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CONCEPT OF MANAGING THE ENVIRONMENTAL SAFETY OF DRINKING WATER IN RESERVOIRS

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ABSTRACT

Ensuring safe drinking water for the global population is a major contemporary challenge due to uneven water distribution and growing consumption. Artificial reservoirs play a key role in storing and regulating freshwater for domestic, agricultural, and industrial use. This study presents a conceptual model for intelligent management of drinking water environmental safety using the Jeyranbatan Reservoir (Azerbaijan) as an example.

Natural and anthropogenic factors affecting water quality—such as chemical and biological contamination, heavy metals, radioactive substances, industrial and municipal effluents, climate change, and shoreline erosion—are analyzed. Water quality is monitored through physicochemical, organoleptic, and microbiological parameters at multiple reservoir points and compared with standards set by WHO, the EU, CIS GOST, and regional norms of the Absheron Peninsula.

A time series analysis (2014–2018) using regression, trend modeling, and autocorrelation identified long-term trends, systematic changes, and random fluctuations. The proposed model integrates monitoring data, regulatory standards, and statistical tools to predict deviations and support centralized decision-making, forming a basis for intelligent water safety management in large reservoirs.

1. INTRODUCTION

On average, about 210 million m³ of water is available per person on Earth; however, water resources are extremely unevenly distributed. Approximately 96.4% of the world's water is contained in the oceans and is unsuitable for direct consumption. Among freshwater resources, most is locked in glaciers (≈2%) and groundwater (≈1.5%). Thus, the freshwater available for use constitutes roughly 2.5% of the total hydrosphere, much of which is in hard-to-access forms (Antarctica, Greenland, mountain systems, Arctic ice, and deep aquifers).

According to the UN, providing the global population with safe drinking water is one of the key challenges of the 21st century. Global water consumption increased from 580 km³ in 1900 to 6,000 km³ in 2005, a 6.8-fold rise. By 2050, the world population is expected to exceed 11 billion, and with an average daily consumption of about 20 liters of clean water per person, nearly two-thirds of the global population could face severe water scarcity by 2025. Already today, almost 2 billion people live under "water stress" conditions.

Countries with the highest freshwater availability include Brazil, Russia, Canada, China, Indonesia, and the USA, whereas Egypt, Burundi, Algeria, Libya, and Kuwait have minimal water resources. A significant portion of water consumption is irreversible and used in agriculture, mainly for irrigation. The highest per capita water use is observed in countries with intensive irrigated agriculture, such as Turkmenistan (up to 7,000 m^3 per person per year), followed by Uzbekistan, Kyrgyzstan, Kazakhstan, Tajikistan, Azerbaijan, Iraq, Pakistan, and others, where water scarcity is persistent.

2. PROBLEM STATEMENT

Both natural and artificial reservoirs are considered. The commonly accepted definition of a reservoir is a water body located in a riverbed or a low-lying area, created artificially using dams, embankments, or excavated basins to store water.

By origin, reservoirs are classified as:

- Valley-river type;
- Lake-type;
- Located at groundwater outlets;
- Estuarine (at river mouths).

Despite differences in origin, their primary function remains the same: water storage and regulation of river flow.

The geographical distribution of large reservoirs is also noteworthy: over 40% are located in the temperate zone of the Northern Hemisphere, where most economically developed countries are situated. These countries actively use reservoirs for energy generation, water supply, and transportation. Artificial reservoirs represent a form of anthropogenic impact on nature, reflecting the uneven spatial and temporal distribution of water resources.

By the early 21st century, the total number of reservoirs worldwide exceeded 60,000. In Azerbaijan, there are 61 reservoirs with a total volume of about 1 million m^3. Among them, the Jeyranbatan Reservoir ranks 7th in volume (e.g. Table 1). It is an artificial water body designed for water storage, use, and regulation. Its primary source is the Samur-Absheron channel, fed by the Samurchay, Velvelechay, and Gudyalchay rivers.

Table 1. *Main Characteristics of the Jeyranbatan Reservoir*

Main Characteristics of the Jeyranbatan Reservoir	
Total Volume	186 million m^3
Usable Volume	150 million m^3
Length	8.74 km
Maximum Width	2.15 km
Shoreline Length	23.3 km
Maximum Depth	28.5 m
Dead Storage Level	14.5 m
Surface Area	1,389 ha

The reservoir supplies water to the cities of Baku and Sumgait and is a strategically important facility, where ensuring environmental safety is a top priority. Environmental safety includes the protection of the reservoir as a physical object, organization of monitoring of inflow and outflow, laboratory analyses, and expert assessment of the reservoir’s condition. Effective management of environmental safety requires the creation of a centralized intelligent system, comprising specialized subsystems, decision support systems, knowledge bases, and databases.

This study proposes a functional and conceptual model for monitoring, comparing, and predicting the state of the reservoir.

3. SOLUTION OF THE PROBLEM

Ensuring environmental safety requires a systematic analysis of the object, including the study of natural and anthropogenic factors affecting the ecosystem. These factors include chemical and radioactive substances, heavy metals, other pollutants, as well as agricultural, industrial, and urban discharges. Natural processes and phenomena—such as mud volcanoes, earthquakes, groundwater fluctuations, climate change, and shoreline erosion—also play a significant role. Additional threats arise from biological contamination, landscape changes related to vegetation and other environmental components, and diverse land use in areas adjacent to the reservoir. Particular attention is given to four classes of factors influencing drinking water quality: physical, chemical, organoleptic, and microbiological.

To assess water quality, samples are collected from various points and subjected to laboratory analyses, including: temperature (T, °C); turbidity (NTU); transparency (cm); color and odor; electrical conductivity (μS/cm); sulfides; dissolved gases (O_2, CO_2); chlorine (free Cl_2, total Cl_2); hardness and alkalinity; major ions (Cl^-, HCO_3^-, CO_3^{2-}, Ca^{2+}, Mg^{2+}); degree of mineralization; and biogenic substances (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}), among others [4,5].

At the Jeyranbatan Reservoir, various instruments are used for different measurements, including a pH meter (measuring water pH and hydrogen ion activity), a chlorometer (a versatile device for determining active chlorine concentration and pH level), a TDS meter (a modern electronic device for measuring salt and mineral content, water hardness, and electrical conductivity), a conductometer (a high-precision portable instrument for detailed chemical analysis of electrolytes through electrical conductivity), and a spectrophotometer (stationary instruments are used in laboratory measurements, specifically the HACH DR 2800 spectrophotometer).

For high-quality, real-time analysis and monitoring of compliance with drinking water standards at the facility, water quality analyzers are employed.

To ensure highly accurate real-time analysis and monitor compliance with established drinking water standards at the facility, modern water quality analyzers are used.

First, it is necessary to clarify the concept of drinking water quality standards, taking into account the specifics of the Absheron Peninsula ecosystem. It should be noted that the standards established by the WHO, the European Union, and CIS GOSTs differ from the average values observed in the region where the Jeyranbatan Reservoir is located. Examples of a small number of such parameters are presented in Table 2 [6].

Table 2. *Comparative Table of Selected Parameters*

No.	Parameter	Unit	WHO	EU	CIS GOST	Average Values for Absheron Peninsula
1	Color (Pt-CO scale)	degree	15	20	20	0
2	Color (Bichromate CO scale)	degree	15	20	20 (35)	0
3	Electrical Conductivity (20°C)	μS/cm	-	2,500	-	450
4	Aluminum (Al)	mg/L	0.2	0.2	0.5	0.1
5	NH_3 and NH_4^+	mg/L	1.5	-	0.5	0–0.17
6	Arsenic (As)	mg/L	0.01	0.01	0.05	0
7	Iron (Fe^{2+}, Fe^{3+})	mg/L	0.3	0.2	0.3	0–0.03
8	Silver (Ag)	mg/L	-	0.01	0.05	0
9	Chlorides (Cl^-)	mg/L	250	250	350	29–154
10	Calcium (Ca^{2+})	mg/L	-	100	250	60
11	Sodium (Na^+)	mg/L	200	200	200	45–97
12	Polyphosphate ions (PO_4^{3-})	mg/L	-	-	3.5	1.1

Based on the average water quality values of the Absheron Peninsula for the factors monitored in the Jeyranbatan Reservoir, the maximum allowable concentrations of these factors can be determined, which we will refer to as the factor standard. Correspondingly, the actual measured values will be referred to as the current indicators. In the future, the current indicators will be compared with the standards established by CIS GOST, the European Union, and the WHO.

For convenience, the following notations are introduced:

{ I_{q_A}}: The table of maximum allowable concentrations of factors in the water of the Jeyranbatan Reservoir.

{ I_{q_Γ} }: The table of norms for water factors according to GOST (State Standards of CIS countries).

{ I_{q_E} }: The table of norms for water factors according to the European Union standards.

{ I_{q_B}}: The table of norms for water factors according to the World Health Organization (WHO).

{I_{q_i}}-: The current values of water quality factors at measurement point i (i=1, 2,…, 6).

k{ I_{q_i} }: The coefficient comparing current data

{I_{q_A}} with the Jeyranbatan Reservoir norms.

Kj{Iq}: The coefficient comparing current data with WHO, EU, and CIS standards (j=1, 2, 3).

{Pq}: The set of activated parameters.

O{Pq}: The set of variations in the activated parameter values.

{S}: The impact operator.

{SOq }: The scale of the impact factors.

(*): The result of the impact of the operator S_{O_q}.

$$\left\{\{I_{q_A}\};\{I_{q_\Gamma}\};\{I_{q_{\mathrm{E}}}\};\{I_{q_B}\};\{I_{q_i}\};k\{I_{q_i}\};k_j\{I_q\};O\{P_q\}\right\}\xrightarrow{\{S_{O_q}\}\Rightarrow O\{P_q\}}\{(I_{q^*});k^*(I_{q^*})\}.$$

Conceptually, this functionality can be represented as shown in Fig. 1. Initial water sampling is carried out at several key points: at the reservoir inlet, near the water intake structure, at the southern pumping station, adjacent to the southwest dam (wastewater), at the southern dam (wastewater), at the northeast dam (wastewater), at the inlet of the irrigation pumping station, and so on. The next sample is formed as a mixture of all previous samplings. In the primary data processing block, physicochemical and microbiological analyses of the water are conducted, enabling the assessment of its quality and the identification of deviations from established standards.

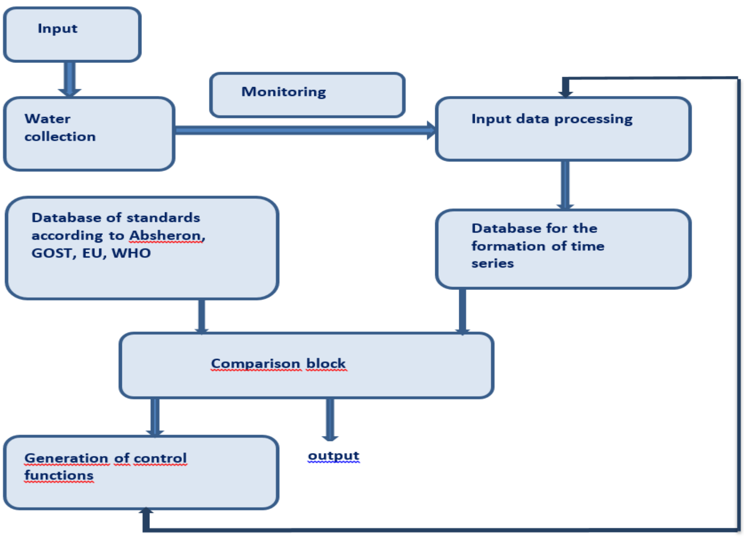

Fig. 1. *Conceptual Model of Water Environmental Safety Management*

The measurement frequency during monitoring is determined by population density: for populations exceeding 100,000 people, (100 + 1) measurements should be conducted for every 5,000 inhabitants. Based on the collected data, a time series is formed. To analyze various parameters over a specific period, methods and indicators are applied that allow characterization of processes over time. When working with time series, three main components should be considered: a periodically varying component, systematic changes in the parameter, and a random component arising from stochastic factors [8]. Thus, the value of a parameter at time ttt is defined as follows:

$$y_i = u_i + v_i + \varepsilon_i ,$$

where u_i - systematic changes in the parameter; v_i – periodically varying component; ε_i– random component.

A parameter in time series exhibits ergodic properties, meaning that it is possible to assess the recurring characteristics of the parameter over an extended period. For example, monitoring disease incidence is recommended over 3–10 years, educational processes over 5–10 years, and eco- and biosystems over 3–5 years. In this way, the time series reflects long-term changes in the parameter as well as fluctuations in its periodic component.

For the Jeyranbatan Reservoir, observations and measurements were conducted from 2014 to 2018, and the time series covers this period. To analyze changes in a parameter, it is appropriate to apply single-factor regression analysis, where the independent variable is the time index $t=1,2,\dots,n$ and the dependent variable is the level of the studied parameters $y_1, y_2, \dots, y_n$. To identify changes in parameters over time, autocorrelation functions as well as parametric and non-parametric statistical tests can be used. The autocorrelation function allows characterization of the dependence of parameter values in the time series on the time interval. Pairwise autocorrelation coefficients are calculated as follows:

$$K_{y(t)} = \frac{\sum_{i=1}^{n}[y_i(t)y_i(t+\tau)] - n\bar{y}(t)\bar{y}(t+\tau)}{\sqrt{[\sum_{i=1}^{n} y_i^2(t) - n\overline{y^2}(t)][\sum_{i=1}^{n} y_i^2(t+\tau) - n\bar{y}^2(t+\tau)]}},$$

where $y_i(t)$ is the value of the parameter at time t; $y_i(t+\tau)$ is the value of the parameter at time t+τt, i.e., after a time shift of τ.

Autocorrelation coefficient values increase with the number of paired observations, i.e., as monitoring continues. The relationship between parameter values and their significance is determined by the magnitude and sign of the coefficient: a positive value indicates a direct relationship, while a negative value indicates an inverse relationship. Conventionally, a coefficient < 0.3 is considered weak, 0.3–0.7 moderate, and ≥ 0.7 strong.

A time series is a sequence of variable values corresponding to an increasing sequence of time points T. Time series analysis allows the separation of deterministic and random components, the estimation of their parameters, and, on this basis, the solution of forecasting problems. The trend line equation is chosen to best approximate the empirical data, with preference given to the simplest functional relationship [7]. Complex trend line equations reduce the reliability of parameter estimates.

To select the trend line equation, linear, exponential, hyperbolic, power, polynomial, logarithmic, and logistic types were examined. The linear trend reflects a roughly uniform change in parameter levels, allowing the description of average changes in the factors under consideration. The approximate uniformity of absolute increases or decreases is explained by the influence of diverse and differently accelerating factors, which mutually average and partially compensate each other. The resultant effect of these influences tends toward uniformity. Thus, the observed uniform dynamics result from the complex interaction of multiple factors affecting the changes in the studied parameter.

The conceptual model provides for the creation of a database of standards established for drinking water according to CIS GOST, EU standards, and WHO guidelines, taking into account the specific characteristics of the Absheron Peninsula.

Comparing the current indicators with these standards allows the formation of control functions **{SO$_q$}**, which act on the parameters $\{P_q\}$, indicating trends of deviation from the maximum permissible concentrations in either direction. The development of these requirements is carried out with the involvement of highly qualified specialists.

The task is considered solvable if the absolute increases or decreases in parameter levels over equal time intervals can be described using the simplest and most illustrative form, reflecting the dynamics of the studied parameters.

$$\lim\{Iq* \} \rightarrow \{Iq\{\mathrm{P_q}\}_A\}; \{Iq_\Gamma\}; \{Iq_\mathrm{E} \}; \{Iq_B\}.$$

4. CONCLUSION

The conducted systems analysis demonstrates that the environmental safety of the reservoir directly depends on the comprehensive consideration of a wide range of factors, including natural processes, anthropogenic pressures, and the dynamics of the surrounding environment. The diversity of pollution sources and variability of natural conditions require continuous monitoring, the creation of a standards database, and the development of management decisions based on actual measurements. This approach enables timely detection of deviations in water quality parameters, forecasting of possible changes, and implementation of effective measures to maintain the resilience of the Jeyranbatan Reservoir ecosystem and ensure safe drinking water for the population. In this study, a functional model was developed to achieve these objectives, upon which the proposed conceptual implementation framework is based.

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