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INTEGRAL ASSESSMENT OF THE SPRING WATER QUALITY WITH THE USE OF FUZZY LOGIC TOOLKIT

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Abstract. *Water, as an important strategic resource, ensures the livelihood of people and the economic development of society. The effective use of water resources is one of the main goals of sustainable development. The possibility of using a particular water body depends on the degree of water pollution. The drinking water quality is characterized by the content of a significant number of chemical elements, while not only instrumental and analytical methods are used to determine certain criteria, but also methods in which parameters are assessed by experts, in particular organoleptic indicators. Accordingly, considering the use of the survey for expert assessment, the integral indicator of the drinking spring water quality is determined using the fuzzy logic toolkit. For the integral assessment of the drinking water quality, indicators are divided into three groups: organoleptic indicators of the water quality, general physical and chemical indicators of the water quality and quality indicators of the content of inorganic chemical elements. A universal set and corresponding terms are determined for the factors of each group as linguistic variables. For each linguistic variable, fuzzy sets are determined, a knowledge base is formed, and fuzzy logic equations are constructed. The results of the work are checked with the help of the Matlab Fuzzy Logic Toolbox package by obtaining the corresponding models. The models developed by the fuzzy logic toolkit will make it possible to assess the possibility of using drinking water sources and make informed decisions when using them for industrial and domestic needs.*

Keywords: water quality, chemical parameters, fuzzy logic, linguistic variable, integral assessment

INTEGRALNA OCENA JAKOŚCI WODY ŹRÓDLANEJ Z WYKORZYSTANIEM ZESTAWU NARZĘDZI LOGIKI ROZMYTEJ

Streszczenie. *Woda, jako kluczowy zasób strategiczny, stanowi podstawę życia oraz warunkuje rozwój społeczno-gospodarczy. Racjonalne gospodarowanie zasobami wodnymi jest jednym z głównych celów zrównoważonego rozwoju. Sposób wykorzystania określonego zbiornika wodnego uzależniony jest od stopnia jego zanieczyszczenia. Jakość wody przeznaczonej do spożycia zależy od zawartości licznych pierwiastków chemicznych, których obecność wpływa na jej właściwości fizykochemiczne i organoleptyczne. Do oceny jakości wody stosuje się nie tylko metody instrumentalne i analityczne, lecz także ekspertyzy specjalistów, w szczególności w zakresie wskaźników organoleptycznych. W związku z tym, przy wykorzystaniu ankiety eksperckiej oraz narzędzi logiki rozmytej, opracowano integralny wskaźnik jakości wody źródlanej przeznaczonej do spożycia. Na potrzeby zintegrowanej oceny jakości wskaźniki podzielono na trzy grupy: organoleptyczne, ogólne fizykochemiczne oraz dotyczące zawartości nieorganicznych pierwiastków chemicznych. Dla czynników każdej grupy określono zbiór uniwersalny i odpowiadające mu terminy jako zmienne językowe. Następnie dla każdej zmiennej językowej utworzono zbiory rozmyte, opracowano bazę wiedzy oraz skonstruowano równania logiki rozmytej. Wyniki badań zweryfikowano w środowisku MATLAB Fuzzy Logic Toolbox poprzez opracowanie odpowiednich modeli. Modele te, zbudowane z wykorzystaniem zasad logiki rozmytej, umożliwiają kompleksową ocenę przydatności źródeł wody pitnej oraz wspierają podejmowanie świadomych decyzji dotyczących ich wykorzystania w celach przemysłowych i gospodarczych.*

Słowa kluczowe: jakość wody, parametry chemiczne, logika rozmyta, zmienna lingwistyczna, ocena integralna

Introduction

The issue of water quality and safety is important in view of the need to provide quality water both for economic and domestic purposes and for industrial use. If one talks about modern challenges for humanity, then the issue of providing the population with high-quality drinking water is relevant and urgent. Water plays a huge role in human life. The main requirements for the drinking water quality are cleanliness, transparency, absence of unpleasant taste and odor, presence of mineral components necessary for humans in optimal concentration. Physiologically high-quality water is a liquid whose physical and chemical characteristics meet the standards of the International Health Organization. Only if the characteristics of drinking water match these standards, it can be considered suitable for use [5, 26]. In December 2020, the EU adopted amendments to the Drinking Water Directive [3]. The Directive entered into force in January 2021, according to which all EU states must transpose the Directive's requirements into national legislation and implement its provisions by January 12, 2023. Taking into account the new changes will allow additional protection of people's health due to updated water quality standards, the fight against problematic pollutants.

To determine the drinking water quality, it is assessed according to many parameters (hardness, mineralization, pH, microbiological condition, etc.). An important indicator is the MPC — the maximum permissible concentration of a certain substance. For each substance, its own MPC value is determined, and if it exceeds the standard value, then the water is harmful to human health. The presence of pollutants in water can cause diseases of the teeth, digestive organs and excretory systems, etc. Non-compliance of water with sanitary requirements can cause bacterial, viral, as well as diseases associated with water chemical pollution [5]. It is believed that the increased hardness of drinking water is one of the reasons for the development of urolithiasis. The increased content of chlorides in water can contribute to the development of the circulatory system diseases, neoplasms of the genitourinary organs, and the increased content of chlorides and sulfates can cause neoplasms of the esophagus and stomach. Ferrum excess disrupts the process of hematopoiesis.

Most of the water bodies that are used as drinking water supply sources are surface, and they constantly suffer from anthropogenic stress. As a result, the quality of surface water in water bodies does not meet the requirements of sanitary legislation, and as it is known the drinking water quality directly depends on the water quality in the drinking water supply source. The issue of providing high-quality drinking water becomes especially urgent in the conditions of martial law and the country recovery in order to prevent a number of infectious diseases and diseases associated with water chemical pollution. The situation is complicated not only by the influence of man-made and anthropogenic factors, but also by prolonged military actions on a large territory of our country. Therefore, the drinking water quality is regulated according to safety and quality indicators in the conditions of martial law. According to the current standards: State Sanitary Standards and Regulations "Hygienic Requirements for Drinking Water Intended for Human Consumption" [21], State Sanitary Standards and Regulations "Drinking Water Quality Safety Indicators and Specific Quality Indicators in Martial Law and Other Emergency" [20], drinking water should be safe in epidemiological and radiation terms, harmless in chemical composition and have favourable organoleptic properties.

Most water bodies used as sources of drinking water are surface waters, and they are constantly exposed to anthropogenic pressure. Analysis of the results of environmental monitoring of surface waters [8] shows seasonal fluctuations in pollution levels. Surface waters are classified as "moderately polluted" and "slightly polluted" according to [11]. This classification is general and does not contain clear criteria for characterizing the quality of surface waters.

A comprehensive assessment of water quality is necessary to prevent the negative impact of using polluted water. To do this, it is necessary to group various water quality parameters with different units of measurement into a single integrated indicator, which requires the construction of appropriate information and mathematical structures.

1. Analysis of latest researches and publications

A number of scientists are currently studying the quality of drinking water. The quality of water is determined by a number of indicators, the maximum permissible values of which are set by the relevant regulatory indicators. In work [10] comprehensive assessment of drinking water quality is based on the use of ranking of quality indicators and control points of an extensive water supply network. The quality indicators are differentiated by the hazardousness and hazard classes of pollutants using cumulative coefficients and standardization relative to the controlled values of the indicators – as a rule, maximum permissible concentrations. As an important tool for assessing the environmental safety of drinking water, the effectiveness of using the methodology for calculating environmental potential risk has been proven. This approach makes it possible to take into account the possible negative impact of pollution on the human body, which can cause diseases. In paper [16, 17] present a water quality monitoring system that will consist of various sensors measuring the quality of the source water, a microcontroller to process the collected data, and various communication systems to connect the node to the server. Various monitoring systems and the Internet of Things (IoT) are involved in the system to access the collected data from remote locations. The work [15] presents the results of the calculation of the integral assessment of the drinking city tap water quality according to indicators of chemical harmlessness using the thresholdless model method, which is based on probable assessments of the development of unfavourable effects in the human body. This approach involves assessing the potential risk to human health, taking into account the long-term negative impact of hazardous compounds contained in drinking tap water on the human body. Carcinogenic and non-carcinogenic risks, as well as an integral indicator of the drinking water danger, are calculated taking into account a significant number of pollutants. The issue of environmental monitoring is addressed in paper [25], which proposes an ecological monitoring system for nature reserves. This system can be fully automated, elevating environmental monitoring to a fundamentally new level by enabling continuous surveillance of a given area along with automatic data storage and analysis.

Study [24] focuses on assessing the environmental risks of ammonium in surface waters affected by a nuclear power plant. The authors developed predictive models using fuzzy logic to classify water quality and predict ammonium toxicity. The predictive models presented in [24] need to be expanded to take into account other surface water pollutants. The work [23] proposes a modified method for assessing river water quality using fuzzy logic models. The limitations of these methods are the use of monitoring data on water pollution in the river.

The use of a fuzzy expert system approach to predict water production performance at a desalination plant [19] helps to make informed decisions about monitoring and controlling distilled water production.

One example of the application of fuzzy logic to assess water quality is a study that analyzes the suitability of groundwater for irrigation in Tamil Nadu. This study demonstrates how fuzzy logic effectively deals with uncertainty and ambiguity in water quality data, providing more accurate classifications than traditional methods [12]. The water quality assessment models presented refer to specific components of the overall water quality assessment.

Experimental data on chemical safety indicators of water sources in the Peremyshliany district, together with their monitoring results [9, 14], were employed to validate the integrated water quality assessment model.

It is clear that monitoring and statistical analysis remains indispensable for precise trend analysis. The distinctive feature of fuzzy logic, however, is that it does not replace statistics but complements it, especially when water needs to be assessed based on combined criteria, vague descriptions, and expert evaluations.

The aim of this study is to conduct an integrated assessment of spring water quality using fuzzy logic tools.

2. Methods

Fuzzy logic is known to use linguistic variables with rules that reproduce the principles of human reasoning and are close to spoken language. The term "a linguistic variable" was introduced in the work of Lotfi Zadeh [27], who laid the foundations of fuzzy logic. Fuzzy logic systems have an advantage in processing fuzzy input data. One of the main stages of fuzzy logic is the fuzzification operation, which transforms numerical data into a distribution corresponding to the terms of a linguistic variable. Each numerical value can be described by one or more terms, and the degree of its correspondence to a term is given as the degree of membership to a certain fuzzy set [13].

The assessment of quality indicators using fuzzy logic includes the following:

- the determination of a universal term-set of values and its corresponding linguistic terms of selected quality factors (linguistic variables);
- the construction of a matrix of pairwise comparisons for a set of linguistic terms of the corresponding interval of the universal set values and obtaining the membership functions for each of the matrix;
- the development of a fuzzy knowledge base using fuzzy logic statements of "if - then" type;
- the construction of fuzzy logic equations and membership functions that determine the connection between the membership functions of input and output data;
- the defuzzification of the fuzzy set, which is revealed in the calculation of the numerical indicator of the predicted quality, for example, by the principle of the center of gravity of a flat object [1, 2, 4, 27].

To test the knowledge base and construct a model of the influence of priority factors, a system for developing fuzzy control systems – Fuzzy Logic Toolbox system of the Matlab (version 2016a) technological calculation environment and Mamdani principle is used [6]. When modeling in the Matlab environment, we will apply the decomposition of each input variable into three terms with representation using symmetric Gaussian membership functions. It provides a smooth and continuous transition between membership functions.

The defuzzification operation according to the center of gravity principle for the stepwise determination of the water quality indicators is carried out according to the formula [7, 18, 19]:

$$Q = \frac{\sum_{i=1}^{m} u_i \cdot \mu(u_i)}{\sum_{i=1}^{m} \mu(u_i)} \quad (1)$$

where: Q – the final crisp value after defuzzification; u – output variable; $\mu(u_i)$ – degree of membership (between 0 and 1) of the value u_i.

Fuzzy logic is well-suited for computing an integral water quality indicator, as it effectively handles uncertainty and subjective assessments. Unlike data-driven methods, fuzzy systems require minimal datasets, making them applicable in contexts with limited or inconsistent information. They also enable the aggregation of heterogeneous water quality parameters, expressed in different units or scales, into a single, interpretable indicator.

3. Results and discussions

The spring water quality depends on organoleptic indicators, general physical and chemical indicators and indicators of the content of inorganic chemical elements. Accordingly, the spring water quality can be defined as:

$$Q = f\,(X, Y, Z) \quad (2)$$

where X is a linguistic variable that characterizes the value of organoleptic indicators; Y is a linguistic variable that characterizes the value of physical and chemical indicators; Z is a linguistic variable that characterizes the concentration content of inorganic chemical elements.

The linguistic variable that describes the organoleptic indicators is determined by the dependency:

$$X = f\,(x_1, x_2, x_3) \quad (3)$$

where x_1 is an odor indicator; x_2 is a color indicator; x_3 is a turbidity indicator.

The linguistic variable that describes physical and chemical indicators is determined by the dependency:

$$Y = f\,(y_1, y_2, y_3) \quad (4)$$

where y_1 is an acidity indicator; y_2 is a mineralization indicator; y_3 is a general hardness indicator.

The linguistic variable that a feature of the concentration chemical elements is determined by the dependency:

$$Z = f\,(z_1, z_2, z_3, z_4) \quad (5)$$

where z_1 is calcium content; z_2 is magnesium content; z_3 is iron content; z_4 is nitrate content.

Table 1. Linguistic variables of factors influence on the water quality

Factors	Variable	Universal set	Assessment terms
x_1	Odor, units	1–5	Odorless, noticeable, distinct
x_2	Coloration, degrees	0–70	Colorless, slightly colored, colored
x_3	Turbidity, units	0–7	Transparent, slightly turbid, turbid
y_1	Hydrogen indicator, pH	4–10	Acidic, neutral, alkaline
y_2	Total mineralization, mg/dm^3	10–2500	Weakly mineralized, permissible mineralization, strongly mineralized
y_3	Total hardness, mmol/dm^3	0–10	Soft, standard hardness, hard
z_1	Calcium content, mg/l	0–200	Safe, permissible, dangerous
z_2	Magnesium content, mg/l	0–100	Safe, permissible, dangerous
z_3	Total Iron, mg/l	0–0.2	Safe, dangerous
z_4	Nitrate content, mg/l	0–100	Safe, dangerous

The assessment of the values of linguistic variables is carried out using a system of qualitative concepts. Each of these concepts constitutes a corresponding fuzzy set, that is, some property, which is considered as a linguistic term.

The assessment terms for linguistic variables that determine water quality factors are presented in Table 1.

In accordance with the results of expert judgments and experimental studies, a scheme of logical formation of an integral assessment of water quality is formed (Fig. 1).

Let one form fuzzy sets of membership functions for the variable "Odor". According to the requirements and data of Table 1, the level of the drinking water odor is determined by the universal set: u_1 = 1 un.; u_2 = 2 un.; u_3 = 3 un.; u_4 = 4 un.; u_5 = 5 un. A set of fuzzy terms $T(x_1)$ = <*odorless, noticeable, distinct*> is used for the linguistic assessment of the factor.

Factor x_2 is water color. This quantitative factor is defined on the universal set $U(x_2)$ = [0; 70] degrees using a set of terms $T(x_2)$ = < *colorless, slightly colored, colored* >.

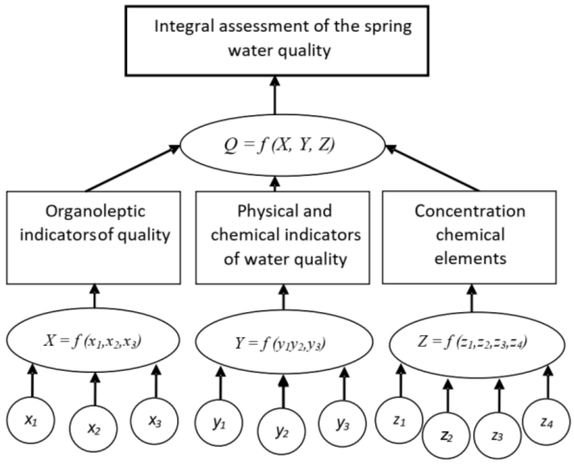

Fig. 1. The model of logical formation of an integral assessment of water quality

Factor x_3 "water turbidity" is defined on the universal set $U(x_3)$ = [0; 7] un. using a set of terms $T(x_3)$ = < *transparent, slightly turbid, turbid* >.

For the variables included in the group of general physical and chemical indicators of water quality, the following universal sets are defined:

- factor y_1 is water pH acidity $U(y_1)$ = [4; 10] un. using a set of terms <*acid, neutral, alkaline*>.
- factor y_2 is total mineralization $U(y_2)$ = [10; 2500] mg/dm^3 using a set of terms <*weakly mineralized, permissible mineralization, strongly mineralized* >.
- factor y_3 is water hardness $U(y_3)$ = [0; 10] mmol/dm^3 using the set of terms <*soft, standard hardness, hard* >.

For the variable z_1 "Calcium content", according to the requirements and data of Table 1, a universal set is defined: u_1 = 0 mg/l; u_2 = 50 mg/l; u_3 = 100 mg/l; u_4 = 150 mg/l; u_5 = 200 mg/l. A set of fuzzy terms $T(z_1)$ = <*safe, permissible, dangerous*> is used for the linguistic assessment of the factor.

For factor z_2 – magnesium content, a universal set is defined: u_1 = 0 mg/l; u_2 = 25 mg/l; u_3 = 50 mg/l; u_4 = 75 mg/l; u_5 = 100 mg/l. A set of fuzzy terms $T(z_2)$ = <*safe, permissible, dangerous*> is used for the linguistic assessment of the factor.

Factor z_3 – total Ferrum content is determined by the universal set $U(z_3)$ = [0; 0.2] mg/l using the set of terms <*safe, dangerous*>.

Factor z_4 is nitrate content. For this factor, the universal set $U(z_4)$ = [0; 100] mg/l is defined using the set of terms <*safe, dangerous*>.

In accordance with these terms, the membership functions of the linguistic variable "Odor" are obtained. The values of the variable in the form of fuzzy sets are as follows:

$$\text{Odorless} = \left(\frac{1}{1};\frac{0.89}{2};\frac{0.78}{3};\frac{0.22}{4};\frac{0.11}{5}\right)\ \text{un};$$

$$\text{Noticeable} = \left(\frac{0.11}{1};\frac{0.78}{2};\frac{1}{3};\frac{0.78}{4};\frac{0.11}{5}\right)\text{un};$$

$$\text{Distinct} = \left(\frac{0.11}{1};\frac{0.22}{2};\frac{0.78}{3};\frac{0.89}{4};\frac{1}{5}\right)\text{un.}$$

Let one form fuzzy sets of membership functions of the following linguistic variables. Thus, for example, the linguistic variable x_2 "water color" (coloration) on the universal set $U(x_2)$ = [0;17;35;52;70] degrees is identified with the following values of membership functions:

$$\text{Colorless} = \left(\frac{1}{0};\frac{0.88}{17};\frac{0.55}{35};\frac{0.33}{52};\frac{0.11}{70}\right)\text{degr};$$

$$\text{Slightly colored} = \left(\frac{0.11}{0};\frac{0.55}{17};\frac{1}{35};\frac{0.55}{52};\frac{0.11}{70}\right)\text{degr};$$

$$\text{Colored} = \left(\frac{0.11}{0};\frac{0.33}{17};\frac{0.55}{35};\frac{0.88}{52};\frac{1}{70}\right)\text{degr.}$$

For the linguistic variable x_3 "water turbidity" the following fuzzy set is formed:

Transparent = $\left(\frac{1}{0};\frac{0.89}{1.5};\frac{0.78}{3};\frac{0.22}{5};\frac{0.11}{7}\right)$ un;

Slightly turbid = $\left(\frac{0.11}{0};\frac{0.78}{1.5};\frac{1}{3};\frac{0.78}{5};\frac{0.11}{7}\right)$ un;

Turbid = $\left(\frac{0.11}{0};\frac{0.22}{1.5};\frac{0.78}{3};\frac{0.89}{5};\frac{1}{7}\right)$ un.

Let's form logical equations that are a reflection of the knowledge base on the fulfillment of the "If-Then" condition.

$$\begin{aligned}
&\mu^{low} = \mu^{dis}(x_1) \wedge \mu^{color}(x_2) \wedge \mu^{turb}(x_3) \vee \\
&\mu^{dis}(x_1) \wedge \mu^{sl.col}(x_2) \wedge \mu^{turb}(x_3); \\
&\mu^{med} = \mu^{nt}(x_1) \wedge \mu^{sl.col}(x_2) \wedge \mu^{sl.turb}(x_3) \vee \\
&\mu^{od}(x_1) \wedge \mu^{col.l}(x_2) \wedge \mu^{turb}(x_3); \\
&\mu^{high} = \mu^{odl}(x_1) \wedge \mu^{col.l}(x_2) \wedge \mu^{turb}(x_3) \vee \\
&\mu^{odl}(x_1) \wedge \mu^{sl.col}(x_2) \wedge \mu^{sl.turb}(x_3);
\end{aligned} \tag{6}$$

The notation $\wedge$ and $\vee$ are the operations for determining the minimum and maximum in logic equations.

When substituting the degrees of belonging to the system of fuzzy logical equations, one of the options for calculating the water quality is obtained:

$$\mu^{low} = 0.22 \wedge 0.33 \wedge 0.22 \vee 0.89 \wedge 0.33 \wedge 0.89 = 0.33$$
$$\mu^{med} = 0.78 \wedge 0.55 \wedge 0.78 \vee 0.78 \wedge 0.55 \wedge 0.89 = 0.55$$
$$\mu^{high} = 0.89 \wedge 0.88 \wedge 0.89 \vee 0.89 \wedge 0.88 \wedge 0.78 = 0.88$$

To calculate by formula (6), the conditional limits for the variable are determined, i.e. 1–100 un.

$$X = \frac{1 \cdot 0.33 + 50 \cdot 0.55 + 100 \cdot 0.88}{0.33 + 0.55 + 0.88} = 65.8un$$

The rest of the linguistic variables are studied in a similar way.

The following fuzzy set is formed for the linguistic variable y_1 "Hydrogen water indicator":

Acidic = $\left(\frac{1}{4};\frac{0.75}{6};\frac{0.5}{7};\frac{0.25}{8};\frac{0.125}{10}\right)$ un;

Neutral = $\left(\frac{0.125}{4};\frac{0.5}{6};\frac{1}{7};\frac{0.5}{8};\frac{0.125}{10}\right)$ un;

Alkaline = $\left(\frac{0.125}{4};\frac{0.25}{6};\frac{0.5}{7};\frac{0.75}{8};\frac{1}{10}\right)$ un.

For the linguistic variable y_2 "Total mineralization" the following fuzzy set is formed:

Weakly mineralized = $\left(\frac{1}{10};\frac{0.75}{625};\frac{0.5}{1250};\frac{0.25}{1875};\frac{0.125}{2500}\right)$ mg/dm^3;

Permissible mineralization =

$=\left(\frac{0.125}{10};\frac{0.5}{625};\frac{1}{1250};\frac{0.5}{1875};\frac{0.125}{2500}\right)$ mg/dm^3;

Strongly mineralized = $\left(\frac{0.125}{10};\frac{0.25}{625};\frac{0.5}{1250};\frac{0.75}{1875};\frac{1}{2500}\right)$ mg/dm^3.

The following fuzzy set is formed for the linguistic variable y_3 "water hardness":

Soft = $\left(\frac{1}{0};\frac{0.88}{2.5};\frac{0.55}{5};\frac{0.33}{7.5};\frac{0.11}{10}\right)$ mmol/dm^3;

Standard hardness = $\left(\frac{0.11}{0};\frac{0.55}{2.5};\frac{1}{5};\frac{0.55}{7.5};\frac{0.11}{10}\right)$ mmol/dm^3;

Hard = $\left(\frac{0.11}{0};\frac{0.33}{2.5};\frac{0.55}{5};\frac{0.88}{7.5};\frac{1}{10}\right)$ mmol/dm^3.

As in the previous case, we form logical equations that are a reflection of the knowledge base.

$$\begin{aligned}
&\mu^{low} = \mu^{ac}(y_1) \wedge \mu^{st.mnr}(y_2) \wedge \mu^{hard}(y_3) \vee \\
&\mu^{ac}(y_1) \wedge \mu^{p.mnr}(y_2) \wedge \mu^{hard}(y_3); \\
&\mu^{med} = \mu^{ac}(y_1) \wedge \mu^{p.mnr}(y_2) \wedge \mu^{st.hard}(y_3) \vee \\
&\mu^{al}(y_1) \wedge \mu^{p.mnr}(y_2) \wedge \mu^{soft}(y_3); \\
&\mu^{high} = \mu^{n}(y_1) \wedge \mu^{p.mnr}(y_2) \wedge \mu^{st.hard}(y_3) \vee \\
&\mu^{n}(y_1) \wedge \mu^{w.mnr}(y_2) \wedge \mu^{st.hard}(y_3).
\end{aligned} \tag{7}$$

$$\mu^{low} = 0.75 \wedge 0.75 \wedge 0.33 \vee 0.75 \wedge 0.5 \wedge 0.33 = 0.33$$
$$\mu^{med} = 0.75 \wedge 0.5 \wedge 0.88 \vee 0.25 \wedge 0.5 \wedge 0.88 = 0.5$$
$$\mu^{high} = 1.0 \wedge 0.5 \wedge 0.88 \vee 1.0 \wedge 0.75 \wedge 0.88 = 0.75$$

When substituting degrees of membership to a system of fuzzy logic equations, one of the options for calculating the quality based on physical and chemical indicators is obtained:

$$Y = \frac{1 \cdot 0.33 + 50 \cdot 0.5 + 100 \cdot 0.75}{0.33 + 0.5 + 0.75} = 63.5un$$

For the linguistic variable z_1 "calcium content" the following fuzzy set is formed:

Safe = $\left(\frac{1}{0};\frac{0.85}{50};\frac{0.6}{100};\frac{0.25}{150};\frac{0.11}{200}\right)$ mg/l;

Permissible = $\left(\frac{0.11}{0};\frac{0.6}{50};\frac{1}{100};\frac{0.6}{150};\frac{0.11}{200}\right)$ mg/l;

Dangerous = $\left(\frac{0.11}{0};\frac{0.25}{50};\frac{0.6}{100};\frac{0.85}{150};\frac{1}{200}\right)$ mg/l.

For the linguistic variable z_2 "Magnesium content" the following fuzzy set is formed:

Safe $\left(\frac{1}{0};\frac{0.88}{25};\frac{0.55}{50};\frac{0.33}{75};\frac{0.11}{100}\right)$ mg/l;

Permissible = $\left(\frac{0.11}{0};\frac{0.88}{25};\frac{1}{50};\frac{0.33}{75};\frac{0.11}{100}\right)$ mg/l;

Dangerous = $\left(\frac{0.11}{0};\frac{0.33}{25};\frac{0.77}{50};\frac{0.88}{75};\frac{1}{100}\right)$ mg/l.

For the linguistic variable z_3 "total Iron" the following fuzzy set is formed:

Safe = $\left(\frac{1}{0};\frac{0.75}{0.5};\frac{0.5}{1};\frac{0.25}{1.5};\frac{0.11}{2}\right)$ mg/l;

Dangerous = $\left(\frac{0.11}{0};\frac{0.25}{0.5};\frac{0.5}{1};\frac{0.75}{1.5};\frac{1}{2}\right)$ mg/l.

For the linguistic variable z_4 "nitrate content" the following fuzzy set is formed:

Safe = $\left(\frac{1}{0};\frac{0.89}{25};\frac{0.78}{50};\frac{0.22}{75};\frac{0.11}{100}\right)$ mg/l;

Dangerous = $\left(\frac{0.11}{0};\frac{0.22}{25};\frac{0.78}{50};\frac{0.89}{75};\frac{1}{100}\right)$ mg/l.

$$\begin{aligned}
&\mu^{low} = \mu^{ac}(z_1) \wedge \mu^{st.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4) \vee \\
&\mu^{ac}(z_1) \wedge \mu^{p.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4); \\
&\mu^{med} = \mu^{ac}(z_1) \wedge \mu^{st.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4) \vee \\
&\mu^{ac}(z_1) \wedge \mu^{p.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4); \\
&\mu^{high} = \mu^{ac}(z_1) \wedge \mu^{st.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4) \vee \\
&\mu^{ac}(z_1) \wedge \mu^{p.mnr}(z_2) \wedge \mu^{hard}(z_3) \wedge \mu^{hard}(z_4);
\end{aligned} \tag{8}$$

When substituting degrees of membership to a system of fuzzy logic equations, one of the options for calculating the quality based on the content of chemical inorganic elements is obtained:

$$\mu^{low} = 0.25 \wedge 0.33 \wedge 0.75 \wedge 0.89 \vee$$
$$0.25 \wedge 0.88 \wedge 0.75 \wedge 0.89 = 0.25$$
$$\mu^{med} = 0.6 \wedge 0.88 \wedge 0.75 \wedge 0.89 \vee$$
$$0.85 \wedge 0.6 \wedge 0.75 \wedge 0.89 = 0.6$$
$$\mu^{high} = 0.85 \wedge 0.88 \wedge 0.75 \wedge 0.89 \vee$$
$$0.6 \wedge 0.88 \wedge 0.75 \wedge 0.89 = 0.75$$
$$Z = \frac{1 \cdot 0.25 + 50 \cdot 0.6 + 100 \cdot 0.75}{0.25 + 0.6 + 0.75} = 65.78un$$

For the linguistic variable Q "Spring water quality" the function $Q = f(X, Y, Z)$ is considered, the arguments of which are linguistic variables: X is "the value of organoleptic indicators"; Y is "the value of physical and chemical indicators"; Z is "the concentration content of inorganic chemical elements". The total effect of linguistic variables as identifiers of water quality groups is obtained by means of fuzzy sets, for which the corresponding term-set of values is set. The analyzed linguistic variables are set on the universal set Ui = [1;25;50;75;100] % by linguistic terms Ti = <*low*, *medium*, *high*>.

The generalized output knowledge base of the influence of indicators groups on the water quality will take the form:

If (X = *low*) or (X = *medium*) or (X = *high*) or (Y = *low*) or (Y = *medium*) or (Y = *high*) or (Z = *low*) or (Z = *medium*) or (Z= *high*), Then (Q = *low*) or (Q = *medium*) or (Q = *high*)

When substituting the degrees of membership to a system of fuzzy logic equations, the integral indicator of the drinking spring water quality is calculated:

$$Q = \frac{65.8 \cdot 0.33 + 63.5 \cdot 0.55 + 65.78 \cdot 0.88}{0.33 + 0.55 + 0.88} = 52.9un$$

Therefore, having performed the defuzzification operation, a quantitative parameter of the water quality is obtained.

Figure 2 presents the developed models of the influence of factors on water quality, obtained by processing membership functions of linguistic variables.

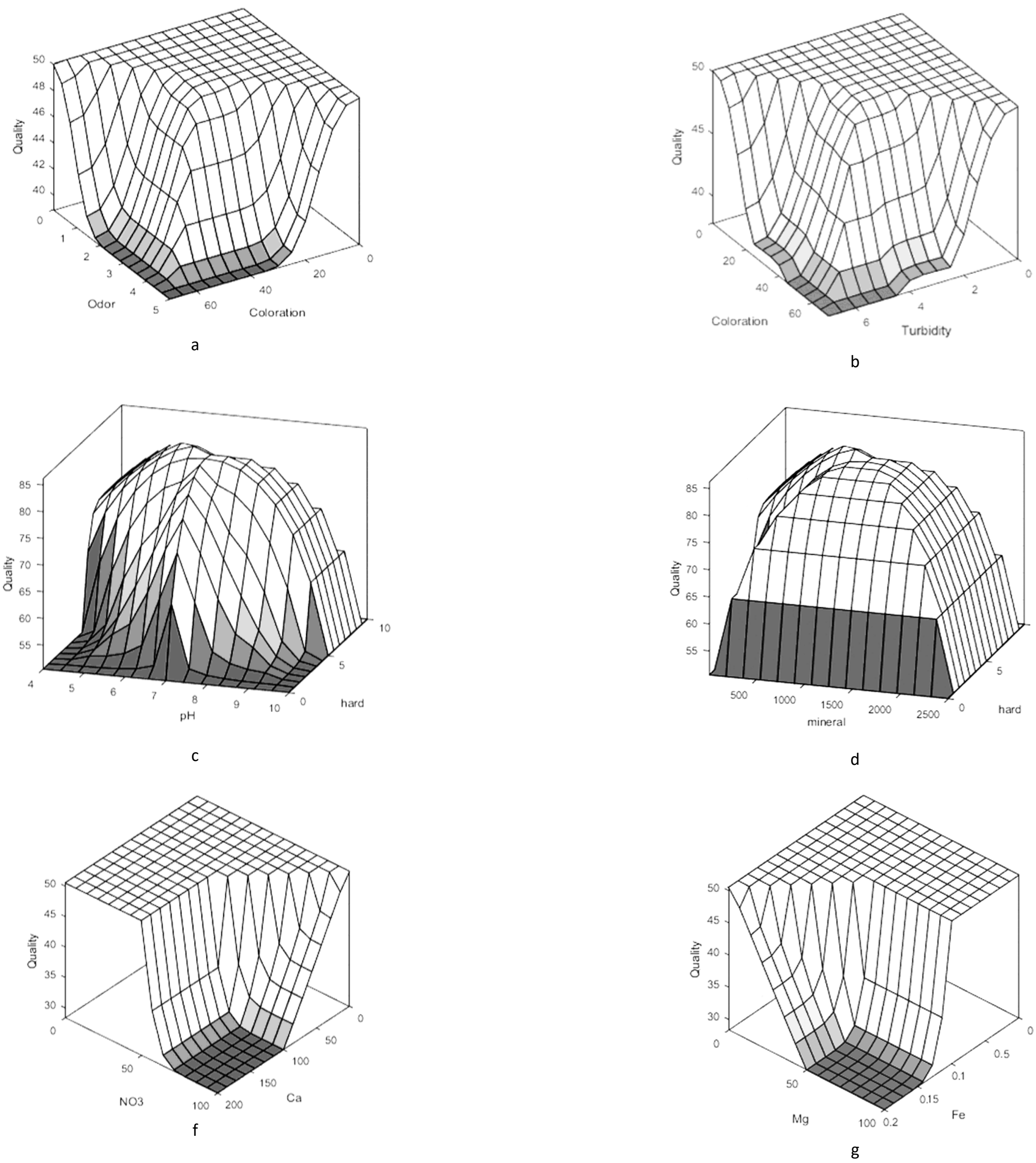

Fig. 2. Models of the factor influence on the water quality: a – odor and coloration; b – turbidity and coloration; c – hydrogen water indicator and water hardness; d – total mineralization and water hardness; f – calcium and nitrate content; g – magnesium and ferrum content

The specification of value ranges for each analyzed water parameter in accordance with established requirements, along with the application of 'If–then' condition, enabled the visualization of parameter influence within the constructed models (Fig. 2). The models illustrate how variations in the values of each examined factor affect the quality of spring water.

In the work [14], the authors have studied the quality indicators of the sources of Peremyshliany district of the Lviv region. The data are presented in Table 2.

Table 2. Indicators of water quality in the Peremyshlyany region

Indicators	Permissible indicator	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Odor	≤3	1	1	1	1	1	1
Coloration	≤35	0	0	0	0	0	0
Turbidity	≤3.5	2	1	1	1	1	1
pH	6.5–8.5	7.31	7.75	7.32	7.50	7.53	7.59
Total minerali-zation	≤1000	248	127	175	186	276	154
Total hardness	≤7.0-10.0	7.10	4.90	6.50	5.80	5.90	5.76
Ca	25-75	122.2	78.1	114.3	90.2	100.2	96.2
Mg	10 - 50	12.15	12.15	9.72	15.80	10.94	11.66
Iron	<0.2	0.0075	0.005	0.009	0.007	0.007	0.006
Nitrate	≤50	13.0	6.7	21.7	13.6	7.6	11.6

*Sample 1 – the village of Zatemne; Sample 2 – the village of Ushkovychi; Sample 3 – the village of Vypysky; Sample 4 – the area of "Syniy Kamin" (Peremyshliany); Sample 5 – the village of Univ; Sample 6 – the village of Korelychi

Based on the results presented in Table 2 and using fuzzy models, we calculated the integral indicator of drinking spring water quality (Table 3).

Based on the developed models of the influence of factors on water quality, the assessment was carried out in three groups. Then, an integral quality indicator was calculated for the spring water samples using the parameter values obtained in study [15]. This approach enables a comprehensive assessment of spring water quality and allows for data analysis both by individual groups and through an overall evaluation. The simulation results are summarized in Table 3 and show that all spring water samples are characterized by high quality indicators in three groups.

Table 3. Integral assessment of spring water quality using fuzzy logic tools

Water sample	Quality assessment by organoleptic indicators	Quality assessment by physical and chemical indicators	Quality assessment by indicators of the content of inorganic elements	Integral indicator of drinking spring water quality
1	50.1	76.1	62.2	70.1
2	50.4	57.9	68.8	65.0
3	50.4	74.9	61.6	71.2
4	50.4	72.8	53.3	70.5
5	50.4	75.1	65.4	72.1
6	50.4	75.2	59.6	71.3
Model minimum value of factors	14.9	15.8	28.3	16.4
Model maximum value of factors	50.4	80.4	86.9	72.4

4. Conclusions

All things considered, this study presents a model for the logical formation of an integral assessment of spring water quality, structured as a multi-level hierarchical system that reflects the sequence and logic of the evaluation process. The model is based on the analysis of linguistic variables such as organoleptic properties, general physical and chemical indicators, and the content of inorganic chemical elements, using predefined universal term sets and their corresponding linguistic terms. The application of fuzzy logic tools enables the use of both instrumental and analytical data as well as expert scoring, particularly when determining organoleptic values, by constructing fuzzy sets as the basis for membership functions. The calculations were based on analysis results from spring water samples obtained in a previous study. Simulation results show that all spring water samples are characterized by high-quality scores across all three indicator groups and, accordingly, exhibit high integral assessment values. Although the developed fuzzy model provides a high level of informativeness, it exhibits certain limitations in terms of result interpretation. The overall water quality index is expressed as a single numerical value, which complicates the identification of the most influential factors. Therefore, additional procedures are required to determine which specific parameter exerts the greatest influence on the integrated index in each particular case.

Further research should focus on the integration of the proposed fuzzy logic model into IoT-based water quality monitoring systems. The use of distributed sensor networks combined with wireless communication technologies would allow real-time data collection, remote access, and continuous assessment of water sources. In such systems, fuzzy logic would serve as an intelligent reasoning layer, ensuring robust performance under uncertainty, or incomplete datasets. Another promising direction is the development of hybrid neuro-fuzzy approaches, where machine learning algorithms can optimize membership functions and decision rules based on accumulated historical data. This would enable not only the assessment of current water quality but also the prediction of future changes and potential risks.

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