Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2023, 11, 351-366
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Evolution of the Physico-Chemical Quality of the Water in the Manantali Dam Reservoir from 1989 (One Year after Impoundment) to 2022

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How to cite this paper: Faye, J. M., Ndao, S., & Sambou, L. E. V. (2023). Evolution of the Physico-Chemical Quality of the Water in the Manantali Dam Reservoir from 1989 (One Year after Impoundment) to 2022. *Journal of Geoscience and Environment Protection, 11,* 351-366.
https://doi.org/10.4236/gep.2023.119022

Received: July 29, 2023
Accepted: September 25, 2023
Published: September 28, 2023

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Abstract

The Manantali dam is located on the Bafing River in the Kayes region of Mali. It is the main tributary of the Senegal River. The water released from the dam provides year-round access to water for drinking, irrigation and livestock watering. The Manantali dam regulates the river's flow, generates energy and supports agricultural development in all three countries (Mali, Mauritania, and Senegal). The aim of this article is to monitor changes in the physico-chemical quality of the water in the dam's reservoir from 1989 (one year after the dam was impounded) to 2022. In order to carry out this work, we analysed the evolution of physico-chemical parameters in Stations 1 and 3 of the dam, on the basis of fluctuating water levels in the reservoir. The results obtained show a similarity in the parameters measured at the two stations, except for iron content, which is higher at Station 3. The average pH is weakly basic (7.44 at Station 1 and 7.29 at Station 3) and the average water temperature is between 26.5˚C at Station 1 and 26.2˚C at Station 3. The average conductivity of the water at Station 1 is 38.8 µS/cm and 39.8 µS/cm at Station 3, attesting to low mineralization of the water. The oxygen content of 5.75 mg/L at Station 1 and 5.00 mg/L at Station 3 shows good oxygenation of the water, which is favorable for the development of most fish and aquatic plant species. Ammonium levels of 0.02 mg/L at Station 1 and 0.06 mg/L at Station 3 show that the water is not contaminated. In addition, the Water Quality Index (WQI) was calculated, showing excellent water quality at Station 1 and good quality at Station 3. Overall, the results obtained show that the water is of good quality, enabling the authorities of the Organization for the Development of the Senegal River (OMVS) to achieve their development objectives.

Keywords

OMVS, WQI, Senegal River, Physicochemical Parameters

1. Introduction

The Manantali multi-purpose dam, commissioned in 1988, is located on the Bafing River in Mali, and has a total storage capacity of 11.3 billion cm. It was built as part of an ambitious program of investment in water control infrastructure on the Senegal River. This program has a threefold objective: to regulate the river's flow (flood control and low-water support) and produce energy; to make the river navigable from Kayes in Mali to its mouth at Saint Louis in Senegal; and to promote agricultural development in the three countries (Mali, Mauritania and Senegal) (AFD, 2008).

It emerges that the construction of a dam leads to the creation of a more or less large reservoir (as in the case of Manantali), causing the transformation of a lotic environment into a lentic environment, resulting in profound changes to the ecosystem, particularly with socio-environmental repercussions, the most worrying of which are the displacement of populations, the proliferation of aquatic plants, the high prevalence of water-borne diseases, and so on.

Water is a natural resource that is essential to life in any ecosystem (Tampo, Gnazou, Akpataku, Bawa, & Djaneye-Boundjou, 2015), maintaining its quality is a major concern for a society that has to meet ever-increasing water needs (Foto, Zebaze, Nyamsi, Ajeagah, & Njine, 2011).

On the other hand, the environmental impact study predicted that the Manantali reservoir would undergo thermal stratification each year between February and December, during which period, the bottom waters would be poorly oxygenated and would see their hydrogen sulphuric acid content increase. During this period, the impact study predicted that this bottom water, once turbined, would deteriorate the quality of the water downstream over a distance of around 7 km, causing losses in fish productivity and posing a threat to human health when this water was consumed (Gannett Fleming, Carpenter, & Orgatec, 1980).

In order to monitor, optimise and mitigate these impacts, the Organisation for the Development of the Senegal River (OMVS), in cooperation with its partners, has decided to set up a Limnology Unit to monitor the aquatic environment of the Manantali dam (upstream and downstream) (Naudet, Ficatier, & Schmidt, 2008).

Water quality is an important criterion for meeting water demand and supply. Ensuring that freshwater quality is appropriate to human and ecological needs is, therefore, an important aspect of integrated environmental management and sustainable development. To provide a clear picture of water quality, various water quality indices are used to assess the quality of surface water (Telhaoui, El Hmaidi, Hajar Jaddi, & Ousmana, 2020).

The aim of this article is to study the evolution of water quality in the Manantali dam reservoir from 1989 to 2022 by monitoring parameters, such as pH, electrical conductivity, temperature, dissolved oxygen, ammonium and iron in relation to water quality indices.

The Water Quality Index (WQI) is a simple method used as part of the analysis of overall water quality using a group of parameters that reduce large amounts of information to a single, usually dimensionless, number in a simple and reproducible way (Abassi & Abassi, 2012).

2. Material and Methods

2.1. Site Presentation

With a length of 1800 km and a catchment area of around 300,000 km^2, the Senegal River is the second largest river in West Africa after the Niger (Rochette, 1974). Four countries (Guinea, Mali, Mauritania and Senegal) share the catchment area, which covers between 7% and 14% of the national territory of each of these countries (UNESCO, 2003). The Senegal River rises in the north of Guinea, crosses the western part of Mali and forms the border between the Republic of Senegal and the Islamic Republic of Mauritania for the rest of its course (Rochette, 1974).

The Manantali reservoir, which was impounded in July 1987, lies between latitudes 13˚11'246"N and 12˚56'003"N and longitudes 10˚25'772"W and 10˚16'565"W. The reservoir covers an area of 475 sq·km, at an elevation of 208 m above sea level (IGN), with a maximum depth of 55 m. The maximum volume of water is approximately 11.3 billion cm (Cisse, 2016).

Figure 1 and **Figure 2** show the Bafing area before and after the creation of the reservoir.

2.2. Sampling Strategy and Analysis Methods

Sampling was carried out at three different stations marked with red dots (**Figure 3**). These are Stations 1, 3 and 4.

Station 1, the most representative for the measurements, is the reference station, located approximately 300 m from the dam at the deepest point. Station 3 will be used for a comparative spatial study.

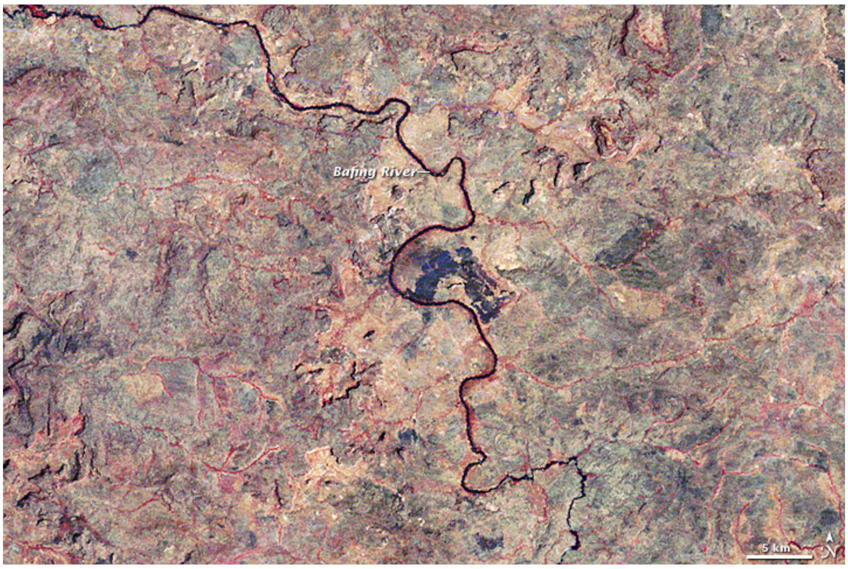

Figure 1. Manantali site before the dam (NASA).

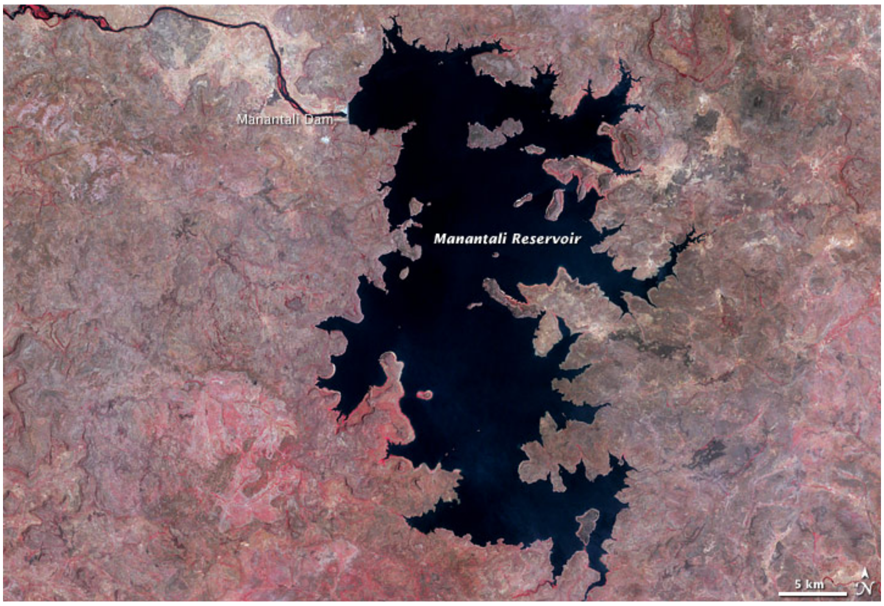

Figure 2. Manantali site after the dam (NASA).

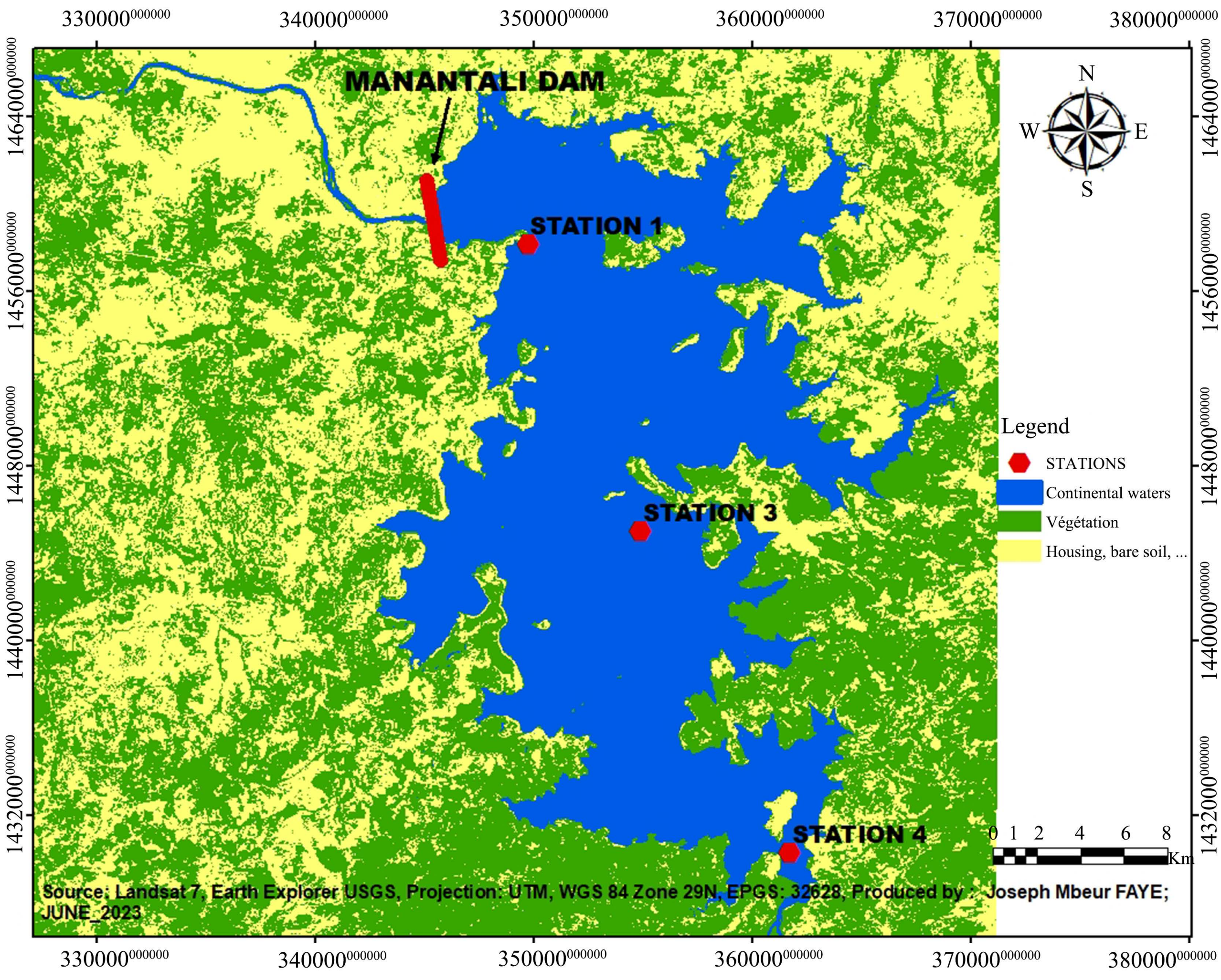

Figure 3. Location of measurement stations.

Samples are taken at random, once a year, from 1989 to 2002, from January to November. From 2003 onwards, samples are taken quarterly (Cisse, 2016).

Physico-chemical measurements were taken *in situ* every 5 meters, from the surface to the bottom of the lake at all stations (1, 3, and 4). Eleven physico-chemical parameters were measured. The physical parameters are: temperature, electrical conductivity, pH, turbidity and transparency. Chemical parameters include oxygen, hydrogen sulphide, ammonium, silica, iron and phosphate.

For the present study, we will use three physical parameters (Temperature, Electrical Conductivity and pH) and three chemical parameters: (oxygen (O_2), ammonium (NH_4) and iron (Fe) content). This choice is motivated by the fact that they are fairly characteristic of water.

Water temperature is an important factor, as aquatic organisms live and reproduce in optimal conditions within specific temperature ranges. Temperature plays an important role in the solubility of gases, the dissociation of salts and the determination of pH, as well as in understanding the origin of water and possible mixtures (Ayad, 2017).

Electrical conductivity is the ability of an aqueous solution to conduct electrical current; it determines the overall mineral content of a solution: soft water generally has a low conductivity, while hard water has a high conductivity (Ayad & Kahoul, 2016).

The pH is a good indicator of water toxicity (when the pH is too low or too high). It is related to the hydrogen ion (H^+) content, acidity and alkalinity of the sample.

In an aquatic environment with low levels of dissolved oxygen (O_2), organisms tend to suffocate. When the amount of dissolved oxygen is high, so is plant production. This leads to eutrophication of the water. The oxygen content of water depends on its origin. Surface water can contain relatively large quantities of oxygen close to saturation, whereas deep water usually contains only a few milligrams per litre (Rodier, 2009).

The presence of iron (Fe) in natural water supplies is attributable to the decomposition of rock into minerals, acid mine drainage water, leachate from controlled landfill sites, sewage effluent and industrial discharges (Hem, 1972; James, 1977).

Ammonium (NH_4^+) is an ion naturally present in the environment that rarely accumulates in terrestrial and aquatic ecosystems when pollution is absent (Corriveau, 2009). Since ammonium is toxic to the human body, its presence in large quantities degrades water quality. According to the WHO, the normal level of ammonium in natural water is 0.5 mg/L. Urine is the main source of ammonium in domestic wastewater (Ndiaye & Sarr, 2009).

Electrical conductivity, pH and dissolved oxygen are measured at the time of sampling by the 1970i WTW conductivity meter, the 1970i WTW pH meter and the 1970i WTW oximeter, respectively. Temperature can be measured by the oximeter, the pH meter and the conductivity meter. However, for the purposes of this study we are using the conductivity meter.

Ammonium and iron are measured colorimetrically on water samples taken from the surface to the bottom every 5 meters using *Merck's* NH_4^+ *Test1 range* and *Aquaquant's Fe Test1 range*, respectively.

2.3. Method for Calculating the Water Quality Index

The water quality index will be calculated on the basis of the six parameters selected. This index is a water quality classification technique based on the comparison of water quality parameters with international standards (Abassi & Abassi, 2012). Internationally, the United Nations Environment Programme has agreed to use the CCME WQI in three forms: as the Global Drinking Water Quality Index, as the Health Water Quality Index and as the Acceptability Water Quality Index (CCME, 2017).

The WQI summarises large quantities of data on water quality in simple terms (Excellent, Good, Poor, Very Poor, Non-drinking water) according to the characteristics defined in **Table 1**.

This index is calculated using the weighted arithmetic index method (Brown, Mcclelland, Deininger, & Tozer, 1970; Chatterji & Raziuddin, 2002; Yidana & Yidana, 2010). In this approach, a numerical value called relative weight (Wi), specific to each physico-chemical parameter, is calculated (**Table 1**) according to the following formula:

$$Wi = \frac{k}{Si}$$

where:

k: a constant of proportionality and can be calculated using the following equation:

$$k = \frac{1}{\sum_{I=1}^{n} \frac{1}{Si}}$$

n: number of parameters;

Si: maximum value of the WHO (World Health Organization) water standard for each parameter in mg/l, except for pH, temperature and electrical conductivity according to the WHO standard (Fassinou et al., 2023).

Table 1. Classification and possible use of water according to the WQI (Brown, Mcclelland, Deininger, & O'Connor, 1972; Chatterji & Raziuddin, 2002; Aher, Kele, Malwade, & Shelke, 2016).

WQI Classes	Types of Water	Possible Uses
0 - 25	Excellent quality	Drinking water, irrigation and industries
>25 - 50	Good quality	Drinking water, irrigation and industries
>50 - 75	Bad quality	Irrigation and industries
>75 - 100	Very bad quality	Irrigation
>100	Non-drinking water	Appropriate treatment required before use

Next, a quality rating scale (Qi) is calculated for each parameter by dividing the concentration by the standard for that parameter and multiplying by 100 as in the following formula

$$Qi = \frac{Ci}{Si} \times 100$$

Qi: quality assessment scale for each parameter;

Ci: the concentration of each parameter in mg/l.

Finally, the overall water quality index is calculated using the following equation:

$$\text{WQI} = \frac{\sum_{I=1}^{n} Qi \times Wi}{\sum_{I=1}^{n} Wi}$$

3. Results and Discussion

3.1. Evolution of Physico-Chemical Parameters and Fluctuations in the Level of the Reservoir

The annual physico-chemical parameters of the water in the Manantali dam reservoir during the study period are shown in Table 2.

In situ measurements of temperatures recorded at Stations 1 and 3 ranged from 28.10˚C to 22.07˚C and from 29.13˚C to 21.08˚C, respectively, with temperature amplitudes of 6.03˚C and 8.05˚C. Conductivities recorded during the study ranged from 50 to 34.59 µS/cm at Station 1, and from 52.38 to 35.15 µS/cm at Station 3, with a maximum amplitude of 17.22 µS/cm recorded at Station 3. The pH ranged from 8.38 to 6.58 at Station 1, and from 7.84 to 6.66 at Station 3, with a maximum variation of 1.8 recorded at Station 1.

Dissolved oxygen content varied from 7.42 to 3.27 mg/l at Station 1, and from 7.49 to 2.83 mg/l at Station 3, with a maximum variation of 4.66 mg/l. Ammonium content varied from 0.1 to 0.01 mg/l at Station 1, from 0.2 to 0.02 mg/l

Table 2. Descriptive statistics for physico-chemical parameters for the 2 stations from 1989 to 2022.

		Temperature (T˚)	Electrical Conductivity (EC)	pH	Dissolved Oxygen (O)	Ammonium (NH_4)	Iron (Fe)
		˚C	µS/cm		mg/l	mg/l	mg/l
Station 1	Maximum	28.10	50.00	8.38	7.42	0.10	0.16
	Minimum	22.07	34.59	6.58	3.27	0.01	0.02
	Average	26.47	38.84	7.44	5.75	0.05	0.06
	Standard Deviation	1.22	3.39	0.42	0.95	0.02	0.03
Station 3	Maximum	29.13	52.38	7.84	7.49	0.20	0.70
	Minimum	21.08	35.15	6.66	2.83	0.02	0.02
	Average	26.23	39.84	7.29	5.00	0.06	0.16
	Standard Deviation	1.37	4.10	0.32	0.93	0.03	0.17

with a maximum variation of 0.18 mg/l at Station 3. Iron content varied from 0.16 to 0.02 mg/l at Station 1, and from 0.70 to 0.02 mg/l at Station 3, with a maximum variation of 0.68 mg/l.

The annual temperatures recorded at the three stations range from 21.08˚C to 29.13˚C and are similar to those recorded at the SÔ river in southern Benin (Koudenoukpo et al., 2017), very similar to those found in the Ouéme river delta (Zinsou, Attingli, Gnohossou, Adandedjan, & Laleye, 2016) in West Africa. In addition, these average values are likely to encourage the growth of aquatic organisms, as they are in line with the ecological or physiological preferences of these organisms, whose functions, such as the consumption of oxygen and food and the reaction speed of certain enzymes, depend on water temperature (Covich, Palmer, & Crowl, 1999). These temperatures are conducive to the growth of fish species that are commonly found in high water (Pouomogne, 1998). These values comply with the Moroccan standard for surface water (Standard, 2009).

The first two years (1989 and 1990) of the dam's impoundment showed high conductivities of almost 50 µS/cm, indicating that the trophic level was higher, leading not only to an increase in primary production, but also to greater decomposition of the algal biomass. Excessive mineral input to the water contributes to its mineralisation. It is, therefore, the combination of these two phenomena (supply and absorption of mineral salts) that governs the overall mineralisation and, therefore, the conductivity of the lake (Ossey, 2008). This mineralisation is a function of the solubility of dissolved and dissociated compounds, which predicts a high content of ions (Buhungu, 2018).

Average conductivity values for subsequent years varied around 39 µS/cm, indicating low conductivity. Parameters such as conductivity are closely linked to the nature and concentration of dissolved substances in the environment. Thus, low electrical conductivity in a watercourse is also synonymous with low mineralisation of the salts present in the environment (Ben Moussa, Chahlaoui, & Rour, 2012).

The pH, for its part, is influenced by the environment through which the river flows, in particular the mineral composition, the type of soil and the rock itself (Korfali & Jurdi, 2011; Mmualefhe & Torto, 2011; Mubedi et al., 2013). This study shows that the average pH is 7.3, which is almost neutral. Over the last 10 years, there has been an upward trend in the pH, which is above 7, indicating that the water is alkaline. These values are close to those reported for surface water, i.e. between 6.5 and 9.5 (Masamba & Mazvimavi, 2008; Nanituma, 2011) and also those recorded in the water of the Kinyankonge river, a tributary of Lake Tanganyika, Burundi (Buhungu, 2018).

Generally speaking, acidic lakes (pH < 7) appear to be more mineralised than alkaline lakes (pH > 7), and alkaline lakes more so than lakes with a pH close to neutral (pH = 7) (Legendre, Chodorowsk, Chodorowska, Pichet, & Potvin, 1980).

A pH of between 5 and 9 allows fauna and flora to develop normally (Blinda, 2007).

At the stations, dissolved oxygen levels varied between 2.83 and 7.49 mg/l, with an average of around 5 mg/l at the 2 stations. These values are similar to those recorded at the SÔ River in southern Benin, which show that the water is oxygenated and of good quality (Koudenoukpo et al., 2017).

For dissolved oxygen, the range of data, from 4 to 7 mg/l, means that oxygen levels are acceptable for warm-water fish species but low for cold-water fish species. Oxygen levels give an indication of the health of watercourses and make it possible, among other things, to assess the quality of fish habitats. Oxygen values within this range are acceptable for the initial and other life stages in tropical ecosystems in accordance with Canadian water quality guidelines (CCME, 2011).

Dissolved oxygen in surface waters comes mainly from the atmosphere and from the photosynthetic activity of algae and aquatic plants. The concentration of dissolved oxygen varies on a daily and seasonal basis because it depends on numerous factors such as the partial pressure of oxygen in the atmosphere, water temperature, salinity, light penetration, water agitation and nutrient availability. Dissolved oxygen concentration is also a function of the rate at which the environment is depleted of oxygen by the activity of aquatic organisms and the processes of oxidation and decomposition of the organic matter present in the water (Institut Bruxellois pour la Gestion de l'Environnement (IGBE)/Observatoire des Données de l'Environnement, 2005).

The dissolved oxygen found in watercourses is used by aquatic organisms to breathe. However, this phenomenon is only effective if oxygen is present above a certain concentration, as aquatic organisms need a minimum quantity of dissolved oxygen to survive. Determining dissolved oxygen levels, therefore, provides information on the health of watercourses and, among other things, makes it possible to assess the quality of fish habitats (Chouti, 2010).

Generally speaking, ammonium is an indicator of microbiological contamination. It also alters the taste of the water and encourages the proliferation of nitrifying bacteria. Nitrite comes from the transformation of ammonium by bacteria. Their presence is a sign of bacteriological and organic pollution. Nitrites are also the most toxic (Miquel, 2003).

However, the direct effects of ammonium on health have not been clearly identified.

At station level, ammonium levels vary from 0.01 to 0.20 mg/l, with an average of 0.06 mg/l. These levels are not very high and therefore not alarming, especially as the trend over the last 10 years has been constant, with an ammonium level of 0.05 mg/l.

Ammoniacal nitrogen (NH_4^+) results essentially from the aerobic degradation of organic nitrogen (proteins, amino acids, urea, etc.), which, in urban environments, comes largely from the discharge of untreated or inadequately treated wastewater. The breakdown of NH_4^+ into nitrites (NO_2^-) and then nitrates (NO_3^-) via the nitrification process consumes dissolved oxygen and contributes to eutrophication (nitrogen is often the limiting factor for the growth of algae in the marine environment). NH_4^+ itself is not harmful, but under certain conditions it can be transformed into ammonia (NH_3), a gas that is soluble in water and toxic to aquatic life. NH_4^+ is generally rapidly absorbed by aquatic organisms, but can be present in significant quantities in water polluted by organic matter and with low oxygen levels (Chouti, 2010).

Average iron levels at Stations 1 and 3 are very low, given that iron levels in drinking water must be less than 0.3 mg/l (Canada, 1987), withdrawing water for a drinking water supply at the 2 stations would not require any specific iron treatment. This is because the presence of iron in natural water supplies is attributable to the decomposition of rock into minerals, acid drainage water, leaching water, effluents and industrial waste.

The area submerged by the fluctuating water level could serve as a potential source of nutrients, releasing nutrients from plants and soils below the water surface. **Figure 4** shows the variation in water level over time, with a maximum of around 20,900 cm corresponding to the first period when the reservoir was filled. From November 1994, due to urgent repair work on the dam, the level of the reservoir was lowered. Following the delay in carrying out the repair work, the level of the lake was lowered a second time in 1996 to the 18,000 cm mark (OMVS Limnological Unit, 2012).

The Pearson correlation matrix established between water level fluctuation and physico-chemical parameters shows no direct correlation.

3.2. Results of the Calculation of the Water Quality Index (WQI)

The Water Quality Index (WQI) is an integrative indicator used to assess changes in water quality based on several measured parameters. After calculating the overall WQI quality index using the results of physico-chemical analyses and the standard values of the WHO water quality standard, the water quality class is determined for all 2 stations.

The relative weight (Wi) of each physico-chemical parameter and the proportionality constant k are calculated firstly using the maximum values of the WHO standard for the physico-chemical parameters studied (**Table 3**).

Table 3. Weight of physico-chemical parameters.

	Temperature (T°)	Electrical Conductivity (EC)	pH	Dissolved Oxygen (O)	Ammonium (NH_4)	Iron (Fe)
	°C	μS/cm		mg/l	mg/l	mg/l
WHO Standards	20 - 30	<1500	6.5 - 9.5	5.00 - 8.00	0.1 - 0.5	0.30
Si	30	1500	9.5	8	0.5	0.3
1/*Si*	0.03	0.00067	0.11	0.13	2.00	3.33
Sum (1/*Si*)			5.60			
K			0.18			
Wi	0.0060	0.0001	0.0189	0.0225	0.3600	0.6000

Figure 4. (a) Annual temperature variation in stations; (b) Annual pH variation in stations; (c) Annual electrical conductivity variation in stations; (d) Annual dissolved oxygen variation in stations; (e) Annual ammonium content variation in stations; (f) Annual iron content variation in stations; (g) Variation of the water level in the reservoir from 1989 to 2022.

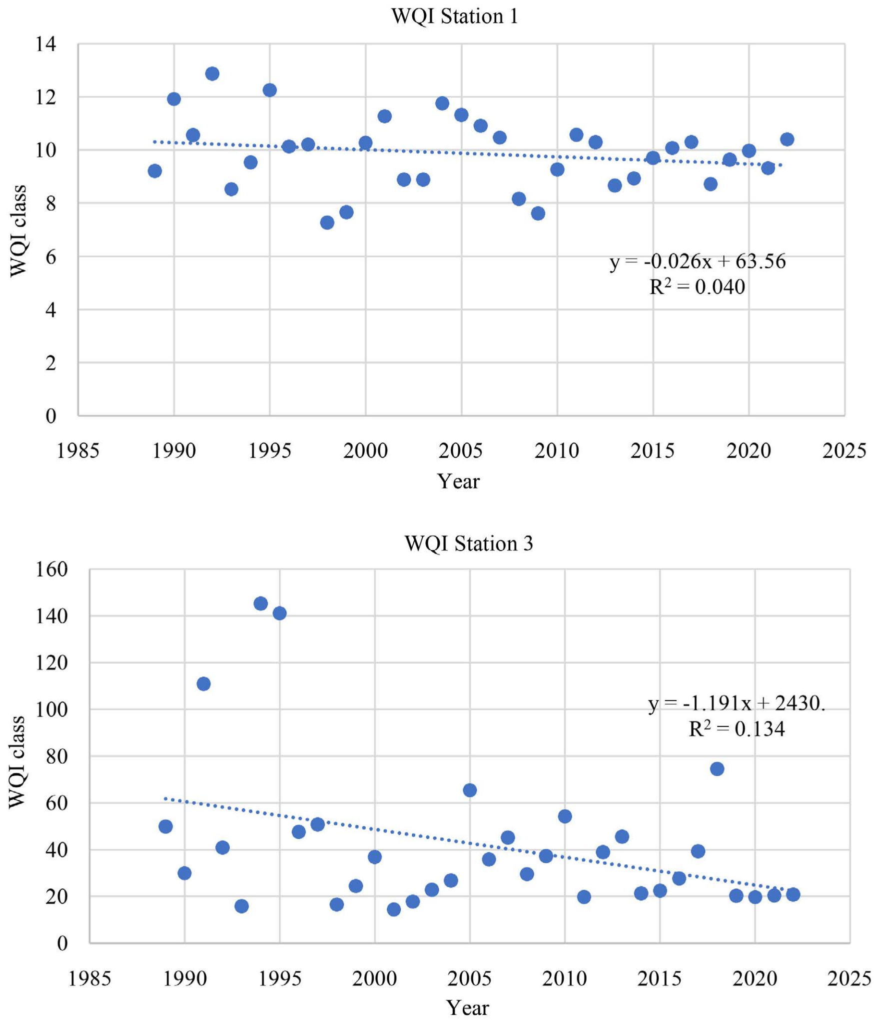

Figure 5. Correlation of WQIs at the 2 stations.

The water quality index for Station 1, with an average over the study period of 9.87, shows water of "Excellent" quality with possible uses in drinking water, irrigation and industry. Station 3, with an average of 42.04, has water of "Good" quality with possible uses in drinking water, irrigation and industry.

In addition, the linear regression presented in **Figure 5** showed trends towards improved water quality for all 2 stations. The slopes are −0.027 and −1.19 respectively for Stations 1 and 3; the negative value indicates an improvement in water quality as the dam's water is used.

4. Conclusion

This study has made it possible to monitor changes in the physico-chemical quality of the water in the Manantali dam reservoir since it was impounded in 1989. The results of the analyses show that most of the parameters studied comply with current surface water standards and that the water in the reservoir is of good quality. The temperatures recorded show that the water is conducive to the growth of aquatic organisms. The conductivity and pH values show that the water is not very mineralised, which means that aquatic flora and fauna are developing normally. Dissolved oxygen, ammonium and iron levels show that the water is well oxygenated, is not a source of microbiological contamination and does not require specific iron treatment for drinking water supply. Studies also need to be continued on other parameters, such as transparency, turbidity, nitrite, nitrate, hydrogen sulphide, silica and manganese, with a view to extending the range of measurements to ensure very good physico-chemical quality, as well as certain biological parameters (ichthyological and planktonic).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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