Optimization of Water Supply in Smart Cities: An Integrated Approach to Data Management, Artificial Intelligence, and Smart Water Technologies

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Abstract: Amid growing water scarcity and losses in distribution networks, it is crucial to find effective solutions that increase efficiency and ensure the sustainability of water management. This global demand is reflected in the regional scenario of the state of Bahia, especially in the capital, Salvador. Data from the Bahia State Basic Sanitation Regulatory Agency (AGERSA) points to recurring problems with water interruptions that are not sufficiently unpredictable. Based on this issue, this article presents a literature review on emerging technologies to improve water supply management in smart cities, with specific application to the capital of Bahia. The methodology employed involves a technical review of the main technologies currently applied in Smart Water Networks, including smart meters and advanced sensors for water quality monitoring, proposing an integrated model based on the Internet of Things (IoT) and Big Data analysis (AI; Machine Learning).The expected results include improved operational efficiency, greater accuracy in early detection and response to critical events such as leaks and supply interruptions, as well as greater transparency of water supply and treatment information for users and managers. The conclusion is that the implementation of the solution will significantly contribute to the technical, operational, and environmental sustainability of urban water systems.
Keywords: Smart Water. Artificial Intelligence. Internet of Things. Data Management. Smart Cities.

1. Introduction

Water management is facing a scenario of increasing complexity, marked by a growing global water scarcity and continuously rising consumption. It's estimated that the world will face a 40% water deficit by 2030 [1], a situation that climate change is expected to worsen. A substantial part of this challenge lies in the significant losses in obsolete water distribution systems, where the average waste in Europe reaches 26% and, in some regions, can exceed 50% [2]. In Brazil, this percentage is 37.8%, but states such as Acre and Amapá exceed 60% [3]. In Salvador, approximately 57% of drinking water is lost before reaching consumers [4]. Data from the Basic Sanitation Regulatory Agency of the State of Bahia (AGERSA) reveal that water supply management faces significant challenges. In 2023, Salvador accounted for 37.74% of all complaints received by the AGERSA ombudsman's office across the state, with water scarcity alone accounting for 35.47% of these complaints [5]. Frequently associated with unpredictable and irregular supply interruptions by the Baiana Water and Sanitation Company (Embasa), these complaints signal not only a direct impact on citizens' quality of life but also substantial difficulties for the planning and regulatory efficiency of public services. Thus, innovative technological solutions, such as integrated smart systems based on IoT and predictive data analysis, are emerging as promising alternatives to optimize management, anticipate interruptions, improve transparency, and support both consumers and the agencies responsible for providing and supervising these services.

In addition to waste, the existing, often aging, water infrastructure presents critical operational challenges. Problems like leaks, meter failures, water theft, and contamination are recurring, directly impacting the efficiency of the supply and the quality of the water provided [6]. The lack of real-time monitoring and analysis in this infrastructure worsens the situation, making the identification and correction of anomalies a slow and costly process. Complementing these issues is the pressing matter of non-revenue water, which refers to water that is produced and introduced into the distribution system but does not generate revenue for sanitation companies [6-8]. This loss, directly linked to leaks, theft, and faulty meters, has a significant financial impact, drastically reducing the revenues of water utilities.

In response to growing urban challenges, smart cities are emerging as a development paradigm, using advanced technologies to improve the management of infrastructure and urban services [9-11]. At the heart of this concept is the application of big data, vast quantities of information generated by sensors, devices, and human interactions which, when properly analyzed, offer profound insights into urban systems [9], [11]. This real-time monitoring capability allows cities to optimize the efficiency, sustainability, and resilience of their infrastructures, anticipating future demands and ensuring the allocation of resources according to current and future needs.

Against this backdrop of challenges and technological advances, this article aims to conduct a literature review on water supply system optimization, focusing on the integration and synergy between advanced data management technologies, Artificial Intelligence, and Smart Water. The analysis of these concepts sought to explore how their combination can revolutionize urban water systems, enabling more accurate monitoring, proactive anomaly detection, and more strategic and efficient decision-making.

2. Methodology

This section details the methodological approach used for the systematic literature review, aiming to identify, analyze, and synthesize the most relevant information on optimizing water supply in smart cities through the integration of data management, Artificial Intelligence, and smart water technologies.

The literature search was conducted in renowned academic databases, including Scopus, Web of Science, and IEEE Xplore. The search strategy involved combining key terms related to the main concepts of the article. The terms were grouped and combined using Boolean operators ("AND," "OR") to maximize the scope and relevance of the results.

Identifying the central themes of this review allowed for the best combination of terms. The keywords and Boolean operators used were

("Smart Water Technologies" OR "Smart Water") AND "Smart Cities" AND ("Data Management" OR "Big Data" OR "Data Analytics") AND ("Artificial Intelligence"). The publication period of the documents was limited to 2014 to the present to cover the recent years relevant to the popularization of the concepts evaluated. A descriptive analysis of the literature revealed that most of the studies are very recent (from 2020 to 2025), demonstrating the topic's relevance and relevance.

The article selection process followed the steps of searching, using the aforementioned strategy; selecting, through a preliminary reading of titles and abstracts, and then reading in full, those articles most closely related to the topic; and finally, a qualitative analysis of eligible articles: peer-reviewed articles addressing the optimization of water supply in urban environments, smart cities, or water systems, and discussing the application of data management (including Big Data), Artificial Intelligence (including Machine Learning), and/or smart water technologies (such as IoT, sensors, and smart meters).

3. Thematic analysis

In response to these water management challenges, the water sector is evolving toward a more sophisticated paradigm characterized by the integration of physical, cyber, and human components, giving rise to Cyber-Physical-Human Systems (CPHSs) [7], [12-13]

3.1. Cyber-Physical-Human Systems (CPHSs) in Water

The evolution of sanitation companies to CPHSs represents a fundamental shift in how water services are managed and delivered. In these systems, there is a growing interconnectedness and interdependence between physical assets, such as pumps, pipes, and valves, and cyber systems, which encompass software, data, the Internet of Things (IoT), and Artificial Intelligence (AI) [14]. Human-social interactions, involving employees, customers, and the community, are equally crucial as they influence and are influenced by these components [12]. This integration aims to optimize demand management, improve customer service, and enhance contamination detection, among other operational and strategic benefits.

Improved water demand management is driven by the collection of real-time consumption data through smart meters and IoT sensors, overcoming the limitations of mechanical meters that require manual reading and offer low data resolution [15]. This data granularity and temporality allow for a deep understanding of water usage patterns, helping utilities to optimize distribution, predict demand peaks, and implement more effective demand management strategies. Furthermore, customer service is enhanced with the availability of transparent information and the ability to make payments and report problems online [12]. Machine Learning (ML) and AI algorithms can analyze large volumes of data to identify abnormal patterns, such as leaks and unusual consumption, with high accuracy, even in low-resolution data [16].

There are several examples of this approach being applied in the water sector by cities, companies, and governments. In leak detection and prevention, the city of Oslo, for example, monitors more than 1,550 km of water pipes to obtain real-time information and reduce leaks [12]. Similarly, in Melbourne, Australia, Southeast Water, Yarra Valley Water, and City West Water collaborated on a digital metering program that saved more than 40,000 liters of water per day through leak detection and correction, in addition to identifying the loss of 50,000 liters per day on customer properties [12]. The Mackay Regional Council in Queensland, using AMI (Advanced Metering Infrastructure) technology, issued approximately 400 leak notifications per month, saving approximately 834 ml of water [14]. In water quality, Veolia developed the "waternamics" platform, which, when applied to the drinking water network in Lyon, France, helped identify emerging chemical substances in the Rhône River [12].

Despite the benefits, the complexity and emerging risks of interconnectedness in CPHSs are notable. A limited understanding of these interdependencies can result in wasted resources, service interruptions, systemic failures, and a compromised customer experience [8], [12]. Specific challenges include the integration of existing IT systems, which are difficult to integrate with newer systems and incur high maintenance costs. The aging infrastructure, with many pipes at the end of their useful life (averaging 50 years, but many at 70-100 years), increases the propensity for leaks and ruptures [16]. Environmental sustainability is a concern, given the impact of climate change on rainfall patterns and water quality, in addition to the energy costs of data processing. Data management presents challenges of volume, velocity, and variety, as well as security and privacy issues. A lack of cybersecurity and data analysis expertise and skills in the workforce, as well as customer and community engagement, are additional barriers to technological adoption [12].

3.2. Theories of Smart Cities, Sustainability, and Urban Resilience

The theories of Smart Cities, Sustainability, and Urban Resilience converge to provide a fundamental conceptual framework for optimizing water supply in the contemporary scenario. At its core, the Smart City Theory conceives of urban environments that use the integration of Information and Communication Technologies (ICT) to enhance urban services and infrastructure [12]. AI and big data are essential components of this vision, maximizing resources and increasing sustainability [17]. In this context, water utilities are transformed into "digital utilities," employing smart meters, sensors, and analytical platforms to manage the water cycle more efficiently.

The Theory of Sustainability, in turn, emphasizes the need to meet the demands of the present without compromising the ability of future generations to meet their own needs. Predictive analysis allows for optimizing resource use, minimizing water waste, and reducing the carbon emissions associated with treatment and distribution, contributing to a smaller urban environmental footprint [18]. The ability to predict water demand and detect leaks in real time, for example, ensures that water is used more consciously and efficiently. Although AI is not a universal solution for all sustainability problems, its value lies in its ability to facilitate improved environmental governance and promote resource conservation [18].

Finally, the Theory of Urban Resilience focuses on the ability of cities to resist, absorb, and recover from shocks and stresses, such as natural disasters, infrastructure failures, or supply interruptions [19]. The integration of ICT and big data strengthens this resilience, optimizing environmental management and risk mitigation. Real-time monitoring of water infrastructure allows for the proactive detection of anomalies, such as pressure variations or contamination, enabling rapid responses and minimizing the impact of disruptive events [19]. Predictive analysis, powered by AI, can anticipate floods, droughts, or demand peaks, empowering cities to dynamically adapt their systems and ensure the continuity of essential services.

4. Current Challenges and Barriers

Despite the promising benefits, the digital transformation in the water sector faces significant challenges and barriers that need to be addressed to ensure a successful and sustainable implementation of Smart Water systems. One of the main obstacles is the integration of legacy IT systems and aging infrastructure [12], [20-21].

Many sanitation companies still depend on outdated software and hardware, which are expensive to maintain and difficult to integrate with new technologies. This reliance on old systems hinders the full adoption of Industry 4.0 technologies, making modernization a complex and costly process. The physical infrastructure, with pipes that are decades old, requires high investments for modernization, which exacerbates the challenges of technological updates.

Data security and privacy in IoT networks and critical systems constitute another crucial barrier. The growing interconnectedness of IoT devices in water systems increases the likelihood of cyberattacks, with documented incidents already resulting in sewage leaks and water contamination [21-22]. The privacy of consumer data is an ethical concern, as detailed information about water consumption can reveal personal lifestyle patterns and behaviors, such as times of home occupancy, meal schedules, and even religious habits. Ensuring data sovereignty and compliance with data protection regulations, which vary between countries, is fundamental to building user trust and preventing the misuse of sensitive information.

The lack of standardization and interoperability among technologies is a persistent problem that prevents the mass adoption of Smart Water solutions. The diversity of IoT technologies and protocols makes it difficult to integrate heterogeneous systems, resulting in "excessive pilots" instead of widespread adoption. The absence of clear interfaces and standardized implementation guidelines for smart water solutions creates barriers to scalability and interoperability between platforms and devices.

Data quality and methodological gaps in CPHS representation also pose significant challenges. The vast amount of big data generated can be inconsistent, incomplete, or in varied formats, making analysis and the extraction of actionable insights difficult [12]. The lack of logical approaches to optimize data value and the absence of long-term strategic planning for technology adoption and data management are important methodological gaps. Additionally, there is a lack of methods to identify, categorize, and prioritize evolving risks, as well as to model the emergent behavior of CPHSs, which are complex systems with dynamic and unpredictable interactions. A limited understanding of increasing interconnections can lead to unintended consequences and the ineffectiveness of interventions.

5. Research Directions

To overcome current challenges and maximize the potential of water supply optimization in smart cities, several research directions are essential, focusing on enhancing the synergy between data, AI, and Smart Water.

The development of new models for consumer behavior and anomaly detection is fundamental. Research can delve into the application of advanced Machine Learning and Deep Learning techniques to improve the accuracy of identifying abnormal consumption patterns, such as leaks and unauthorized water use. It is crucial to develop models that effectively handle low-resolution and inconsistent data, a common reality in legacy systems. The ability to proactively identify the intent of fraud or the causes of anomalies, such as faulty meters or tampering, can optimize field inspections and reduce non-revenue water losses.

Advances in sensor and communication technologies are continuous and critical. Research should focus on developing next-generation sensors that offer greater accuracy, reliability, and resilience, with capabilities for monitoring network management and operational parameters such as flow, pressure, consumption, and water level; and quality parameters such as pH, turbidity, total dissolved solids, dissolved oxygen, residual chlorine, and biological parameters. The improvement of Low Power Wide Area Network (LPWAN) technologies, such as LoRaWAN, SigFox, and

NB-IoT, is vital to ensure long-range, low-energy connectivity in massive IoT deployments in urban and rural environments [22-23]. The ability to deal with interference and optimize spectrum allocation in massive IoT scenarios should also be a priority.

Finally, the development of governance frameworks for CPHSs and AI is essential. As technology is not neutral and can reconfigure social relationships and values, it is crucial for future research to address how AI and CPHS systems can be governed responsibly and ethically. Research should also explore how changes in human relationships, roles, and processes within organizations are renegotiated by the adoption of smart technologies, and how interdisciplinarity can support the understanding and management of these complexities.

6. Final Considerations

The optimization of water supply in smart cities, through the synergy between Artificial Intelligence and data management in Smart Water systems, is emerging as an indispensable strategy to face global water challenges. This article explored the transformative potential of this approach, detailing how the evolution toward Cyber-Physical-Human Systems (CPHSs) and the integration of advanced technologies can revolutionize water management. The references addressed demonstrate that digitalization allows for real-time monitoring, the precise detection of anomalies such as leaks and contamination, and the implementation of predictive maintenance strategies, resulting in water savings, reduced operational costs, and improved service quality.

The fundamental contribution of this study lies in the synthesis of knowledge that highlights the importance of a more comprehensive and multidisciplinary approach. Integrating social and ecosystem dimensions into the design and governance of CPHSs is crucial, given that this technology can reconfigure access to water. Smart meters, for example, can help identify losses and manage consumption, but if implemented unevenly, they can marginalize low-income communities that cannot afford them or lack access to monitoring devices. Proper governance would ensure that all citizens have equitable access to the technology and its benefits.

Water system optimization must go beyond reducing financial losses. Governance must ensure that AI and data management systems also work to protect water ecosystems, reduce pollution, and ensure long-term sustainability.

Recommendations for future actions involve the development of robust policies that encourage technological adoption and the ethical use of AI, the training of the workforce to deal with new digital demands, and the promotion of close collaboration among all stakeholders—governments, utilities, the private sector, academia, and civil society. By addressing these challenges in an integrated and proactive manner, the potential of AI and data management in Smart Water can be fully realized, contributing significantly to the water security and sustainability of global cities.

References

[1] UN WATER. World water assessment programme. *The united nations world water development report 4:* Managing water under uncertainty and risk, 2012.

[2] EUREAU. *Europe's water in figures.* 2021 edition, 2021. [cited 2025 June 03]. Available from: https://www.eureau.org/resources/publications/eureau-publications/5824-europe-s-water-in-figures-2021/file.

[3] INSTITUTO TRATA BRASIL. *Sete estados desperdiçam mais da metade da água potável antes de chegar às residências.* Instituto Trata Brasil, 2022. [cited 2025 June 03]. Available from: https://tratabrasil.org.br/sete-estados-desperdicam-agua-potavel/.

[4] G1 BAHIA, *Levantamento aponta que 57% da água potável de Salvador é perdida; percentual é maior que média nacional*. G1 Bahia, 2023. [cited 2025 August 08]. Available from: https://g1.globo.com/ba/bahia/noticia/2023/03/22/pesquisa-aponta-que-salvador-tem-percentual-de-agua-perdida-acima-da-media-nacional.ghtml.

[5] AGERSA. Agência Reguladora de Saneamento Básico do Estado da Bahia. *Relatório de Gestão 2023.* Salvador, p. 18. 2023.

[6] LALLE, Yandja et al. Communication technologies for Smart Water Grid applications: Overview, opportunities, and research directions. *Computer Networks*, v. 190, p. 107940, 2021.

[7] BHANDARI, Pratik et al. Ongoing transformation of critical infrastructure systems as cyberphysical-human systems. In: *2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC).* IEEE, 2021. 3342-3347.

[8] VAN DUUREN, Diederik et al. Potential transformative changes in water provision systems: Impact of decentralised water systems on centralised water supply regime. *Water*, v. 11, n. 8, p. 1709, 2019.

[9] ACUÑA, Edwin Gerardo Acuña et al. Optimization of Urban Mobility with IoT and Big Data: Technology for the Information and Knowledge Society in Industry 5.0. In: *Ibero-American Congress of Smart Cities. Cham: Springer Nature Switzerland*, 2024. p. 46-61.

[10] PAUL AGBOOLA, Oluwagbemiga; MUZEYYEN FINDIKGIL, Meryem. A comparative framework analysis of the strategies, challenges and opportunities for sustainable smart cities. *Fostering sustainable development in the age of technologies*, p. 187-211, 2023.

[11] YU, Dianyou et al. Lifecycle management of urban renewal enabled by internet of things: Development, application, and challenges. *Results in Engineering*, p. 105706, 2025.

[12] BHANDARI, Pratik et al. Evolution of cyber-physical-human water systems: Challenges and gaps. Technological *Forecasting and Social Change*, v. 191, p. 122540, 2023.

[13] GRAFIUS, Darren R.; VARGA, Liz; JUDE, Simon. Infrastructure interdependencies: Opportunities from complexity. *Journal of Infrastructure Systems*, v. 26, n. 4, p. 04020036, 2020.

[14] BEAL, Cara D.; FLYNN, Joe. Toward the digital water age: Survey and case studies of Australian water utility smart-metering programs. *Utilities Policy*, v. 32, p. 29-37, 2015.

[15] TANG, Changwen; QIU, Chao; XIAO, Xinqing. Machine-learning and water energy harvesting based wireless water consumption sensing system in buildings. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*, v. 5, p. 100260, 2023.

[16] FOLKMAN, Steven. Validation of the long life of PVC pipes. In: *Proceedings of the 17th International Conference on Plastics Pipes*, Chicago, USA. 2014. p. 1-9.

[17] DAVID, Love O. et al. Integrating fourth industrial revolution (4IR) technologies into the water, energy & food nexus for sustainable security: A bibliometric analysis. *Journal of Cleaner Production*, v. 363, p. 132522, 2022.

[18] OGUNKAN, David Victor; OGUNKAN, Stella Kehinde. Exploring Big Data Applications in Sustainable Urban Infrastructure: A Review. *Urban Governance*, 2025.

[19] EBISI, Fahed et al. Machine Learning Schemes for Leak Detection in IoT-enabled Water Transmission System. In: *2023 International Conference on IT Innovation and Knowledge Discovery (ITIKD)*. IEEE, 2023. p. 1-7.

[20] ALEXANDRA, Carla et al. Cyber-physical systems in water management and governance. *Current Opinion in Environmental Sustainability*, v. 62, p. 101290, 2023.

[21] AMAXILATIS, Dimitrios et al. A smart water metering deployment based on the fog computing paradigm. *Applied Sciences*, v. 10, n. 6, p. 1965, 2020.

[22] BLANCO, José Miguel et al. A formal model for reliable digital transformation of water distribution networks. *Procedia Computer Science*, v. 225, p. 2076-2085, 2023.

[23] DONG, Jianhua et al. A survey of smart water quality monitoring system. *Environmental Science and Pollution Research*, v. 22, p. 4893-4906, 2015.