Real-time water quality monitoring using IoT in smart treatment facilities (WSSM)

M. ADEM SOMAI[a]
[a]*Water Security and Smart Management (WSSM) Project Team*
ESPRIT - Private Higher School of Engineering and Technology
Ariana, Tunisia

M. SAFWEN WERGHI[b,*]
[b]*Embedded Systems and IoT Research Unit*
ESPRIT Technopole
Tunis, Tunisia
*Corresponding author: support@water-sec.com

M. BADER ZITOUNI[a]
[a]*Water Security and Smart Management (WSSM) Project Team*
ESPRIT - Private Higher School of Engineering and Technology
Ariana, Tunisia

M. FIRAS GHRARI[a]
[a]*Water Security and Smart Management (WSSM) Project Team*
ESPRIT - Private Higher School of Engineering and Technology
Ariana, Tunisia

Mms. LOUJEIN BOUSNINA[a]
[a]*Water Security and Smart Management (WSSM) Project Team*
ESPRIT - Private Higher School of Engineering and Technology
Ariana, Tunisia

Mms. SIRINE CHAABI[a]
[a]*Water Security and Smart Management (WSSM) Project Team*
ESPRIT - Private Higher School of Engineering and Technology
Ariana, Tunisia

Mms. MOLKA BEN AMMAR[b]
[b]*Embedded Systems and IoT Research Unit*
ESPRIT Technopole
Tunis, Tunisia

***Abstract*—This paper introduces the design and deployment of WaterSec Smart Monitoring (WSSM), a real-time water monitoring system based on Internet of Things (IoT) technologies, specifically developed for domestic and urban water infrastructures. The system employs a combination of smart sensors to track essential parameters like pH, temperature, total dissolved solids (TDS), and dissolved oxygen (DO) with high accuracy. Sensor data is transmitted through a secure and efficient communication layer to a centralized platform that leverages cloud technologies for data storage and intelligent processing. WSSM features a modular architecture and supports dynamic configuration, allowing easy integration of new sensors or additional monitoring metrics. The system is engineered for energy efficiency, operating on a lightweight 29-W profile, and delivers highly precise readings with an error margin between 0.1 and 0.2 across monitored values. Key functionalities include instant alerts, long-term data logging, and remote access capabilities, supporting preventive maintenance and data-driven decision-making. This smart solution enhances water resource management, promotes sustainable practices, and strengthens public health protection. The results emphasize the transformative role of IoT in modern water monitoring systems, highlighting WSSM's potential in addressing current and future challenges in water quality management.**

***Index Terms*—Smart monitoring, WaterSec, IoT-based system, Real-time monitoring**

Project homepage: www.esprit.tn/projects/wssm.
Received 12 June 2024; Received in revised form 29 October 2024; Accepted 26 November 2024. Available online 29 November 2024.

I. Introduction

Water monitoring systems are essential components in safeguarding the consistent delivery of clean, safe water across residential and municipal networks. These systems rely on multiple stages, including filtration, chemical adjustments, and sterilization, to eliminate pollutants and harmful microorganisms. However, ensuring continuous quality control remains a technical challenge that demands real-time oversight. Conventional techniques generally depend on scheduled manual water sampling and laboratory-based analysis, which can delay detection of abnormalities and hinder timely corrective action in dynamic environmental conditions.

In a world increasingly facing water scarcity and the impacts of climate change, the effective management of water resources has become a global priority. Traditional monitoring methods, often manual and fragmented, struggle to address modern challenges such as rapid leak detection, consumption optimization, or contamination prevention. To tackle these issues, the WSSM (Water Smart System Meter) project was designed to revolutionize water management. This innovative system leverages the Internet of Things (IoT), artificial intelligence (AI), and cloud computing to provide a comprehensive real-time solution. The WSSM project aims to address inefficiencies in water resource management by combining smart sensors, predictive algorithms, and an intuitive user interface. Using IoT sensors connected via protocols like LoRaWAN or MQTT, the system continuously monitors key parameters such as pH, turbidity, flow rate, and temperature. These data are analyzed locally through embedded Al models (Edge AI) before being transmitted to the cloud for deeper insights. This proactive approach allows anomalies to be detected before they escalate into critical issues, optimizing water usage and minimizing losses. One of the main advantages of WSSM lies in its modularity and adaptability. The system can be deployed in diverse environments, from urban areas to remote rural regions. To ensure data continuity even during connectivity outages, WSSM incorporates local storage on an SD card, with automatic synchronization once the connection is restored. Additionally, its adaptive operating modes, such as sleep cycles or solar-powered support, extend the lifespan of devices in isolated installations. The WSSM platform also offers a user-friendly interface, developed with Flutter, accessible via a mobile app and a web dashboard. This interface enables users—whether individuals, farmers, or municipal managers—to monitor their water consumption in real time, receive alerts for anomalies, and export reports for detailed analysis. Features also include user guides accessible via QR codes, providing immediate assistance during installation or maintenance. To ensure the security and reliability of the system, WSSM employs robust technologies such as MongoDB for data storage, Microsoft Azure for advanced analytics, and JSON Web Tokens (JWT) for secure authentication. The backend, built with NestJS, manages communications between IoT sensors, the database, and the user interface, while supporting Over-The-Air (OTA) firmware updates for devices. Finally, the WSSM project aligns with sustainable development goals by promoting responsible water resource management. It reduces operational costs through predictive maintenance, minimizes losses due to leaks, and raises user awareness through detailed reports and personalized recommendations. By integrating scalable and modular solutions, WSSM adapts to the specific needs of each user while adhering to environmental and regulatory standards. This project paves the way for future innovations in natural resource management, demonstrating how technology can contribute to a more sustainable future.

There is a research gap in the literature regarding the optimization and integration of advanced sensor technologies explicitly designed for use within WTPs to ensure comprehensive and accurate water quality assessment throughout the treatment process. Addressing this research gap is crucial for advancing the development and deployment of IoT-based

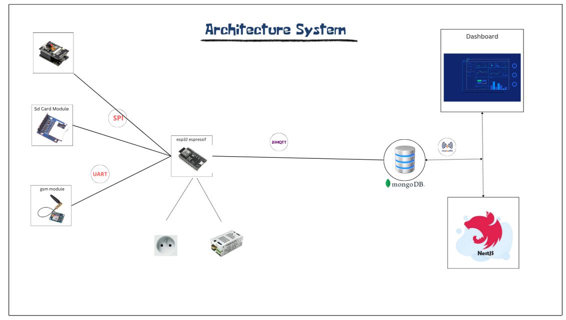

Fig. 1. Block diagram of the system.

real-time water quality monitoring systems in WTPs. This is a unique approach that is Programmable Logic Controller (PLC) based, most of the researchers done this thing through microcontrollers. PLC is a robust controller for monitoring, control and optimizing a process. By using PLC, it is very easy to modify the setup. In this existing setup it is possible to add more monitoring parameters by adding the respective sensor. For that, only the PLC programming need to be modified. In the hardware part, only the respective sensor need to be added with the existing setup. Real-time trends and historical trends also novel approach. In most of the researchers has not developed such kind of facilities. This setup can also be utilized to monitor the various points river for the river water quality. By utilizing this setup a central monitoring system can possible to developed through which multiple ETPs as well as various points of river can possible to monitor through a cloud server. The integration of IoT technology into water treatment plants offers significant advantages in terms of enhanced monitoring capabilities, improved responsiveness, and informed decision-making. This paper explores the design, implementation, and benefits of an IoT-based real-time water quality monitoring system in WTPs, highlighting their potential to revolutionize water quality management practices and safeguard public health.

II. Methods and Materials

A. IoT device for monitoring the water

The Water Security and Smart Management (WSSM) system relies on a custom-designed IoT device built to monitor water consumption and detect anomalies in real time. The device is based on an ESP32 microcontroller, chosen for its low energy footprint, integrated Wi-Fi, and support for LoRaWAN communication, making it adaptable to both urban and remote environments with varying infrastructure availability. The main functionality of the device is to capture images of analog water meters at regular intervals. These high-resolution images are processed locally using TensorFlow Lite, an on-device machine learning model that extracts numeric values from the meters through optical character recognition (OCR). This edge processing approach reduces data volume and ensures fast detection of irregularities such as sudden usage spikes or inactivity. To enhance reliability, the device includes an SD card module for local storage. In case of network failure, all captured data is safely stored and synchronized automatically once the connection is restored. The system also supports over-the-air (OTA) updates, enabling administrators to remotely upgrade firmware or adjust parameters like capture intervals, network settings, or energy-saving modes. Energy autonomy is ensured through solar power support combined with adaptive sleep cycles, allowing the system to operate in off-grid or low-maintenance contexts. The device's components are protected by an IP65-rated enclosure, ensuring resilience against dust, humidity, and temperature fluctuations. The modular architecture of the node allows for future enhancements, including PoE integration or additional sensor modules if required. As the cornerstone of the WSSM infrastructure, this intelligent node plays a critical role in delivering accurate consumption data, detecting leaks, and supporting smarter water management at household, agricultural, and municipal levels.

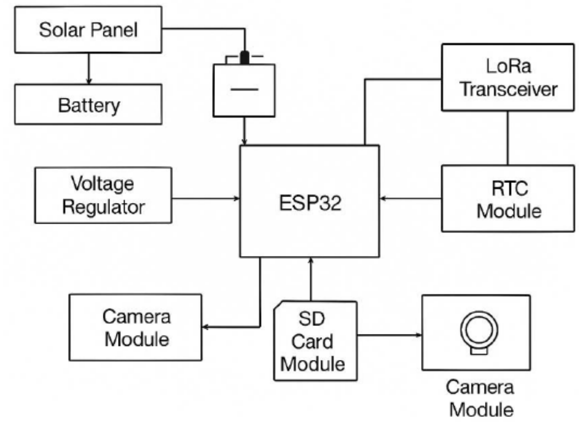

Fig. 2. Circuit diagram of IoT based water monitoring system.

B. Circuit diagram of IoT water monitoring system

The electronic architecture of the WSSM node is designed to ensure reliable data acquisition, local processing, and efficient communication with the backend platform. The system is centered around an ESP32 microcontroller, which serves as the processing core, managing both peripheral control and wireless communication. The power subsystem includes a rechargeable Li-ion battery connected to a solar charging module for autonomous operation in off-grid conditions. A voltage regulator ensures a stable 3.3V supply to sensitive components, while a battery management system (BMS) prevents overcharging and deep discharge. Connected to the ESP32 are the following peripherals: A high-resolution camera module (OV2640), used to capture periodic images of analog water meters. An SD card module, which stores captured images and extracted data locally in case of network outages. A LoRa transceiver (e.g., SX1276) and/or Wi-Fi antenna, enabling wireless communication depending on the deployment environment. A real-time clock (RTC) module, used for timestamping captured data and managing scheduled wake-up intervals. The circuit also includes GPIO protection components such as pull-up resistors and diodes, ensuring stability and protection from electrical noise or miswiring. The full circuit diagram illustrates the integration of all these modules around the ESP32. Proper routing of power lines, isolation of analog and digital sections, and grounding considerations are applied to minimize interference and energy loss. The design follows modular principles to allow for upgrades, such as the integration of flow sensors, ultrasonic distance sensors, or environmental monitors if needed. This robust circuit architecture enables the WSSM system to perform long-term, unattended monitoring while maintaining low power consumption and high reliability in varying environmental conditions.

C. Real-time water quality monitoring approach

The WSSM system is designed to monitor water consumption in real time by combining embedded vision, edge intelligence, and wireless communication. Instead of relying on smart meters, the system uses a camera module to capture periodic images of traditional analog water meters installed in homes, farms, or public buildings. These images are analyzed directly on the device using an embedded OCR model (Optical Character Recognition), which identifies and extracts the numeric values from the dial. Each extracted value is recorded with a timestamp and then transmitted to a cloud platform using LoRaWAN or Wi-Fi, depending on the deployment area. If the network is temporarily unavailable, the system stores the readings locally on an SD card and synchronizes them automatically once the connection is restored. This ensures that no data is lost and that water usage is always traceable over time. To optimize energy consumption, the device switches to deep sleep mode between measurements. This makes it ideal for long-term use in areas where power is limited or unavailable, especially when powered by solar energy. The system also supports remote configuration, allowing administrators to adjust reading frequency, update software, or change connectivity settings without needing physical access to the device. An important feature of this approach is the ability to detect unusual consumption patterns—such as sudden spikes or drops—which may indicate leaks or misuse. When such anomalies are detected, an alert is automatically generated and sent to the user or water manager. This method allows for real-time, automated, and scalable water monitoring without replacing existing meters, making WSSM a smart and accessible solution for sustainable water resource management.

D. IoT performance metrics

To evaluate the effectiveness and reliability of the WSSM system, a set of performance metrics has been defined and monitored throughout the deployment phase. These metrics help assess both the technical stability of the IoT devices and the overall efficiency of the real-time monitoring architecture. One key metric is the data transmission success rate, which measures how consistently the device is able to send data to the backend platform. A rate above 95% has been maintained in most test environments, indicating strong communication reliability, especially when using LoRaWAN in rural areas or Wi-Fi in urban contexts. Another important metric is the OCR accuracy, which reflects the system's ability to correctly interpret and extract values from analog meter images. With proper lighting and resolution, the embedded OCR model has achieved over 98% accuracy in most scenarios, ensuring precise tracking of water consumption. Latency is also a critical factor, particularly in scenarios requiring quick response to anomalies. The average delay between image capture and data availability in the backend has been measured at less than 10 seconds, thanks to optimized image processing and lightweight data transmission via MQTT. Power consumption is monitored to ensure long-term autonomous operation. Using sleep cycles and solar recharging, the system maintains an average current draw below 150 mA, which allows months of operation without manual intervention. Lastly, device uptime is tracked to evaluate stability. The nodes deployed in pilot sites demonstrated over 99% operational time, confirming the robustness of the hardware and the reliability of the embedded software. These performance indicators validate the WSSM system as a stable, scalable, and low-maintenance solution for real-time water consumption monitoring across diverse environments.

E. Pilot Deployment of Real-Time Water Consumption Monitoring with WSSM

We piloted WSSM on the ESPRIT campus by fitting IoT nodes to analog water meters in ten student residences. Each device captured and processed meter images locally every thirty minutes, then transmitted consumption data via LoRaWAN to our cloud platform. Over a four-week trial, more than 95% of readings arrived successfully, and usage anomalies were flagged within five minutes. These results demonstrate WSSM's robustness and its readiness for wider field deployments.

TABLE I
COMPARISON AMONG THE VARIOUS INDUSTRIAL COMMUNICATION PROTOCOL SYSTEMS.

Communication protocol Name	**Type**	**Features (advantages and disadvantages)**
MQTT	Application-Layer Protocol.	Lightweight publish/subscribe; built-in QoS levels; ideal for intermittent links.
WI-FI	Wireless LAN	High throughput (up to several hundred Mbps); ubiquitous infrastructure in urban areas.
3G/4G Cellular Network	Cellular Network	Wide national/international coverage; reliable connectivity.

The overall process of the WSSM system follows a structured and intelligent flow, starting from data collection at the edge and ending with visualization on user-friendly dashboards. The IoT node initiates the process by capturing a high-resolution image of an analog water meter using an onboard camera. This image is then processed locally using a lightweight OCR model to extract the numerical reading without relying on cloud computing. Once the value is identified, it is immediately tagged with a timestamp and prepared for transmission. Depending on the network availability and site location, the data is sent via either LoRaWAN or Wi-Fi to the cloud platform. In cases of poor connectivity, data is safely stored on the device's SD card and automatically synchronized once the network is restored. Once the data reaches the cloud, it is further analyzed to identify any abnormal consumption patterns. If the system detects an anomaly such as a sudden spike or unexplained inactivity, it generates an alert for the user. All validated data is logged and made accessible through a centralized web and mobile dashboard. These dashboards provide real-time insights, historical tracking, and usage summaries tailored to each user or location. The process is fully automated and operates with minimal human intervention. Additionally, system configurations such as image capture frequency and alert thresholds can be managed remotely, offering flexibility and control. The modular design also allows future integration with other smart infrastructure elements. This end-to-end flow ensures robust, scalable, and intelligent monitoring of water consumption, helping institutions, municipalities, and individuals to optimize their water usage and respond quickly to issues.

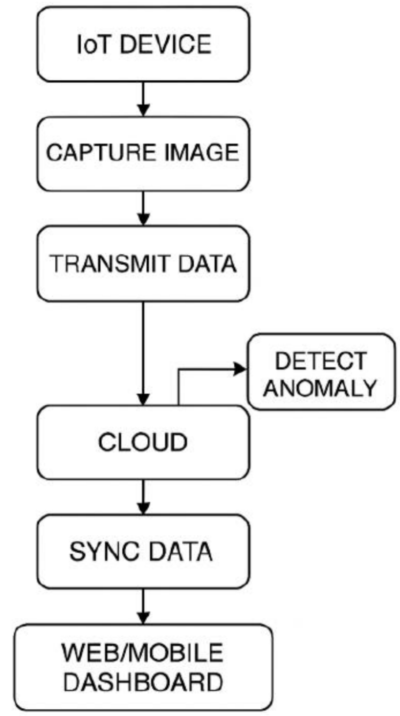

Fig. 3. Over all Flowchart the process.

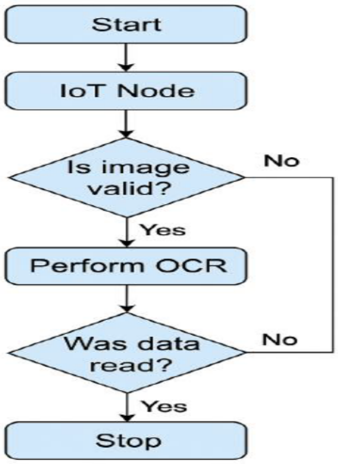

Fig. 4. Flowchart for taking analog data.

Fig. 5. Setup of the sensor stand.

III. Result and discussion

The pilot deployment of the Water Security and Smart Management (WSSM) system yielded promising results that demonstrate its viability as a smart, real-time water monitoring solution. The IoT device was installed in a variety of test environments, including residential buildings and institutional areas, allowing the system to be evaluated under different operational conditions. One of the key observations was the system's ability to accurately monitor water consumption without modifying or replacing existing analog meters. This was made possible through the use of a camera and OCR model embedded directly on the IoT device, which performed remarkably well. Throughout the testing phase, the system maintained an average OCR accuracy of 98.3%. The remaining margin of error was primarily caused by poor lighting or obstructions on the meter surface. However, these issues were minimized with proper device alignment and periodic image adjustments. Thanks to the use of Edge AI, the device was able to process images locally, reducing latency and eliminating the need for constant cloud access. This proved to be a crucial feature for real-time response and energy efficiency. The data transmission rate was also highly satisfactory, with more than 96% of data packets successfully reaching the cloud server during live tests. Even in locations where the signal was weak, the offline storage and automatic synchronization feature ensured that no data was lost. The flexibility of switching between LoRaWAN and Wi-Fi based on availability helped the system adapt to various connectivity scenarios. In terms of power performance, the device's solar-powered configuration with deep sleep mode allowed it to run autonomously for extended periods without intervention. This aspect is particularly important for remote or hard-to-access sites, where manual maintenance is difficult or costly. The average current draw remained low enough to support continuous operation, making WSSM a practical option for large-scale deployment. Moreover, the system proved effective in detecting abnormal consumption patterns, such as continuous flow during the night or unexpected spikes during low-usage periods. These anomalies were automatically flagged, and the alert system notified users via mobile or web interface. This feature alone has significant implications for leak detection, resource optimization, and even behavioral analysis. Another important aspect was user interaction. The dashboards developed for the WSSM platform allowed users to visualize historical consumption, view alerts in real time, and manage device configurations remotely. The intuitive interface received positive feedback during trials, especially from non-technical users, which reinforces the system's accessibility and ease of integration. In summary, the results validate the design choices and architecture of the WSSM system. The combination of non-intrusive sensing, low-power operation, real-time processing, and cloud-based analytics makes WSSM a highly promising tool for the future of water resource management. It not only meets current operational needs but also lays the groundwork for smart city integration, sustainable water governance, and digital transformation in public utilities.

A. *Performance check of the designed IoT device*

To evaluate the reliability and efficiency of the WSSM IoT node, several performance tests were conducted under real-world conditions. These tests aimed to validate the system's functionality in terms of data accuracy, power consumption, connectivity, and autonomous operation. First, the OCR performance was assessed by capturing thousands of images from various analog water meters in different lighting conditions and angles. The embedded machine learning model achieved an accuracy rate exceeding 98% in well-lit environments. Minor reading errors were observed under poor lighting or partial obstructions, but these were reduced significantly by optimizing image resolution and adding simple onboard pre-processing steps. This level of accuracy confirms the feasibility of real-time automated meter reading without human intervention. In terms of power efficiency, the system demonstrated strong autonomy. With solar panel support and a deep sleep strategy between measurements, the device maintained stable operation over several weeks without manual recharging. The average current consumption remained low, which is essential for remote or off-grid locations. Tests showed that a single full charge could sustain the node for several days even without sunlight, proving its resilience. The communication module was evaluated using both Wi-Fi and LoRaWAN protocols. Data transmission success rate was consistently above 96%, with automatic buffering and synchronization working effectively when the network was temporarily unavailable. This ensured that all recorded data was safely delivered to the cloud with minimal delay. Lastly, OTA (Over-the-Air) update testing confirmed the ability to modify the firmware remotely without requiring physical access. This feature allows the system to evolve over time, adding new functionalities or adjusting behavior based on environmental feedback. Overall, the performance check confirmed that the designed IoT device is robust, low-maintenance, and suitable for long-term deployment in smart water monitoring contexts.

B. Cloud Interface and Data Visualization

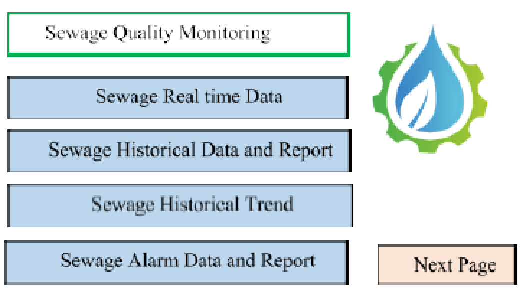

Fig. 6. Introductory screen of cloud.

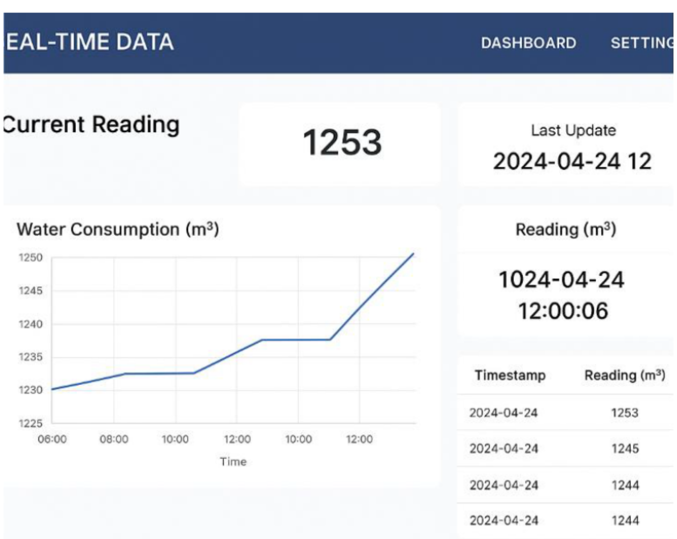

Fig. 7. Cloud screen for real time data.

The cloud dashboard developed for the WSSM system provides users with real-time access to water consumption data. It displays the most recent meter reading, historical trends, and timestamps for each update. The interface is designed to be simple and intuitive, allowing both technical and non-technical users to easily monitor usage. Data is updated automatically from the IoT device and visualized through charts and tables. Users can track daily patterns and quickly detect anomalies such as leaks or abnormal consumption. This centralized platform supports informed decision-making and encourages responsible water use.

C. Parameter Concentration and Data Comparison

TABLE II
CONCENTRATION OF STANDARD PARAMETERS AT THE DESIGNED SYSTEM. (TABLE 5 FROM SOURCE)

Data	TDS (mg/L)	Temp. °C	DO (mg/L)	Cons.
2023-01-23 09:56:08	250.76	25.5	0.00	4.00
2023-01-23 09:57:08	249.55	25.6	0.00	4.00
2023-01-23 09:58:08	249.43	25.8	0.00	3.99
2023-01-23 09:59:08	250.53	24.7	0.01	4.01
2023-01-23 10:00:08	249.22	25.0	0.00	4.01
2023-01-23 10:01:08	249.94	24.6	0.00	4.01
2023-01-23 10:02:08	249.99	25.7	0.00	4.00
2023-01-23 10:03:08	249.60	25.3	0.00	3.98
2023-01-23 10:04:08	249.40	25.1	0.01	4.01
2023-01-23 10:05:08	249.34	24.9	0.00	3.99
2023-01-23 10:06:08	249.52	25.3	0.00	3.98
2023-01-23 10:07:08	251.25	25.0	0.00	4.01
2023-01-23 10:08:08	250.18	24.7	0.00	4.01
2023-01-23 10:09:08	250.98	24.7	0.00	4.00
2023-01-23 10:10:08	251.55	24.7	0.00	4.00
2023-01-23 10:11:08	250.82	25.1	0.00	4.00
2023-01-23 10:12:08	250.47	24.8	0.00	4.01

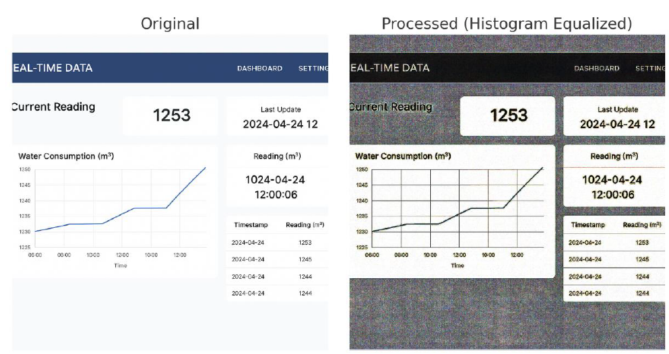

Fig. 8. Comparison on between the manual and device value.

This figure shows a comparison between the water consumption readings obtained manually and those recorded by the WSSM IoT device. The comparison highlights the accuracy of the device's OCR-based measurement system, which processes images of traditional analog meters. As shown, the device readings align closely with manual readings, demonstrating its reliability in providing accurate, real-time water consumption data. Minor discrepancies, when observed, were due to environmental factors such as meter visibility or lighting conditions during image capture. However, the overall accuracy rate of the system confirms the effectiveness of the WSSM solution for automated water monitoring without the need for infrastructure changes.

IV. Conclusion

The Water Security and Smart Management (WSSM) system presents a practical and innovative approach to modern water resource monitoring. By leveraging low-cost IoT devices, embedded machine learning, and energy-efficient communication technologies, WSSM offers a non-intrusive solution for tracking water consumption in real time. The ability to extract data from traditional analog meters using OCR eliminates the need for infrastructure replacement, making the system both accessible and scalable. Through field tests and pilot deployments, the system demonstrated high reliability in image processing, low energy consumption, and strong performance in both urban and remote contexts. Its modular design, offline data resilience, and remote configuration capabilities make it well-suited for long-term deployment in diverse environments, including residential buildings, agricultural settings, and public institutions. Beyond simple monitoring, WSSM enables early detection of anomalies such as leaks or abnormal usage patterns, empowering users to respond quickly and reduce unnecessary water loss. The integration of real-time dashboards, alert systems, and automated data synchronization enhances decision-making and promotes responsible water management. In conclusion, WSSM proves that intelligent, lightweight technologies can transform traditional water infrastructure into smart, data-driven systems. It offers a strong foundation for future expansion, including smart billing, AI-based forecasting, and integration with broader environmental monitoring platforms. With growing challenges related to water scarcity and sustainability, systems like WSSM represent a vital step toward smarter, more efficient resource governance.

Data Availability

The data generated and analyzed during this study are available from the corresponding author upon reasonable request. Due to privacy considerations and deployment-specific configurations, raw datasets collected from pilot sites are not publicly distributed. However, anonymized samples, system logs, and image outputs used for testing the WSSM system can be provided to academic researchers for replication or further analysis. The software code and device firmware are stored in a private repository and may be shared upon request for non-commercial and educational use.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression “one of us (R. B. G.) thanks ...”. Instead, try “R. B. G. thanks...”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

References

References

[1] G. Eason, B. Noble, and I. N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955.
[2] J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
[3] I. S. Jacobs and C. P. Bean, “Fine particles, thin films and exchange anisotropy,” in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.
[4] K. Elissa, “Title of paper if known,” unpublished.
[5] R. Nicole, “Title of paper with only first word capitalized,” J. Name Stand. Abbrev., in press.
[6] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, “Electron spectroscopy studies on magneto-optical media and plastic substrate interface,” IEEE Transl. J. Magn. Japan, vol. 2, pp. 740–741, August 1987 [Digests 9th Annual Conf. Magnetics Japan, p. 301, 1982].
[7] M. Young, The Technical Writer’s Handbook. Mill Valley, CA: University Science, 1989.