METHODS FOR RAPID DETECTION OF POLLUTANTS IN THE AQUATIC ENVIRONMENT

Oleksii Kosohin[1], *Olga Linyucheva*[1], *Artur Kosohin*[1], *Olha Amburtseva*[1], *Iryna Kosogina* [1*]

[1]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

Beresteiskyi Ave, 37, building 4, Kyiv, Ukraine, 03056, email: kosogina@xtf.kpi.ua

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Global changes in geopolitics and economics, directly or indirectly, significantly affect the state of the environment, in particular, water resources. In addition to the mining and energy industry, the chemical industry and agriculture, significant changes in the ecological state of the environment are caused by man-made accidents and military conflicts, which lead to uncontrolled emissions of a large number of pollutants into the air, soil and water environment. While air pollution is instantaneous and noticeable, water pollution is characterized by a more "delayed effect" due to the dilution of pollutants, absorption by plants and accumulation in bottom silt deposits, which increases the duration of the negative impact and over time can lead to repeated pollution of the environment (for example, due to the shallowing of surface water sources). Monitoring of the aquatic environment has its own characteristics compared to the implementation of air monitoring and can include both the determination of the content of dissolved gases (for example, dissolved oxygen), and the determination of the content of various ionic and molecular forms. The latter is especially important if these compounds are formed as a result of the ingress of toxic compounds into the water (including those of military origin – fuel, combustion products of explosives), and therefore can serve as a kind of markers for taking immediate action to eliminate man-made threats. The development of methods for determining dissolved gases and soluble nitrogen compounds – ammonium, nitrites and nitrates – is aimed not only at increasing sensitivity, but also at expanding functionality in real-world conditions. Modern methods for directly determining dissolved substances in water, which allow for real-time monitoring, and which involve the use of sensor systems, remote sensing using non-contact methods and the so-called Internet of Things, are analyzed.

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1. Introduction

Modern methods for determining dissolved compounds cover a wide range of approaches - from classical chemical methods to high-tech biosensor platforms.

The main laboratory methods for determining dissolved substances in water include optical, electrochemical and chromatographic methods (Moorcroft et al., 2001; Richardson & Kimura, 2020).

The group of optical methods is based on the course of a chemical reaction with the formation of a colored compound and the determination of the intensity of light absorption through a layer of a colored solution colorimetrically or spectrophotometrically. To determine trace amounts of contaminants, atomic absorption spectroscopy and atomic emission spectroscopy are used, which require specialized equipment and highly qualified personnel to maintain it.

Spectrophotometric methods, despite their popularity, have limitations in the speed of analysis and require special equipment located in laboratories.

Electrochemical methods are based on the determination of dissolved substances through the course of chemical reactions with the formation of substances that can affect the conductivity of an aqueous solution (conductometry), or the measurement of certain electrochemical parameters with the participation of the substance being determined - the change in electrode potential (potentiometry), the magnitude of the oxidation/reduction current of the component being determined (amperometry), the amount of electricity consumed (coulometry).

Chromatography is based on methods that are based on the determination of dissolved substances in water by separating and identifying volatile and semi-volatile substances in water (gas chromatography) or non-volatile substances in water (liquid chromatography) (Chaudhary, S. et al., 20253).

Non-targeted screening (NTS) using high-resolution electrospray ionization liquid chromatography (LC/ESI/HRMS) is increasingly being used to identify environmental contaminants (Malm et al., 2024).

The main disadvantages of traditional methods for determining dissolved substances in water are the need to use expensive laboratory equipment that is difficult to maintain and the need for highly qualified specialists to perform the analysis, the complexity of the procedure for preparing a water sample for analysis, and the dependence of the equipment's operation on the availability of an energy source. In addition, the process requires the use of expensive reagents that are capable of forming compounds with substances that require determination.

Modern methods for direct determination of dissolved substances in water (direct methods) are carried out in real time and include sensor systems, remote sensing (non-contact methods) and the Internet of Things.

Each of the existing methods has its advantages and limitations, but the general trend is the desire for automation, portability, reducing the cost of analysis and expanding the possibilities for use in conditions of limited access to laboratory infrastructure.

2. General overview of pollutant monitoring systems

It is impossible to fully review all methods of monitoring those substances that may be present in water bodies, because of their multitude, and the constant change in the composition of environmental components due to natural and anthropogenic factors. In general, 86 indicators are monitored to determine the suitability of water for drinking, but a non-compliance with even one of them requires a thorough analysis of the causes of occurrence and the use of appropriate measures.

Sometimes, water quality indicators are distinguished, which include 11 main ones, but given the realities of today, namely the conduct of military operations, constant shelling of the territory using artillery, missile and drone systems, it is advisable to analyze water bodies for an increased content of compounds that are part of the fuel or enter the water as a result of combustion or decomposition of various substances. In particular, such potential markers of water quality may be the content of nitrogen-containing compounds (ammonium, nitrites and nitrates, since most of the used combustible and explosive substances contain nitrogen in one form or another) and dissolved oxygen in water (as an indicator of chemical processes associated with oxygen consumption). In particular, the entry of hydrazine derivatives, which are used as a component of aviation fuel, into water bodies leads to a decrease in the content of dissolved oxygen, which provokes the uncontrolled development of blue-green algae and causes mass fish mortality.

The development of methods for the determination of ammonium, nitrites and nitrates is aimed not only at increasing sensitivity, but also at expanding functionality in real-world applications.

Nitrite (NO_2^-) determination methods play a key role in monitoring the quality of water, food and biological fluids, since even low concentrations can be toxic to humans and the environment. One of the most common and most standardized methods of analysis is the classical Griess reaction, which, due to its reliability, availability and ease of implementation, is used in most laboratories (Zhang et al., 2018). The method allows for accurate quantitative determination of nitrites in the concentration range from 0.01 mg/L to 1 mg/L, which is sufficient for monitoring the quality of drinking water in accordance with WHO standards and Ukrainian DSanPiN 2.2.4-171-10 “Hygienic requirements for drinking water intended for human consumption”. Among the main advantages of this approach are its simplicity, relative cheapness of reagents and equipment, as well as excellent reproducibility of results. In many countries, in particular in Ukraine, the Griess reaction is officially approved as a method for monitoring tap and natural water, and is also used in sanitary and epidemiological studies.

At the same time, modern analytical chemistry is moving towards improving classical reactions. Recent research has focused on nanotechnologies, which can significantly reduce the detection limit. For example, the use of silver nanoparticles as catalysts in the Griess reaction allows to increase the sensitivity of the method, which is critically important for the analysis of very low concentrations (Vazquez et al., 2017).

A modified method for the reduction of nitrates to nitrites has also been proposed, which replaces the well-known cadmium column method. Instead, an acidic solution of vanadium (III) is used for the reduction, avoiding the use of toxic cadmium. Existing and newly formed nitrites are quantified using the Griess reaction. Sample preparation is simple, with nitrate reduction efficiency of 100 ± 3% using a reaction time of 60 min at 45 °C or 10–20 h at room temperature (Schnetger & Lehners, 2014). Measurements can be performed using conventional UV-visible spectrophotometry, the method is simple and cost-effective; sample preparation is rapid, and measurement error or interference from dissolved organic carbon is not noticeable (Fang et al., 2021; Valiente et al., 2018).

Current spectroscopic methods have difficulty accurately and consistently measuring a number of water quality parameters. For example, increasing the accuracy of measuring such an indicator as chemical oxygen demand (COD) in the work (Zhang et al., 2014) was achieved by combining the spectral transformer model taking into account physicochemical information (PIST) with research in a wide wavelength range covering the ultraviolet, visible and near infrared ranges (UV-vis-SWNIR).

3. Trends in the development of monitoring methods and systems

The choice of a water quality monitoring method can be based on the accuracy of the method, the accessibility of the area and the available financial and physical resources (Kumar et al., 2016).

The determination of dissolved substances in freshwater bodies and in the coastal zone is carried out in real time by sensor systems. There are optical sensor systems that have high resolution and response speed, accuracy and precision, but are expensive, require high maintenance costs, use specific reagents to form a colored compound, require the disposal of used systems and are quickly subject to pollution in the aquatic environment. Typically, such systems are able to detect one type of pollutant in water (Boyer et al., 2015). The most common are for determining ammonium, nitrates and phosphates in water.

The use of ion-selective electrodes for the indication of soluble compounds such as ammonium and nitrates in water by direct potentiometry (registration of the potential difference between the sensitive electrode and the reference electrode) is relatively inexpensive, easy to use and available on the market. They are characterized by a short response time and independence from the quality indicators of the water in which the determination of pollutants is carried out, for example, color and turbidity of the water. Along with significant advantages, these systems have a number of disadvantages, in particular, low measurement accuracy, resolution and limited shelf life.

For example, one of the important achievements is the creation of biosensors based on the use of enzymes sensitive to ammonium, in particular, glutamate dehydrogenase (Lee, S., Park, S., 2022). In such sensors, ammonium participates in an enzymatic reaction, which is accompanied by a change in electrochemical or optical parameters, which is easily recorded using detectors. Biosensors have a significant advantage in selectivity and allow you to avoid interionic interference, which is often observed in chemical methods. Furthermore, enzymatic systems are able to work in complex matrices, such as wastewater or groundwater.

For example, new electrochemical sensor designs for nitrate and nitrite detection have been developed using nanomaterials such as carbon nanotubes (CNTs), metal nanoparticles, nanocomposites or nanoclusters (Gómez & Pacheco, 2019), which demonstrate high stability and no loss of sensitivity over time. Due to their selectivity, repeatability, simplicity, fast response, sensitivity and ease of operation, nanoelectrodes can be used for environmental monitoring. Nitrate determination using electrochemical sensors is an excellent alternative to all other available analytical methods.

In addition, significant progress has been made in the development of portable and automated test systems for the determination of ammonium ions (NH_4^+), nitrates (NO_3^-) and nitrites (NO_2^-). These innovations are aimed at increasing the accuracy, convenience and speed of analysis, which is critically important for environmental monitoring, water quality control and food products.

In the direction of digitalization of analysis, intelligent test strips are becoming increasingly popular. The manufacturer of test strips is the world-famous company Johnson

Test Papers (Great Britain). These systems are often made on the basis of a cellulose or polymer carrier infused with reagents that change color upon contact with ammonium. The result is evaluated using a special mobile application that analyzes the shade and intensity of the color through the smartphone camera. Thus, even a non-professional can perform the analysis in field conditions. At the same time, geolocation and cloud technologies allow you to create interactive pollution maps in real time. In addition, the use of paper nanobiosensors can solve the problem of real-time identification of pathogens in water as an important indicator of its pollution (Kumar et al., 2024).

A combination of test strips and a smartphone application for on-site quantification of colorimetric water quality indicators is a low-cost solution for water quality monitoring (Zhang et al., 2015). The system uses a paper-based analytical device that generates a colorimetric signal that depends on the concentration of a specific compound; a mobile phone equipped with a camera to capture two pictures – one with the tested water sample and the other with clean water used as a reference; and an on-site image processing application that uses a novel algorithm to quantify color intensity and correlate it with contaminant concentration. The mobile phone application uses a pixel-counting algorithm rather than the traditional laboratory software ImageJ. The use of a test and control strip reduces the error from ambient light fluctuations, allowing images to be acquired and processed on-site. The mobile phone is also capable of marking the test location using GPS and transmitting the results to the recently developed WaterMap.ca™ website, which displays the quantitative results of water samples on a map (Zhang et al., 2015).

The development of special platforms that represent a “lab on a chip”, where all stages of analysis – from sample preparation to detection – occur on a single chip is relevant (Lu et al., 2013). These systems minimize reagent and sample consumption, reduce analysis time and allow for multi-component analysis. For example, automated microfluidic devices have been developed for continuous monitoring of nitrite in aquatic environments, which is particularly useful for aquaculture and environmental monitoring. It is worth mentioning separately the photometric microfluidic devices that integrate optical detectors with microchannels on a silicon or polymer basis. They allow to minimize the volume of the sample (up to several microliters) and reagents, which makes the analysis not only cheaper, but also environmentally safer. Such platforms are already used in medical diagnostics (urine, blood analysis), eco-testing and agrochemical control (Lu et al., 2013).

Indirect monitoring of pollutants in water by fluorescence spectroscopy, which is based on the correlation between pollutant concentrations and dissolved organic matter concentrations, is one of the methods that can be implemented in commercially available or specialized field fluorescent sensors, allowing for real-time and/or on site monitoring of pollutants (Ahmed et al., 2025), however, it should be noted that interactions between pollutants and substances used for analysis can provoke a decrease in absorption values, such as in the case of PFOS determination (Li et al., 2025).

Therefore, traditional on site monitoring methods cannot provide a complete picture of freshwater systems. To address the challenges of geographical and temporal coverage, remote sensing has emerged as an effective solution, utilizing the latest advances in sensor technologies and methodologies. The combination of GPS and geographic information systems technologies, as well as remote sensing data, provides an effective resource for continuous monitoring and assessment of water bodies (Zhang et al., 2024).

An effective network for monitoring the quality of surface (Singh et al., 2015) and groundwater (Srinivasan et al., 2015) is important not only for water quality prediction but also for resource management. For example, in India, by linking remote sensing data, morphometric characteristics, topographic analysis, land use/cover assessment and groundwater status, hydrogeomorphological maps were prepared (Snelder & Booker, 2013) which can be used as a positive experience for other countries to build a domestic water resources monitoring and management system. Improving sensor systems, creating and using open data sites are key to realizing the benefits of a large-scale integrated monitoring network.

4. State of Surface Water Bodies of Ukraine

Currently, Ukraine is actively implementing modern technologies for water quality control, in particular automated analyzers, which are successfully used at water supply enterprises, as well as in environmental monitoring laboratories. At the same time, domestic scientific institutions are working intensively to create competitive Ukrainian test systems. These developments are not inferior in accuracy and reliability to their foreign counterparts and have the potential for widespread implementation in practice. It is worth noting the initiatives to create mobile laboratories for operational analysis of water quality in the field. Such laboratories use easy-to-use, affordable, and at the same time accurate chemical test kits, which allows for effective monitoring even in remote regions without access to stationary laboratories.

In general, modern portable and automated test systems significantly expand the possibilities for rapid and accurate control of the quality of water, soil and food, contributing to increased safety and preservation of public health (Li et al., 2025).

In response to the need for fast, reliable and mobile tools, scientists are actively working on the development and improvement of existing and the development of portable systems.

In Ukraine, water resources monitoring is carried out by the State Agency for Water Resources, in which measurements of priority pollutants are carried out by four basic laboratories - Western (Ivano-Frankivsk), Eastern (Slovyansk, Donetsk region), Northern (Vyshgorod, Kyiv region) and Southern (Odessa) regions. The structure of the mentioned laboratories includes Basin Councils (Derzhavne ahentstvo, 2025) and Basin Water Resources Management of the relevant water body - the Dnipro, Pripyat, Dniester, Southern Bug, Danube, Seversky Donets and the rivers of the Black Sea region. The water monitoring laboratories of these organizations have their own websites, where you can get publicly available information on the results of sample analysis performed using certified methods, summarized either in the form of tables or in the form of an interactive map (Fig. 1, EcoWater, 2025).

However, it is worth noting that the updating of information on the websites does not always correspond to real-time for a number of reasons. Lack of funding, a small number of sampling sites (compared to the spread of surface water bodies), the complexity and duration of sample delivery from remote locations, and starting in 2022, the full-scale military aggression of the Russian Federation, complicate the work of monitoring laboratories, and in some cases even make it impossible in areas of shelling.

Conducting an in-depth analysis that would allow establishing the exact impact of anthropogenic and natural factors on the quality of water bodies, predicting possible consequences for the environment, and proposing possible measures to minimize such threats is currently not possible due to the above-mentioned factors and their heterogeneity.

However, a preliminary analysis of the monitoring results available in open sources allows us to draw the following conclusions (Tables 1-4).

The content of dissolved oxygen in the waters of rivers and reservoirs often fluctuates within limits close to the standards, but in some cases values lower than environmental standards are recorded.

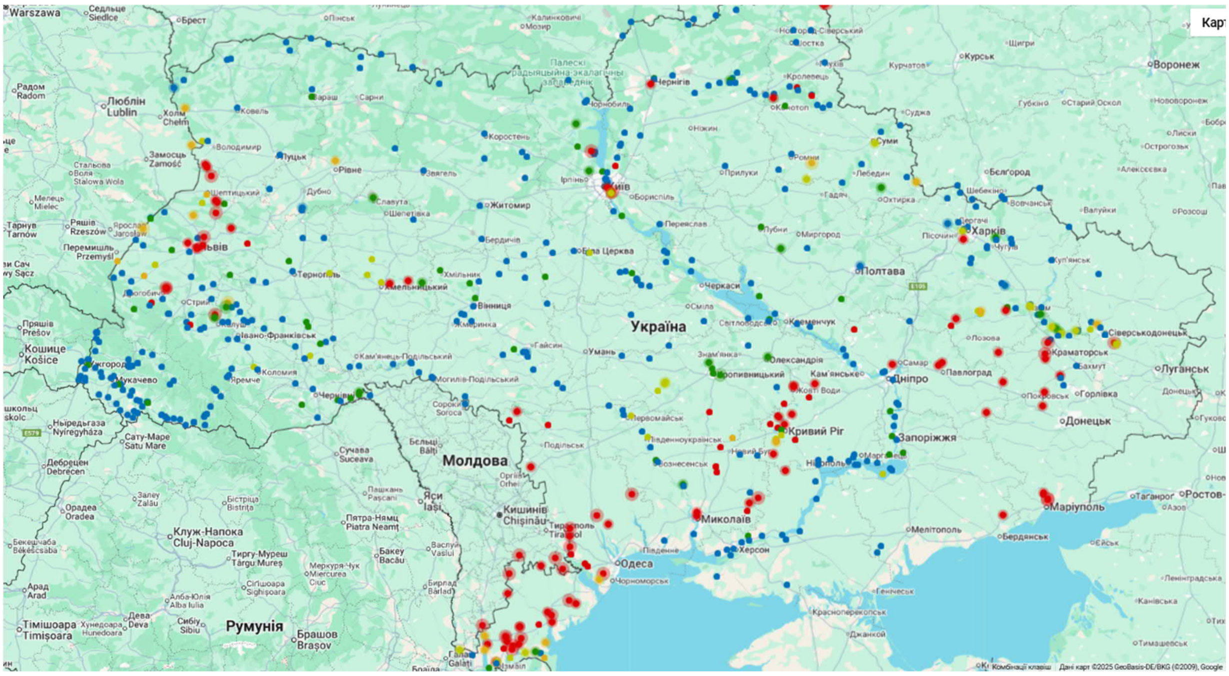

Fig. 1. *Water quality monitoring map of the State Agency of Water Resources of Ukraine*

Table 1. *Results of the combined analysis of waters of the Northern region (Dnipro river basin)*

Indicator	Actual value in the period from 2018 to 2022	Actual value in the period from 2022 to 2024	Maximum permissible concentration for river water
Biological oxygen demand (BOD), mg/L	2.12 – 7.60, single cases up to 82.0	3.2 – 3.3	3
Dissolved oxygen, mg/L	2.20 – 9.35	7.51 – 10.48	4
Ammonium, mg/L	2.23 – 22.0	0.19 – 0.32, single cases up to 27.0	0.5
Nitrate, mg/L	1.07 – 5.4	1.24 – 1.33	40
Nitrite, mg/L	0.23 – 4.6	0.022 – 0.074	0.08

Table 2. *Results of the combined analysis of waters of the Eastern region (Dnipro, Don river basins)*

Indicator	**Actual value in the period from 2018 to 2022**	**Actual value in the period from 2022 to 2024**	**Maximum permissible concentration for river water**
Biological oxygen demand (BOD), mg/L	2.2 – 4.34	4.56 – 5.7	3
Dissolved oxygen, mg/L	8.4 – 9.22	6.77 – 7.38	4
Ammonium, mg/L	1.1 – 1.22	1.21 – 2.56	0.5
Nitrate, mg/L	0.346 – 18.61	1.95 – 3.74	40
Nitrite, mg/L	0.085 – 0.39	0.256 – 0.43	0.08

Table 3. *Results of the combined analysis of waters of the Southern region (Southern Bug, Danube, Black Sea basins)*

Indicator	**Actual value in the period from 2018 to 2022**	**Actual value in the period from 2022 to 2024**	**Maximum permissible concentration for river water**
Biological oxygen demand (BOD), mg/L	1.09 – 3.2	1.3 – 4.1	3
Dissolved oxygen, mg/L	4.8 – 10.6	1.8 – 8.0	4
Ammonium, mg/L	0.24 – 0.71	0 – 0.68	0.5
Nitrate, mg/L	1.73 – 58.52, single cases up to 126.0	4.3 – 12.7	40
Nitrite, mg/L	0.082 – 0.47	0.11 – 0.43	0.08

Table 4. *Results of the combined analysis of waters of the Western region (Danube, Vistula, Dniester river basins)*

Indicator	**Actual value in the period from 2018 to 2022**	**Actual value in the period from 2022 to 2024**	**Maximum permissible concentration for river water**
Biological oxygen demand (BOD), mg/L	1.1 – 9.36	3.2 – 4.5, single cases up to 89.0	3
Dissolved oxygen, mg/L	5.04 – 11.7	4.7 – 8.9	4
Ammonium, mg/L	0.15 – 4.83	0 – 13.0	0.5
Nitrate, mg/L	0.13 – 15.6	2.0 – 21.0	40
Nitrite, mg/L	0.022 – 0.86	0.015 – 1.1	0.08

For example, in some areas of the Sejm and Desna, when the organic load was exceeded, a significant decrease in the concentration of dissolved oxygen below the regulatory values was observed, which poses a direct threat to the flora and fauna of the rivers.

In general, fluctuations in the concentration of dissolved oxygen are seasonal: in summer, with increased temperature and a greater amount of organic pollutants, the oxygen content naturally decreases, and in cold periods of the year it more often approaches the upper range of the norm.

The content of ammonium compounds, as a marker of fresh organic pollution, reflects the degree of impact of treatment facilities, the results of agricultural activities and the ingress of livestock waste. Monitoring data indicate that the ammonium content sometimes exceeds the regulatory values in water bodies near large settlements during seasonal impacts, especially during floods or heavy rains. This indicates that traditional control based on periodic sampling is not always able to promptly record short-term peaks of pollution that are of ecological significance.

Even a slight increase in the concentration of nitrites in water can be associated with both seasonal processes of nitrification/denitrification in water and the result of the ingress of substances of purely military purpose (products of conversion of aviation fuel, explosives). Nitrates are more stable markers of anthropogenic load, in particular runoff from agricultural lands. Increased nitrate concentrations are observed in the basins of Transcarpathia, Dniester and Middle Dnieper, which is partly due to the intensive use of nitrogen fertilizers in agriculture.

Thus, the analyzed distribution of water quality indicators allows us to see not only the generalized state of surface waters, but also regional heterogeneity, which is due to the specifics of wastewater discharge from local industries, the organization of agricultural practices and hydrological conditions. Although the certified methods used to determine water quality indicators provide high accuracy and specificity, they depend on the frequency and periodicity of sampling, their transportation and processing, which can take from several hours to several days, reducing the speed of response to possible threats to the environment.

At the same time, continuous monitoring using sensor systems allows for the collection of a large amount of data that can be used to develop predictive models for water quality indicators and to develop recommendations for future water resources management. The use of remote sensing data helps to create a reliable geospatial database that will serve as a basis for assessing possible threats.

When analyzing the quality of freshwater bodies, satellite and airborne remote sensing methods are valuable tools. Satellite sensors do an excellent job of monitoring larger bodies of water, while airborne sensors are more effective for monitoring smaller bodies of water such as streams, basins and estuaries. The use of multiple satellite images can help assess water quality.

Remote sensing allows for the continuous monitoring of critical water quality parameters such as salinity, temperature and chlorophyll concentration, which directly affect the state of these ecosystems and their biodiversity (Jaywant & Arif, 2024). However, some important water quality parameters, such as pH, dissolved phosphorus, ammonia nitrogen, nitrate nitrogen and total nitrogen, cannot yet be determined by remote sensing methods due to the weak photosensitive properties and low selectivity of existing devices.

5. Conclusions

The combination of GPS and geographic information systems technologies, as well as remote sensing data, will provide an effective resource for continuous monitoring and assessment of the state of water bodies. The use of remote sensing data allows for the creation of a durable geographically linked database that can serve as a reference for future assessments of potential environmental threats.

By providing large-scale data on aquatic ecosystems in real time, remote sensing and monitoring of water quality parameters using extensive sensor systems are important for understanding the state of water bodies and their impact on the environment.

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МЕТОДИ ОПЕРАТИВНОГО ВИЯВЛЕННЯ ЗАБРУДНЮЮЧИХ РЕЧОВИН У ВОДНОМУ СЕРЕДОВИЩІ

Олексій Косогін[1], *Ольга Лінючева*[1], *Артур Косогін*[1], *Ольга Амбурцева*[1], *Ірина Косогіна*[1*]

Національний технічний університет України

«Київський політехнічний інститут імені Ігоря Сікорського», Україна

Глобальні зміни в геополітиці та економіці значним чином прямо чи опосередковано відображаються на стані навколишнього середовища, зокрема, на водних ресурсах. Крім гірничовидобувної і енергетичної галузі, хімічної промисловості та сільського господарства, значні зміни в екологічному стані довкілля спричиняють техногенні аварії та військові конфлікти, що призводить до неконтрольованого викиду в повітря, ґрунти та водне середовище великої кількості забруднюючих речовин. В той час як забруднення повітряного середовища має миттєвий та помітний характер, забруднення водних ресурсів характеризується більш «відкладеним ефектом» через розведення забрудників, поглинання рослинами та акумулювання донними муловими відкладеннями, що збільшує тривалість негативного впливу та з часом може призвести до повторного забруднення довкілля (наприклад, внаслідок обміління водних поверхневих джерел). Моніторинг водного середовища має свої особливості порівняно із реалізацією моніторингу повітря і може включати як встановлення вмісту розчинених газів (наприклад, розчинений кисень), так і визначення вмісту різних іонних та молекулярних форм. Останнє особливо важливо, якщо ці сполуки утворюються в результаті потрапляння в воду токсичних сполук (зокрема, і військового походження – пальне, продукти згорання вибухових речовин), а тому можуть слугувати своєрідними маркерами для вчинення негайних дій із ліквідації техногенних загроз. Розвиток методів визначення розчинених газів та розчинних сполук азоту – амонію, нітритів та нітратів – націлений не лише на підвищення чутливості, а й на розширення функціональності в умовах реального застосування. Проаналізовано сучасні методи безпосереднього визначення розчинених речовин у воді, що дозволяють здійснювати моніторинг в режимі реального часу, і які передбачають використання сенсорних систем, дистанційне зондування з використанням безконтактних методів та так званий інтернет речей.

Ключові слова: *амоній, методи аналізу, моніторинг водного середовища, нітрати, нітрити, показники якості води, розчинений кисень.*