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IMPROVING ENVIRONMENTAL PROTECTION USING FUZZY LOGIC ALGORITHMS FOR ANALYSIS OF WATER RESOURCE CHANGES

Problem. As humanity develops and the planet's population increases every day, the problem of environmental threats is becoming increasingly serious. In order to reduce damage to the environment, some people monitor conditions and take action to ensure a better future. This includes cleaning up rivers, lakes and oceans, planting new trees in place of felled ones, and introducing carbon-free technologies. The development of information systems that use artificial intelligence, quadcopters and remote sensing methods to analyse changes in water resources and identify environmental risks allows for a quick and accurate assessment of water resource dynamics. These systems can collect large amounts of data for further analysis and are an important tool for maintaining ecological balance.

The article presents the results of a study on an information system that automates the assessment of water resource conditions by using neural networks, geographic information systems and remotely sensed data acquired by quadcopters. This system will help users optimize their working environment by providing tools for automating analysis and monitoring tasks. All calculations involving mathematical models and fuzzy logic are performed on the server part, which is responsible for storing data and calculation results in the database. Due to its flexible API architecture, the server component can be integrated into any application. The study also presents mathematical models based on fuzzy logic for analysing water resource indicators and the final state of a body of water.

Purpose. The research objective is to develop an artificial intelligence-based system for monitoring and analysing changes in water resources, using quadcopters and remote sensing methods. The system should provide accurate and timely assessments of the condition of water bodies to inform decisions regarding their preservation and restoration. Fuzzy logic algorithms were employed to achieve the required forecasting outcomes.

Research results. An information monitoring system was designed to assess the pollution of water resources. The main advantages of this system are its ability to predict the general state of water bodies based on photo and video information, and its graphical interface, which displays biological, hydromorphological, chemical, physicochemical and specific polluting indicators of water bodies on a map.

The study of water body pollution indicators was carried out in two stages, using the fuzzy logic apparatus of the MATLAB environment. At the first stage, the poor, average or good condition of the reservoir concerning the above indicators was detected. These indicators included numerous biological indicators related to phytoplankton, hydromorphological indicators in the form of water level and interaction with the environment, chemical indicators in the form of the number of chemical pollutants, and physicochemical indicators determined by temperature, oxygen availability and the physical condition of the water body. At the second stage, a forecast of the reservoir's pollution level was made based on the analysed indicators, and a conclusion was reached by experts about the condition being very poor, poor, moderate, good or excellent.

Conclusions. The information system developed for monitoring water resources uses fuzzy logic algorithms and biological, hydromorphological, chemical and physicochemical indicators.An important stage is ensuring the functionality and speed with which the predicted result is obtained through the use of information technologies associated with the improved, high-precision processing of photos and videos, as well as the fast processing of large volumes of information, due to the features of relational and non-relational databases. The system works correctly by following the developed base of fuzzy rules to produce a forecast, enabling the necessary actions to be taken to improve the environmental safety of water bodies.

Keywords: information system, monitoring, forecasting, water resource, pollution, mathematical model, database, fuzzy logic.

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ПОКРАЩЕННЯ ЕКОЛОГІЧНОГО ЗАХИСТУ ДОВКІЛЛЯ З ВИКОРИСТАННЯМ АЛГОРИТМІВ НЕЧІТКОЇ ЛОГІКИ ДЛЯ АНАЛІЗУ ЗМІН ВОДНИХ РЕСУРСІВ

Проблема. Людство розвивається і населення планети з кожним днем збільшується, а тому проблема екологічної загрози стає дедалі більшою. Для зменшення шкоди частина людей слідкує за станом навколишнього середовища щоб забезпечити краще майбутнє, очищуючи річки, озера, океани, висаджуючи на місці вирубаних дерев нові дерева, впроваджуючи безвуглецеві технології існування. Розробка інформаційних систем для аналізу змін водних ресурсів та визначення екологічних ризиків із використанням штучного інтелекту, квадрокоптерів і методів дистанційного зондування дозволяє швидко та точно оцінювати динаміку водних ресурсів, збираючи великі обсяги даних для подальшого аналізу, що може стати важливим інструментом у збереженні екологічної рівноваги.

В статті наведено результати досліджень розробленої інформаційної системи, в якій автоматизовано процес аналізу стану водних ресурсів, використовуючи нейронні мережі, географічні інформаційні системи та дані з квадрокоптерів. Така система зможе допомогти користувачам оптимізувати їхнє робоче середовище шляхом надання інструментарію для автоматизації завдань аналізу та моніторингу. Усі обчислення за допомогою математичних моделей та нечіткої логіки відбуваються на серверній частині, яка відповідає за збереження даних та результатів обчислень в базі даних. Сама серверна частина дозволяє інтегрувати систему в будь-який додаток завдяки гнучкій API архітектурі. Також в роботі наведено спроектовані математичні моделі нечіткої логіки для аналізу показників водних ресурсів, а також і для аналізу заключного стану водного об’єкту.

Мета. Завданням проведеного дослідження є створення системи на базі штучного інтелекту для моніторингу та аналізу змін водних ресурсів із використанням квадрокоптерів та методів дистанційного зондування. Система повинна забезпечити точну та оперативну оцінку стану водних об'єктів і допомогти в прийнятті рішень щодо їх збереження та відновлення. Для досягнення необхідних результатів прогнозування використано алгоритми нечіткої логіки.

Результати дослідження. Для оцінки забрудненості водних ресурсів спроектовано інформаційну систему моніторингу, основними перевагами якої є можливість прогнозування загального стану водойм на основі фото і відео інформації, а також використання графічного інтерфейсу для перегляду біологічних, гідроморфологічних, хімічних, фізико-хімічних, специфічних забруднюючих показників водних об’єктів на карті.

Дослідження показників забруднення водойм проходило в два етапи, використовуючи апарат нечіткої логіки середовища Matlab. На першому етані з великої кількості біологічних показників, пов’язаних з фітопланктоном, гідроморфологічних показників у вигляді рівня води та взаємодії з оточуючим середовищем, хімічних показників, якими є кількість хімічних забруднюючих речовин, і фізико-хімічних показників, що визначаються температурою, наявністю кисню і фізичним станом водного об’єкту визначався поганий, середній чи добрий стан водойми стосовно названих показників. На другому етапі здійснювався прогноз стану забруднення водойми на основі проаналізованих показників і був зроблений експертний висновок про дуже поганий, поганий, помірний, добрий, дуже добрий стан.

Висновки. Розроблена інформаційна система моніторингу водних ресурсів з використанням алгоритмів нечіткої логіки використовує біологічні, гідроморфологічні, хімічні та фізико-хімічні показники. Важливим етапом є забезпечення функціональності і достатньої швидкості отримання прогнозованого результату за рахунок використання інформаційних технологій, пов’язаних з покращеною високоточною обробкою фотографій та відео, швидкою обробкою великих обсягів інформації завдяки особливостям застосування реляційних та нереляційних баз даних. Система працює коректно, відповідно до розробленої бази нечітких правил і видає результат прогнозування, який дозволяє зробити висновки про необхідні дії для покращення екологічної безпеки водних об’єктів.

Ключові слова: інформаційна система, моніторинг, прогнозування, водний ресурс, забруднення, математична модель, база даних, нечітка логіка.

Introduction

Monitoring the ecological state of water bodies is an important and indispensable tool for effective water resource management and ensuring environmental safety. Pollution of water bodies can occur with anthropogenic activities, industrial emissions, agricultural waste, improper disposal of chemicals, and pollution of urban wastewater.

The relevance of the work lies in the importance of solving problems related to climate change, land degradation, and water resource pollution, which require new solutions for their monitoring and conservation. Conventional methods of monitoring water resources are often not effective enough, as they require significant human and time resources. Today, most traditional monitoring methods, such as sampling of water parameters and laboratory analysis, have certain disadvantages, in particular, it is not always possible to get to the water body due to its location. In laboratory analysis, incorrect research results that determine the real state of water bodies may be obtained due to the human factor. The application of geographic information systems and quadcopters can solve the problem of accessibility of the territory and the speed of monitoring. The development of mathematical models for research and the use of artificial intelligence technologies with machine learning methods will provide an opportunity to automate the monitoring process and increase the accuracy of research.

The article analyses existing water body monitoring systems, presents the research results on the designed information system using quadcopters, remote sensing methods, and fuzzy logic algorithms for predicting the ecological situation, together with the analysis of changes in water resources. The principal task of the system is to ensure accurate and prompt assessment of the state of water bodies and help in decision-making regarding their preservation and restoration.

Analysis of existing systems and methods for monitoring water bodies

Water resources monitoring involves collecting and analysing large amounts of data on various physicochemical and biological water quality parameters. These parameters may include the concentration of pollutants such as nitrates, sulphates, chlorides, temperature, oxygen level, pH, water transparency, and the availability of harmful microorganisms. Currently, there are various approaches to monitoring the quality of water bodies. An effective monitoring system must be able to integrate diverse data sources, provide opportunities for automated analysis, and offer tools for their visualization in a convenient and understandable format. The main components of such a system are the means of collecting, processing, storing data, and its further analysis [1].

It is also important that an effective monitoring data analysis system must have the ability to integrate with analytical models and various forecasting models. This will enable a record of the current state of water resources and the prediction of possible changes in the ecological state, allowing for taking measures in advance to preserve ecosystems. In synergy with automated sensors and modern data analysis technologies, such a system can become the basis for the development of comprehensive strategies for the conservation of water resources. Therefore, integrating modern visualization and data analysis technologies allows not only to improve the control of surface water quality but also provides opportunities for timely decision-making to minimize environmental risks.

We will first select Global Water Watch for a comparative analysis of known water resources monitoring systems [2]. This monitoring system uses satellite images, quadcopters, sensors, and artificial intelligence, and it provides data on water level, quality, pollution, and the ecological state of rivers, lakes, and reservoirs in real time. Satellite data make it possible to monitor changes in water resources regularly. Artificial intelligence in the system is used to analyze large volumes of data and neural networks for automatic change detection and forecasting. Remote sensing is carried out using quadcopters for detailed monitoring of individual reservoirs, collecting data on their quality and ecological state. All observation results are contained in open databases, which allows them to be used for decision-making.

In Ukraine, for monitoring water bodies, the State Agency for Water Resources has developed a website with an interactive map "Monitoring and Environmental Assessment of Water Resources of Ukraine" (Fig. 1). On this website, you can find every water body in Ukraine and get detailed information about its monitoring at any time [3].

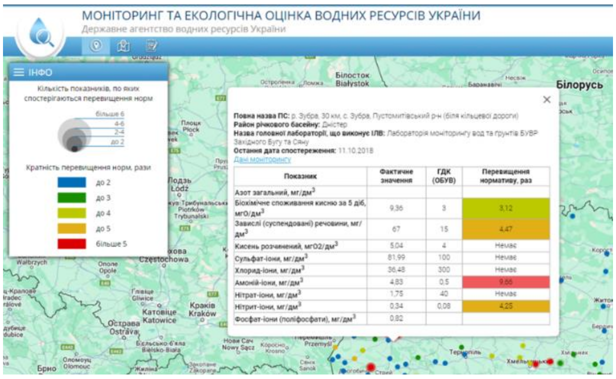

Figure 1 – Information system for monitoring water resources of Ukraine

Analysis of information technologies for the design of monitoring information systems

To create an information system for visualizing and analyzing water resources monitoring data, it is necessary to determine the input and output parameters of the system. The structural diagram of the monitoring system consists of two blocks of input parameters, three blocks for presenting output results, and a block for analyzing and visualizing data for monitoring the environmental safety of water resources (Fig. 2).

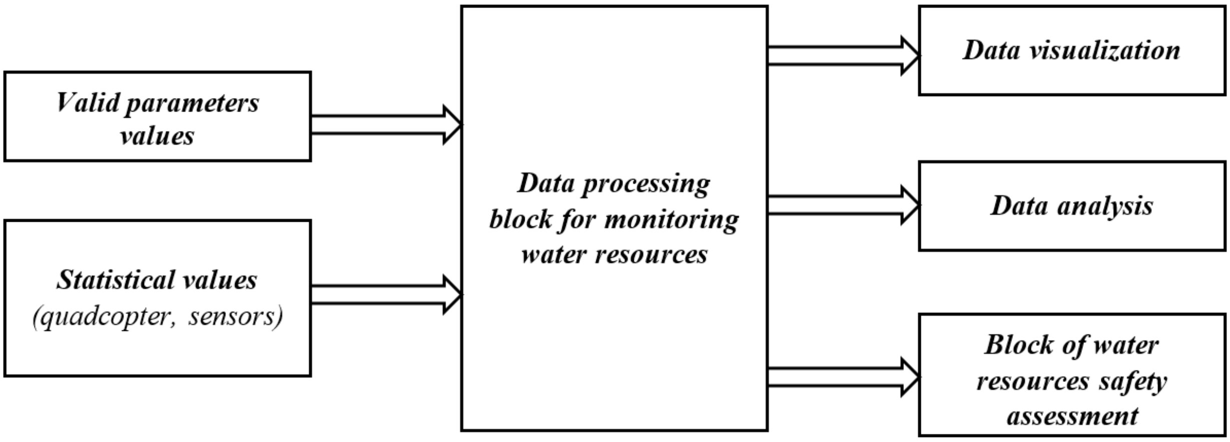

Figure 2 – Structural diagram of the water resources monitoring system

The safe level of harmful substances in a water body, which is used to assess the ecological safety of a water body, is the maximum permissible concentration of substances. Statistical values are information about water resources, collected using quadcopters and sensors. These data are used to study the dynamics of changes and identify tendencies in the improvement or deterioration of water resources. Visualization of monitoring results consists of displaying information in the form of diagrams and interactive maps showing the location of water bodies with which monitoring is carried out. Data analysis occurs by loading personal data into the system and displaying it as infographics. Assessment of ecological safety involves displaying the state of water resources according to the maximum permissible concentration, which is the forecasting outcome of the state using fuzzy logic algorithms [4].

We will analyze information technologies for developing a water resource monitoring system.

The most popular programming language for artificial intelligence and machine learning is Python, which has various libraries for data analysis, neural network training, and big data processing. The R programming language can be used for statistical generation and analysis of large amounts of environmental data. In synergy with Python, the C++ programming language is used to develop high-performance systems and algorithms, and can provide high data processing speed for real-time systems. For web application design, data visualization, and application of artificial intelligence algorithms, JavaScript [5] with the TensorFlow.js library (an open source library for machine learning and neural networks supported by Google) can be used.

Relational and non-relational databases are used to store monitoring data. The most common relational databases are MySQL for storing structured data and PostgreSQL, which contains analytical capabilities and support for geospatial data (PostGIS extension) [6]. Non-relational databases include MongoDB, which works with unstructured and semi-structured data and is best suited for storing large amounts of data from sensors and quadcopters; Cassandra, a scalable database for processing real-time data streams; and InfluxDB, a specialized database for monitoring sensor data in real time.

The following Python libraries can be used to conduct machine learning in research. Scikit-learn is a set of machine learning tools that includes regression, clustering, and dimensionality reduction algorithms. Keras provides a simple and user-friendly interface for building and training machine learning models and is designed to simplify the process of creating neural networks [7]. OpenCV is used for computer vision and can be useful for processing images and videos collected by quadcopters, particularly for detecting anomalies on the water surface. Python language libraries, Pandas and NumPy, are very efficient for data processing.

To visualize the obtained data, you can use Microsoft's Power BI technologies for data visualization and creating interactive maps. Power BI's integration with other Microsoft services, including Azure, is important. Tableau is used in designing monitoring information systems for data visualization and analytics, and creating interactive maps and reports based on water monitoring data.

Formation of a mathematical model of the object of study

Firstly, it is necessary to determine which indicators need to be monitored to analyze the state of water resources. These values will be necessary for the analysis of water resources, namely rivers, lakes, transitional and surface waters [8].

The developed mathematical model for monitoring water bodies contains five classes of indicators:

1. Biological indicators are determined by analyzing phytoplankton, microphytes,

phytobenthos, invertebrate fauna, and fish fauna for all possible water resources, as well as additional analysis of macro algae and angiosperms for transitional waters.

2. Hydromorphological indicators differ for the four types of resources. For rivers, it is necessary to determine the amount and dynamics of the flow, the relationship with groundwater, the continuity of the river, the shape of the channel, fluctuations in width and depth, flow speed, and the condition of the coastal zones of the rivers. When studying lakes, the relationship with groundwater and the analysis of lake depth fluctuations, the amount and structure of the substrate, and the condition of the lake's coastal zone are important. When monitoring transitional waters, the inflow of fresh water, depth fluctuations, and the condition of the substrate are analyzed, and for surface waters, additionally, the direction and speed of dominant currents, depth fluctuations, and the structure of the coastal bottom are analyzed.

3. Chemical indicators include cadmium, lead, mercury, chromium, petroleum products, pesticides, polyaromatic hydrocarbons, chlorides, and sulphates present in water.

4. When monitoring physicochemical indicators, the oxygen content in water, water temperature, water acidity/alkalinity, the presence of ammonium, nitrates, nitrites, and phosphates are determined.

5. Specific synthetic and non-synthetic pollutants are determined by the total concentration of heavy metals in water.

To assess the pollution of water bodies, an information monitoring system has been created, the main advantages of which are the possibility of machine learning to predict the general condition of water bodies based on photos and videos obtained from quadcopters [9], as well as the use of a graphical interface to view biological, hydromorphological, physicochemical, and specific pollutant indicators of water bodies on the map.

Uploading a photo or video provides the ability to flexibly upload photos or videos to classify the necessary objects in them. The user can upload a photo or video that must contain water bodies or other necessary natural objects, such as fallen trees, for further processing in the system.

Obtaining a processed photo/video consists of successfully uploading the user's file to the server and receiving the corresponding file with the results from the server. A photo or video may contain the expected classification of objects if they were in the user's files. New files downloaded from the server will contain the object labels specified by the user.

Training a machine learning model and editing the necessary elements in the photos provides the opportunity to replenish the database for better classification of natural and water objects. If it is necessary to add new objects for classification, the user will be able to personally assign a class to this object, label this object using the graphical interface, and send the specified data to the server for processing and machine learning. Using the graphical interface of the system, the user receives a flexible tool for marking and classifying objects.

For ease of use, the information system has a graphical interface page. The component for creating marks and forming an object allows the user to place marks on the map, and if necessary, to form graphic figures from these marks that can be used as a display of the perimeter of a water object. At the stage of entering data about the object, the user specifies the name of the object, its location, and photos. It is possible to enter current data on the state of the object, its indicators, and detailed information for monitoring. These indicators will be used for machine learning so that in the future, the system can automatically predict possible changes in the indicators and the state of the object. The component for selecting an existing object on the map and viewing information about this object enables the selection of any available objects on the map.

Viewing indicators for a specified period and viewing detailed information about the indicators of each class of the object allows the user to view all available research data that they will need during the entered period. The function of predicting the object indicators will allow the user to use the mathematical model of the system to determine the indicators.

An important part of the monitoring information system is the database used to store all user data for analysis and monitoring. PostgreSQL technology was chosen for the design, since it is suitable for storing a large amount of data and is easily scalable [10].

To store information about the indicators, four tables were created - hydromorphological (water flow, water level, flow dynamics, channel shape, channel depth, channel width, water volume, integration with other adjacent ecosystems, natural or anthropogenic changes to the banks), biological (phytoplankton quantity, phytoplankton composition, phytoplankton biomass, phytoplankton production, phytoplankton species diversity), physicochemical (oxygen, temperature, acidity/alkalinity, nitrates, nitrites, phosphates, mineralization) and chemical (cadmium, lead, mercury, chromium, heavy metals, petroleum products, pesticides, polyaromatic hydrocarbons, chlorides, sulphates) (Fig. 3).

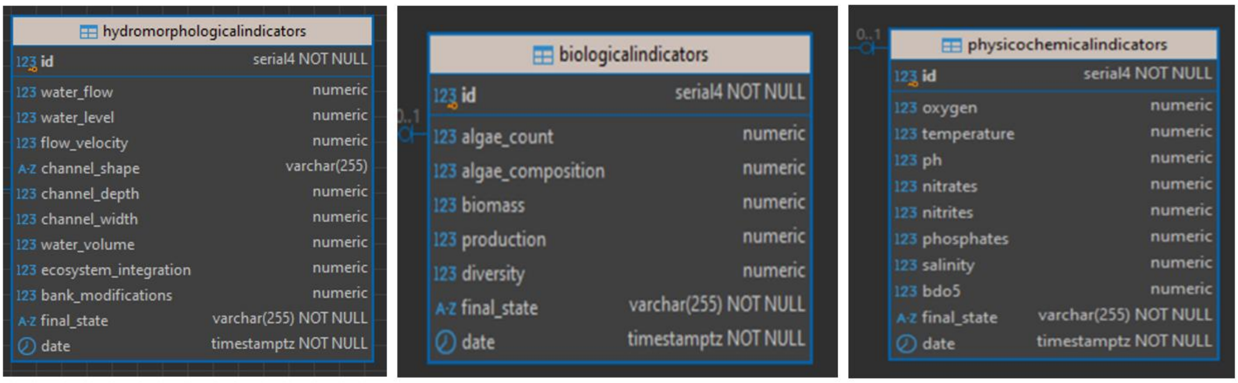

Figure 3 – Tables of hydromorphological, biological, and physicochemical indicators

Research results

For research on the qualitative state of water bodies, the Fuzzy Logic Toolbox fuzzy logic inference editor of the MATLAB environment was used [11].

To build a fuzzy logic system, input variables were defined, fuzzification, formulation of fuzzy inference rules, and defuzzification were performed. Clear input values are converted to fuzzy using membership functions.

Input biological indicators were determined from the following ranges of values in percentages (low [0;50], medium [0;100], high [50;100]) for the amount of phytoplankton, phytoplankton composition, phytoplankton biomass, phytoplankton production, and phytoplankton species diversity.

The input indicators for assessing the hydromorphological state of the reservoir were the following: (low [0;500], medium [0;1000], high [500;1000]) for water flow and water volume in thousands of litres, (low [0;5], medium [0;10], high [5;10]) for water level in meters, (low [0;50], medium [0;100], high [50;100]) for the coefficient of integration of the river or lake with adjacent ecosystems and the coefficient of naturalness or anthropogenic changes of the banks in percent.

To assess the chemical status of a water body, the following ranges of input indicators were used for different substances, namely (low [0;1], medium [0;2], high [1;2]) for cadmium in ng/m^3, for mercury in μg/l, for chromium in mg/l, (low [0;5], medium [0;10], high [5;10]) for the total concentration of heavy metals in g/l, (low [0;2.5], medium [0;5], high [2.5;5]) for the concentration of petroleum products in mg/l and the content of pesticides in the value of the hydrogen indicator pH, (low [0;500], medium [0;1000], high [500;1000]) for chlorides in mg/l.

Input parameters for determining the physical and chemical parameters of the reservoir were set in the following ranges (low [0;5], medium [0;10], high [5;10]) for oxygen in mg/l, (low [0;10], medium [0;20], high [10;40]) for temperature in °C, (low [0;5], medium [5;9], high [7;15]) for acidity in the value of the hydrogen indicator pH, (low [0;1], medium [0;3], high [1;10]) for ammonium level in mg/l, (low [0;10], medium [0;30], high [10;50]) for nitrate concentration in mg/l, (low [0;1], medium [0;5], high [1;10]) for phosphate content in mg/l, (low [0;1000], medium [0;3000], high [1000;5000]) for mineralization in mg/l.

The output indicator that determines the state of the water body is estimated by the following values: very poor, poor, moderate, good, and very good. In fuzzy logic, the formed rules determine the input and output membership functions that are used in the formation of a logical conclusion. After conducting research for the given values of the input indicators given in Table 1, the indicator of the biological state of water was obtained as 50%; for the values from Table 2, the indicator of the hydromorphological state of the water body is 50%; for the input parameters given in Table 3, the chemical state of the water body is 44.06%; for the values contained in Table 4, the physicochemical state of the water body is 45.37%.

Table 1

Values of indicators for determining the biological state of a water body

Biological indicators	Indicator value
Phytoplankton quantity	60
Phytoplankton composition	30
Phytoplankton biomass	15
Phytoplankton production	55
Phytoplankton species diversity	15

Table 2

Values of indicators for determining hydromorphological state

Hydromorphological indicators	Indicator value
Water flow	600
Water level	5
Water volume	7000
Integration of a river or lake with adjacent ecosys-tems	55
Naturalness or anthropo-genic changes to the banks	15

Table 3

Values of indicators for determining the chemical state of a water body

Indicators for chemical state	Indicator value
Cadmium	1.5
Lead	1
Mercury	0.5
Chromium	0.84
Heavy metals	6
Petroleum products	3
Pesticides	2
Chlorides	600

Table 4

Values of indicators for assessing the physical and chemical state of a reservoir

Physicochemical indicators	Indicator value
Oxygen	4
Temperature	15
Acidity	7
Ammonium	2
Nitrates	20
Phosphates	1
Mineralization	1000

To predict the general state of the reservoir, the ranges of biological, hydromorphological, chemical, and physicochemical states are taken into account, such as poor, average, and good. Fig. 4 shows the model for predicting the state of a water body.

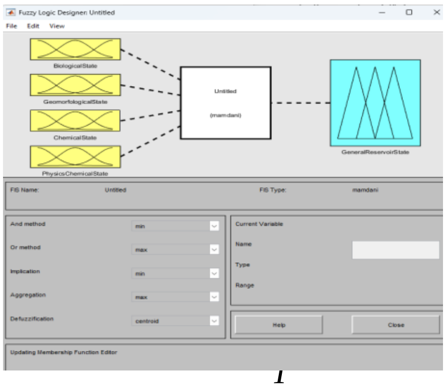

Figure 4 – Model for predicting the state of a water body

Fig. 5 shows graphs of the membership functions of the input variables that determine the biological, geomorphological, chemical, and physicochemical state. Graphs for the output value that determines the state of pollution of the water body are shown in Fig. 6.

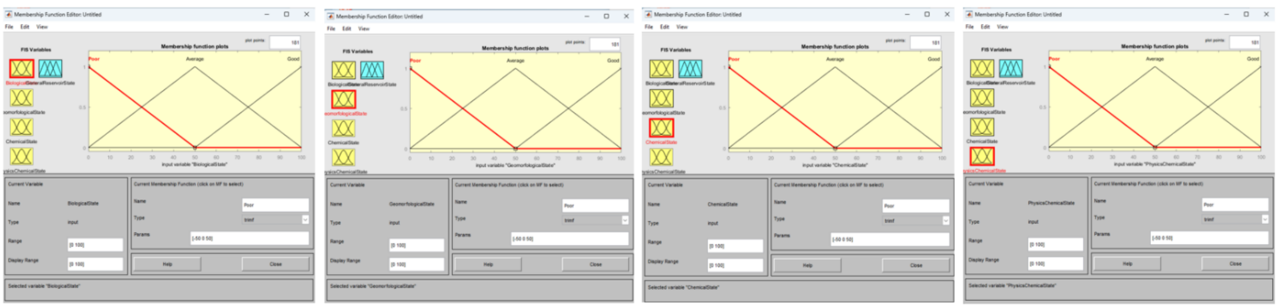

Figure 5 – Membership functions of input variables for biological, hydromorphological, chemical, and physicochemical indicators

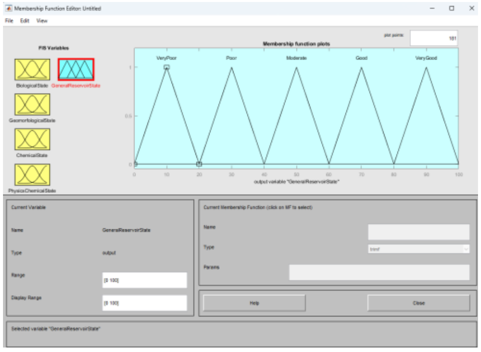

Figure 6 – Membership functions of the output variable, determining the state of pollution of the reservoir

After modeling the system for the formed rules (Fig. 7), the values of the pollution coefficient of the reservoir for the specified values of the input quantities were obtained using fuzzy logic algorithms. In Fig. 8, the graphs show the relationship between the input variables and the output ones, which is determined by the rule base.

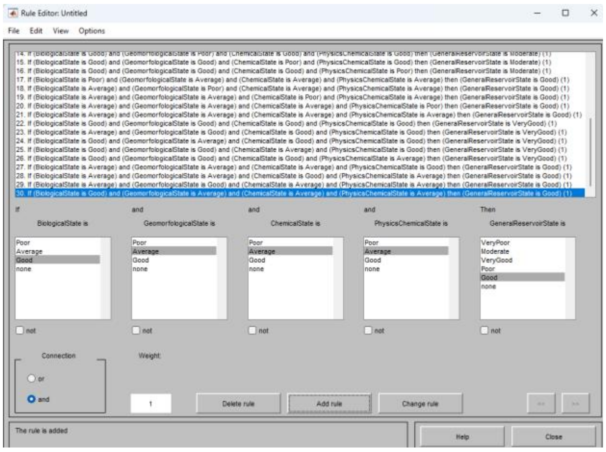

Figure 7 – Formed rules for membership functions

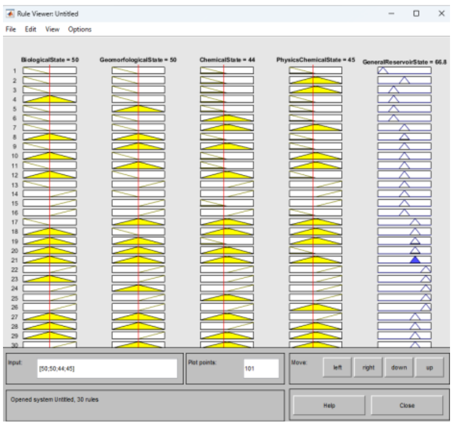

Figure 8 – Representation of modeling results in the form of images

The fuzzy logic method is used to display the input fuzzy values into the corresponding output fuzzy sets and allows generating conclusions for the resulting dependence. For four input variables, represented by four fuzzy sets, 30 rules are formed: The Rule Viewer is used in the fuzzy inference diagram to diagnose active rules, particularly how a separate function affects the result. Figure 8 shows how equal biological, geomorphological, chemical, and physicochemical indicators affect the pollution coefficient of a water body. If biological indicators are determined by the value of 50, hydromorphological – 50, chemical – 44, and physicochemical – 45, then the predicted pollution state of the water body is 66.8, which corresponds to the value of "Good".

Conclusions

The described system for monitoring water pollution is extremely relevant, since its use will enable the solution of problems related to climate change, land degradation, and water resource pollution, and the creation of new solutions for their monitoring and conservation. The monitoring system uses artificial intelligence technologies to monitor and analyze changes in water resources and information from quadcopters for remote sensing of water bodies.

The software was developed using the Python programming language with the Scikit-learn libraries, Keras for machine learning, OpenCV for using computer vision algorithms, image and video processing. Pandas and NumPy for data processing.

The implemented mathematical model for automatic assessment of the state of water resources is based on biological, chemical, hydromorphological, physicochemical, and other indicators that are necessary for a full analysis of the state of water resources. The study was carried out in two stages, namely, first, the biological state was determined based on the specified numerical values, the hydromorphological state for species and specific parameters of water bodies, and the chemical and physicochemical state for various numerical characteristics of pollutants.

To determine the biological state of the water body were selected quantitative indicators of biomass composition and species diversity of the present phytoplankton in ranging from 15% to 60%. Hydromorphological indicators were determined by the average water volume of 7,000 thousand liters and the degree of integration of the water body with adjacent ecosystems and shorelines, ranging from 15% to 55%. The chemical composition of the water body was mainly determined by the concentration of chlorides at around 600 mg/L, petroleum products at approximately 3 mg/L, and pesticide content inferred from the hydrogen ion concentration (pH), which was 2. The assessment of the physico-chemical state of the water body significantly depended on the temperature, which was approximately 15 ºC, acidity — with a pH of 7, and nitrate concentration of 20 mg/L.

Comparison of the results of fuzzy inference for the considered options for the values of the input variables (poor, average, good) determines the predicted state of pollution of the water body.

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