Blockchain and Internet of Things-Based Technologies for Intelligent Water Management System

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1 Introduction

Water is a critical commodity that connects every aspect of the day-to-day running of cities and communities with direct sociopolitical and economic implications. With projected population explosion, rapid urbanization and climate change induced by the volatility of weather patterns across the globe calls for efficient ways of conserving, utilizing, and managing of the dwindling water resource [53], particularly in emerging economies such as the African region. It is estimated that 70% of world population will live in cities in water-stressed regions by the year

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2025 and the current centralized piped infrastructure being relied upon by water utilities will be inadequate. According to the United Nations (UN) world population prospects, 2017 revision, Europe's population will shrink by 26 million between 2017 and 2050, whereas Africa's population will grow by 1.27 billion over the same period, which makes Europe's challenge tiny in comparison to Africa's.

Internet of Things (IoT) stands out as the core technology and solution to address water conservation and management issues, through digitization and building in intelligence in the water management system, to address water insecurity and attaining the 2030 United Nations' target for the Sustainable Development Goal (SDG 6) on clean water and sanitation [64].

IoT has dramatically changed the way we interact with each other and the environment and provides us with a better way of understanding what's going on around us. IoT is also playing a central role in making our cities and infrastructure more intelligent. It is projected by Cisco Internet Business Solutions Group (IBSG) that the number of interconnected IoT devices will reach 50 billion by 2020, just two (2) years from now, and with an even higher prediction by ARM, a semiconductor and software design company, of 1 trillion IoT devices by 2035. Despite all the promises IoT provides, a key concern about IoT technology is centered around security and privacy of the data continuously being generated by these large-scale sensing devices [25, 55], heterogeneity of devices, scalability, power efficiency and interoperability, and standardization of network communication protocols [51]. Many researchers have proposed several ways of tackling these IoT challenges such as in [46, 63], for real-time IoT [10] and in Industrial Internet of Things (IIoT) industry application scenario [2]. However, there are still unresolved issues and challenges especially with security and privacy owing to the decentralized topology of IoT devices that are constantly prone to physical and cyberattacks due to the sensitive information generated and transmitted by these smart and resource-constrained devices [18].

In [46], researchers identified the following specific security threats to IoT sensors deployed in an intelligent water management system (IWMS):

- Physical attack on sensor devices deployed in remote field locations
- Network hacking and jamming, device cloning, and eavesdropping
- Challenge with securely updating firmware of sensors already deployed in the field
- Issue with secure and trusted communication between devices

Blockchain, a peer-to-peer (P2P) distributed ledger technology (DLT), is emerging as a viable option to improve on the security and other technical challenges of IoT by integrating it with IoT devices to provide a secure network communication platform in a decentralized and distributed architectural arrangement, away from the traditional centralized databases in a cloud-centric design that most IoT has been built upon [15, 19, 59].

The chapter seeks to explore the impact of the combined usage of blockchain and IoT technologies on intelligent water management system (IWMS) through an African perspective. This chapter also summarizes security solutions specifically designed for IWMS and discusses some use case scenarios that could benefit from the hybridization of these two technologies. Although there are works in literature on blockchain-IoT integration [4, 12, 25, 33, 35], to the best of our knowledge, there is currently no study of its applicability in the context of IWMS with an African view and perspective.

2 Overview of Background Concepts

In this section, an overview of the key concepts and technologies is given as it relates to intelligent water management system (IWMS).

2.1 Internet of Things

2.1.1 Technical Definition, Features, and Architecture

IoT is a broad and vast area of research encompassing numerous sets of intertwined ideas from different perspectives. It represents the coming together of several enabling technologies as IP-based networking, wireless communication, miniaturization as envisioned in Moore's law, data analytics, and cloud computing [52], comprising people, machine, and information and having a direct and unprecedented impact on the society in so many ways. It is in light of this that it becomes challenging to give a holistic definition of IoT due to its complex characteristics, different perspectives, and deployment scale. Two definitions of IoT are adopted for the purpose of this chapter, which are based on deployment scale as proffered in [42] as follows:

- Small-scaled IoT deployment: "An IoT is a network that connects uniquely identifiable "Things" to the Internet. The "Things" have sensing/actuation and potential programmability capabilities. Through the exploitation of unique identification and sensing, information about the "Thing" can be collected and the state of the 'Thing' can be changed from anywhere, anytime, by anything."
- Large-scaled IoT deployment: "Internet of Things envisions a self-configuring, adaptive, complex network that interconnects 'things' to the Internet through the use of standard communication protocols. The interconnected things have physical or virtual representation in the digital world, sensing/actuation capability, a programmability feature and are uniquely identifiable. The representation contains information including the thing's identity, status, location or any other business, social or privately relevant information. The things offer services, with or without human intervention, through the exploitation of unique identification, data capture and communication, and actuation capability. The service is exploited through the use of intelligent interfaces and is made available anywhere, anytime, and for anything taking security into consideration."

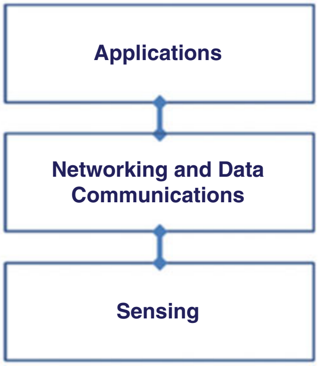

Fig. 1 Simplified IoT functional architecture

IoT has the following characteristics and features:

- Interconnection of devices and between devices and the Internet
- Devices have unique identifier, such as IP and MAC addresses
- Sensing and actuation capabilities
- Inbuilt intelligence
- Self-configurability and programmability

Since smart devices are broad and diverse such as sensors, RFIDs, smart phone, and people, it becomes more glaring and challenging to have a single and common IoT reference model that is applicable to all domains and scenarios. However, a common and simplified three-layered IoT functional reference architecture comprising of physical sensing devices, network with data communication, and application layers, as depicted in Fig. 1, is adopted in many literatures. It is worth mentioning the study by researchers in [51], where an IoT-based reference architecture is proposed for various smart water management processes by using a model developed for a project to establish water management standardization applied in irrigation, known as MEGA, and adopting an existing standard from the manufacturing and logistic domains for the control of processes, known as Object Linking and Embedding for Process Control Unified Architecture (OPC UA). The aim of this study was to define a feasible and all-encompassing industrial standard for water management processes.

2.1.2 IoT Technical Issues and Challenges

IoT can be beneficial to water management in the following ways: water leakage detection, water quality and security monitoring, transparency on consumption and awards of water contracts, predictive maintenance on infrastructure, and more efficient water management system through smart metering system. Despite these benefits that IoT offers, there are still some issues with IoT implementation mainly bordering around security and privacy, regulatory and legal concerns, standards and interoperability, and developmental issues in emerging economies [52]. These mentioned issues are briefly explained:

- Security and Privacy Issues: With rapid entrenchment of IoT in virtually all spheres of our daily lives, concerns are being raised as to degree of security and privacy of the data generated, transmitted, and analyzed over the Internet by these sensing devices, as well as the access rights of this sensitive information. Commonly known cyberattacks on IoT devices include DDoS attack, hacking, data theft, and remote hijacking.
- Interoperability and Standardization: This issue arises due to a combination of multiple technologies that make up the IoT ecosystem, such as sensor technology, wireless communication, embedded system, cloud computing and virtualization, and IoT hardware design considerations.
- Regulatory, Legal, and Right Issues: This issue is related to the way data continuously generated by IoT devices is being utilized, as well as who have access to the data, especially if the data is stored and analyzed across international borders with different jurisdictions from where the data is being generated, raising concerns about user rights, information misuse, and legal liabilities.
- Emerging Economy and Developmental Issues: The IoT hold promise to improve on the economic, political, and social status of emerging and developing nations, just as with the developed ICT economies. However, to realize the full potentials of IoT, the unique African challenges must be taken into consideration.

Readers are referred to [28, 42, 52] and for detailed discussion on technical IoT concept, challenges, standardization, and economy prospects.

2.2 Blockchain

2.2.1 Technical Definition and Features

Blockchain is a peer-to-peer (P2P) distributed ledger technology (DLT) for transparent transaction devoid of a trusted intermediary that leverages on the Internet, originally developed for cryptocurrency virtual currency transactions. The concept and idea were first proposed in [22] on time-stamping of a digital document, before it was later called blockchain in [44]. *Blockchain is defined as an appendable immutable universally distributed open ledger* [36]. The key elements of this definition rest with the keywords: *appendable* means can add to the ledger, *immutable* means nothing can be deleted or altered from the ledger, and *universally distributed* means equal accessibility of everyone in the network to the same copy of the ledger each time information is updated to ensure validity of all transactions called blocks. This makes a blockchain trustworthy and an open ledger database where all transactions (blocks) are recorded in a clear, shared, and transparent manner securely linked together using cryptography. We refer readers to [6, 14, 44] for details on blockchain technology.

Currently, many blockchain start-ups are springing up in Africa [7] as shown in Table 1, mostly in the banking and financial sector, rightly so, because of its origin from the cryptocurrency virtual currency world. We however envision these and other new start-ups venturing into the water management ecosystem.

Table 1 Blockchain technology start-ups in Africa

Start-ups	Network consensus platforms	Country	Application domain
Blockchain Academy	Bitcoin/tellar/Ethereum/ IPFS/Hybrid systems	South Africa	Education/social engagement
Satoshicentre		Botswana	Education/training/ social projects
Wala		Uganda	Finance
BitPesa		Kenya	Finance/forex transactions
BitGive		US based (But with partnership operations in Africa)	NGO/charitable organiza-tion/philanthropy
SureRemit		Nigeria	Finance/noncash remittance
Custos Media Technologies		South Africa	Media and music industry piracy
Kobocoin		Nigeria	Finance/payment system
Cryptogene		Nigeria	Education/training
BitMari		Zimbabwe	Finance/forex transactions
ChamaPesa		Kenya	Library/bookkeeping system
NairaEx		Nigeria	Finance/exchange and remittance
Bankymoon		South Africa	Energy and utilities payments/smart grid/consultancy
BitFinance		Zimbabwe	Finance/noncash remittance
The Sun Exchange		South Africa	Solar energy marketplace connect platform
Bitland		Ghana	Land and properties registry
GeoPay		South Africa	Finance/forex remittance
OTLW		Kenya	Online educational system

2.2.2 Components of Blockchain

- Blockchain structure
- Hash function and encryption
- Peer-to-peer (P2P) distributed network
- Consensus protocols
- Mining

2.2.3 Blockchain Stakeholders

The parties, groups, and organizations with interest and concern in this innovative technology are blockchain infrastructure maintainers, external auditors, regulators and law enforcement of blockchain activities and operation, blockchain users or miners, and other pertinent stakeholders.

2.2.4 Benefits of Blockchain to IoT IWMS

The following are well-known benefits which blockchain and IoT convergence promises [17, 37, 59]:

- IoT autonomous transactions using smart contracts in a secure manner among participating devices
- Allows for shared transactions in private blockchain ledgers among parties involved in transactions
- Visibility and transparency in water trading
- Identity and asset management
- Cost reduction through blockchain model as against cloud model
- Tamperproof data
- Open and transparent transactions
- Elimination of intermediaries to consummate transactions
- Improved trust
- Availability of historical records of transactions on multiple IoT smart devices
- Cost reduction linked to deployment and maintenance of Internet infrastructure
- Faster rate of consummating transactions
- Enabling distributed file sharing

2.2.5 Comparison of IoT with Blockchain

Table 2 summarizes the comparison between IoT and blockchain.

Table 2 Comparison between IoT and blockchain [25]

Features	IoT	Blockchain
Security	Low	High
Computational cost	Low	High
Bandwidth	Low consumption	High consumption
Decentralization	No	Yes
Latency	Low	High block mining time
Scalability of nodes	Scales well	Scales poorly

Table 3 IoT challenges and potential blockchain solutions

IoT challenges	Potential blockchain solution
Cost, capacity, and exponential growth of IoT devices constraints	Allows for autonomous, decentralized, and secure communication among devices through smart contracts
Vulnerabilities in IoT architecture, such as hacking, DDoS, and data theft	Cryptographically secured and verified communication/transactions between participating devices
Impact of cloud server downtime and inaccessibility of services owing to several causes, since IoT rely on this arrangement	Elimination of single point of failure, as records are decentralized on numerous devices within the network
Trust and manipulation of data residing in a central location	Decentralization, immutability, and auditability of all transactions

2.2.6 Blockchain-IoT Integration Challenges and Solutions

A summary of IoT challenges and potential blockchain solutions based on a study conducted in [37] is presented in Table 3.

2.3 Intelligent Water Management Network and System

Increasing global population, unpredicted weather patterns, increasing demand for safe water supply by consumers, water stress, and aging water infrastructure call for an innovative and sustainable means of safe and secure water supply for domestic and other usage by water utilities. One key challenge is the loss of water in the distribution network due to pipe bursts, technically known as non-revenue water (NRW), which has direct effect on increased power consumption needed to pump water on the water utilities, financial loss [56], as well as a heightened health risk on consumers. This calls for the use of sustainable technologies for intelligent water management in order to mitigate and proactively monitor the entire water system. Intelligent water system is the harmonious use of water among people, industry, and the environment in a sustainable, safe, and secured water environment and supply service and contributing toward low energy consumption and carbon

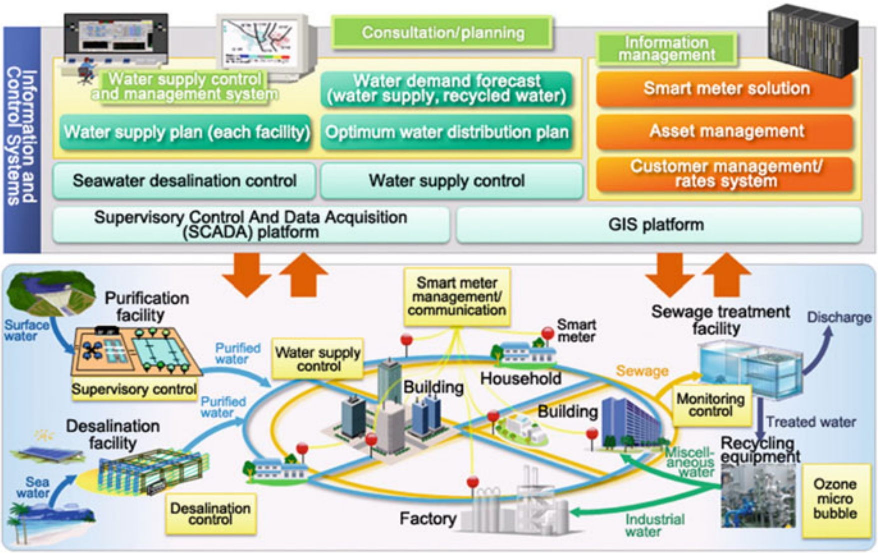

Fig. 2 Intelligent water system conceptual framework [26]

emission [61]. Smart water network is an *integrated set of products, solutions and systems that enable utilities to remotely and continuously monitor and diagnose problems, pre-emptively prioritize and manage maintenance issues and use data-driven insights to remotely control and optimize all aspects of the water distribution network,* as well as *comply transparently and confidently with regulatory and policy requirements on water quality and conservation* and *provide water customers with the information and tools they need to make informed choices about their behaviors and water usage patterns* [56]. The overall objective of smart water solutions includes smart measuring and monitoring across the water distribution, enhanced security, better analysis of the generated data, and enhanced revenue and efficiency [56]. Figure 2 depicts Hitachi's [26] conceptual intelligent water management system which integrates smart supervisory control, instrumentation, information management, and water treatment system, taking into consideration the balance between people and environment in the water environment, ensuring that demand for safe and stable water supply is met in conjunction with concrete environmental conservation strategies for the entire water cycle – water resource cycle, water use, and recycling. In addition to this, practical efforts are as well made to ensure maintenance management of the utility's infrastructure and overall operating efficiency using information and communications technology (ICT).

3 Blockchain-IoT Solutions for Smart Water Management

3.1 Overview of Global Perspective

As a result of the recent increase in cases of droughts, floods, hurricanes, and tsunamis, governmental agencies and private bodies around the world are now compelled to devise smart measures and build sustainable infrastructures for ensuring water security and management [21, 41]. This goal of implementing pragmatic solutions for securing the quality and quantity of water in rural regions and urban areas is still a technologically challenging task which has been successfully tackled in select developed ICT economies like Australia and Singapore [38, 43, 50].

In Australia, the South East Queensland (SEQ) water grid was established as an integrated system for managing and securing urban water supply [38, 43, 51]. This smart integrated system consists of water demand forecasting platforms, water reservoirs and connected dams, water treatment installations, desalination plants, water pumping stations, duplex pipelines for two-way water movement, and, most importantly, a wide range of water sources through recycling, desalination, and precipitation/rainwater [11, 38, 43]. The key benefit of incorporating alternative sources of water supply in the SEQ water grid is to curb scarcity and achieve climate resiliency and critical crisis prevention [11, 51, 57].

In Singapore, the water supply network (WSN) of the Public Utilities Board (PUB) was set up to contrive a self-sufficient network for water management through a holistic process that involves water collection, reclamation, production, and distribution [1, 38, 48]. This holistic process was implemented through the nationwide deployment of smart sensors for real-time monitoring and analytic tools for decision support system in order to achieve an effective and sustainable water supply network management [38, 43]. The operational focus of this smart water grid are water quality monitoring (real-time monitoring, event prediction, and demand forecasting), water conservation (recycling, prevention of wastage, and optimum usage), automated meter reading (real-time water utility information/updates), leak management (leaks/faults detection and preventive maintenance), and asset/infrastructure management (risk management platform development, data mining, and database integration) [1, 43]. WSN also employs a wide range of water sources such as desalinated brine/seawater, harvested rainwater, reclaimed water, and stormwater. This smart water grid consists of water reclamation plants, desalination plants, duplex pipelines, water reservoirs, waste management system, and other core integral infrastructures [1, 38].

3.2 African Perspective

The pace of smart water grid development and intelligent water management in Africa is still very slow due to endemic issues associated with limited access to clean water and lack of reliable water supply/sources [8, 30, 32]. In addition to this, rapid population growth coupled with climate change and other catalysts of water insecurity such as reckless industrial practices, inconsistent water policies, loose water quality control, feeble infrastructure, intentional pipeline damages, poor maintenance culture, high operational costs, huge water utility bills/charges, wanton domestic water wastage, and frequent uncontrolled water losses has subjected many Africans living in urban and rural areas to perennial water scarcity and other severe water-stressed conditions [4, 20, 23, 39, 40]. The implication of these existing challenges is that about 50% of the water supply is inevitably lost before reaching the domestic and industrial consumers in Africa. Nonetheless, there are genuine efforts recently geared toward intelligent water management in Africa [8, 58].

In Kenya, HydroIQ is an indigenous innovation from *Hydrologistics Africa* (Techstars Company) [8]. This solution operates as a water virtual network operator (WNVO) by incorporating smart/automated metering device into the existing traditional water supply network [47]. The WNVO relies on analytic tools, IoT, and payment automation [8, 47]. Consequently, this smart device integration transforms the old traditional water infrastructure into smart water grids by infusing intelligence into water distribution and allowing real-time pipeline condition monitoring for leaks/faults, water pressure, and water quality [8, 47]. In addition to this, by setting up and installing this technology at households, it makes it possible to monitor and control domestic water consumption, thereby allowing local consumers to pay for only the consumed quantity on a pay-as-you-go (PAYG) basis using mobile payment or any other preferred electronic payment channel [8, 47].

In Kyuso, a largely rural district of Kenya, Oxford University researchers implemented the idea of harnessing the pervasive and penetrative powers of mobile networks for indicating when hand pumps are dysfunctional or nonfunctional [31]. These smart hand pumps rely on pump handle movement, mobile data transmitter, water flow measurement, real-time hourly water usage reporting, database processes, information processing, pump location estimator, backbone/central server, and online pump condition alerts [31].

Another innovative solution is the *MajiData* developed by Kenya's Ministry of Water and Irrigation in conjunction with Water Services Trust Fund and in cooperation with the German Development Bank (KfW), German Cooperation for International Cooperation (GIZ), United Nations Human Settlements Programme (UN-Habitat), and Google [31]. Aided by satellite imagery, this online database service provides vital data on slums and low-income areas for water boards and water service providers in order to systematically plan and implement effective water distribution and sanitation schemes for the slums and urban low-income areas [31]. Another case worth mentioning is the technological cooperation and intervention of Culligan (United States Water Treatment Company) in Kigali, Rwanda, to build a smart water grid for the area [49].

3.3 Blockchain-IoT Conceptual Framework

Cloud computing has been an enabling technology for IoT for storage, processing, and analysis of data generated by IoT sensing devices in real time. However, with the proliferation of IoT devices projected to reach over 50 billion mark in the near future, coupled with the assumptions of good Internet connectivity, high bandwidth, and low latency upon which cloud computing concepts have been built on, this cloud-centered architectural arrangement is no longer going to be optimally feasible. Other issues such as trust and transparency are also legitimate concerns raised by cloud computing stakeholders. Even though cloud computing over the years has evolved into new and complimentary concepts such as edge, fog, mist, and dew computing to enhance the capabilities of the cloud computing, most of these inherent challenges with cloud computing persist. Hence, the integration of blockchain and IoT is a promising synergy that could enhance the potential of IoT by providing security, trust, fidelity, and confidentiality in information sharing since the data will remain immutable, appendable in a universally distributed open ledger. Decentralization, scalability, identification of nodes in a trustworthy manner, autonomy, reliability, security, and secured deployment of firmware into devices are some of the benefits identified in [50] that the integration of blockchain-IoT promises. For blockchain-IoT integration in IWMS, we suggest a hybrid approach integration proposed in [50], where cloud computing together with its evolving new concepts like edge, fog, and mist computing could be incorporated into the design to play a complimentary role, as depicted in Fig. 3.

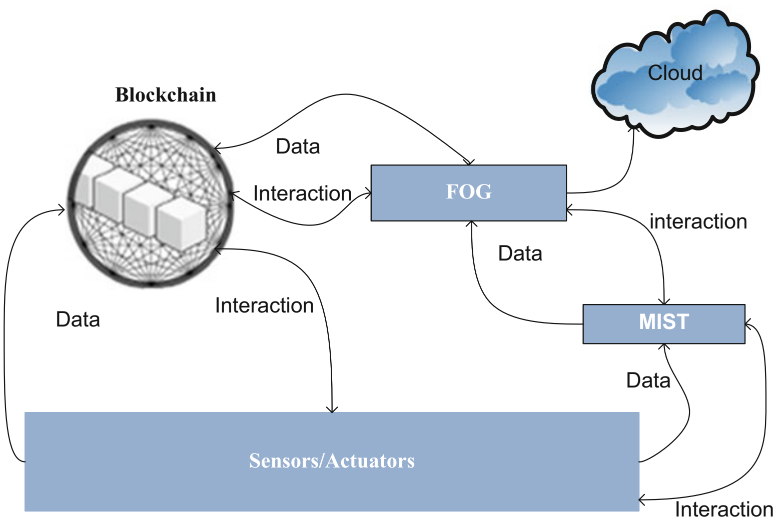

Fig. 3 Conceptual hybrid blockchain-IoT integration (adapted from) [50]

4 Potential Use Cases in Intelligent Water Management

4.1 Stormwater Management

Technical Description and Existing Challenges: With respect to stormwater management, most African cities still adopt ineffective techniques, and as a result, the accumulated runoff of unabsorbed water due to impermeable surfaces lead to pollution, flooding, and other effects deleterious to the environment [16, 37]. In technologically advanced countries, an innovative blend of green infrastructure, gray infrastructure, and smart IoT solutions are employed, deployed, and strategically positioned to monitor stormwater, runoff volumes, peak flows, and short-term and long-range weather conditions in order to take preventive, effective, and sustainable measures for water recycling/reuse, water conservation, and environmental protection [16, 29]. In this research context, gray infrastructure is the stock of engineered facilities and equipment such as water treatment plants, sewage system, and piped drainage system [16, 54]. On the other hand, green infrastructures are the eco-friendly structures like stormwater planters, urban tree canopies, constructed wetlands, green roofs, rainwater harvester, bio-retention facilities, downspout pipes, permeable pavements, detention ponds, retention basins, and land conservation schemes [16, 62]. The smart IoT infrastructures are usually autonomous devices with inbuilt intelligence for event sensing, condition monitoring, data caching/storage, status reporting, and decentralized processing and, most importantly, equipped with seamless and real-time accessibility [3, 27, 45]. In these developed ICT economies, stormwater is considered as a vital resource, and the objectives of blending this tripartite infrastructure are to achieve effective stormwater channeling, storage for evacuation, treatment of water discharge, flow regulation, reintegration, and reuse of stormwater [9, 45].

Current State and Opportunities: A pertinent use case scenario is that of Dogondoutchi city in Niger Republic where land reforms, hillside retention systems (half-moon terraces), desert reforestation, and infiltration systems (filter dykes) were used to control stormwater runoff and quell water stagnation issues in order to revitalize aquaculture, local farming, and irrigation [32]. Another relevant use case scenario is a project funded by the Danish International Development Agency (DANIDA) which is a technological partnership between the Department of Geosciences and Natural Resource Management (IGN), University of Copenhagen, Denmark, Institute of Human Settlements Studies (IHSS) at Ardhi University, Tanzania, and Ethiopian Institute of Architecture, Building Construction and City Development (EiABC) at Addis Ababa University, Ethiopia [62]. The initiative of this project is to introduce and implement the concept of landscape-based stormwater management (LSM) to the African cities of Dar es Salaam and Addis Ababa [62]. LSM entails adopting a robust green infrastructure coupled with adequate storage capacity for the retention, recycling, and reuse of accumulated stormwater runoff during rainy seasons in order to ensure sustainable and intelligent water management [62]. The practical implementation of the LSM employs local retention structures, infiltration systems, land conservation schemes, and other green infrastructures pertinent to these African cities [62]. The benefit of this eco-friendly approach is that it reduces flood risks, revives urban water supply, can be easily used and managed by local consumers, and, most importantly, provides an alternative to the sewage system which is a gray infrastructure [62]. Another germane use case scenario is that of Atlantis town, Western Cape, South Africa, where stormwater is harvested by infiltrating the runoff into the local aquifer with the aid of two large retention ponds [9, 45]. The captured water is injected into a system of boreholes for refinement, reintegration, and reuse in a process popularly known as aquifer recharge management [9, 45]. This intelligent water management technique has ensured sustainable and steady water supply in the region for many years [9, 45].

Recommendation – Public-Private Partnerships and Strong Linkages Between Rural Authorities and Urban Stakeholders: There is the urgent need for respective governments of different African countries to establish runoff monitoring and control unit in strategic rural regions in order to reduce, reuse, and recycle stormwater and wastewater. This can only be achieved through the synergy of government agencies, corporate bodies, rural engineering departments, environmentalists, land use experts, sustainability specialists, industrial technologists, and other stakeholders.

Access to Up-to-Date Technologies, Management Knowledge, Knowhow, Technical Information, Operational Data, and Vital Statistics: Local water authorities and agencies in different African countries need to genuinely and judiciously invest in green infrastructure, technical knowledge, reliable meteorological data collection, storage and analysis, technology management, analytic and forecasting tools, blockchain-IoT trends, sustainable water practices, and other indispensable innovations needed for stormwater management. This will reinforce and better equip the local water authorities to adopt predictive, proactive, and preventive measures for intelligent water management.

4.2 Water Quality Monitoring and Reporting

Technical Description and Existing Challenges: In most African cities, water quality monitoring and smart water metering is still lacking, and most water contamination cases are often detected and reported by the local consumers who have been already exposed to the hazard [5, 24]. It must be highlighted that water contamination occurs more in the water distribution system than in the treatment plants [5, 32]. Contamination in the water distribution system are as a result of colorization, microbial intrusion, disinfectant expiration, biofilms, water staleness, pressure differentials, biochemical abnormalities, industrial accidents, treatment errors, storage wears, pipe stress and bursts, untidy pipe works, pipe corrosion, release of pollutants/toxicants, and acts of sabotage [13, 60]. Apart from this, one of the biggest challenges to optimum water resource management, equitable water distribution, and reliable water access is the issue of losses attached to non-revenue water [5, 40]. Non-revenue water is as a result of unbilled authorized consumption (from unbilled un-metered consumption and unbilled metered consumption), physical losses (from storage leaks, transmission leakages, storage tanks overflow, distribution mains supply leakages, and metering service connection leaks), and commercial losses (from end-user meter inaccuracies, fraudulent manipulation, unauthorized consumption, systemic bugs, and data processing/handling errors) [5, 40].

In developed countries, water quality monitoring in smart water grids is usually achieved by deployed multi-contaminant sensors and biosensors through physiochemical measurement (to detect pH, optical properties, temperature, turbidity, flow, electrical conductivity, chlorine content, oxidation reduction potential (ORP)) and/or microbial measurement (to detect toxicity) [3, 13]. These parameters are sensed in real time, measured with online instrumentation, and connected to microcontrollers for processing and analyzing the water quality data through event detection and forecasting systems [13, 58]. Local water authorities are then promptly alerted on the location and severity of the detected anomalies in order to take proper preventive actions [27, 60]. The real-time sensed data is also useful for continuous water sampling and hydraulic model calibration which is a replacement to the costly, monotonous, and tedious traditional calibration process [43, 48]. Specifically, smart water meters are used to effectively curb non-revenue water costs, control water wastage, and address pressure differentials, leakages, damages, fraud attempts, consumption rate problems, inaccessibility to account and consumption data, service quality issues, charging and billing issues, and uncontrolled water losses through smart pressure management processes, smart step testing, and other intelligent techniques [40, 60]. Smart valves are employed to prevent contaminant intrusion and cut off polluted water from mixing with potable water through contaminant isolation technique and smart flood management schemes [40, 48]. Generally, smart water grids systemically integrate these automated meters, actuators, sensor array, controllers, and analytic tools for intelligent control and sustainable water management in order to ensure high-quality water supply is reliably and efficiently delivered only when and where it is needed [27, 40].

Current State and Opportunities: Power Ledger from Australia is pioneering a number of interesting and innovative blockchain-powered trading platforms for smart water metering data management, especially in the city of Freemantle [60]. With respect to water quality monitoring and smart water metering, the African market is growing with a good prospect due to the presence of important players coming up with innovative solutions to serve the purpose of intelligent water management. Some of these players are Junaco Trading from Kenya, Aqua-loc from South Africa, Maji Milele Limited from Kenya, Honeywell Elster in South Africa, Metron-Farnier from the United States of America, Amanzi Meters from South Africa, Ideal Prepaid from South Africa, Lesira-Teq Smart Metering from South Africa, Krohne in South Africa, PEC Africa from South Africa, Kamstrup from South Africa, and other technology players [5, 34]. For example, iMvubu from Amanzi Meters employs AMR and GSM for remote meter reading and provides equal treatment to all local consumers by restricting water consumption to a predetermined volume [5].

Generally, smart water metering coupled with water quality monitoring and control is garnering increasing attention and interest in Africa which is forcing local water authorities to take the issue of water conservation, fair/accurate billing, and water management seriously. For instance, water authorities in Nairobi and Nyeri, Kenya, are now issuing meter readers equipped with utility mobile phones which are used in taking, sending, and storing snapshots of correct meter readings for verification and validation purposes [5]. An improvement of this technology was developed which allows local consumers to read meters and cross-validate by simply taking and transmitting an iOS snapshot of the accurate reading to the central utility authorities [5]. In addition to this, some utility authorities in Durban, Dakar, Nairobi, and Nyeri are now incorporating GIS to check city population with respect to water consumption, monitor/report on weather data and climatic conditions, plan service extension, monitor water pipes, and inspect domestic units connected to the water grid and other pertinent information [5].

Recommendation – Developing Multiservice Strategies and Integrated Management Approaches: Water conservation schemes, quality monitoring initiatives, and quality control strategies should not be limited and restricted to the treatment plants, but these techniques should be systematically integrated network-wide (with the aid of IoT sensors, actuators, cognitive systems, and lightweight intelligent codes/programs) in order to achieve end-to-end total quality management for the entire water supply network. This intelligent network will further enhance the performance of the smart water meters by providing a robust, reliable, and resilient water management that can cater for the immediate and future water demands of respective African cities and communities.

4.3 Smart Payment and Contract

Technical Description and Existing Challenges: In Africa, many entrepreneurs operating small- and medium-scale enterprises with the vision of tackling critical water challenges by developing innovative solutions are often restricted as a result of inaccessible loans and standard financing channels from banks due to institutional bureaucracies and stringent collateral terms and conditions [11, 20, 50]. This central financial authority bottleneck slows down innovation process and introduces high risks, verification delays, and currency/country barriers especially in scenarios where there is need for regional cooperation or international collaboration to enable the initial implementation and continued success of the smart water projects [11, 50]. Blockchain is a disruptive and explosive technology that can de-bureaucratize this centralized funding process and facilitate the growth of technological start-ups willing to produce enabling infrastructure, smart facilities, and key IoT solutions that will spur and sustain intelligent water management in Africa [20, 50].

Some developed nations are now developing innovative blockchain applications for water treatment contracts, smart payment, sharing utility data and facility information, water rights trading, and many other interesting applications [11].

Smart payment in this context is done with the aid of a cryptocurrency where every smart water device has its own online "bank account" which is shareable with other devices and/or consumers, and most importantly, micro-transactions enable automated compensation for water consumption [11, 20]. On the other hand, a smart contract is an inbuilt program in the blockchain network for automatically transferring cryptocurrencies between parties (consumers, smart water devices, and other relevant utility units) when certain stipulated conditions are fulfilled [11, 20]. Smart payments and contracts solve the existing inconsistencies and errors associated with the traditional performance evaluation, maintenance, and commercialization of water facilities [11, 50]. By adopting these smart methodologies, business transactions are seamlessly streamlined, costs are minimized, and fraud attempts are effectively checked/prevented [11, 50].

Current State and Opportunities: In Australia, Civic Ledger developed a blockchain-powered P2P platform, Water Ledger that utilizes token management system and smart contract for monitoring water transactions and automatically updating records of state water departments [11]. OriginClear from the United States is developing an application called WaterChain which is a blockchain protocol that employs cryptocurrency and smart contracts to ensure service efficiency and operational transparency in the water treatment industry [11]. AQUAOSO from the United States is architecting blockchain to track ownership of water rights and also integrating smart contracts into existing solutions with the aid of IoT-enabled sensors to monitor water supply chain and quality of service delivery and ensure smart payments [3, 11]. In China, partnership between NW Blockchain Limited and Newater Technology is reached for managing water facilities/plants and industrial wastewater projects through asset-based token sales [11]. In Senegal, Banque Regionale de Marches launched eCFA Franc cryptocurrency for West African Monetary Union in order to drive Internet of Intelligent Things to build and maintain key infrastructure for economic development [24]. In South Africa, Bankymoon launched a blockchain humanitarian platform that allows donors to top up specific schools' meters from any location around the world [11]. Generally, blockchain technology can be integrated into smart meters in order to enable consumers to pay bills with cryptocurrencies and adopt sustainable water practices.

Recommendation – Genuine Interest and Investment in Distributed Computing and Blockchain-Powered IoT Engineering: Respective governments of different African countries need to urgently invest in remote-access data processing, data mining, tele-computing, computational intelligence, big data analytics, and blockchain-based IoT design methodologies. By doing this, transparency will be ensured, and all stakeholders (domestic consumers, industrial users, local water authorities, private investors, rural water managers, conservationists, policymakers, and other pertinent participants in the water sector) will have access to reliable, relevant, and recent data on water quality and quantity in order to formulate policies and make more informed decisions. This will also stem corrupt practices and fraudulent activities especially in scenarios where local water authorities have been bribed to tamper with water quality data and falsify consumption rates and charges. In addition to this, adopting these intelligent distributed computing techniques will catalyze P2P water rights trading enabling local consumers with extra water resources to trade off this excess (or any saleable portion) without involving and relying on the central authority. This smart trading decision is often based on information on market trends, latest weather forecast data, long-range climatic predictions, and other bulk of processed data available and accessible through the Internet and/or mobile devices. This will also boost market fidelity/outlook and open up novel invest opportunities, smart business models, and innovative finance strategies for start-ups and enterprises willing to integrate IoT, AI, and blockchain solutions into their products or designs in order to tackle existing water challenges in various African regions.

5 Conclusion

Blockchain and IoT are still in their developmental stage in Africa. The current trend suggests that blockchain and IoT with artificial intelligence will be dominant technologies in the near future. In this era of the 4IR, Africa must key into the numerous benefits these technologies offer. One such area that could benefit from this synergy is in the water industry; this of course stems from the fact that water connects every aspect of life and it is critical to the social and economic survival of the African region. There is no one-size-fits-all solution to the water and sanitation crisis saddling the region; however, the integration of blockchain and IoT has the power to revolutionize water and sanitation management toward achieving SDG 6 as envisioned by the UN in 2035, through innovative, efficient, scalable solutions, based on these two technologies. This will ensure that African cities are adequately prepared with technologies to respond and address the perennial challenges associated with water crisis, such as in Cape Town of recent and other parts of Africa in a sustainable and efficient way.

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