UDC 519.854.2 DOI:10.34229/2707-451X.26.2.10

AUTOMATED INTELLIGENT INFORMATION SYSTEM FOR MONITORING AND ENSURING THE ECOLOGICAL SAFETY OF DRINKING WATER

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УДК 519.854.2

Автоматизована інтелектуальна інформаційна система моніторингу та забезпечення екологічної безпеки питної води

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Вступ. Вплив глобальних проблем на міжнародні відносини неухильно зростає, а контроль над водними ресурсами стає ключовим чинником міждержавної взаємодії. Доступ до питної води нині є критично важливим компонентом сучасних політичних процесів, що зумовлює концепцію «водної дипломатії». Забезпечення екологічної безпеки водосховищ питної води є стратегічним завданням, яке потребує впровадження інноваційних рішень для моніторингу та управління.

Мета. Метою дослідження є розроблення автоматизованої інтелектуальної інформаційної системи для єдиного управління та моніторингу якості питної води у водосховищах у режимі реального часу з урахуванням фізичних, хімічних, мікробіологічних та експлуатаційних параметрів. Система спрямована на забезпечення як автономного функціонування, так і централізованого управління в умовах надзвичайних ситуацій.

Результати. Систему було впроваджено та апробовано на водосховищі Джейранбатан (2021–2024 рр.). Дослідження охоплювало 6–7 точок вимірювання та 22 параметри якості води. Статистичний аналіз, зокрема *t*-тести та дисперсійний аналіз (ANOVA), підтвердив достовірність отриманих вимірювань. Система забезпечує моніторинг у режимі реального часу, сповіщає про виявлення відхилень параметрів та зберігає дані в нормативних, поточних і архівних базах даних. Порівняльний аналіз засвідчив високий рівень адекватності та надійності системи (≈ 87–91 %), що дозволяє ефективно контролювати екологічний стан водосховища та проводити прогнозний аналіз якості води.

Висновок. Розроблена інтелектуальна інформаційна система забезпечує оперативний і надійний екологічний моніторинг водосховищ шляхом інтегрування автономного та централізованого управління. Система функціонує як цифрова платформа для безперервного обміну даними та прийняття рішень, сприяючи підвищенню рівня безпеки води та забезпечуючи основу для загальнонаціональної мережі моніторингу.

Ключові слова: якість питної води, інтелектуальна інформаційна система, моніторинг водосховищ, ANOVA, контроль у режимі реального часу, екологічна безпека.

Abstract

The impact of global challenges on international relations is steadily increasing. One of the most serious problems is ensuring the supply of safe drinking water for the world's population. Control over water resources plays an important role in interstate relations and has become an increasingly significant factor in modern geopolitical interactions. Within this context, the issue of drinking water availability and safety represents one of the key components of contemporary political and socio-economic relations. The concept of water diplomacy has emerged in the international arena to describe situations where water resources may be used as an instrument of political influence. Similar to many other countries, the Republic of Azerbaijan also faces the problem of water scarcity. Among the most important issues in this area are maintaining the balance of water circulation, substance exchange processes, energy balance, and ecological safety.

In this regard, the development of an automated intelligent information system for ensuring the ecological safety of drinking water in the republic is considered appropriate. The proposed system is implemented on a client–server platform. Based on the conceptual and functional models of the problem, the architecture of system objects has been developed. Reservoirs integrated into the network can be centrally controlled from the server–center node during emergency situations, while under normal operating conditions they retain autonomous functionality. The communication routes “object–server–center” and “center–server–object” remain continuously active. The paper provides information on measurement instruments, computational algorithms, and the developed software components. Experimental studies were conducted at the Jeyranbatan Reservoir during 2021–2024 based on 720 measurements obtained from 6–7 monitoring points. The main objective of the research is to ensure operational monitoring of drinking water quality and early detection of potential risks based on long-term measurements of parameters of different origins (physical, chemical, organoleptic, etc.). To verify the adequacy of the automated system, archival data from 2017–2020 were also used. The obtained results demonstrate that the proposed system detects deviations of parameters from normative values with high accuracy (approximately 86–92 %) and effectively supports the decision-making mechanism.

Keywords: natural and artificial reservoirs, measurements, automated intelligent information system, database, conceptual and functional model.

1. Introduction

According to the United Nations, one of the most serious problems of the present century is ensuring the supply of safe drinking water for the world’s population. Experts predict that by 2050 the global population will exceed 11 billion. Considering that the daily consumption of clean water per person is about 20 liters, it is expected that by 2025 about two-thirds of the world’s population may face serious shortages of drinking water. It should also be noted that currently about 2 billion people live under conditions referred to as water stress. The leading countries in freshwater supply include Brazil, Russia, Canada, China, Indonesia, and the United States. Countries with the lowest water reserves include Egypt, Burundi, Algeria, Libya, and Kuwait [1].

Today, the signs of the environmental crisis have acquired a global character and are gradually spreading to many countries. Issues related to global climate change have become particularly significant. Several explanations for this phenomenon are discussed: warming caused by volcanic activity, changes in the Earth's magnetic field, and warming due to anthropogenic activity. In light of these factors, the efforts of many countries are directed toward restoring ecological balance and ensuring environmental safety. As in many other countries, the problem of water scarcity is also highly relevant for the Republic of Azerbaijan. Among the most important issues are maintaining balance in the water cycle, substance exchange processes, energy balance, and ecological safety.

The term environmental safety can be considered a relatively new concept. It became one of the important global issues in the 1980s. A number of international documents are directly related to this problem and aimed at its solution, including the environmental protection declarations adopted within the framework of the United Nations, the Rio Declaration on Environment and Development, the United Nations Millennium Declaration, and the declaration on sustainable development and environmental safety adopted in World Summit on Sustainable Development [2–5].

In this context, one of the most recent international events was the United Nations Climate Change Conference (COP29), held in Baku from 12 to 24 November 2024 within the framework of the United Nations Framework Convention on Climate Change. Of particular interest is the declaration signed by nearly 50 countries during the conference session held on 21 November 2024, known as the COP29 Declaration on Water for Climate Action. The declaration emphasizes the integration of mitigation and adaptation measures related to water into national climate strategies, such as Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs).

To support these efforts, the countries that signed the declaration committed themselves to strengthening cooperation in scientific research on factors causing climate change in water resources and water basins, as well as on their impacts. This also includes the exchange of information and the development of new climate plans for water basins. Commenting on the launch of the Water for Climate Action initiative, the President of United Nations Climate Change Conference (COP29), Mukhtar Babayev, noted: "Water acts as a link between the crises of climate, biodiversity, and desertification. By strengthening cooperation among countries and COP conferences, the Water for Climate Action initiative will allow us to address all three challenges simultaneously."

The Deputy Secretary-General of the United Nations and Executive Director of the United Nations Environment Programme, Inger Andersen, also emphasized that as the impacts of the climate crisis continue to intensify, the management of freshwater ecosystems has become more necessary than ever. According to her statement, the purpose of the Baku Dialogue on Water for Climate Action launched during United Nations Climate Change Conference (COP29) is to increase attention to water-related issues within the global climate agenda [6]. One of the sources that store water resources is natural and artificial reservoirs. Among the most important morphometric characteristics of reservoirs are the surface area SSS, volume VVV, and the amplitude of water level fluctuations. The income part of the water balance of reservoirs includes atmospheric precipitation, surface runoff, condensation of water vapor on the reservoir surface, and subsurface inflows. The expenditure part consists of surface outflow from the reservoir, underground outflow, and surface evaporation. The structure of the water balance of any basin represents the relationships between different types of inflows and outflows.

Morphologically, the geometric models of simple lake basins can be represented in various forms. In most cases, four basic forms are considered: cylinder, hemisphere, paraboloid, and cone (Fig. 1) [7].

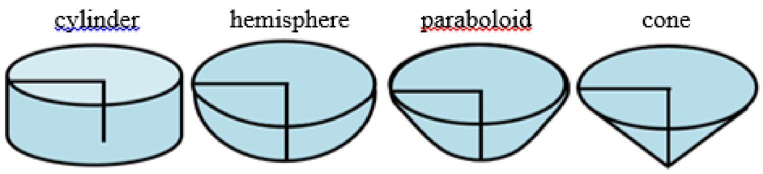

FIG. 1. Geometric models of lake basins

Reservoirs can vary according to their types, such as lake-type, river-type, or pond-type. Lake-type reservoirs are largely influenced by wind, while river-type reservoirs usually have an elongated shape, and the characteristics of their water resemble those of river waters. Pond-type reservoirs are generally small in volume and are used for irrigation, sanitary, recreational, or aesthetic purposes. Reservoirs can also be classified according to various characteristics, for example, by their bed structure, water filling methods, geographic location, position within a river system, flow regulation mechanisms, and so on. Regarding their operation, the hydrological regime of a reservoir – that is, the parameters and technical means required for its management – is controlled by humans. Nevertheless, over time, these artificial structures integrate into the overall water cycle.

2. Justification and Problem Statement

The general safety of water basins remains an ever-relevant issue. Ensuring the ecological safety of reservoirs essentially means their overall protection. This includes the physical safeguarding of the surrounding area, monitoring the flora and fauna of the water, measuring chemical and physical substances, assessing microbiological conditions, and other related measures. To provide drinking water throughout the country, different regions are supplied by separate reservoirs. Each reservoir differs in its internal composition and in its interaction with the external environment. Approximately 80 % of Azerbaijan's drinking and irrigation water enters the country via the Kura, Aras, and Samur rivers, originating from abroad, specifically from Turkey, Russia, Georgia, and Iran. In Georgia, the per capita water availability is 5–7 times higher than in Azerbaijan, while in Armenia it is 2.5–3 times higher. Considering our large population, extensive territory, irrigated lands, and water usage in industry, this situation is quite natural. The high proportion of drought-prone areas in our territory also increases natural evaporation. The greatest threat to national security is contamination of drinking water [8]. Regardless of the volume or location of the basins, there are established requirements and standards for drinking water quality. In order to protect water resources from pollution and depletion, all water users must comply with general rules defined by water legislation:

- Must not harm the environment or natural objects, nor violate the rights of other water users;
- Water resources must be used efficiently and economically, with continuous improvement of water quality;
- Treatment facilities must always be operated in proper condition, and their operational efficiency should be enhanced;
- Measures must be taken to completely prevent the discharge of wastewater containing pollutants into water resources;
- The quantity and quality of both used and discharged water must be monitored, recorded, and analyzed.

General requirements and standards:

1. Drinking water must be chemically safe from epidemiological and radiological perspectives;
2. The quality of drinking water before entering the distribution network must meet hygienic standards;
3. The composition of drinking water must comply with microbiological and parasitological norms.

The impact of global issues on international relations is steadily increasing. Control over water resources has become crucial in interstate relations. Through these factors, states are increasingly able to exert pressure on one another. Within this framework, access to drinking water has become a key component of modern political relations. The concept of "water diplomacy" has emerged as an instrument for using water as a tool of political influence on the international stage.

Considering the above, it is expedient to develop an automated intelligent information system in the Republic that provides a unified approach to managing drinking water.

To achieve this goal, it is necessary to implement a comprehensive technological approach that considers the specific characteristics of existing reservoirs and coordinates their operation within an integrated network environment. For each basin included in the structure, an automated information and control system should be equipped with various directional components and operate under both autonomous and centralized monitoring and management.

A client–server type distributed network architecture is employed in this system, enabling different reservoirs and components to communicate with a central server while supporting both independent operation and centralized control (Fig. 2) [9, 10].

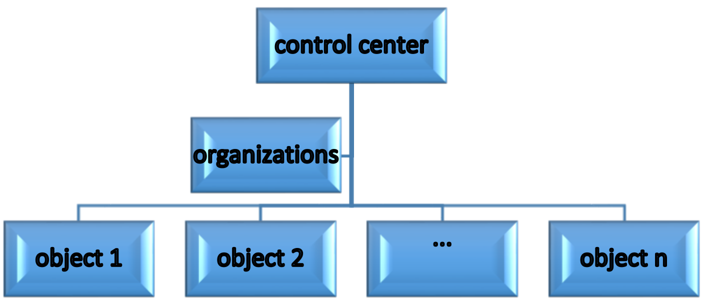

FIG. 2. Client-server type distributed network

Below, the development of such a system is presented.

3. Problem Solution

3.1. Spatial Selection

Currently, Azerbaijan has 61 reservoirs with a total capacity of 1 million m^3 each, amounting to an overall volume of 21.5 km^3. Considering the uneven distribution of these basins across the country, a monitoring system based on a distributed network architecture operating within a unified information space is proposed. Unlike centralized single-point management, the distributed network model ensures that the structural elements of the system, located in different geographic areas, operate in mutual coordination [11].

According to this architecture, each reservoir functions as a separate functional subsystem, performing local data collection, initial processing, and storage. The distributed network infrastructure allows data flows to be transmitted in parallel and synchronously, enhancing the system's reliability and robustness. Any technical failure in a subsystem does not disrupt the operation of the entire system, as other nodes continue to operate independently. This feature ensures high availability and uninterrupted service. Data transmitted over the network is integrated at the central management platform and processed in a unified analytical environment. Consequently, the system enables both operational decision-making at the local level and aggregated monitoring and strategic management at the national level. The distributed architecture also possesses scalability: adding new reservoirs to the system does not require modifying the existing structure, and integrating additional functional nodes into the network can be performed easily.

3.2. Conceptual and Functional Approach to the System and Architecture Development

A conceptual approach is a problem-solving method based on the initial development of a unified concept, principles, and core ideas that define the overall strategy, objectives, and understanding of the research object. In our case, this represents an abstract description of the system's structure, interconnections, and semantic content, which is used for practical implementation. The concept of the automated information and control system outlines the foundations of its components (Fig. 3):

FIG. 3. Concept of the automated information and control system

The system components perform the following functions:

- **Hardware** – includes various measuring devices, computers, and peripheral equipment;
- **Software** – refers to application packages and programs;
- **Data** – comprises normative data, current data, and archived data stored in computer memory;
- **Processing** – operations performed on the data;
- **Process** – a sequence of steps taken to achieve the target;
- **Decision-making** – mechanisms for both autonomous and centralized output. *Autonomous* refers to each object making decisions and executing them independently; *Centralized* is particularly important in cases of technological, anthropogenic, epidemiological, or conflict-related events.

First of all, a systematic approach to the object is required; in other words, it is necessary to study the natural and anthropogenic factors that affect the reservoir ecosystem in one way or another and may negatively impact its operation (life) and safety. The more significant factors can be highlighted as follows: chemical substances, radioactive materials, heavy metals, and other pollutants; agricultural, industrial, and domestic waste; natural events such as mud volcanoes and earthquakes; changes in groundwater levels; natural climate change; shoreline soil erosion; biological contamination; changes in the coastal landscape (vegetation, etc.); and the multi-purpose use of soils in and around the reservoirs.

Based on this information, the following notations are adopted [12].
$\{I_q\}$ – Table of Maximum Allowable Concentrations of Substances in Reservoir Water;
$\{I_{q_i}\}$ – Table of Current Values of Substances in Water Sampled from Measurement Point *i*;
k$\{I_{q_i}\}$ –$\{I_q\}$ Coefficient of Comparison of Current Data with Reservoir Standards;
$\{P_q\}$ – Collection of Alert Parameters;
$O\{P_q\}$ – Range of Variations of Alarm Parameters;
{S} – Impact Operator;
$\{S_{Oq}\}$ – Influence Factors Value Scale;
(*) – $\{S_{Oq}\}$ Result of the Operator's Effect.
Thus, the functional model of the object under consideration can be represented in a generalized form:

$$\left\{\{I_q\};\{I_{q_i}\};k\{I_{q_i}\};O\{P_q\}\right\}\xrightarrow{\{S_{O_q}\}\Rightarrow O\{P_q\}}\{(I_{q^*});k^*(I_{q^*})\}.$$

Considering the variation range of the parameters that determine drinking water quality, a large number of alternative vectors arise in the overall description. Based on modern decision-making theory, these can formally be represented as a criterion space. In our case, the alternatives are not purely mathematical objects but physical states of the system, i.e., the condition of water in the reservoir depending on specific parameters.

To construct the set of alternative states, all possible solutions must be collected, measured parameters standardized, and each state evaluated according to the relevant criteria. Expert knowledge is applied at this stage of the process. Based on the conceptual and functional models, it is possible to design the architecture supporting each object within the system. The "Object–Server–Center" and "Center–Server–Object" communication routes are constantly active. The number of measurement points in each reservoir, the number of parameters specific to the reservoir, and the measurement frequency vary. These factors are incorporated into the software. The developed program can serve as an example of paperless technology. Thus, the system architecture is constructed taking into account all alternative states and measurement parameters (Fig. 4).

3.3. Technical Means

Various laboratory techniques and devices are used to determine pollutant levels in water. Spectrophotometers are applied to identify the concentration of ions as well as organic and inorganic substances in water samples. Analyzers are used to measure physical and chemical indicators of water, such as pH, oxygen level, turbidity, and salinity. Electroanalytical devices are employed for the determination of ions using electrode-based methods, while titrimetric equipment is widely used to measure pollutant amounts through chemical reactions. Additionally, multimeters, conductometers, turbidimeters, fluorescence analyzers, oxygen sensors, ion-selective electrodes, and atomic absorption spectrometers are used for accurate analysis of the physical and chemical parameters of water. During the measurements in this study, analyzers, pH meters, conductometers, and spectrophotometers (particularly the Hach DR 2800 Portable Spectrophotometer) were utilized.

4. Processing

The quality indicators of drinking water supplied to consumers in the Republic of Azerbaijan are determined in accordance with the Interstate Standard adopted jointly by the CIS countries (GOST 2874-82), which includes over 35 measured parameters. In the future, it is planned to align the quality indicators of drinking water with international standards (World Health Organization – 50 parameters; European Union – 75 parameters) [13].

In the system, a separate subsystem is established for each reservoir, considering the number, diversity, measurement frequency, and real-time processing of the measured parameters (e.g., physical, chemical, organoleptic, microbiological, etc.), and these parameters are classified accordingly. Each subsystem consists of a norm-base (officially accepted values during the measurement period) and a current-base (values obtained at the time of measurement). Time series are created for all measurement results and stored in the archive database.

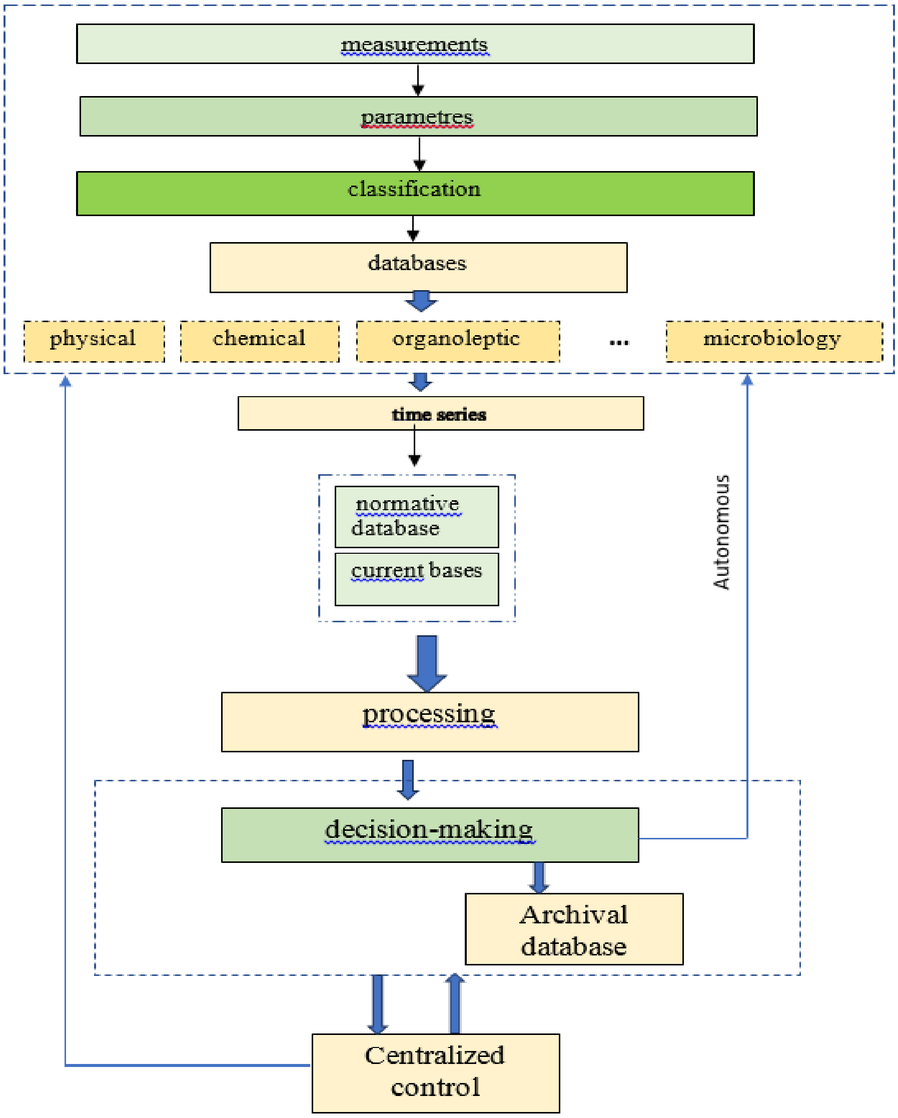

FIG. 4. Architecture

4.1. Computational Algorithms

Mathematical statistics methods were extensively used in the work process. Analysis of variance (ANOVA) is a statistical method employed to study relationships. It is used to determine the effect of one or more qualitative variables on a dependent quantitative variable. ANOVA is based on the assumption that some variables can be considered causes (independent variables), while others are effects (dependent variables or responses). The main purpose of variance analysis is to examine the significance of differences between the mean values of a dependent quantitative variable across factor groups. This is achieved by decomposing the total variance of the dependent variable into components: variance due to group differences (between-group variation) and variance due to other factors (within-group variation). By analyzing these components, it is possible to estimate the contribution of each factor to the dependent variable. A separate task of ANOVA is to identify which groups are responsible for the observed differences in the mean values of the dependent variable [14].

First, for each time period (daily, monthly, quarterly, etc.), the mean values ($\bar{X}$) are calculated, followed by the standard deviation (σ), standard error, and skewness. Based on these, confidence intervals are determined. The results of the experiments were subjected to expert evaluation, and the t-Student criterion was applied to perform a comparative analysis of the accuracy of the indicators [15].

It is well known that the Student's t-test is one of the most widely used tests in statistical analysis. This test is particularly applied to compare the means of groups with small sample sizes [16]. Alongside parametric methods of variance analysis, non-parametric tests such as the Kruskal-Wallis test, Jonckheere-Terpstra test, Friedman test, and Page test for ranked measurements are also commonly employed [16]. Analysis of Variance (ANOVA) is a statistical method used to evaluate potential differences in a dependent variable measured at a scale level, based on a nominal-level independent variable with two or more categories. At this point, multiple comparison tests are available, including t-tests for checking mean differences between groups while controlling the Type I error rate: Bonferroni, Scheffé, Dunnett, and Tukey tests.

The Bonferroni correction is a multiple-comparison adjustment used when several dependent or independent statistical tests are performed simultaneously. This is because a given significance level α may apply to each individual comparison but not to the entire set of comparisons. To prevent multiple false positives, the α level should be reduced considering the number of comparisons [17]. The simplest and most conservative approach is the Bonferroni correction, which divides α by the number of comparisons n, assigning α/n to each individual test, ensuring that the overall α level for all n comparisons is maintained

For a set of $n$explicitly defined tests with hypotheses $H_i(1 \le i \le n)$, if the significance level for each individual test does not exceed α/n, then the overall significance level of the experiment does not exceed α. This assessment can be expressed as follows:

$$P(T_i \text{ rejects } H_0) \le \frac{\alpha}{n}, 1 \le i \le n,$$

then

$$P(\mathit{at\,least\,one}\, T_i \ \mathit{rejects}\, H_0 \mid H_0) \le \alpha,$$

which follows from the Bonferroni inequalities [17].

Dunnett's test (also known as Dunnett's method or Dunnett's multiple comparison procedure) is used to compare the means of several experimental groups with a control group in order to determine whether significant differences exist. While analysis of variance (ANOVA) may indicate that differences exist among groups, it does not specify which pairs differ. Dunnett's test is therefore applied after ANOVA to identify which groups differ significantly from the control.

$$D_{\text{Dunnett}} = t_{\text{Dunnett}} \sqrt{\frac{2MS_{S/A}}{n}}.$$

A fixed control group is compared with all other samples; therefore, this method should only be used when a control group is present [18]. When a control group is not available, Tukey's test is used:

$$T = q\sqrt{\frac{MSE}{n}}.$$

In this study, Levene's test, its modification the Brown–Forsythe (B–F) test, the F-statistic from standard analysis of variance [16], as well as Student's t-test, confidence intervals, and the Mann–Whitney U test were also used to verify the reliability of the indicators' variability.

4.2. Software

The system architecture is based on a three-tier model. The presentation layer (frontend) consists of a user interface built using HTML and CSS. The interface is adaptive and optimized to operate across various devices. Dynamic functionality and real-time data updates are implemented using JavaScript technologies.

At the application level, the server-side software receives data from sensors, processes it, and directs it to analysis modules. At the data level, all indicators are stored and archived in a structured database. Network interaction is organized according to the client–server model. Data exchange is performed over HTTP/HTTPS protocols, with JSON used as the structured data format.

To ensure real-time monitoring, the system can utilize periodic AJAX requests or WebSocket technology. This mechanism enables the operator panel to update indicators dynamically and generate immediate alerts in critical situations.

For security purposes, the system implements authentication and role-based access control. User privileges are restricted according to their management level. Data transmission is carried out over encrypted connections, and a backup mechanism is provided on the server. The most accurate results resembling real-world conditions are obtained using the Visual Studio Code platform, HTML [19, 20] markup language (frontend code), CSS [21] coding (for headers, layout, and visual effects), and JavaScript [22] programming language (ensuring sequence).

The databases in the software are of an open type. The objective is to enable the application of the program across all reservoirs. Depending on the reservoir's topography, shape, size, and water capacity, the number of water sampling points and the number of information-carrying factors are initially unknown.

4.3. Implementation Example

```
def createstat:
    stat = tk.Toplevel()
    stat.geometry('200x2000')

    def esasionmg_stat():
        def esasionmginfo():
            k = 0
            while k not in dasas:
                k = simpledialog.askstring(title='Sorgu', prompt='Hansı ay və 
il üzrə?')
                k = k.capitalize()

            c = dates.index(k)
            c = c * 7
            h = locations - menteçeler
            abbs1 = abbs

            for i in range(7):
                h.append(esaimg(c))
                c = c + 1

            root = tk.Toplevel()
            root.geometry("500x4400")
            root.title("Əsas ion - Mg 2+ - " + k)

            tree = Treeview(root, columns='qiymetler')
            tree.heading("#0", text='Məntəqə')
            tree.heading('qiymetler', text='Qiymətlər')
```

```
for i in range(len(locations)):
    tree.insert('', tk.END, text=locations[i], values=h[i])

sonrabtn = Button(root, text='Qələvilik', command=qelelilikstat)

Infomg = Button(root, text='Əlavə məlumat')
Infomg = Button(root, text='Əlavə məlumat', command=esasionmginfo)

tree.pack()

treeatn = Button('qələvilik', command=qelelilikstat)
Infomg = Button(root, text='Əlavə məlumat', command=esasionmginfo)

tree.pack()
```

5. Conducting Experiments

Considering the variation range of the parameters that determine drinking water quality, a large number of alternative vectors arise in the overall description. Formally, these can be represented as a criterion space. In our case, the alternatives are not purely mathematical objects but physical states of the system, i.e., the condition of the reservoirs depending on specific parameters. To construct the set of alternative states, all possible solutions must be collected, measured parameters standardized, and each state evaluated according to the relevant criteria. Expert knowledge is applied at this stage of the process. The experiments were conducted at the Ceyranbatan Reservoir (CSA) located on the Absheron Peninsula, covering the years 2021–2024. CSA and the water treatment complex built on its shore play a major role in supplying drinking water to the Absheron Peninsula. The reservoir has a total capacity of 186 million m³, with a useful volume of 150 million m³. Its length is 8.74 km, maximum width 2.15 km, shoreline 23.3 km, maximum depth 28.5 m, dead storage level 14.5 m, and water surface area 1,389 hectares. One of the main advantages of the reservoir is that 80 % of the collected water undergoes natural sedimentation before entering the treatment process. Currently, 22 parameters affecting drinking water quality are measured at 6–7 sampling points. During the observation period, 720 measurements were carried out. When statistical data for the same parameters are collected from different points of a single object, decision-making problems arise. This is particularly important for regular measurements. The processing of measurements was primarily conducted using the One-Way Analysis of Variance (ANOVA) system.

In the *t*-test, the ***t*** statistic is calculated, and this value is used to determine the *p*-value. The *p*-value represents the probability that the observed difference between group means occurred by chance. If the *p*-value is below the predetermined significance level (e.g., 0.05), the difference is considered statistically significant, and the null hypothesis is rejected. Based on the obtained results,

$$t \geq t_{table}$$

this means that there is a significant difference among these indicators.

It is well known that the Student's t-test is one of the most widely used tests in statistical analysis. This test is particularly applied to compare the means of groups with small sample sizes [23]. The average results for all sampling points are calculated, and then a two-sample t-test is applied to compare them. Even the difference of a single point from the other five points has been evaluated based on multifactorial samples and its reliability has been confirmed. As a result of all these processing steps, the system successfully passed testing without issues. As an example, let us examine the processing of the turbidity parameter. The comparison results of the JWR Takhtakoru indicators with two other sampling points are presented in Table 1.

TABLE 1. Comparison of JWR Takhtakoru Indicators with Two Other Points

	JWR Takhtakoru Jeyranbatan canal	JWR-Near the intake structure		JWR Takhtakoru Jeyranbatan canal	JWR - Near the South Pumping Station
	1,00	2,00		1	1
	1,00	1,00		1	1
	1,00	1,00		1	1
	3,00	2,00		3	3
	...	...		...	...
	16,00	2,20		16	2,5
	7,00	0,90		7	3
	2,00	4,00		2	6
	3,00	1,00		3	2
	4,33	4,29		6,49375	4,25625
	5,27	3,53		5,272934	2,822483
	0,93	3,07-5,51			
	1,83				
Average	5,27	0,62		0,932132	0,498949
Standard Deviation	2,51	1,22184		1,826978	0,977941
Confidence Interval		5,51		8,320728	5,234191
		3,07		4,666772	3,278309
t-statistic		0,041248			2,116299

The turbidity parameter can also be monitored graphically. In Fig. 5, measurements taken every 5 days from March to July 2023 (32 measurements) at 7 sampling points are presented, with cumulative values shown in violet and the standard (norm) indicated in red. It should be noted that the results obtained from different points for the same parameter are not identical. The presence of such differences complicates the process of deriving a final conclusion for the entire water reservoir. Therefore, cumulative results were also calculated across all sampling points, and their corresponding graph was analyzed.

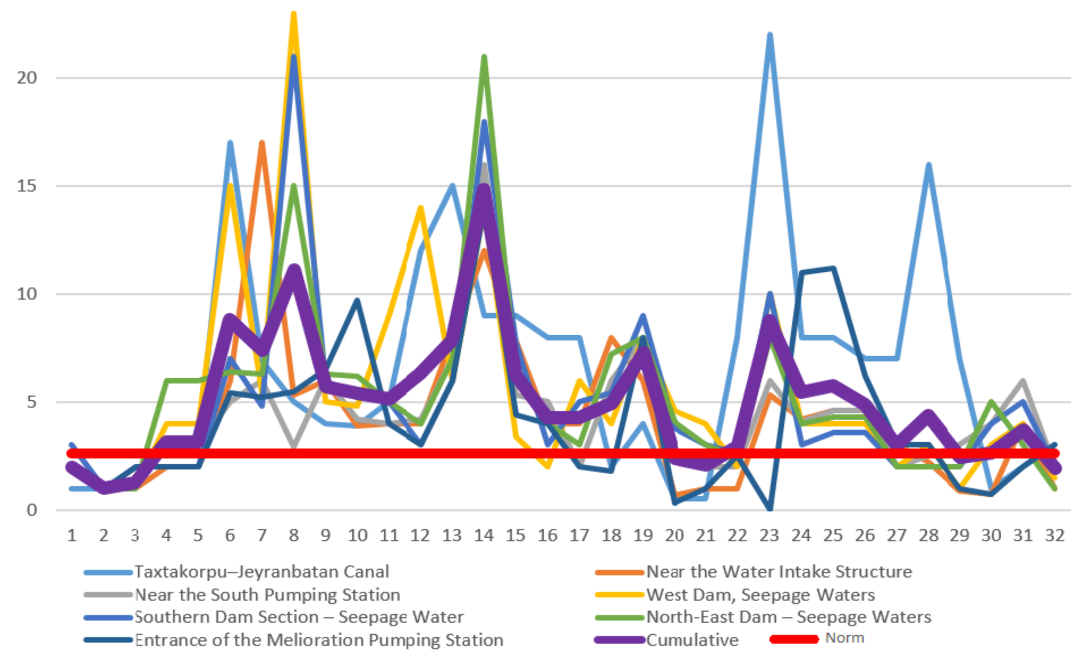

FIG. 5. Turbidity Measurement Results for 2023

For the turbidity parameter at the points "CSA Takhtakoru Ceyranbatan Channel – near CSA Water Intake Facility," the Student's *t*-value was calculated as 0.04125. Considering that the tabulated *t*-value for the number of measurements is 1.671, it is evident that no significant difference exists between the indicators. The same conclusion is confirmed by the results of the one-way analysis of variance for the same indicators (Table 2). For the points "CSA Takhtakoru Ceyranbatan Channel – near CSA South Pumping Station," the Student's t-value was 2.1163. Considering the tabulated t-value for the number of measurements, this indicates that a significant difference exists between these indicators.

TABLE 2. Processing Results Using ANOVA

One-Way Analysis of Variance (ANOVA)

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	32	207.8	6.49375	27.80383065
Column 2	32	136.2	4.25625	7.96641129

ANOVA

Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	80.1025	1	80.1025	4.478722853	0.038341247	3.995887126
Within Groups	1108.8775	62	17.88512097			
Total	**1188.98**	**63**				

One-Way Analysis of Variance (ANOVA)

SUMMARY

Groups	Count	Sum	Average	Discpersia	Variance
Column 1	17	207	12.17647		4.639375
Column 2	13	157	12.076923		27.6883055

ANOVA

Source of Variation	SS	df	MS	F P-value	F critical
Between Groups	77.43585	1	77.43585	3.686754282	3.9587126
Within Groups	410.2177	61	6.72651011		
Total	487.65302	62			
Itogo	487.6532	62			

In the system, this type of processing is applied to all parameters individually for each measurement, as well as cumulatively; the results are analyzed and decisions are made accordingly.

After each measurement, the indicators are compared with the corresponding norm database. The system detects which parameter deviates at which point and issues an alert. A few examples are given below.

On October 10, 2023, the system recorded the following (sampling point names are provided):

- For suspended solids, where the permissible concentration limit is 0.75 mg/L, the water sample from **Takhtakoru – Ceyranbatan Channel** measured 2 mg/L (2.66 times higher);
- From **near the water intake facility**, 3 mg/L (4 times higher);
- Near the **South Pumping Station**, 3 mg/L (4 times higher);
- In **south-west dam leakage waters**, 3 mg/L (4 times higher);
- In **south dam leakage waters**, 7 mg/L (9.3 times higher);
- In **north-east dam leakage waters**, 4 mg/L (5.33 times higher);
- From the **melioration pumping station intake**, 2 mg/L (2.66 times higher).

A second example from **April 17, 2024**, shows the results of hydrochemical analyses:

- In the water sample from **south dam leakage waters**, $PO4^{3-}$ orthophosphate ions exceeded the permissible concentration of 3.5 mg/L, measuring 4.1 mg/L (1.17 times higher);
- In the water sample from the **south-east part of Qumyataq Lake**, suspended solids exceeded the permissible limit of 0.75 mg/L, measuring 2 mg/L (2.66 times higher);
- Additionally, the pH value, which should be within 6.5–8.5, measured 9 in the sample from Qumyataq Lake.

All measurement and analysis results are stored in the decision-making archive database for future use in predictive assessments.

Conclusion

Natural and artificial water reservoirs are strategic facilities, and ensuring their physical and ecological safety is of state-level importance. From this perspective, the development of a unified automated intelligent information system is a pressing issue. Water reservoirs connected within a network can be centrally managed from the server–center node during emergencies, while in normal operation they retain autonomous functionality. The “Object–Server–Center” and “Center–Server–Object” routes remain constantly active. The number of sampling points for each reservoir, the specific parameters of the reservoir, and the measurement frequency vary, and these factors are considered in the software design.

Based on the functional and conceptual model, an automated intelligent information system has been developed to ensure the ecological safety of water in reservoirs, and its software has been implemented. The system functions as a real-time, network-based digital platform, utilizing paperless technologies and enabling seamless information exchange between various institutions [24, 25]. The conducted studies have demonstrated the feasibility of providing operational and reliable control over the ecological safety of drinking water in reservoirs [26]. The system allows comprehensive monitoring of physical, chemical, organoleptic, and other parameters using multidimensional time series. The norm database, current database, and archive database structure ensures systematic storage of measurement results, comparative analysis, detection of long-term trends, and predictive capabilities. The application of mathematical tools has enabled accurate evaluation of parameter differences and scientific justification of the decision-making mechanism. The software’s real-time visual-analytical capabilities make it possible to detect deviations from norms with high precision and issue immediate alerts. Testing conducted between 2021 and 2024, along with field validations in 2022–2023, confirmed the system’s adequacy and practical effectiveness. The results indicate that the proposed solution can be an effective tool for enhancing the ecological safety of water reservoirs. The system’s functional capabilities were verified using real monitoring data collected from 2021 to 2024, and comparative analyses across various input–output points and parameters demonstrated high adequacy and reliability of the system (≈ 87–91 %). This confirms that the system is fully operational and suitable for practical application. Considering the critical importance of drinking water safety in the country and dependence on transboundary water sources, the automated intelligent information system represents a promising platform for unified and centralized ecological control across national reservoirs and can serve as the foundation for a large-scale monitoring network in the future.

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Received/Одержано 13.03.2026 Accepted/Прийнято 26.05.2026 Published/Надруковано 01.06.2026