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IOT AND ARTIFICIAL INTELLIGENCE-BASED SYSTEMATIC ANALYSIS OF WATER RESOURCE MONITORING AND MANAGEMENT

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Abstract. The integration of IoT and artificial intelligence technologies into water resource management is emerging as an effective solution in modern monitoring and forecasting processes. IoT sensors measure indicators such as pH, turbidity, temperature, electrical conductivity, and dissolved oxygen in real time, ensuring rapid control, while artificial intelligence algorithms enable the prediction of microbiological parameters. Analyses show that IoT–AI-based systems improve accuracy, energy efficiency, and management effectiveness. At the same time, limitations of biological sensors, model standardization, and cybersecurity issues remain relevant. This approach serves as a methodological basis for sustainable water resource management under the conditions of Uzbekistan.

Keywords: Drinking water quality, IoT (Internet of Things), real-time monitoring, pH, turbidity, NB-IoT, LoRaWAN, temperature, electrical conductivity, Arduino, sensors, water pollution, Artificial Intelligence.

Annotatsiya. Suv resurslarini boshqarishda IoT va sun’iy intellekt texnologiyalarini integratsiya qilish zamonaviy monitoring va prognozlash jarayonlarida samarali yechim sifatida namoyon bo‘lmoqda. IoT sensorlari pH,

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loyqalik, harorat, elektr o‘tkazuvchanlik va erigan kislorod kabi ko‘rsatkichlarni real vaqt rejimida o‘lchab, tezkor nazoratni ta’minlaydi, sun’iy intellekt algoritmlari esa mikrobiologik parametrlarni bashorat qilish imkonini beradi. Tahlillar shuni ko‘rsatadiki, IoT–AI asosidagi tizimlar aniqlikni, energiya samaradorligini va boshqaruv samaradorligini oshiradi. Shu bilan birga, biologik sensorlarning cheklovlari, modellarning standartlashtirilishi va kiberxavfsizlik masalalari dolzarb bo‘lib qolmoqda. Ushbu yondashuv O‘zbekiston sharoitida barqaror suv resurslarini boshqarish uchun metodologik asos bo‘lib xizmat qiladi.

Kalit so‘zlar: Ichimlik suvi sifati, IoT (Narsalar interneti), real vaqt monitoringi, pH, loyqalik, NB-IoT, LoRaWAN, harorat, elektr o‘tkazuvchanlik, Arduino, sensorlar, suv ifloslanishi, sun’iy intellekt.

Аннотация. Интеграция технологий IoT и искусственного интеллекта в управление водными ресурсами становится эффективным решением в современных процессах мониторинга и прогнозирования. Датчики IoT в реальном времени измеряют такие показатели, как pH, мутность, температура, электрическая проводимость и растворённый кислород, обеспечивая оперативный контроль, а алгоритмы искусственного интеллекта позволяют прогнозировать микробиологические параметры. Анализы показывают, что системы на основе IoT–AI повышают точность, энергоэффективность и эффективность управления. В то же время ограничения биологических сенсоров, стандартизация моделей и вопросы кибербезопасности остаются актуальными. Данный подход служит методологической основой для устойчивого управления водными ресурсами в условиях Узбекистана.

Ключевые слова: Качество питьевой воды, IoT (Интернет вещей), мониторинг в реальном времени, pH, мутность, NB-IoT, LoRaWAN, температура, электрическая проводимость, Arduino, датчики, загрязнение воды, искусственный интеллект.

INTRODUCTION.

Water is one of the most essential natural resources for sustaining life, supporting economic development, and maintaining ecological balance. However, effective water resource management has become increasingly challenging due to rapid urbanization, industrial growth, population expansion, and the growing impacts of climate change. In many regions, water monitoring and distribution systems still rely on traditional approaches based on manual control and laboratory analysis. Although these methods can provide accurate measurements, they are often slow and unable to deliver real-time information, which is necessary for

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responding quickly to environmental changes and emergency situations such as floods or pollution incidents.

Recent advances in digital technologies have created new opportunities to improve water monitoring and management. In particular, the Internet of Things (IoT) enables the deployment of sensor networks capable of continuously collecting and transmitting environmental data. IoT sensors can measure important water quality and water level parameters, including pH, turbidity, temperature, electrical conductivity, dissolved oxygen, and flow conditions. Through wireless communication technologies such as LoRaWAN, NB-IoT, ZigBee, Wi-Fi, and MQTT, these sensors allow real-time data exchange and remote monitoring, even in geographically dispersed environments.

Artificial intelligence (AI) further enhances the potential of IoT-based systems by enabling advanced data analysis and prediction. Machine learning algorithms, including regression models, decision trees, random forests, and support vector machines, are increasingly applied to analyze environmental data and predict changes in water quality. Deep learning models, such as long short-term memory (LSTM) networks, are particularly effective for analyzing time-series data and forecasting water system behavior. The integration of IoT and AI technologies therefore enables the development of intelligent monitoring systems that can improve operational efficiency and support sustainable water resource management.

Previous studies have demonstrated the practical benefits of such systems. IoT-based reservoir monitoring platforms using ultrasonic sensors and microcontrollers have shown high accuracy in detecting water level changes and enabling automated control of reservoir gates. In addition, AI models have been successfully used to estimate parameters such as E. coli concentrations in situations where direct electronic sensors are not available. These technologies can improve water resource efficiency, reduce operational costs, and support more effective environmental management.

Nevertheless, several challenges still limit the widespread implementation of intelligent water monitoring systems. Some biological and chemical indicators cannot yet be directly measured with electronic sensors, requiring the use of predictive AI models. Issues related to sensor durability, cybersecurity, interoperability between different platforms, and the lack of standardized regulatory frameworks also remain important concerns. Furthermore, many studies have been conducted only in laboratory or pilot-scale environments, with limited validation in large-scale water management systems.

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For regions such as Uzbekistan and Central Asia, where water scarcity and climate-related risks are becoming increasingly significant, the integration of IoT and AI technologies offers considerable potential. Real-time monitoring, predictive analytics, and automated decision-support systems can improve the efficiency of reservoir management and contribute to more sustainable use of water resources. This study therefore analyzes six recent scientific works related to IoT and AI applications in water monitoring and reservoir management. Based on this systematic analysis, the paper identifies current technological trends, existing research gaps, and potential directions for adapting intelligent water management solutions to the regional conditions of Central Asia.

METHODOLOGY: SYSTEMATIC LITERATURE ANALYSIS.

This study is based on the methodology of a systematic review, aimed at providing a comprehensive analysis of the modern applications of IoT and artificial intelligence (AI) technologies in water monitoring and resource management. The main reason for choosing a systematic review approach is that it allows for consistent, replicable, and objective evaluation of technological solutions, methods, and results presented in existing scientific works. This methodology is widely used to identify the strengths and weaknesses of individual studies, determine general trends, and highlight unresolved issues for future research.

Within the scope of this study, scientific articles published between 2019 and 2024 were analyzed. This time frame was selected because IoT and AI technologies have rapidly advanced in recent years, with the introduction of low-power sensors, wireless communication protocols, and machine learning algorithms actively applied to water resource management. Consequently, research from this period was considered both technologically relevant and practically significant.

The article selection process was carried out in several stages. First, studies related to water quality monitoring, water level control, smart water management, IoT-based environmental monitoring, and AI-driven prediction of water parameters were identified. From these, only full-text articles published in international scientific journals and containing practical or experimental results were included. Purely theoretical or conceptual works without empirical validation were excluded from the review.

Six selected articles were evaluated according to clearly defined criteria. The first criterion focused on the problems addressed and their relevance. Particular attention was paid to how studies highlighted shortcomings of traditional approaches in water monitoring and management, such as lack of real-time data, reliance on manual control, and delayed responses to emergencies. The global and

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regional significance of these issues—especially water scarcity and climate change—was also assessed.

The second criterion examined the methods and technologies employed. At this stage, IoT-based sensor systems, wireless sensor networks (WSN), communication protocols (e.g., LoRaWAN, NB-IoT, ZigBee, Wi-Fi), and AI algorithms used for data processing were analyzed. Specifically, regression models, decision trees, random forests, support vector machines (SVM), and deep learning approaches were compared in terms of their applications and functions. This enabled conclusions about the diversity of technological approaches and their suitability for specific tasks.

The third criterion assessed the results and proposed solutions. Key indicators included accuracy, responsiveness, energy efficiency, and reliability of monitoring systems. Some studies reported near-zero error in reservoir level monitoring, real-time alert mechanisms, and concrete outcomes in optimizing water resource distribution. These findings confirm the practical effectiveness of IoT and AI technologies in water monitoring.

The fourth criterion identified unresolved scientific and technological issues. Limitations included the absence of electronic sensors for certain biological and microbiological parameters, lack of standardized approaches for AI models, and the fact that most systems were tested only at small or laboratory scales. Additional challenges such as long-term sensor reliability, cybersecurity threats, and interoperability across platforms were also highlighted.

For systematic comparison of the selected articles, a qualitative analysis approach was employed. Results for each criterion were synthesized, similarities and differences identified, and broader scientific trends outlined. This enabled the determination of development directions in the field and clarified under which conditions specific technologies or algorithms are more effective. The systematic review methodology not only described the current state of research but also provided a critical evaluation. As a result, both the present capabilities of IoT and AI in water monitoring and management, and the challenges that must be addressed for large-scale implementation, were identified. This methodological approach serves as a solid scientific foundation for the comparative analysis and conclusions presented in the following sections.

RESULTS AND DISCUSSION.

In this section, the results of six analyzed scientific studies are discussed using a systematic and comparative approach. The studies are compared in terms of existing challenges in water resource monitoring and management, applied methodologies, achieved outcomes, and unresolved scientific issues. Such an

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approach makes it possible to identify common patterns across the research, evaluate their differences, and outline promising directions for future investigations.

The main purpose of this comparative analysis is not to describe each study sequentially, but rather to highlight their similarities and differences, reveal overarching trends among existing scientific approaches, and identify research gaps in the field. Furthermore, the results of the analysis serve to evaluate the effectiveness of IoT and AI technologies in water monitoring systems, determine their applicability under real-world conditions, and define prospective directions for future research.

This section consists of four thematic subsections. First, the key problems addressed in the analyzed studies and their relevance are discussed. Next, the applied methods and technological approaches are compared, followed by an evaluation of the achieved results. Finally, the limitations and unresolved scientific issues are identified.

Problems Identified in the Analyzed Studies

The studies reviewed highlight inefficiency in managing water levels in reservoirs and dams as a major problem. In many regions, water gates are still operated manually, and operators lack real-time information about water levels. Under such conditions, sudden rises in water levels are not detected in time, increasing the likelihood of floods and emergencies. With climate change, heavy rainfall, and population growth, ensuring reservoir safety has become an increasingly urgent issue. Manual control and delayed information lead to water wastage, infrastructure damage, and heightened risks to public safety [1–2]. Therefore, real-time monitoring of water levels and the introduction of automated control systems are considered pressing scientific and technical challenges [1].

Closely related to this issue, a significant portion of the analyzed studies emphasize the growing complexity of water resource management under global climate change [3]. Intensifying extreme rainfall and drought events make it difficult to maintain balance in reservoirs and ecosystems. Unequal distribution of water resources, population growth, and industrial expansion sharply increase demand for water [8,9,10]. The limited availability of potable water further underscores the urgency of this problem. From this perspective, the implementation of real-time, energy-efficient, and cost-effective water monitoring systems for ecological environments and smart cities is regarded as a critical task [11,12].

In another analyzed study, significant limitations of traditional laboratory-based approaches to water quality monitoring are noted. Manual collection of water samples and laboratory analysis often lead to errors, delays in

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data processing, and, in some cases, inaccurate records. Such approaches do not allow for rapid and effective decision-making in emergency situations. Therefore, intelligent monitoring systems based on IoT and wireless sensor networks (WSN) are considered relevant and promising solutions [13]. Continuous real-time monitoring of water quality is crucial for ensuring environmental safety, protecting public health, and efficiently managing urban infrastructure [4].

The reviewed studies show that traditional approaches to water quality monitoring are inefficient. Manual sampling and laboratory analysis are slow, costly, and prone to human error. Accelerating urbanization and industrialization increase pollution levels in water resources, thereby intensifying the demands placed on monitoring systems [14,15]. Traditional monitoring methods cannot provide rapid responses to emergencies. WSN and IoT technologies enable continuous water quality monitoring, automated control through multi-sensor systems, and wireless data transmission [16]. Developing intelligent systems capable of continuous, automated, real-time monitoring of water quality is regarded as a pressing scientific and technical challenge [5].

A significant portion of the analyzed studies also emphasize the limited capabilities of traditional approaches in water resource management. Globally, urbanization, industrialization, and climate change are intensifying pressures on water resources, exacerbating problems related to both quality and quantity. Traditional water distribution and treatment systems lack real-time monitoring capabilities, resulting in low efficiency [6], high water wastage, and difficulties in responding quickly to emergencies. From this perspective, the concept of smart water management is considered a relevant solution. IoT sensors enable real-time data collection, while AI algorithms provide deep analysis, allowing effective control of water quality, rational use of resources, improved energy efficiency, and enhanced environmental safety.

The analyzed studies also highlight insufficient digitalization of monitoring and management in water supply systems as a major issue. In industrial processes involving technical water reuse and in urban drinking water distribution systems, problems such as pipeline leakages, inefficient allocation of water resources among sources, and energy wastage are widespread. These shortcomings lead to negative ecological, economic, and social consequences. Traditional monitoring systems are often based on wired networks, which are costly and technically complex to implement across large areas. Therefore, IoT technologies based on wireless communication protocols such as LoRaWAN and NB-IoT are considered promising solutions for ensuring real-time monitoring and automated management.

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This approach enables continuous control in water supply systems, improves energy efficiency, and helps prevent accidents [7].

Applied Methodologies and Technologies

To address the problem, the authors of [1] employed modern technologies. In their study, a system was developed based on Internet of Things (IoT) technology. This approach enabled the collection, storage, and transmission of data from various sensors in real time.



Figure 1. Reservoir level monitoring system [1]

Water level measurement was carried out using ultrasonic sensors. These sensors use sound waves to determine the height of the water level. Data are processed through Raspberry Pi and ESP32 microcontrollers, enabling automatic control of the gates. Real-time monitoring is provided via a cloud server and mobile/web interface, allowing users to remotely supervise the system [1].

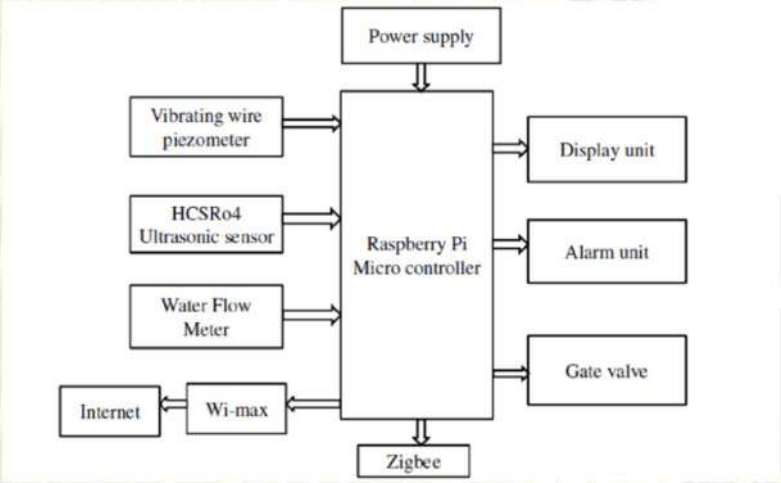


Figure 2. System Architecture [2]

Data collection, storage, and transmission were carried out through a Wireless Sensor Network (WSN) [1]. This makes the system energy-efficient and adaptable to different environments [18]. The advantage of these methods is that they enable the system to be remotely controlled, fast, reliable, low-power, and suitable for operation under diverse conditions.

To address the problem, the authors developed a comprehensive system based on IoT and artificial intelligence. Each component was described separately:

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Water monitoring sensors: pH, turbidity, dissolved oxygen (DO), and water level sensors. These sensors were deployed in each lake to ensure continuous real-time monitoring of water quality [6].

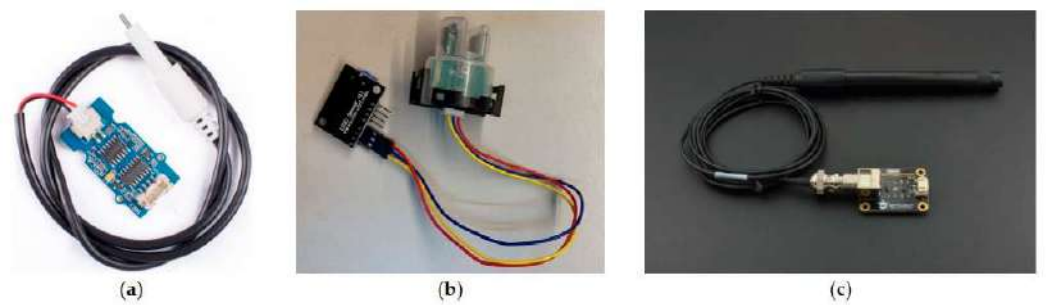


Figure 3. (a) pH sensor, (b) water turbidity sensor, (c) dissolved oxygen (DO) sensor [3]

Table 1.

Water Quality Parameters and Acceptable Ranges [1]

pH value	Turbidity	Dissolved Oxygen
6.0–9.0	3.1–40 NTU	4.5 mg/L dan yuqori

For each studied water source, the measured values of pH, turbidity, and dissolved oxygen are presented in comparative form in Table 1.

ESP-32 node for data reception and transmission:

This module collects sensor data and sends it to the cloud server via Wi-Fi. It is low-cost, energy-efficient, and suitable for monitoring multiple lakes.

Mega 2560 control unit and pump mechanism: This unit controls pumps and drainage systems. When the water level exceeds a limit, the pump automatically redirects water to other lakes. Microcontroller comparison based on computing power, energy efficiency, and communication interfaces helps select the optimal device.

Water level sensors: Non-contact sensors measure water levels in real time. Capacitive sensors provide high accuracy, long-term stability, and reliable operation in harsh environments while reducing maintenance needs.

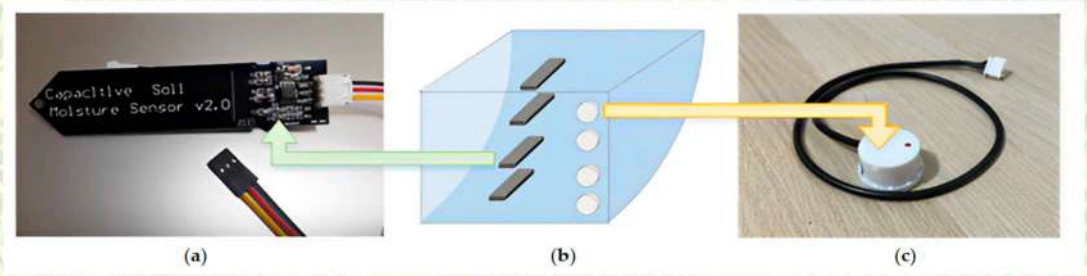


Figure 4. (a) Part of the sensor set for water level monitoring, (b) installed water level sensors, (c) liquid level sensor [4]

The intelligent monitoring system proposed by the authors consists of three main components: the sensing system, the communication system, and the head

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end system (HES). These components are integrated to provide real-time monitoring and analysis of water quality [5].

Sensing system module: Designed for water quality monitoring, this module includes a set of sensors that measure key hydrochemical parameters such as pH, turbidity, conductivity, nitrates, and chlorophyll. The collected data are processed using two mechanisms: In-node Processing (InP), where each sensor node independently processes its own data, and Collaborative Task Processing (CTP), which enables data exchange among neighboring nodes to improve overall accuracy. This approach not only enhances the precision of water quality measurements but also helps identify sources of pollution.

Communication system module: This module transmits data from sensor nodes using various network technologies. Wireless protocols such as ZigBee [19], Wi-Fi, LoRa, and NB-IoT are employed. However, due to the high attenuation of electromagnetic and optical signals in underwater environments, their effectiveness is limited. For underwater communication, acoustic transmission is considered the most reliable solution. Acoustic communication supports long-distance data transfer thanks to low attenuation, but it is sensitive to noise, delays, and Doppler effects.

Head End System (HES) module: Serving as the central control unit, this module collects, stores, analyzes, and presents data to users. Through cloud platforms such as ThingSpeak, monitoring results are visualized in the form of graphs, tables, and geographic maps. This approach enables spatial assessment of water quality and supports rapid decision-making.

In this study, the parameters used for calculating the Water Quality Index (WQI) and the availability of electronic sensors for these parameters were analyzed based on previous studies. The analysis highlights the scientific basis of the selected methodology and emphasizes the need for AI-based predictive models for parameters that cannot be measured directly using electronic sensors [4].

The study employed the Systematic Literature Review (SLR) methodology, which enabled a structured analysis of recent scientific articles on water quality monitoring. The research was conducted following the PRISMA protocol and consisted of three stages: article collection, filtering based on titles and abstracts, and full-text reading. Initially, a total of 946 articles were retrieved from the Web of Science, ScienceDirect, and IEEE Xplore databases. After removing duplicates, 874 articles remained, and through rigorous filtering, 50 articles were finally included in the analysis.

During the filtering process, inclusion and exclusion criteria were defined. The inclusion criteria comprised English-language articles, studies focused on

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water quality monitoring, and works applying IoT technologies either practically or theoretically. The exclusion criteria encompassed general IoT applications, studies discussing only hardware technologies, or works not directly related to water monitoring.

The selected articles were categorized into two main groups: AI-based methods and Non-AI-based methods. AI-based approaches included machine learning, fuzzy logic, and deep learning algorithms. Non-AI-based approaches focused on energy efficiency, system design, big data analysis, and IoT-based data transmission using GSM, WSN, and Wi-Fi [20]. This classification allowed for clearer grouping of the studies and facilitated evaluation of their effectiveness.

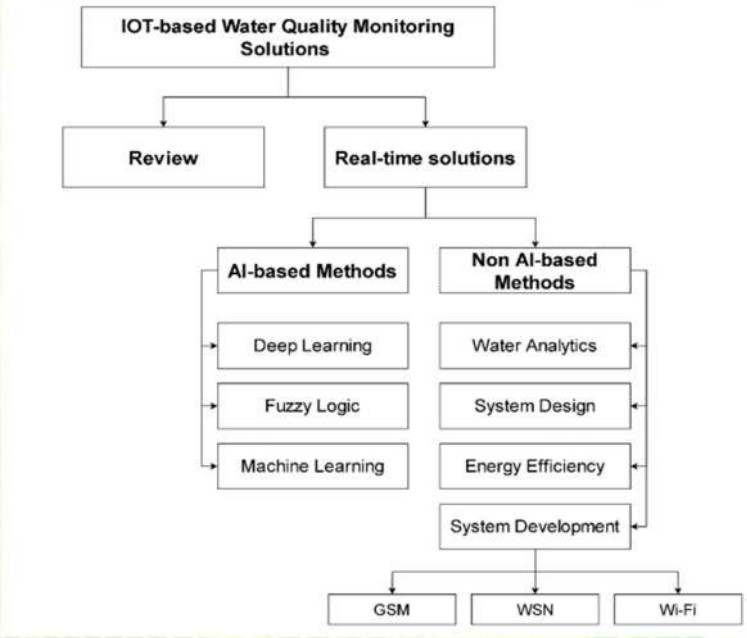


Figure 5. Research Taxonomy [5]

Based on the literature review, the authors analyzed the application of IoT and AI technologies in water and wastewater management. They examined various scientific sources (IEEE, ScienceDirect, Scopus, Web of Science) and provided a methodological evaluation of the smart water management concept.

IoT technologies are applied at all stages of the water supply chain—from water sources to distribution networks and down to the consumer level. Sensors measure parameters such as pH, turbidity, chemical concentration, water pressure, and flow rate in real time. AI algorithms then analyze this large volume of data to detect anomalies, perform forecasting, and automate decision-making [6].

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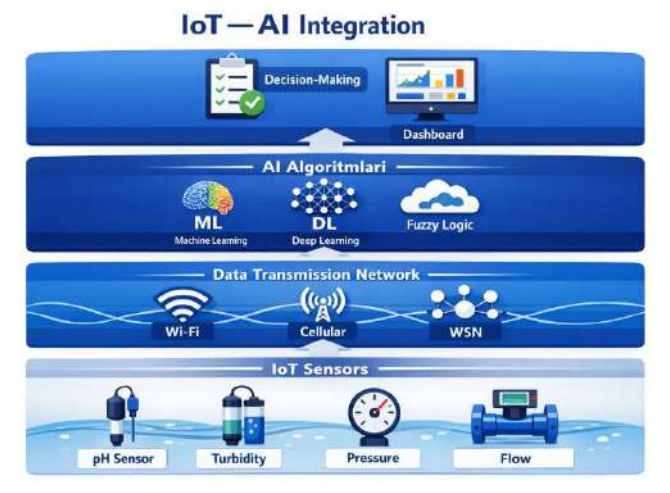


Figure 6. General architecture of IoT and AI-based smart water monitoring system [6]

The multi-layered architecture of the intelligent water monitoring system based on IoT and artificial intelligence is illustrated in Figure 6. The system collects data through pH, turbidity, pressure, and flow sensors, and transmits it via Wi-Fi, GSM, and WSN networks [17]. At the upper layer, machine learning, deep learning, and fuzzy logic algorithms are applied to support decision-making and monitoring through a visual dashboard.

The methodology demonstrates a holistic approach to IoT and AI integration: IoT collects the data, while AI processes and transmits the results to the management system. This approach enables real-time monitoring, predictive maintenance, and optimal resource allocation.

The article provides a methodological analysis of IoT applications in water supply systems. The author highlights the advantages of LoRaWAN and NB-IoT protocols. LoRaWAN enables long-distance data transmission with low energy consumption, allowing devices to operate for years on battery power. The system's main elements include sensors (pressure, temperature, pulse), a gateway (base station), a network server, and an application server. This star-shaped architecture allows sensors to transmit data directly to the gateway, which then forwards it to the server, enabling real-time monitoring.

NB-IoT operates through mobile operators' base stations, ensuring reliable data transmission at low speeds. The article also emphasizes the role of the MQTT protocol, which is based on a "publisher–subscriber" model and distributes data via a broker. This approach ensures accurate and efficient data transmission without loss [7].

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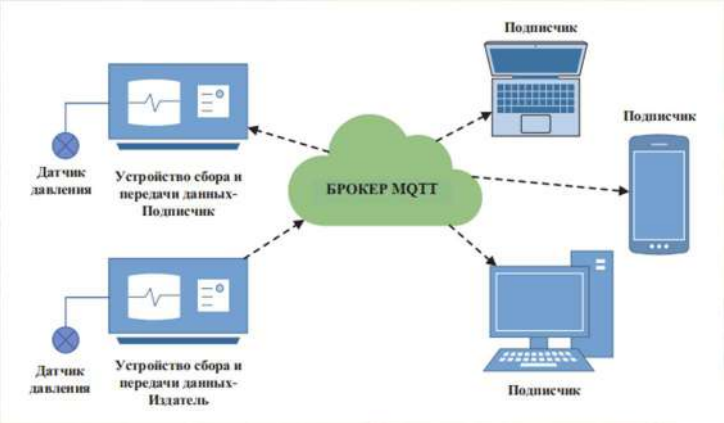


Figure 7. Architecture of the MQTT Protocol [7]

Achieved results and performance analysis

The research results are considerably positive: the system successfully detected water levels in real time and demonstrated automatic gate opening and closing [6]. The outcomes of 20 experiments, presented in Table 2, show that the system operated with 0% error rate and an average delay of only 2 seconds, thereby highlighting its high accuracy and responsiveness.

Table 2.

Performance Indicators of an IoT-Based Gate Control System [2]

Indicator	Value
Number of experiments	20
Error rate	0%
Data transmission delay	2 seconds
Sensor type	HC-SR04 ultrasonic sensor
Microcontroller	Raspberry Pi + ESP32
Control mechanism	Gate doors operated via stepper motor
Monitoring interface	Web server + mobile application

The results of the subsequent study demonstrate that the system contributes to water resource conservation, flood risk reduction, and remote control capabilities. The Raspberry Pi-based architecture made the system flexible, scalable, and easily integrable into diverse IoT environments. Its affordability and energy efficiency further support wide practical adoption. These findings confirm the effectiveness of IoT technologies in water resource management and highlight the necessity of their broader application in the future [2].

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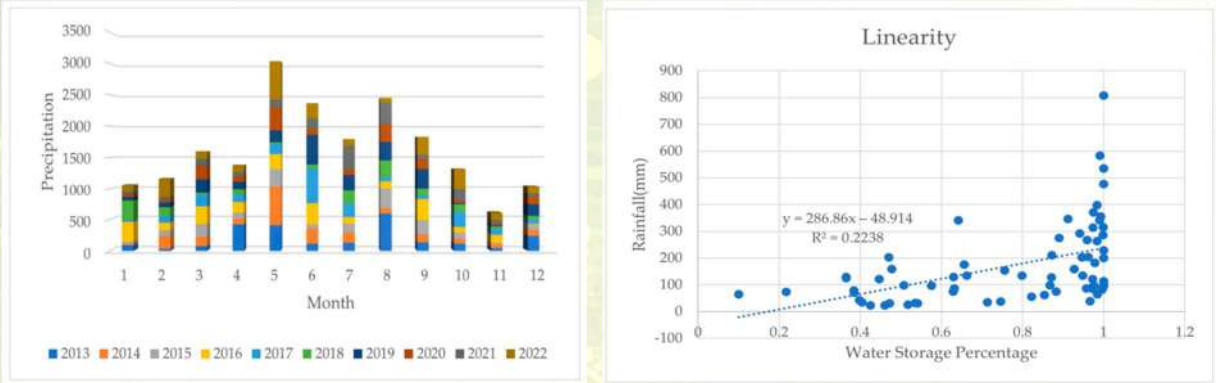


Figure 8. Monthly precipitation and reservoir water levels in Taoyuan (2013–2022) [8]

Through the ThingSpeak platform, the collected data were visualized in the form of graphs, heatmaps, and diagrams, as shown in Figure 8. The proposed system consists of two main modules: the water quality monitoring module and the water level monitoring module.

Water quality monitoring module: Raw data gathered from various sensors via the ESP-32 microcontroller are successfully transmitted to the cloud and stored for later use. If the measured water quality falls below the threshold values defined by the system, a warning notification is sent to the user through the mobile application. Otherwise, the monitoring process continues to be uninterrupted.

Water level monitoring module: When water reaches one of the numbered sensors, the system performs two actions. First, the Mega 2560 board analyzes the data to determine whether the water level exceeds the threshold [2]. If the level is too high, the pump is automatically activated to redirect water to other reservoirs, thereby preventing flooding. Second, relative water level data are simultaneously transmitted to the cloud platform for further analysis.

Another intelligent water monitoring system developed in related studies was tested in a field experiment in Taoyuan City. The study area included four interconnected lakes (Figure 9), where water level and water quality mutually influenced each other [4]. Each lake was equipped with pH, turbidity, dissolved oxygen (DO), and water level sensors. These sensors collected real-time data, which were transmitted to the cloud server via the ESP-32 module.

The Mega 2560 microcontroller controlled the pumps and drainage mechanisms, redirecting excess water from reservoirs with higher levels to those with lower levels. This helped achieve balanced water resource distribution. Through the ThingSpeak interface, users could monitor water quality and water levels in the form of graphs, heatmaps, and diagrams. If water quality fell below the defined standards, the system immediately sent an alert notification.

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Figure 9. Actual Aerial Photograph of the Reservoirs [9]

In Figure 9, numbers 1–4 correspond to reservoirs 1–4 respectively.

The results demonstrated that the system worked effectively under real conditions: water level detection accuracy increased by 15%, costs were reduced by 60%, and water resource savings exceeded 15%. This system is considered a sustainable solution for environmental protection, agriculture, and urban infrastructure.

In the study, several machine learning algorithms were tested: ridge regression, random forest, stochastic gradient boosting, support vector machine, k-nearest neighbors, and AdaBoost regressor.

The AdaBoost regressor achieved the best performance (MAE = 14.37 counts/100 mL) in predicting E. coli concentration in water. In contrast, stochastic gradient boosting produced the weakest results (MAE = 42.27 counts/100 mL). The most effective parameter set was Set A, which included pH, conductivity, chloride, turbidity, nitrates, and chlorophyll.

These findings in Table 3 indicate that AI can be used to predict parameters even when electronic sensors are unavailable. The system offers real-time operation, energy efficiency, and wide-area coverage, making it highly significant for ensuring environmental safety.

Table 3.

MAE and RMSE Comparison of Predictive Models [3]

Model	MAE	RMSE
Ridge Regression	32.66	60.38
Random Forest Regressor	41.61	74.68
Stochastic Gradient Boosting	42.27	81.13

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Support Vector Machine	22.74	62.69
k-Nearest Neighbors	20.52	54.80
AdaBoost	14.37	21.74

According to the results of the systematic analysis, the 50 selected articles employed different approaches. Among them, 9 articles applied AI-based methods. Machine learning algorithms such as K-means, Random Forest, and Decision Tree were used for water quality prediction. For example, the K-means algorithm clustered data from turbidity, conductivity, and pH sensors to detect anomalies in water. Random Forest achieved high accuracy in predicting water quality in aquaculture systems. The fuzzy logic approach was applied in water distribution systems to assess pollution risks at the local level. Deep learning models, particularly the LSTM algorithm, were used to forecast drinking water quality over time and applied in aquaculture and water distribution systems.

Meanwhile, 40 articles employed non-AI-based methods. These studies focused on energy efficiency, system design, and IoT-based data transmission using GSM, WSN, and Wi-Fi. For instance, GSM modules were used to transmit data to the ThingSpeak platform, ZigBee was applied to build WSN networks, and Wi-Fi supported real-time monitoring systems. In some studies, blockchain technology was integrated with IoT and GIS to identify sources of water pollution.

These findings in Table 4 demonstrate the widespread application of IoT technologies in water monitoring and show that different approaches can enhance system effectiveness. AI algorithms provide high accuracy in predicting water quality, while non-AI approaches ensure system stability and energy efficiency.

Table 4.

IoT Technology Assessment: Coverage, Efficiency, and Use Cases [4]

IoT Technology	Advantages	Limitations	Application Areas
GSM	Wide coverage, based on mobile networks	High energy consumption, costly	Pipeline monitoring, emergency alert systems
WSN (ZigBee, LoRa)	Energy-efficient, supports multi-sensor networks	Limited range, complex configuration	Lakes, aquaculture, small reservoirs

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Wi-Fi	Fast transmission, cloud integration	Short range, high energy consumption	Drinking water monitoring

The article presents practical examples of IoT technology applications. In Gomel city, a test was conducted using a LoRaWAN network. With the Vega BS-2.2 gateway and 868-01 antenna, stable communication was achieved within a 2–3 km radius. It was determined that 7 base stations would be required for full city-wide coverage. This result demonstrates LoRaWAN's effectiveness in small-scale areas. In contrast, NB-IoT technology provided reliable communication over wide areas by leveraging mobile operators' infrastructure. Data were transmitted in JSON format via the MQTT protocol, simplifying analysis and storage [7]. The tests showed that the monthly data volume was around 50 MB, which is highly efficient for mobile networks.

Limitations of the Study

Although the authors successfully developed the system, several aspects remain unresolved [1]. The system currently measures only physical parameters (pH, turbidity, temperature, conductivity). Biological and chemical indicators are not yet fully included, which reduces the accuracy of comprehensive water quality assessment. The study was conducted at laboratory scale, with insufficient evidence for large reservoirs. Long-term performance and stability under diverse climatic conditions have not been fully investigated. Future work aims to make the system more adaptable, multifunctional, and scalable.

Shih-Lun Chen and colleagues [2] achieved promising results, but several issues remain. The system is mainly focused on physical parameters (pH, turbidity, dissolved oxygen, water level). For comprehensive water quality evaluation, chemical parameters (e.g., heavy metal ions) and biological indicators (e.g., microorganisms, bacteria) must be included. The study was limited to small lakes in Taoyuan, without testing in large reservoirs, transboundary water systems, or diverse climates. This restricts the evaluation of the system's global applicability.

Yurav Singh and Tom Walingo [5] emphasized the need for further research on sensor durability and stability under varying climatic conditions. For example, capacitive sensors are affected by temperature and humidity, which can negatively impact accuracy. Therefore, regular calibration and maintenance mechanisms are required. Additionally, the AI algorithms used in the system are mainly regression-based. In the future, adopting deep learning and neural networks could improve water level prediction and strengthen the system's forecasting capabilities.

Another important issue is that the system has so far only been tested in individual lakes. Integration at the city scale, connection with other ecological

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monitoring systems, and incorporation into a comprehensive water resource management framework have not yet been implemented. This direction is considered a significant prospect for future research.

Che Zalina Zulkifli, Salem Garfan, and colleagues [21] developed a successful system, but several challenges remain unresolved.

Lack of electronic sensors: For certain parameters (e.g., E. coli, fecal coliform), electronic sensors are not available. In such cases, AI-based prediction has been applied, but this approach is not yet fully accepted or standardized in industry.

Long-term stability: Further studies are required on sensor durability and reliability under diverse climatic conditions. For example, underwater acoustic communication is sensitive to noise and delays, which can reduce system reliability.

Improvement of AI algorithms: The current system mainly relies on regression models. In the future, adopting deep learning, neural networks, and hybrid models could enhance water quality prediction accuracy.

Integration and scalability: The system has so far been tested only in laboratory and small-scale environments. Full integration at the city level, connection with other ecological monitoring systems, and incorporation into a comprehensive water resource management framework have not yet been achieved.

Michael Ayorinde Dada and colleagues [6] identified several challenges. Water pollution and limited resources reduce the efficiency of monitoring systems. Traditional methods are slow and have low effectiveness, and they are not fully integrated with IoT solutions. IoT systems consume high energy, which creates difficulties in ensuring long-term stability. The application of AI algorithms is not yet fully standardized or widely accepted in industry. Moreover, most studies are based on laboratory or small-scale trials, with insufficient testing in large reservoirs and transboundary water systems.

At the same time, security issues in IoT systems have been highlighted as a major challenge. It is essential to ensure security during wireless data transmission, maintain data integrity, and protect systems against cyberattacks. To improve energy efficiency, new technologies have been recommended, such as energy-harvesting sensors and the adoption of low-power communication protocols.

A.A. Kapansky [7] highlighted several challenges. In the LoRaWAN network, signal stability was low, and occasional delays in data transmission were observed, which complicates rapid response in emergency situations. Deploying

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base stations in urban infrastructure also presents difficulties, as tall buildings, trees, and other obstacles affect signal quality. NB-IoT technology depends on mobile operators, which can make service costs relatively high.

Cybersecurity remains a critical issue in IoT systems. Since data are transmitted wirelessly, robust protection is required to ensure security. Although the MQTT protocol is efficient, misconfiguration can pose serious threats. Another major challenge is the shortage of skilled professionals. The limited availability of experts capable of managing IoT and AI technologies slows down their widespread adoption.

INTELLECTUAL WATER RESOURCE MANAGEMENT: PROPOSED CONCEPTUAL MODEL

Justification of the Proposed Model

The results of the systematic analysis show that while IoT-based monitoring and AI-driven analytical approaches hold high potential for water resource management, most existing solutions are fragmented, task-specific, and limited in scalability. Many systems focus only on monitoring either water quality or water levels separately, with insufficient development of predictive capabilities. Furthermore, issues of interoperability, cybersecurity, and large-scale deployment remain inadequately addressed.

To overcome these scientific and practical gaps, this study proposes an integrated IoT–AI-based multi-layer conceptual model for intelligent management of reservoirs and water resources. The model is designed to unify real-time monitoring, predictive analytics, automated control, and decision-support mechanisms within a single architecture. It can be flexibly applied to both urban and transboundary water systems, ensuring adaptability across diverse contexts.

Architecture of the Proposed Model

The proposed architecture is organized as a four-layer integrated system, covering processes from sensor data collection to decision-making and automated control.

First Layer — Sensor Layer: Composed of multi-parameter sensors that measure water quality and water level indicators in real time. This layer collects data on pH, turbidity, dissolved oxygen, conductivity, water level, and flow velocity.

Second Layer — Communication Layer: Ensures data transmission to the central system via wireless protocols such as LoRaWAN, NB-IoT, ZigBee, and GSM. A hybrid communication model provides stability in long-distance reservoir environments.

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Third Layer — Intelligent Analytics Layer: Processes data using artificial intelligence algorithms. Time-series models (e.g., LSTM), regression methods, and ensemble techniques are applied for forecasting, anomaly detection, and optimization.

Fourth Layer — Decision-Making and Automated Control Layer: Operates on a cloud-based platform. The system identifies risk levels and, when necessary, automatically controls water gates and pumps.

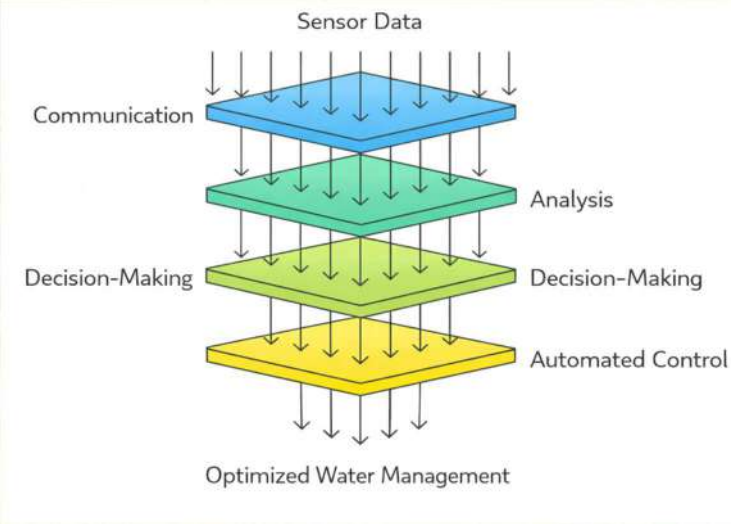


Figure 10. Architecture of the Proposed Model [10]

The proposed architecture integrates water quality, water level, and energy management into a single intelligent system. The diagram visually illustrates the flow of data across the layers, its analysis through artificial intelligence, and the subsequent transmission to automated control mechanisms. Unlike existing fragmented systems, this integrated approach ensures real-time monitoring, predictive management, and resource optimization in a comprehensive manner.

CONCLUSION

In this study, existing scientific developments on IoT- and AI-based water monitoring and management systems were systematically analyzed. The results show that traditional water management systems cannot fully meet modern requirements due to their limited real-time monitoring and predictive analysis capabilities.

The reviewed studies confirm the effectiveness of IoT sensors and AI algorithms in monitoring water quality and water levels. However, most current systems remain fragmented and are not adapted for large-scale or transboundary water systems.

To address these scientific gaps, an integrated IoT–AI conceptual model was proposed. This model aims to unify water quality, water level, and energy management within a single intelligent platform.

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The proposed approach is particularly relevant for countries like Uzbekistan, where hydro-energetic infrastructure is well developed. It enables more efficient water resource management, optimization of energy production, and assurance of environmental safety.

Future research should focus on experimental testing under real conditions, strengthening cybersecurity, and improving hybrid AI algorithms to enhance predictive capabilities and system resilience.

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