



INTELLIGENT MODEL FOR MONITORING AND MANAGING WATER CONSUMPTION BASED ON WSN, IOT AND AI

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Abstract: This work proposes the implementation of an intelligent system based on Wireless Sensor Networks (WSN) and the Internet of Things (IoT) for real-time water consumption monitoring using a digital water meter. The research is framed within a qualitative, empirical, and descriptive approach, aiming to analyze the potential of emerging technologies in improving water resource management, reducing losses, and increasing the efficiency of measurement processes. The proposed system uses the Arduino Uno microcontroller as a processing unit, due to its accessibility, flexibility, low cost, and compatibility with different computing platforms, including Windows and Linux operating systems. The solution aims to overcome limitations of traditional measurement models, such as reading errors, malfunctions, and equipment inaccuracies, allowing for the continuous collection, processing, and transmission of data on water consumption. The integration between IoT, smart sensors, and digital water meters represents an innovative alternative to support decision-making, promote the sustainable use of water, and contribute to the digital transformation of water supply systems.

Keywords: Digital water meter, Internet of Things, Wireless sensor networks, Real-time monitoring, Smart water management.

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Introduction

The availability and efficient management of water resources constitute strategic challenges in the contemporary context, as a consequence of population growth, accelerated urbanization, increased demand for water, and the need to reduce losses in supply systems. In this scenario, the operational efficiency of distribution networks increasingly depends on the ability to monitor, analyze, and control consumption in real time, allowing for a more rational use of resources and data-driven decision-making. Water security therefore requires innovative technological solutions associated with integrated resource management, capable of improving system performance and reducing environmental impacts (UNESCO, 2024). Water losses constitute one of

the main problems faced by managing entities, being related to leaks, failures in measurement systems, obsolete equipment, and limitations of traditional control mechanisms. Studies indicate that the digitalization of supply systems allows for the identification of consumption patterns, the detection of anomalies, and improved operational control of hydraulic networks (Li et. all, 2021). In this sense, conventional measurement methods, which rely on manual readings and infrequent updates, reveal limitations in the timely identification of waste and abnormal occurrences.

The development of the Internet of Things (IoT) has driven new approaches to intelligent water management, integrating sensors, communication devices, processing

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units, and digital platforms capable of collecting, transmitting, and analyzing data in real time. IoT enables the interconnection between physical objects and computational systems, creating conditions for continuous monitoring and automated control of different processes (Ray, 2021). In the water sector, this approach has favored the emergence of Smart Water Management, in which Wireless Sensor Networks (WSNs) are particularly important because they allow for distributed data collection with greater installation flexibility and less dependence on conventional infrastructure. These networks can monitor variables such as flow rate, pressure, water quality, and consumption patterns, providing relevant information for the efficient and sustainable management of supply systems (Akyildiz & Vuran, 2020). The integration between IoT and WSNs thus expands the communication capacity between physical devices and digital platforms, favoring remote monitoring and continuous data analysis.

In this context, smart digital water meters represent an evolution compared to conventional models, as they incorporate sensors, processing units, and communication mechanisms capable of automating the collection and transmission of consumption information. These systems can contribute to identifying abnormal behaviors, excessive consumption, and potential leaks, as well as improving measurement and billing processes (Farahani et. all, 2022). Simultaneously, Artificial Intelligence (AI) has the potential to transform the data collected by sensors into useful information for identifying patterns, forecasting consumption, and detecting anomalies. The combination of IoT, RSSF, and intelligent techniques thus favors the development of data-driven water management systems capable of supporting operational decisions (Russell & Norvig, 2021; Zhang et. all, 2023).

Despite the advances made in the application of these technologies, challenges persist related to the selection of communication protocols, the energy consumption of devices, the reliability of transmission, data security, and the adaptation of solutions to the economic and infrastructural conditions of different contexts. The choice of communication technologies, such as Wi-Fi, Bluetooth Low Energy, LoRaWAN, and ZigBee, should consider factors such as range, energy efficiency, data volume, and application characteristics (Mishra et. all, 2022). Similarly, security is a fundamental requirement, since the increasing interconnection of devices can expose systems to risks related to authentication, privacy, integrity, and availability of information (Sicari et. all, 2021). These aspects justify the need to develop technological solutions that, in addition to being functional and accessible, are suitable for the demands of continuous monitoring and efficient management of water resources.

Faced with this problem, the present study aims to develop and analyze an intelligent model based on IoT and Wireless Sensor Networks for monitoring and managing water consumption in real time, using a digital water meter and the Arduino Uno microcontroller as a processing unit. Specifically, it intends to integrate sensors and communication mechanisms to automate data acquisition and transmission, enable continuous monitoring of consumption, and demonstrate the solution's potential in identifying patterns and possible anomalies. The use of the Arduino Uno is justified by its open architecture, ease of programming, availability of components, and feasibility for developing low-cost prototypes applied to intelligent systems (Monk, 2021). The relevance of the research therefore lies in the need to contribute to the modernization of water measurement and management processes, offering a technological alternative oriented towards reducing waste, improving operational efficiency, and promoting sustainable practices. The incorporation of digital technologies in public services can strengthen data-driven management and expand institutional capacity to respond to challenges related to the availability and rational use of water resources (World Bank, 2021).

Methods

Characterization of the research: This research adopted a predominantly qualitative approach, of an applied and experimental nature, oriented towards the development of an intelligent model for monitoring and managing water consumption in real time. The proposal is based on the integration of Internet of Things (IoT) technologies, Wireless Sensor Networks (WSN), smart digital water meters, and Artificial Intelligence (AI) techniques, with the purpose of collecting, transmitting, processing, and analyzing data related to water consumption. Regarding the objectives, the research is characterized as exploratory and descriptive. It is exploratory because it seeks to analyze the potential of applying digital and intelligent technologies in the monitoring and management of water resources. It is descriptive because it presents and analyzes the architecture, components, operation, and performance of the proposed model, as well as the behavior of the data collected by the system. The research also presents an experimental component, since it involves the design, development, integration, and evaluation of a technological prototype. The prototype consists of sensors for data collection, an Arduino Uno microcontroller as the processing unit, communication modules for transmitting information, and a monitoring platform for storing, displaying, and analyzing the collected data.

The investigation was developed within the context of a study defined for the implementation and evaluation of an intelligent water consumption monitoring prototype. The experimental phase comprised the design of the system

architecture, the assembly and integration of electronic components, the configuration of communication mechanisms, the collection of data generated by the prototype, and the performance of functional tests. The research period corresponded to the stages of requirements gathering and analysis, prototype development, implementation of monitoring mechanisms and data processing, testing, and evaluation of results. The temporal definition allowed for the progressive monitoring of the system's performance from its conception to the experimental validation phase.

Population, sample, and unit of analysis: Considering the technological and experimental nature of the study, the research population consists of systems and processes related to monitoring and measuring water consumption that can benefit from the integration of smart technologies. The sample corresponds to the prototype developed for experimental purposes, including its main technological components, namely the water flow or consumption measurement sensor, the Arduino Uno microcontroller, the communication modules, the data storage and transmission mechanisms, and the monitoring platform. The unit of analysis corresponds to the water consumption data collected by the system during the experimental operation period. Therefore, the research is not based on a human sample, but on a technological and experimental sample, analyzing the prototype's behavior and its ability to collect, transmit, and process information in real time.

Variables and indicators of the investigation: the main variables analyzed are related to the performance of the intelligent system and the data produced during the monitoring process. Among the main variables are the volume or consumption of water, the flow rate recorded by the sensor, the system's operating time, the frequency of data collection, and the capacity to transmit information to the monitoring platform. Indicators related to the technological performance of the prototype were also considered, such as the continuity of communication, data availability, information update time, and the system's ability to identify patterns or abnormal behaviors in water consumption. In the Artificial Intelligence component, the collected data can be used to identify consumption patterns, analyze behaviors over time, and support the detection of possible anomalies, contributing to smarter, data-driven management.

The research development was organized into five main stages: First stage - problem identification and justification: this consisted of analyzing the problem related to monitoring and managing water consumption and identifying the technologies suitable for developing the proposed solution; Second stage - requirements gathering and architecture definition: in this phase, the functional and technological requirements of the system were identified, as

well as the necessary components, the communication architecture, and the data flow between the sensor, the microcontroller, and the monitoring platform; Third stage - prototype development and integration: this included assembling and programming the system using the Arduino Uno, sensors, and communication modules. In this stage, the components responsible for data collection, processing, and transmission were integrated; Fourth stage - implementation of data analysis and processing mechanisms: the data collected by the system were organized and processed to allow for consumption monitoring and pattern identification. In this phase, analysis mechanisms based on the principles of Artificial Intelligence were integrated, according to the available data and the objectives defined for the model; The fifth stage - testing, validation, and evaluation of the model - consisted of conducting experimental tests to verify the integrated functioning of the components, the data collection capacity, the information transmission, the availability of records, and the overall behavior of the system.

Data Collection Techniques and Procedures: Data collection was carried out using sensors integrated into the prototype, responsible for automatically capturing information related to water consumption and flow. The collected data was sent to the processing unit, where it was organized and prepared for transmission or storage. Collection occurred automatically during the experimental operation of the system, allowing for continuous or periodic recordings, according to the configuration defined in the prototype. The information collected included data related to water consumption, flow rate, and the time of the recording. Additionally, technical observations were carried out during the experimental phase to verify the operation of the components, the stability of the communication, the consistency of the data, and the system's ability to perform the planned operations.

Data Analysis Procedures: The collected data underwent organization, processing, and analysis procedures. Initially, the records obtained by the sensors were structured according to the variables defined for the study, allowing the identification of consumption values, flow rate, and respective recording periods. Qualitative analysis was used to interpret the operation, architecture, and general behavior of the system during experimental tests. Complementarily, descriptive analysis procedures were used on the data generated by the prototype, allowing the observation of consumption patterns, recorded variations, and any abnormal behaviors. The results obtained during the tests were compared with the requirements defined for the system, allowing the evaluation of the model's ability to perform real-time water consumption monitoring. The analysis sought to verify the efficiency of the integration between the sensors, the Arduino Uno, the communication mechanisms, and the monitoring platform,

as well as the contribution of intelligent analysis mechanisms to the interpretation of the data.

With ethical considerations and information security in mind, the research adhered to ethical principles related to the responsible use of digital technologies. The data collected by the system were used exclusively for scientific and experimental purposes and for the evaluation of the proposed model, without involving the disclosure of personal or sensitive information.

Information security was considered a cross-cutting requirement in the system's development. The principles of confidentiality, integrity, and availability of data were observed during the processes of data collection, transmission, storage, and processing in the IoT

environment. The research also sought to ensure that the use of monitoring technologies was geared towards improving water resource management, reducing waste, and promoting responsible and sustainable technological practices.

Results and Discussions

The results obtained show that the integration between RSSF, IoT, digital water meters, and AI constitutes a technologically viable solution for monitoring and managing water consumption in real time. Figures 1, 2, and 3 demonstrate the main stages of model development, from the design of the hardware architecture to integration with a monitoring application, allowing for the collection, storage, transmission, and intelligent analysis of consumption data.

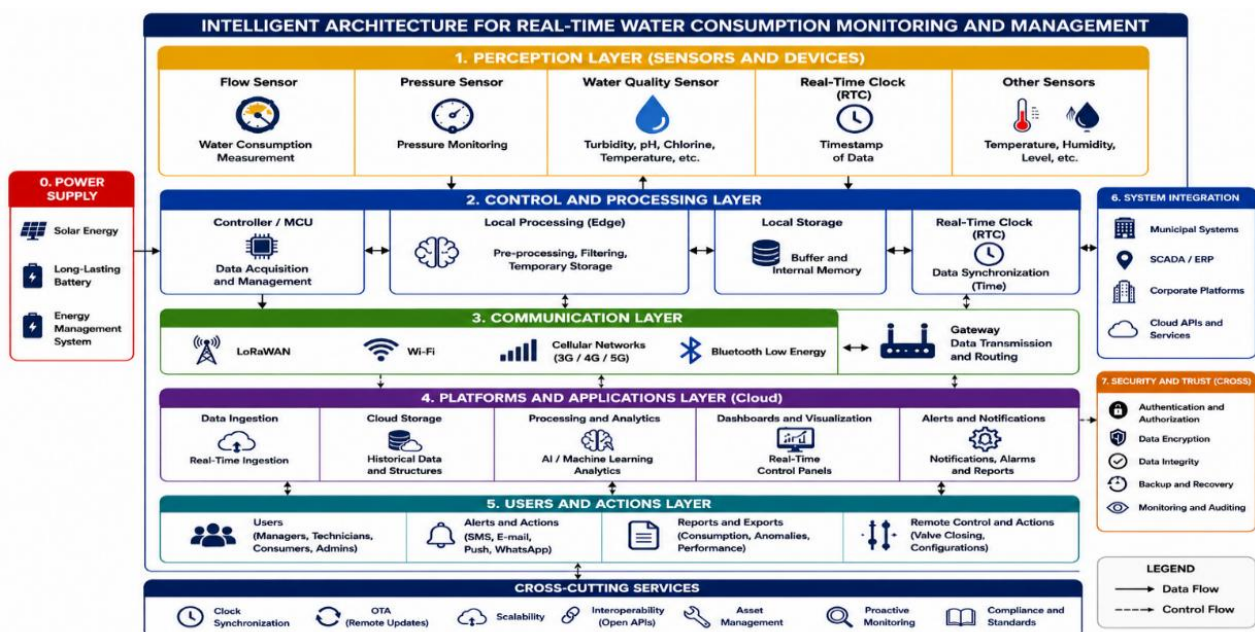


Figure 1. Intelligent System Architecture for Real-Time Water Consumption Monitoring and Management

The block diagram represents the functional architecture of the proposed intelligent system. It can be observed that the power supply ensures the continuous operation of the device, and can use batteries, solar energy, or other renewable sources, increasing the system's autonomy in locations with limited electrical infrastructure. The Arduino microcontroller acts as the central processing unit, responsible for acquiring data from the flow sensor, processing the information, and controlling the other system modules. The real-time clock (RTC) ensures the precise recording of the date and time of each measurement, enabling historical analysis and identification of consumption patterns. The water flow sensor is the main

monitoring element, allowing continuous measurement of the volume of water consumed by the residence. The collected data is stored on a memory card, ensuring the preservation of information even in the temporary absence of communication with the network. The LCD display provides the user with instant information on accumulated consumption, date, and time, promoting greater transparency in water use. In turn, the Bluetooth communication module allows data transmission to a smartphone or other mobile device, facilitating synchronization with cloud-based applications for report generation, billing, and decision support.

Prototype Development

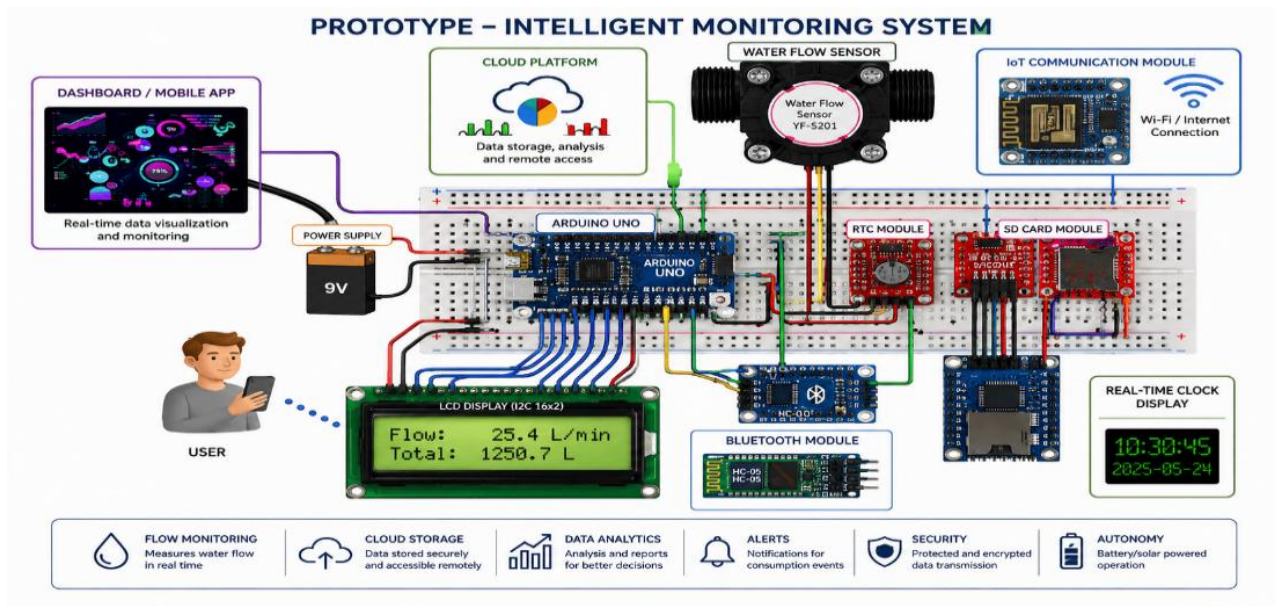


Figure 2. Prototype - Intelligent Monitoring System

Figure 2 shows the prototype developed to validate the system's operation. The experimental implementation allowed for verification of the proper integration between the electronic components, confirming the sensor's ability to perform continuous measurements of water flow and transmit the data to the controller. The tests performed demonstrated stability in data acquisition, allowing for the identification of consumption during different periods of use. The prototype also confirmed that local data storage reduces the risk of data loss during temporary

communication failures. Another relevant result concerns the simplicity of the implementation, since the use of the Arduino platform significantly reduces development and maintenance costs compared to commercial telemetry systems. This characteristic makes the model particularly suitable for developing countries, where reducing water losses is a strategic challenge. Furthermore, the prototype shows potential for future expansions, including the integration of additional pressure sensors, water quality sensors, and automatic leak detection.

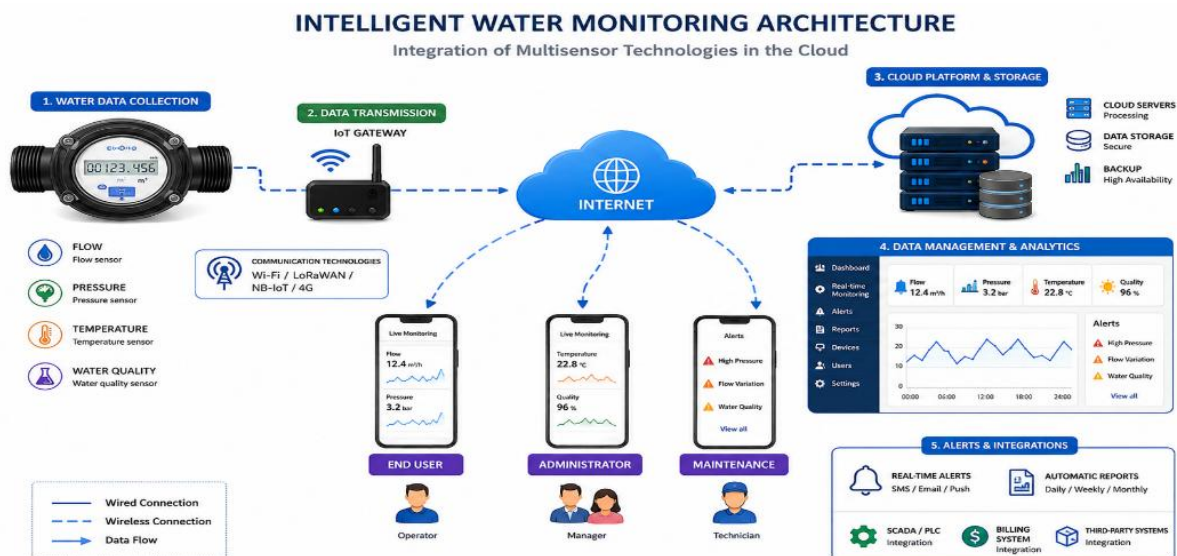


Figure 3: Intelligent water monitoring architecture with integration of the water meter with an internet application.

The integration between the physical device and the mobile application represents one of the main contributions of the proposed model. The results demonstrate that the data collected by the digital water meter can be automatically transmitted to an application, allowing real-time monitoring. The application allows the user to view instantaneous consumption, track usage history, identify abnormal patterns, and receive notifications in case of excessive consumption or possible leaks. These functionalities contribute to a more rational use of water and the reduction of waste. Integration with cloud computing platforms also allows for the storage of large volumes of data, enabling the application of Artificial Intelligence algorithms for consumption forecasting, anomaly detection, and automatic generation of reports for water supply management entities. In this way, the combination of IoT and AI transforms the data collected by the sensors into strategic information to support operational decisions, improve distribution efficiency, and optimize billing processes.

Discussion of the results

The results obtained confirm that the intelligent model has a high capacity to modernize conventional water consumption monitoring systems. The use of intelligent sensors allows for the replacement of manual reading processes with an automatic, continuous, and more precise system. The modular architecture facilitates the expansion of the solution to larger supply networks, and it can integrate technologies such as Wi-Fi, LoRaWAN, NB-IoT, and 5G, increasing communication range and reducing energy consumption. The incorporation of AI represents an important differentiator, as it makes it possible to predict consumption patterns, identify waste, detect leaks in real time, and support sustainable water resource management policies. Thus, Figures 1, 2, and 3 demonstrate that the proposed model brings together the main technological elements necessary for the implementation of an intelligent water consumption monitoring system, showing potential to reduce losses, improve the operational efficiency of supply companies, and promote the sustainable use of water in residential and urban environments.

Conclusions

This research has shown that the integration of these technologies constitutes an efficient solution to overcome the limitations of traditional water measurement and management systems. The research results demonstrate that the combination of WSNs, IoT, digital water meters, and AI enables automatic data collection, continuous consumption monitoring, anomaly detection, and support for decision-making based on real-time information. The proposed model contributes to more efficient and sustainable water resource management, allowing for reduced losses, early

identification of leaks, optimization of consumption patterns, and improved forecasting of water demand. The application of intelligent algorithms adds value to the system, transforming raw data into strategic information for managers and users. However, the implementation of this approach faces challenges related to installation costs, availability of communication infrastructure, data security, and the need for technical capacity building. Despite these limitations, it is concluded that intelligent systems based on IoT and AI represent a viable technological alternative to modernize water management and promote environmental sustainability. Based on the conclusions obtained, the following recommendations are presented: The gradual adoption of digital water meters integrated with IoT technologies, replacing manual processes with automated real-time monitoring systems; Development of pilot projects in real-world environments, the experimental application of the model in water supply systems, public institutions or communities, allowing for performance evaluation and improvements before large-scale expansion; Strengthening of technological infrastructure and data security, investment in reliable communication networks, secure data storage and cybersecurity mechanisms to ensure the availability and integrity of information; Technical capacity building and multidisciplinary integration, continuous training of technicians and managers in the areas of IoT, sensor networks, artificial intelligence and data analysis, ensuring efficient system operation; and Continued research and evolution of the intelligent model, deepening future studies involving advanced AI techniques, Edge Computing, Geographic Information Systems (GIS) and predictive models for increasingly intelligent and sustainable water management.

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