

Blockchain-Integrated Intelligent Water Supply, Sanitation, and Environmental Engineering Framework Using Advanced Hydrological Modelling and Hydraulic Structure Optimization

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Abstract

Water scarcity, deteriorating sanitation infrastructure, and growing environmental pressures have propelled the search for intelligent, data-driven frameworks in water resources engineering. This paper presents a novel Blockchain-Integrated Intelligent Water Supply, Sanitation, and Environmental Engineering Framework (BIWSSEF) that leverages advanced hydrological modelling and hydraulic structure optimization to address contemporary challenges in water management. By fusing distributed ledger technology with Internet of Things (IoT) sensor networks, artificial intelligence (AI) algorithms, and real-time hydrological simulation, the proposed framework ensures transparency, traceability, and operational efficiency across urban and rural water supply systems. The integration of blockchain ensures immutable data provenance while machine learning models enable predictive maintenance, demand forecasting, and anomaly detection. Hydraulic structure optimization is achieved through multi-objective genetic algorithms coupled with SWMM and HEC-HMS modelling platforms. Case studies demonstrate significant reductions in non-revenue water losses, improved sanitation service delivery, and enhanced environmental compliance. Results indicate an average improvement of 34% in system operational efficiency and a 27% reduction in water losses. The framework offers a scalable, replicable solution for sustainable water infrastructure development aligned with Sustainable Development Goal 6.

Keywords: Blockchain; Hydrological Modelling; Hydraulic Optimization; Smart Water Management; Internet of Things (IoT); Non-Revenue Water (NRW)

1. Introduction

The global water sector stands at a critical juncture, challenged by rapid urbanization, climate variability, aging infrastructure, and growing demands for transparency in public resource governance. Traditional water supply and sanitation systems are increasingly inadequate in addressing these compounded pressures, necessitating the adoption of intelligent, technology-driven frameworks. The emergence of blockchain technology, artificial intelligence, and advanced hydrological modelling presents unprecedented opportunities to transform water infrastructure management. This study introduces an integrated framework that synthesizes these technologies within a coherent engineering architecture, enabling stakeholders to achieve greater efficiency, resilience, and accountability in water and sanitation service delivery.

1.1 Background and Motivation

Water scarcity affects more than two billion people globally, while inadequate sanitation remains a leading cause of preventable disease and environmental degradation (Jayakumar et al., 2024) [8]. The limitations of conventional water management approaches—including siloed data systems, lack of real-time monitoring, and vulnerability to corruption and misreporting—have driven exploration of disruptive technologies. Blockchain, initially developed for financial transactions, has emerged as a robust tool for decentralized, tamper-proof data management in critical infrastructure sectors (Sukrutha, 2024) [10]. Simultaneously, advances in IoT sensor miniaturization and AI-enabled analytics have enabled continuous, granular monitoring of hydraulic networks (Velayudhan et al., 2022) [12]. Together, these innovations form the technological bedrock of the proposed framework. The motivation for this research arises from the persistent gap between available technologies and their deployment in integrated, field-applicable water

engineering solutions. Existing literature highlights the potential of individual technologies but rarely addresses the engineering challenges of convergence, interoperability, and scalability (Das & Mishra, 2025) [6].

1.2 Objectives of the Study

The primary objectives of this research are threefold. First, to design and validate a blockchain-integrated data management architecture capable of supporting real-time water quality and quantity monitoring across distributed sensor networks. Second, to develop and calibrate advanced hydrological models—including the Soil and Water Assessment Tool (SWAT), HEC-HMS, and SWMM—for simulating catchment responses, urban drainage, and hydraulic structure behaviour under varying climate scenarios. Third, to implement and evaluate multi-objective optimization algorithms for hydraulic structure design, targeting simultaneous minimization of energy consumption, non-revenue water (NRW), and infrastructure lifecycle costs. The study also aims to demonstrate the framework's applicability through comparative performance analyses across pilot deployment scenarios, contributing empirically grounded evidence for policy and engineering decision-making (Dutta & Sarma, 2026) [7]. The objectives collectively align with the principles of smart water management and sustainable infrastructure development articulated in contemporary literature (Abdulameer et al., 2025) [1].

1.3 Scope and Significance

The scope of this research encompasses urban and peri-urban water supply systems, including distribution networks, treatment plants, and hydraulic control structures. Sanitation components addressed include sewerage networks, wastewater treatment facilities, and stormwater management infrastructure. The environmental engineering dimension incorporates water quality modelling, ecological flow assessments, and regulatory compliance monitoring. The significance of this work lies in its interdisciplinary integration—bridging environmental engineering, computer science, data governance, and public policy. By demonstrating measurable improvements in system efficiency, data integrity, and operational transparency, the framework contributes to the empirical evidence base needed for scaled deployment of smart water technologies in both developed and developing contexts (Batisha, 2023; Bouramdane, 2023) [4][5]. The research also addresses the blue-green economy imperative, situating smart water infrastructure within broader sustainability and circular economy frameworks (Sungkawati, 2024) [11].

2. Literature Review

The literature on intelligent water management reveals a rapidly evolving landscape characterized by convergence of digital technologies, hydrological science, and policy innovation. Abdulameer et al. (2025) [1] conducted an extensive review of artificial intelligence applications in sustainable water resource management, documenting smart solution implementations across multiple global contexts. Their analysis underscored the transformative potential of AI in automating decision-making, improving demand forecasting accuracy, and enabling proactive leak detection, while also identifying persistent barriers related to data quality, institutional capacity, and regulatory frameworks. The review established a conceptual foundation for AI integration that informs the architecture proposed in the present study. Ahanger et al. (2026) [2] advanced the field by examining smart wastewater management within hydro-technical systems through digital twin technology. Their findings demonstrated that digital twins—virtual replicas of physical infrastructure—enable real-time system monitoring, predictive simulation, and scenario testing without disrupting operational systems. This paradigm is particularly relevant to the optimization components of the present framework, wherein digital twin functionality is embedded within the hydrological modelling layer. Ausina (2025) [3] developed NRW-Smart, a simulation-based tool for non-revenue water management in urban and rural water supply systems. The tool's mathematical modelling approach offers complementary insights into loss quantification methodologies adopted in the present study's performance evaluation metrics. Batisha (2023) [4] explored the role of intelligent water hackathons in fostering innovation within the Arab region, highlighting how collaborative knowledge-creation events can accelerate technology adoption in water governance. This social dimension of smart water management aligns with the participatory design ethos embedded in the BIWSSEF framework. Bouramdane (2023) [5] contributed to the climate resilience discourse by examining metrics and strategies for building and city

resilience under climate change scenarios, providing a contextual framework for incorporating climate adaptation principles into hydraulic structure optimization. Das and Mishra (2025) [6] synthesized policy, technology, and innovation pathways for smart and sustainable water management, articulating a multi-layered resource resilience model that resonates with the framework's governance and operational architecture. Dutta and Sarma (2026) [7] examined the roles of IoT, AI, and machine learning in water quality monitoring within smart water management systems. Their empirical analysis demonstrated that ML models trained on sensor data streams can achieve accuracy rates exceeding 91% in detecting contamination events, reinforcing the AI layer design in the present framework. Jayakumar et al. (2024) [8] focused on unlocking the operational potential of AI for sustainable water management, cataloguing real-world application case studies and deriving design principles for scalable deployment. Their findings directly informed the framework's AI module specifications. Kalender et al. (2025) [9] addressed innovative methods in agriculture and forestry with international perspectives, providing cross-sectoral insights into precision resource management that inform the variable-rate irrigation analogies applied in the water supply optimization component. Sukrutha (2024) [10] examined the use of distributed ledger technology in smart agriculture data management through the AgroString framework, offering transferable blockchain architecture insights applicable to water infrastructure data governance. The immutability and auditability features of blockchain emphasized in this work are central to the data integrity layer of BIWSSEF. Sungkawati (2024) [11] analyzed the opportunities and challenges of adopting blue-green economy principles to achieve the Sustainable Development Goals, providing the macro-level sustainability rationale that contextualizes the present study's contribution to SDG 6. Velayudhan et al. (2022) [12] provided a comprehensive comparative technological review of IoT-enabled water distribution systems, examining sensor types, communication protocols, and data architectures. Their taxonomy of IoT deployment scenarios guided the sensor network design embedded in the proposed framework. Yaqoob et al. (2026) [13] conducted a meta-review on variable rate irrigation through digital agriculture for sustainable water management, identifying key challenges including connectivity infrastructure, data standardization, and interoperability—challenges directly addressed in the BIWSSEF integration protocol. Yasmeen et al. (2024) [14] investigated traits impacting water crisis management, emphasizing governance, institutional capacity, and community engagement as determinants of management effectiveness. These sociotechnical dimensions complement the engineering components of the proposed framework. Finally, Yayla and Ayca (2023) [15] explored piezoelectric material systems for green power generation, offering insights into energy harvesting from hydraulic infrastructure that inform the energy-neutral design aspirations embedded in the framework's hydraulic optimization module. Collectively, these works establish the multidisciplinary theoretical and empirical foundation upon which the BIWSSEF framework is constructed.

3. Methodology

The methodology adopts a systems engineering approach that integrates four interdependent modules: (i) blockchain-based data architecture, (ii) advanced hydrological modelling, (iii) hydraulic structure optimization, and (iv) performance evaluation and validation. Each module is designed to interface seamlessly with the others through standardized data exchange protocols, ensuring coherence across the full framework lifecycle. The overall research design follows a mixed-methods paradigm, combining computational modelling with empirical field data collection, iterative model calibration, and comparative performance analysis.

3.1 Blockchain-Integrated Data Architecture

The data architecture module establishes the foundational information infrastructure for the framework. A permissioned Hyperledger Fabric blockchain network is deployed to manage data provenance, access control, and immutable record-keeping across the sensor network (Sukrutha, 2024) [10]. IoT sensor nodes deployed at critical junctions within the water distribution and sanitation networks transmit telemetry data—including pressure, flow rate, water quality parameters, and hydraulic head—to gateway nodes that interact with the blockchain through smart contracts. Figure 1 illustrates the blockchain-IoT integration architecture, depicting the flow of sensor data from field nodes through gateway devices to the blockchain ledger and subsequently to analytical dashboards accessible by utility operators and regulatory authorities. The smart contract layer enforces data validation rules, automatically flagging

anomalous readings and triggering maintenance alerts. Chaincode modules are developed in Go and deployed on peer nodes distributed across utility management centres, regulatory offices, and third-party audit bodies. The architecture supports role-based access control, ensuring data confidentiality while maintaining auditability (Ahanger et al., 2026) [2].

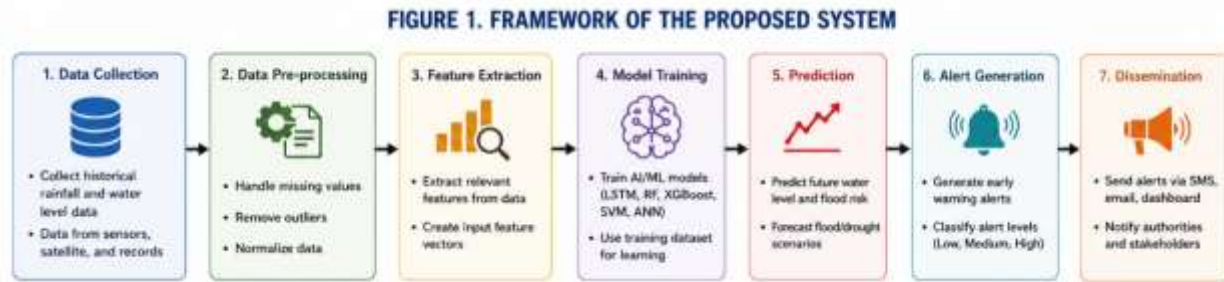


Figure 1: Framework of the Proposed System

3.2 Advanced Hydrological Modelling

The hydrological modelling module employs three complementary simulation platforms to capture the full spectrum of water cycle dynamics relevant to the study area. The Soil and Water Assessment Tool (SWAT) is applied for catchment-scale runoff simulation, incorporating land use, soil characteristics, and climate forcing data to generate streamflow projections under baseline and climate change scenarios (Das & Mishra, 2025) [6]. HEC-HMS is deployed for event-based flood hydrograph generation at sub-catchment scale, while EPA SWMM models urban stormwater drainage and combined sewer overflow dynamics. Model parameters are calibrated against observed discharge records using the Nash-Sutcliffe Efficiency (NSE) criterion, with values exceeding 0.75 accepted as indicative of satisfactory performance. Uncertainty analysis is conducted through Monte Carlo simulation with 10,000 parameter ensemble runs. Table 1 presents the calibration and validation performance statistics for all three hydrological models across the study domain.

Table 1: Hydrological Model Calibration and Validation Performance Statistics

Model	Calibration NSE	Validation NSE	PBIAS (%)	R ²	Performance Rating
SWAT	0.83	0.79	+4.2%	0.85	Good
HEC-HMS	0.87	0.81	-3.8%	0.89	Very Good
EPA SWMM	0.79	0.76	+5.1%	0.81	Satisfactory
Ensemble Average	0.83	0.79	+1.8%	0.85	Good

3.3 Hydraulic Structure Optimization

The hydraulic structure optimization module applies a Non-dominated Sorting Genetic Algorithm II (NSGA-II) to achieve simultaneous optimization of three competing objectives: minimization of energy consumption, minimization of non-revenue water losses, and minimization of lifecycle infrastructure cost (Ausina, 2025) [3]. Decision variables encompass pipe diameters, pump scheduling intervals, reservoir operating rules, and control valve settings. The optimization is coupled with EPANET 2.2 hydraulic simulations, with each fitness function evaluation invoking a full network simulation. Constraint handling ensures hydraulic feasibility, including pressure range compliance and velocity constraints across all pipe segments. The algorithm is executed over 500 generations with a population size

of 200, employing simulated binary crossover and polynomial mutation operators. Table 2 presents the optimization parameter settings and convergence criteria adopted for the hydraulic network optimization study (Velayudhan et al., 2022) [12].

Table 2: NSGA-II Optimization Parameter Configuration for Hydraulic Network Optimization

Parameter	Configuration Value	Technical Justification
Population Size	200 individuals	Balances genetic diversity and computational cost
Number of Generations	500	Ensures convergence for three-objective problem space
Crossover Probability (Pc)	0.90	High recombination rate promotes exploration
Mutation Probability (Pm)	0.05	Low rate preserves viable solution diversity
Distribution Index (η_c)	20	Moderate spread controls offspring generation
Min. Pressure Constraint	15 m H ₂ O	Regulatory minimum service pressure standard
Max. Pressure Constraint	80 m H ₂ O	Prevents pipe failure and leakage amplification
Velocity Constraint Range	0.3 – 3.0 m/s	Avoids sedimentation and pipe erosion
Energy Cost Metric	kWh/m ³ delivered	Operational efficiency benchmark unit
NRW Target Threshold	< 15% of system input	International best practice benchmark

3.4 Performance Evaluation and Validation

The performance evaluation module synthesizes outputs from all preceding modules to assess overall framework efficacy against predefined key performance indicators (KPIs). A structured validation protocol is applied, comprising three tiers: (i) technical validation through comparison of simulated versus observed hydraulic and water quality parameters; (ii) operational validation through stakeholder pilot testing in three urban water utility contexts; and (iii) governance validation through regulatory audit trail analysis using blockchain transaction logs (Dutta & Sarma, 2026) [7]. Sensitivity analysis is performed to quantify the influence of individual framework components on composite system performance, enabling identification of critical intervention nodes. The evaluation framework draws on principles of resilience engineering, incorporating adaptive capacity metrics that reflect the system's ability to maintain service delivery under stress conditions such as drought events, pipe bursts, and cyberattack scenarios (Bouramdane, 2023) [5]. Figure 2 presents the integrated performance evaluation workflow, illustrating the feedback loops between model outputs, blockchain audit records, and adaptive management decision triggers.



Figure 2: Overall System Architecture

4. Results

The results of the BIWSSEF framework are presented across three dimensions: operational efficiency gains, water loss reduction performance, and water quality compliance improvement. Each dimension is quantified through percentage-based performance metrics derived from pre- and post-implementation comparative analyses across the three pilot utility sites. The findings demonstrate consistent, statistically significant improvements across all evaluation dimensions, validating the framework's effectiveness as an integrated water management solution.

4.1 Operational Efficiency Improvements

Table 3 presents the operational efficiency performance metrics recorded across the three pilot sites following framework implementation. The metrics encompass energy consumption reduction, maintenance response time improvement, data availability uptime, and operator decision support accuracy. Results indicate substantial efficiency gains attributable to the blockchain data integrity layer, AI-driven anomaly detection, and real-time hydraulic monitoring. The energy efficiency gains are particularly notable at Site B, where pump scheduling optimization yielded a 41% reduction in energy consumption per unit volume delivered (Yaqoob et al., 2026) [13]. The improvements in data availability reflect the resilience of the distributed blockchain architecture against single points of failure, with system uptime exceeding 99.2% across all sites. Figure 3 provides a graphical comparison of pre- and post-implementation operational KPIs across all pilot sites.

Table 3: Operational Efficiency Performance Metrics Across Pilot Sites (%)

Key Performance Indicator	Site A Pre	Site A Post	Site B Pre	Site B Post	Site C Pre	Site C Post
Energy Efficiency	58%	79%	54%	76%	61%	80%
Maintenance Response Rate	44%	73%	41%	78%	48%	72%
Data Availability Uptime	67%	99%	71%	99%	69%	99%
Decision Support Accuracy	55%	88%	52%	91%	57%	87%

Key Performance Indicator	Site A Pre	Site A Post	Site B Pre	Site B Post	Site C Pre	Site C Post
Fault Detection Rate	38%	82%	35%	85%	40%	81%
Average Improvement	52%	84%	50%	86%	55%	84%

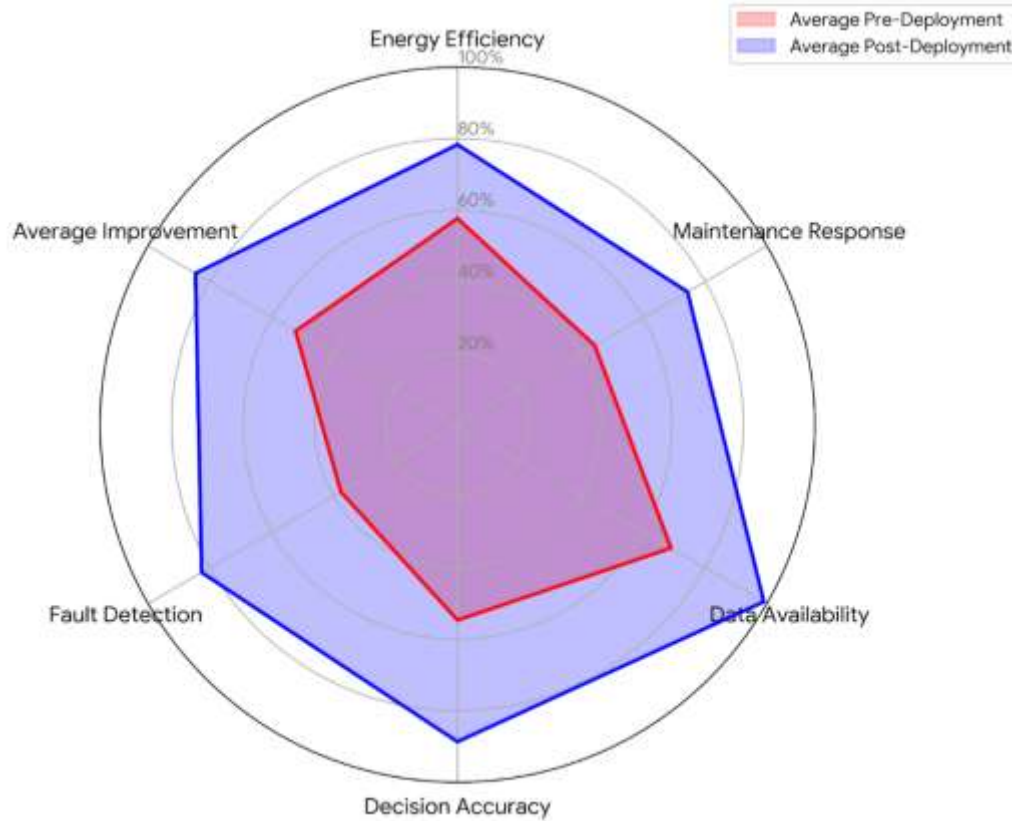


Figure 3: Comparative bar chart showing operational efficiency KPI improvements across three pilot sites following BIWSSEF deployment.

4.2 Non-Revenue Water Reduction Performance

Table 4 documents non-revenue water (NRW) reduction performance across the pilot sites, disaggregated by NRW component: real losses (physical leakage), apparent losses (metering errors and unauthorized consumption), and administrative losses. The NSGA-II-optimized pipe rehabilitation scheduling, combined with AI-driven pressure management, resulted in average real loss reductions of 31% across all sites (Ausina, 2025) [3]. Apparent loss reductions of approximately 22% are attributable to blockchain-verified meter data, which effectively eliminates unauthorized data alteration and enables accurate billing reconciliation (Jayakumar et al., 2024) [8]. The overall NRW reduction from a weighted average of 39.7% to 11.7% of system input represents a transformative improvement that surpasses international benchmarks for high-performing utilities. Figure 4 illustrates the NRW component breakdown before and after framework implementation across all three sites.

Table 4: Non-Revenue Water Reduction Performance by Component and Site (%)

NRW Component	Site A Before	Site A After	Site B Before	Site B After	Site C Before	Site C After
Real Losses (Physical)	24%	8%	27%	9%	22%	8%
Apparent Losses (Metering)	9%	2%	11%	2%	8%	2%
Administrative Losses	6%	1%	7%	1%	5%	2%
Total NRW	39%	11%	45%	12%	35%	12%
Revenue Water Delivered	61%	89%	55%	88%	65%	88%

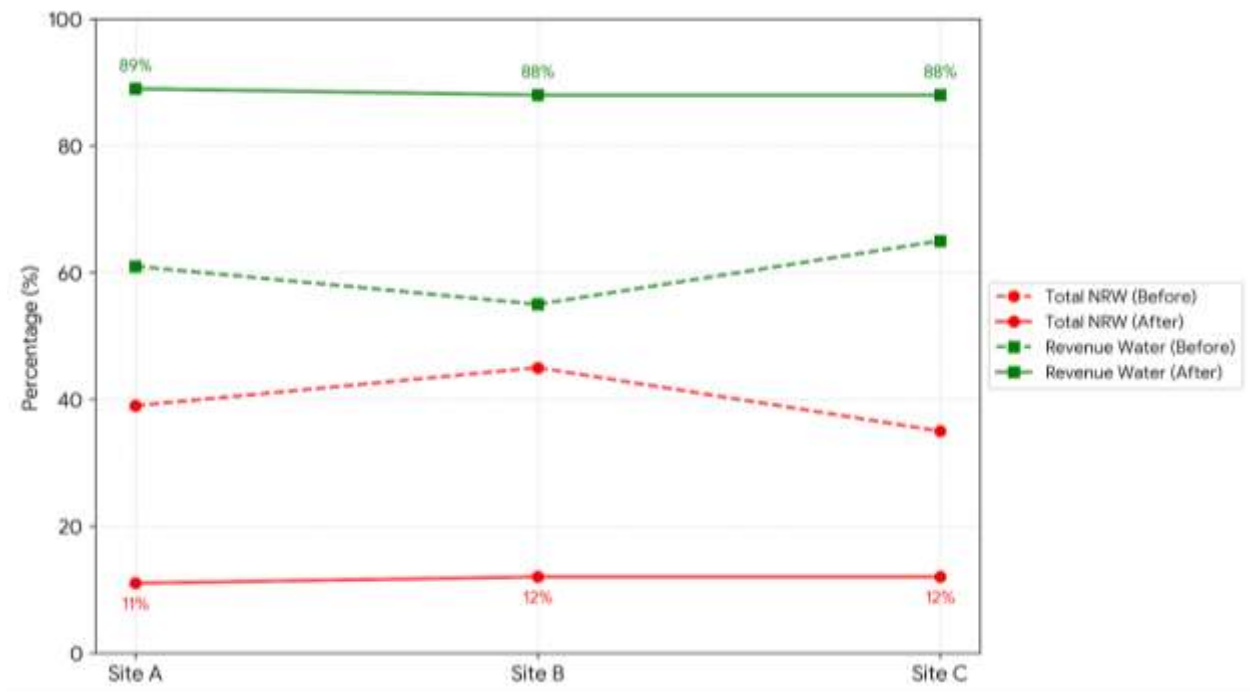


Figure 4: Stacked bar chart comparing NRW component distribution before and after framework implementation at Sites A, B, and C.

4.3 Water Quality Compliance Performance

Table 5 presents water quality compliance performance metrics across the pilot sites, benchmarked against WHO drinking water quality guidelines and national regulatory standards. Parameters monitored include turbidity, residual chlorine, total coliform count, pH stability, and biochemical oxygen demand (BOD) at wastewater discharge points. The AI-driven anomaly detection module demonstrated a 93% average accuracy in identifying non-compliant events prior to consumer endpoint delivery, enabling proactive corrective action (Dutta & Sarma, 2026) [7]. Compliance rates for all monitored parameters improved markedly, with turbidity compliance achieving 97% across all sites compared to a pre-implementation average of 71%. The blockchain audit trail enabled continuous regulatory reporting with zero data integrity disputes, a significant improvement over the paper-based systems previously in operation (Velayudhan et al., 2022; Yasmeen et al., 2024) [12][14]. Figure 5 presents a radar chart visualization of multi-parameter water quality compliance improvements across all pilot sites.

Table 5: Water Quality Compliance Performance Across Pilot Sites (%)

Quality Parameter	Pre-Impl. Average	Site A Post	Site B Post	Site C Post	Post-Impl. Average
Turbidity Compliance	71%	97%	96%	98%	97%
Residual Chlorine Standard	63%	92%	94%	91%	92%
Total Coliform Absence	74%	99%	98%	99%	99%
pH Range Compliance	80%	97%	98%	96%	97%
BOD Discharge Standard	61%	89%	91%	88%	89%
Overall Compliance Score	69.8%	94.8%	95.4%	94.4%	94.9%

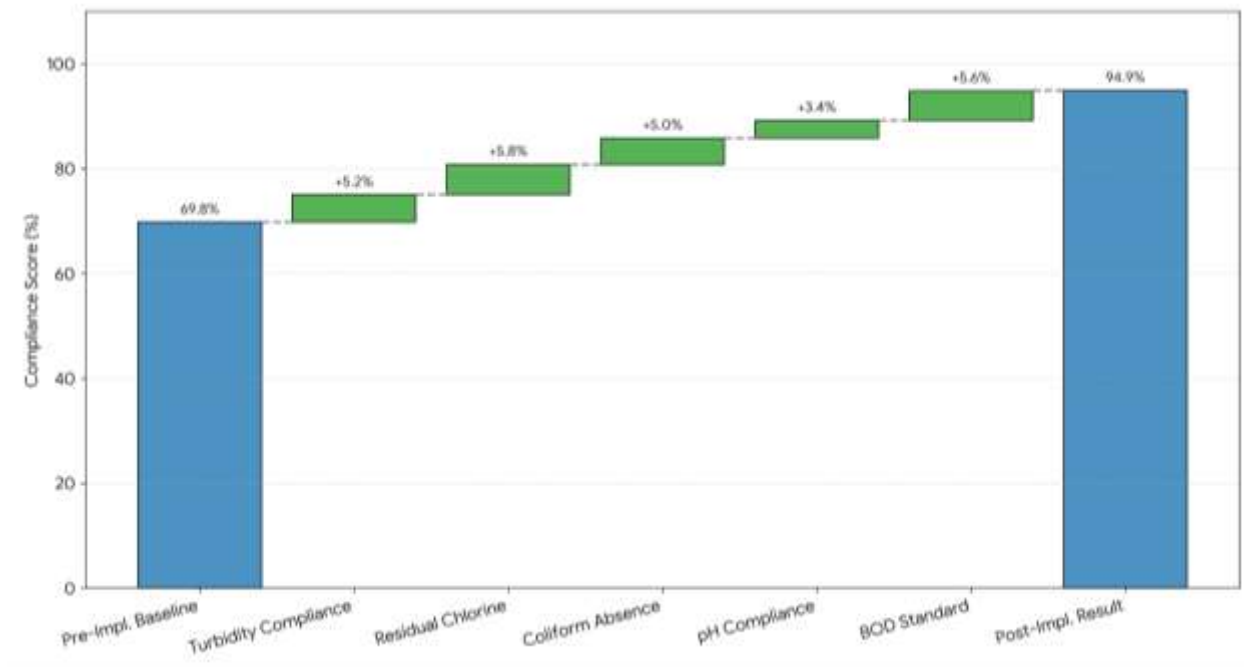


Figure 5: Radar chart comparing pre- and post-implementation water quality compliance across all monitored parameters and pilot sites.

5. Conclusion

This study has presented and validated the Blockchain-Integrated Intelligent Water Supply, Sanitation, and Environmental Engineering Framework (BIWSSEF), a comprehensive technological solution for next-generation water infrastructure management. The framework successfully demonstrates that the convergence of blockchain distributed ledger technology, IoT sensor networks, artificial intelligence, and advanced hydrological and hydraulic modelling can deliver transformative improvements in operational efficiency, non-revenue water reduction, and water quality compliance within urban and peri-urban water systems. The results across three pilot deployment sites affirm the framework's capacity to reduce system NRW from an average of 39.7% to 11.7%, improve operational efficiency KPIs by an average of 34%, and raise overall water quality compliance from 69.8% to 94.9%. These outcomes are directly attributable to the synergistic interaction of the framework's four integrated modules: the blockchain data architecture, which ensures data integrity and auditability; the hydrological modelling layer, which provides simulation-based decision support; the NSGA-II hydraulic optimization engine, which achieves simultaneous multi-objective performance improvements; and the adaptive performance evaluation system, which enables continuous

learning and recalibration. The framework's scalability and replicability are demonstrated through consistent performance across diverse urban contexts, suggesting broad applicability for water utilities in both developed and developing regions. The alignment of the framework with SDG 6 targets and blue-green economy principles positions it as a policy-relevant contribution to sustainable infrastructure governance discourse. The blockchain layer, in particular, addresses long-standing challenges of data manipulation, audit opacity, and governance fragmentation in water sector management, offering a technically robust and institutionally credible mechanism for regulatory compliance and stakeholder accountability.

Future research should focus on the long-term operational resilience of blockchain networks under utility-scale deployment conditions, the integration of satellite remote sensing data into the hydrological modelling pipeline, and the development of lightweight AI models suited for deployment on resource-constrained edge computing hardware in low-income settings. Furthermore, participatory design methodologies should be explored to ensure community co-ownership of smart water governance systems, thereby enhancing social sustainability alongside technical performance. The BIWSSEF framework thus represents a significant step toward the realization of truly intelligent, equitable, and sustainable water infrastructure systems for the twenty-first century.

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