Cyber-physical system for monitoring water resources*

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Abstract

The relevance of implementing a cyber-physical system for monitoring water resources in Ukraine is determined by several critical factors that emphasize the need to use such technologies for sustainable water resources management. Taking these factors into account, the implementation of cyber-physical systems for monitoring water resources is an important step towards sustainable water management in Ukraine, which will contribute to preserving the ecological balance, improving water quality, and the efficient use of this strategic resource. The article develops a method for the operation of a cyber-physical system for monitoring water resources, which provides automated, continuous, and highly accurate real-time monitoring of the state of the aquatic environment. Thanks to the combination of sensors, controllers, and analytical software solutions, the system quickly detects deviations, responds to critical events, generates forecasts, and supports decision-making. It is easily scalable, cost-effective, and promotes transparency in environmental monitoring. The architecture has been designed and a cyber-physical system for monitoring water resources has been implemented, which is capable of detecting pollution and anomalies in the aquatic environment, building trends and forecasts of changes in water quality, and automatically responding to critical situations by notifying or activating appropriate technical measures. The system allows data to be stored and analyzed, reports to be generated, and ensures transparency and access to information. Overall, its use improves the effectiveness of environmental monitoring, promotes informed decision-making, and supports the implementation of sustainable water management strategies. Examples of the functioning of cyber-physical systems for monitoring water resources illustrate the high adaptability of the system to different environments and tasks – from protecting natural ecosystems to managing urban infrastructure, from ensuring the safety of citizens and the environment to improving the efficiency of urban management.

Keywords

cyber-physical system, water resource monitoring, water resource monitoring parameters, sensors and IoT devices for measuring water parameters, Raspberry Pi controller, Wi-Fi and Bluetooth data transmission standards[1]

1. Introduction

Water is an indispensable resource that plays a key role in the sustainable development of humanity, meeting the basic needs of the population, and the functioning of critical sectors of the economy, including energy, industry, and agricultural production. In the context of increasing anthropogenic pressure and global climate change, water quality is becoming particularly important as an indicator of environmental well-being and public health. This highlights the relevance of research aimed at creating reliable, cost-effective, and technologically advanced water environment monitoring systems. They should ensure continuous monitoring of water conditions (from drinking water sources to large water basins) in order to identify threats in a timely manner, prevent negative changes, and preserve water ecosystems and public safety [1, 2].

* *ITTAP'2025: The 5th International Conference on Information Technologies: Theoretical and Applied Problems, October22-24, 2025, Ternopil, Ukraine, Opole, Poland*

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One promising solution for effective monitoring of the aquatic environment is the use of cyber-physical systems, which combine physical processes with information and communication technologies, ensuring continuous measurement of key water parameters [3, 4]. The development and implementation of such systems is a multifaceted task that requires an integrated approach that takes into account both engineering and technical solutions and the specifics of natural conditions and operational constraints that significantly affect the stability and effectiveness of the system [5, 6].

The relevance of designing and developing a cyber-physical system for monitoring water resources for Ukraine is due to the need for effective water resource management in the context of climate change, water pollution, and growing water supply needs [7]. The use of sensor networks, artificial intelligence, and cloud computing allows for the rapid collection of information on water quality and quantity, forecasting changes, and preventing emergencies. Thanks to the use of Internet of Things (IoT), Big Data, and artificial intelligence technologies, it is possible to automate the processes of collection, analysis, and forecasting, which will help optimize water use, prevent pollution, and increase the efficiency of water infrastructure [8-10]. The use of digital models and simulations will allow analyzing scenarios for the development of the water situation, identifying potential risks, and planning measures to minimize negative consequences. Thus, the introduction of a cyber-physical system in the field of monitoring water resources will contribute to improving the efficiency of water resource management, reducing losses, improving the ecological state of water bodies, and providing the population with high-quality water. The creation of an effective monitoring system will not only allow real-time control of water quality, but also enable timely response to emergency situations, which is especially important for reservoirs, rivers, and underground sources [11-13].

Therefore, there is an urgent need for a cyber-physical water resource monitoring system that operates in real time, automatically collects, processes, and analyzes data on the physical and chemical properties of water, detects deviations from established norms, and transmits the results to cloud or local servers, operates continuously (round-the-clock monitoring), is scalable and autonomous (able to function without constant human intervention). In addition, a cyber-physical system for monitoring water resources must be of high quality, which is a prerequisite for its reliable and effective functioning in a real environment [14-16]. At the same time, it is important to ensure its resistance to vulnerabilities, which will protect information from possible cyber threats and unauthorized access [17, 18].

2. Review of the known systems

Several effective examples of cyber-physical systems have been implemented in various countries to monitor the state of water resources and maintain the ecological balance of aquatic ecosystems.

Smart Water Management System (SWMS) [19, 20] is an intelligent water management system that uses modern digital technologies to monitor, analyze, and optimize water consumption in real time. It integrates sensors that measure water flow, soil moisture levels, pipeline pressure, and water quality with analytical software capable of predicting water demand, detecting leaks, and identifying inefficient use. The collected data is transmitted via wireless networks to a central server or cloud, where it is processed for further visualization and management decisions. Thanks to automated control and remote management capabilities, such a system reduces water loss, improves the efficiency and stability of water supply, and promotes environmental sustainability, especially in conditions of limited water resources or climate change.

Sustainable Water Management in Urban China (SWITCH) [21, 22] is an international initiative aimed at implementing integrated and sustainable approaches to water management in the context of China's rapid urbanization. The project focused on developing water and environmental strategies that combine scientific research, cutting-edge technologies, and sustainable urban practices to improve water quality, reduce consumption, reuse, and effectively treat wastewater. SWITCH promoted the development of policies that take into account the complex interactions between water infrastructure, the environment, and the needs of the population, while supporting adaptation to climate change and ensuring long-term water security.

The River and Lake Water Quality Monitoring System in the European Union (WATERMON) [23] is a system designed to continuously monitor and assess water quality in rivers and lakes in European Union countries in accordance with the requirements of the EU Water Framework Directive. The system uses a network of automated stations equipped with sensors to measure key water parameters such as temperature, pH, oxygen content, and concentrations of nitrates, phosphates, heavy metals, and other pollutants. Data is collected in real time and transmitted to centralized platforms for further analysis, allowing trends in the deterioration of the ecological status of water bodies to be identified, risks to aquatic ecosystems to be predicted, and rapid responses to pollution incidents to be made. WATERMON promotes scientifically sound decision-making in the field of water resource management, ensures transparency and public access to information on water status, and supports cooperation between EU member states to achieve common environmental goals.

India's National Hydrology Project (NHP) [24] is a large-scale government initiative aimed at creating modern hydrological infrastructure and strengthening water resource management systems throughout India. The project aims to ensure the reliable collection, processing, storage, and dissemination of hydrometeorological data for effective decision-making in the field of water use, particularly for agriculture, energy, flood management, and water supply. NHP implements a unified digital information platform that integrates data from a large number of automated hydrological stations that measure river levels, precipitation, groundwater, water quality, and other parameters. The system uses GIS technologies, forecasting models, and analytical tools to increase the transparency of water resource management and promote integrated water planning between states.

Aquarius System (USA & Canada) [25] is a modern platform for managing hydrological and environmental data, widely used in the US and Canada by government agencies, research organizations, and environmental agencies. The system is designed to automatically collect, process, store, and visualize large amounts of water resource data, including water level, flow, temperature, water quality, and other parameters from various sources, including automated sensors and monitoring stations. Aquarius ensures high data accuracy and consistency, supports international standards, and allows for real-time online monitoring of water bodies.

Smart Water Grid in South Korea [26] is an innovative water management system that integrates digital technologies, sensors, automated equipment, and artificial intelligence to ensure stable, efficient, and sustainable use of water resources in urban and industrial areas. This system allows real-time monitoring of water quality and quantity, detection of leaks, demand forecasting, network pressure management, and optimization of water distribution in accordance with changing consumption conditions. The main goal is to improve the energy efficiency of water supply infrastructure, reduce water losses, and ensure uninterrupted supply even during peak load periods or under conditions of limited resources.

The systems considered confirm the effectiveness of cyber-physical technologies for monitoring water resources, which contributes to their conservation, rational use, and timely detection of environmental threats. These examples also demonstrate the widespread international practice of implementing cyber-physical solutions in the field of water monitoring, which indicates their high potential. At the same time, this concept is not yet sufficiently developed in Ukrainian cities, mainly due to the high cost of implementation, although it can play an important role in the processes of post-war reconstruction and infrastructure modernization.

Therefore, the design and development of a cyber-physical system for monitoring water resources that provides autonomy (the ability to function without constant human intervention), scalability (the ability to expand the geography of monitoring), and continuity of monitoring (round-the-clock real-time observation) is relevant. This study is aimed at designing and developing such a cyber-physical system.

3. Cyber-physical system for monitoring water resources

The design of a cyber-physical water resource monitoring system will begin with the development of a cyber-physical system operating method that describes the sequence of actions performed by the system to collect, process, analyze, and respond to information about the state of the aquatic environment. This method covers the interaction of physical components (sensors, controllers) with software modules to ensure continuous, automated monitoring and control. The diagram of the method of operation of the cyber-physical system for monitoring water resources is shown in Fig. 1.

The developed method provides automatic, continuous, and reliable monitoring of the state of the aquatic environment, allowing for timely response to hazards, informed management decisions, and sustainable use of water resources. The main advantages of the method are: continuity and real-time operation, high accuracy and reliability, rapid response, scalability and flexibility, energy efficiency and resource savings, the ability to integrate with other information technologies and systems, decision support, transparency, and openness, etc.

The practical significance of this method is in the fact that it allows for effective management of water resources, ensuring their sustainability, quality, and availability for various uses, from domestic to industrial. The implementation of this system helps to reduce the risks of environmental disasters, improve pollution monitoring, and ensure effective water resource management in the context of climate change and urbanization. It allows for the timely detection of potentially dangerous levels of water pollution, such as increased concentrations of toxic substances, heavy metals, pesticides, or pathogenic microorganisms, and for prompt measures to be taken to prevent or reduce negative impacts on ecosystems and human health. In addition, the system helps to avoid environmental disasters and contamination of drinking water sources, and to make informed decisions about water consumption in agriculture, industry, and water supply. It also allows for the automation of data collection and processing stages, reducing time and resource costs, increasing the speed of response to changes in the environmental situation, and improving the accuracy of forecasts to ensure compliance with environmental requirements and international standards.

The cyber-physical system for monitoring water resources is an integrated technological environment that combines physical components (sensors, controllers, actuators) with digital ones (software, analysis algorithms, data transmission) to ensure continuous water quality control. The system operates in real time, automatically collecting, processing, and analyzing information about the physical and chemical characteristics of water, detecting deviations from standards, and transmitting the results to cloud or local servers. Its activities cover all levels, from reading environmental parameters to making decisions based on artificial intelligence algorithms or predictive analytics. Such a system allows for rapid response to environmental threats, optimisation of water resource use and improved water environment management efficiency.

An analysis of the functions assigned to the cyber-physical system for monitoring water resources made it possible to select the main components of the cyber-physical system: Risinglink Smart Monitor sensors for measuring water levels; HOBO MX2201 sensors for measuring water temperature; PASCO Wireless pH Sensor (PS-3204) sensors for measuring the acid-base balance (pH) of water; Yosemitech Y4001 Handheld Multiparameter Water Quality Meter sensors for determining the chemical composition of water; AquaQube 1000 sensors for measuring water flow velocity; Aqua TROLL 500 sensors for determining the presence of impurities in water; Raspberry Pi controller; Wi-Fi and Bluetooth data transmission standards. Now let's design the architecture of a cyber-physical system for monitoring water resources – Fig. 2.

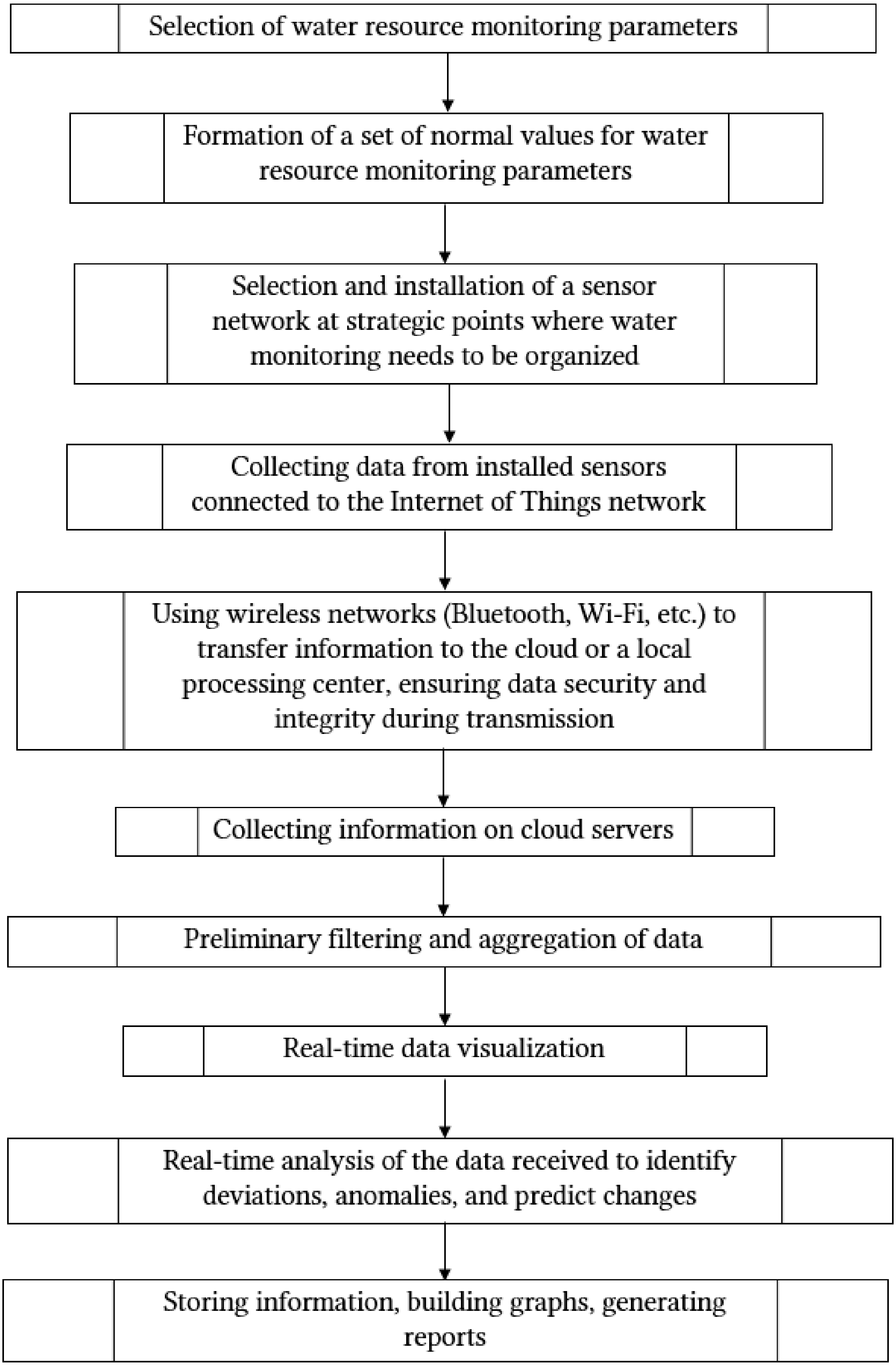

Figure 1: The diagram of the method of operation of the cyber-physical system for monitoring water resources.

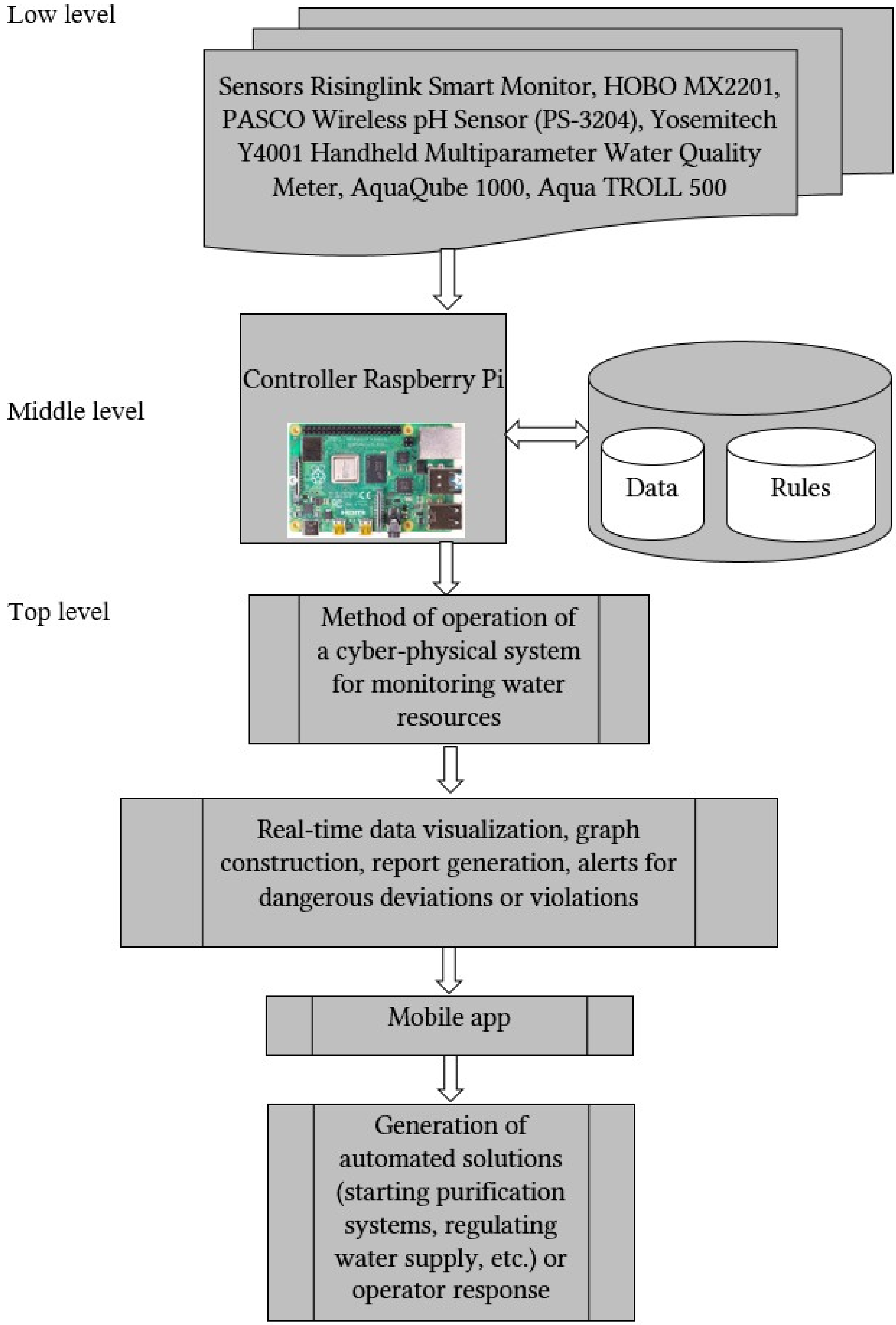

Figure 2: Architecture of a cyber-physical system for monitoring water resources.

A key feature of the cyber-physical system for monitoring water resources is its ability to adapt and self-organize – it can change monitoring parameters according to external conditions, such as during floods, droughts, or pollutant emissions. Thanks to the interaction between physical sensors and computing modules, the system not only records the current state of the aquatic environment, but also identifies trends in changes, which is particularly important for long-term forecasting of environmental risks. Data is transmitted using wireless technologies such as Wi-Fi, Bluetooth, etc., which allows the system to be deployed even in remote regions. Information flows are processed centrally with the possibility of further visualization of results on control panels, open platforms, or mobile devices. As a result, such a system becomes an effective tool for ensuring environmental safety, monitoring compliance with sanitary standards, supporting decisions in the field of water supply, agricultural planning, urban planning, and emergency response.

4. Results & discussion

Let's consider examples of the functioning of a cyber-physical system for monitoring water resources.

A sensor network has been installed in the central part of the city, including Risinglink Smart Monitor, HOBO MX2201, and PASCO Wireless pH Sensor sensors. The system records hourly increases in impurity levels and pH changes, which coincide with wastewater discharge from the industrial zone. After detecting deviations from normal values, Raspberry Pi transmits data via Wi-Fi to a cloud server, where an alarm signal is generated. A notification is automatically sent to the municipal service with recommendations to check the source of pollution and start local purification filters.

In mountainous areas where flash floods are possible, water level (Risinglink) and flow velocity (AquaQube 1000) sensors are installed in the riverbed. The system detects rapid increases in water level and flow rate that exceed threshold values. The Raspberry Pi controller immediately sends the information via Bluetooth to the local gateway and then to the cloud. The data is visualized on a digital panel in the monitoring center, and an alert is activated for the local population and emergency services.

A system for continuous monitoring of water quality has been installed in a rural community. Aqua TROLL 500 and Yosemitech Y4001 sensors measure impurities and chemical composition. If elevated nitrate levels exceeding the threshold value are detected, the system automatically generates an alarm signal that is sent to the operator's mobile application. The filtration unit is activated and the data is recorded in cloud storage for further analysis.

A low-power sensor network powered by solar batteries has been installed in the nature reserve. All indicators (level, temperature, pH, chemical composition, impurities) are monitored using energy-efficient communication (Wi-Fi/Bluetooth). Detecting abnormal increases in water temperature allows predicting a possible threat to the fish population. The data is automatically transmitted to the environmental center, where a scientific report is generated and recommendations are made on how to adapt to the new conditions.

The agricultural enterprise uses water from a canal to irrigate its fields. A system based on HOBO MX2201 sensors, PASCO Wireless pH Sensor, and Aqua TROLL 500 records temperature, pH, and impurity levels on a daily basis. After an excessive increase in temperature during a hot period and an excess of impurities, the system automatically notifies the agronomist via a cloud portal and suggests adjusting the irrigation schedule to avoid damage to crops. The data is stored for analysis of irrigation performance throughout the season.

Aqua TROLL 500 and Risinglink Smart Monitor sensors are installed near the plant to measure the level of runoff and impurities. If the level of impurities in the water exceeds the norm, the system transmits the data to the cloud, where it is automatically compared with previous records. If a negative trend is observed, a report is generated for the environmental inspectorate with geolocation of the incident. At the same time, an internal re-cleaning procedure is launched, as provided for by the enterprise management system.

Sensors are installed in the coastal zone of the river to monitor water temperature (HOBO MX2201), acid-base balance (PASCO Wireless pH Sensor), and the presence of impurities (Aqua TROLL 500). At the height of the summer season, the system records changes in pH and an increase in the concentration of impurities after heavy rains. The data is automatically transmitted to a digital control panel, and the system generates a message for the local administration about the need to temporarily restrict swimming and increase water filtration. Thanks to timely intervention, sanitary violations are avoided and visitor safety is ensured.

Examples of the functioning of cyber-physical systems for monitoring water resources illustrate the high adaptability of the system to different environments and tasks – from protecting natural ecosystems to managing urban infrastructure, from ensuring the safety of citizens and the environment to improving the efficiency of urban management.

5. Conclusions

The relevance of implementing a cyber-physical system for monitoring water resources in Ukraine is determined by several critical factors that emphasize the need to use such technologies for sustainable water resources management. Firstly, Ukraine faces a number of problems in the field of water resources, in particular, water shortages in certain regions, pollution of water bodies, and climate change, which leads to changes in precipitation patterns and rising temperatures. A cyber-physical system allows for the rapid collection of information on the state of water resources, immediate response to changes, and effective management of water resources, minimizing the negative effects of such changes. Secondly, modern monitoring methods that use sensors to measure the chemical composition of water, level, temperature, and other parameters provide more accurate and faster information about the state of water bodies, allowing for the timely detection of pollution and the implementation of measures to prevent environmental disasters, as well as the optimization of water consumption in agriculture and industry. Thirdly, in the context of climate change and growing demand for water resources for various sectors of Ukraine's economy, it is necessary to implement innovative approaches to water resource management. A cyber-physical system is an important tool for integrating data from various sources and automating the decision-making process, allowing for the effective optimization of water use and reduction of water consumption. Taking these factors into account, the implementation of cyber-physical systems for monitoring water resources is an important step towards sustainable water management in Ukraine, which will contribute to preserving the ecological balance, improving water quality, and the efficient use of this strategic resource.

The conducted analysis of known water resource monitoring systems confirmed the effectiveness of cyber-physical technologies for monitoring water resources, which contributes to their conservation, rational use, and timely detection of environmental threats. The examples considered also demonstrate the widespread international practice of implementing cyber-physical solutions in the field of water monitoring, which indicates their high potential. At the same time, this concept is still underdeveloped in Ukrainian cities, mainly due to the high cost of implementation, although it can play an important role in the processes of post-war reconstruction and infrastructure modernization. Therefore, the design and development of a cyber-physical water resource monitoring system that ensures autonomy, scalability, and continuous real-time monitoring is relevant. This study aims to design and develop such a cyber-physical system.

The article develops a method for the operation of a cyber-physical system for monitoring water resources, which provides automated, continuous, and highly accurate real-time monitoring of the state of the aquatic environment. Thanks to the combination of sensors, controllers, and analytical software solutions, the system quickly detects deviations, responds to critical events, generates forecasts, and supports decision-making. It is easily scalable, cost-effective, and promotes transparency in environmental monitoring.

The architecture has been designed and a cyber-physical system for monitoring water resources has been implemented, which is capable of detecting pollution and anomalies in the aquatic environment, building trends and forecasts of changes in water quality, and automatically responding to critical situations by notifying or activating appropriate technical measures. The system allows data to be stored and analyzed, reports to be generated, and ensures transparency and access to information. Overall, its use improves the effectiveness of environmental monitoring, promotes informed decision-making, and supports the implementation of sustainable water management strategies.

Examples of the functioning of cyber-physical systems for monitoring water resources illustrate the high adaptability of the system to different environments and tasks – from protecting natural ecosystems to managing urban infrastructure, from ensuring the safety of citizens and the environment to improving the efficiency of urban management.

Declaration on Generative AI

During the preparation of this work, the authors used Grammarly in order to: grammar and spelling check; DeepL Translate in order to: some phrases translation into English. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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