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USE OF GEO-INFORMATION SYSTEMS FOR GROUNDWATER MONITORING

Abstract *. The article is devoted to the study of the possibilities of using geographic information systems (GIS) for monitoring the state of groundwater, which is important for ensuring environmental safety and sustainable management of water resources. Groundwater is an important source of fresh water for the population, industry and agriculture, but it is vulnerable to various pollutions caused by both natural and anthropogenic factors. Therefore, the implementation of reliable monitoring systems that allow timely detection, assessment and forecasting of changes in water quality is necessary to prevent the deterioration of the ecological situation and prevent the spread of pollution.*

Geographic information systems (GIS) offer significant opportunities for the collection and integration of large volumes of spatial data, including satellite images, remote sensing results, automated sensor data, and field observations. GIS allow creating multi-layered maps reflecting the ecological state of underground aquifers, modeling pollution processes and predicting their possible impact on nearby ecosystems and water sources. Thanks to the use of GIS, it is possible to combine data from different sources in a single interactive system, which simplifies analysis and provides the ability to quickly respond to any detected deviations.

The article examines in detail the key methods used within GIS for groundwater monitoring, including satellite sounding to analyze changes in the earth's surface, spectral indices to assess the state of vegetation and soil salinity, and radar methods to determine soil electrical conductivity. Particular attention is paid to the application of three-dimensional modeling, which allows visualization of the spread of pollution in underground aquifers, which facilitates decision-making regarding the optimal location of monitoring stations and the design of protective structures. In combination with automated sensors recording water parameters in real time, GIS provides continuous monitoring of the physico-chemical indicators of groundwater and allows for prompt assessment of their condition.

The article also analyzes the possibilities of using predictive modeling in GIS to assess the further spread of pollution and develop environmental risk management measures. It is described how mathematical models in GIS can help predict the impact of anthropogenic and natural factors on groundwater, which ensures the development of scientifically based solutions to reduce pollution and maintain water quality at a safe level. The implementation of GIS in groundwater monitoring is an important step towards increasing the efficiency of water resources management, ensuring their protection from pollution and preserving the ecological stability of the regions.

Keywords: *geoinformation systems, groundwater monitoring, environmental safety, satellite sounding, automated sensors, three-dimensional modeling, predictive modeling, water resources management, aquifer pollution.*

Introduction . Groundwater monitoring is a key element for ensuring ecological stability and sustainable management of water resources, especially in regions with increased anthropogenic activity. In industrial and mining areas where the level of contamination can change rapidly due to leaks, increased mineralization or contamination with toxic substances, groundwater monitoring is critically important. Thus, on the territory of the Dombrovsky quarry, the accumulation of brines creates an ecological threat to aquifers, which emphasizes the need for highly accurate and integrated systems for monitoring the state of groundwater.

Geographic Information Systems (GIS) provide an integrated approach to groundwater monitoring by providing the ability to collect, store, analyze and visualize a variety of environmental data from a variety of sources. The use of these systems allows detecting changes in the state of groundwater, assessing the degree of contamination, predicting the dynamics of contamination, and creating models that reflect the interaction between contaminated zones and aquifers. GIS programs , such as ArcGIS and QGIS, are capable of processing large volumes of spatial data, which allows you to quickly obtain information about the state of aquifers and make effective management decisions to protect water resources.

The application of GIS includes the use of satellite sounding, remote sensing data, and spectral indicators that allow us to assess the state of surface and groundwater in large areas. An important aspect is the creation and analysis of thematic maps, which provide a reliable representation of the ecological situation. For example, maps that display the salinity level or the chemical composition of groundwater help to investigate areas with increased levels of pollution and develop measures to minimize their impact on the ecosystem.

Modern geoinformation systems also support the creation of three-dimensional models of aquifers, which allows you to explore not only the plane, but also the deep aspects. Such 3D models make it possible to estimate the depth of the contaminated layers, adjust the optimal points for installing monitoring stations, and more accurately predict the movement of contaminants in aquifers. The use of mathematical models ensures the creation of forecasts regarding the further spread of pollution under the influence of natural and man-made factors, which is a case for timely use of measures to prevent environmental damage.

Thus, the implementation of a geo-information system for groundwater monitoring not only ensures the accuracy and efficiency of obtaining environmental information, but also contributes to more effective management of natural resources. GIS technologies are a tool for specialists in the field of ecology and water resources, which should ensure long-term environmental security of regions with a high risk of groundwater pollution.

Purpose and task. The purpose of the research is to provide effective monitoring of the state of groundwater using geoinformation systems for timely detection and forecasting of pollution. The task of the work is the study of GIS methods that contribute to the detection, analysis and visualization of groundwater data, as well as the assessment of their application for building models and making decisions in the field of water resources protection.

Presentation of the main research material. Today, geographic information systems (GIS) are one of the most effective tools for monitoring the ecological state of groundwater. Thanks to these systems, it is possible to integrate and analyze data from various sources, visualize the dynamics of changes and predict possible scenarios of the spread of pollution in aquifers. It allows you to create multi-layered maps and models that help assess the state of groundwater and the interaction between various environmental factors that affect their quality and quantity.

Geographic information systems (GIS) are indispensable in groundwater monitoring due to their ability to integrate, analyze and visualize large volumes of data that cover the physical and chemical characteristics of groundwater, the ecological status of regions, the level of damage, and spatial and temporal changes in ecosystems. The use of GIS contributes to greater accuracy, efficiency and systematic environmental control, providing the possibility of making informed decisions for the protection of water resources [1] .

First, there is the possibility of collecting and processing large volumes of data from various sources, such as satellite images, sensors, field studies and automated monitoring stations. This data may include information on salinity levels, concentrations of toxic substances, water conductivity, temperature, and other parameters that affect groundwater quality. The integration of such data into a single system makes it possible to maintain a comprehensive picture of the state of waters in the selected territory. The use of satellite images allows monitoring of large areas and surface changes that may affect aquifers, such as landslides, changes in vegetation or aquifers, which are the result of both natural and anthropogenic factors.

In addition, GIS contribute to the identification of regularities and the analysis of spatial and temporal dynamics of pollution. The use of spatio-temporal data allows creating maps and models that reflect the dynamics of changes in groundwater at different time stages. This is especially important for monitoring areas with a high level of anthropogenic influence, such as industrial or mining areas. Regular monitoring of pollutant concentrations makes it possible to accidentally detect anomalous increases in pollution levels, which may indicate leaks or other sources of pollution, and to ensure a rapid response to environmental threats.

There is a huge potential for predictive modeling, which allows predicting how the state of groundwater will change under the influence of natural or man-made factors [2] . Predictive modeling can be used to assess different scenarios, for example, the deterioration of the ecological situation due to increased precipitation, changing climatic conditions or the expansion of industrial production. Based on such forecasts, experts can develop measures to prevent further deterioration of water quality, such as the construction of drainage systems, the creation of protective barriers or the installation of monitoring stations at key points .

Three-dimensional modeling, which is supported by GIS, allows visualization of the distribution of pollutants not only in the horizontal but also in the vertical dimension, providing a more detailed understanding of distribution at different depths. This makes it possible to determine the depth of the contaminated layers and their connection with fresh water horizons. This approach is especially valuable in regions with complex geological conditions, where surface and underground distribution can be significantly different [3] .

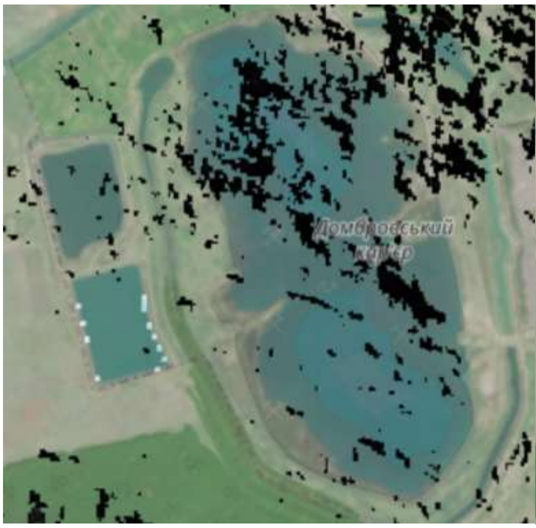
It is possible to analyze the interrelationships of environmental factors, such as climatic conditions, the intensity of industrial production, the condition of the soil and vegetation, the degree of anthropogenic load on the territory. Such a comprehensive approach will make it possible to determine the main causes of pollution and develop effective measures to reduce them. They also provide an opportunity to quickly respond to environmental threats. Data from satellites, sensors, and field studies can quickly track abnormal changes, such as rising salinity levels in a given area, that may indicate expanding water salinization. These systems can quickly analyze data, assess their impact on the environment and decide on preventive measures, such as installing temporary barriers or diverting water to prevent further impacts.

The use of modern approaches makes it possible to develop long-term environmental programs that take into account the peculiarities of a certain region, the dynamics of disturbance and environmental risks. On the basis of the obtained data, it is possible to plan measures to prevent pollution for many years ahead, such as the construction of protective structures, the implementation of water purification and desalination methods, and the installation of drainage systems to maintain water quality at a stable level [4] .

GIS also facilitate an interdisciplinary approach and collaboration between higher scientific, public, and private institutions involved in groundwater monitoring. The use of a single platform allows different organizations to exchange data and coordinate their actions, which is especially important for large environmental projects that require the involvement of significant resources and specialists from various fields.

Information capabilities are widely used for training specialists in the field of ecology, hydrogeology and groundwater monitoring. Real data from various projects help to practically apply monitoring methods, improve skills in working with spatial data, and obtain up-to-date knowledge about predictive modeling and systematic management of natural resources [5] .

Analyzing the data of the Dombrovsky quarry from the GIS system for 2015 (Fig. 1) and 2024 (Fig. 2), we can conclude about a significant increase in brines, marked in black in the photo as zones with high salinity. In the image for 2024, the amount black areas are much larger, indicating a high level of salinity [6] . This indicates an increase in the concentration of salts in underground and surface waters of the quarry.



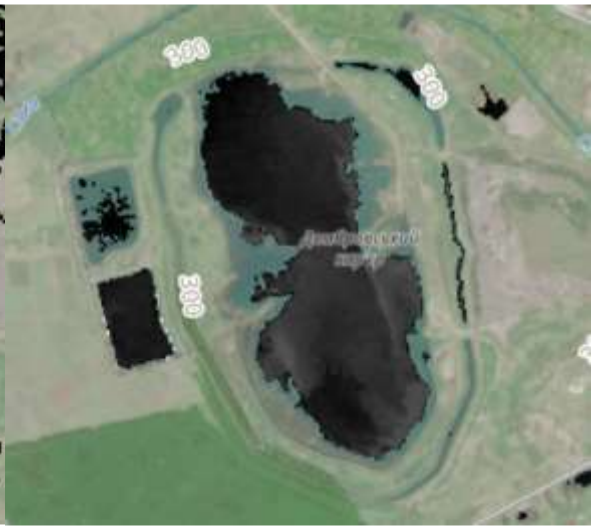


Figure 1 – *Snapshot (2015) from Sentinel Hub* Figure 2 – *Snapshot (2024) from Sentinel Hub*

Such a series of salinity levels is a serious signal of the aggravation of the problem of salinization of water resources in the region. The spread of brines can lead to ecosystem degradation, as high salt concentrations negatively affect vegetation and soil, making the area unsuitable for many species of flora and fauna. In addition, such changes can cause the migration of contaminated water into nearby aquifers, which threatens the quality of drinking water for the surrounding areas.

Without the implementation of control measures and the construction of protective structures , the level of salinity in the Dombrovsky quarry and adjacent aquifers will increase. This is due to several factors:

1. Cumulative nature of the process . Salinity tends to accumulate, reducing the salt level in water is a very slow process. Accumulated salts will continue to accumulate in the lower horizons, seeping into the ground and aquifer layers.

2. Infiltration of salts into adjacent horizons. Over time, saltwater can begin to seep into nearby aquifers, increasing the extent and depth of contamination. This can cause water quality in the region to deteriorate, making it unfit for consumption and threatening ecosystems.

3. Increasing the risk of fresh water pollution. Since the Dombrovsky quarry is located close to other water bodies, there is a risk that, through capillary or underground processes, brines may penetrate into fresh water sources, which are connected for economic and drinking needs [7].

Based on the trends observed in the 2015 and 2024 images, it can be predicted that the area of saline areas will increase by 15-20% by 2030 if no protective measures are taken. This forecast is based on an analysis of current salinization dynamics and the maintenance of current infection rates.

In the longer term, without effective control, the salinization of aquifers can lead to serious environmental consequences for the region:

1. Extension of sounding. Brines can penetrate aquifers that are currently completely protected. This will lead to a significant expansion of the zone with high salinity, which will make the area unsuitable for economic and agricultural use.

2. Negative impact on local ecosystems. An increase in soil and water salinity will negatively affect the state of local ecosystems, including degradation of vegetation and changes in biodiversity. Many plants and animals are unable to withstand high levels of salinity, which will lead to a decrease in the number and types of biodiversity depletion.

3. Risk of environmental disaster. If the salinization process is not stopped or isolated, the penetration of brines into aquifers of regional or global importance is possible. This will threaten not only local water sources, but may also have greater consequences for the adjacent regions of Ukraine and neighboring countries, such as Moldova, especially in conditions of a possible expansion of production works [8] .

GIS data play an extremely important role in the process of monitoring and minimizing the risks of groundwater salinization. Thanks to the ability to process and analyze a large amount of spatial data, GIS allows specialists to create interactive maps, predictive models and monitoring systems that help to quickly monitor changes in the state of aquifers and respond to some threats.

The main ways of using GIS to minimize the risks of salinity are as follows.

1. Constant monitoring and periodic detection of changes.

GIS provides the possibility of regular monitoring of the state of groundwater and allows recording changes in salinity, levels of damage and other physicochemical parameters. The use of satellite images, automated sensors and ground observations allows for constant storage of updated data, which significantly increases the accuracy of assessing the current state of aquifers.

For example, with the help of regular analysis of GIS data, it is possible to detect the tendency of increasing salinity in a certain area in time. This allows for prompt decision-making, for example, regarding the installation of additional drainage systems to avoid the further spread of brines.

2. Use of 3D modeling to assess the spread of pollution.

Three-dimensional modeling in GIS is a powerful tool for studying the dynamics of the spread of pollutants in groundwater. With the help of 3D models, it is possible to visualize not only the horizontal, but also the vertical movement of brines, which clearly assesses the depth of their penetration and the impact on deep aquifers.

For example, in the case of the Dombrovskyi quarry, 3D modeling can be used to determine the places of the greatest accumulation of brines in deeper horizons, which allows obtaining risk points for fresh water. Thanks to such modeling, specialists can develop more effective strategies to stop or slow down the seepage of salts, in particular, to determine the optimal places for the construction of protective barriers.

3. Predictive modeling.

Using GIS mathematical models, it is possible to predict how the level of groundwater salinity will change in the future, depending on factors such as rainfall, temperature fluctuations, geological conditions and other factors.

For example, if forecast modeling shows that precipitation is expected to increase in the near future, this could contribute to further spread of brines. In such a case, based on the forecast, risk reduction measures such as expansion of the drainage system or strengthening of existing barriers can be planned in advance.

4. Optimizing the location of monitoring stations.

GIS data help to optimize the location of monitoring stations, which allows for more accurate control of the state of groundwater in different parts of the territory. Thanks to the analysis of thematic maps and 3D modeling, it is possible to determine the place with the highest concentration of pollution, where the installation of monitoring stations is most appropriate.

Optimum location of stations reduces monitoring costs and provides more accurate data that can better predict the spread of pollution.

5. Timely response to environmental threats.

Thanks to the data obtained from GIS, specialists can quickly respond to sudden changes in the state of groundwater, for example, to a sharp increase in the level of salinity or the emergence of new polluted areas. Using GIS, you can quickly analyze data, assess the impact of changes on the environment and make appropriate decisions.

GIS also allows for the creation of long-term monitoring and management programs that take into account environmental risks and allow planning activities for many years ahead. The use of historical data and models of salinity dynamics additionally allows specialists to develop forecasts and plan measures to prevent environmental disasters in the future.

Long-term planning based on GIS includes, for example, the construction of protective structures, the creation of complex drainage systems, the implementation of cleaning and desalination methods that minimize risks for the region and preserve water resources [9].

Conclusion. The implementation of geographic information systems (GIS) in groundwater monitoring is an extremely effective approach to ensuring environmental security and sustainable management of water resources. Modern capabilities allow for the integration of huge amounts of data, including satellite images, automated sensors and the results of field studies, into a single platform for comprehensive analysis of the state of groundwater. The use of GIS provides not only efficiency and accuracy in data collection, but also creates a tool for identifying dynamics and regularities in changes in water quality, especially in conditions of anthropogenic influence.

One of the key achievements of GIS is the possibility of creating thematic and three-dimensional maps that allow a deeper understanding of the spatial and temporal distribution of pollution in aquifers. Thanks to such maps, experts can not only identify current "hot spots" of pollution, but also predict potential risks that may arise in the future. For example, the use of 3D models helps to investigate how deeply polluted waters spread and to identify areas that require additional protection measures.

Predictive GIS-based modeling is another extremely important aspect that allows for the development of different scenarios for the development of the salinity situation. The inclusion of climatic and anthropogenic factors in the calculations makes it possible to build forecasts that take into account possible changes in natural conditions, such as an increase in the level of precipitation or changes in temperature, which can affect the salinity of aquifers. Such forecasts are the basis for creating long-term risk management strategies, developing measures to reduce the impact on ecosystems and ensure a stable state of groundwater.

Modern GIS also make it possible to create early warning systems that can detect changes in water parameters in real time. Such a system provides the ability to immediately respond to sudden changes in the state of groundwater, which is critical for preventing environmental disasters. This opens up prospects for more efficient management of water resources, especially in regions with a high level of anthropogenic load, such as the Dombrovsky quarry, where the risk of pollution is increased.

Using the example of Dombrovsky quarry monitoring for 2015 and 2024, it is possible to draw a conclusion about the effectiveness of the GIS system in studying the dynamics of brines, which shows an increase in the concentration of salts in the underground and surface waters of the quarry, which threatens the pollution of surface and underground waters in the environment. Based on the trends observed in the 2015 and 2024 images, it can be predicted that the area of saline areas will increase by 15-20% by 2030 if no protective measures are taken. The application of 3D modeling can be used to determine the places of the greatest accumulation of brines in deeper horizons, which allows to obtain points of risk for fresh water. Thanks to such modeling, it is possible to develop more effective strategies to stop or slow down the seepage of salts, to determine the optimal places for the construction of protective barriers.

Therefore, the implementation of GIS in groundwater monitoring is an important step on the way to ecologically balanced development. Geoinformation systems provide specialists in the field of ecology, hydrogeology and water resources management with an effective tool for analysis, forecasting and timely response to environmental challenges. The development and improvement of GIS technologies allows to increase the level of safety of water resources, providing a reliable basis for preserving ecological stability and protecting the quality of groundwater in the long term.

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ВИКОРИСТАННЯ ГЕОІНФОРМАЦІЙНИХ СИСТЕМ ДЛЯ МОНІТОРИНГУ СТАНУ ПІДЗЕМНИХ ВОД

Стаття присвячена вивченню можливостей використання геоінформаційних систем (ГІС) для моніторингу стану підземних вод, що має важливе значення для забезпечення екологічної безпеки та сталого управління водними ресурсами. Підземні води є важливим джерелом прісної води для населення, промисловості та сільського господарства, однак вони вразливі до різноманітних забруднень, спричинених як природними, так і антропогенними факторами. Тому впровадження надійних систем моніторингу, які дозволяють своєчасно виявляти, оцінювати та прогнозувати зміни якості води, є необхідним для запобігання погіршенню екологічної ситуації та запобігання поширенню забруднення.

Геоінформаційні системи (ГІС) відкривають значні можливості для збирання та інтеграції великих обсягів просторових даних, зокрема супутникових знімків, результатів дистанційного зондування, даних автоматизованих сенсорів та польових спостережень. ГІС дозволяють створювати багатошарові карти, що відображають екологічний стан підземних водоносних горизонтів, моделювати процеси забруднення і прогнозувати їх можливий вплив на прилеглі екосистеми та джерела води. Завдяки використанню ГІС можна поєднувати дані з різних джерел у єдиній інтерактивній системі, що спрощує аналіз і забезпечує можливість швидкого реагування на будь-які виявлені відхилення.

У статті докладно розглядаються ключові методи, які використовуються в рамках ГІС для моніторингу підземних вод, зокрема супутникове зондування для аналізу змін на поверхні землі, спектральні індекси для оцінки стану рослинності та солоності ґрунтів, а також радіолокаційні методи для визначення електропровідності ґрунтів. Окрему увагу приділено застосуванню тривимірного моделювання, яке дозволяє візуалізувати поширення забруднень у підземних водоносних шарах, що полегшує прийняття рішень щодо оптимального розташування моніторингових станцій та проектування захисних споруд. У поєднанні з автоматизованими сенсорами, що фіксують параметри води в режимі реального часу, ГІС забезпечує безперервний контроль за фізико-хімічними показниками підземних вод і дозволяє оперативно оцінювати їх стан.

Стаття також аналізує можливості застосування прогнозного моделювання у ГІС для оцінки подальшого поширення забруднення та розробки заходів з управління екологічними ризиками. Описано, як математичні моделі у ГІС можуть допомогти передбачити вплив антропогенних та природних факторів на підземні води, що забезпечує розробку науково обґрунтованих рішень для зменшення забруднення та підтримання якості води на безпечному рівні. Впровадження ГІС у моніторинг підземних вод є важливим кроком до підвищення ефективності управління водними ресурсами, забезпечення їх захисту від забруднень та збереження екологічної стабільності регіонів.

Ключові слова: *геоінформаційні системи, моніторинг підземних вод, екологічна безпека, супутникове зондування, автоматизовані сенсори, тривимірне моделювання, прогнозне моделювання, управління водними ресурсами, забруднення водоносних горизонтів.*

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