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Control of TDS Parameter Using IoT Technologies as a Factor in Improving Equipment Reliability and Cost-Efficiency

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ABSTRACT This article presents a comprehensive Internet of Things (IoT) based solution for monitoring the efficiency of filtration systems based on the analysis of Total Dissolved Solids (TDS). The proposed system integrates a measuring device, a cloud-based IoT platform, and algorithms for filter condition assessment. The device performs TDS measurements before and after the filtration unit using a modified Gravity Analog TDS sensor, which operates by measuring the electrical conductivity of water using alternating current. Multiple measurements collected throughout the day are averaged and transmitted to the ThingsBoard platform, where the processing logic is implemented, including residual filter life estimation, efficiency evaluation, and automatic alert generation. The system architecture enables not only real-time water quality monitoring but also adaptive response to changes in operating conditions, improving the accuracy of filter degradation forecasting. This approach differs from traditional maintenance models that rely on fixed time intervals or consumption volumes, offering reduced operational costs, prevention of premature failures, and enhanced equipment reliability. A key feature of the system is the transition from local to centralized cloud-based data processing, which simplifies the scalability of the solution for large-scale, distributed infrastructures. The proposed design is particularly relevant for commercial equipment and industrial water treatment systems, where stable water quality and timely replacement of filtration components are critical.

KEYWORDS IoT, filtration, ThingsBoard, cloud processing, condition diagnostics.

I. INTRODUCTION

The Internet of Things (IoT) is rapidly transforming approaches to equipment monitoring and maintenance across various domains: from agriculture and transportation to utilities and the food industry. The core value of IoT solutions lies in their ability to provide continuous or periodic environmental monitoring, generate analytical insights, and automatically influence maintenance processes [1-7]. This is particularly relevant in scenarios where even minor parameter fluctuations can lead to significant financial losses or system degradation.

One such critical area is water treatment systems used in commercial equipment, particularly in professional coffee machines. In this context, water quality directly affects operational stability, maintenance frequency, and the overall lifecycle of the device. The main threat is limescale – a mineral deposit that forms during water heating, especially when the total dissolved solids level is high. This is assessed using the Total Dissolved Solids (TDS) indicator, which reflects the concentration of dissolved salts, minerals and other solid particles in the water.

Traditional approaches to filter replacement in such systems are typically based on fixed time intervals or estimated water consumption. However, these methods fail to account for dynamic changes in incoming water quality, which has a considerable impact on the filter's lifespan. As a result, filters may be replaced either prematurely (incurring unnecessary costs) or too late (causing limescale buildup, component degradation, and downtime).

This paper aims to develop a comprehensive IoT solution that combines a modified device for periodic TDS measurements (before and after filtration) with a cloud-based data processing platform – ThingsBoard [8]. Unlike local or single-parameter methods, this system provides a multifactor assessment of filtration efficiency based on the relative reduction in mineral content. Measurements are performed at fixed time intervals, averaged to minimize the influence of outliers, and transmitted to the system for further analysis.

The developed solution enables real-time evaluation of filter degradation and supports alert generation when efficiency drops below a critical threshold. Due to centralized processing logic, all calculations are performed on the ThingsBoard platform, significantly simplifying the scaling of the system across dozens or hundreds of devices. This approach allows service intervals to be adapted to actual water conditions, reducing maintenance costs and improving overall equipment reliability.

In this work, the ThingsBoard platform was selected as it is an open-source IoT solution that supports data acquisition, processing, visualization, and device management. It provides connectivity via standard protocols such as MQTT, CoAP, and HTTP, and allows both cloud-based and on-premises deployment [8].

II. TECHNICAL IMPLEMENTATION OF THE DEVICE

The core of the device is based on the Arduino-compatible Gravity Analog TDS Sensor, which operates on the principle of measuring the electrical conductivity of water using alternating current [9-10]. To prevent electrode polarization, the circuit employs an AC signal generator based on an integrated oscillator operating at 3 kHz. Power is supplied through a dual-polarity ±3.0 V source (Fig. 1).

Once the signal is captured from the electrodes, water serves as the conductive medium. The weak signal is amplified using a multi-channel operational amplifier that implements several stages: initial amplification, differentiation, rectification via a diode, and final conversion into an analog signal proportional to the TDS level. To improve measurement selectivity, the circuit includes two parallel measurement blocks connected to separate probe pairs. The electrical schematic diagram and a photograph of the PCB of the modified TDS measurement module are shown in Figs. 1 and 2.

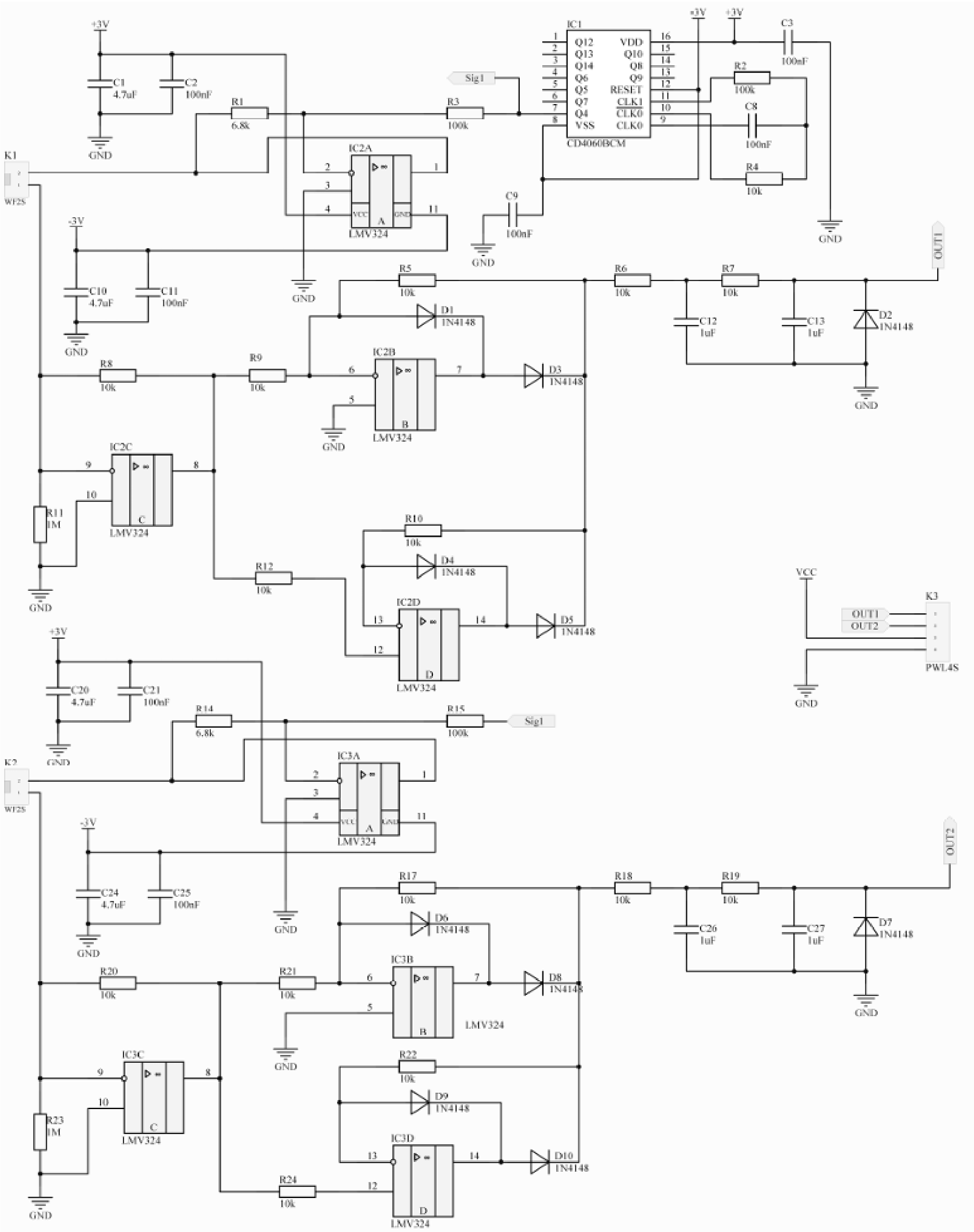

FIG. 1. Electrical schematic diagram of the modified TDS measurement module [10].

Vol 3, No 2, Paper 02005, pp. 1-7 (2025)

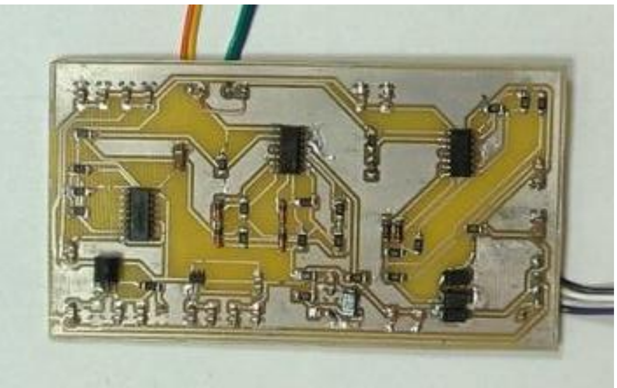

FIG. 2. Prototype of the TDS monitoring device PCB.

The resulting analog signal is fed into the analog-to-digital converter (ADC) of the ESP32, where it is transformed into a digital representation. Upon completion of the measurement session, the results are averaged, formatted in JSON, and transmitted to the ThingsBoard platform. Instead of the ESP32, other boards equipped with a built-in ADC and wireless internet connectivity can also be used to transmit data to ThingsBoard.

The generalized structural diagram of the IoT-based TDS monitoring system is shown in Fig. 3. The connection to ThingsBoard is established via a wireless Wi-Fi interface using the MQTT protocol [10]. The device publishes telemetry data to the ThingsBoard server, using a specific authentication token provided as the username in the MQTT connection.

The structure of each message includes the parameters ppm_before, ppm_after, and a timestamp. Data is transmitted to the designated endpoint address.

This approach ensures efficient interaction with the cloud platform, facilitates solution scalability, and enables centralized data processing and visualization.

III. DEPLOYMENT OF THE IOT PLATFORM ENVIRONMENT

As part of the water quality monitoring system implementation, it was necessary to establish a reliable server environment for collecting, storing, processing, and visualizing data from peripheral devices. The core software platform selected for this purpose was ThingsBoard, which provides a comprehensive set of tools for building scalable and configurable infrastructure.

To meet the requirements of stable, near-industrial operation, the platform was deployed following best practices for production-grade environments.

The server environment is based on Ubuntu Server 22.04 LTS and runs on either a physical or virtual machine with baseline specifications (at least 2 CPU cores, 4 – 8 GB of RAM, and an SSD of 50 GB or more). A key principle of the implementation is containerization: all platform components are deployed in isolated containers using Docker technology [11]. This approach ensures service separation, simplifies dependency management, and provides consistent installation. Moreover, it enables rapid scalability, reliable backups, and the seamless updating of individual components without interrupting the entire system.

The platform architecture is centered around the ThingsBoard core, which handles device management, telemetry processing, event generation, and user interface rendering (Fig. 3). PostgreSQL is used as the primary database engine – a full-featured relational DBMS responsible for storing information about devices, configurations, access tokens, telemetry data, and rule definitions. For asynchronous event handling, Redis is employed as a high-performance in-memory caching system that serves as middleware between the platform core and the rule engine services.

A critical element of the system is the MQTT broker, which handles incoming telemetry messages from devices. Since ThingsBoard provides native MQTT support, the internal broker can be used. However, under higher workloads, it is recommended to replace it with an external broker such as EMQX or Mosquitto, which offer enhanced capabilities for scaling, clustering, and secure authentication [10].

To ensure secure access to the ThingsBoard interface and external APIs, a reverse proxy server Nginx is used for routing HTTPS requests. SSL certificates are acquired automatically via Let's Encrypt or can be imported manually, enabling seamless integration into corporate infrastructure with custom encryption policies.

The entire system architecture is described in a docker-compose.yml configuration file, which defines platform components, port mappings, volume mounts, environment variables, and network relationships between services [11]. This allows both easy deployment (via a single command) and full transparency for maintenance and scaling.

In summary, the resulting platform architecture is robust, flexible, and extensible. It ensures technical compatibility with edge devices while meeting key requirements for security, maintainability, and performance expected of modern IoT systems.

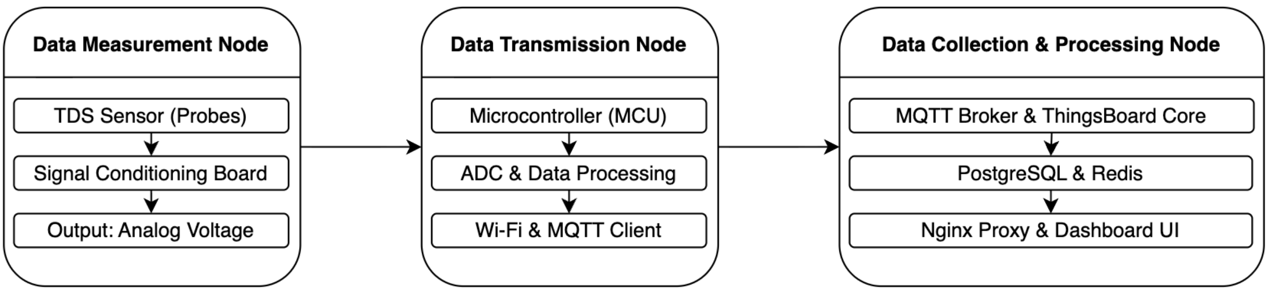

FIG. 3. Structural diagram of the IoT-based TDS monitoring system.

IV. TELEMETRY PROCESSING AND DECISION LOGIC IN THINGSBOARD

Telemetry data transmitted by the devices is received by the ThingsBoard MQTT broker, where it is automatically associated with the appropriate device instance based on an authentication token [8]. Once verified, the data is written into the telemetry database, visualized through dashboard widgets, and processed according to predefined logic.

Based on the measured TDS values before and after filtration, the system calculates the filter's efficiency, as illustrated in Fig. 4. This is carried out through a basic arithmetic operation within a Rule Engine node using a JavaScript function.

The function appends a new field, efficiency, to the incoming message payload. This field is then used for dashboard visualization, generating alerts, or triggering automated responses if efficiency drops below a critical threshold.

The result of this computation reflects the current performance of the filter in real time. Based on this value, a trigger mechanism is implemented that generates alerts when the filtration efficiency falls below a defined threshold, such as 7%. These alerts may be displayed on the user interface, sent via email, or used to initiate events in external systems.

The ThingsBoard platform also allows tracking the efficiency history in the form of time-series graphs, enabling users or service engineers to monitor the dynamics of filtration performance over time. This accumulated data provides a basis for predicting the point at which the filter will lose effectiveness and require replacement. In addition, the calculation logic can be extended using custom Rule Chains, which are logical elements within ThingsBoard that allow the construction of event processing flows. Each node within a Rule Chain can perform condition checks, data filtering, transformation, external API calls, or event generation. This opens the way for implementing adaptive system behavior, such as dynamically changing the measurement interval based on historical data or automatically triggering service requests.

Beyond basic efficiency calculation, the platform supports the implementation of advanced data processing logic via the Rule Engine. This allows for the creation of flexible telemetry response scenarios, including deviation notifications, external API invocations, event logging, and adaptive control over data acquisition frequency.

Each device is equipped with a dedicated monitoring dashboard comprising custom widgets, such as numeric indicators, historical graphs, and state-based triggers. This level of detail allows operators to quickly assess the filter condition or overall system status.

It is also important to note that the system is inherently scalable: new devices can be added without modifying the existing logic. Authentication is handled via unique tokens, and both computations and interfaces are tied to templates that are automatically applied to new nodes in the system.

Thanks to this flexibility, the platform ensures seamless integration of the measuring device with the cloud environment, real-time decision-making, and fast adaptation to changing conditions. Moreover, data processing is not limited to real-time readings – it enables trend analysis, prediction of critical states, and the formation of service plans based on long-term patterns.

Fig. 5 shows real-time TDS measurements (in ppm) over time, visualized in the ThingsBoard dashboard. The graphs reflect the system's ability to track filtration efficiency based on the difference between input and output TDS levels, enabling timely detection of filter degradation and supporting adaptive maintenance decisions.

The next stage in the development of this IoT solution involves modeling the accumulated impact of TDS on equipment condition. A degradation model is implemented in the system to account for the long-term effect of water mineralization, enabling more accurate identification of the moment when critical degradation occurs. This approach is discussed in the following section.

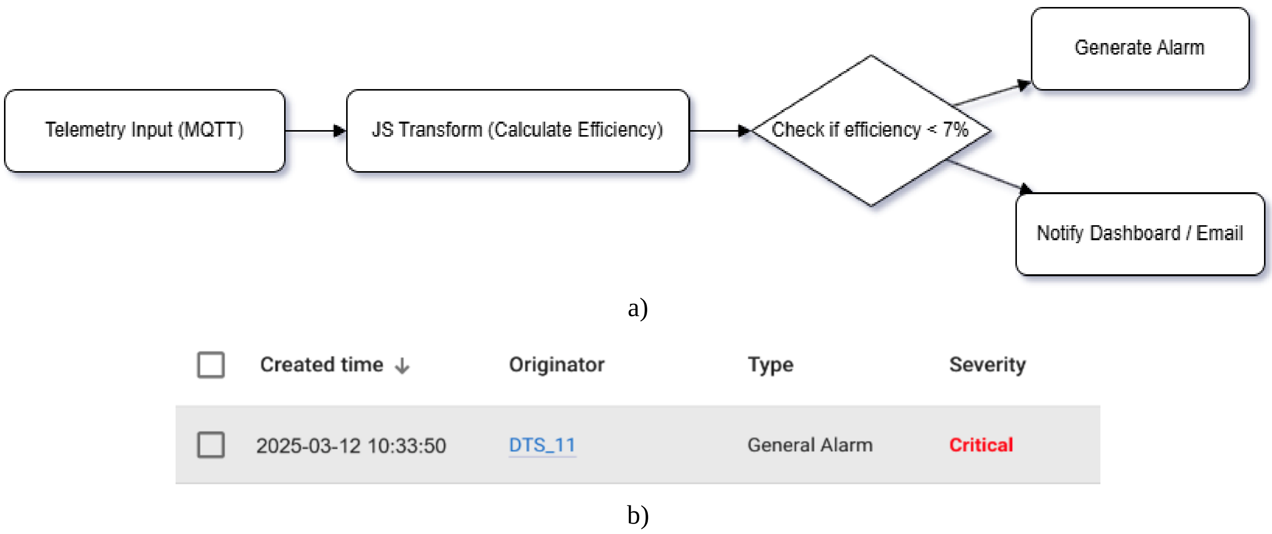

FIG. 4. Schematic representation of alert generation based on TDS efficiency threshold (a), and its visualization on the ThingsBoard dashboard (b).

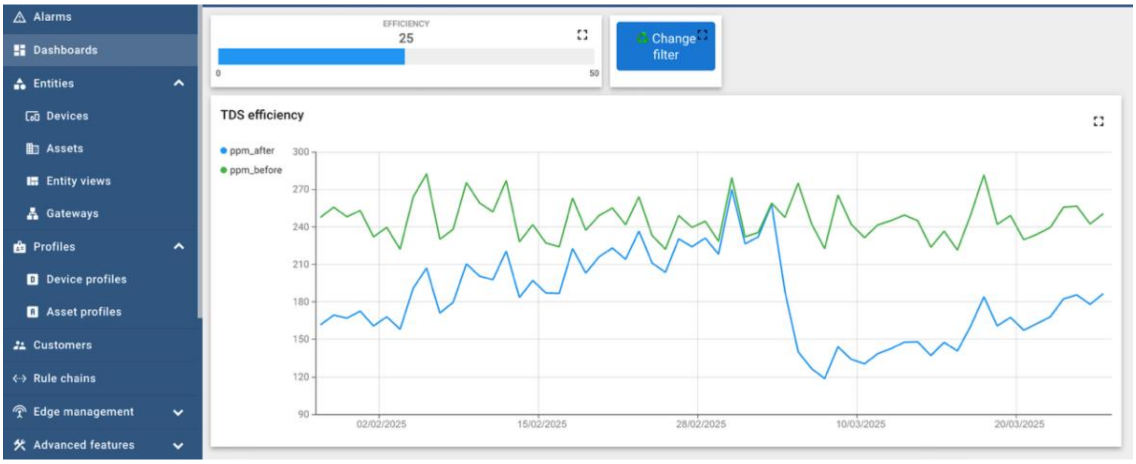

FIG. 5. Water quality monitoring interface on the ThingsBoard platform.

V. EQUIPMENT DEGRADATION MODEL BASED ON HISTORICAL TDS VALUES

The TDS level after filtration serves not only as an indicator of filter performance but also as a critical parameter reflecting the long-term impact on equipment condition – particularly in terms of scale formation, heater element degradation, valve blockage, and wear of hydraulic connections.

To account for these effects, a degradation assessment model based on historical telemetry data has been implemented within the ThingsBoard platform.

The core idea of the model lies in accumulating a conditional degradation index that is updated with each new measurement based on the TDS value after filtration. Since the intensity of scale formation depends on mineralization in a nonlinear manner, an approximation of the impact has been introduced using a scaling function *f(TDS)*, whose value increases as the TDS level rises. As a result, even with the same water consumption, the impact on the equipment will be significantly greater when the water quality is poor.

The general formula for calculating the accumulated degradation is as follows:

$$D = \sum_{i=1}^{n} f(TDS_i) \cdot V_i, \qquad (1)$$

where TDS_i is the total dissolved solids level of the water after filtration at the *i*-th step; V_i is the volume of water that passed through the equipment at the *i*-th step; $f(TDS_i)$ is a scaling function that represents how a specific TDS value contributes to the overall system degradation.

In cases where real-time water flow measurements are not available, the model operates using average consumption volumes, which are typically fixed for each device (e.g., 25 liters per cycle). The value of the *f(TDS)* function is defined in tabular form, based on empirical observations and trends in equipment degradation. An example set of coefficients used in the model is as follows:

TABLE 1. Multiplicator factors based on TDS levels.

TDS Value, ppm	Multiplicator factor
up to 170	0.1
171 – 199	0.2
200 – 230	0.3
231 – 290	0.4
291 – 330	0.6
331 – 400	0.9
above 400	1.2

The accumulated degradation value is stored in the ThingsBoard telemetry database. This enables graphical visualization (e.g., Figs. 6 and 7), estimation of residual resource, and identification of the moment when a degradation threshold (e.g., 80%) is reached. Based on this, appropriate actions can be triggered, including sending notifications, submitting maintenance requests, or limiting equipment functions.

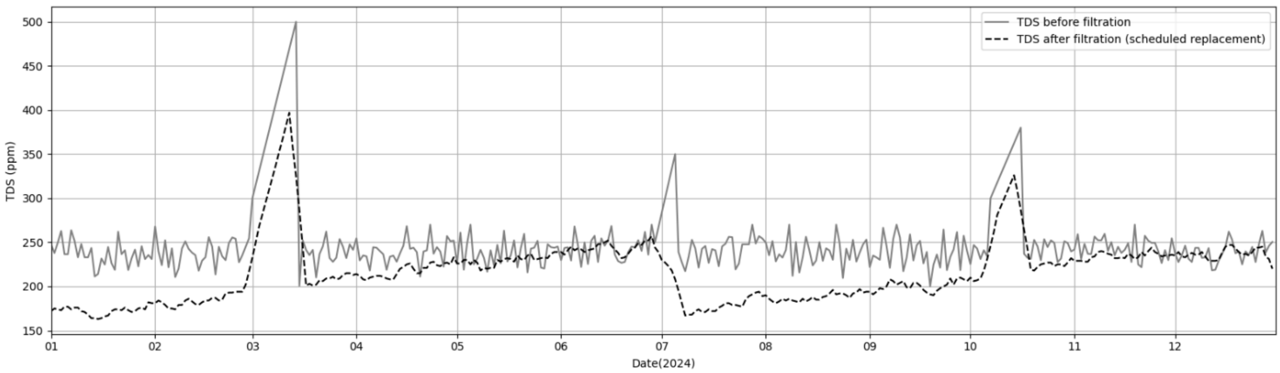

FIG. 6. Comparison of TDS before and after filtration with scheduled replacement model, illustrating variation across the twelve months of 2024 (01 – 12).

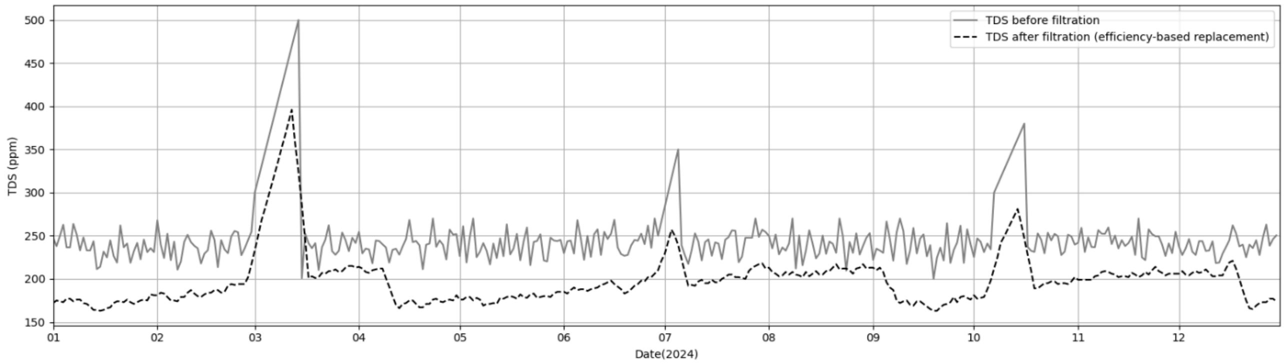

FIG. 7. Comparison of TDS before and after filtration with efficiency-based replacement model, illustrating variation across the twelve months of 2024 (01 – 12).

Such a method shifts the system from a reactive to a predictive model, where decisions are made not only based on current values but also by considering the cumulative effect of water quality on the technical condition of the equipment. This allows for optimized maintenance planning, fewer failures, and long-term operational stability.

To validate the model, simulations were conducted using synthetic annual datasets of TDS values after filtration, representing typical equipment operating conditions in a commercial environment. The simulated limescale accumulation levels for two filtration models are presented in Fig. 8.

The results showed that when average TDS levels after filtration remained in the 180 – 250 ppm range, the 80% degradation threshold was reached after approximately 13 – 15 months of use. In cases of elevated mineralization (330 ppm and above), this period shortened to 9 – 10 months. These results confirm the system's sensitivity to water quality deterioration and justify the cumulative approach for assessing equipment condition.

This approach enables not only real-time decision-making based on current filtration efficiency but also the development of a service schedule tailored to actual operating conditions.

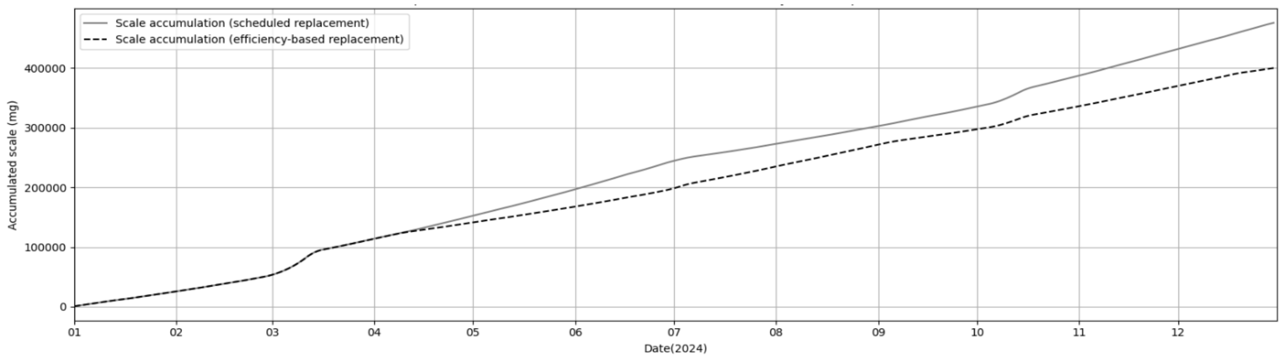

FIG. 8. Limescale accumulation in two filtration models.

VI. CONCLUSION

This paper presents the design and implementation of an IoT-enabled framework for water quality assessment, centered on the continuous monitoring of TDS and cloud-based analytics using the ThingsBoard platform. The proposed system demonstrates effective integration of the hardware component with cloud infrastructure, enabling centralized telemetry processing, decision logic implementation, and long-term tracking of equipment degradation indicators.

A key feature of the solution lies in its transition from traditional filter replacement strategies – based on fixed intervals or cumulative volume counters – to a dynamic model that considers actual water quality. This allows for more accurate prediction of filter efficiency loss, timely maintenance alerts, and the avoidance of premature equipment failures.

The degradation model, developed using historical telemetry data, opens the door for predictive maintenance strategies, which are particularly relevant in high-demand or continuous operation environments. Due to the simplified connection scheme, low component cost, and flexibility of the platform, the system can be readily adapted to various equipment types, including commercial beverage systems, water treatment installations, and domestic filtration units.

In summary, the proposed approach is not only technically feasible but also economically viable. It demonstrates strong potential for broad deployment in sectors where water quality control is critical for reliable equipment performance.

AUTHOR CONTRIBUTIONS

R.R. – conceptualization, methodology, software, formal analysis, resources, investigation, validation, writing-original draft preparation, visualization; M.R. – conceptualization, methodology, validation, writing-review and editing, supervision.

COMPETING INTERESTS

The authors declare no conflict of interest.

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Контроль параметра TDS засобами IoT як фактор підвищення надійності та економічності обладнання

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АНОТАЦІЯ У статті розглядається комплексне рішення Інтернету речей (Internet of Things, IoT) для моніторингу ефективності фільтраційних систем на основі аналізу загальної кількості розчинених твердих речовин (Total Dissolved Solids, TDS). TDS є ключовим показником якості води, оскільки визначає концентрацію розчинених частинок, як-от солі, мінерали та органічні речовини. Перевищення допустимих значень може свідчити про зниження ефективності фільтрації, що потребує своєчасного технічного обслуговування або заміни фільтра. Запропонована система поєднує вимірювальний пристрій, хмарну IoT-платформу ThingsBoard та алгоритми оцінки стану фільтра. Центральним елементом є модифікований давач Gravity Analog TDS, який дозволяє визначати рівень TDS до та після фільтрації. Цей давач вимірює електропровідність розчину, що корелює із загальною концентрацією розчинених речовин у воді, надаючи можливість оцінити рівень TDS у реальному часі. Зібрані дані з сенсора проходять попередню обробку та усереднюються, після чого вони передаються до IoT-платформи ThingsBoard, яка реалізує централізовану логіку аналізу та управління. ThingsBoard забезпечує інтерактивний моніторинг параметрів, виконання розрахунків залишкового ресурсу фільтра, оцінку його ефективності та автоматичне формування сповіщень для користувача. Запропонована архітектура IoT-рішення дозволяє не лише контролювати якість води, а й адаптивно реагувати на зміну умов експлуатації, що підвищує точність прогнозування деградації фільтра. Такий підхід є більш ефективним, ніж традиційні моделі обслуговування, які базуються на фіксованих інтервалах часу або обсягах споживання. Система дає змогу оптимізувати витрати, уникнути передчасних поломок та підвищити надійність роботи фільтраційного устаткування. Особливістю розробки є відмова від локальної обробки на користь централізованої логіки в хмарі, що спрощує масштабування рішення для моніторингу великої кількості пристроїв у розподіленій інфраструктурі. Такий підхід особливо актуальний для використання у торговому обладнанні, промислових системах водопідготовки та інших галузях, де важливо забезпечити стабільну якість води і своєчасну заміну фільтраційних вузлів.

КЛЮЧОВІ СЛОВА IoT, фільтрація, ThingsBoard, хмарна обробка, діагностика стану.