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Systemic-Entropic Approach for Assessing Water Quality of Rivers, Reservoirs, and Lakes

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Abstract

Water is a nonrenewable resource, and its unsustainable use almost everywhere has led to a decrease in water quality. The development of water quality indices and the introduction of indexing methods used in assessing the quality of surface waters (pollution) are particularly relevant in recent years. As a result of anthropogenic pollution of the aquatic environment, the entropy of the system changes, which is not always taken into account in hydrochemical studies. This chapter analyzes dozens of freshwater quality indicators existing in science literature and presents the advantages of the water quality indicators developed by the author and colleagues: the geoecological evolving organized index (GEVORG), and the Armenian Water Quality Index. Water quality analyses have been tested for most of the rivers, reservoirs, and lakes of Armenia. It was found that the Armenian Water Quality Index has a linear relationship with most water quality indexes, and an inverse relationship with the Canadian Water Quality Index. The quality of river and reservoir water has been assessed according to the new standards for background concentrations.

Keywords: water quality index, GEVORG index, Armenian Water Quality Index, rivers, reservoirs and lakes

1. Introduction

Water resources play a vital role in various sectors of economy, such as industrial activities, agriculture, forestry, fisheries, hydropower, and other creative activities [1].

The study of the ecological status of rivers, reservoirs, and lakes in Armenia is important for assessing the quality of their water, as well as for their further rational use.

The suitability of water sources for human consumption is studied using a water quality index (WQI), which is one of the most effective ways to describe water quality. WQI uses water quality data and helps in changing policies that are formulated by various environmental monitoring agencies [2].

WQI was first developed by Horton (HWQI) [3] in the United States, and is based on the 10 most frequently used water quality variables, such as dissolved oxygen (DO), pH, coliform, conductivity, alkalinity, chloride, etc., which are widely used and accepted in European, African, and Asian countries. Horton placed

grading scales and weights for determining factors to give the relative importance of each parameter for assessing water quality. Furthermore, a new WQI similar to Horton's index has also been developed by the group of Brown in 1970 [4], which is based on weights to individual parameter. Recently, many modifications have been considered for WQI (BWQI) concept by various scientists and experts. Canadian Council of Ministers of the Environment has developed a WQI, Canadian Water Quality Index (CWQI), which can be applied by many water agencies in various countries with slight modification [5]. In 1995, the Canadian Ministry of the Environment developed the British Columbia Water Quality Index [6]. The Oregon Water Quality Index (OWQI) takes into account eight water quality variables (temperature, DO, pH, BOD, total phosphorus, total solids, fecal *E. coli*, ammonia, and nitrate nitrogen). The Delphi method has been used to select variables [7]. Malaysia Water Quality Index (MWQI) developed by the Department of the Environment of Malaysia was successfully applied for measuring water quality of 462 rivers in Malaysia. The calculation includes six water parameters: DO, BOD, COD, ammonia nitrogen, suspended solids, and pH [7]. The Bascaron Water Quality Index was developed by Bascaron specifically for Spain [8]. In 1976, the Scottish Engineering Department improved and developed the Scottish Water Quality Index [9]. An effective gradation index for diagnosing a generalized river quality has been developed and illustrated with the case study of the Keya River in Taiwan (TWGI) [10]. The Universal Water Quality Index for Turkey was developed by Boyacioglu [11] based on water quality standards set by the Council of European Communities. Sargaonkar and Deshpande [12] developed Overall Index of Pollution (OIP) for Indian rivers based on measurements and subsequent classification of pH, turbidity, dissolved oxygen, BOD, hardness, total dissolved solids, total coliforms, arsenic, and fluoride.

Some indexes and their variables are given in **Table 1**.

For the evaluation of the degree of water contamination, the comprehensive indicators are used, which make it possible to evaluate the contamination of water at the same time on a wide range of quality indicators. Water Contamination Index (WCI), CWQI, and specific combinatorial water quality index (SCWQI) are used for the evaluation of surface water quality in Republic of Armenia [5, 13, 14]. It must be noted that most developed complex characteristics of water bodies are in one way or another connected with the existing maximum allowable concentration (MAC) [15, 16].

According to the Water Framework Directive (WFA) (2000/60/EC) developed by the European Union (EU), all European surface waters should be in good ecological condition after 2015, and water bodies with poor quality water should be improved through targeted measuring. Each EU Member State has developed schemes for water quality classification according to WFD [17]. For example, in France, the SEQ-system is used for the classification of river water quality, consisting of three sections. To classify water quality, 15 descriptors are separated into 156 indicators, taking into account similar factors and effects. The evaluation is carried out using the boundary value table, which defines the boundaries of classes.

The index values are calculated based on parameters, which are classified into five classes based on the water usability. Germany's chemical quality classification scheme consists of four main classes and three subclasses, with a similar biological classification. The grades obtained are mapped through color codes.

Water quality assessment in the Danube River Basin according to the EU WFD (2000/60/EC) program is carried out according to separate indicators [17, 18]. In this classification scheme, indicators are classified into five classes. Class I is referred to as "reference" or background concentration; class II is a target value that should be followed; classes III–V are part of the "non-executable" classification scheme and their values are usually 2–5 times higher than the target value.

Parameters	HWQI	BWQI	MWQI	OWQI	OIR	TWQI
DO	+	+	+	+	+	+
BOD ₅		+	+	+	+	+
COD			+			
pH	+	+	+	+	+	+
t°	+	+		+		+
Conductivity	+					
Carbon chloroform extract	+					
Turbidity		+			+	+
Hardness					+	
Suspended solids			+			+
Alkalinity	+					
Obvious pollution	+					
Sanitation facility	+					
Fecal <i>E. coli</i>				+		
Total coliforms					+	
Fecal coliforms count	+	+				+
Nitrate		+				
Nitrate nitrogen				+		
Ammonia nitrogen			+			+
Ammonia				+		
Total phosphorus		+		+		
Total dissolved solids				+	+	
Total solid content		+				
Chloride	+					
Fluoride					+	
As					+	
Cd						+
Cu						+
Cr						+
Pb						+
Zn						+

Table 1.
Some indexes and their variables.

According to the EU WFW Rural Water Quality Assessment, due to the lack of biological monitoring, assessment was made only with the use of chemical indicators of water quality. Natural background concentrations of hydrochemical indices were taken into account. The determination of background concentrations according to the EU WFD was performed using a statistical method using the logarithmic probability distribution function. The expected background status of the reference state is the absence or insignificance of anthropogenic pressure. It is closely connected with background concentration (BC). Background concentration

is the value of the water quality indicator concentration before exposure to any source of pollution.

The Government of the Republic of Armenia (“Decree No. 75-N of March 27, 2011”) established a new system for assessing surface water quality in Armenia for each water quality indicator for each watercourse [19]. The advantages of the new water quality standards in Armenia are that, firstly, the classification of environmental norms is based on natural BC, and secondly, the choice of indicators was made taking into account the load on the surface waters of the Republic of Armenia (based on 43 water indicators). The calculations of the BC took place in the RA rivers in 2005–2010 hydrochemical monitoring.

In recent years, for a comprehensive assessment of surface water quality, we have proposed the geoeological evolving organized index (GEVORG) or entropy water quality index (EWQI) and the Armenian Water Quality Index (AWQI) [20, 21].

Using EWQI and AWQI, a comprehensive assessment of surface water quality was carried out [22–26], and a structural analysis of the state of biological systems at the level of proteins, ribonucleic acid, and cell [27, 28]; of the state of trees [29]; and of the state of naftide systems [30] was made.

The aim of this work is to assess the water quality of the rivers, reservoirs, and Lake Sevan using the Armenian Water Quality Index and for the WFD using BC.

2. Materials and methods

2.1 Study area

2.1.1 Rivers

Dzknaget River is a river in the Gegharkunik and Tavush regions of Armenia. It is located in the eastern slopes of the Pambak Mountains and 1 km south of Tsovaghyugh in the north-western corner of Lake Sevan. The river's length is 22 km. In this river, the fish caviar of Lake Sevan are debugged. Partly because of this reason, the river was named after a *river of fish*. There are two monitoring posts: No. 60—0.5 km above Semyonovka and No. 61—at the mouth of the river [31–33].

Masrik is a river in the Gegharkunik region of Armenia. It starts from the slopes of the eastern Sevan Mountains and flows into Lake Sevan in the north of the village of Tsovak. Its length is 45 km. The catchment area is 682 km², and the annual runoff is 131 million m³. There is a monitoring post, No. 63—at the river's mouth [31–33].

Sotk (Zod), a river in the Gegharkunik region, is the right tributary of Masrik. It starts from the western slopes of the eastern Sevan ridge at a height of 2670 m. The length of the river is 21 km, the catchment basin area is 59.5 km². In the upper and middle streams, it flows through the V-shaped valley. Average annual expenditure is 0.28 m³/s. Its water is used for irrigation. There are two monitoring posts: No. 64—0.5 km from the mine top and No. 65—at the mouth of the river [31–33].

Vardenis River, is a river in the Gegharkunik region, in the Lake Sevan basin. It starts from the northern slopes of the central part of the Vardenis Range, at an altitude of 3215 m. The river's length is 28 km, the catchment basin area is 116 km². River valley is V-shaped in the upper and middle currents, extending below it, leaving the semi-desert plain and north of Lake Vardenik into Lake Sevan. Its water is used for irrigation. There is a monitoring post, No. 70—at the mouth of the river [31–33].

Martuni River, is a river in the Gegharkunik region, in the Lake Sevan basin. It starts from the northern slopes of the Vardenis Ridge, at an altitude of 3300 meters. Its length is 27.6 km, and the catchment basin area is 101 km². River valley is a

V-shaped at an upper flow, on average, a cane. There are two monitoring posts: No. 71—0.5 km from Geghahovit top and No. 72—at the mouth of the river [31–33].

Argichi is a river in the Gegharkunik region, in the basin of Lake Sevan; it starts from the northern slope of the Gndasar mountains of the Geghama mountain range, at a height of 2600 m. The river's length is 51 km, and the drainage basin area is 384 km². Its water is used for irrigation purposes and energy production. There is a monitoring post, No. 74—at the river's mouth [31–33].

Gavaraget is a river in the Gegharkunik region, in Lake Sevan basin. It starts from the northern slope of the Geghama mountain range, at a height of 3050 m and flows into Lake Sevan. The river's length is 50 km, the drainage basin area is 480 km². The river freezes in winter. Its water is used for irrigation purposes and energy production. There is a monitoring post, No. 74—at the river's mouth [31–33].

The locations and monitoring posts of all the mentioned rivers are given in **Figure 1**.

2.1.2 Reservoirs

Akhurian Reservoir is located in the Akhurian River basin in Armenia and Turkey. The reservoir has a surface area of 54 km², and maximum length of 20 km. It is one of the largest reservoirs in the Caucasus, with coordinates 40° 33' 47.67" N 43° 39' 16.26" E.

Lake Arpi is situated in the north-west of the Republic of Armenia. The lake is fed by meltwater and four streams, and it is the source of the Akhurian River. Being an alpine-specific ecosystem with its rare flora and fauna, it ensures ecological balance of adjacent extensive area. The reservoir-lake is 7.3 km long and 4.3 km wide, with an area of 20 km² and coordinates 41° 03' 0" N 43° 37' 00" E.

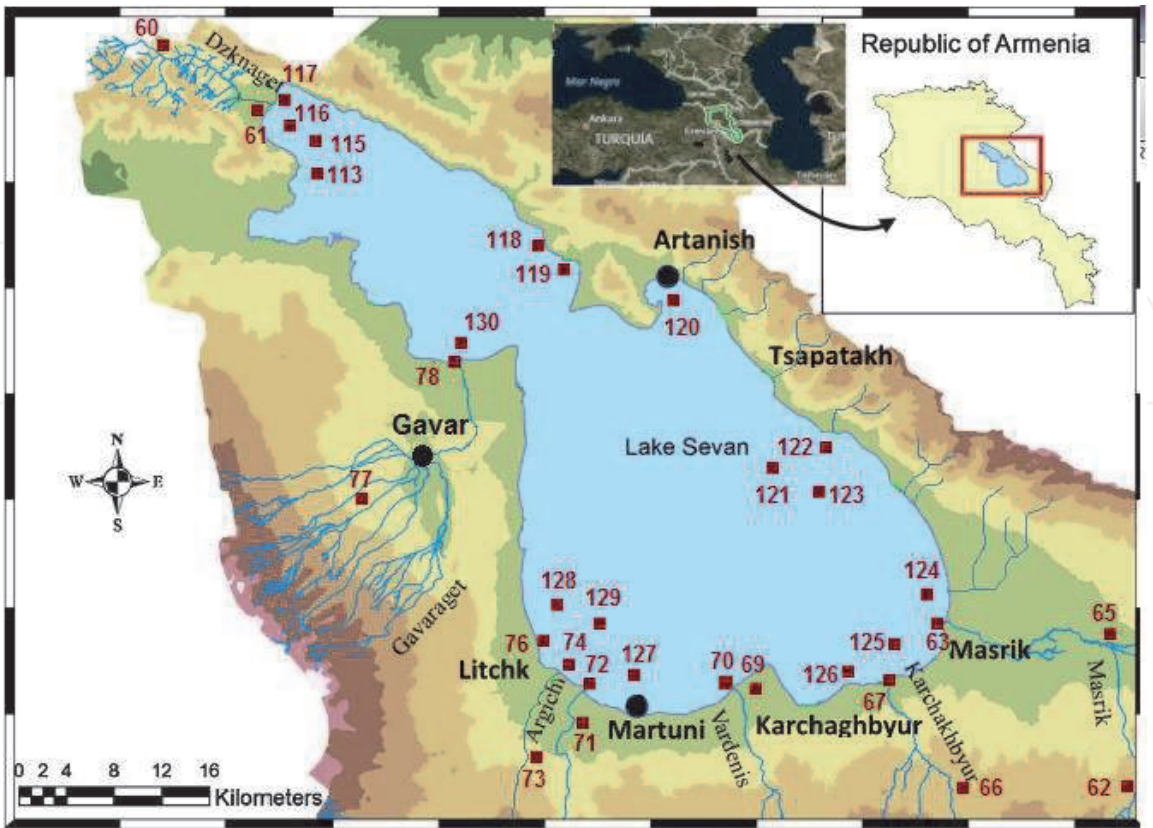


Figure 1.
Location of monitoring posts in Lake Sevan and rivers Dzknaget, Gavaraget, Argichi, Martuni, Vardenis, Masrik, and Sotq.

Yerevan Lake is an artificial reservoir located in the capital of Armenia in Yerevan. The reservoir-lake Yerevan is 7.3 km long and 5.0 km wide, with an area of 0.65 km² and coordinates 40° 9' 35.04" N 44° 28' 36.54" E.

Aparan Reservoir is located in the Aragatsotn region of Armenia. It has been built on the river Kassah. It has an area of 7.9 km² and coordinates 40° 29' 49" N 44° 26' 07" E. Its water is used for irrigation.

Kechut Reservoir is located in the Vayots Dzor region of Armenia, on the river Arpa, 3.5 km south of the resort town of Jermuk. The reservoir was built in 1981. Water from it through the conduit enters Lake Sevan to regulate the level. It has coordinates 39° 47' 54" N 45° 39' 22" E.

Azat Reservoir is located in Armenia, in the Ararat region, above the village of Lanjatzat, at an altitude of 1050 m above sea level. The reservoir was built on the Azat River. The volume of the lake is 70 million m³. Its water is used to irrigate the Ararat Plain. It has coordinates 40° 04' 00" N 44° 36' 00" E [21, 31–33].

2.1.3 Lake Sevan

Lake Sevan is located in the north-eastern part of the Armenian Highland, in the Gegharkunik Region. Sevan is considered to be one of the three ancient and biggest lakes (Vana and Urmia) of the Armenian Kingdom. It was called the “blue eyes” of Armenia and is surrounded by Geghama, Vardenis, Pambak, Sevan, and Areguni mountain chains. The blue beauty of Armenia is situated at an altitude of 1900 m above sea level and the total surface area is about 5000 km². It was famously known as “Geghama Tsov (in English sea), Gegharkunyats Tsov.” It is the world’s second-highest lake with freshwater after the Titicaca in South America and is the largest in the South Caucasus. The lake’s length is 70 km, and maximum width is 55 km. It has an area of 1240 km² (1360 km² before the level is lowered). Twenty-eight rivers flow into the lake, the largest of which reaches a length of 50 km. Only one river flows from Sevan-Hrazdan, which flows into the Araks. The mineralization of water is about 700 mg/l. Lake is of tectonic barren nature. The basin of the same name is of tectonic origin, and the dam was formed due to the outflow of the Holocene lavas. The lake consists of two unequal parts called Big and Small. The Sevan’s Peninsula is located in the north-western part of the lake and it is famous for its medieval monasteries and khachkars (cross-stones). Sevanavank is a monastery complex situated on the peninsula.

Small and Big Sevan: Small Sevan is very deep—up to 83 m and has rugged banks. It is in this part that the greater volume of lake water is concentrated. In the Big Sevan, the bottom is flat, the banks are not very rugged, and the depth does not exceed 30 meters. There are 26 stations on the Lake Sevan (monitoring posts), from No. 115 to No. 119; also stations No. 130 and 131 are located in the Small Sevan and those from No. 120 to 129 in the Big Sevan. These monitoring posts are shown in **Figure 1**.

The water monitoring posts of Lake Sevan are located at: No. 115—3.5 km distance from the peninsula to the east; No. 116—70° azimuth from the peninsula, from the surface; No. 117—a distance of 1 km from the Dzknaget river, from the surface; No. 117—a distance of 1 km from the Dzknaget river, at depth of 20 m; No. 118—0.5 km south-west from the village Shorzha, from the surface; No. 119—6 km south-west from the village Shorzha, from the surface; No. 119'—6 km south-west from the village Shorzha, at a depth of 20 m; No. 120—2 km from the village Artanish with 135° azimuth, from the surface; No. 120'—2 km from the village Artanish with 135° azimuth, at depth of 20 m; No. 121—10 km from the village Pambak with 270° azimuth, from the surface; No. 121'—10 km from the village Pambak with 270° azimuth, at a depth of 20 m; No. 122—2.2 km from the

village Pambak with 255° azimuth from the surface; No. 122'—2.2 km from the village Pambak with 255° azimuth, at a depth of 20 m; No. 123—13 km from the village Pambak with 235° azimuth, from the surface; No. 123'—13 km from the village Pambak with 235° azimuth, at a depth of 20 m; No. 124—1 km from the village Tsovak to the north-west from the surface; No. 125—1 km from the mouth of the river Karchaghbyur to the west, from the surface; No. 126—at Arpa-Sevan tunnel exit; No. 127—1.5 km from the city of Martuni, to the north, from the surface; No. 128—15 km from the village Eranos with 90° azimuth, from the surface; No. 128'—15 km from the village Eranos with 90° azimuth, at a depth of 20 m; No. 129—24 km from the village Eranos with 90° azimuth, from the surface; No. 129'—24 km from the village Eranos with 90° azimuth, from the surface, at a depth of 20 m; No. 130—7 km north-west of the village of Noratus, from the surface; No. 131—7.5 km north of the village of Chkalovka, from the surface; No. 131'—7.5 km north of the village of Chkalovka, at a depth of 20 m [21, 31–33].

2.2 Index determination

2.2.1 Canadian Water Quality Index (CWQI)

CWQI provides a consistent method, which has been formulated by Canadian jurisdictions, for conveying water quality information to both the management and public [5]. Moreover, a committee has been established under the Canadian Council of Ministers of the Environment WQI, which can be applied by numerous water agencies in various countries with slight modification. This method has been developed to evaluate surface water for protection of aquatic life in accordance to specific guidelines. The parameters related with various measurements may vary from one station to the other and sampling protocol requires at least four parameters, sampled at least four times. The calculation of index scores in CWQI method can be obtained by using the following relation:

$$CWQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}, \quad (1)$$

where scope (F_1) represent the percentage of variable that do not meet their objectives at least once during the time period under consideration (“failed variables”), relative to the total number of variables measured frequency (F_2) is the number of times by which the objectives do not meet; and amplitude (F_3) is the amount by which the objectives do not meet.

Therefore, five categories have been suggested for classification of water quality, which are summarized in **Table 2**.

2.2.2 Water contamination index (WCI)

WCI was established by the USSR Goskomgidromet (State Committee of Hydrometeorology) [13] and belongs to the category of indicators most often used to assess the quality of water bodies. This index is a typical additive coefficient and represents the average percentage of exceeding the MAC for a strictly limited number of individual ingredients:

$$WCI = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{MAC_i}, \quad (2)$$

CWQI value	Rating of water quality	Water quality classes
95–100	Excellent water quality	1
80–94	Good water quality	2
60–79	Fair water quality	3
45–59	Marginal water quality	4
0–44	Poor water quality	5

Table 2.
Classes of water quality depending on the value of CWQI.

WCI value	Rating of water quality	Water quality classes
up to 0.2	Very clean	I
0.2–1.0	Clean	II
1.0–2.0	Moderately polluted	III
2.0–4.0	Contaminated	IV
4.0–6.0	Dirty	V
6.0–10.0	Very dirty	VI
>10.0	Extremely dirty	VII

Table 3.
Classes of water quality depending on the value of WCI.

where C_i is the concentration of the component (in some cases the value of the physicochemical parameter) and n is the number of indicators used for calculating the index, $n = 6$ (pH, biological oxygen demand of BOD₅ dissolved oxygen in water, petroleum products, nitrite ions (NO₂[−]), and ammonium ion (NH₄⁺)). Seven categories have been proposed for the classification of water quality, which are listed in **Table 3**.

2.2.3 Specific combinatory water quality index (SCWQI)

In accordance with RD 52.24.643-2002, “The method for the integrated assessment of the degree of contamination of surface waters by hydrochemical indicators” the calculation of the specific combinatorial water quality index has been introduced [14]. To assess the quality of water of rivers and water bodies, it is divided into several contamination classes. The classes are based on the intervals of the specific combinatory water pollution index, depending on the number of critical pollution indicators. At least 15 indicators are analyzed. The required list includes: dissolved oxygen in water, BOD₅, chemical oxygen consumption—COD, phenols, petroleum products, nitrite ions (NO₂[−]), nitrate ions (NO₃[−]), ammonium ion (NH₄⁺), iron total (Fe²⁺ and Fe³⁺), copper (Cu²⁺), zinc (Zn²⁺), nickel (Ni²⁺), manganese (Mn²⁺), chlorides, and sulfates. The value of SCWQI is determined by the frequency and the multiplicity of the MPC exceeding by several indicators and can vary in waters of different degrees of contamination from 1 to 16 (for pure water is 0). The highest index value corresponds to the worst water quality. Taking into account the number of bullpen, it allows dividing the surface waters into five classes, depending on the degree of their contamination. The third and fourth classes for more detailed water quality assessment are respectively divided into two and four categories.

2.2.4 Geoecological evolving organized index and Armenian index of water quality

An open system can exchange energy, material, and, which is not less important, information from environment. The system consumes information from the environment and provides information to environment for acting and interacting with environment. Shannon [34, 35] was the first who related concepts of entropy and information. He has suggested that entropy is the amount of information attributable to one basic message source, generating statistically independent reports. The information entropy for independent random event x with N possible states is calculated by the following equation:

$$H = - \sum_{i=1}^N p_i \log_2 p_i, \quad (3)$$

where P_i is the probability of frequency of occurrence of an event.

Different processes in hydroecological systems can occur both with increase and decrease in of entropy. Pollution of water systems can be represented as a system of the hydrochemical parameters (elements), the concentration of which exceeds the MAC. Then, in the equation, Shannon P_i is the probability of the number of cases of MAC excess of i -substance or indicator of water of total cases of $MAC-N$, $P_i = n_i/N$.

For determination of the values of the EWQI and AWQI of environmental quality, the following computational algorithm is used [17–19]:

1. To determine the number of cases of MAC excess of i -substance or indicator of water
2. Estimate the total amount of cases at the maximum allowable concentration (N)— $N = \sum n$.
3. Compute $\log_2 N$, $n \log_2 n$ and $\sum n \log_2 n$.
4. Determine geoecological syntropy (I) and entropy (H):

$$I = \sum n \log_2 n / N \quad (4)$$

and

$$H = \log_2 N - I. \quad (5)$$

5. Then GEVORG index (G) is determined:

$$G = H/I \quad (6)$$

6. Further, the total amount multiplicity of MAC exceedances is estimated: (M)— $M = \sum m$.
7. Then, $\log_2 M$ is computed.
8. Finally, Armenian Water Quality Index is obtained:

$$AWQI = G + 0.1 \log_2 M. \quad (7)$$

Therefore, five categories have been suggested for classification of the water qualities, which are summarized in **Table 4**.

GEVORG value	AWQI value	Rating of water quality	Water quality classes
< 0.7	< 1.1	Excellent water quality	1
0.7–1.0	1.1–1.4	Good water quality	2
1.0–1.4	1.4–1.8	Fair water quality	3
1.4–1.7	1.8–2.1	Marginal water quality	4
> 1.7	> 2.1	Poor water quality	5

Table 4.
Classes of water quality depending on the value of EWQI and AWQI.



Water quality class	Assessment	Water quality
1		Excellent
2		Good
3		Moderate
4		Unsatisfactory
5		Bad

Table 5.
Water quality classification by EU WFD.

2.2.5 Water quality classification by EU WFD

The calculations of the BC took place in the RA rivers in 2005–2010 hydrochemical monitoring.

According to the decision of the Government of the Republic of Armenia, “On establishing standards for ensuring water quality for each area of water basin management,” there are five classes: “Excellent” (1st grade), “Good” (2nd grade), “Moderate” (3rd grade), “Unsatisfactory” (4th grade), and “Bad” (5th grade). Each class is indicated by color (**Table 5**). A general assessment of the chemical quality of water is performed by the class of the lowest quality indicator. So if different quality indicators of a surface water body fall into different quality classes, the final classification is considered the worst. The following principle applies: “If someone is in bad shape, then everyone is in poor condition” or the principle “someone is out, everyone is out.”

3. Results and discussion

3.1 Results for rivers

In this work, we present data on the study of water quality of rivers in 2009–2019. Since 2013, in Armenia, the quality of river water has been assessed by the new standards for background concentrations.

The quality of the waters of the Dzknaget, Sotk, Masrik, Vardenis, Martuni, Argichi, and Gavaraget rivers is comprehensively evaluated by the indices: AWQI, EWQI, WCI, CWQI, and SCWQI.

The values of the WQIs are shown in **Table 6**.

With the help of the computer program “Origin-6,” an analysis of the linear relationship between AWQI and other WQIs is done: $AWQI = a + b (WQI)$.

Sampling points	EWQI	AWQI	WCI	CWQI	SCWQI
60	0.415	0.650	0.77	90.38	0.8
61	0.856	1.208	0.92	83.98	1.48
63	0.604	0.993	2.21	78.71	1.74
64	0.321	0.559	0.64	88.74	1.31
65	0.642	0.989	1.2	75.25	1.86
70	0.370	0.625	0.82	90.63	1.20
71	0.625	0.899	0.66	90.52	0.68
72	0.333	0.584	0.95	86.62	1.40
74	0.303	0603	1.51	81.7	1.04
77	0.955	1.325	1.62	83.8	1.38
78	0.625	1.077	3.86	70.14	2.15

Table 6.
Water quality indices of rivers (2009).

$AWQI = (0.196 \pm 0.060) + (1.217 \pm 0.095) \cdot EWQI, R = 0.97914, N = 9$

$AWQI = (0.717 \pm 0.142) + (0.127 \pm 0.085) \cdot WCI, R = 0.46584, N = 9$

$AWQI = (0.539 \pm 0.287) + (0.251 \pm 0.196) \cdot SCWQI, R = 0.41219, N = 9$

$AWQI = (2.685 \pm 0.957) - (0.021 \pm 0.011) \cdot CWQI, R = 0.55362, N = 9$

Analysis of obtained data indicates that AWQI has liner dependence on WCI, SCWQI, and EWQI and an inverse dependence on CWQI. This result is based on the fact that the scale of the Canadian index of quality of water begins from 100, and scales of indexes of impurity of water, and EWQI, WQI, and SCWQI, start from scratch.

The quality of the water in the rivers was also evaluated according to the new standards of background concentrations (see **Table 7**).

In 2013–2019, the waters of the Dzknaget, Martuni, Sotk, Gavarvget rivers (monitoring post 77) and Martuni (monitoring post 71) were found to be of “moderate” or “good” quality. The water at the mouth of the Vardenis and Gavarvget

River	Sampling points	2013	2014	2015	2016	2017	2018	2019
Dzknaget	60 0.5 km above Semyonovka	Good	Good	Good	Good	Good	Good	Good
	61 River mouth	Good	Moderate	Good	Good	Good	Moderate	Good
Masrik	63 River mouth	Moderate	Moderate	Moderate	Moderate	Poor	Poor	Poor
Sotq	64 0.5 km from the mine top	Moderate	Good	Good	Good	Good	Good	Good
	65 River mouth	Good	Good	Good	Moderate	Moderate	Moderate	Moderate
Vardenis	70 River mouth	Moderate	Moderate	Moderate	Moderate	Moderate	Good	Moderate
Martuni	71 0.5 km from Geghhovit	Good	Moderate	Good	Good	Good	Good	Moderate
	72 River mouth	Good	Poor	Moderate	Moderate	Moderate	Good	Moderate
Argichi	74 River mouth	Good	Moderate	Good	Moderate	Moderate	Moderate	Moderate
Gavaraget	77 0.5 km from Tsakhkvan	Good	Good	Good	Good	Good	Good	Good
	78 River mouth	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

Table 7.
Water quality classes of analyzed rivers.

rivers had an average and “unsatisfactory” quality for ammonium ions and phosphate. The water at the mouth of the Martuni River in 2014 was of “poor” quality for ammonium and phosphate ions, and the water at the mouth of the Masrik River in 2017–2019 was also of “poor” quality for vanadium.

3.2 Results for reservoirs

In this chapter [26], we studied the quality of water in the years 2009–2012 of the reservoirs of the lakes of Arpi, Yerevan, Akhuryan, Azat, Aparaan, and ketchut using AWQI, EWQI WCI, and SCWQI, and CWQI. An analysis of the data shows that AWQI has a linear relationship with WCI, SCWQI, and EWQI and an inverse relationship with CWQI.

In this work, we presented data on the study of water quality in reservoirs in 2013–2019. Since 2014, in Armenia, the quality of reservoir water has been assessed by the new standards for background concentrations.

In 2013, it was found out that the reservoirs of lakes Arpi, Yerevan and Akhuryan regularly increased the MACs of nitrite ions, ammonium, copper, vanadium, aluminum, chromium, manganese and iron. For example, in reservoir Akhuryan for NO_2^- , Al, V, Cu, Mn, and Cr the number of cases of an increase in the MAC is 5, 8, 8, 8, 6 and 7 times, respectively. The amount of excess cases of MPC – $N = 42$, $\sum n \log_2 n = 118.76$, $I = 118.76/42 = 2.8276$, $H = \log_2 42 - 2.8276 = 2.5616$, $\text{AWGI} = G = 2.5616/ 2.8276 = 0.9059$. The total amount of the multiplicity of MAC

Reservoir	Lake Arpi		Akhuryan		Aparan		Lake Yerevan	
Positions	109		110		111		112	
Indicator	n	nlog ₂ n	n	nlog ₂ n	n	nlog ₂ n	n	nlog ₂ n
BOD ₅	0	0	0	0	5	11.61	0	0
NH ₄ ⁺	0	0	0	0	0	0	10	33.2
NO ₂ ⁻	0	0	5	11.61	0	0	12	43
Al	6	15.51	8	24	8	24	2	2
V	6	15.51	8	24	8	24	12	43
Cu	6	15.51	8	24	6	15.51	11	38
Mn	5	11.61	6	15.51	8	24	11	38
Se	0	0	0	0	0	0	8	24
Cr	5	11.61	7	19.64	0	0	12	43
N	28		42		35		78	
∑nlog ₂ n	69.75		118.76		99.12		264.2	
I	2.491		2.8276		2.8320		3.3871	
H	2.313		2.5616		2.2943		2.8946	
EQWI	0.9288		0.9059		0.8101		0.8546	
M = ∑m	33.6		24.5		15.2		49.3	
log ₂ M	5.067		4.612		3.924		5.620	
AQWI	1.4355		1.3671		1.2025		1.4166	

Table 8. Entropic and Armenian water quality indexes for reservoirs of Lake Arpi, Akhuryan, Aparan, and Lake Yerevan (2013).

Reservoir	Azat		Ketchut	
Positions	113		114	
Indicator	n	nlog ₂ n	n	nlog ₂ n
BOD ₅	4	8	0	0
Al	0	0	6	15.51
V	6	15.51	11	38
Cu	0	0	4	8
Mn	3	4.752	7	19.64
N	13		28	
Σnlog ₂ n	28.262		81.15	
I	2.173		2.898	
H	1.5253		1.9066	
EQWI	0.7019		0.6579	
M = Σm	17.9		9	
log ₂ M	4.159		3.168	
AQWI	1.1178		0.9746	

Table 9.
EQWI and AQWI for reservoirs of Azat and Ketchut (2013).

Reservoirs	2014	2015	2016	2017	2018	2019
Lake Arpi	Yellow	Yellow	Green	Green	Yellow	Yellow
Lake Yerevan	Red	Yellow	Orange	Orange	Orange	Orange
Akhuryan	Yellow	Yellow	Yellow	Green	Yellow	Yellow
Aparan	Green	Green	Yellow	Green	Yellow	Green
Azat	Yellow	Yellow	Green	Green	Green	Green
Ketchut	Green	Green	Yellow	Green	Green	Green

Table 10.
Water quality classes of analyzed reservoirs.

exceedances- $M = \sum m = 24.5$, $\log_2 M = 4.6123$, $AWQI = 0.9059 + 0.4612 = 1.3671$.
The values of the indices EWQI and AWQI are given in **Tables 8 and 9**.

An analysis of the data shows that AWQI has a linear relationship with EWQI.
 $AWQI = -(0.054 \pm 0.205) + (1.613 \pm 0.251) \cdot EWQI$; $R^2 = 0.95.457$; $N = 6$.

The quality of the water in the reservoirs was also evaluated according to the new standards of background concentrations (see **Table 10**).

In 2014, the water of the Arpi Lake reservoir was of “moderate” quality in terms of phosphate ion and COD, and the water of the Akhuryan reservoir was “moderate” in terms of ammonium, nitrite, and phosphate ions. The water of the Azat reservoir was also of “moderate” quality in terms of phosphate ion, the water of the Aparan reservoir was “good” in terms of phosphate ion, and the water of Yerevan lake was of “poor” quality. The waters of the Kechut and Aparan reservoirs were of “good” quality. In 2015, the water of the reservoir of Lake Arpi had a “moderate” quality in terms of COD and the water of the Akhuryan reservoir had a “moderate” quality in terms of phosphate ion and COD. The water in Yerevan Lake had a “moderate” quality in terms of ammonium, nitrite, and phosphate ions and COD.

The water of the Azat reservoir was also of “moderate” quality according to COD, and the water of the Kechut and Aparan reservoir was of “good” quality. In 2016, the water of the reservoirs of Lake Arpi and Azat was of “good” quality, and the waters of the Akhuryan, Aparan, and Kechut reservoirs were “moderate” in COD. The water of Yerevan Lake had a “poor” quality in terms of ammonium, nitrate, nitrite, and phosphate ions and COD.

In 2017, the water of the reservoirs of Lake Arpi, Akhuryan, Aparan, Kechut, and Azat was of “good” quality, and the water of Yerevan Lake was of “unsatisfactory” quality for ammonium and nitrite ions. In 2018, the water in the reservoir of Lake Arpi had “moderate” quality in terms of phosphate ion and suspended solids, and the water in the Akhuryan reservoir had “moderate” quality in ammonium and phosphate ions, as well as in COD and BOD₅. The water of the Aparan reservoir also had “moderate” COD quality. The water of Yerevan Lake had “unsatisfactory” quality for ammonium and nitrite ions. The waters of the Kechutsky and Azat reservoirs were of “good” quality. In 2019, the water in the reservoir of Lake Arpi had “moderate” quality in terms of phosphate ion and suspended solids, and the water in the Akhuryan reservoir had “moderate” quality in terms of COD and suspended solids. The water of Yerevan Lake had “unsatisfactory” quality in terms of nitrite ion. The waters of the Kechut, Aparan, and Azat reservoirs were of “good” quality.

According to WQI values, the water quality in the Aparan, Azat, and Kechut reservoirs has “good” and “excellent” grade. The water quality of the reservoirs of Akhuryan, Lake Arpi and in Yerevan Lake, on the contrary, is “poor” from 3rd to 2nd class, and restricts the use of water for irrigation purposes. The poor water quality of the Lake Arpi reservoir is associated with an increase in the amount of metals. The reduced water quality of the Akhuryan reservoir and Yerevan lake is associated with pollution from the main settlements in the river basin, respectively, in Gyumri and Yerevan, with municipal wastewater.

3.3 Results for Lake Sevan

The purpose of this section is to assess the water quality of Lake Sevan using the Armenian Water Quality Index and other indicators of water quality, as well as to identify the causes of the appearance of blue-green algae that contribute to growth.

In July 2019, an increase in the blue-green algae of Anaben was recorded in Lake Sevan. These algae were first found in Lake Sevan in the middle of the last century,

Year	Mg	V	Cr	Cu	Se	BOD ₅
2009	1.1–1.4	5.0–7.0	2.0–3.0	2.0–3.0	3.0–4.0	—
2010	1.1–1.3	5.0	2.0	2.0–3.0	2.0	2.0–3.0
2011	1.1	5.0	2.0	—	2.0	1.1–1.9
2012	1.1–1.2	6.2–6.4	—	2.1	2.1–2.6	—
2013	1.1–1.2	5.0–5.7	1.8	—	2.5	—
2014	1.1	3.8–5.6	1.2–3.4	—	1.2–19	1.2–1.5
2015	1.2–1.7	2.9–5.9	1.2–3.9	—	1.2–5.0	1.2–1.4
2016	1.2	3.8–8.0	1.2–1.7	1.4–1.5	1.2–6.5	1.2
2017	1.2	5.0–5.9	2.0–3.8	1.3–7.3	5.7–7.0	1.2–1.4
2018	1.2–1.3	3.7–6.6	1.7–3.3	1.2–2.9	1.4–2.7	1.2
2019	—	4.5–8.9	1.2–6.6	1.2–3.5	3.1–3.3	—

Table 11.
Excess concentration from MAC (times).

Positions	115		116		117		118		119		130	
Indicator	n	nlog2n	n	nlog2n	n	nlog2n	n	nlog2n	n	nlog2n	n	nlog2n
Mg	0	0	5	11.6	5	11.6	6	15.5	4	8	5	11.6
Cu	0	0	0	0	0	0	1	0	0	0	0	0
V	8	24	8	24	8	24	8	24	8	24	8	24
Cr	5	11.6	6	15.5	6	15.5	6	15.5	5	11.6	6	15.5
Br	8	24	8	24	8	24	8	24	8	24	8	24
Se	8	24	8	24	7	19.64	7	19.64	6	15.5	7	19.64
N	29		35		34		36		31		34	
$\sum n\log_2 n$	83.6		99.1		94.74		98.64		83.1		94.74	
I	2.882		2.831		2.786		2.74		2.68		2.786	
H	1.974		2.295		2.298		2.427		2.271		2.298	
G	0.686		0.811		0.826		0.886		0.847		0.825	
$M = \sum m$	11.8		13		14		17.1		14.1		14.3	
$\log_2 M$	3.56		3.7		3.81		4.093		3.815		3.836	
AWQI	1.041		1.181		1.207		1.294		1.228		1.209	

Table 12.
Entropic and Armenian water quality indexes for Small Lake Sevan (2009).

and the first manifestation of flowers was recorded in 1964 and repeated in different volumes at different times. Large-scale flourishing was observed in 2018.

It has been established that the maximum permissible concentration of vanadium, copper, chromium, magnesium, BOD₅, and selenium is regularly exceeded in the waters of Lake Sevan (see **Table 11**).

For example, in position No. 118 of Lake Sevan, number of MAC increasing cases for V, Br, Se, Cr, Mg, and Cu has been changed 8, 8, 7, 6, 6 and 1 times, respectively [36]. The amount of excess cases of MAC – $N = 36$, $\sum n \log_2 n = 98.64$, $I = 98.64/36 = 2.740$, $H = \log_2 36 - 2.740 = 2.427$, $G = 2.740/2.427 = 0.886$. The total amount of the multiplicity of MAC exceedances - $M = \sum m = 17.1$, $\log_2 M = 4.093$, $AWQI = 0.886 + 0.409 = 1.294$. The calculation algorithm and the values of the EWQI and AWQI indices of other position of Smally Sevan are given in **Table 12**.

Quality of Lake Sevan water was also comprehensively evaluated by other indexes: WCI, CWQI, and SCWQI. Values of the WQIs are given in **Table 13**.

It is shown that water quality by the EWQI and AWQI of the 2nd pollution class, by the WCI and CWQI of the 3rd pollution class, and by SPWQI is mainly the 2nd and in some cases up to the 3rd class of pollution.

With the help of the computer program “Origin-6”, the analysis of the linear relationship between AWQI and other WQIs was provided: $AWQI = a + b (WQI)$.

Analysis of obtained data indicates that AWQI has liner dependence with WCI, SCWQI, and EWQI, and an inverse dependence with CWQI.

A satisfactory correlation is obtained when all the positions of the Lake Sevan are considered together.

- $AWQI = (0.739 \pm 0.074) + (0.313 \pm 0.047) \blacksquare WCI, R = 0.80233, N = 26$
- $AWQI = (1.047 \pm 0.127) + (0.096 \pm 0.069) \blacksquare SCWQI, R = 0.27301, N = 26$
- $AWQI = (0.203 \pm 0.038) + (1.225 \pm 0.046) \blacksquare EWQI, R = 0.98339, N = 26$

Sampling points	EWQI	AWQI	WCI	CWQI	SCWQI
115	0.686	1.041	1.35	68.65	1.75
116	0.811	1.181	1.41	70.37	1.65
117	0.826	1.207	1.42	70.95	1.56
117'	0.831	1.201	1.43	70.21	1.81
118	0.867	1.276	1.87	65.98	1.88
119	0.847	1.228	1.48	69.12	1.81
119'	0.923	1.334	1.90	66.35	2.11
120	0.939	1.340	1.67	67.24	1.65
120'	0.921	1.332	1.92	65.50	1.96
121	0.803	1.187	1.60	66.79	1.94
121'	0.799	1.192	1.56	66.89	1.83
122	0.820	1.204	1.50	66.65	2.19
122'	0.820	1.214	1.49	68.68	1.59
123	0.811	1.205	1.50	67.05	1.69
123'	0.819	1.212	1.55	66.58	1.75
124	0.819	1.212	1.53	68.16	1.85
125	0.819	1.222	1.52	66.49	1.59
126	0.825	1.229	1.54	67.27	1.82
127	0.833	1.237	1.55	67.14	1.78
128	0.883	1.312	1.75	66.02	2.11
128'	0.825	1.209	1.44	68.25	2.03
129	0.815	1.198	1.44	67.60	1.93
129'	0.815	1.198	1.52	67.96	1.79
130	0.825	1.209	1.43	68.64	1.63
131	0.834	1.217	1.43	68.48	1.88
131'	0.825	1.208	1.46	68.45	1.95

Table 13.
Water quality indices of Lake Sevan (2009).

- $AWQI = (2.637 \pm 0.513) - (0.021 \pm 0.008) \blacksquare CWQI$, $R = 0.49061$, $N = 26$:

For the Small Lake Sevan:

- $AWQI = (0.787 \pm 0.213) + (0.275 \pm 0.143) \blacksquare WCI$, $R = 0.65192$, $N = 7$
- $AWQI = (0.965 \pm 0.438) + (0.131 \pm 0.252) \blacksquare SCWQI$, $R = 0.22730$, $N = 7$
- $AWQI = (0.189 \pm 0.053) + (1.234 \pm 0.064) \blacksquare EWQI$, $R = 0.99321$, $N = 7$
- $AWQI = (2.097 \pm 1.361) - (0.013 \pm 0.019) \blacksquare CWQI$, $R = 0.28427$, $N = 7$:

For the Big Lake Sevan:

- $AWQI = (0.529 \pm 0.181) + (0.452 \pm 0.116) \blacksquare WCI$, $R = 0.81003$, $N = 10$
- $AWQI = (1.292 \pm 0.172) + (0.031 \pm 0.092) \blacksquare SCWQI$, $R = 0.11946$, $N = 10$
- $AWQI = (0.252 \pm 0.082) + (1.174 \pm 0.099) \blacksquare EWQI$, $R = 0.97297$, $N = 10$
- $AWQI = (2.776 \pm 0.1935) - (0.023 \pm 0.028) \blacksquare CWQI$, $R = 0.27118$, $N = 10$:

A good correlation is also obtained when the underlying layers are considered together

- $AWQI = (0.778 \pm 0.054) + (0.287 \pm 0.034) \blacksquare WCI$, $R = 0.9545$, $N = 9$
- $AWQI = (0.849 \pm 0.208) + (0.205 \pm 0.111) \blacksquare SCWQI$, $R = 0.57343$, $N = 9$
- $AWQI = (0.209 \pm 0.061) + (1.217 \pm 0.072) \blacksquare EWQI$, $R = 0.98775$, $N = 9$
- $AWQI = (2.998 \pm 0.753) - (0.026 \pm 0.011) \blacksquare CWQI$, $R = 0.66353$, $N = 9$:

Thus, a correlation between AWQI and other WQIs was established. Analysis of obtained data indicates that AWQI has liner dependence on WCI, SCWQI, EWQI and an inverse dependence on CWQI. This result is based on the fact that the scale of the Canadian index of quality of water begins from 100, and scales of indexes of impurity of water, EWQI, WQI, and SCWQI, start from scratch. It has been established that the maximum permissible concentrations of copper, vanadium, chromium, magnesium, and selenium regularly increase in the waters of Lake Sevan. It has been found that the Armenian Water Quality Index demonstrates a linear dependence on the water contamination index, a specific combinatorial water quality index, and an index of geoecological evolving organization and an inverse relationship to the Canadian Water Quality Index. It is shown that water quality by the geoecological evolving organized index and Armenian Water Quality Index of the 2nd pollution class, by the water contamination index and Canadian Water Quality Index of the 3rd pollution class, and by specific combinatorial water quality index is mainly the 2nd and in some cases up to the 3rd class of pollution.

Over the past 10 years, the water level in Sevan has risen by 3 meters, leaving under water trees, stubble and buildings that have not yet been cleaned. The ecosystem of Lake Sevan is also polluted due to debris entering the lake. In addition to sewage systems from dozens of settlements in Lake Sevan, sewage and agricultural and wastewater from service and recreation facilities operating on the shores of Lake Sevan are also discharged into Sevan.

It should be noted that in 2019 there was little rain. For example, in May, 36 million m^3 of precipitation was recorded in the lake, which is close to the historically minimal (33 million m^3) precipitation. Due to the strong wind force, evaporation in the spring was twice as high as normal.

According to the results of research conducted by the Ministry of Nature Protection in 2018, the concentrations of phosphate and ammonium ions in Lake Sevan were high, and a sharp rise in temperature created favorable conditions for intensive flowering of the lake. The average concentration of phosphate ion in the surface and middle layers was 0.08 mg/l, and in the underlying layer—0.15 mg/l, which did not exceed the norm of the RA environment (0.3 mg/l). The average concentration of ammonium ion in the surface layer is 0.25 mg/l, and in the

underlying layer 0.17 mg/l, which does not exceed the norm of the environment RA (0.5 mg/l). The average concentration of nitrate ions in the surface layer was 0.19 mg/l, and in the underlying layer—0.12 mg/l. The observed concentrations do not exceed the ecological norm of RA (11 mg/l).

4. Conclusions

The quality of the waters of the Dzknaget, Sotk, Masrik, Vardenis, Martuni, Argichi, and Gavaraget rivers and the lakes of Arpi, Yerevan, Akhuryan, Azat, Aparan and Kechut reservoirs comprehensively evaluated by the indices: AWQI, EWQI, WCI, CWQI, and SCWQI.

The quality of rivers and reservoirs water has been assessed by the new standards for background concentrations.

The water at the mouth of the Martuni River in 2014 was of “poor” quality for ammonium and phosphate ions, and the water at the mouth of the Masrik River in 2017–2019 was also of “poor” quality for vanadium. In 2013–2019, the waters of the Dzknaget, Martuni, Sotk, and Gavaraget rivers (monitoring post No. 77) and Martuni (monitoring post No. 71) were mostly of “good” quality. The water at the mouth of the Vardenis and Gavaraget rivers had an average and “unsatisfactory” quality for ammonium ions and phosphate.

The poor water quality of the Lake Arpi reservoir is associated with an increase in the amount of metals. Reduced water quality of the Akhuryan reservoir and Lake Yerevan is associated with pollution from the main settlements in the river basin, respectively, in Gyumri and Yerevan, with municipal wastewater.

For the first time, the water quality in the reservoirs of Lake Sevan was evaluated using the Armenian Water Quality Index. It was found out that the water of Lake Sevan is regularly increased MAC of vanadium, copper, chromium, magnesium, bromine, and selenium. The water quality in the Lake Sevan is poor.


It has been found that the Armenian Water Quality Index is linearly dependent on the water contamination index, the specific combinatorial water quality index, the geoeological evolving organized index, and has inverse relationship to the Canadian Water Quality Index.

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