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METHOD OF OPERATION OF THE CYBER-PHYSICAL WATER RESOURCES MONITORING SYSTEM

The relevance of designing and developing a cyber-physical water monitoring system for Ukraine is driven by the need for effective water management in the face of climate change, water pollution, and growing water supply needs. Modern challenges, such as the lack of clean drinking water, irrational use of resources, emergency condition of water supply networks and environmental threats, require the introduction of innovative technologies. The use of sensor networks, artificial intelligence, and cloud computing allows us to quickly obtain information about water quality and quantity, predict changes, and prevent emergencies. The introduction of cyber-physical systems in the field of water resources monitoring will help to increase the efficiency of water management, reduce losses, improve the ecological condition of water bodies and provide the population with quality water. For Ukraine, where water security is a strategic issue, such solutions will be an important step towards sustainable development and environmental balance. The use of Internet of Things (IoT), Big Data, and artificial intelligence technologies can automate the processes of data collection, analysis, and forecasting, which will help optimize water use, prevent pollution, and increase the efficiency of water infrastructures. Thus, the task of designing and developing a cyber-physical water resources monitoring system is currently relevant for Ukraine.

The article develops a method for the operation of a cyber-physical water resources monitoring system that provides cyber-physical integration (a combination of physical (sensors, objects) and cybernetic (analytics, control) components), autonomy (the ability to function without constant human intervention), scalability (the ability to expand the geography of monitoring), and monitoring continuity (round-the-clock real-time monitoring).

Keywords: cyber-physical system, water resources monitoring parameters, water resources monitoring, sensors and IoT devices for measuring water level, water temperature, water ph-balance, water chemical composition, water flow rate, impurities presence in water.

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МЕТОД ДІЯЛЬНОСТІ КІБЕРФІЗИЧНОЇ СИСТЕМИ МОНІТОРИНГУ ВОДНИХ РЕСУРСІВ

Актуальність проєктування та розроблення кіберфізичної системи моніторингу водних ресурсів для України обумовлена необхідністю ефективного управління водними ресурсами в умовах змін клімату, забруднення водойм та зростаючих потреб у водопостачанні. Сучасні виклики, такі як нестача чистої питної води, нераціональне використання ресурсів, аварійний стан водопровідних мереж та екологічні загрози, вимагають запровадження інноваційних технологій. Використання сенсорних мереж, штучного інтелекту та хмарних обчислень дозволяє оперативно отримувати інформацію про якість та кількість води, прогнозувати зміни та запобігати надзвичайним ситуаціям. Впровадження кіберфізичних систем у сфері моніторингу водних ресурсів сприятиме підвищенню ефективності управління водними ресурсами, зменшенню втрат, покращенню екологічного стану водойм та забезпеченню населення якісною водою. Для України, де питання водної безпеки є стратегічним, такі рішення стануть важливим кроком до сталого розвитку та екологічної рівноваги. Завдяки застосуванню технологій Інтернету речей (IoT), великих даних (Big Data) та штучного інтелекту можна автоматизувати процеси збору, аналізу та прогнозування, що допоможе оптимізувати водокористування, запобігати забрудненню та підвищувати ефективність водних інфраструктур. Отже, задача проєктування та розроблення кіберфізичної системи моніторингу водних ресурсів є наразі актуальною для України.

У статті розроблений метод діяльності кіберфізичної системи моніторингу водних ресурсів, який забезпечує кіберфізичну інтеграцію (поєднання фізичних (сенсори, об'єкти) та кібернетичних (аналітика, керування) компонентів), автономність (здатність функціонувати без постійного втручання людини), масштабованість (можливість розширення географії моніторингу), безперервність моніторингу (цілодобове спостереження в реальному часі).

Ключові слова: кіберфізична система, параметри моніторингу водних ресурсів, моніторинг водних ресурсів, датчики та IoT -пристрої для вимірювання рівня води, температури, кислотно-лужного балансу, хімічного складу води, швидкості потоку, наявності домішок у воді.

Introduction

The relevance of water resources monitoring is determined by their critical importance for human life, the economy, and ecosystems. In the face of increasing pressure on water resources, climate change, urbanization, and pollution, it is necessary to ensure timely monitoring of their condition for effective management and conservation [1].

Monitoring water resources is essential for ensuring water security, as monitoring the quality of drinking water helps prevent the spread of diseases, and identifying pollution and its sources makes it possible to respond to environmental threats in a timely manner. It also plays an important role in preserving environmental safety and biodiversity, as pollution of aquatic ecosystems negatively affects the level of oxygen in water and leads to eutrophication, which can lead to the death of aquatic organisms [2].

An important aspect is the impact of water resources on the economy and the agricultural sector, as their use in industry, energy, and agriculture requires monitoring the water level in reservoirs to ensure the stability of irrigation systems and the operation of hydroelectric power plants. In the context of climate change, monitoring helps to detect changes in hydrological processes, control precipitation, droughts, and floods, which is important for adaptation to new climate conditions [3].

In addition, international obligations and legislation require compliance with environmental standards and the introduction of modern technologies for precise control, including satellite monitoring, IoT sensors, and GIS technologies. Monitoring of water resources helps reduce risks, increase management efficiency, and ensure the sustainability of ecosystems [4].

The development of technologies significantly expands the possibilities of water resources monitoring, ensuring high accuracy and efficiency of data acquisition. The use of satellite imagery makes it possible to track changes in aquatic ecosystems on a global scale, including fluctuations in water levels in rivers, lakes and reservoirs, as well as the impact of climate change on their condition. Remote sensing and drones allow for localized research with high detail, which is especially important for water quality control [5].

Sensor systems and the Internet of Things (IoT) play an important role, allowing for real-time monitoring of physical and chemical parameters of water, such as pH, temperature, dissolved oxygen concentration, and the presence of toxic substances. This allows not only to respond quickly to pollution threats, but also to predict possible environmental risks, model the spread of pollution, and assess the impact of various factors on the state of water resources [6].

Water monitoring is also an important tool for developing effective water management policies. It helps governments and international organizations to implement measures to rationalize water use, protect water bodies from depletion and pollution, and adapt to climate change. In the context of global warming and the increase in extreme weather events, monitoring allows forecasting floods and droughts, helping to reduce their negative impact on the economy.

International cooperation plays a significant role in the development of monitoring systems, as many water bodies are transboundary and environmental problems have no national borders. Joint monitoring programs and data exchange between countries contribute to more efficient water management, which, in turn, has a positive impact on environmental safety and sustainable development [7].

Thus, modern water resources monitoring is a multicomponent system that combines advanced technologies, scientific research, and management solutions. Its relevance is only growing in the face of global challenges, which requires further development of data collection, analysis, and forecasting methods. Investments in these areas will help to preserve water resources, improve the quality of life and ensure sustainable development of society [8].

A cyber-physical water monitoring system is a set of interconnected technological solutions that combine physical components, sensors, computer algorithms, and communication tools to collect, process, and analyze data on the state of the aquatic environment. It provides continuous monitoring of water quality, water level, temperature, flow rate, and other parameters, allowing for rapid response to changes and identification of potential threats [9].

The basis of such a system is a network of sensors and detectors placed in water bodies, water intake points, and other key locations. They transmit data via wireless technologies, such as NB-IoT, LoRaWAN, or satellite channels, to data centers where the information is analyzed using artificial intelligence and machine learning algorithms. This allows not only to monitor the current state of water resources, but also to predict possible threats, such as pollution, droughts, or floods.

Such systems play a key role in data visualization, creating pollution maps, and modeling the spread of pollutants. The use of Big Data allows for the identification of patterns and the generation of recommendations to optimize water management. Such systems can be integrated with smart city platforms to improve the efficiency of water use in utilities and industry [10].

A cyber-physical system can also include automated control mechanisms, such as controlling gateways or pumping stations based on forecasts and actual data. This helps minimize the impact of natural disasters, prevent overuse of water resources, and maintain water quality at the required level.

Due to its adaptability and integration with cloud technologies, such a system can be scaled to meet the needs of different regions and ensure sustainable development of the water sector. The introduction of cyber-physical systems in the field of water resources monitoring is an important step towards effective management of natural resources, environmental safety and reduction of the negative impact of human activity on the environment [11].

A cyber-physical water resources monitoring system consists of several main components that ensure its effective operation.

The sensor network is a key element of the system, as it includes a variety of sensors that measure water parameters such as pollution levels, temperature, pH, dissolved oxygen, electrical conductivity, and other characteristics. These sensors can be located on the surface of water bodies, underwater, or on the banks and operate in real time [12].

Transmission technologies provide a continuous flow of data from sensors to computing centers. They can include cellular communications (3G, 4G, 5G), LPWAN protocols (LoRa, NB-IoT), satellite communications, or wired connections depending on the location and data rate requirements.

Computing power and analytical algorithms allow processing the received data, analyzing it and generating forecasts. The use of artificial intelligence and machine learning helps to detect anomalies in water resources, predict environmental threats, and optimize the management of water systems [13].

Geographic information systems (GIS) provide data visualization in the form of interactive maps that display changes in water resources. This helps to make informed decisions about their management, track sources of pollution, and analyze spatial patterns.

User interfaces allow professionals to work with the system through special web platforms, mobile applications, or integrated solutions for municipal authorities, businesses, and environmental services. They provide access to current and archived data, analytical reports, and management tools [14].

Automated control systems can include response mechanisms, such as adjusting gateways, controlling pumping stations, or activating water treatment systems when dangerous changes in its composition are detected.

Cloud technologies and data warehouses provide centralized storage and processing of information, allowing the system to be scaled to meet user needs and integrated with other environmental or industrial platforms [15].

Thus, a cyber-physical water resources monitoring system combines physical, digital, and analytical components to create an effective mechanism for monitoring, analyzing, and managing the state of aquatic ecosystems.

The development of cyber-physical systems for water resources monitoring faces a number of challenges that require an integrated approach to their solution [16, 17].

One of the main problems is infrastructure constraints. In many regions, especially in developing countries, there is a lack of adequate technical base for the implementation of smart sensor networks and IoT solutions. Insufficient digitalization and the poor quality of existing water communications can make it difficult to integrate cyber-physical systems.

Financial barriers also play an important role. The high cost of implementing modern sensors, cloud platforms, and analytical algorithms can be an obstacle for governments and companies that want to use these technologies. Despite the long-term benefits, such projects require significant investment.

Another challenge is ensuring the accuracy and reliability of the data. In real-world environments, sensors can be subject to errors due to climatic factors, technical malfunctions, or contamination. This requires the development of effective methods for calibration, self-diagnosis, and automatic data correction.

Cybersecurity and data protection are critical aspects of cyber-physical systems. Since they work with a large amount of data in real time, there is a risk of hacker attacks and unauthorized access to information. The development of reliable mechanisms for encryption, secure data storage and transmission is a priority.

As for the future, cyber-physical water monitoring systems have great potential for improvement through artificial intelligence and machine learning. Integration of big data analysis algorithms will allow for more accurate forecasting of changes in aquatic ecosystems, predicting droughts, floods, or pollution.

Satellite monitoring and remote sensing play a significant role in the development of such systems. The combination of satellite imagery and sensor networks provides a more detailed picture of the state of water resources at the global level, which is important for climate change control and water balance management.

Expanding cooperation between government agencies, research institutes, and the private sector will facilitate the massive implementation of cyber-physical systems. The creation of open platforms for environmental data exchange will help improve the efficiency of water management and develop more sustainable water strategies.

In general, further development of cyber-physical water monitoring systems will contribute to the rational use of water, reduce environmental risks, and ensure a stable water supply for future generations.

There are several well-known cyber-physical water resources monitoring systems that have been implemented in different countries and are used to monitor the state of aquatic ecosystems.

Smart Water Management System (SWMS) [18-21] is a smart water management system that is being implemented in many countries to monitor water quality and quantity. It uses sensors, IoT devices, satellite imagery, and machine learning algorithms to analyze changes in water resources. It is a comprehensive cyber-physical system that combines modern technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and big data analytics to effectively manage water resources. The main functions of SWMS are: 1) real-time water resource monitoring – the system uses sensors to collect information about water level, water quality, temperature, pipeline pressure, pollution levels, and other parameters; the data is transmitted to a cloud platform for further processing; 2) control and optimization of water consumption – SWMS allows consumers (cities, enterprises, households) to analyze water consumption and find ways to reduce it; smart water meters help identify leaks and inefficient use of water resources; 3) automatic detection of leaks and accidents - thanks to machine learning algorithms, the system can detect anomalies in the operation of water supply networks and signal possible leaks or accidents, which significantly reduces water losses; 4) forecasting changes in water resources - SWMS analyzes large data sets (historical, climatic, environmental) to predict droughts, floods or changes in water quality; this helps management bodies respond to potential threats in a timely manner; 5) automation of processes in water management - the system can automatically manage water supply, regulate the operation of pumping stations, activate treatment systems or redistribute resources between different consumers; 6) support for sustainable development and ecological balance - SWMS contributes to the conservation of water resources, minimizes the negative impact of human activity on the environment and helps provide clean water for the population. Examples of SWMS implementation: Singapore Smart Water Grid [22] – a smart water management system in Singapore that monitors water quality and optimizes its distribution; IBM Intelligent Water Platform [23] – a solution for cities and industries that helps reduce water losses and improve water network management; Smart Water Pilot Project in Barcelona [24] – integration of sensors to track water consumption and reduce costs. SWMS is an important tool in the field of water resources management, as it helps to optimize water use, improve its quality, minimize losses and prevent environmental disasters. In the future, the implementation of such systems will become a key factor in solving global water supply problems and climate change.

Sustainable Water Management in Urban China (SWITCH) [25, 26] is a water and wastewater monitoring system in China that helps improve water management in megacities. It integrates data from water quality sensors, climate models, and GIS analytics.

River and Lake Water Quality Monitoring System in the European Union (WATERMON) [27] is a pan-European water quality monitoring system operating under the EU Water Policy Directive. It uses automated monitoring stations that measure the physical and chemical parameters of water and transmit the data to a single database for analysis and management.

India's National Hydrology Project (NHP) [28] is an initiative of the Government of India that uses cyber-physical systems to collect and analyze hydrological data. It includes intelligent sensor networks, big data analytics, and predictive models for water management.

Aquarius System (USA & Canada) [29] is a cyber-physical water monitoring system used in the USA and Canada to monitor drinking water quality, manage rivers and reservoirs. It uses IoT, satellite monitoring and cloud technologies to process large amounts of data.

Smart Water Grid in South Korea [30] is an innovative water management system in South Korea that uses cyber-physical approaches to optimize water supply and minimize water losses in urban networks.

Copernicus Programme – Water Monitoring Service is a European satellite monitoring program that analyzes the state of water bodies based on remote sensing data of the Earth. It is used to assess the level of pollution, changes in the water balance and identify environmental threats.

All these systems demonstrate the effectiveness of using cyber-physical technologies to monitor water resources, contributing to their conservation, rational use and timely response to potential threats.

These examples indicate that the concept of using cyber-physical technologies for monitoring water resources is widely used worldwide and has significant potential. Currently, such a concept is poorly used for the development of Ukrainian cities, mainly due to the high cost, although it has enormous potential for them, especially during post-war reconstruction.

Therefore, the task of designing and developing a cyber-physical system for monitoring water resources is currently relevant for Ukraine. This study will be devoted to the development of a method that underlies the operation of a cyber-physical system for monitoring water resources.

Method of Operation of The Cyber-Physical Water Resources Monitoring System

For this study, the specific objective will be to measure various parameters of water resources and ongoing monitoring of water resources.

The method of operation of the cyber-physical water resources monitoring system consists of the following steps:

physical level (sensor network):

1) selection of water resources monitoring parameters: water level (*wl*), water temperature (*wt*), water ph-balance (*wph*), water chemical composition (*wcc*), water flow rate (*wfr*), impurities presence in water (*ipw*), etc.;
2) formation of a set of normal values of water resources monitoring parameters (taking into account the location of water resources monitoring): water level (*nwl*), water temperature (*nwt*), water ph-balance (*nwph*), water chemical composition (*nwss*), water flow rate (*nwfr*), impurities presence in water (*nipw*), etc.: $NWMP = \{nwmp1, nwmp2,..., nwmp6\} = \{nwl, nwt, nwph, nwcc, nwfr, nipw\}$, upon exceeding which, for example, the generation of automated solutions (launching treatment systems, regulating water supply, etc.) and notification of operators occurs;
3) selection and installation of a sensor network at strategic points where it is necessary to organize water monitoring – selection of sensors and IoT devices for measuring water level, temperature, ph-balance, chemical composition of water, flow rate, presence of impurities in water, etc. for continuous data collection from reservoirs, rivers, lakes, groundwater;
4) collection of data from installed sensors connected to the Internet of Things network, and formation of the set $WMP = \{wmp1, wmp2,..., wmp6\} = \{wl, wt, wph, wcc, wfr, ipw\}$ at a certain point in time;

cybernetic level (data processing and transmission):

5) use of wireless networks (LoRa, NB-IoT, LTE, Wi-Fi, etc.) to transmit information to the cloud or local processing center with ensuring data security and integrity during transmission;

6) collection of information on cloud servers or local computing nodes;
7) preliminary filtering and aggregation of data;
8) visualization of data in real time through digital panels;

analytical and management levels (data processing and decision-making):

9) analysis of received data in real time in order to identify deviations, anomalies, predict changes, model scenarios of the impact of various factors on the state of water resources, identify potential threats within the framework of ensuring water resources monitoring:
   9.1) if the water level (*wl*) is significantly higher or significantly lower than the normal water level (*nwl*), then signals about dangerous deviations or violations are generated, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;
   9.2) if the water temperature (*wt*) is significantly higher or significantly lower than the normal water temperture for a given season in a given area (*nwt*), then signals are generated about dangerous deviations or violations, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;
   9.3) if the ph-balance (*wph*) is significantly higher or significantly lower than the normal ph-balance (*nwph*), then signals are generated about dangerous deviations or violations, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;
   9.4) if the chemical composition of water (*wcc*) differs significantly from the normal water chemical composition (*nwcc*), then signals are generated about dangerous deviations or violations, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;
   9.5) if the water flow rate (*wfr*) is significantly higher or significantly lower than the normal water flow rate (*nwfr*), then signals are generated about dangerous deviations or violations, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;
   9.6) if the level of impurities in water (*ipw*) is significantly higher than the normal level of impurities (*nipw*), then signals are generated about dangerous deviations or violations, operators are notified, after which automated decisions are generated (launching treatment systems, regulating water supply, etc.) or operator response;

reporting and visualization:

10) long-term storage of information for trend analysis and forecasting;
11) construction of graphs, maps, control panels;
12) generation of reports for state bodies, environmental institutions, the public, etc. with support for data transparency and openness standards.

The developed method for the operation of a cyber-physical water resources monitoring system provides cyber-physical integration (a combination of physical (sensors, objects) and cybernetic (analytics, control) components), autonomy (the ability to function without constant human intervention), scalability (the ability to expand the geography of monitoring), and monitoring continuity (round-the-clock real-time monitoring).

Conclusions

The relevance of designing and developing a cyber-physical water monitoring system for Ukraine is driven by the need for effective water management in the face of climate change, water pollution, and growing water supply needs. Modern challenges, such as the lack of clean drinking water, irrational use of resources, emergency condition of water supply networks and environmental threats, require the introduction of innovative technologies. The use of sensor networks, artificial intelligence, and cloud computing allows us to quickly obtain information about water quality and quantity, predict changes, and prevent emergencies. The introduction of cyber-physical systems in the field of water resources monitoring will help to increase the efficiency of water management, reduce losses, improve the ecological condition of water bodies and provide the population with quality water. For Ukraine, where water security is a strategic issue, such solutions will be an important step towards sustainable development and environmental balance. The use of Internet of Things (IoT), Big Data, and artificial intelligence technologies can automate the processes of data collection, analysis, and forecasting, which will help optimize water use, prevent pollution, and increase the efficiency of water infrastructures. Thus, the task of designing and developing a cyber-physical water resources monitoring system is currently relevant for Ukraine.

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