Original Paper

Assessment of Water Quality of Reservoirs by a Comprehensive Study of Hydrobiological and Hydrochemical Indicators Using the Example of the Hrazdan Reservoir (Armenia)

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Article Details: Received: 2025-04-07 | Accepted: 2025-06-30 | Available online: 2025-09-30

https://doi.org/10.15414/afz.2025.28.03.221-234

The water quality of the Razdan reservoir was assessed using hydrobiological, hydrochemical and microbiological methods in different seasons of the year. As a result of studies at three observation stations, it was found that at the outlet of the reservoir, in almost all the seasons under study, the quality of water does not meet the accepted standards used for agricultural irrigation. This is a consequence of the increase in organic pollution of the reservoir due to seasonal fluctuations in its water level in different seasons, leading to significant changes in temperature and concentration of biogenic substances. PCA analysis of bacterial counts, algal cell counts, and water chemistry showed that a total of 65.4% of the data variance was explained by the two principal components. In total, only two different groups showed factor loadings >0.1. The highest abundance of S_20 and *Bacillariophyta* species may be related to the typical August environmental conditions. In contrast, the high abundance of S_37 and *E. coli* may depend on the nitrogen availability in autumn (October and November). Such comprehensive studies of reservoirs allow for a more accurate assessment of the quality of their water. At the same time, not all water quality indicators may exceed the accepted standards. However, the appearance of even some indicators exceeding these standards may become a significant argument for developing recommendations for reviewing the possibilities of using reservoirs for agricultural needs.

Keywords: water quality, Hrazdan Reservoir, integrated approach, principal component biplot

1 Introduction

Reservoirs are artificially created ecological systems that have no analogues in nature in a number of parameters (Avakyan et al., 1987). In reservoirs, special hydrological (level regime, water flow, water exchange, flow, currents, waves) and hydrochemical (mineralization, main ions, nutrients, microelements, dissolved gases) regimes are formed which in turn determine the specificity of the development of reservoir ecosystems and the features of the formation of their biota.

A characteristic feature of reservoirs is a variable water regime – frequent and significant fluctuations in the level, as a result of which the coastal zone dries up in the summer and freezes in the winter, which leads to the death of many aquatic organisms in this zone. The plankton formed in the reservoir contains several more species of bacteria than the plankton of rivers (Shcherbakov, 2016).

Reservoirs are basic for large-scale water management systems, with their multifunctionality they help in adjustment of natural run-off with its seasonal variations and climatic irregularities to meet the increasing demand for irrigated agriculture, power generation, domestic, industrial water supply and navigation. The reservoirs are constructed for domestic use where large natural lakes are usually sparse and unsuitable for human exploitation,

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enhancement of fisheries and improvement of water transport.

Sources of water for irrigation can be surface and underground waters, and in case of their deficiency, collector-drainage and sea waters. There are currently no officially established safety standards for irrigation water.

In the Republic of Armenia, the standards adopted for surface waters are used as the standard for irrigation water (standards up to the 4th class of ecological purity are acceptable for irrigation). To ensure a comprehensive assessment of irrigation water quality, agronomic, technical and environmental criteria should be taken into account.

Environmental criteria should determine the quality of water for irrigation, taking into account the need to ensure a safe sanitary and hygienic environment in a given area and environmental protection.

However, the quality of water in reservoirs does not always meet the requirements of a particular area of the national economy, which of course affects the efficiency of work and the quality of the resulting products.

In this regard, the need to assess the appropriate quality of water and reservoirs in different seasons of the year is an urgent need. This is especially true for reservoirs whose water is intended for irrigation. At the same time, conducting only hydrochemical or hydrobiological analysis of water separately often does not give the desired results. Therefore, to obtain a more complete picture, it is necessary to conduct comprehensive studies of the water quality in reservoirs.

One of the important hydrobiological indicators of water quality in hydroecosystems is a phytoplankton. Research of phytoplankton of reservoirs allows us to assess the ecological state of the ecosystem and determine the impact of the development of various indicator algae on the formation of water quality indicators. Phytoplankton is considered a good indicator of water quality and trophic conditions due to its rapid response to environmental changes and deterioration of water quality. Due to their short lifespan, plankton reacts quickly to environmental changes, and therefore the yield and species composition indicate the quality of the water body in which they are found (Himalayan, 2019). Phytoplankton play an important role in aquatic ecosystems, acting as primary producers and stimulating the functioning of food webs. Dynamic changes in plankton communities are closely related to the physicochemical characteristics of water, such as water level, nutrient concentrations, light conditions and other environmental factors. In reservoirs, as in other bodies of water, phytoplankton is an indicator of water quality and can indicate the presence of pollution or eutrophication processes.

Microbiological indicators are usually used to determine the degree of water pollution, its quality, characteristics of the sanitary condition of the reservoir, and the self-purification process (Tekanova, 2016). Bacteria, which have high ecological plasticity and the ability to regenerate, are the best indicators of even the most minor changes in the environment. The response of bacteriocenoses to the influx of pollutants into the aquatic ecosystem is reflected in changes in the quantitative and functional indicators of the development of those ecological trophic groups of bacteria that use these substances as an energy and constructive substrate (Ladeira de Melo, 2019). Good water quality indicators include saprophytic bacteria which are a major component of aquatic ecosystems and play an important role in the circulation of materials and energy. Heterotrophic bacteria play an important role in aquatic ecosystems by decomposing allochthonous organic matter. They also make a significant contribution to the self-purification of water bodies and the formation of water quality. The content of saprophytic bacteria in water bodies largely depends on the influence of anthropogenic factors. It is known that saprophytic bacteria in an aquatic ecosystem are a more sensitive indicator than the total number of bacteria, since a slight change in easily oxidizable substances leads to a corresponding change in saprophytic bacteria (Drachev, 1964; Tekanova, Makarova, 2016; Kavka et al., 2006; Mosharova et al., 2019).

In this work, complex hydrobiological, hydrochemical and microbiological studies were carried out on the quality of water in the Hrazdan Reservoir in Armenia which is one of the key sources of water used for irrigation in the central part of the country.

2 Materials and Methods

2.1 Study area and Sampling Stations

The studies were conducted at the Hrazdan Reservoir (Republic of Armenia 40° 30′ 27.1″ N 44° 44′ 44.3″ E). The reservoir was built in 1953, has a height of 1695 m, and consists of two parts. It is located in Kotayk region, near the city of Hrazdan. The surface area of the reservoir at its maximum level is 1.7 km^2, the volume is 5.6 million m^3, and the useful volume is 4.1 million m^3, the level fluctuations are 3 m (Ayvazyan, 2006). It is fed by the Hrazdan and Marmarik rivers. Although the reservoir has a significant flow, it is covered with ice in winter. The main purpose of the reservoir is to redistribute river flow. The Hrazdan Reservoir is part of the Sevan-Hrazdan hydrosystem cascade and is a regulating reservoir for the Argel HPP. The Hrazdan Reservoir is a very important

Figure 1 Observation stations of the Hrazdan Reservoir

reservoir for the republic, the water of which is used for agricultural and industrial purposes (Chilingaryan et al., 2002). The water in the reservoir often drains which does not ensure the sustainable development of biocenoses. During our research, the water level changed but did not drop completely which allowed us to study the biological and physicochemical changes in the reservoir.

Sampling from the Hrazdan Reservoir was carried out from February to October 2023, from three different sites (Figure 1):

- Observation station I (40° 30′ 33.1″ N 44° 45′ 23.9″ E) – the entrance section of the Hrazdan River, where there is practically no water flow, a large projective cover of aquatic plants. On the opposite bank there is an operating hydroelectric power station, which also affects the fluctuations of the water level.
- Observation station II (40° 30′ 20.0″ N 44° 44′ 58.2″ E) is the junction of two sections of the reservoir, where a constant water flow is observed.
- Observation station III (40° 30′ 44.3″ N 44° 44′ 38.0″ E) – the right shore of the reservoir, where the greatest fluctuations in water level are usually observed.

During the study period hydrophysical, hydrochemical and hydrobiological studies were carried out monthly.

The data were statistically processed using the Statistica 8.0 software package.

2.2 *Hydrochemical and Hydrophysical Analysis*

Dissolved oxygen (DO) concentration, biochemical oxygen demand (BOD_5), nutrients (nitrates, nitrites, ammonium ions, and phosphates) and pH were determined in the water samples.

Temperature, pH, DO and BOD_5 were measured via the electrochemical method by Hanna HI98130 waterproof pH/EC/TDS/temperature meter (Romania) and Milwaukee (MW 600) Dissolved Oxygen meter (USA). The nutrients' concentration (NO_3-N, NO_2-N, PO_4-P) were measured according to the methods of International Organization for Standardization using visible UV 68 TOUCH spectrophotometer (USA) nitrite nitrogen (ISO 6777:1984), nitrate nitrogen (ISO 7890-3:1988), phosphate phosphorus (ISO 6878:2004). Ammonium nitrogen analysis was carried out by Nessler's reagent colorimetry method (Jing-Ping Wang et al., 2019).

For delayed fluorescence (DF) analysis, 50 ml of freshwater samples were filtered through Vladipore No. 10 membrane filters in ordr to concentrate phytoplankton. To measure the second-order components of DF (from 5 to 20 seconds), concentrated phytoplankton was exposed to the light for one minute at an illumination intensity of 500 lux, then the sample was transferred to the dark chamber of the device and the kinetics of the intensity decline of the luminescence for a period of 5 to 20 seconds was recorded using an instrument assembled by us from standard equipment (Sargsyan, 2019). The content of easily oxidizable organic substances in water samples was measured by determining the degree of water oxidation using the Kubel method (Lure, 1973). Water hardness was determined using the complexometric method (Lurie, 1971). Biochemical oxygen consumption was determined by the manometric method, according to the accepted scheme (Theoretical principles of the manometric method for determining BOD, 2015; Methodology for determining BOD_5 in drinking, natural and waste water samples, 2016). The concentration of hydrogen ions in water was measured both at the sampling site and immediately after transportation to the laboratory using a pH meter-121.

2.3 *Microbiological Analysis*

Microbiological studies were carried out using accepted hydrobiology methods (Rodina, 1965; Namsaraev et al., 2006). The coli index was determined by membrane filtration with triplicate repetition. Saprophytic bacteria were grown on agar medium

(DNA) in triplicate and at different temperatures: 20–22 °C and 35–37 °C (Larionova et al., 2010; Leonova, 2012).

The ratio of saprophytic bacteria incubated at different temperatures allows us to determine the intensity of the bacteriological self-purification process. The self-purification process is considered complete when the ratio of bacteria grown at these two temperatures is 4 (Parshukov & Sidorova, 2010; MUK 2.1884-04).

2.4 Phytoplankton Analysis

Phytoplankton samples were collected once a month from February to November. A 1-liter water sample taken at each observation point was spiked with 40% formaldehyde solution (final concentration was 0.4%) and transported to the laboratory where further studies were performed. Fixed phytoplankton samples were left to settle in the dark for 10–12 days, then the volume of the experimental samples was reduced from 1,000 ml to 100 ml using a siphon. By repeating the same process, the volume of the samples studied was reduced to 10 ml (Abakumov, 1992). Qualitative and quantitative analysis of phytoplankton were carried out under a microscope using a Najot chamber. Taxonomic groups of phytoplankton and establishment of species composition were identified using guides to freshwater systems (Linne von Berg et al., 2012; Streble & Krauter, 2001; Tsarenko, 1990).

2.5 Macrophyte Analysis

For the qualitative and quantitative assessment of macrophytes, areas measuring 1 × 1 m were selected, and plant samples were collected at each observation point in 7-fold replication. In laboratory conditions, plants were classified into species. Scientific names verified against Plants of the World Online (POWO, 2024) and World Flora Online (WFO, 2024) databases.

The percentage of projective cover of each taxon was determined in the field: 1: <0.1%, 2: 0.1–1%, 3: 1–2.5%, 4: 2.5–5%, 5: 5–10%, 6: 10–25%, 7: 25–50%, 8: 50–75% and 9: >75% (Holmes et al., 1999).

2.6 Statistical Analyses

Principal component analysis (PCA) was used to reveal linkages among the bacterial and algal cell numbers and water chemistry. Factor loadings more than 0.1 (by absolute value) were used for interpretation of the linkages. PCA was run in R 2024.04.1 Build 748 version.

3 Results and Discussion

3.1 Hydrochemical and Hydrophysical Analyses

The results of hydrophysical and chemical studies clearly show the influence of anthropogenic factors on the lake, especially in spring (starting from 4th month). At station III, a sharp increase, almost threefold, in pH (from pH 8.6 to 9.8) was observed. An increase in permanganate oxidizability of water (PO) from 3.8 to 12.0 mgO·l^{-1}, which was accompanied by an unprecedented threefold decrease in the average water hardness from 4.5 to 1.5 mg-eq·l^{-1}. Apparently these anomalies are due to the influence of heavy rainfall during the sampling period, which, washing the coastal areas, sharply increases the concentration of PO, especially the values, which in the following month return to the typical range of 4.0–3.8 mgO·L^{-1}. The relatively low BOD_5 values recorded under these conditions can be explained by the suppressive effect of high concentrations of organic matter and nutrients on bacterial growth. With a delay of 2–3 days, BOD_5 begins to develop slowly. However, BOD_{20} already records values close to the maximum of 8.2 mgO_2·l^{-1}. The same regularities with decreasing dynamics are basically repeated at stations II and I (Table 1).

The average annual value of water hardness at all observation points was 4.3–4.4 mg eq·l^{-1}. During the summer months, a noticeable increase in this indicator was observed to 5.2–5.5 mg.eq·l^{-1}, which is due to an increase in the solubility of mineral substances with an increase in water temperature.

The observed patterns were completely preserved in all three recordings, which indicates the reliability of the results. Some differences in the dynamics at different stations are explained by the gradual decrease in the water level in the lake to 1,500 cm and its increase by 10 cm (in autumn) (Figure 2).

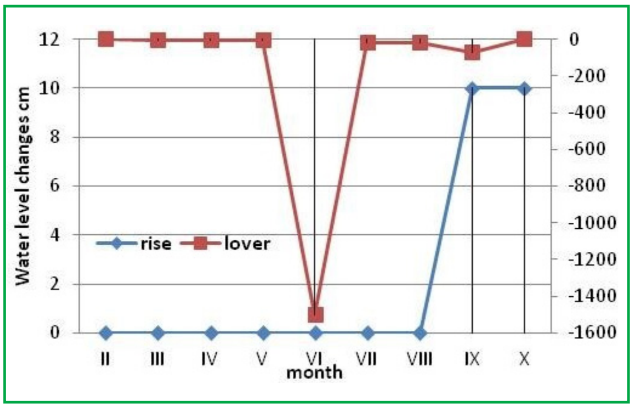

Figure 2 Monthly fluctuations in the water level in the Hrazdan Reservoir at station III

Table 1 Physicochemical parameters of water at different stations of the Hrazdan Reservoir

Months	T (˚C)	pH	Water hardness (mg.eq·l^{-1})	DO (mgO$_2$·l^{-1})	PO (mgO·l^{-1})	BOD$_5$ (mgO$_2$·l^{-1})	BOD$_{20}$ (mgO$_2$·l^{-1})	DF relative values		
								5 s	10 s	20 s
Station I										
2	–	–	–		–	–	–	–	–	–
3	–	–	–		–	–	–	–	–	–
4	10.2	8.6	2.0	7,8	9.2	2.0*	6.0	15	8	6
5	–	–	–		–	–	–	–	–	–
6	19	9.0	5.2	5,4	4.2	2.03	6.3	44	25	20
7	18.0	9.2	5.5	7,2	5.0	2.73	7.6	33	25	18
8	20.0	9.2	4.5	15,8	4.7	2.73	7.8	73	51	26
9	11.2	8.0	4.5	3	3.5	2.70	7.8	33	19	11
10	10	8.7	4.5	6,8	3.6	4.16	9.2	56	31	20
Station II										
2	–	–	–	–	–	–	–	–	–	–
3	10.9	8.8	2.7	5,1	4.2	1.22	6.3	70	50	25
4	11.4	8.6	1.9	5,6	10.8	1.09	6.4	50	32	12
5	9,7	9.3	5.2	6,5	3.8	2.40	6.3	89	53	28
6	19	9.0	5.2	4,3	3.9	1.73	6.5	34	28	12
7	18.0	9.2	5.5	6,1	5.2	2.09	8.3	46	28	17
8	20	9.2	4.5		4.2	3.28	8.1	73	53	25
9	11.2	8.9	4.5	11.8	3.9	2.20	8.2	212	124	63
10	10.7	8.8	4.5	5.6	3.5	4.68	9.0	123	78	38
Station III										
2	0	8.6	4.27	8,3	3.3	1.0	5.0	–	–	–
3	7.5	8.6	3.5	5,6	3.8	1.61	5.0	215	124	63
4	18.7	9.8	1.5	11,4	12.0	2.03	8.2	150	120	30
5	12.7	9.6	5.2	9,2	4.0	2.84	7.4	170	140	43
6	21.0	9.2	5.2	6,5	4.4	2.08	6.5	115	68	43
7	18.0	9.6	5.4	7,2	5.6	2.0	7.1	80	56	36
8	20.0	9.4	5.2	10,9	5.2	3.09	8.2	125	78	38
9	11.2	8.9	5.2	9,4	4.9	2.73	8.3	223	152	77
10	12,9	8.9	4.5	4,9	3.9	3.36	8.7	150	110	58

DF has three annual peaks (Table 1): at stations III and II in March, May and September, and at station I in June, August and October. It is obvious that these phytoplankton peaks, the recorded values of DF, refer only to the amount of green algae (hourly unit).

The content of nutrients in the reservoir did not undergo drastic changes during the study period. For example, at station III, the ammonium nitrogen content fluctuated minimally: 0.02 (August) – 0.39 mg N·l^{-1} (July). At station II, the variation limits are lower: 0.11–0.29 mg N·l^{-1}. At station I, the maximum ammonium nitrogen values were recorded in September – 0.4 mg N·l^{-1}, and a sharp decrease of the ammonium nitrogen content in October was observed (Figure 3).

The smallest quantitative changes during the year were recorded for nitrite ions. Basically, a decrease in the amount of such ions was recorded at all observation points of the reservoir in the spring-summer period, with maximum values recorded in September (Figure 4). We consider that the seasonal increase in the concentration of nitrite ions is associated with the activity of microorganisms and algae, as

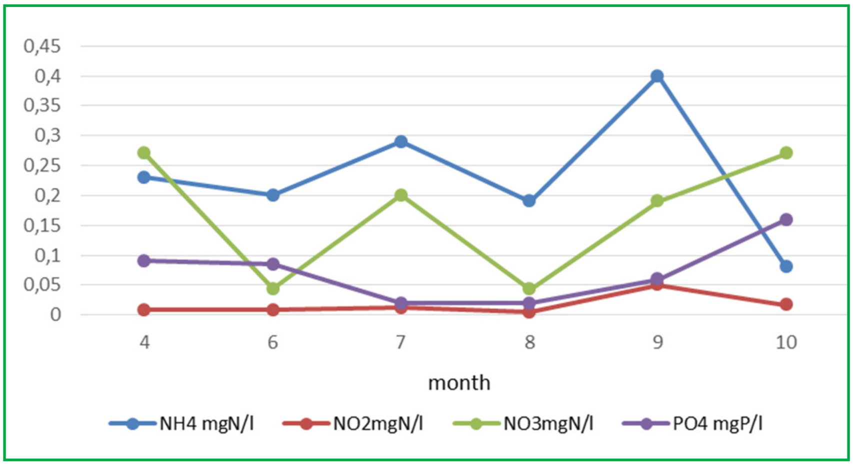

Figure 3 Dynamics of nutrients at station I

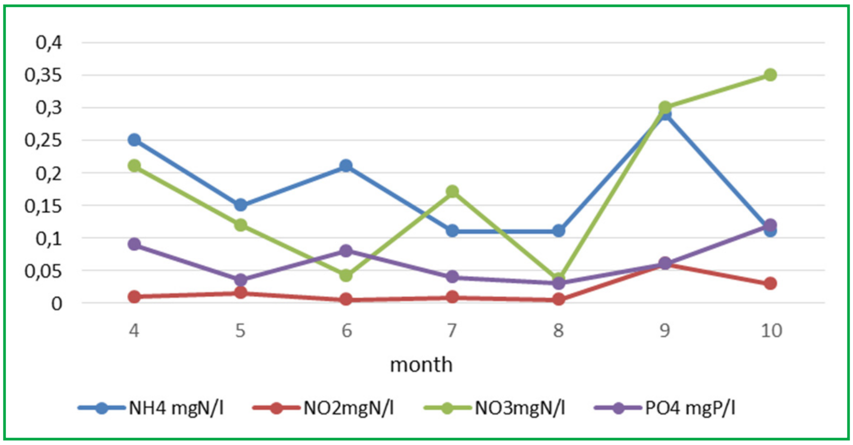

Figure 4 Dynamics of nutrients at station II

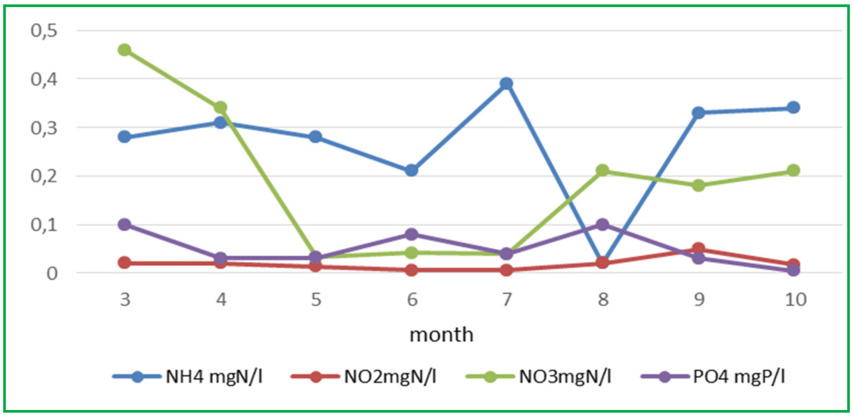

Figure 5 Dynamics of biogenic elements at station III

well as with the intensification of the decomposition processes of organic matter. Overall, nitrite ion levels did not exceed environmental limits.

Nitrates are the result of mineralization of ammonia and nitrites, which are formed as a result of the decomposition of organic matter. The maximum values of nitrate ions in the reservoir were recorded at station III in March: 0.46 mg $N \cdot l^{-1}$ (Figure 5). In the spring-summer period, a decrease in nitrate nitrogen levels was noted, which is probably due to the quantitative development of macrophytes and algae in the reservoir. During the study, similar dynamics of variation in nitrate nitrogen indicators were recorded at stations I and II. At the indicated stations, the minimum values of nitrate nitrogen were recorded in the 8^{th} month, and the maximum values in the 10^{th} month (Figures 3, 4).

Note, in general the content of nitrate ions in the reservoir throughout the entire study period did not exceed the environmental standard.

The minimum values of mineral phosphorus content in the Hrazdan Reservoir were recorded in October: 0.005 $mgP \cdot l^{-1}$, at station III. The quantitative dynamics of mineral phosphorus varies significantly among the observation stations studied. If at stations I and II the minimum values of mineral phosphorus were recorded in August, and the maximum in October, then at station III the opposite dynamics were observed (Figures 3, 4, 5).

3.2 Microbiological Analysis

The number of mesophilic (37 °C) saprophytic bacteria in the Hrazdan Reservoir fluctuated between 70–18,000 $CFU \cdot ml^{-1}$. The lowest value (70 $CFU \cdot ml^{-1}$) was recorded at observation point III, in

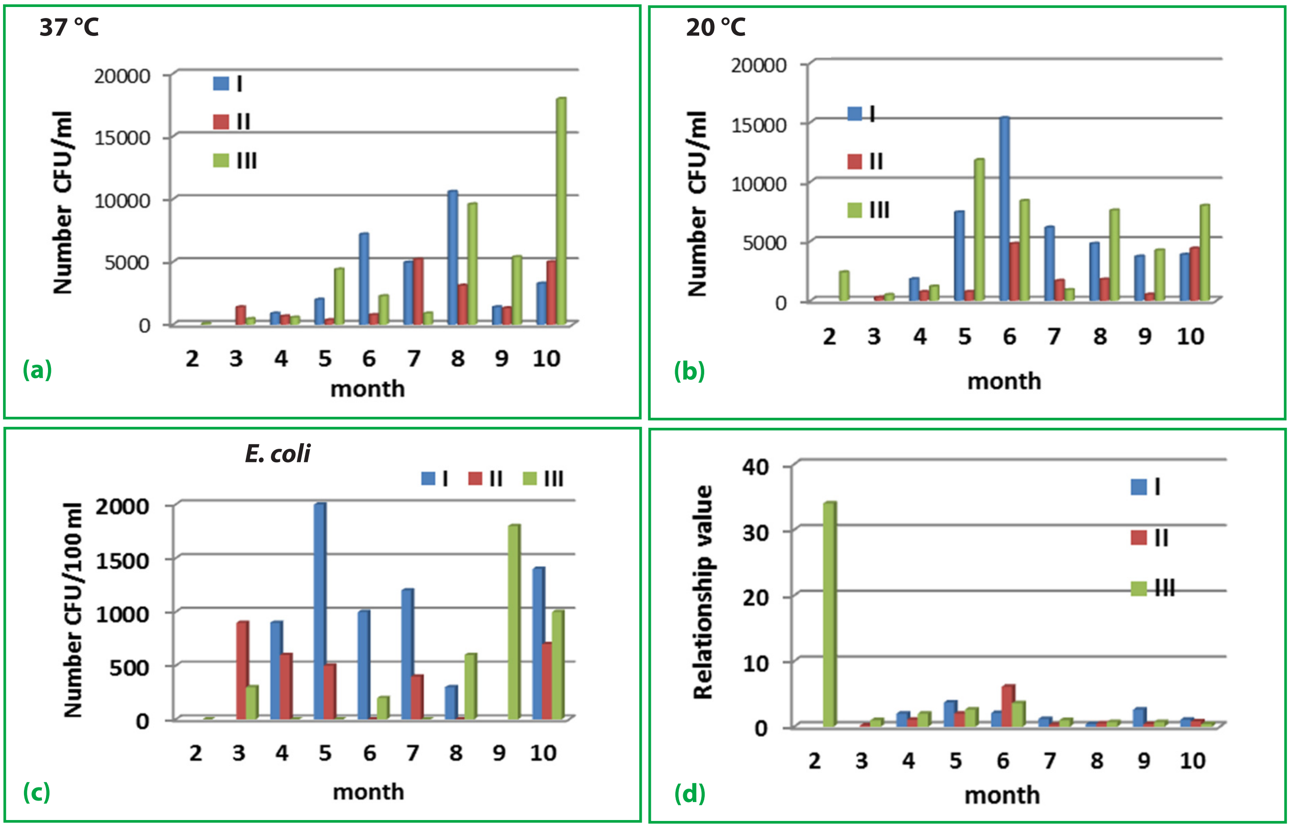

Figure 6 (a) The number of saprophytic bacteria in CFU·ml^{-1} growing at 37 °C; (b) The number of saprophytic bacteria in CFU·ml^{-1} growing at 20 °C; (c) The number of *E. coli* bacteria in CFU·100 ml^{-1}; (d) The intensity of the self-purification process is estimated based on saprophytic bacteria
I – before the reservoir, II – connection, III – right shore

the second month (Fig. 6a), which was due to the low water temperature and the completely frozen surface of the reservoir, which made it difficult for the soil to penetrate the coastal zone layer.In the following months, the number of mesophilic saprophytic bacteria increased due to the increase in water level and temperature.The highest value (18,000 CFU·ml^{-1}) of bacteria was recorded at observation station III, in the 10th month, which is associated with a decrease in the number of algae.

The *E. coli* count ranged from 200 to 2,000 CFU·100 ml^{-1} (Figure 6c). Relatively high values for the year were recorded at observation station I due to the river inlet. The area in question is rich in aquatic plants, and some of the bacteria attach to the aquatic plants, thus protecting themselves from ultraviolet rays, while others settle to the bottom of the reservoir. Due to the decrease in the reservoir level, the mentioned bacteria mix with the reservoir water, making it dangerous for irrigation. A striking example of this is the relatively high values of *E. coli* bacteria (1,000–1,800 CFU·100 ml^{-1}) recorded at the observation station III of the reservoir under conditions of drawdown of more than 1.5 m.

A relatively high value of the number of saprophytic bacteria growing at a temperature of 20 °C was recorded in the 6th month (Fig. 6b), probably due to a decrease in the water level (1,500 cm) (Figure 2).

In surface waters, autochthonous (20 °C) microflora should prevail over allochthonous (37 °C). However, the opposite picture was often observed in the reservoir (Figure 6a, b).The values of the intensity of the self-purification process of water by saprophytic bacteria grown at two different temperatures (20 °C and 37 °C) ranged from 0.2 to 34 (Figure 6d). The maximum value of the intensity of the self-purification process (34) was recorded in the second month, since the sampling was carried out from under the ice, the water temperature was very low, and the reservoir water did not flood the coastal zone. In the remaining months, the intensity of the self-cleaning process fluctuated within 0.4–3.6. The self-cleaning process assessment indicators gradually increased until the sixth month and decreased from the seventh month.

3.3 Phytoplankton Analysis

The species composition and quantitative indicators of phytoplankton of the Hrazdan Reservoir were studied in different seasons of the year as well as species-indicators of water quality and dominant groups were identified. The basis of phytoplankton of the Hrazdan Reservoir were species belonging to the Cyanophyta, Bacillariophyta and Chlorophyta departments. Species of the Euglenophyta, Charophyta and Xanthophyta departments were noted in individual seasons and did not play a large role in the quantitative development of the community.

The distribution of dominant phytoplankton groups in the reservoir varied seasonally: cyanobacteria dominated in February (65% of the total abundance), diatoms dominated in spring and autumn (11–84% of the total abundance), and the highest levels of green algae were recorded in May – July, accounting for 55–75% of the total abundance.The minimum values for the year in terms of quantitative development were recorded in February, the maximum values in terms of numbers were in May, and the maximum values in terms of biomass were in June (Figure 7). As studies have shown, the green species Binuclearia lauterbornii had a particularly high development in phytoplankton and caused weak water bloom, the maximum values were 1,748,000 cells·L^{-1}; 0.82 g·m^{-3}, were present in June at observation point I, causing weak bloom. Kirchnerirella obesa (21,000 cells·L^{-1}; 0.6 g·m^{-3}) in March, Ankistrodesmus angustus (224,000 cells·L^{-1}; 0.19 g·m^{-3}) in May, Scenedesmus quadrucauda (104,000 cells·L^{-1}; 0.46 g·m^{-3}) in September. The development of the main groups of phytoplankton in 2023 had the following figure (Figure 7).

Diatoms were more uniformly developed and distributed in the studied observation points, the dominant complexes were *Stephanodiscus astrae* (240,000 cells·L^{-1}; 1.08 g·m^{-3}), *Asterionella formosa* (304,000 cells·L^{-1}; 0.36 g·m^{-3}), *Fragilaria capucina* (416,000 cells·L^{-1}; 1.16 g·m^{-3}), *Nitzschia dissipata* (200,000 cells·L^{-1}; 1.2 g·m^{-3}), *Cyclotella kuetzingiana* (292,000 cells·L^{-1}; 0.64 g·m^{-3}) species. The quantitative development of blue-green algae is often associated with high temperature conditions and the presence of organic matter, especially in summer, which can lead to dangerous blooms. Cyanobacteria species were found at all observation points in the Hrazdan Reservoir in different seasons. Compared to the previous year, 2022, a significant expansion of the species composition was noted. Hydrobiological studies were conducted in the Akhpyurak reservoir, where the following species were noted: *Aphanothece clathrata*, *Microcystis aeruginosa*, *M. wessenbergii* (Stepanyan et al., 2021). In 2023 the following species have been added to the group of blue-green algae: *Phormidium foveolarum*, *P. papyraceum*, *Dactylococcopsis acicularis*, *Oscilaltosia lacustris*, *O. brevii*, *O. agardhii*, *O. tennius*, *O. chlorina*, *Spirulina platensis*, *Aphanocapsa delicatissima*, *Merismopedia elegans*, *Aphanothece stagnina*. The most extensive species composition, more than 10 species, was noted in June at observation station I where the influence of the Hrazdan River is great.

In the group of green algae, the development of large-celled and colonial species *Pandorina morum*, *Planctosphaeria gelatinosa*, *Gonatozigon brebissonii*, *Oocystis pusilla*, *Dictyosphaerium pulchellum*, *Ankira ancora*, *Coelastrum reticulatum*, *Sphaerocystis schoeteri*, *Pediastrum angustatum* contributed to the recording of high biomass values, as in the samples taken from observation stations II and III (Figure 8).

In the summer months, the development of phytoplankton was almost the same at stations I and II, and the highest biomass indicators were observed at station III, where the colonial species *Pandorina morum* developed in June, with a biomass of 8.3 g·m^{-3}, which is the maximum indicator for the entire study area.

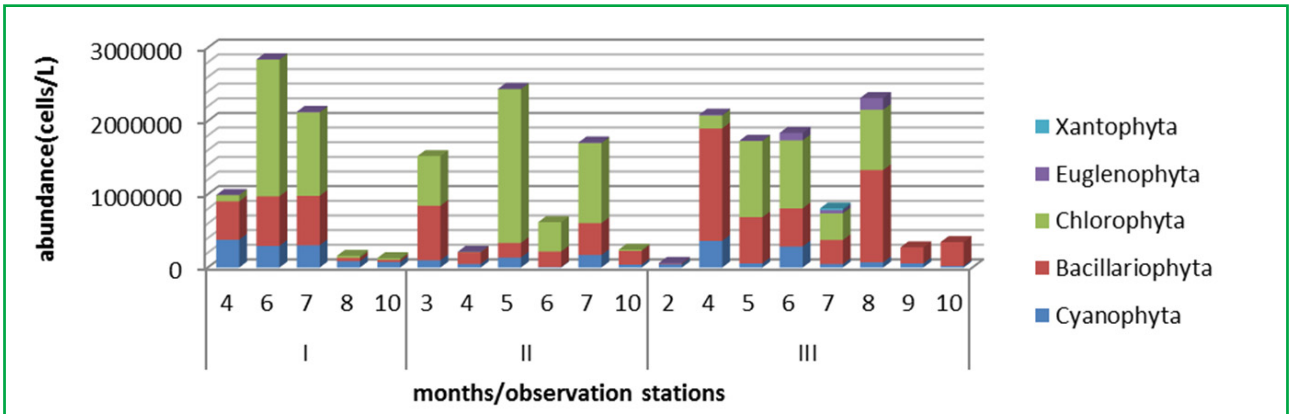

Figure 7 Dynamics of the main groups of phytoplankton in different months at individual observation station
I – before the reservoir, II – connection, III – right shore, by quantity (cells·L^{-1})

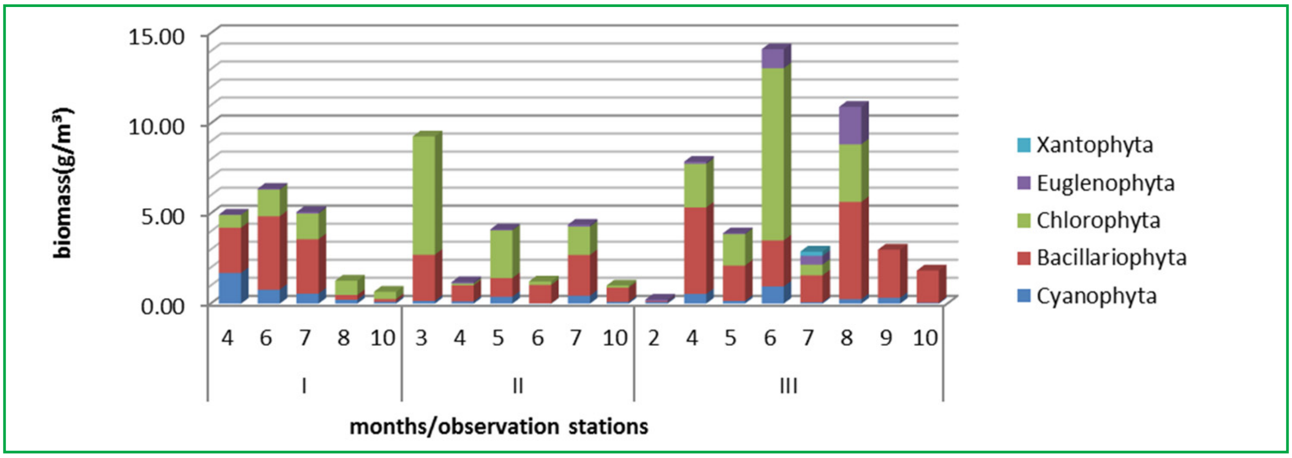

Figure 8 Dynamics of the main groups of phytoplankton of the Hrazdan Reservoir in different months at individual observation stations by biomass (g·m^{-3})
I – before the reservoir, II – connection, III – right shore

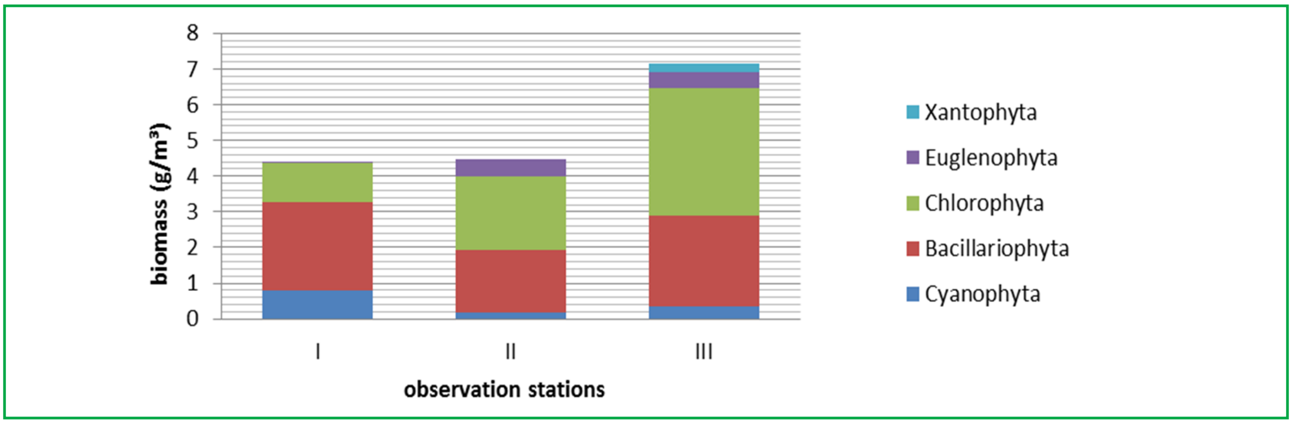

Figure 9 Average values of phytoplankton biomass (g·m^{-3}) in 2023 at different observation stations of the Hrazdan Reservoir
I – before the reservoir, II – connection, III – right shore

The development of the main groups according to average indicators had the following figure (Figure 9).

During the phytoplankton studies, more than 130 species of microalgae were found. The most numerous were diatoms – 64 species (49%), followed by green algae – 38 (29%) and cyanobacteria – 18 (14%) species (Figure 10a). 85% of the species found were good indicators of organic pollution, with β-mesosaprobe species dominating in terms of saprophytosis (65%) (Figure 10b).

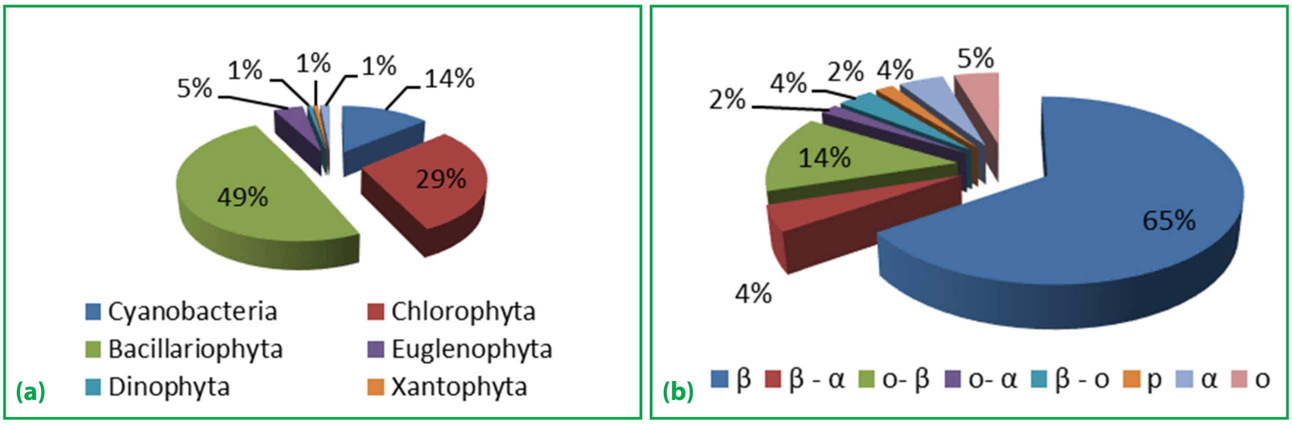

Figure 10 a) Species diversity (%); b) Species-indicators of saprobity in the community (%) of phytoplankton algae found in the Hrazdan Reservoir in 2023

In 2023 at various observation stations of the Razdan reservoir, diatoms dominated in spring and autumn, and green algae dominated in summer. Cyanobacteria also played a constant role in the quantitative and qualitative indicators of phytoplankton throughout the year and were detected at all observation points. The highest phytoplankton indicators were observed at station III of the Hrazdan Reservoir under conditions of maximum water level fluctuations, especially in the summer. The widespread distribution of cyanobacteria and the presence of toxic species in the plankton indicate an increase in the trophic status of the reservoir and other risks associated with a possible outbreak of bloom.

3.4 Macrophyte Analysis

The projective cover of macrophytes at observation station I in summer and autumn was 90% and 50%, respectively. In summer and autumn surveys, the species *Ceratophyllum demersum* and *Myriophyllum spicatum* formed bidominant associations. *Potamogeton pectinatus*, *P. perfoliatus*, *Zannichellia palustris*, and *Cladophora glomerata* were also recorded. At station III, the species *Myriophyllum spicatum* and *Ceratophyllum demersum* were noted with a projective cover of 15% in summer and 5% in autumn; the shore is almost always bordered by the species *Enteromorpha intestinalis* L. and *Cladophora glomerata* L. This difference in macrophytes is probably due to the position of station I, which is located at the entrance of the Hrazdan River. The river enriches the reservoir water with nutrients, ensures constant availability of water and a suitable depth for the growth of macrophytes. Unlike station I, at station III there are constant changes in the water level, as a result of which the water recedes and creates unfavourable conditions for the growth of macrophytes, while the presence of green algae is due to agricultural activity, in particular, the constant presence of farm animals in the surrounding area.

Thus, in 2023, the development of phytoplankton in the Hrazdan Reservoir manifested itself in dynamic changes that were closely related to seasonal fluctuations in water levels and changes in physical and chemical parameters. A change in the dominant groups of algae was also observed in different seasons of the year: diatoms, green algae and cyanobacteria, which indicates the cyclical development of phytoplankton in the ecosystem. At monitoring station III, mesophilic saprophytic bacteria were recorded to be close to minimum values and the maximum phytoplankton biomass was recorded in June, which was due to the development of the colonial species *Pandorina morum*, known as a toxic species and can produce products that affect the vital functions of some bacteria and higher plants (Gregory et al., 2007). This species was also discovered in 2021. During the studies, despite the high water temperature, high algae activity rates and low bacterial rates were recorded (Stepanyan et al., 2021). In autumn, due to low water temperatures a decrease in the quantitative indicators of phytoplankton was observed at all stations.

The conducted analysis of the quantitative and qualitative development of phytoplankton allows us to assess the quality of the reservoir water and identify trends in increasing the trophic status of the reservoir, caused by the toxicity of cyanobacteria and green algae species, indicators of organic pollution.

A significant increase in DF values was recorded at all three observation stations due to seasonal fluctuations in the water level: about 1,500 cm, then in the ninth month in the case of a 10 cm increase in the lake level. The highest values of DF are recorded at observation stations III and II, while at observation point I the results are close to the lowest values. The obvious reason for this is that as the lake level rises, water from the river flows into the reservoir, and the indicator reflects the low number of green algae in the river itself. And at observation stations III and II, the water rises and covers the humus-rich coastal zones, which promotes the growth of green algae. And at observation stations III and II, the water rises and covers the humus-rich coastal zones, promoting the growth of green algae.

The constant change in the number of bacteria in different parts of the reservoir is also associated with changes in the number and biomass of algae. Algal growth inhibits bacterial growth (Gregory et al., 2007; Glagoleva et al., 1992) as the number of mesophilic (37 °C) saprophytic bacteria decreases in parallel with the increase in algal quantity and biomass. For example, at station III, in the tenth month, the maximum values of mesophilic saprophytic bacteria and the minimum values of algae were recorded, and at the same time, the minimum value of the self-purification process was recorded (0.4). Compared with the results of previous studies (Stepanyan et al., 2021), a 3–4-fold increase in the number of mesophilic saprophytic bacteria was noted.

However, not all algal groups influence the growth of saprophytic bacteria, as statistical analysis revealed a positive correlation between the number of saprophytic bacteria growing at 37 °C and the number and biomass of Euglenophyta algae ($r = 0.9$; $p = 0.01$). The values of the studied physical and chemical indicators do not exceed the standards established for irrigation waters adopted in the Republic of Armenia and correspond to the class of clean waters, with the exception of the pH indicator according to which the water of the reservoir does not correspond to the accepted standards established for irrigation of lands (reference). Based on the obtained results, it can be concluded that, according to the accepted permissible sanitary and hygienic standards according to Romanenko (1990) (Romanenko, 1990), the waters of the Hrazdan Reservoir are within the permissible norm until September, and in the remaining months of the studied period, an excess of the accepted norms is observed. The BOD_{20} results confirm and complement the picture, and its high values indicate that the reservoir is dominated by difficult-to-oxidize organic matter. The latter is also clearly confirmed by the positive correlation between the number of saprophytic bacteria growing at 22 °C and 37 °C and the BOD_5 values at observation station III (r = 0.7; p = 0.04 and r = 0.8; p = 0.005), as well as the positive correlation between 10-second fluorescence at station I and the number of saprophytic bacteria growing at 37 °C (r = 0.8653; p = 0.0260). *E. coli* bacteria can regenerate on nitrites, which explains the positive relationship between the number of *E. coli* bacteria and NO_2 in the studied monitoring stations (r = 0.8–0.9; p = 0.007–0.02) (Tiso & Shekhter, 2015).

As a result of statistical analysis of the average annual values of the studied parameters, a positive correlation was revealed between the number of saprophytic bacteria growing at 22 °C and water hardness (r = 0.6616; p = 0.0523), as well as the number of saprophytic bacteria growing at 37 °C and BOD_5 (r = 0.9046; p = 0.0008, NH_4). There was also a negative correlation between the Euglenophyta group of algae, biomass, number of bacteria and NH_4 (r = -0.9282; p = 0.0228; r = -0.9296; p = 0.0222), and a positive correlation with PO_4 (r = 0.9494; p = 0.0136; r = 0.9516; p = 0.0127). A positive correlation was also recorded between the number, biomass and PO_4 of algae of the *Cyanophyta* group (r = 0.7869; p = 0.0119; r = 0.7961; p = 0.0103).

3.5 Statistical Analyses

The PCA analysis on the numbers of bacteria, algal cells and water chemistry is shown in Figure 11. In total, 65.4% of variance in data was explained by the two principal components. While in environmental quality assessments, factor loadings more than 0.4 have been commonly used (e.g., Aghajanyan et al., 2018; Rodríguez-Romero et al., 2016), lower factor loadings in PCA analysis can also be interpreted if they demonstrate clear groupings of variables on any of the principal components. In Figure 11, two different groups were demonstrated by the factor loadings >0.1. The highest numbers of S_20 and *Bacillariophyta* species might be stipulated by environmental conditions characteristic for the month of August. On the contrary, the large quantities of S_37

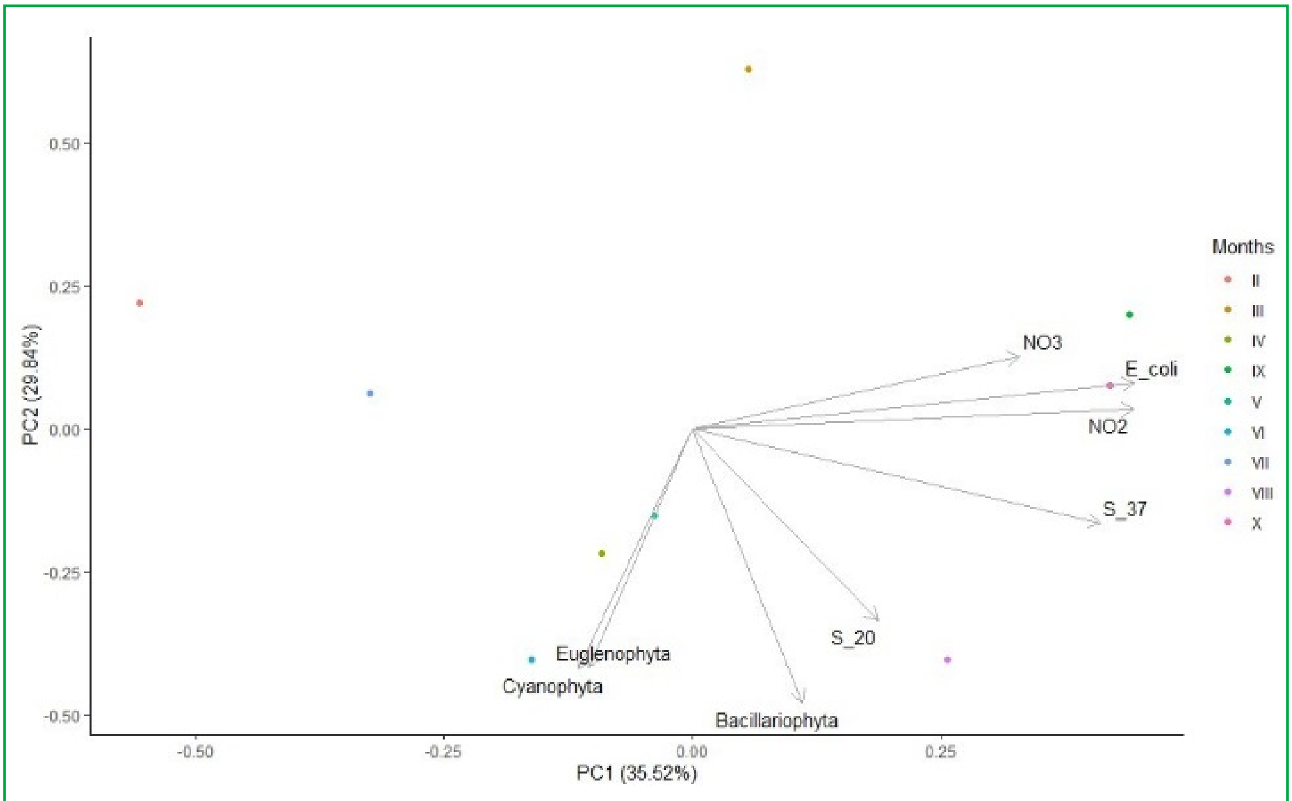

Figure 11 Principal component biplot of factor loadings and scores in the coordinate system of two main components

and *E. coli* can be influenced by the nitrogen availability in the autumn (October and November).

According to the updated classification table of water quality assessment by BOD_5/10/, the pollution of the lake waters was assessed as follows: Up to the eighth month, the water quality at all monitoring stations corresponded to the "moderately polluted" category; at stations III and II on the eighth month and at III on the tenth month it was assessed as "polluted"; and at stations I and II on the tenth month – as "high polluted" water. Monitoring station III on the tenth month was classified as α-mesosaprobic waters.

According to V.D. Romanenko (1990) (Romanenko, 1990), the number of mesophilic saprophytic bacteria in the Razdan reservoir varied from the "clean" to "high polluted" categories. The reservoir water was classified as "high polluted" for the eighth month at monitoring station I and for the tenth month at monitoring station III.

Based on the amount of *E. coli* bacteria, the reservoir's water quality ranged from "clean" to "polluted." The reservoir water was characterized by saprobity within the range of β-oligosaprobic (second-fourth month) and β-polysaprobic (tenth month) (Table 2).

According to the standards of the Republic of Armenia, water up to class 4 is considered acceptable for irrigation (https://www.arlis.am/documentview.aspx?docid=154730).

4 Conclusion

Thus, studies of the water quality of the Hrazdan Reservoir (Armenia) showed that at the outlet of the reservoir, starting in April, elevated pH values (8.6–9.8) were detected which did not meet the accepted standards. Similar elevated values were also observed for the content of saprophytic bacteria in October which makes the reservoir water unsuitable for irrigation.

An analysis of the relationship between biomass and the number of individual groups of phytoplankton, saprophytic bacteria and phosphate content in different seasons of the year showed high correlations between these indicators.

During the study period, the highest number of saprophytic bacteria (20 °C) and *Bacillariophyta* species was observed in August which may be due to the temperature conditions typical for the season. In contrast, the highest numbers of saprophytic bacteria (37 °C) and *E. coli* were observed in the autumn months, indicating that these indicators depend on nitrogen availability.

As a result of the conducted studies to assess the quality of water at the outlet of the Hrazdan Reservoir, it was found that according to some physical and chemical indicators (in particular pH), its water does not meet the accepted standards during the entire irrigation period, which, of course, can affect the efficiency of agricultural

Table 2 Water quality of the Hrazdan Reservoir at observation station III according to physicochemical, hydrobiological and microbiological indicators by month

Months	DO	BOD_5	NH_4^+	NO_2^-	NO_3^-	PO_4^{3-}	Hardness	pH	Saprobity Index for *E. coli* bacteria	Saprobity index for saprophytic bacteria	Saprobity index for phytoplankton
III Station											
II	excellent	lexcellent	–	–	excellent	–	good	good	fair	excellent	excellent
III	fair	excellent	good	good	excellent	good	good	good	fair	excellent	–
IV	excellent	excellent	good	good	excellent	excellent	good	poor	fair	excellent	fair
V	excellent	excellent	good	good	excellent	good	good	poor	fair	fair	moderately
VI	good	excellent	good	excellent	excellent	good	good	poor	fair	good	fair
VII	excellent	excellent	good	excellent	excellent	good	good	poor	fair	excellent	moderately
VIII	excellent	excellent	excellent	good	excellent	good	good	poor	fair	moderateely	fair
IX	excellent	excellent	good	good	excellent	excellent	good	poor	moderately	moderateely	moderately
X	moderately	good	good	good	excellent	excellent	good	poor	moderately	poor	fair

production. Moreover, by the autumn period, there is also an excess of the norms for the number of saprophytic bacteria which indicates an increase in organic pollution of the reservoir. All this is explained by seasonal fluctuations in the water level of the reservoir leading to significant changes in temperature and concentration of nutrients. In particular, a decrease in water level in summer, accompanied by an increase in temperature, leads to rapid algal blooms, as a result of which a large amount of nutrients is utilized. This in turn helps to reduce saprophytic bacteria and other microorganisms that depend on the presence of nutrients. However, as the number and biomass of phytoplankton decreases due to its gradual death and settling to the bottom, the amount of nutrients in the reservoir increases, which leads to an increase in BOD values and, consequently, to an increase in the number of saprophytic bacteria.

It is interesting to note that not all the studied water parameters exceed the standards adopted for irrigation. However, the identification of even some indicators that exceed these standards may be a significant argument for giving recommendations on revising the possibilities of using reservoir water for agricultural needs. This indicates the need for monthly comprehensive hydrochemical, hydrobiological and microbiological monitoring of reservoirs intended for irrigation

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