Assessment of the ecological state of a water body for biodiversity monitoring according to biological and hydrochemical indicators

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Abstract. The purpose of the work is to assess the ecological state of the reservoir for biodiversity monitoring. Biodiversity monitoring is the systematic and continuous observation and measurement of the diversity of life in a given area or ecosystem. It is carried out to assess changes in biodiversity, identify trends, and determine the effectiveness of management measures and conservation programs. Biodiversity monitoring is a key tool for understanding the state and changes in natural systems, and its results can be used to make decisions in the field of nature conservation and sustainable use of resources. Bioindication can be used for long-term environmental monitoring. Biological organisms can be collected and analyzed over a long period of time, which makes it possible to assess trends in ecosystem changes and their relationship to anthropogenic factors. This takes into account the complex nature of pollution, that is, not only the concentration of certain substances, but also their interaction, synergistic effects and other aspects.

1 Introduction

Biodiversity monitoring is the systematic process of observing and measuring the diversity of living organisms in a given area or ecosystem over time. It provides information on the status and changes in biodiversity, including species diversity, genetic diversity and ecosystem functionality. Monitoring allows assessing the current state of biodiversity in a particular area. This includes the study of species composition, species distribution, population structure and genetic diversity. The following main methods and tools are used to monitor biodiversity [1-3]:

Species Inventory: Collecting data on the presence and distribution of different species in a particular area. Includes the application of techniques such as field surveys, species identification, photography, sound recordings, and specimen collection.

Population monitoring: The study of the size, structure and dynamics of populations of a species. Includes periodic measurements, counts of individuals, marking and tracking of individuals, collection of data on survival, reproductive success and other factors that affect the population.

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Genetic Monitoring: The study of genetic diversity within populations and between populations. Includes analysis of genetic markers such as DNA to assess genetic structure, potential for adaptation and risk of loss of genetic diversity.

Ecosystem Monitoring: The study of the health and functioning of an ecosystem, including factors such as landscape structure, vegetation density, water parameters and soil quality. Remote sensing methods, drone photography, soil and water sampling, and other techniques are being used.

Tracking systems: Developing systematic monitoring programs that involve tracking specific species, regions or ecosystems over time. An important component is the standardization of methods for collecting data, analyzing and interpreting results.

Environmental monitoring is the systematic assessment and observation of the state of the environment in order to determine its changes, analyze the impact of human activities and take appropriate measures for its protection and sustainable use. Environmental monitoring subsystems include [4-5]:

Meteorological Monitoring.

Hydrological Monitoring.This includes the measurement of water level, flow, temperature, chemistry and contaminants.

Soil monitoring: carried out to assess soil fertility, nutrient content, pollutants and land use. This makes it possible to determine the effectiveness of agricultural practices and take measures to prevent soil erosion and degradation.

Biological monitoring: This is the study of the diversity and distribution of living organisms in ecosystems. It includes monitoring of flora and fauna, as well as assessment of the state of ecosystems and species diversity.

Air monitoring: carried out to study air quality, pollutant content and emissions. This includes analysis of emissions from industry, vehicles and other sources of air pollution.

Noise monitoring: carried out to measure noise levels caused by various sources such as traffic, industry and construction. This helps to determine the impact of noise on the environment and health.

The use of bioindication methods in environmental monitoring has advantages in cases where the measurement of direct factors of anthropogenic pressure on biocenoses is a difficult or inconvenient task. Biocenoses are exposed to various pollutants and anthropogenic pressure factors, which can have synergistic effects and interactions. Measuring all of these factors directly can be difficult and costly. Bioindication makes it possible to obtain a comprehensive assessment of the impact based on the response of living organisms to these factors. Biological organisms used in bioindication interact with their environment at various levels of organization (from cells to populations and communities). Their reactions and changes in biological parameters may reflect the combined effect of all factors, including those that are difficult to measure directly. Thus, bioindication provides integral information about the state of the ecosystem. Living organisms are active and sensitive reactants to changes in the environment. They may show responses to changes that may not be noticeable with other measurement methods. Bioindication makes it possible to detect early disturbances in biotic communities that may indicate problems in the ecosystem [6-7].

There are several measures of biodiversity that help assess the diversity of life in a particular area or ecosystem. Some of the most common measures of biodiversity include [8-9]:

Species Richness: This is simply the total number of different species present in a particular area or ecosystem.

Species Diversity: Evaluates not only the number of species, but also their uniformity in distribution. High species diversity indicates the uniformity of the representation of different species.

Genetic Diversity: Refers to the diversity of genetic characteristics within species. High genetic diversity is important for the adaptation of species to changing conditions and the sustainability of populations.

Ecosystem Functioning: Associated with the variety of ecological roles and functions performed by different species in an ecosystem. The diversity of functions such as dust pollination, decomposition of organic matter and regulation of biological cycles is an important aspect of biodiversity.

These are just some of the measures of biodiversity, and in reality various combinations of these and other indicators are used to fully capture the biodiversity in a given area or ecosystem [10-12].

An important aspect is also the ability of bioindication to diagnose early disturbances in the most sensitive components of biotic communities. This means that the biological organisms used as indicators must be sensitive enough to changes in the environment to detect disturbances even at early stages, when they may not yet be visible using other methods.

The development of such methods and criteria requires the joint work of ecologists, biologists, chemists and other specialists. They should take into account the characteristics of specific ecosystems, species of organisms, as well as the properties of pollutants and their impact on biological systems.

The purpose of developing such methods is to create reliable tools for monitoring and assessing the state of the environment, which in turn allows you to make informed decisions on the protection and management of ecosystems.

Thus, bioindication provides valuable data on the state of the environment, especially in cases where direct measurement of anthropogenic factors is difficult or inconvenient.

Some conclusions may be subjective or based on insufficiently reliable data. This may be due to the following factors:

Subjectivity of assessment: Some assessments in bioindication may be visual and subjective. In some cases, especially when using qualitative indicators, the rating "good/bad" or "clean/dirty" can be made based on the subjective opinion and experience of the researcher, rather than on the basis of quantitative data.

Insufficiently Reliable Indices: In some cases, indices or indicators may be used that do not have sufficient scientific validity or do not take into account all the necessary aspects. Some indices may be applied based on simplified models or assumptions, which may lead to unreliable results.

Lack of Quantitative Data: In some cases, there is no quantitative data that allows a more accurate and objective assessment of the state of the environment. In such cases, estimates may be based on qualitative observations or relative comparisons, which may reduce the validity of the conclusions [10–11].

To overcome these problems and increase the reliability of assessments in bioindication, it is important:

Use quantitative data and reliable methods of analysis where possible.

Use standardized protocols and indexes based on scientific research and sound methodologies.

Involve experts and specialists with experience in bioindication for a more objective assessment and interpretation of the results.

Take into account various factors and integrate data from different sources to obtain comprehensive and reliable information.

In general, continuous improvement of methods and the application of a scientific approach will help reduce subjectivity and increase the reliability of assessments in bioindication.

2 Materials and methods

There are two traditional approaches to the analysis of biodiversity and the degree of dominance in different situations [5-7]:

Alpha Diversity: This approach focuses on the study of species diversity within a particular area or ecosystem. It estimates the number and diversity of species present in a given area. Measures of alpha biodiversity include species richness (number of species) and species diversity (evenness in the distribution of species).

Beta Diversity: This approach aims to study the variability in species composition between different areas or ecosystems. It allows comparison and evaluation of similarities or differences in species composition between different locations. Measures of beta biodiversity include similarity coefficients (eg Jaccard coefficient or Sørensen coefficient) and multivariate analysis methods (eg principal coordinate space analysis or cluster analysis).

A combined analysis of alpha and beta biodiversity can help to fully understand the overall diversity of species in a given area and their spatial distribution. These approaches are widely used in environmental research, conservation planning, monitoring of changes in biodiversity and decision-making in the field of natural resource management.

Building a fuzzy Mamdani model for monitoring the biodiversity of water resources involves the use of fuzzy logic to describe and analyze various variables and conditions associated with the biodiversity of aquatic ecosystems. The Mamdani fuzzy model consists of three main components: a set of fuzzy rules, a knowledge base, and an inference mechanism [13-17].

Set of Fuzzy Rules: Fuzzy rules are formulated that describe the relationships between input variables (eg water quality, pollution levels, presence of aquatic organisms, etc.) and output variable (biodiversity of water resources). Fuzzy rules are based on expert knowledge and experience in the field of biodiversity and aquatic ecosystems.

Knowledge base: The knowledge base contains linguistic variables and their fuzzy sets, which are defined using linguistic terms (eg "low", "medium", "high"). For each variable, its range of values and the corresponding fuzzy sets are specified, which describe the degree of membership of each value in each fuzzy set.

Inference engine: The inference engine uses fuzzy rules and a knowledge base to draw inferences and make decisions. Input values of variables are reduced to fuzzy values based on their degree of belonging to fuzzy sets. Then, using fuzzy logic and aggregation of rules, the output value of the variable (biodiversity of water resources) is determined. This value can be interpreted and used to monitor and make decisions about the biodiversity of aquatic ecosystems.

It is important to note that the construction of the Mamdani fuzzy model requires the definition of linguistic variables, the formulation of fuzzy rules, and the adjustment of model parameters. To achieve good results, it is necessary to use expertise in the field of water biodiversity.

Building a fuzzy Mamdani model for monitoring the biodiversity of water resources includes the following steps [17-20]:

Definition of input variables: Identification of the main parameters or indicators that will be used to assess the biodiversity of water resources. For example, this could be water quality, pollution levels, vegetation cover, or other indicators that reflect the state of the aquatic ecosystem.

Linguistic Description of Variables: Define the linguistic variables and their values that will be used to describe the state of each input measure. For example, the terms "good", "average", and "poor" can be used for water quality.

Definition of the output variable: Define an output variable that will reflect the level of biodiversity in the water resources. For example, it could be "level of biodiversity" with the terms "low", "medium" and "high".

Defining Linguistic Rules: Create a set of linguistic rules that define the relationship between the input variables and the output variable. For example, a rule could be phrased as "If water quality is good AND pollution is low, then biodiversity is high."

The relationship between the inputs and output of the system is given as a set of the following linguistic rules:

$$\begin{aligned} &L_1 \equiv \text{IF} \quad (x_1 = T_1^1 \,\&\, x_2 = T_1^2 \&\ldots\& \, x_n = T_1^n), \\ &\text{Then } y = P_1, \text{ Else:} \\ &L_2 \equiv \text{IF} \quad (x_1 = T_2^1 \,\&\, x_2 = T_1^2 \&\ldots\& \, x_n = T_2^n), \\ &\text{Then } y = P_2, \text{ Else:} \\ &L_s \equiv \text{IF} \ (x_1 = T_s^1 \,\&\, x_2 = T_s^2 \&\ldots\& \, x_n = T_s^n), \\ &\text{Then } y = P_s \end{aligned} \tag{1}$$

Where $T_i^j \ (j = \overline{1,n})$ and P_i - terms from the term-set of linguistic variables x_i and y used in the i-th linguistic rule.

The elements of the (n+1)-dimensional matrix $R(x_1, x_2,..., x_n, y)$ of the relation induced by the rules (1) are determined according to the following rule:

$$r^i_{K_1K_2\ldots K_n} = \max\min\left\{\mu_{T_i^1}\left(u^1_{R_1}\right),\ldots,\mu_{T_i^n}\left(u^n_{R_n}\right),\mu_{P_i}(v_1)\right\} \tag{2}$$

Where $\mu_{T_i^j}\left(u^j_{R_j}\right)$ and $\mu(v_1)$ - membership functions of terms used in rules. Using the ratio obtained for an arbitrary input $T = \left(T_0^1, T_0^2,..., T_0^n\right)$ characterized by membership functions $\mu_{T_0^j}\left(u^j_{R_j}\right)$, we obtain an estimate for the output:

$$P_0 = T_0^1 \otimes T_0^2 \otimes \ldots \otimes T_0^n \otimes R(x_1, x_2,..., x_n, y) \tag{3}$$

Defining Membership Functions: For each linguistic variable, define membership functions that describe the degree to which each value belongs to that variable. Membership functions can be triangular, trapezoidal, or other shapes.

The values of the fuzzy output membership function will be determined as follows:

$$\mu_{P_0}(v_1) = \max_K \min\left\{\mu_{T^1}\left(u^1_{R_1}\right),\ldots,\mu_{T^n}\left(u^n_{R_n}\right), r^1_{K_1K_2\ldots K_n}\right\} \tag{4}$$

Where $K = (K_1K_2 \ldots K_n)$.

Using this expression to determine the output parameter is difficult, because the number of elements of the (n + 1)-dimensional relation matrix $R = (x_1, x_2,..., x_n, y)$ is

$N = m \times \prod_{i=1}^{n} K_i$, where K_i is the number of discrete values of the base variable (i-th linguistic parameter, and m is the number of discrete values of the base output variable. The need to store such a large number of values in the computer memory and execute on them maximin operations presents significant computational difficulties.

Building inference rules: Define methods for combining linguistic variables and applying rules to obtain the value of an output variable. For example, you can use the Mamdani fuzzy logic method for aggregation and inference.

It is known that formula (3) can be replaced by the equivalent formula:

$$P_0 = \bigcup_{i=1}^{s} \left\{ \left[\bigcap_{j=1}^{n} \left(T_1^j \otimes T_0^j \right) \right] \cap P_i \right\} \tag{5}$$

Which in the language of membership functions will look like this:

$$\begin{aligned} &\mu_{P_0}(v_i) = \max_i \min\{\min[\max_{k_1} \min(\mu_{T_0^1}(u_{k_1}^1), \mu_{T_1^1}(u_{k_1}^1)), ..., \\ &\max_{k_n} \min(\mu_{T_0^n}(u_{k_n}^n), \mu_{T_1^n}(u_{k_n}^n))], \mu_{P_i}(v_i)\}. \end{aligned} \tag{6}$$

Defuzzification: Convert fuzzy output to a specific numerical value for an output variable using the defuzzification method. For example, it could be center of gravity (center of mass) or another method that converts fuzzy output to a single numeric value.

3 Results and Discussion

A fuzzy logical Mamdani model for assessing the ecological state of a reservoir was built to monitor biodiversity in terms of biological and hydrochemical indicators [21–25].

If:

$$\begin{aligned} &\left(x_1 = \frac{\sum_{j=1}^{q} \mu(a_{11}^j) a_{11}^j}{\sum_{j=1}^{q} \mu(a_{11}^j)} \wedge x_2 = \frac{\sum_{j=1}^{q} \mu(a_{12}^j) a_{12}^j}{\sum_{j=1}^{q} \mu(a_{12}^j)} \wedge ... \wedge x_8 = \frac{\sum_{j=1}^{q} \mu(a_{18}^j) a_{18}^j}{\sum_{j=1}^{q} \mu(a_{18}^j)} \right) \vee \\ &\vee \left(x_1 = \frac{\sum_{j=1}^{q} \mu(a_{21}^j) a_{21}^j}{\sum_{j=1}^{q} \mu(a_{21}^j)} \wedge x_2 = \frac{\sum_{j=1}^{q} \mu(a_{22}^j) a_{22}^j}{\sum_{j=1}^{q} \mu(a_{22}^j)} \wedge ... \wedge x_8 = \frac{\sum_{j=1}^{q} \mu(a_{28}^j) a_{28}^j}{\sum_{j=1}^{q} \mu(a_{28}^j)} \right) \end{aligned} \tag{7}$$

Then:

y = ecological well-being.

If:

$$\left(x_1=\frac{\sum_{j=1}^{q}\mu(a_{31}^{j})a_{31}^{j}}{\sum_{j=1}^{q}\mu(a_{31}^{j})}\wedge x_2=\frac{\sum_{j=1}^{q}\mu(a_{32}^{j})a_{32}^{j}}{\sum_{j=1}^{q}\mu(a_{32}^{j})}\wedge\ldots\wedge x_8=\frac{\sum_{j=1}^{q}\mu(a_{38}^{j})a_{38}^{j}}{\sum_{j=1}^{q}\mu(a_{38}^{j})}\right)\vee$$
$$\vee\left(x_1=\frac{\sum_{j=1}^{q}\mu(a_{41}^{j})a_{41}^{j}}{\sum_{j=1}^{q}\mu(a_{41}^{j})}\wedge x_2=\frac{\sum_{j=1}^{q}\mu(a_{42}^{j})a_{42}^{j}}{\sum_{j=1}^{q}\mu(a_{42}^{j})}\wedge\ldots\wedge x_8=\frac{\sum_{j=1}^{q}\mu(a_{48}^{j})a_{48}^{j}}{\sum_{j=1}^{q}\mu(a_{48}^{j})}\right) \quad (8)$$

Then:
y = ecological crisis.
If:

$$\left(x_1=\frac{\sum_{j=1}^{q}\mu(a_{51}^{j})a_{51}^{j}}{\sum_{j=1}^{q}\mu(a_{51}^{j})}\wedge x_2=\frac{\sum_{j=1}^{q}\mu(a_{52}^{j})a_{52}^{j}}{\sum_{j=1}^{q}\mu(a_{52}^{j})}\wedge\ldots\wedge x_8=\frac{\sum_{j=1}^{q}\mu(a_{58}^{j})a_{58}^{j}}{\sum_{j=1}^{q}\mu(a_{58}^{j})}\right)\vee$$
$$\vee\left(x_1=\frac{\sum_{j=1}^{q}\mu(a_{61}^{j})a_{61}^{j}}{\sum_{j=1}^{q}\mu(a_{61}^{j})}\wedge x_2=\frac{\sum_{j=1}^{q}\mu(a_{62}^{j})a_{62}^{j}}{\sum_{j=1}^{q}\mu(a_{62}^{j})}\wedge\ldots\wedge x_8=\frac{\sum_{j=1}^{q}\mu(a_{66}^{j})a_{68}^{j}}{\sum_{j=1}^{q}\mu(a_{68}^{j})}\right) \quad (9)$$

Then
y = ecological disaster.

Here: x_1 - Chemical oxygen demand (COD); x_2 - Ammonia nitrogen *N-NH₄*; x_3 - Nitrate nitrogen *N-NO₃*; x_4 - Nitrate nitrogen *N-NO₂*; x_5 - Phosphates *P-PO₄*; x_6 - Biomass, g/m^2; x_7 - Number of species; x_8 - Shannon diversity index, bit/spec.

The statement "Chemical oxygen demand is low" can be represented as follows:

$$\mu(a_{11}^{j})=\left[1+\frac{(a_{11}-43{,}7)^2}{9}\right]^{-1}. \quad (10)$$

The statement "N-NH$_4$ ammonium nitrogen medium" can be represented as follows:

$$\mu(a_{12}^{j})=\left[1+1428(a_{12}-0{,}23)^2\right]^{-1}. \quad (11)$$

The statement "nitrogen nitrate N-NO$_3$ high" can be represented as follows:

$$\mu(a_{13}^{j})=\left[1+1112(a_{13}-0{,}27)^2\right]^{-1}. \quad (12)$$

The statement "nitrogen nitrate N-NO$_2$ high" can be represented as follows:

$$\mu(a_{14}^{j}) = \left[1 + 15000(a_{14} - 0{,}002)^2\right]^{-1}. \tag{13}$$

The saying "P-PO_4 phosphates high" can be represented as follows:

$$\mu(a_{16}^{j}) = \left[1 + 15000(a_{16} - 0{,}023)^2\right]^{-1}. \tag{14}$$

The proposition "Number of species is average" can be represented as follows:

$$\mu(a_{17}^{j}) = \left[1 + \frac{(a_{17} - 11)^2}{2}\right]^{-1}. \tag{15}$$

The statement "Shannon Diversity Index, bps low" can be expressed as follows:

$$\mu(a_{18}^{j}) = \left[1 + 25(a_{18} - 1{,}77)^2\right]^{-1}. \tag{16}$$

Monitoring of bioindication of water bodies based on hydrobiological indicators can be used to assess water quality and determine the degree of pollution of aquatic ecosystems based on the Mamdani fuzzy model.

If:

$$\begin{aligned} &\left(x_1 = B \wedge x_2 C \wedge \ldots \wedge x_8 = B\right) \vee \\ &\vee \left(x_1 = B \wedge x_2 = H \wedge \ldots \wedge x_8 = C\right) \end{aligned} \tag{17}$$

Then

y = ecological well-being.

$$\begin{aligned} &\left(x_1 = C \wedge x_2 = C \wedge \ldots \wedge x_8 = H\right) \vee \\ &\vee \left(x_1 = C \wedge x_2 = H \wedge \ldots \wedge x_8 = C\right) \end{aligned} \tag{18}$$

Then

y = ecological disaster.

If:

$$\begin{aligned} &\left(x_1 = H \wedge x_2 = H \wedge \ldots \wedge x_8 = H\right) \vee \\ &\vee \left(x_1 = H \wedge x_2 = C \wedge \ldots \wedge x_8 = H\right) \end{aligned} \tag{19}$$

Then

y = ecological disaster.

If the water quality is considered poor for one or more of the indicators, the system displays "Water quality is poor".

If all indicators are within the normal range, the system displays "Water quality is good".

4 Conclusion

Monitoring allows you to identify trends and changes in biodiversity over time. This helps identify threats and problems such as population declines, habitat loss and the introduction of invasive species. Monitoring also makes it possible to assess the effectiveness of the protection and conservation measures taken. It helps to determine how successful management measures and programs are in supporting biodiversity. Information received from monitoring is used for decision-making and planning of measures for biodiversity protection. It helps to define priorities and directions of action for the conservation and restoration of biodiversity. It provides valuable information for scientific research, policy development and conservation practice.

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