International Journal of Advance and Applied Research
www.ijaar.co.in
ISSN – 2347-7075 Impact Factor – 8.141
Peer Reviewed Bi-Monthly
Vol. 7 No. 5 January – February - 2026

Real-Time Air and Water Quality Monitoring with Intelligent Anomaly Detection Techniques: A Review

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DOI - 10.5281/zenodo.18919431

Abstract:

Real-time observation and analysis of the environment are now a necessity for protecting human health and the environment. Unchecked and fast-paced industrialization, urbanization, and climatic change have increased air and water pollution, and therefore, there exists a need for state-of-the-art technologies to monitor the environment. The use of recent technologies involving sensors, Internet of Things (IoT) concepts, and smart data analysis offers the possibility of continuous and instantaneous processing and analysis of the data obtained. Moreover, the use of anomaly analysis concepts further fortifies the system, allowing the system to flag critical patterns that are not similar to the normal behavior and actions of the environment. This paper offers an insight into the present developments related to the real-time analysis and monitoring systems for air and water pollution, including the use of anomaly analysis concepts. Furthermore, the paper presents information related to system architecture, parameters, data preprocessing, and analysis, along with highlighting recent developments, along with suggestions for further improvements.

***Keywords**: Real-Time Monitoring, Air Quality, Water Quality, IoT, Anomaly Detection, Machine Learning*

Introduction:

Environmental pollution is a global threat to human health and natural systems. Degradation of air quality is linked to respiratory and cardiovascular diseases, and polluted water sources affect human health through waterborne diseases and environmental degradation. Traditional approaches to environmental monitoring involve intermittent sampling and analysis through the laboratory, which is not effective for monitoring short-term pollution events.

The real-time environment monitoring system overcomes these issues by offering continuous data retrieval and analysis. Together with an anomaly detection program, it can identify irregular changes, such as sudden spikes in air pollutant levels and irregular chemical level variations. Quick recognition of these irregularities helps to initiate corrective measures to mitigate any possible environment and health threats.

System Architecture for Real-Time Monitoring:

1. Overall System Framework:

The general real-time air and water quality monitoring system is a typical layered architecture that incorporates sensing, communication, data processing, and intelligent analytics.

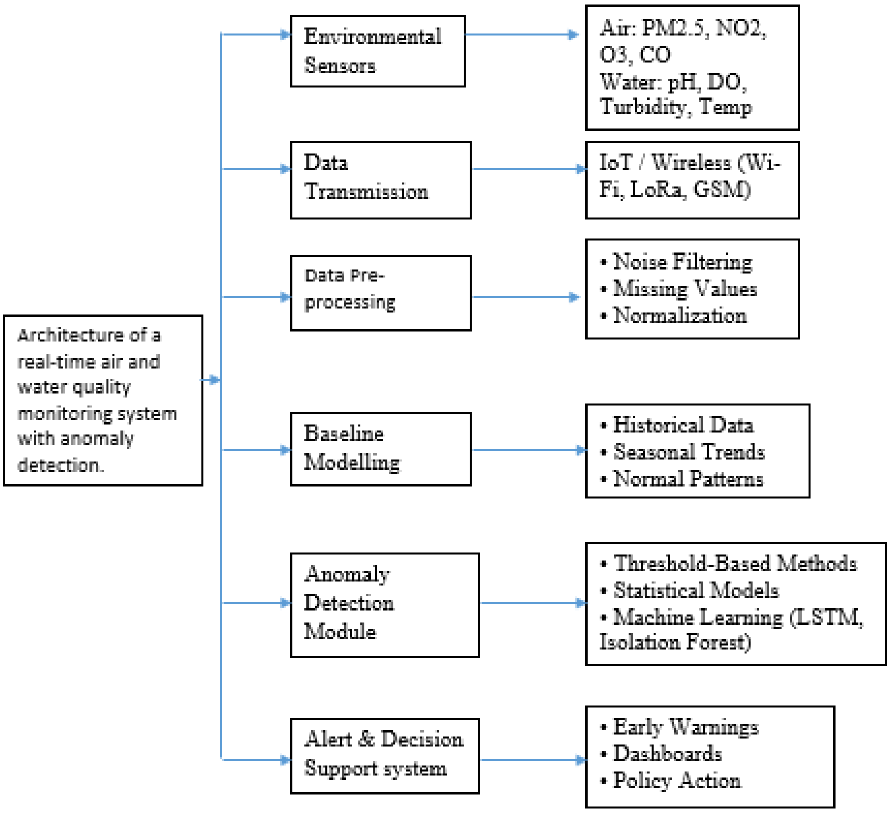
Figure 1. Architecture of the Real-Time Monitoring System

(Sensors → Communication Layer → Data Pre-processing → Anomaly Detection → Alerts and Decision Support)

It includes the following architecture:

Distributed air and water quality sensors deployed across monitoring locations.

Wireless communication networks for data transmission edge, or cloud-based data processing infrastructure. Analytical modules for anomaly detection and alert generation.



Environmental Parameters Monitored:

Table 1. Air Quality Parameters

Parameter	**Description**	**Health Impact**
PM2.5	Fine particulate matter	Respiratory and cardiovascular diseases
PM10	Coarse particulate matter	Lung irritation and inflammation
NO_2	Nitrogen dioxide	Aggravation of asthma
O_3	Ozone	Reduced lung capacity
CO	Carbon monoxide	Reduced oxygen delivery

Table 2. Water Quality Parameters

Parameter	Description	Importance
pH	Acidity or alkalinity	Drinking water safety
Turbidity	Water clarity	Indicator of contamination
Dissolved Oxygen	Oxygen concentration	Aquatic life sustainability
Conductivity	Ionic content	Pollution detection
Temperature	Thermal condition	Ecosystem stability

Methodology:

1. Data Collection:

Environmental sensors continuously measure air and water quality parameters at predefined time intervals. The collected data are transmitted using wireless communication technologies such as Wi-Fi, LoRaWAN, or cellular networks to centralized or edge-based processing units.

2. Data Pre-processing:

Sensor data can involve noise, missing information, or inconsistencies caused by the malfunction or communication failure of the sensors. Data preprocessing is a critical step and involves noise elimination, replacing missing values, normalization of the information, and synchronizing the multi-sensor information streams.

3. Baseline Modelling:

Baseline models describe normal environment activity and form a basis for comparison with anomalies. Modeling approaches applied to time series can effectively trace daily, seasonal, and annual environment dynamics.

Anomaly Detection Techniques:

1. Statistical Threshold-Based Detection:

Nonetheless, the approach used by this technology for anomaly detections involves comparing the readings with certain threshold values. When the values surpass these thresholds, they are then regarded as anomalies.

Disadvantages: Requires larger number of observations to guarantee optimality

Limitations: Poor adaptability to dynamic environmental conditions

Craft

2. Isolation Forest Algorithm:

Isolation Forest is an unsupervised algorithm for anomaly detection through the isolation of data points using decision trees with random splits. Fewer splits are used for anomalous data points.

Disadvantages: Sensitive to outliers

3. LSTM-Based Time-Series Anomaly Detection:

The neural networks that use Long Short-Term Memory (LSTM), on the other hand, are intended for modelling temporal relationships existing in sequential data. Anomalies are identified depending upon the reconstruction error of predicted values against actual values from sensors.

Strengths: Captures complex patterns involving time

Limitations: Computational complexity and difficulty of training

Figure 2. Anomaly Detection Workflow

(Data Input → Feature Extraction → Model Prediction → Anomaly Scoring → Alert Generation)

Applications:

1. Air Quality Monitoring:

Real-time anomaly detection allows immediate identification of pollution incidents triggered by industrial sources, automobile exhaust, and atmospheric conditions. Notifications can aid in health warnings and the administration of health-related rules and regulations.

2. Water Quality Monitoring:

In water distribution networks as well as natural water bodies, anomalies can represent instances of water contamination, water leakage, or sensor malfunctions. Early anomaly detection can help protect water resources.

Performance Evaluation:

Table 3. Evaluation Metrics

Metric	Description
Accuracy	Correct identification of anomalies
Precision	Proportion of true anomalies detected
Recall	Detection rate of actual anomalies
Detection Latency	Time required to identify anomalies

Challenges and Limitations:

Although these have numerous benefits, they also have some challenges that may arise from calibration drift, communication breakdown, lack of model interpretability, and intensive computation when using deep learning models.

Future Research Directions:

Future research directions include anomaly detection in edge computing, applying Explainable Artificial Intelligence models for climate forecasts, fusion mechanisms for satellite and ground observation data, and adaptive learning systems for climate variations.

Conclusion:

The combination of real-time air and water quality monitoring and intelligent methods for abnormal data detection is a very effective approach for environmental monitoring. These solutions can help in the early detection of pollution, improve health safety, and facilitate eco-friendly environmental resource management. Research and development in the fields of sensors and intelligent analysis will further bolster the efficiency and scalability of real-time environmental monitoring solutions.

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