmeter-based systems have been implemented in cities like Yanbu to track seawater flow and pressure, these systems provide only partial insights and often fail to deliver accurate measurements of actual consumption. Furthermore, the absence of an integrated, centralized dashboard for real-time data monitoring restricts the ability to analyze usage trends, detect anomalies, and forecast future demand effectively [6]. These limitations emphasize the urgent need for intelligent, automated, and cost-effective solutions that integrate real-time monitoring, data analytics, and efficient resource management to enhance both water quality assessment and distribution efficiency.

## **2. LITERATURE SURVEY**

Krishnan, et al. [7] presented a comprehensive review of AI and DL applications in WMT, covering key domains such as wastewater treatment, irrigation optimization, and water distribution systems. Their study highlighted the challenges associated with handling heterogeneous and large-scale datasets generated from multiple sources, including sensors, environmental data, and operational systems. The authors emphasized that traditional models often fail to generalize across diverse conditions, thereby necessitating adaptive and scalable AI-driven approaches. By integrating AI, DL, and IoT frameworks, the study demonstrated significant improvements in predictive accuracy, operational efficiency, and sustainability. The work also underscored the importance of real-time analytics and intelligent decision-making systems in achieving efficient water resource utilization. Seel, et al. [8] explored the effectiveness of IoT-based smart water management systems in comparison with conventional manual approaches. Their implementation demonstrated that real-time monitoring through interconnected sensors enables continuous data acquisition, anomaly detection, and automated control of water systems. The study showed that IoT-driven systems significantly reduce human intervention, minimize operational errors, and enhance system responsiveness. \_\_\_\_\_

Furthermore, the authors highlighted that such systems improve reliability and enable proactive management by identifying issues such as leaks or irregular consumption patterns at an early stage. Their findings support the adoption of IoT technologies as a critical component in modernizing water infrastructure. Al Amin, et al. [9] proposed a blockchain-based framework aimed at enhancing sustainability and transparency in complex operational systems. Their approach utilizes smart contracts to enforce predefined rules and ensure accountability among stakeholders involved in resource management processes. The framework provides real-time visibility into transactions and operations, thereby improving trust and reducing the risk of data manipulation. Although the study primarily focused on supply chain sustainability, its underlying architecture demonstrates strong applicability to water management systems, particularly in ensuring secure, traceable, and tamper-resistant data handling. The authors also emphasized the role of blockchain in improving coordination and efficiency in multi-stakeholder environments.

Du, et al. [10] examined the current state and future potential of blockchain technology in sustainable management systems. Their study highlighted key challenges in traditional systems, including lack of transparency, limited traceability, and vulnerabilities in data security. Blockchain was identified as a promising solution due to its decentralized architecture and immutable ledger capabilities. The authors provided a generalized framework outlining how blockchain can be integrated into resource management applications to enhance accountability and operational performance. However, they also pointed out existing limitations such as scalability issues, interoperability challenges, and difficulties in integrating blockchain with legacy systems. The study concluded by identifying future research directions to overcome these challenges and enable wider adoption. Raj, et al. [11] conducted a detailed analysis of smart IoT-based sensors used in WMT, focusing on their role in real-time monitoring, leak detection, and optimization of water usage. Their study compared various sensor technologies based on performance metrics such as accuracy, response time, predictive capabilities, and support for data-driven decision-making. The findings indicated that IoT-enabled sensing systems significantly enhance operational efficiency by enabling continuous monitoring and early detection of anomalies. Additionally, the integration of predictive analytics allows for proactive management of water resources, reducing wastage and improving sustainability. The authors emphasized that sensor-based systems are essential for building intelligent and responsive water management infrastructures. Zyoud, et al. [12] conducted a comprehensive global analysis of the adoption of IoT technologies in urbanwater management systems, focusing on trends, research contributions, and practical implementations. Their study highlighted how IoT enables continuous monitoring of water quality, efficient demand management, and early detection of leaks through real-time data collection and analysis. The authors emphasized that IoT-driven systems significantly improve operational efficiency and reduce resource wastage by enabling data-driven decision-making. However, the study also identified several critical challenges, including data privacy concerns, lack of interoperability between heterogeneous systems, and the absence of standardized frameworks. These limitations hinder large-scale deployment and require coordinated efforts in policy development, system design, and technological standardization.

Alam, et al. [13] proposed a blockchain-based decentralized framework designed to enhance security, transparency, and resilience in distributed systems. Their model leverages cryptographic techniques and smart contracts to ensure secure data storage, automate processes, and maintain data integrity across multiple stakeholders. Although the primary application of the framework was in supply chain management within the energy sector, its architectural design demonstrates strong applicability to water management systems. The decentralized nature of the system eliminates reliance on centralized authorities, thereby reducing the risk of data tampering and improving trust among participants. The study highlights that integrating blockchain with IoT-based systems can further strengthen data

reliability and enable secure, real-time monitoring. Rustemi, et al. [14] analyzed the structural and operational differences between centralized and blockchain-based systems, providing a detailed architectural perspective on data processing, authentication, and system integration. Their study introduced a blockchain-based system that ensures secure generation and verification of digital records, demonstrating how decentralization enhances system reliability and trust. The authors highlighted that centralized systems are more vulnerable to single points of failure and data manipulation, whereas blockchain-based systems provide improved fault tolerance and tamper resistance. Additionally, the study explored challenges related to system integration, scalability, and cross-platform compatibility, emphasizing the need for efficient design strategies to fully leverage blockchain capabilities. Sahoo, et al. [15] presented an extensive review of blockchain applications in sustainable supply chain management, analyzing high-quality research contributions across multiple domains. Their study identified key themes such as blockchain-enabled transparency, traceability, decision support systems, and intelligent logistics management. The authors demonstrated how blockchain facilitates secure data sharing among stakeholders, ensuring accountability and reducing fraud across supply chains. Furthermore, the review provided insights into current research trends, leading journals, and major contributing institutions, offering a comprehensive overview of the field. The study also outlined future research directions, particularly focusing on scalability, integration with emerging technologies, and the development of standardized frameworks for widespread adoption.

### 3. PROPOSED SYSTEM

The system architecture is designed as an integrated and robust framework that combines blockchain technology, ML, and a web-based application layer to enable secure, transparent, and intelligent WMT, as illustrated in Fig. 1. The system begins with initialization, where a connection to the blockchain network is established using Web3, and the smart contract is loaded through its ABI and deployed contract address. This setup enables seamless interaction with on-chain data structures such as resourceList and billList, which are simultaneously retrieved and cached in local storage to enhance access speed and reduce repeated blockchain queries. At the same time, the pre-trained RF model along with the StandardScaler is loaded into memory, ensuring that real-time predictions can be performed efficiently during allocation operations. The architecture supports two primary user workflows: public users and administrators. Public users can access the system without authentication and are allowed to view water allocation details, resource distribution data, and water quality status in a read-only mode, ensuring system transparency while preventing unauthorized modifications. In contrast, administrators must securely log in to access core functionalities. Once authenticated, they are redirected to a centralized dashboard where they can perform operations such as water allocation, billing generation, and payment updates.

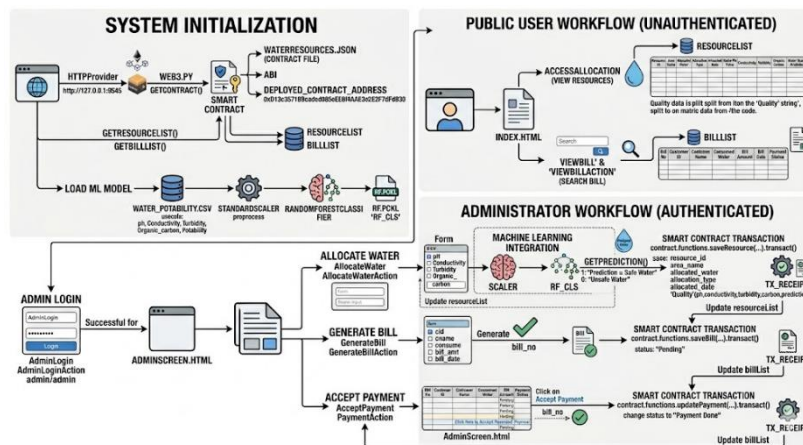


Fig. 1: Proposed system architecture.

During the water allocation process, administrators input parameters including pH, conductivity, turbidity, and carbon levels. These inputs are first processed using the StandardScaler to normalize feature values and are then passed into the RF model, which predicts water potability as safe or unsafe based on learned patterns. The prediction result, along with allocation details such as area, allocation type, and timestamp, is then securely recorded on the blockchain through smart contract transactions, ensuring immutability and traceability. For billing, administrators generate bills by entering consumer details and water usage information, which are then stored on the blockchain with an initial status marked as pending. Each billing transaction produces a unique transaction receipt, providing a verifiable audit trail. In the payment processing phase, administrators monitor pending bills and update their status upon successful payment. This update is executed through another blockchain transaction, changing the status to payment done and ensuring secure and tamper-proof financial tracking. Overall, the tight integration of ML-based prediction with blockchain-backed storage ensures that all system operations are data-driven, transparent, immutable, and reliable, thereby improving decision-making, minimizing manual errors, and delivering an efficient and secure WMT solution.



### 3.1 RFC

The RFC as shown in Fig. 2 works by building multiple decision trees and combining their predictions to produce a more accurate and stable output. Instead of relying on a single tree, the algorithm creates a “forest” of trees, each trained on slightly different portions of the dataset to capture diverse patterns. During prediction, every tree votes on whether the water sample is safe or unsafe, and the forest selects the class that receives the majority of votes, making the model robust, reliable, and resistant to noise in the data.

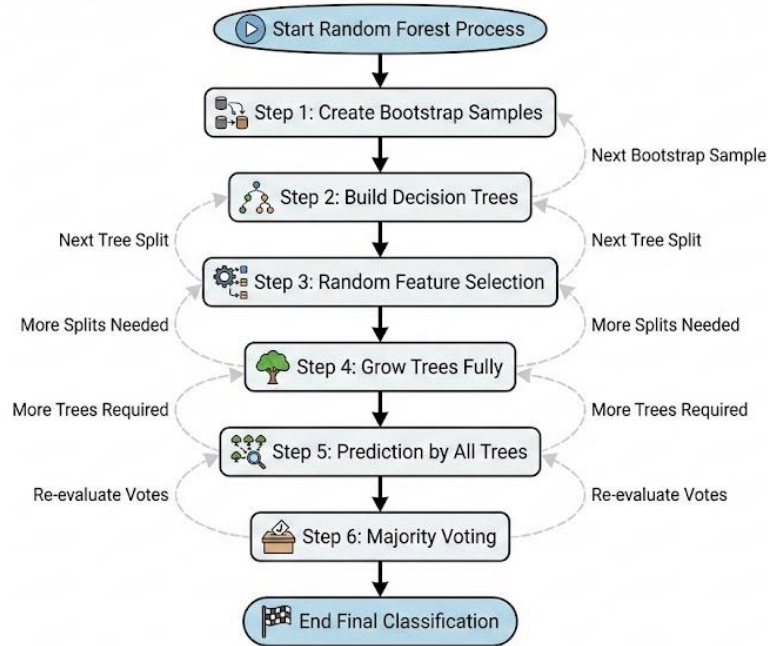


Fig. 2: Internal operation flow of the RFC model.

**Creating Multiple Bootstrap Samples:** RFC begins by generating several subsets of the training data using a method called bootstrapping. Each subset is created by randomly sampling data points with replacement, so some records may repeat. This ensures that every tree receives unique but overlapping portions of the dataset.

**Building Independent Decision Trees:** For every bootstrap sample, the algorithm trains a separate decision tree. Each tree learns patterns by splitting the data based on feature values such as pH, conductivity, turbidity, and organic carbon. Because each tree sees slightly different data, they learn different decision rules.

**Random Feature Selection at Splits:** At each node of a decision tree, the algorithm does not consider all input features only a random subset. This randomness prevents trees from becoming identical and reduces the risk of overfitting. It also helps the forest capture diverse decision boundaries in the dataset.

**Tree Growth and Stopping Conditions:** Each decision tree is allowed to grow as deep as needed unless certain stopping criteria are met, such as purity thresholds or minimum samples per split. The trees are intentionally grown without pruning to maximize diversity among them. This diversity increases the overall strength of the forest.

**Aggregating Predictions:** During prediction, the input sample is passed through every tree in the forest. Each tree independently outputs a class label—either “Safe Water” or “Unsafe Water.” The



immutable, and verifiable across a distributed peer-to-peer network. The blockchain framework removes the risks associated with centralized control, such as unauthorized data manipulation and bribery, by ensuring that no single administrator can secretly alter the supply data once it is committed to the ledger. At the same time, the machine learning component delivers fast, reliable predictions of water safety based on real-time input parameters like pH, conductivity, turbidity, and organic carbon, empowering administrators to make informed allocation decisions. Overall, the combination of decentralized trust and intelligent prediction enhances the fairness, security, and efficiency of water supply management, setting a solid technological foundation for modernizing public utility governance.

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