DOI: https://doi.org/10.25140/2411-5363-2025-3(41)-296-309
UDC 004.9:[504.4.054+355.015]

Phoenix Serhiiovych Aartvork[1], Olena Vasylivna Trunova[2]

[1]PhD Student of the Department of Information Technology and Software Engineering
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: nicksnickslaw@gmail.com. **ORCID:** https://orcid.org/0009-0004-1129-1322

[2]PhD in Pedagogical Sciences, Associate Professor of the Department of Information Technology and Software Engineering
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: e.trunova@stu.cn.ua. **ORCID:** https://orcid.org/0000-0003-0689-8846
ResearcherID: G-3925-2014. **Scopus Author ID:** 57211429427

DESIGNING A SOFTWARE PLATFORM FOR OPERATIONAL MONITORING OF WATER RESOURCES BASED ON THE INTERNET OF THINGS

The relevance of this study is driven by the critical damage to water supply infrastructure in the de-occupied territories of Ukraine, which creates acute risks of anthropogenic contamination of water resources and highlights the inefficiency of traditional monitoring methods.

The core problem lies in the absence of an integrated software platform capable of ensuring the rapid and reliable collection, transmission, and analysis of data under unstable connectivity, enabling quick deployment, and integrating with emergency response systems.

The aim of this article is to develop and substantiate the conceptual architecture of a specialized software platform based on the Internet of Things (IoT), adapted to these challenges.

The study proposes a detailed four-layer architecture, comprising a sensing layer with a modular design for monitoring specific threats (heavy metals, petroleum products), a network layer employing a hybrid approach (LPWAN/4G) and the MQTT protocol to ensure guaranteed data delivery, a data processing and storage layer based on cloud services, an MQTT broker, a machine learning module, and a multi-model data repository, and an application and presentation layer that integrates a web dashboard, mobile applications, an alerting system, and APIs for system integration.

The conclusions indicate that the proposed architecture provides a foundation for developing a fault-tolerant and scalable platform, enabling a shift from reactive to proactive environmental safety management, supporting informed real-time decision-making, and promoting the sustainable recovery of affected territories.

Keywords: *Internet of Things (IoT); operational monitoring; water resources; de-occupied territories; environmental safety; software platform architecture; fault tolerance; autonomous sensors.*

Fig.: 3. Table: 2. References: 27.

Relevance of the research. The ongoing military actions in Ukraine have caused critical damage to water supply infrastructure and wastewater treatment facilities, creating acute risks of technogenic contamination of water resources [1]. The situation in the Seym River basin vividly illustrates the extent of this environmental vulnerability. According to official data [2], there has been a significant deterioration in water quality: the chemical oxygen demand (COD) has risen to 104,2 *mg/dm³* (with the standard limit being 30 *mg/dm³*), the concentration of ammonium nitrogen has exceeded the permissible threshold, and the level of dissolved oxygen has dropped far below the critical minimum.

These conditions expose fundamental shortcomings of traditional monitoring methods based on periodic sampling. Among them are: the considerable time lag between an incident and its detection, caused by logistical constraints and the duration of laboratory analyses; the low spatiotemporal resolution, which creates “blind zones” where short-term yet intense pollution events remain undetected; and, as a result, the predominantly reactive nature of control, which merely records pollution retrospectively and prevents timely measures to contain its spread.

The above limitations highlight the urgent need to adopt a paradigm of operational (crisis) monitoring – intensive observation of natural systems in near real-time within environmentally stressed areas [3, 4]. The central goal of this approach is to ensure immediate response to emergencies, enabling their effective containment, mitigation, and the minimization of adverse consequences.

Accordingly, the relevance of this study lies in the scientific and technical justification and design of a specialized software platform based on the Internet of Things (IoT). This platform serves as a technological tool capable of implementing the principles of operational monitoring

and ensuring the transition from delayed, reactive responses to proactive, data-driven management of environmental safety. The development of a flexible, scalable, and fault-tolerant solution is critically important for the sustainable recovery of affected areas, the protection of public health, and the preservation of biodiversity.

Problem statement. The core issue addressed in this article is the absence of a comprehensive software platform capable of effectively handling the tasks of real-time collection, transmission, storage, processing, and visualization of heterogeneous data from IoT sensor networks in the unstable environment of de-occupied territories. Existing systems are not designed to operate under crisis conditions and fail to meet three critical requirements:

1. Fault tolerance under unstable connectivity. Damaged infrastructure demands that the platform be capable of autonomous operation with guaranteed data synchronization once communication is restored – an essential condition for uninterrupted monitoring.

2. Rapid and flexible deployment. Post-war conditions require "plug-and-play" functionnality, enabling the swift deployment of new monitoring points without significant time or resource expenditures for integration.

3. Interoperability with response systems. Monitoring data must be automatically and seamlessly integrated with the information systems of the State Emergency Service, local administrations, and environmental agencies to support timely decision-making, unlike existing siloed solutions.

Thus, the task is not to develop yet another monitoring system, but rather to design a specialized, adaptive architecture that meets the requirements of fault tolerance, rapid deployment, and seamless integration into a unified crisis management framework.

Analysis of recent studies and publications. A review of current approaches to water resource monitoring indicates active adoption of digital technologies. In Ukraine, initiatives have emerged that are mainly focused on data visualization, such as the "e-Water" project [5] and systems built on the ArcGIS platform [6, 7]. At the same time, international experience demonstrates a shift toward integrated monitoring systems [8, 9]. However, most existing solutions do not account for the specific challenges of operating in areas with damaged infrastructure, which underscores the relevance of this research.

Most such platforms are based on a generalized three-tier architecture (data collection, processing, and presentation) [8, 10, 11]. Yet, for crisis conditions, as emphasized by Ashraf U. et al. [12] and Poke B. [13], this is insufficient, since the reliability of data transmission becomes critical and requires detailed examination at each technological level.

At the data collection level, the key challenges are energy efficiency and reliability. For instance, to reduce network load and improve responsiveness, Attallah N. A. [14] investigated the use of edge computing – primary data processing directly on sensor nodes. For transmitting such data over long distances, research by Pires L. M. [15] shows that LPWAN technologies (LoRaWAN, NB-IoT) are effectively applied. Moreover, to ensure guaranteed information delivery under unstable connectivity, studies by Ghosh D. et al. [11] confirm the effectiveness of the lightweight MQTT protocol due to its support for Quality of Service (QoS).

Once the data reach the server, the challenges shift to efficient processing and storage. In particular, to manage large-scale data streams, Pacella M. et al. [16] highlight the use of scalable cloud frameworks. At the storage stage, Liu P. [17] substantiates the advantages of specialized time-series databases (TSDB), such as InfluxDB, while practical aspects of their integration with MQTT are discussed in EMQ Technologies [18]. Finally, for data analysis, Khattach O. et al. [19] propose the use of machine learning pipelines for real-time processing, whereas Shahid M. et al. [20] further advance this approach by developing predictive models for water quality.

Identification of unexplored aspects of the general problem. A critical review of existing solutions shows that they often fail to account for the unique combination of challenges essential for operational monitoring under crisis conditions. In particular, comprehensive research is lacking in the following areas:

- Absence of architectural patterns that ensure uninterrupted data collection, data integrity, and overall system fault tolerance under frequent connectivity disruptions.
- Lack of models enabling flexible integration of new sensors on a "plug-and-play" basis, which is crucial for the rapid expansion of monitoring networks in environments with restricted access and high risks.
- Existing solutions are limited to visualization, whereas what is needed is deep, seamless integration with the information systems of the State Emergency Service, local administrations, and environmental agencies to support automated decision-making.
- No studies provide recommendations on the optimal combination of technologies (databases, message brokers) that best meet performance and reliability requirements for monitoring tasks in crisis conditions.

Research in the field of IoT systems frequently addresses either hardware aspects or generalized cloud solutions, overlooking the specific requirements of platform design in post-war reconstruction settings, where fault tolerance, adaptability, and deployment speed are of critical importance.

The purpose of this article is to develop and substantiate a conceptual IoT-based software platform architecture for operational monitoring and analysis of water resources in de-occupied territories.

The objectives include identifying the key functional components of the platform, descrybing their interrelations, and selecting the core technologies for their implementation.

Presentation of the Main Material. To address this objective, a multi-layered event-driven architecture (EDA) of the software platform is proposed (Fig. 1), consisting of four logical tiers.

In contrast to the more generalized three-tier model, this architecture explicitly distinguishes the network layer to emphasize the critical aspects of data transmission under unstable connectivity conditions. Such an approach makes it possible to design the system with due consideration of the key requirements for fault tolerance, scalability, and the timeliness of water resource monitoring in de-occupied territories.

1. *Sensor Layer (Data Collection).* This layer is responsible for interacting with the physical environment and for primary data acquisition. Its main objective is the reliable and autonomous collection of baseline data on the state of water resources through a network of intelligent sensor nodes.

1.1. Network of Autonomous IoT Sensors. At the core of this layer lies a network of autonomous nodes equipped with specialized sensors for measuring key water quality indicators, such as:

- pH (acidity/alkalinity);
- temperature (indicator of thermal pollution);
- turbidity (presence of suspended particles);
- dissolved Oxygen (DO) (indicator of organic pollution);
- electrical Conductivity (EC) (concentration of dissolved ions).

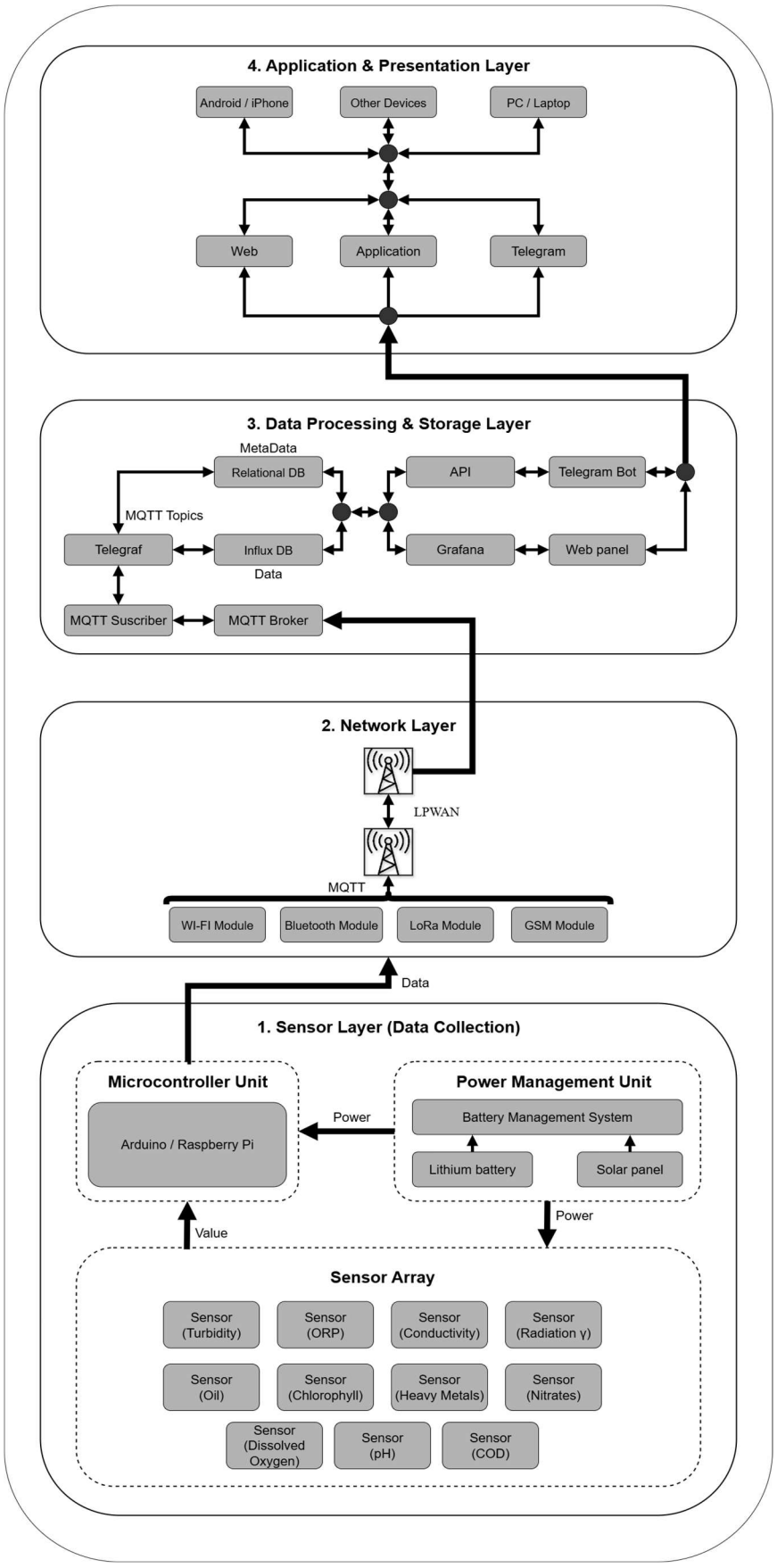

Fig. 1. Architecture for processing and reproducing monitoring data

For de-occupied territories, in addition to standard hydrochemical indicators, priority must be given to monitoring specific threats arising from military activities. Therefore, the integration of sensors for detecting the following becomes particularly relevant:

– heavy metals (lead, cadmium, and mercury), which enter water bodies due to the destruction of industrial facilities and the disposal of munitions;

– petroleum products and nitrates (as indicators of residual explosives), which result directly from the destruction of military equipment and leaks from damaged storage facilities;

– increased radiation background, serving as an indicator of widespread environmental contamination [21].

In designing the architecture, two approaches to equipping sensor nodes were considered: the use of integrated multiparameter probes and the deployment of networks of individual specialized sensors. For conditions where fault tolerance and maintainability are key requirements, the latter approach was chosen. Unlike a multiparameter probe, which constitutes a single point of failure, the malfunction of an individual specialized sensor does not lead to a complete shutdown of monitoring. This modular principle ensures graceful degradation of the system and greatly simplifies its scalability, which is critically important for adaptive crisis management.

The operational and technical characteristics of the main types of sensors that affect overall system reliability are summarized in Table 1.

Table 1 – Operational and technical characteristics of the main types of sensors

№	Sensor type	Typical measurement range	Typical error	Protection class (IP)	Intercalibration interval (typical)	Service life (typical)
1	pH sensor	0-14.00 pH	± 0,15 pH	IP68	1-3 months	1-2 years
2	ORP sensor	-1999…+1999 mV	≤ ± 5 mV	IP68	1-3 months	1-2 years
3	Dissolved oxygen (DO) sensor	0-20 *mg/L*	± 3 % FS	IP68	6-12 months	3-5 years
4	Electrical conductivity (EC) sensor	1-20000 *µS/cm*	± 1 % FS	IP68	6-12 months	3-5+ years
5	Turbidity sensor	0-4000 NTU	± 5 % FS	IP68	6-12 months	3-5+ years
6	COD sensor	0-500 *mg/L*	± 5 % FS	IP68	3-6 months	2-3 years
7	Chlorophyll sensor	0-400 *µg/L*	± 5 % FS	IP68	6 months	3-5 years
8	Petroleum products sensor	0-50 *ppm*	± 5 % FS	IP68	6 months	3-5 years
9	Heavy metal sensor	0,01-10 *mg/L*	± 10 % FS	IP68	3-6 months	2-3 years
10	Nitrate sensor	0-100 *mg/L* (NO_3^-)	± 5 % FS	IP68	3-6 months	2-3 years
11	Radiation sensor (Gamma)	0,01-1000 *µSv/h*	± 15 %	IP65	12 months	5+ years

Source: developed by the authors.

As shown in the table, the system components have different maintenance cycles. The frequent calibration requirements of pH electrodes, in contrast to the long-term stability of turbidity sensors, make the modular architecture the only rational choice. It enables targeted maintenance of only the "demanding" components without interrupting the operation of the entire station, thereby minimizing operational costs.

1.2. Data Transmission Protocols. For transmitting data from sensor nodes, the lightweight MQTT (Message Queuing Telemetry Transport) protocol is proposed. Its key advantages for IoT solutions include low bandwidth requirements and effective support for Quality of Service (QoS). The use of QoS levels 1 ("at least once") or 2 ("exactly once") guarantees data delivery even in the event of temporary communication disruptions, which is a fundamental requirement for operational monitoring.

1.3. Edge Computing. At this level, preliminary data processing is carried out directly on sensor nodes or local gateways. This includes noise filtering, data aggregation (e.g., averaging values over a specific interval), validation (checking data against predefined ranges to filter out anomalous values caused by sensor malfunctions), as well as temporary local storage in case of connectivity loss. Such processing significantly reduces the load on the transmission network, optimizes bandwidth usage, and ensures faster responses to local events, thereby increasing system resilience. This approach supports operational monitoring by enabling real-time collection of critical indicators for the rapid detection of emergency situations.

2. *Network Layer*. The network layer ensures reliable and energy-efficient transmission of data from autonomous sensor nodes to the central platform. Its architecture consists of two key components: wireless access technologies and data transmission protocols.

2.1. Wireless Access Technologies. Sensor nodes are equipped with robust communication modules selected with consideration of coverage, energy efficiency, and bandwidth under unstable infrastructure conditions. A hybrid approach is proposed:

– LPWAN (LoRaWAN, NB-IoT) provides wide coverage and ultra-low power consumption for transmitting small volumes of data at high frequency, making it ideal for baseline monitoring.

– 4G/LTE Cat-M1 offers higher bandwidth for transmitting larger datasets or for nodes requiring faster information exchange.

Additionally, to enhance the system's resilience to failures – a critical factor under damaged infrastructure conditions – the use of self-organizing sensor networks (mesh networks) is considered. In such networks, nodes are capable of relaying each other's data, thereby creating alternative routes in case of individual node or base station failures, which significantly increases overall fault tolerance.

2.2. Data Transmission Protocols. At the application level, the lightweight MQTT (Message Queuing Telemetry Transport) protocol is proposed. It has become the de facto standard for IoT solutions due to its low bandwidth requirements, resource efficiency, and reliable support for Quality of Service (QoS).

To substantiate this choice, a comparative analysis of the main protocols in the context of operational monitoring tasks is provided (Table 2).

Table 2 – Comparative analysis of data transfer protocols

№	Protocol / Technology	Transport / Model	QoS / Reliability	Typical applications	Suitability for operational monitoring
1	MQTT	TCP, pub/sub via broker	QoS 0, 1, 2	IoT, telemetry, sensors	*High* – guaranteed delivery (QoS 1, 2), low overhead, ideal for unreliable networks
2	CoAP	UDP, REST-like	Confirmable / Non-confirmable	Sensor networks, LLN	*Medium* – very lightweight, but operates over less reliable UDP
3	AMQP	TCP, broker/queues	Reliable delivery, persistence	Banking, enterprise systems	*Low* – excessive and "heavy" for resource-constrained IoT devices
4	WebSocket	TCP, full-duplex	TCP reliability	Chats, gaming, live data	*Low* – designed for continuous bidirectional communication, not energy-efficient for autonomous sensors
5	HTTP/REST	TCP/QUIC, request/response	TCP/QUIC reliability	Web APIs, mobile applications	*Medium* – widely used, but has high overhead (headers), inefficient for frequent small messages
6	DDS	UDP/TCP, pub/sub	Flexible QoS parameters	Avionics, robotics, industry	*Low* – very powerful, but complex to configure and excessive for the given task).

Source: developed by the authors.

As the analysis shows, the use of QoS levels 1 (“at least once”) or 2 (“exactly once”) in the MQTT protocol represents a decisive advantage. This guarantees data delivery even in the presence of temporary communication disruptions, minimizing information loss – a fundamental requirement for operational monitoring under unstable conditions.

3. *Data Processing and Storage Layer*. This layer constitutes the core of the platform, deployed either on cloud services (AWS, Azure, Google Cloud) or on a local server, and is responsible for receiving, processing, and reliably storing all data originating from the sensor network. Cloud infrastructure is prioritized, as it enables dynamic system scalability and ensures high fault tolerance.

The data flow at this level is organized as follows: the MQTT broker receives messages, forwards them to the Data Processing Module for validation and transformation, and subsequently, the processed data together with metadata are stored in the corresponding databases.

3.1. MQTT Broker. The central node for receiving and routing messages from all sensors. The broker acts as a buffer that offloads downstream components and ensures system scalability through asynchronous data processing and distribution.

3.2. Data Processing Module. Responsible for validating, decoding, and transforming raw data into a format suitable for analysis. At this stage, more advanced algorithms are implemented for:

– anomaly detection, using statistical methods (e.g., the three-sigma rule) or machine learning approaches (e.g., Isolation Forest, autoencoders for time series).

– monitoring exceedances of maximum permissible concentrations (MPCs), as defined by national and international standards [22].

In the context of limited historical data from de-occupied territories, the module employs a hybrid strategy that combines unsupervised learning with transfer learning from adjacent regions, as well as active online learning (expert-in-the-loop) to enable gradual model adaptation.

3.3. Data Storage System. To ensure both efficiency and reliability, a multi-model data storage architecture is adopted, combining:

– Time-Series Database (TSDB). For storing primary sensor measurements, specialized databases such as InfluxDB or TimescaleDB are optimal. These are designed for high write throughput, data compression, and fast time-based queries – capabilities that are critical for real-time monitoring.

– Relational Database (RDBMS). For storing contextual metadata (e.g., PostgreSQL). This includes sensor information (IDs, types, calibration data), geographic locations, regulatory thresholds, as well as user accounts and access rights.

4. *Application & Presentation Layer*. This layer provides end users with intuitive tools for interacting with the platform, visualizing data, and receiving alerts, which are critical for effective operational monitoring and informed decision-making.

To illustrate the main user interaction scenarios with the system, a Use Case Diagram is presented in Figure 2.

The diagram illustrates who interacts with the environmental monitoring system and in what way.

Ecologists and SES Operators observe the state of the environment by reviewing both real-time and historical data presented in the form of charts and tables. They receive automatic alert notifications whenever the monitored indicators exceed predefined thresholds and can generate analytical reports for a selected period based on the observed data.

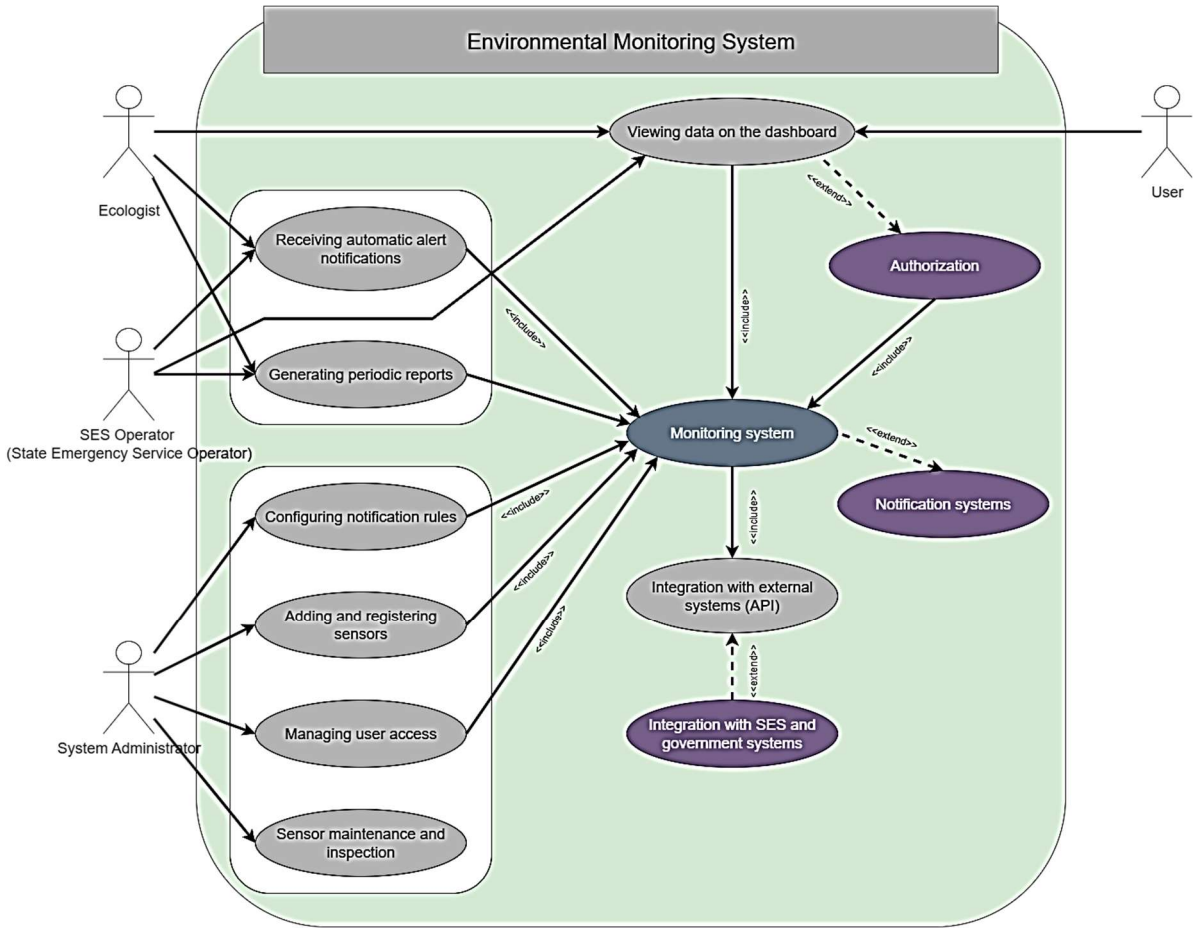

Fig. 2. Diagram of options for using the monitoring platform

The System Administrator is responsible for configuring and managing the system: adding new sensors and monitoring stations, defining notification rules (e.g., threshold values for pollutants), ensuring the proper functioning of all components including sensors, databases, and APIs, managing integrations with external systems, and setting up access control policies for all users.

Thus, the diagram distinguishes between two main user groups: information consumers (Ecologist, SES Operator, and general User) and the technical administrator, who ensures the system's overall operability.

At this level of representation, the system transforms raw data collected by sensors and processed at lower levels of the architecture into actionable insights – that is, clear visual information and timely alerts that enable informed, real-time decision-making to prevent potential crisis situations.

4.1. Access Interfaces (Web Dashboard and Mobile Applications). Two primary tools are provided for data interaction:

1. Interactive Web Dashboard, implemented using Grafana or custom solutions, which offers full functionality for real-time data visualization. It includes an interactive map with sensor locations, indicator trend charts, tabular data, and reporting capabilities. The ability to customize dashboards for different user categories (e.g., environmental specialists, emergency responders, decision-makers) enhances functionality and supports timely decision-making.

2. Mobile Applications (Android and iOS) provide rapid access to key data and alerts directly in the field. They enable responsible personnel to instantly assess the situation and remotely manage the monitoring system, which is critical during crisis situations.

4.2. Alerting Module. An automated notification system that delivers messages (via email, SMS, or messengers such as Telegram/Viber) to responsible stakeholders in case of crisis detection, MPC exceedances, or sensor malfunctions. The system supports flexible rule configuration, escalation mechanisms (notifying higher-level authorities in case of ignored alerts), and comprehensive event logging – making it the core of operational monitoring.

4.3. Integration and API (Application Programming Interface). The platform provides a standardized programmatic interface (RESTful API with JSON data format) to ensure interoperability and data exchange. This enables:

– integration with governmental information systems (e.g., State Emergency Service, Environmental Inspectorate, local authorities) to automate response processes;

– expansion of integration into related domains, such as production management at renewable energy facilities or energy consumption monitoring for comprehensive economic and environmental decision-making;

– utilization of data for scientific research and development.

The API architecture is designed in accordance with the FAIR principles (Findable, Accessible, Interoperable, Reusable), which simplifies the use of platform data for further scientific studies and inter-agency collaboration. While governmental services today often rely on static file exchange [23], successful initiatives such as the alerts.in.ua service [24] demonstrate the societal demand for a unified national API for crisis monitoring. The proposed architecture is prepared for such integration.

To ensure that the theoretical advantages of the proposed architecture – particularly its fault tolerance and scalability – are validated in practice, a step-by-step verification process is required, taking into account key implementation aspects.

The validation strategy consists of three sequential stages:

1. Technical Feasibility (Proof-of-Concept). Development of a minimal laboratory prototype to confirm compatibility of key technologies (MQTT, InfluxDB, Grafana) and establish an end-to-end data pipeline.

2. Fault Tolerance Testing. Software-based simulation of internet disconnections to verify correct data buffering at the sensor node (Edge Computing) and guaranteed delivery upon reconnection.

3. Pilot Deployment. Long-term operation of 3-5 autonomous nodes in real field conditions to analyze system stability, measurement accuracy, and the effectiveness of autonomous power supply.

During platform implementation, particular attention must be given to the following critical aspects:

Autonomy and reliability of nodes. This fundamental requirement is achieved through the selection of low-power microcontrollers, use of sleep modes, and integration with solar panels. The duration of autonomous operation ($T_{autonomy}$) from a battery is calculated using the formula:

$$T_{autonomy}(days) = \frac{C_{batt} \cdot V_{nom} \cdot \eta_d}{E_{day}},$$

where C_{batt} – battery capacity (Ah);

V_{nom} – nominal voltage (V);

η_d – discharge efficiency factor (typically 0,85-0,95);

E_{day} – calculated daily energy consumption (Wh), which depends on the power and operating time in different modes:

$$E_{day} = (P_{sleep} \cdot t_{sleep}) + (P_{active} \cdot t_{active}) + (P_{tx} \cdot t_{tx})$$

where P – power consumption;

t – total time spent in sleep, active measurement, and data transmission modes.

Scalability and flexibility of the platform are ensured through the use of an event-driven architecture (EDA). The central element, the MQTT broker, allows new sensors (event producers) and

data processors (event consumers) to be added independently without modifying the logic of existing components. This creates loose coupling between system elements and enables flexible scaling of individual parts depending on the workload.

Cybersecurity is ensured at all levels: from encrypted data transmission (TLS/SSL) and secure device authentication to protection at the presentation layer. The web dashboard and APIs are developed in accordance with security standards, particularly the OWASP Top 10 [25], to mitigate common vulnerabilities. A role-based access control (RBAC) model is also implemented to differentiate user permissions.

When designing the architecture, the provisions of the CAP theorem (Consistency, Availability, Partition Tolerance) [26] were taken into account. In conditions of unstable connectivity in de-occupied territories, priority is given to availability and partition tolerance. This ensures that the system continues to collect and accept data even during temporary connection loss with some nodes. The architecture adheres to BASE principles (Basically Available, Soft state, Eventually consistent), guaranteeing eventual consistency: after communication is restored, all data accumulated on sensor nodes will be reliably delivered and processed, thereby maintaining monitoring integrity [27].

Economic justification. The project is feasible when the cost of prevented damage ($L_{prevented}$) significantly exceeds the total cost of ownership (C_{TCO}), which consists of capital expenditures (C_{CAPEX}) and operational (C_{OPEX}) expenditures:

$$C_{TCO} = C_{CAPEX} + C_{OPEX}.$$

For the long-term and reliable operation of the platform, its development should include:

– regulated technical maintenance. The development of clear instructions for calibration, cleaning, and component replacement;

– institutional support. Transfer of the system to the balance sheet of a responsible authority (e.g., the State Environmental Inspectorate);

– software update planning. Regular release of updates to improve functionality and strengthen security.

Conclusions. The study developed and substantiated a conceptual architecture of a software platform for rapid monitoring of water resources, adapted to the specific challenges of de-occupied territories.

The scientific novelty lies in the proposed detailed four-layer architecture (sensing, networking, processing, presentation), which systematically addresses the key challenge – ensuring fault tolerance, deployment flexibility, and interoperability under conditions of damaged infrastructure and unstable connectivity. Unlike existing analogues designed for stable environments, the proposed solution comprehensively integrates technologies for operation in crisis scenarios.

Practical results include justification of key technology choices for each architectural layer. For the sensing layer, a modular approach with specialized sensors is proposed, ensuring "graceful degradation" of the system. For the networking layer, the use of the MQTT protocol with QoS is substantiated to guarantee data delivery, along with hybrid communication technologies (LPWAN/4G). For the server layer, a fault-tolerant architecture is proposed based on an MQTT broker, a machine learning module, and a multi-model data repository.

The key advantage of the developed solution is its comprehensive orientation toward fault tolerance, rapid deployment, and integration with emergency response systems. Implementation of such a platform will enable a shift from reactive to proactive, data-driven environmental safety management, ensuring informed decision-making in real time.

Further research will focus on prototyping key system modules, practical validation of fault tolerance by simulating connectivity disruptions, and the development of predictive analytics algorithms for early detection of potential environmental threats.

Thus, the proposed platform is not only a technical solution but also a strategic tool that ensures the environmental dimension of safe and sustainable recovery of Ukraine's de-occupied territories.

Statement on the Use of Generative AI in the Manuscript Preparation Process.

The authors utilized AI (Chat GPT) to enhance the readability and correct stylistic and grammatical errors in this article. Following the use of this tool, the authors reviewed and edited the content as needed, and assume full responsibility for the publication's content.

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Отримано 19.09.2025

УДК 004.9:[504.4.054+355.015]

Фенікс Сергійович Аартворк[1], Олена Василівна Трунова[2]

[1]аспірант кафедри інформаційних технологій та програмної інженерії
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: nicksnickslaw@gmail.com. **ORCID:** https://orcid.org/0009-0004-1129-1322

[2]кандидат педагогічних наук, доцент, доцент кафедри інформаційних технологій та програмної інженерії
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: m.dorosh@stu.cn.ua. **ORCID:** https://orcid.org/0000-0003-0689-8846
ResearcherID: G-3925-2014. **Scopus Author ID:** 57211429427

ПРОЄКТУВАННЯ ПРОГРАМНОЇ ПЛАТФОРМИ ОПЕРАТИВНОГО МОНІТОРИНГУ ВОДНИХ РЕСУРСІВ НА ОСНОВІ ІНТЕРНЕТУ РЕЧЕЙ

Актуальність дослідження зумовлена критичним пошкодженням інфраструктури водопостачання на деокупованих територіях України, що створює гострі ризики техногенного забруднення водних ресурсів та виявляє неефективність традиційних методів моніторингу.

Проблема полягає у відсутності комплексної програмної платформи, здатної забезпечити оперативний та надійний збір, передачу й аналіз даних в умовах нестабільного зв'язку, швидкого розгортання та необхідності інтеграції із системами кризового реагування.

Метою статті є розробка та обґрунтування концептуальної архітектури спеціалізованої програмної платформи на основі Інтернету речей (IoT), адаптованої до цих викликів.

У процесі дослідження запропоновано деталізовану чотирирівневу архітектуру, що включає: рівень датчиків із модульним принципом для моніторингу специфічних загроз (важкі метали, нафтопродукти); мережевий рівень з використанням гібридного підходу (LPWAN/4G) та протоколу MQTT для гарантованої доставки даних; рівень обробки та зберігання на базі хмарних сервісів, MQTT-брокера, модуля машинного навчання та мультимодельного сховища даних; рівень представлення та взаємодії, що об'єднує вебпанель, мобільні додатки, систему сповіщень та API для інтеграції.

Висновки полягають у тому, що запропонована архітектура створює основу для розробки відмовостійкої та масштабованої платформи, яка дозволить перейти від реактивного до проактивного управління екологічною безпекою, забезпечуючи прийняття обґрунтованих рішень у реальному часі та сприяючи сталому відновленню постраждалих територій.

Ключові слова: *інтернет речей (IoT); оперативний моніторинг; водні ресурси; деокуповані території; екологічна безпека; архітектура програмної платформи; відмовостійкість; автономні сенсори.*

Рис.: 3. Табл.: 2. Бібл.: 27.

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