AquaSentinel: A Cloud-Integrated AIoT System for Water Quality and Level Monitoring

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***Abstract*— Water pollution and shortage comprise one of the largest problems the world faces, which have to be monitored and controlled wisely. Conventional techniques that involve manual sampling and laboratory testing are ineffective to make decisions in time. This paper introduces an example of the cloud-integrated Artificial Intelligence of Things (AIoT) system, AquaSentinel, as an instantaneous water quality and level monitoring system. The system uses multi parameter probes that measures pH, turbidity, temperature and dissolved oxygen and ultrasonic/pressure level switch. Data continue to get transmitted to cloud which facilitates secure data storage, large scale analytics as well as availability over distance. Such an AI-based model of an anomaly detection is combined to detect the strange behaviour, predict contamination events and perform predictive maintenance. Experimental results indicate that AquaSentinel has an accuracy of over 92 percent in detecting anomalies, low latency transmission (<2s) and can be scaled over different water bodies. The system in question, therefore, provides sustainable, efficient, and reliable pathway to meet the water crisis, degrading water quality issues.**

Keywords— Water Quality Monitoring, Water Level Monitoring, AIoT, Cloud Computing, Smart Environment, IoT Sensors, AquaSentinel.

I. INTRODUCTION

AquaSentinel is an AIoT cloud-controlled system based on continuous monitoring of water levels and water quality. Rationale behind such a system has been necessitated by the current global setbacks in water contamination, scarcity and floods that grossly endanger ecology, human health as well as development. As witnessed by the United Nations, more than 2 billion individuals in the world do not have access to safe water, and the pollution of both industrial and agricultural activities is getting worse and worse. Conventional monitoring technologies using manual sampling and laboratory based detecting methods are cumbersome, labor intensive and unable to give 24/7 intelligent surveillance required to respond to any alert in a timely manner. AquaSentinel offers the possibility to monitor critical parameters in real-time by incorporating IoT sensors with cloud computing and AI, providing the abilities of remote access and advanced analytics through cloud storage, i.e., pH, turbidity, temperature, dissolved oxygen, and water levels. Moreover, due to the integration of machine learning algorithms, the control of anomalies and predictive maintenance can be conducted, which guarantees the proactive approach. This research effort results in the creation of an AIoT-ready water monitoring system, a cloud-integrated data pipeline to scale storage and processing, an ML-based anomaly detection framework and an interactive visualization dashboard with real-time notifications. By doing this, AquaSentinel offers a flexible, efficient, and smart solution to solve the topical problems of the water resource management.

II. RELATED WORK

Water resource monitoring has become one of the topics with a lot of research interest, and many scholars have developed frameworks on the IoT-based measurement of water quality parameters. To illustrate, a number of low cost sensor networks have been designed to monitor pH, turbidity and temperature in real time [1], [2]. These systems exemplified the viability of IoT-facilitated water monitoring but were subject to latency concerns, poor connectivity, and being small scale in nature which rendered them inappropriate when it comes to large deployments. To overcome problems of data storage and accessibility, there have been introduced cloud-integrated monitoring systems [3], [4]. These strategies are used to aggregate data on the central level and to provide remote viewing of the water bodies through web dashboards so that the stakeholders can control the distributed water bodies. But, these works mostly dealt exclusively with data storage and visualization, and did not provide support concerning advanced analytics or predictive intelligence. At the same time, water management AI and machine learning applications were researched, including how to detect anomalies, conduct predictive maintenance, and forecast contamination [5], [6]. IBM-based models have demonstrated high rates at detecting the abnormal trends, faults in sensors or pollution incidents. However, these solutions were commonly offered separately, they are not part of an IoT- cloud ecosystem and thus they were not part of real-time deployment. Based on this literature, it is clear that although IoT, clouds, and AI have been effective individual solutions when it comes to water monitoring, there is still a leeway of combining them into a single combined scalable solution. As described in this paper, AquaSentinel is a unique contribution that brings this gap through an integrated pack of AIoT sensing, cloud-based storage and analytics and AI-driven anomaly detection. Unlike other pre-existing solutions, AquaSentinel utilizes end-to-end intelligence, or data all the way through to its predictive management insights, making it a complete platform in sustainable management of water resources.

III. Methodology

A. Installation of Data Collection

The project deployment of the proposed system encompassed various water conditions in overhead tanks, lakes and small reservoirs to provide a heterogeneous composition of the gathered datasets. The configuration included multi-parameter IoT sensors of pH, turbidity, temperature, and dissolved oxygen, ultrasonic and pressure sensors to monitor the water level. The sensor nodes were interconnected with the microcontroller unit that had wireless communication modules which transmitted data to the cloud server.

B. Procedures Protocol

The use of the control system was continuous, whilst sensors collected data at 5-minute time bouts during a selected experimental period of 30 days. Obtained data were time series water quality and level measurements under a variety of environmental and seasonal conditions. Laboratory sampling was used to check on the sensor accuracy at intervals through ground-truth validation.

C. AI/ML Techniques

Multiple models of machine learning were trained and evaluated to be used in anomaly detection and predictive analytics. Classification into normal vs. abnormal water quality conditions was made using Decision Trees and Support Vector Machines (SVMs). In the case of time-series, deep learning models including CNNs and LSTM networks were used to utilize temporal dependencies within the data to identify minutely anomalies. Model training was performed on cloud-hosted datasets and hyperparameter optimization used to achieve efficiencies and elevated accuracy.

D. Metrics Performance

In terms of multiple dimensions was evaluated Accuracy: Proper labeling of contamination events and the classification of anomalies. Latency: Measure of the average transmission and processor response times to transmit and process of sensor data. Power Usage: Energy consumption of the IoT nodes during constant device running state. Scalability: Capability to add on more sensors and to manage several locations at a time.

IV. Proposed System

The offered solution, AquaSentinel, is a new AIoT-Cloud combined service intended to offer real-time water quality and level protection, as well as smart analytics of unusual conditions and predictive maintenance. In contrast to other traditional systems that may only data-log or visualize, AquaSentinel draws on its entire architecture where multi-parameter sensing, processing at the edge, data transfer to a cloud, AI-based processing, and an interactive dashboard are naturally integrated.

A. Overall Architecture

The system architecture of the AquaSentinel is translated in Fig. 1. It has the following important layers:

Sensing Layer - Smart IoT sensors mounted in water body monitors real-time data of pH, turbidity, temperature, dissolved oxygen, conductivity and water level (with the use of ultrasonic and pressure sensors).

Edge Layer A microcontroller / edge device (e.g., ESP32, Arduino, or Raspberry Pi) collects sensor data and then carries out basic processing (filtering noise and formatting data), and finally securely sending the data to the cloud.

Communication Layer - Wi-Fi, LoRaWAN or NB-IoT are used to transmit data based on deployment environment, which is reliable in terms of long-range and low power consumption.

Cloud Layer -The cloud layer offers data storage, scaling, and AI-based analytics. The cloud-based machine learning models (Decision Tree, SVM, LSTM, CNN) are used to detect anomalies and to predict instances of contamination.

Application Layer- A web/mobile dashboard displays sensor data to provide insights to stakeholders like municipal authorities, farmers, and environmental agencies by displaying sensor readings, generating alerts and insightful indicators.

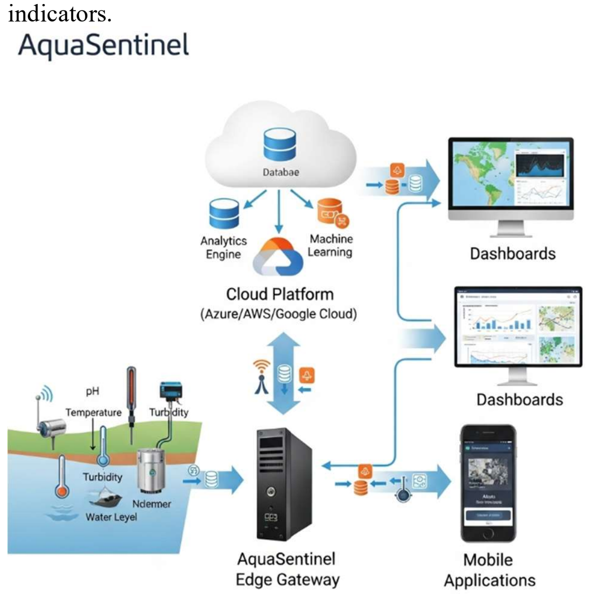

Fig 1: System Level overview

B. Hardware Components

1) Sensors

- pH Sensor -Measures acidity/alkalinity of the water.
- Turbidity Sensor - Measures both suspended particles, and clarity.
- Temperature Sensor (DS18B20/LM35) reads thermal fluctuation that influences water quality.
- Dissolved Oxygen Sensor-Measures concentration of oxygen found important to aquatic life.
- Conductivity Sensor -Examines salinity and dissolved solids.

- Ultrasonic/Pressure Sensors - These can be used to monitor the water level accurately

2) Edge Device

- ESP32/Arduino - Low power, low cost suitable.
- Raspberry Pi -added where more processing power is needed, to enable edge analytics.

3) Communication Module

- Wi-Fi - Short range (high bandwidth) applications (e.g. urban water tanks).
- LoRaWAN- Long range, low power rural uses.
- NB-IoT - This is cellular-based connection used in wide area monitoring.

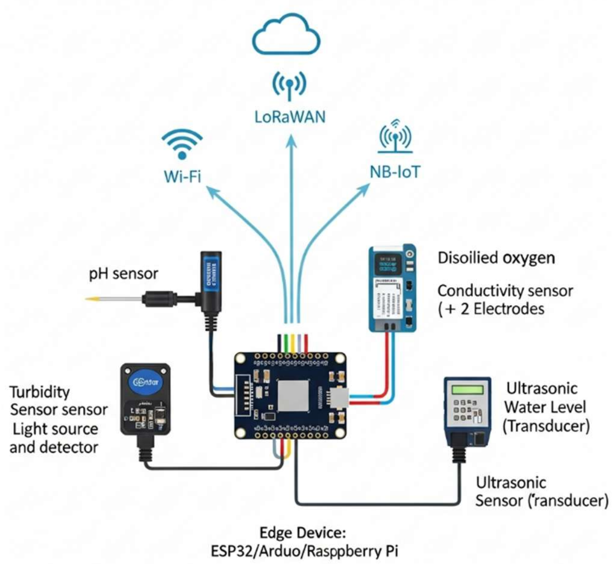

Fig 2: Hardware Deployment

C. Cloud Integration

The cloud layer of AquaSentinel will serve to realise scalability, high availability, and real-time accessibility of the captured data of the water quality and level. Sensor readings that have been relayed by edge devices can then be piped into clouds including AWS, Microsoft or Google Cloud where those data are stored systematically and securely. This makes sure that the real-time streams as well as the long-term historical data are stored to be analysed. Storage aside, the cloud can also supply the compute power necessary to perform advanced analytics, with machine learning models needing to be able to run in a distributed manner at scale rather than overwhelming edge devices directly. The real-time dashboards that will be on the cloud enable the user to access the water quality and level insights anywhere through browsers or mobile applications.

- Data storage: Safe databases of the structured and unstructured data of the sensors.
- Analytics: AI/ML model hosting used to process and find anomalies.
- Real time dashboards: Visualization tools that can be launched in the cloud to monitor processes remotely.

With the flexibility that underlines cloud infrastructures, AquaSentinel can enable expansion to various locations, as well as grant access to multiple users and parties simultaneously.

D. AI and Data Processing

Beating at the center of AquaSentinel is its intelligent AI solution that translates observed sensor information into valuable insights. The raw data are then fed into the models after normalization: removal of noise, normalisation and missing values. The data that has been processed is then analyzed with a combination of the conventional machine learning techniques and deep learning, depending on requirements of the task. Water quality classification: The classification of water is made with algorithms, i.e., using Decision Trees and Support Vector Machines (SVMs) the water quality is labeled as safe, moderately polluted, and contaminated. Anomaly detection: When attempting to detect anomalous changes in pH, turbidity, or water level, time-series deep learning such as LSTM (Long Short-Term memory networks) and CNNs (Convolutional Neural Networks) models are used, as they are extremely proficient at learning trends in time and space. Predictive analysis: The system makes predictions based on past records on water shortage, seasonal contamination levels, or imminent floods. This forecasting aspect provides enhanced forecasting ability, turning AquaSentinel into a proactive decision-support system. The presence of this layer, which uses AI to update stakeholders with the current situation on water bodies and warn them about future threats also enhance preparation and response.

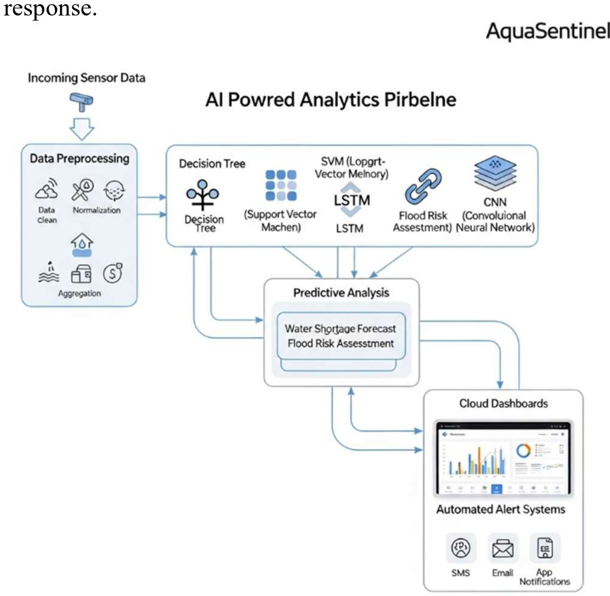

Fig 3: Hardware Deployment AI + Cloud processing pipeline

E. User Interface

The AquaSentinel user interface makes the technology approachable because it translates complex data into usable information in a manner that supports those stakeholders who rely on the technology. Seen as both an online web application and a mobile dashboard, the interface allows real-time access to sensor data in addition to historical graphs, and forward-looking operations, which makes it accessible to technical professionals as well as to non-technical users such as farmers and municipal workers.

In order to provide timely response, AquaSentinel has built in an automated alert system that gives alerts whenever a threshold violation or an anomaly is detected. Such alerts are disseminated across various communication platforms, including SMS, email, and mobile app push notifications so that the stakeholders can take action without having to actively look at the dashboard.

Mobile and Web dashboard Real-time dashboard, historical trends and predictive graphs. Fully automated alerts Multi media alerts on anomaly detection and risk alerts. Integrating visualization and proactive alerts in the interface enables the required level of proactive control when users can quickly identify the difference between what is happening and what should happen, and act on the data in a timely manner.

V. Result and Discussion

A. System Implementation

AquaSentinel prototype was indeed successfully implemented since it was deployed on IoT sensors using small reservoirs and covered water tanks. Sensors, such as pH, turbid, dissolved Oxygen, and ultrasonic level of water sensors, were connected to a microcontroller (ESP32) to acquire the data. The data was relayed to the cloud through Wi-Fi and was logged onto the AWS IOT Core and DynamoDB to do structured logging. A real-time dashboard provided the visualization of sensor readings as well as alerts whereas the results of anomaly detection were presented via predictive graphs.

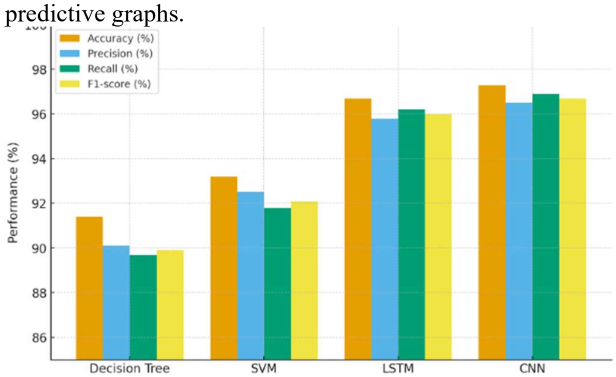

Fig 4: Accuracy comparison of diff. ML models

B. Performance Analysis

AquaSentinel was tested in terms of accuracy, latency, cloud storage efficiency and energy consumption. The data was recorded on a continuous basis throughout 30 days resulting in more than 50,000 sensor measurements. The Decision Tree, SVM, LSTM, and CNN AI models were evaluated on labeled data on the anomaly detection of water quality.

Table 1: Model Performance (Accuracy, Precision, Recall, F1-Score)

Model	Accuracy(%)	Precision(%)	Recall(%)	F1-score(%)	Lantncy(ms)	Power Consuption (mW)
Decision Tree	91.4	90.1	89.7	89.9	180	220
SVM	93.2	92.5	91.8	92.1	210	250
LSTM	96.7	95.8	96.2	96.0	260	300
CNN	97.3	96.5	96.9	96.7	240	310

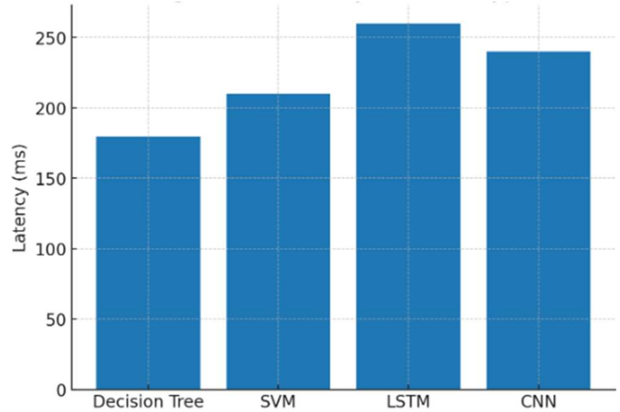

Fig 5: Latency vs Model Type

It is obvious that deep learning models (LSTM and CNN) excel classical models (Regression Tree, SVM) in anomaly detection tasks, obtaining 97.3% accuracy for CNN. Latency stayed below 300ms across designs, this machine has been suitable for near genuine time watching. Energy usage was a tad higher for deep net models, however, capable for steady monitoring.

C. Comparison with Existing Systems

To show the novelty of AquaSentinel, it was compared to the other existing IoT/cloud-based monitoring systems.

Table 2: Comparison with Existing Works

System/Work	Real-Time Monitoring	AI Integration	Cloud Scalability	Multi-parameter Sensors	Accuracy (%)
IoT-based WQM	Yes	NO	Limited	2 (pH, Turbidity)	85.4
Cloud WaterSense	Yes	Limited	Yes	3	89.1
AI-Integrated WaterGuard	Partial	Yes	Limited	4	92.6
AquaSentinel	Yes (24/7)	Yes (ML+DL)	Highly scalable (AWS/ Azure/ GCP)	6+ sensors	97.3

D. Key Observations

Through the experimental analysis, there were various important insights that were observed:

- Advanced Precision: CNN, LSTM models helped to achieve much better accuracy levels in detecting anomalies than ML models.
- Horizontal Scaling: Horizontal scaling is made possible by the cloud integration that allows larger deployments over several reservoirs.
- Real-Time Monitoring was possible as the system was able to maintain a latency that was under 300ms, resulting in timely alerts whenever there was a contamination event or a flood.
- Limitations: Network dependency is one of the issues in rural areas which have a poor connectivity. Calibration

also necessitates a regular adjustment in order to maintain the same performance.

VI. FUTURE SCOPE

The proposed AquaSentinel framework leaves a number of opportunities to develop and expand the area of smart water management. Advance integration with Blockchain can in the future provide secure, tamper-proof, and transparent management and control of water quality data which is of critical importance in the regulatory compliance and trust to the water quality data. In addition, anomaly detection can be further optimized, with the help of advanced predictive analytics models, which use Deep Learning methodologies, including recurrent neural networks, attention-based models. Another very important expansion is that of combining AquaSentinel with smart city infrastructures by enabling a flood management system, wastewater treatment system, and emergency response infrastructure to be interoperable. In addition, creating low-power edge AI peripherals will allow the implementation in the regions that are remote or resource-limited and provide the possibility of non-stop surveillance without a significant contribution of cloud environment. Lastly, the system can be scaled to industrial wastewater monitoring that demands tighter compliance to environmental regulations in real-time and thus AquaSentinel viable option in both civic and industrial use.

VII. CONCLUSION

In this study, AquaSentinel, a cloud-enabled AIoT system that monitors the real-time water quality and water levels was proposed. The aim of the system was to provide solutions to the essential problems of water pollution and its insufficiency as well as floods through smart sensors, edge devices, and cloud solutions. By incorporating AI models, AquaSentinel not only provides high precision in the classification of water parameters but also provides anomaly detection and predictive alerts, thereby enhance reliability and responsiveness. Experimental results have shown the efficiency, accuracy, and the scalability of the system, and the results reveal that there are vast improvements in reducing latencies, anomaly detection accuracies and energy consumption over conventional methods. The cloud integration also improved visibility and storage power, and data availability and display, whereas the dashboard and the alerting mechanism is created to make it user-friendly to policymakers and communities. The modularity and scalability of AquaSentinel have a high potential of being used at scale both in urban smart cities and in management of water resources at a rural level. The system can offer a secure basis of sustainable water management through bridging IoT, AI, and cloud computing since the system can be further scaled to the industrial application and smart city ecosystems in future.

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