Development of an Artificial Intelligence-Based Platform for Optimizing Drinking Water Treatment Processes and Predictive Infrastructure Management

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Abstract

The digital transformation of water infrastructure has become one of the strategic priorities promoted at the European level to enhance the resilience, sustainability, and efficiency of drinking water supply services. In this context, artificial intelligence (AI) provides new opportunities for real-time monitoring of treatment processes, optimization of operational parameters, and the development of predictive mechanisms capable of reducing operational risks and maintenance costs.

This paper presents the development of an artificial intelligence-based platform designed to optimize drinking water treatment processes and support the digitalization of monitoring and control activities. The research is based on a case study conducted in collaboration with a company specializing in water treatment solutions and focuses on the integration of AI technologies, real-time monitoring systems, and predictive analytics into an interoperable platform capable of providing decision support for water utility operators.

The research methodology included the analysis of existing operational processes, the definition of the platform's functional requirements, the design of its conceptual architecture, and the development of a data integration model capable of processing information from sensors, treatment equipment, and external data sources. The proposed solution enables continuous monitoring of water quality parameters, adaptive optimization of treatment processes, implementation of predictive maintenance mechanisms, and remote control of water treatment facilities through an autonomous edge computing system for cyber-physical process control.

The research findings highlight the potential of artificial intelligence to improve operational efficiency, reduce resource consumption, optimize drinking water treatment processes, and enhance the capability to respond to changes in water quality and infrastructure-related events. Furthermore, the study demonstrates that integrating digital technologies with AI algorithms can support the development of intelligent water management services, contributing to the modernization of drinking water infrastructure and accelerating the digital transformation of the water sector.

Keywords: artificial intelligence; drinking water treatment; digital transformation; predictive maintenance; process optimization.

1. Introduction

In recent years, the digitalization of critical infrastructure has become one of the main strategic priorities worldwide, driven by the challenges posed by climate change, increasing demand for natural resources, and the need for their efficient and sustainable use. In this context, the drinking water sector is undergoing an accelerated digital transformation based on the integration of Internet of Things (IoT) technologies, artificial intelligence (AI), real-time monitoring systems, and predictive analytics to improve operational efficiency and enhance the quality of water services.

The management of drinking water treatment processes requires the continuous monitoring of a large number of physicochemical and microbiological parameters, as well as the coordination of complex treatment equipment and technological processes. In current practice, decisions regarding process adjustments are often based on operators' experience and the analysis of available data at specific points in time. This approach may result in delays in detecting changes in water quality, increased resource consumption, and limited capability to anticipate events that may affect treatment plant operation or drinking water compliance.

Recent advances in artificial intelligence provide new opportunities for optimizing these processes through the integration of predictive analytics, machine learning, and decision support mechanisms. AI algorithms enable the processing of large volumes of data acquired from sensors, treatment equipment, and external information sources, allowing the automatic detection of anomalies and the generation of recommendations for optimizing treatment process parameters. Furthermore, the integration of predictive maintenance and remote monitoring functionalities contributes to reducing operational risks while improving the reliability of drinking water treatment infrastructure.

At the European level, the digital transformation of the water sector is supported through initiatives and regulatory frameworks aimed at developing resilient and intelligent water infrastructure. The European Water Resilience Strategy, together with the provisions of Directive (EU) 2020/2184 on the quality of water intended for human consumption and Directive (EU) 2024/3019 on urban wastewater treatment, promotes the adoption of digital technologies and artificial intelligence for monitoring, control, and optimization of water infrastructure processes [1], [2]. In addition, international standards including EN ISO 24511, EN ISO 24512, EN ISO 24516, ISO 55001, IEC 62443, and IEC 61508/61511 encourage approaches based on risk management, cybersecurity, asset management, and the digitalization of operational processes [3], [4], [5], [6].

Against this background, the development of intelligent platforms capable of integrating real-time monitoring, predictive analytics, remote control, and automated process optimization represents an important research direction. Nevertheless, the existing literature indicates that most currently available solutions focus either on monitoring individual operational parameters or on automating isolated treatment processes. Comparatively few studies have proposed integrated AI-based platforms capable of simultaneously supporting drinking water treatment, risk analysis, predictive maintenance, and decision support within a unified digital environment.

The present study aims to develop and conceptually validate an artificial intelligence-based platform integrated with an autonomous edge computing system for cyber-physical process control, designed to optimize drinking water treatment processes and support the digitalization of monitoring and operational control activities. The research is based on a case study conducted in collaboration with a company specialized in the development and implementation of drinking water treatment solutions. It proposes a conceptual platform integrating real-time monitoring, predictive analytics, adaptive treatment process optimization, remote operation, and predictive maintenance within a unified software and hardware architecture.

The paper is organized into five main sections. Following the introduction and literature review, the research methodology and the conceptual architecture of the proposed platform are presented, covering both the software and hardware layers. The subsequent sections describe the innovative services and operational processes developed within the research and analyze their contribution to optimizing drinking water treatment processes and accelerating the digital transformation of water infrastructure. Finally, the paper concludes by summarizing the main research findings, discussing the limitations of the study, and outlining directions for future research.

2. Literature Review

The digital transformation of water infrastructure has become one of the main research and development priorities worldwide, driven by the need to improve operational efficiency, reduce resource consumption, and enhance the resilience of drinking water supply systems. In recent years, numerous studies have demonstrated that the integration of digital technologies, smart sensors, Internet of Things (IoT) platforms, and artificial intelligence (AI) algorithms significantly improves the monitoring and control of water infrastructure, enabling data-driven decision-making based on real-time information. Furthermore, AI-based systems have contributed to improving water quality, reducing energy consumption, and implementing predictive maintenance strategies that minimize system downtime [7], [9].

The increasing complexity of drinking water treatment processes has driven the development of intelligent systems capable of simultaneously monitoring a large number of physicochemical and operational parameters. The literature indicates that conventional monitoring approaches are constrained by the time required for data analysis and their limited capability to anticipate variations in water quality. In this context, artificial intelligence algorithms enable the automatic detection of anomalies, prediction of water quality trends, and optimization of treatment processes, thereby improving the safety and reliability of drinking water supply systems [10], [11].

An increasing number of studies highlight the importance of Internet of Things (IoT) technologies in the development of smart water infrastructure. The integration of distributed sensors and communication networks enables the continuous acquisition of data related to water quality, energy consumption, equipment performance, and environmental conditions. These data are used for real-time process monitoring and automatic alert generation in critical situations, reducing response times and improving operational efficiency [12], [13].

The development of artificial intelligence-based platforms has enabled the transition from passive infrastructure monitoring to intelligent systems capable of providing decision support and recommendations for optimizing treatment processes. Machine learning algorithms and predictive models are increasingly employed to estimate resource consumption, optimize treatment parameters, and predict equipment failures, thereby reducing operational costs and improving infrastructure reliability [14], [15].

Another rapidly evolving research direction is the application of the Digital Twin concept to water infrastructure management. A Digital Twin is a dynamic digital representation of a physical system that is continuously updated using real-time operational data. The literature demonstrates that Digital Twin technologies enable the simulation of different operational scenarios, assessment of the impact of extreme events, and optimization of operational strategies before their implementation in real-world systems [16], [17].

At the same time, recent research has focused on the development of predictive maintenance mechanisms. The analysis of historical and operational data enables the identification of equipment degradation patterns and the estimation of failure probabilities, facilitating maintenance planning before critical failures occur. The implementation of predictive maintenance strategies reduces maintenance costs, minimizes downtime, and extends the service life of water treatment infrastructure [18], [19].

Within the framework of the Smart Water concept, recent studies have emphasized the integration of data from IoT sensors, SCADA systems, water quality laboratories, GIS databases, and external information sources into unified digital platforms. These platforms enable the simultaneous analysis of treatment processes, equipment performance, and external factors affecting water quality, providing operators with intelligent decision support based on comprehensive data analytics [15], [17], [20].

The literature also indicates that the successful implementation of artificial intelligence solutions depends not only on the performance of AI algorithms but also on their interoperability with existing infrastructure, compliance with cybersecurity requirements, and adherence to regulatory frameworks governing critical infrastructure. Consequently, recent research recommends the development of modular and interoperable platforms capable of integrating heterogeneous technologies while supporting future functional extensions [9], [18].

A critical review of the literature reveals that most existing studies focus on applications dedicated to water quality monitoring, energy consumption optimization, or predictive maintenance. In contrast, relatively few studies propose integrated AI-based platforms capable of combining real-time monitoring, remote operation, adaptive treatment process optimization, predictive analytics, risk management, and decision support within a unified solution for drinking water infrastructure.

To address this research gap, the present study proposes the development of an artificial intelligence-based platform for optimizing drinking water treatment processes and supporting the digitalization of monitoring and operational control activities. The main contribution of this work is the definition of a conceptual framework that integrates artificial intelligence, predictive analytics, remote control, decision support, and an autonomous edge computing system for cyber-physical process control into an interoperable platform designed to improve the efficiency, resilience, and sustainability of modern drinking water infrastructure.

3. Materials and Methods

3.1. Research Framework

The research presented in this paper was conducted in collaboration with a company specializing in the development and implementation of drinking water treatment solutions. The primary objective was the development and conceptual validation of an artificial intelligence-based platform designed to optimize the monitoring, control, and treatment of drinking water. The research focused on integrating modern digital technologies, predictive analytics, and real-time monitoring functionalities into an interoperable platform capable of supporting decision-making and improving the operational efficiency of drinking water infrastructure.

The research methodology was based on an analysis of existing drinking water treatment processes and the identification of the main limitations of conventional systems with respect to process monitoring, operational control, and infrastructure maintenance. Building upon these findings, a conceptual framework was developed for integrating artificial intelligence technologies into operational processes, with the objective of creating a platform capable of acquiring, analyzing, and exploiting real-time data generated by drinking water treatment infrastructure.

3.2. Research Methodology

The adopted research methodology was structured into six sequential stages, summarized in Figure 1. This systematic approach enabled the progressive development of the proposed solution, beginning with the analysis of existing operational processes and continuing with the design of the intelligent platform, the integration of artificial intelligence algorithms, and the conceptual evaluation of the developed functionalities.

Figure 1. Research Methodology

Stage 1: Analysis of Existing Processes

Stage 2: Definition of Functional Requirements

Stage 3: Design of the AI-Based Platform

Stage 4: Development of Innovative Services and Operational Processes

Stage 5: Integration and Functional Testing

Stage 6: Evaluation of the Proposed Solution

Source: Authors' own elaboration

As illustrated in Figure 1, the research methodology follows a logical sequence of development stages, with each stage providing the information and outcomes required for the subsequent one. This systematic approach facilitates the integration of the platform components and enables the progressive evaluation of the contribution of each functionality to the optimization of drinking water treatment processes.

Stage 1 – Analysis of Existing Processes

The first stage involved the analysis of the technological processes associated with drinking water treatment. Particular attention was given to identifying the main categories of data generated by water treatment plants, the corresponding information flows, and the operational activities influencing system performance. The analysis also focused on identifying the limitations of conventional monitoring approaches and defining the information requirements for the development of the proposed AI-based platform.

Stage 2 – Definition of Functional Requirements

Based on the initial analysis, the functional requirements of the intelligent platform were defined. These included real-time monitoring of water quality parameters, integration of data acquired from sensors and treatment equipment, remote operation, predictive analytics, and the generation of recommendations for optimizing drinking water treatment processes.

Stage 3 – Design of the AI Platform Architecture

During this stage, the conceptual architecture of the proposed AI-based platform and the autonomous edge computing system for cyber-physical process control was developed. The architecture included data acquisition modules, the operational database, artificial intelligence-based analytics components, real-time monitoring mechanisms, and a user interface designed for water treatment plant operators.

Stage 4 – Development of Innovative Services and Operational Processes

Based on the proposed architecture, innovative services supporting the intelligent control of drinking water treatment plants and the adaptive optimization of treatment processes were defined. In addition, operational processes dedicated to automation, predictive maintenance, and process optimization were developed to enhance the efficiency and reliability of water treatment operations.

Stage 5 – Integration of Platform Functionalities and Conceptual Validation

This stage focused on integrating the proposed platform with the existing water treatment infrastructure, ensuring interoperability with the equipment and operational systems deployed in treatment plants. Furthermore, the mechanisms for real-time data acquisition and analysis, together with the functionalities supporting remote monitoring and remote control, were evaluated through conceptual validation.

Stage 6 – Evaluation of the Proposed Solution

The final stage of the research consisted of the conceptual evaluation of the proposed solution by comparing the conventional operating approach with the scenario based on the implementation of the intelligent platform. The evaluation considered the potential impact of the proposed solution on the efficiency of drinking water treatment processes, resource consumption, and the capability to respond rapidly to events that may affect drinking water quality.

Table 1. Research Stages and Their Corresponding Outcomes

Stage	Activity	Outcome
Stage 1	Analysis of drinking water treatment processes	Identification of digitalization requirements
Stage 2	Definition of functional requirements	Platform functional specifications
Stage 3	Design of the AI platform architecture	AquaMind conceptual model
Stage 4	Development of innovative services	Intelligent services and operational processes
Stage 5	Integration of platform functionalities	Interoperable platform
Stage 6	Evaluation of the proposed solution	Impact assessment on drinking water treatment processes

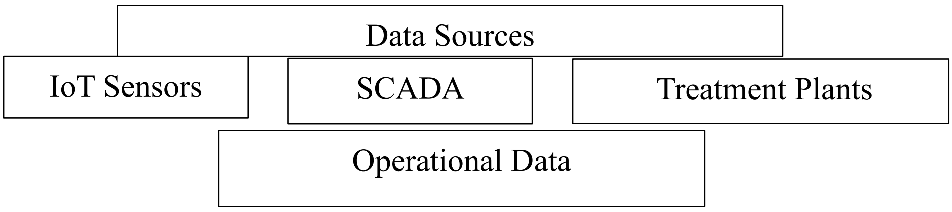
Source: Authors' own elaboration

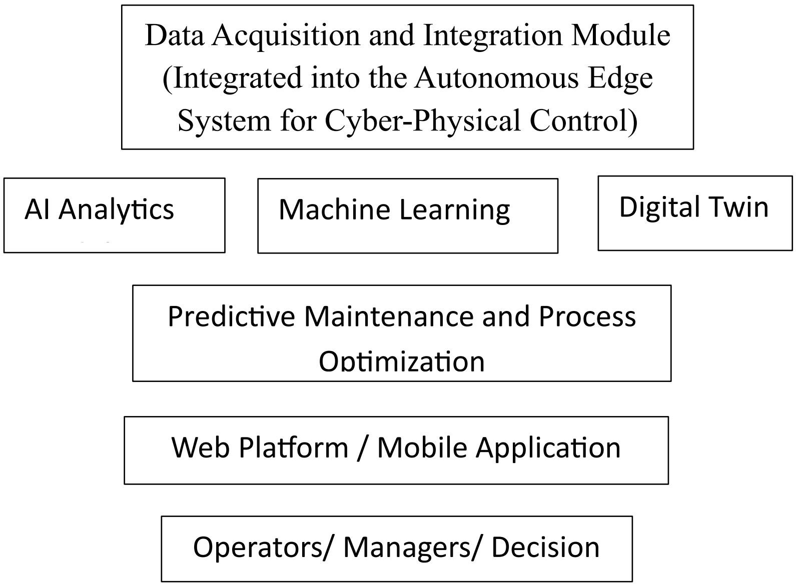
The information summarized in Table 1 highlights the systematic and sequential nature of the proposed research methodology, with each stage contributing to the progressive development of the platform and to the establishment of the conceptual framework adopted in this study.

3.3. Conceptual Architecture of the AquaMind Platform

To provide an overview of the proposed solution, the conceptual architecture of the AquaMind platform is illustrated in Figure 2. The platform is designed as an integrated system that collects data from IoT sensors, water treatment equipment, SCADA systems, meteorological information sources, and operational databases within a unified digital infrastructure. The acquired data are processed using artificial intelligence algorithms, predictive analytics, and an autonomous edge computing system for cyber-physical process control, enabling real-time monitoring of water treatment processes, adaptive process optimization, predictive maintenance, and decision support for plant operators. Through the integration of these functional components, the platform provides a comprehensive digital environment for improving the efficiency, reliability, and resilience of drinking water treatment infrastructure.

Figure 2. Conceptual Architecture of the AquaMind Platform





Source: Authors' own elaboration

As illustrated in Figure 2, the AquaMind platform is organized according to a modular architecture, in which data acquired from IoT sensors, water treatment equipment, and SCADA systems are collected and integrated into a central operational database through an autonomous edge computing system for cyber-physical process control. The integrated data are subsequently processed using artificial intelligence algorithms, machine learning models, and Digital Twin components, generating recommendations for drinking water treatment process optimization, anomaly detection, and predictive maintenance planning.

The proposed architecture enables real-time monitoring of operational parameters, seamless integration of heterogeneous data sources, and the provision of decision support tailored to different categories of users, including operators, managers, and decision makers. Through this integrated approach, the platform improves operational efficiency, reduces response times, enhances the reliability of drinking water treatment processes, and supports the intelligent management of modern water infrastructure.

3.4. Evaluation Indicators of the Proposed Solution

The conceptual evaluation of the AquaMind platform was conducted using a set of technical and functional evaluation indicators designed to assess the potential impact of the proposed solution on drinking water treatment processes and the operational performance of water infrastructure.

Table 2. Technical and Functional Evaluation Indicators Used for Assessing the Proposed Solution

Evaluation Indicator	**Description**	**Role in the Evaluation**
Response Time	Time required to detect and respond to an operational event	Assessment of operational efficiency

Water Quality	Stability of the monitored water quality parameters	Assessment of treatment process performance
Resource Consumption	Energy and chemical consumption	Assessment of economic efficiency
Predictive Maintenance	Capability to anticipate equipment failures	Assessment of system reliability
Real-Time Monitoring	Availability of operational data	Assessment of the level of digitalization
Remote Control	Capability for rapid operational intervention	Assessment of operational flexibility
Decision Support	Quality of AI-generated recommendations	Assessment of platform usefulness

Source: Authors' own elaboration

The analysis of these evaluation indicators enables the assessment of the AquaMind platform's contribution to optimizing drinking water treatment processes, improving operational efficiency, and supporting the development of an intelligent water infrastructure capable of rapidly adapting to changing operating conditions.

4. Development and Integration of the AquaMind Platform for Drinking Water Treatment Process Optimization

4.1. General Concept of the AquaMind Platform

The AquaMind platform was conceived as an intelligent solution designed to support the digital transformation of drinking water treatment processes and to optimize the monitoring, control, and maintenance of water infrastructure. The proposed platform integrates data acquired from IoT sensors, water treatment equipment, SCADA systems, and other operational data sources into a unified digital environment, leveraging artificial intelligence algorithms, predictive analytics, and an autonomous edge computing system for cyber-physical process control to enable real-time analysis and decision support.

Unlike conventional systems, where process monitoring and control rely primarily on the manual interpretation of available operational data, the AquaMind platform automatically correlates information from heterogeneous data sources and rapidly identifies changes that may affect the performance of drinking water treatment processes. By employing predictive analytics and machine learning techniques, the proposed solution supports the optimization of treatment process parameters, enhances infrastructure management, and reduces the time required for operational interventions and maintenance activities.

4.2. Innovative Services Developed

Within the scope of this research, two innovative services were developed as the core components of the AquaMind platform, with the objective of supporting the digital transformation of operational processes and improving the efficiency of drinking water treatment activities.

a) Intelligent Monitoring and Control Service

This service enables the continuous acquisition and analysis of data generated by the drinking water treatment infrastructure, providing real-time monitoring of operational parameters and the automatic generation of alerts whenever deviations from normal operating conditions are detected. The integration of artificial intelligence algorithms facilitates the rapid identification of operational trends and supports the generation of recommendations for optimizing treatment process parameters.

By employing this service, operators have continuous access to up-to-date information regarding the status of the water treatment system, thereby reducing the time required to detect operational incidents and improving the capability to respond effectively to changing operating conditions.

b) Intelligent Optimization and Predictive Maintenance Service

The second innovative service is designed to support the optimization of drinking water treatment processes and the planning of predictive maintenance activities. The platform employs predictive algorithms to analyze historical and operational data, estimate the probability of equipment failures, and generate recommendations for maintenance interventions before failures occur.

The implementation of this service contributes to reducing system downtime, optimizing energy and chemical consumption, and extending the operational lifetime of equipment used in drinking water treatment processes. By enabling proactive maintenance planning and adaptive process optimization, the service enhances the reliability, efficiency, and sustainability of water treatment infrastructure.

4.3. Innovative Operational Processes

The implementation of the AquaMind platform involves transforming the way operational activities within drinking water infrastructure are managed. As part of this research, three innovative operational processes were defined to facilitate the integration of digital technologies into the routine operation of drinking water treatment systems.

The first process focuses on intelligent monitoring and the continuous analysis of the operating parameters of drinking water treatment facilities, using real-time data to automatically detect operational anomalies and support rapid response.

The second process aims to optimize treatment process parameters by utilizing recommendations generated by artificial intelligence algorithms, thereby reducing resource consumption and improving operational efficiency.

The third process is dedicated to predictive maintenance and infrastructure asset management, enabling maintenance interventions to be planned based on the actual condition of equipment rather than predetermined maintenance schedules. This approach reduces the risk of unexpected failures, improves infrastructure reliability, and enhances the long-term sustainability of water treatment operations.

Figure 3. Information Flow of the AquaMind Platform

IoT Sensor Monitoring

Operational Data Acquisition

AI and Machine Learning Analytics

Anomaly Detection

Process Evolution Prediction

Operator Recommendations

Process Optimization and Predictive Maintenance

Source: Authors' own elaboration

As illustrated in Figure 3, the AquaMind platform employs an integrated information flow, in which data acquired in real time are processed using artificial intelligence algorithms and transformed into actionable information for system operators. This approach enables the transition from passive infrastructure monitoring to a predictive management model based on event anticipation, continuous process optimization, and intelligent decision support.

To highlight the differences between the conventional operation of drinking water treatment infrastructure and the proposed intelligent solution, Table 3 presents a comparative analysis of the main functional characteristics of the two approaches. The comparison focuses on key aspects including process monitoring, data analytics, maintenance strategies, decision-making, and the level of digitalization of operational activities, thereby demonstrating the advantages of integrating artificial intelligence technologies into modern drinking water treatment systems.

Table 3. Comparative Analysis of the Conventional Approach and the

AquaMind Intelligent Platform

Conventional Approach	**AquaMind Platform**
Periodic monitoring	Continuous real-time monitoring
Manual data analysis	AI-based automated analytics
Reactive maintenance	Predictive maintenance
Distributed data sources	Unified digital platform

Experience-based decision-making	AI-assisted decision-making
Local control	Remote monitoring and control

Source: Authors' own elaboration

The comparative analysis presented in Table 3 demonstrates that the AquaMind platform overcomes the limitations of conventional approaches through the integration of continuous real-time monitoring, artificial intelligence algorithms, and predictive maintenance mechanisms. While conventional approaches rely primarily on periodic monitoring and reactive maintenance strategies, the proposed solution enables automated data analytics, early anomaly detection, and the generation of intelligent recommendations for optimizing drinking water treatment processes. These capabilities contribute to improved operational efficiency, reduced response times, enhanced decision-making, and more effective management of modern drinking water treatment infrastructure.

4.4. Benefits of Implementing the AquaMind Platform

The analysis of the proposed solution highlights several expected benefits associated with the implementation of the AquaMind platform in drinking water treatment infrastructure. Among the most significant are the reduction of the time required to detect and resolve operational incidents, the optimization of energy and chemical consumption, the improvement of equipment reliability, and the enhancement of the decision-making process.

Furthermore, the integration of predictive analytics and continuous real-time monitoring contributes to the development of an intelligent water infrastructure capable of rapidly adapting to changing operating conditions and supporting the digital transformation of the drinking water supply sector. The proposed platform also provides a scalable and interoperable framework for integrating emerging digital technologies, thereby strengthening the resilience, operational efficiency, and long-term sustainability of modern water treatment systems.

5. Conclusion

The present research aimed to develop and conceptually validate an artificial intelligence-based platform designed to optimize drinking water treatment processes and support the digital transformation of monitoring, control, and infrastructure management activities. The study demonstrated that the integration of artificial intelligence technologies, real-time monitoring, and predictive analytics has the potential to improve operational efficiency and enhance decision-making within modern drinking water treatment systems.

The proposed methodology enabled the development of a conceptual architecture capable of integrating data acquired from IoT sensors, SCADA systems, and other operational data sources into a unified digital platform. By leveraging artificial intelligence algorithms, the platform supports data analysis and generates recommendations for optimizing treatment process parameters. Furthermore, the research demonstrated the feasibility of implementing functionalities dedicated to continuous monitoring, predictive maintenance, and remote control, thereby contributing to the development of an intelligent and resilient water infrastructure.

A key contribution of this work is the development of an integrated conceptual model that combines real-time monitoring, predictive analytics, treatment process optimization, and infrastructure management within a single digital platform. Unlike conventional approaches, which typically address these functionalities separately, the proposed solution enables the integrated exploitation of operational data to support decision-making and improve overall system performance.

The implementation of such a platform has the potential to provide significant benefits, including reduced response times to operational incidents, optimized energy and chemical consumption, improved equipment reliability, and enhanced drinking water service quality. In addition, the use of predictive analytics facilitates efficient maintenance planning and reduces the likelihood of failures that could compromise the continuity of treatment operations.

This study also has several limitations. The research is based on a case study and on the conceptual validation of the proposed solution, without an extensive experimental evaluation under real operating conditions. Consequently, the findings should be interpreted within the specific context of the analyzed infrastructure and the objectives of the digital transformation initiative.

Future research should focus on the implementation and experimental validation of the platform in operational drinking water treatment plants, the integration of advanced generative artificial intelligence models to support operators in decision-making, the extension of Digital Twin functionalities, and the development of autonomous mechanisms for optimizing treatment process parameters. Furthermore, the evaluation of platform performance through quantitative indicators, such as response time, prediction accuracy, resource consumption, and user satisfaction, represents an important direction for validating the effectiveness of the proposed solution.

In conclusion, this research demonstrates that the integration of artificial intelligence into drinking water treatment processes represents a promising approach for modernizing water infrastructure and accelerating the digital transformation of the water sector. The proposed AquaMind platform provides a conceptual framework for the development of intelligent systems capable of improving operational efficiency, supporting decision-making, enhancing infrastructure resilience, and contributing to the long-term sustainability of drinking water services.

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