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Comparative Study of Physico-Chemical and Biological Water Quality Upstream and Downstream of the Manantali Dam and Hydropower Plant from 2019 to 2023

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Abstract

The comparative study is designed to monitor the physico-chemical and biological quality of the water upstream and downstream of the Manantali hydroelectric dam. The physico-chemical parameters are sampled at 3 measuring points located at Station 1 of the dam's reservoir, immediately downstream of the dam and hydroelectric power station at the level of the damping basin, and at the Bafing-Bakoye confluence at Bafoulabe (Bafing side), the biological parameter (ichthyological fauna) is characterized by ichthyological inventories of landings in the various fishing camps around the reservoir and at the Mahina market (Bafing side). The study assesses the environmental impact of hydroelectric structures and facilities on the physico-chemical and biological quality of the water. Physical parameters such as temperature, conductivity, pH, turbidity and chemical parameters such as dissolved oxygen, nitrite, nitrate, manganese, hydrogen sulfide, ammonium, iron, silica and phosphorus are measured in order to identify the various variations existing between the different measurement points. Analysis of the values obtained shows very high similarities between the various measuring points, and most parameters comply with WHO standards, with the exception of turbidity, manganese, hydrogen sulfide and iron. These data attest to good water quality, allowing normal development of flora and fauna with a low level of degradation. Comparative analysis of the ichthyological fauna shows the existence of 34 species of fish belonging to 11 families at the fishing camps around the Manantali dam reservoir, and 37 species belonging to 12 families at Mahina on the Bafing River. At Mahina on the Bafing, the specific composition of the catches is characterized by the presence of the Claroteidae family and four species (*Alestes sp., Brycinus leuciscus, Auchenoglanis occidentalis, Distichodus engycephalus*) not recorded at the camps. In contrast, all the fish families recorded in the camps are present in Mahina, and only one species (*Hydrocynus brevis*) is absent from the Mahina landings. The difference in species richness could be explained by the upwelling of some fish from the Bakoye to the Bafing at the confluence. The Shannon diversity index of 4.07 at Mahina is higher than the 2.98 recorded at camp level, and the equitability index of 0.78 at Mahina and 0.58 at the camp level indicate average diversity and the non-dominance of one species over the others. The diversification index values of 3.09 and 3.08 at camp level and Mahina respectively show that the number of theoretical habitats is three.

Keywords

Manantali Dam, Physical Parameters, Chemical Parameters, Fish Fauna

1. Introduction

The construction of large hydroelectric complexes has long been the subject of intense debate (Biswas, 2004). Because of this, the World Commission on Dams was set up by the United Nations in 1997 to shed light on dams, their impact on the environment and their role in a country's development (WCD, 2000).

The construction of dams leads to the creation of a reservoir (as in the case of Manantali) of varying sizes, transforming a lotic environment into a lentic one. This results in profound changes to the ecosystem, notably with socio-environmental repercussions, the most worrying of which are the displacement of populations, the proliferation of aquatic plants and the high prevalence of water-borne diseases (Faye et al., 2023).

Studying the impact of hydroelectric dams on the physico-chemical quality of water is of paramount importance, since good water quality is an important criterion for meeting water demand and supply, and guaranteeing freshwater quality adapted to human and ecological needs is, therefore, an important aspect of integrated environmental management and sustainable development (Talhaoui et al., 2020).

Since water is a natural resource essential to life in any ecosystem (TAMPO et al., 2015), turbining it at a hydroelectric power station can have an impact, hence the importance of maintaining its quality, which is a major concern for a society that has to meet ever-increasing water needs (FOTO et al., 2011).

A number of studies have focused on the dam's impoundment, making it impossible to assess the quality of the turbined water. This article, whose main objective is to analyze the real impact of the dam on the physico-chemical quality of the water, focuses on the analysis of 13 physico-chemical parameters measured upstream at station 1 of the dam's reservoir (the station closest to the dam), immediately downstream of the dam and the hydroelectric power station at the damping basin and at the Bafing-Bakoye confluence (on the Bafing side), in order to monitor the various variations in water quality.

The biological parameter concerned is ichthyological fauna. Surveys are carried out quarterly at the various fishing camps around the dam reservoir in sub-basin 1, as well as at the Mahina market in sub-basin 2.

Comparative analysis of fish populations has enabled us to identify the species of fish caught in the lake and in the Bafing River. These surveys have made it possible to classify the ichthyological fauna by family and species.

2. Material and Methods

2.1. Study Area

The Senegal River watershed is subdivided into seven (7) sub-basins (SB) (OMVS, 2018). The study area covers sub-basins 1 and 2. SB1: the Bafing upstream to the Manantali dam, this sub-catchment has a rugged upstream section, with a difference in level of around 1130 m between its highest and lowest points (Manantali). It is non-navigable and has little demand for water. Several potential hydroelectric development sites, such as Balassa and Koukoutamba, are located here. With a median daily low water level of 620 l/s and 440 l/s in a five-year dry year, the annual modulus at Bafing Makana is 220 m^3/s. The surface area of this sub-basin is 28,250 km^2. SB2: the downstream Bafing, from the Manantali dam to Bafoulabé, extending as far as the confluence with the Bakoye, where the Senegal River is born; is entirely influenced by the hydraulic management of the Manantali dam, thus eliminating any natural low water on this stretch. It has a surface area of 10,800 km^2, and water requirements are relatively low, with no navigability (**Figure 1**).

The presence of the reservoir has encouraged the development of fishing camps around the lake. In August 2023, a survey carried out by SEMAF's limnology laboratory team identified 28 fishing camps around the Manantali dam reservoir (**Figure 2**).

2.2. Sampling Strategy and Analysis Methods

2.2.1. Physico-Chemical Parameters

Measurements of physico-chemical parameters are carried out quarterly from 2019 to 2023 at the surface at station 1 of the reservoir, immediately downstream of the dam and at the Bafing-Bafing confluence in sub-basin 2 (**Figure 1**, **Figure 2**) and have required the use of several pieces of equipment in particular: the WTW 1970i type pH meter used to measure pH, resistivity and water temperature; the WTW 1970i type conductivity meter measures conductivity, salinity and water temperature; the WTW 1970i type oximeter measures dissolved oxygen and water temperature (to check data repeatability, a WTW 1970i type multi-parameter device is used to measure pH, conductivity, dissolved oxygen and water temperature); the HACH 2100Q turbidimeter is used to measure turbidity and water temperature. For most chemical parameters, the DR3900 spectrophotometer is used to analyze iron using the FerroVer method (Method 8008), manganese using the Periodate oxidation method (Method 8034), ammonium using the Salicylate method (Method 8155) and the Nessler method (Method 8038), Hydrogen sulfide by Methylene Blue (Method 8131), Nitrite by Diazotation (Method 8507) and Ferrous Sulfate (Method 8153), Nitrate by Cadmium Reduction (Methods 8192 and 8171), Phosphorus by Phosver 3 (Method 8048), Silica by Heteropoly Blue (Method 8186) and Silicomolybdate (Method 8185).

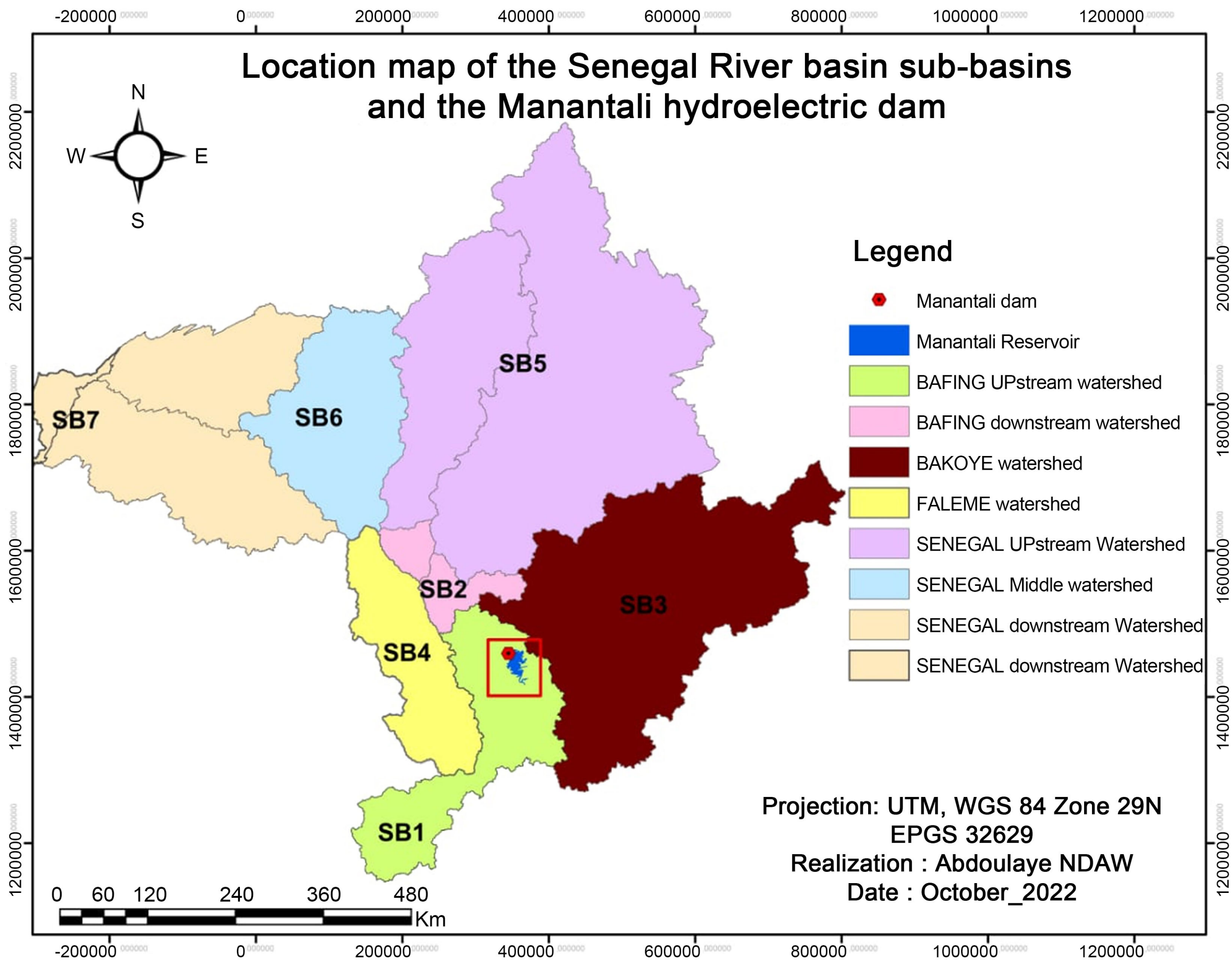


Figure 1. Map showing the location of the Senegal River sub-basins and the Manantali hydroelectric dam.

2.2.2. Biological Parameters

For the ichthyological fauna, the study was based on inventories carried out quarterly from 2019 to 2023 in the landings of the various fishing camps in the dam reservoir (Figure 2) in sub-basin 1, as well as at the Mahina market in sub-basin 2 (Figure 1) (taking into account only fish caught in the Bafing River) in order to identify the fish species caught in the lake and the Bafing River.

2.2.3. Fish Population Diversity Index

The indices used to assess the fish population are species richness (*S*), specific and relative abundance, percentage of occurrence (*F*), as well as Shannon and Weaver's (1964) specific diversity index (*H'*) and Piélou's (1966) equitability index (*E*) (Shannon & Weaver, 1964; Pielou, 1966).

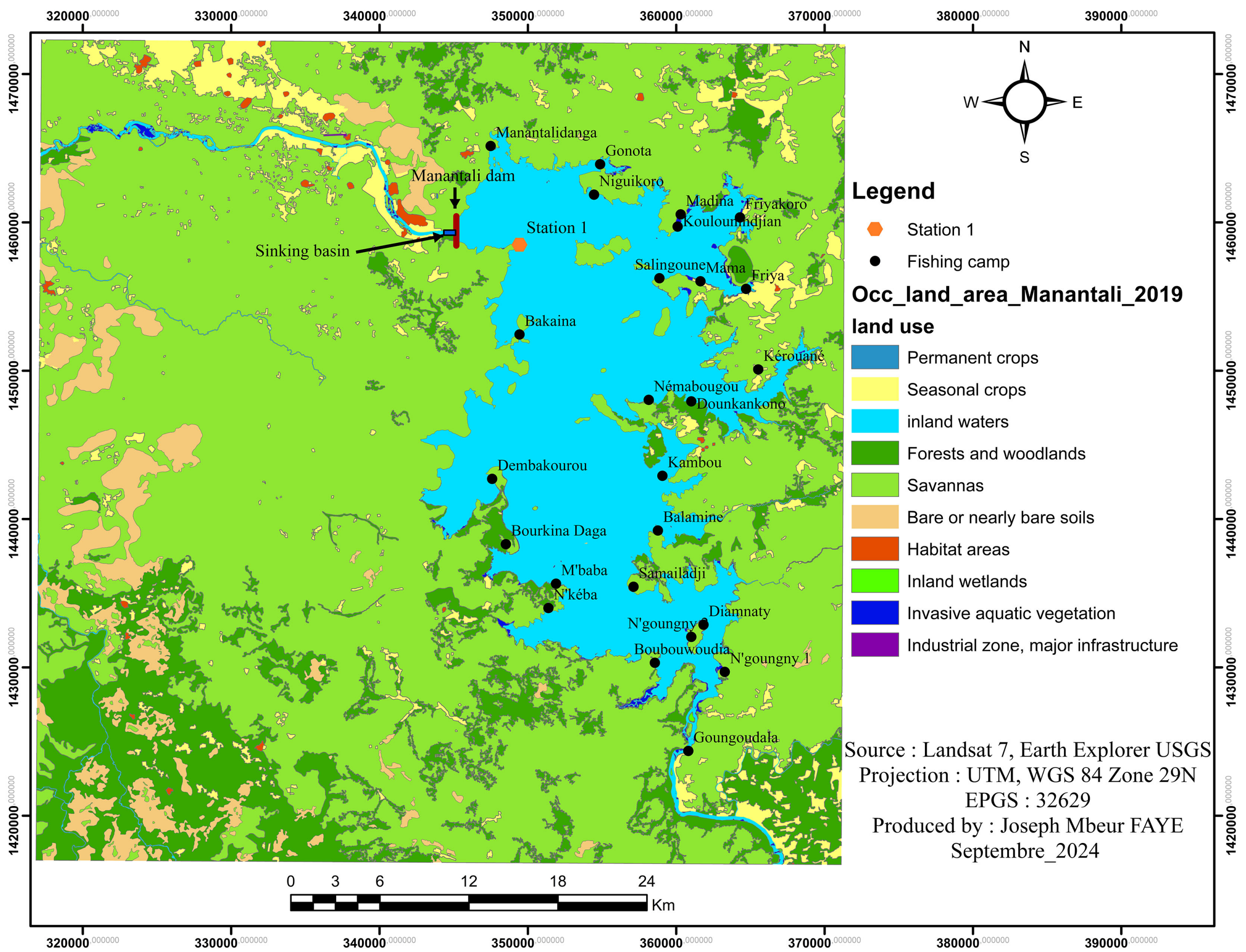


Figure 2. Location of various fishing camps.

1) Species richness (S) expresses the number of species found in the catches.

2) The specific abundance corresponds to the number of specimens of a species in the catches.

3) Relative abundance expresses the percentage ratio of the number of a given species to the total number of fish caught.

4) Percentage of occurrence (F) is the ratio, expressed as a percentage, of the number of catches of a given species (F_i) to the total number of catches (F_t):

$$F = \left(\frac{F_i}{F_t}\right) \times 100 \tag{1}$$

Depending on the value of F, the species is said to be constant if $F \geq 50\%$, accessory when $25\% \leq F \leq 50\%$ and accidental when $F < 25\%$ (Dajoz, 2000);

5) Shannon and Weaver's diversity index (H') measures specific diversity and is expressed as follows:

$$H' = -\sum_{i=1}^{s}\left(\frac{n_i}{N}\right) \times \log 2\left(\frac{n_i}{N}\right) \tag{2}$$

With:

S: total number of species present; n_i: number of species *i* in the sample; *N*: total number of species.

H' varies between 0, in the case where the stand consists of a single species, and log2 S in the case where all the species are present with equivalent abundance (*H'* = 4.5 or 5 for the most diverse stands).

Pielou's (Pielou, 1966) equitability index (*E*) is used to assess the quality of the distribution of individuals within the species in the environment. It is calculated using the following formula:

$$E = H'/\text{Log2}(S) \tag{3}$$

The value of E is between 0 and 1. It tends towards 0 when almost all the individuals are concentrated in one species, and towards 1 when all the species have the same abundance (state of equilibrium). If E is less than or equal to 0.6, the environment is said to be degraded in relation to the species living there, and if E is close to 1, the environment is said to be in equilibrium in relation to the species living there (Sanogo et al., 2023).

The index of species diversification within families is calculated from Equation (3) below:

$$D = S/NF \tag{4}$$

where *S* is the species richness and *NF* is the number of families.

The assessment of species diversification within families gives an idea of the level of species diversification achieved within families and the existence of habitat variability in aquatic environments (Sanogo et al., 2010).

3. Results and Discussions

3.1. Results

Physical parameters measured include temperature, conductivity, pH and turbidity, while chemical parameters include nitrite, nitrate, manganese, hydrogen sulfide, ammonium, iron, silica, phosphorus and dissolved oxygen.

3.1.1. Physico-Chemical Parameters

Physical parameters

In situ temperature measurements ranged from 29.95˚C to 23.9˚C, indicating a thermal amplitude of 6.05˚C. Maximum temperatures were recorded at Bafoulabé, while minimum temperatures were observed at the damping basin. Values recorded at the damping basin remained below average throughout the study. The average temperatures recorded were 28.73˚C at Bafoulabé, 26.30˚C at station 1 and 25.91˚C at the damping basin (**Figure 3(a)**).

Turbidity, a key indicator of water clarity, was measured in all three study areas. The maximum turbidity value was recorded at Bafoulabe with 25.44 NTU, while the minimum value was observed at the damping basin with 0.60 NTU. Turbidity variation was almost identical at the damping basin and station 1. Turbidity was highest at Bafoulabé throughout the study period. Average turbidity values were 11.01 NTU at Bafoulabé, 2.25 NTU at the damping basin and 2.06 NTU at station 1 (**Figure 3(b)**).

The pH of the waters studied ranged from 8.38 to 7.2, with an amplitude of 1.18. The highest value was recorded at station 1, while the lowest was measured at Bafoulabe. Over the entire study period, the average pH was 7.65 at Bafoulabe, 7.68 at the damping basin and 7.96 at station 1, with an average value of around 7.77 at all sampling sites (**Figure 3(c)**).

The maximum conductivity observed was 41.8 µS/cm at the damping basin, while the minimum conductivity of 35.6 µS/cm was recorded at the confluence. Average conductivity values over the course of the study were 37.43 µS/cm at Bafoulabe, 38.75 µS/cm at the damping basin and 37.41 µS/cm at station 1 (**Figure 3(d)**).

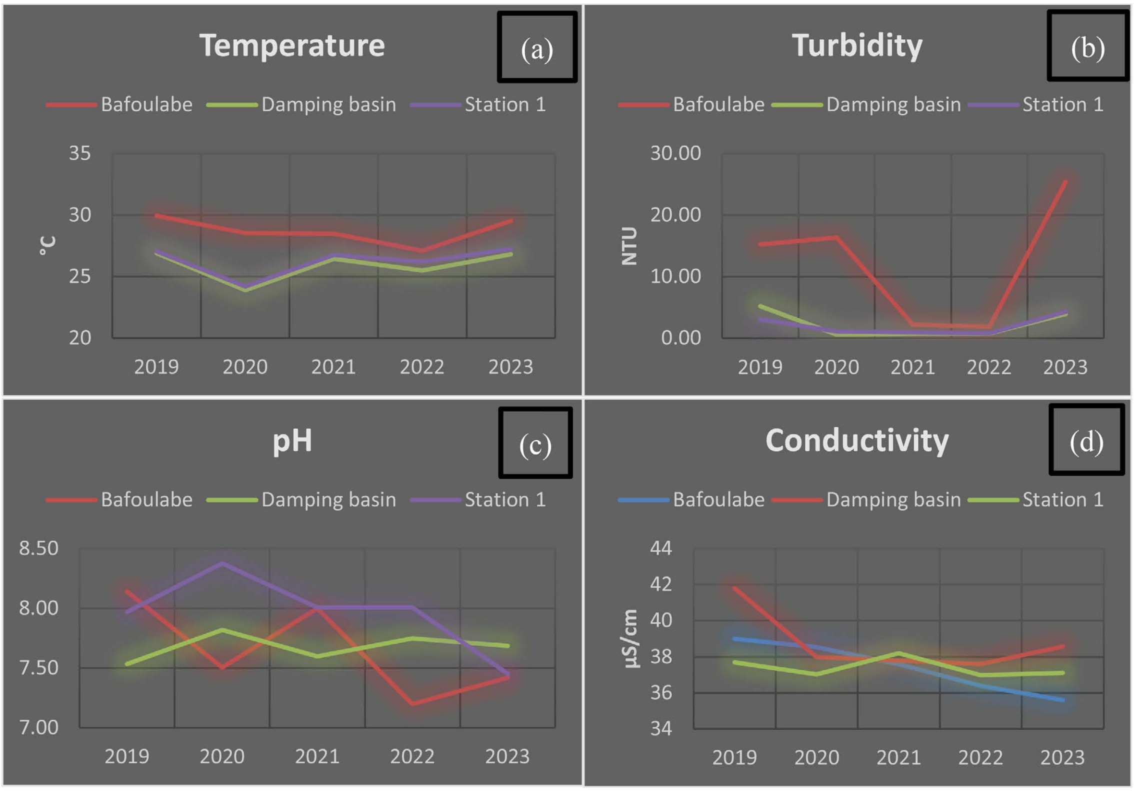


Figure 3. (a) Variation in temperature, (b) Variation in turbidity; (c) Variation in pH; (d) Variation in conductivity.

Chemical parameters

Throughout the study period, dissolved oxygen levels were highest at Bafoulabe, with a maximum value of 9.14 mg/L and a minimum value of 6.60 mg/L, between 7.28 mg/L and 2.60 mg/L at the damping basin and between 6.72 mg/L and 3.71 mg/L at station 1 (**Figure 4(a)**).

The maximum nitrite content of 0.03 mg/L was recorded at Bafoulabe in 2023. Outside this year, the maximum values were 0.008 mg/L at the damping basin and 0.007 mg/L at station 1 (**Figure 4(b)**).

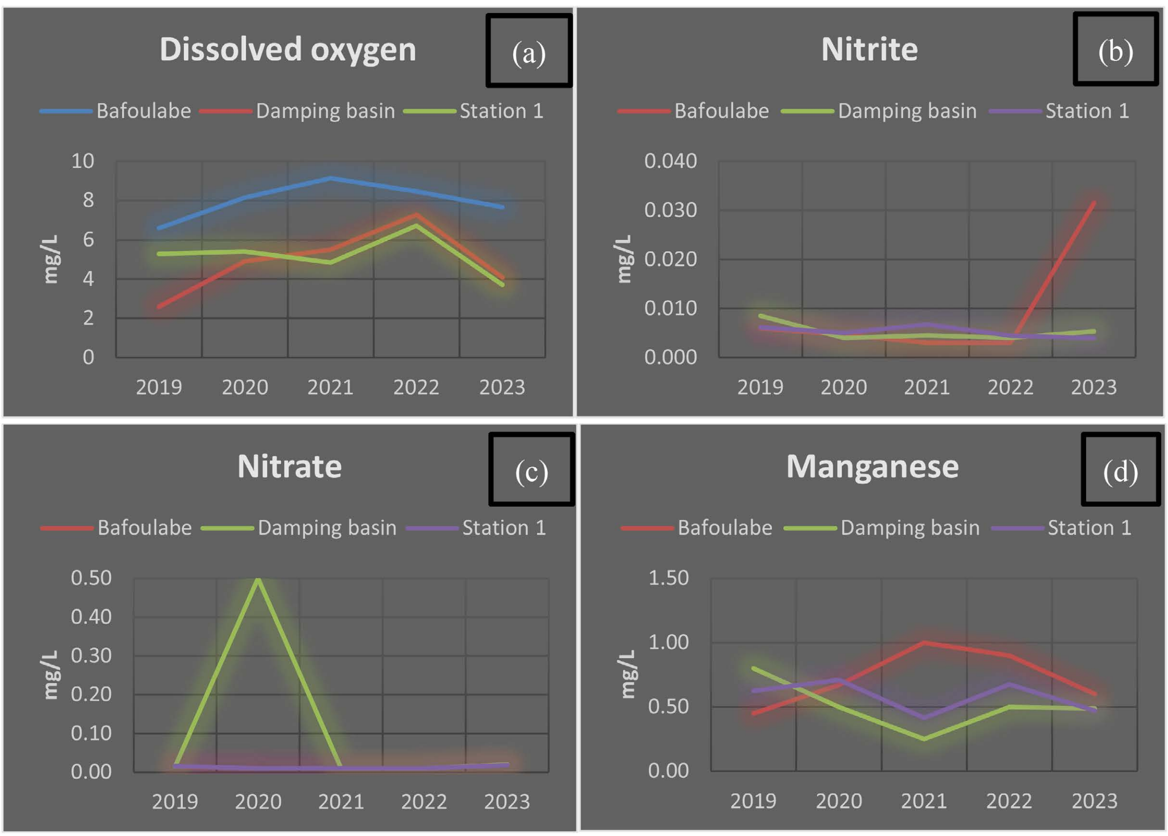
The highest maximum nitrate content, 0.5 mg/L, was recorded at the damping basin in 2020. With the exception of this value, nitrate levels remained constant across all sampling sites, with an average of 0.01 mg/L (Figure 4(c)).

The maximum manganese concentration of 1.00 mg/L was recorded at Bafoulabe, while the minimum concentration of 0.25 mg/L was recorded at the buffer basin. Mean manganese concentrations were 0.72 mg/L; 0.51 mg/L and 0.58 mg/L at Bafoulabe, the damping basin and Station 1 respectively (Figure 4(d)).

Maximum hydrogen sulfide levels of 1.37 mg/L at station 1, 0.34 mg/L at the damping basin and 0.17 mg/L at Bafoulabe were recorded in 2023. Average levels of 0.27 mg/L, 0.08 mg/L and 0.04 mg/L were recorded at station 1, the amortization basin and Bafoulabe respectively (Figure 4(e)).

The maximum ammonium content of 0.12 mg/L is recorded at Bafoulabe in 2021, and the minimum value of 0.01 mg/L at station 1. A decrease in content has been noted at Bafoulabe since 2021. Mean ammonium values of 0.09 mg/L; 0.03 mg/L and 0.04 mg/L are recorded at Bafoulabe, the damping basin and station 1 respectively (Figure 4(f)).

Maximum iron levels of 2.78 mg/L and 2.63 mg/L are recorded at the damping basin in 2021 and 2019. The minimum content of 0.02 mg/L is recorded at the damping basin and station 1. Average levels are 0.22 mg/L; 1.14 mg/L and 0.06 mg/L, recorded at Bafoulabe, the amortization basin and station 1 respectively (Figure 4(g)).



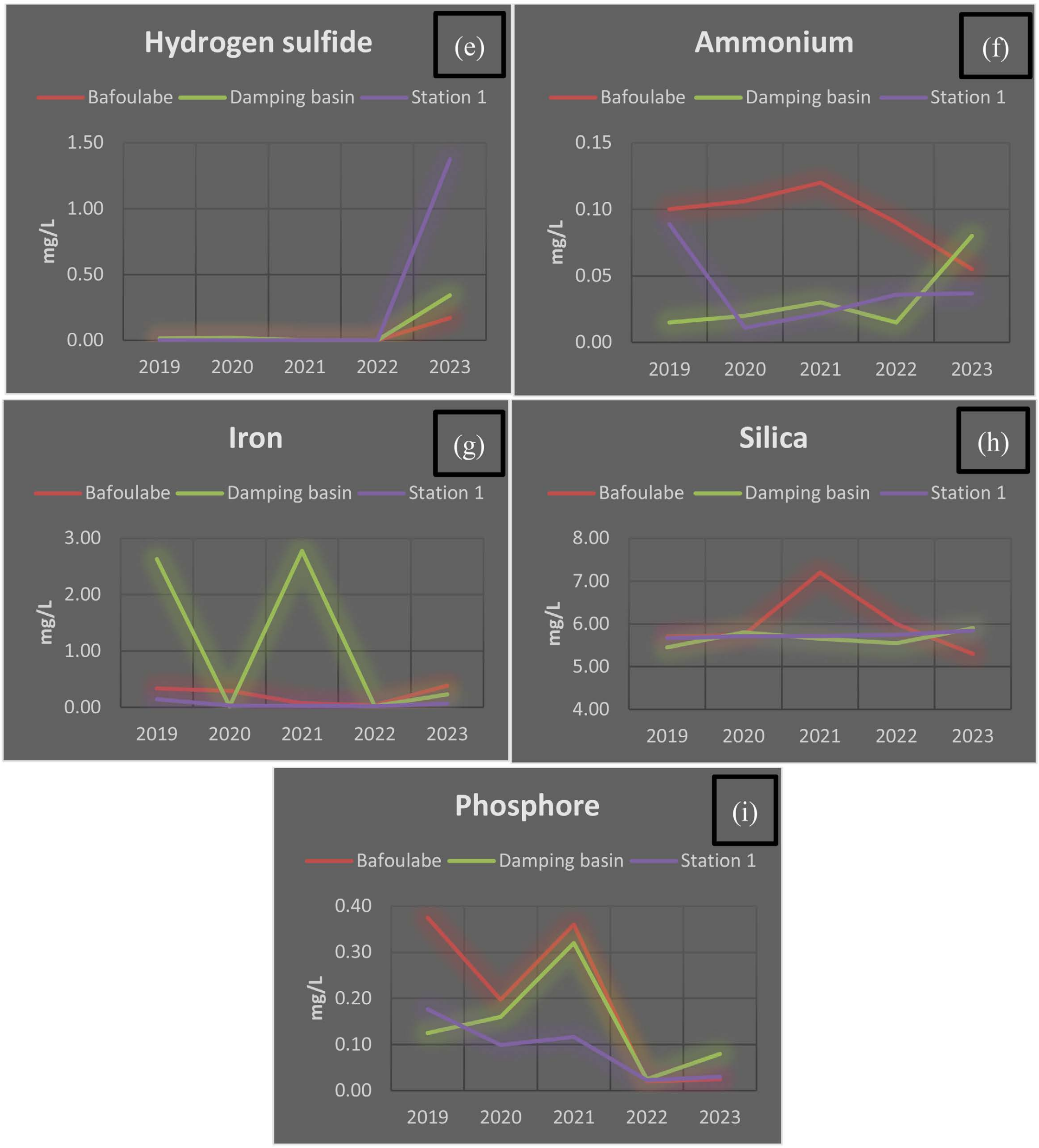


Figure 4. (a) Variation in dissolved oxygen content; (b) Variation in nitrite content; (c) Variation in nitrate content; (d) Variation in manganese content; (e) Variation in hydrogen sulfide content; (f) Variation in ammonium content; (g) Variation in iron content; (h) Variation in silica content; (i) Variation in phosphorus content.

Maximum and minimum silica levels of 7.2 mg/L and 5.30 mg/L were recorded at Bafoulabe in 2021 and 2023. An almost identical variation in content was noted at the damping basin and station 1. Mean silica values are 5.99 mg/L, 5.67 mg/L and 5.73 mg/L, recorded at Bafoulabe, the amortization basin and station 1 respectively (**Figure 4(h)**).

Maximum phosphorus levels of 0.37 mg/L and 0.36 mg/L are recorded in 2019 and 2021 at Bafoulabe. Average phosphorus levels of 0.2 mg/L, 0.14 mg/L and 0.09 mg/L were recorded at Bafoulabe, the amortization basin and station 1 respectively (**Figure 4(i)**).

3.1.2. Biological Parameters (Ichthyological Fauna)

A total of 113874 fish individuals were sampled at the camps, divided into 34 species belonging to 11 families. The Cichlidae and Mochokidae families are the most represented, with 7 species each (20.6%), followed by the Cyprinidae with 6 species (17.6%), the Alestidae with 5 species (14.7%), the Bagridae and Schlibeidae with 2 species each (5.9%) and finally the Anabantidae, Centropomidae, Distichodontidae, Malateruridae and Tetraodontioae with one species each (2.9%) (Table 1).

Table 1. Diversity and abundance of fish species caught at lake camps.

*** Constant, ** Accessory, * Accidental		Fishing camps			
Family	**Species**	**Specific abundance**	**Relative abundance (%)**	**% occurrence**	
ALESTIDAE	*Brycinus macrolepidotus*	216	0.19	100	***
	Brycinus nurse	2594	2.28	100	***
	Hydrocynus brevis	34	0.03	100	***
	Hydrocynus forskalii	15388	13.51	100	***
	Hyperopisus bebe	524	0.46	100	***
ANABANTIDAE	*Ctenopoma petherici*	11	0.01	33	**
BAGRIOAE	*Bagrus docmac*	203	0.18	100	***
	Chrysichthys auratus	5928	5.21	100	***
CENTROPOMIDAE	*Lates niloticus*	4101	3.60	100	***
CICHLIDAE	*Clarias anguillaris*	1093	0.96	100	***
	Hemichromis bimaculatus	80	0.07	100	***
	Hemichromis fasciatus	2330	2.05	83	***
	Oreochromis aureus	14	0.01	17	*
	Oreochromis niloticus	922	0.81	100	***
	Sarotherodon galilaeus	28564	25.08	100	***
	Tilapia sp.	36416	31.98	100	***
CYPRINIDAE	*Barbus macrops*	6	0.01	33	**
	Barbus occidentalis	1	0.00	17	*
	Labeo coubie	420	0.37	100	***
	Labeo senegalensis	877	0.77	100	***
	Labeo parvus	2	0.00	17	*
	Raiamas senegalensis	6	0.01	17	*
DISTICHODONTIDAE	*Distichodus rostratus*	6	0.01	33	**
MALAPTERURIDAE	*Malapterurus electricus*	520	0.46	100	***

Continued

MOCHOKIDAE	*Marcusenius senegalensis*	628	0.55	100	***
	Mormyrops anguilloïdes	340	0.30	100	***
	Mormyrus rume	1987	1.74	100	***
	Petrocephalus bovei	201	0.18	100	***
	Synodontis ocellifer	854	0.75	100	***
	Synodontis schall	8287	7.28	100	***
	Synodontis violaceus	6	0.01	50	**
SCHILBEIDAE	*Schilbe intermedius*	622	0.55	100	***
	Schilbe mystus	13	0.01	17	*
TETRAODONTIOAE	*Tetraodon lineatus*	680	0.60	100	***
Numbers			113874		
Specific richness *S*			34		
Shannon and Weaver diversity index (*H'*)			2,98		
Pielou equitability index (*E*)			0,58		
Diversification index (*D*)			3,09		

In terms of abundance, *Tilapia sp.* (31.98%), *Sarotherodon galilaeus* (25.08%), *Hydrocynus forskalii* (13.51%), *Synodontis schall* (7.28%) and *Chrysichthys auratus* (5.21%) are the 5 most represented species, with a percentage of 77.85%.

Frequencies of occurrence show that 25 species are constant, 4 species are accidental and 5 species are accidental.

The Shannon diversity index calculated over the period of this study is 2.98, with an equitability index of 0.58 and a diversification index of 3.09.

A total of 5890 fish individuals were sampled in the Bafing River at Mahina. They are divided into 37 species belonging to 12 families. The Cichlidae and Mochokidae families are the most represented, with seven species each (18.9%), followed by the Cyprinidae and Alestidae families with six species (16.2%), the Bagridae, Distichodontidae and Schlibeidae with two species each (5.4%) and finally the Anabantidae, Centropomidae, Claroteidae, Malateruridae and Tetraodontioae with one species each (2.7%) (Table 2).

Table 2. Diversity and abundance of fish species caught at the confluence (Bafing side).

*** Constant, ** Accessory, * Accidental		**Mahina (Bafing)**			
Family	**Species**	**Specific abundance**	**Relative abundance (%)**	**% occurrence**	
ALESTIDAE	*Alestes sp.*	93	1.58	83	***
	Brycinus macrolepidotus	87	1.48	100	***
	Brycinus nurse	208	3.53	100	***
	Brycinus leuciscus	40	0.68	33	**
	Hydrocynus forskalii	96	1.63	100	***
	Hyperopisus bebe	36	0.61	83	***

Continued

ANABANTIDAE	*Ctenopoma petherici*	146	2.48	100	***
BAGRIOAE	*Bagrus docmac*	42	0.71	83	***
	Chrysichthys auratus	734	12.46	100	***
CENTROPOMIDAE	*Lates niloticus*	19	0.32	100	***
CICHLIDAE	*Clarias anguillaris*	526	8.93	100	***
	Hemichromis bimaculatus	53	0.90	83	***
	Hemichromis fasciatus	94	1.60	67	***
	Oreochromis aureus	6	0.10	17	*
	Oreochromis niloticus	151	2.56	50	***
	Sarotherodon galilaeus	358	6.08	100	***
	Tilapia sp.	1097	18.62	100	***
CLAROTEIDAE	*Auchenoglanis occidentalis*	40	0.68	83	***
CYPRINIDAE	*Barbus macrops*	3	0.05	17	*
	Barbus occidentalis	17	0.29	83	***
	Labeo coubie	457	7.76	100	***
	Labeo senegalensis	23	0.39	67	***
	Labeo parvus	15	0.25	50	**
	Raiamas senegalensis	4	0.07	50	**
DISTICHODONTIDAE	*Distichodus rostratus*	9	0.15	83	***
	Distichodus engycephalus	18	0.31	67	***
MALAPTERURIDAE	*Malapterurus electricus*	21	0.36	83	***
MOCHOKIDAE	*Marcusenius senegalensis*	153	2.60	83	***
	Mormyrops anguilloïdes	114	1.94	100	***
	Mormyrus rume	80	1.36	100	***
	Petrocephalus bovei	41	0.70	67	***
	Synodontis ocellifer	90	1.53	100	***
	Synodontis schall	716	12.16	100	***
	Synodontis violaceus	46	0.78	83	***
SCHILBEIDAE	*Schilbe intermedius*	186	3.16	100	***
	Schilbe mystus	1	0.02	17	*
TETRAODONTIOAE	*Tetraodon lineatus*	70	1.19	100	***
Numbers			5890		
Specific richness *S*			37		
Shannon and Weaver diversity index (*H'*)			4.07		
Pielou equitability index (*E*)			0.78		
Diversification index (*D*)			3.08		

Tilapia sp. (18.62%), *Chrysichthys auratus* (12.46%), *Synodontis schall* (12.16%), *Clarias anguillaris* (8.93%), *Labeo coubie* (7.76%), *Sarotherodon galilaeus* (6.08%) are the 6 most represented species with a percentage of 66.01%.

The frequencies of occurrence show that 31 species are constant, 3 species are accidental and 3 species are accidental.

The Shannon diversity index calculated over the period of this study is 4.07, with an equitability index of 0.78 and a diversification index of 3.08.

3.2. Discussions

Physico-chemical parameters

Annual temperature values range from 29.9˚C to 27.1˚C at Bafoulabe, from 27.25˚C to 24.2˚C at station 1, and from 26.9˚C to 23.9˚C at the damping basin. These data are comparable to those observed at the lake level of the Kossou hydroelectric dam (KONÉ et al., 2022) and the Buyo dam in Ivory Cost (OSSEY, 2008). The lower temperature at the damming basin is attributable to the turbid water coming mainly from the deep layer of the reservoir, which is relatively cold (OMVG, 2014).

Turbidity results from the presence of suspended matter in the water, such as organic debris, clays and microscopic organisms. Assessing the abundance of such matter is a measure of its degree of turbidity (Jemali & Kefati, 2002). Turbidity is an important element of water quality, both for aquatic life, as it reduces transparency and prevents light penetration, thus hindering the photosynthesis essential for plant growth, and for drinking water production, by reducing the effectiveness of potabilization treatments (Miquel, 2003). The average turbidity at station 1 and in the buffer basin is around 2.2 NTU, in line with the WHO standard for drinking water quality, whose maximum tolerated value in a single sample is 5NTU (WHO, 1996). On the other hand, the average turbidity of 12 NTU observed at the confluence far exceeds the acceptable limit value for water intended for human consumption. This high value can be attributed to the drainage of organic matter from the Bakoye, the 2nd tributary of the Senegal River, and could be detrimental to the survival and development of aquatic organism (DCE, 2016).

The average pH of 7.96, slightly higher at station 1, remains within the range recommended by the WHO standard for water quality, which lies between 6.5 and 9.5. A slight decrease in pH is observed at station 1, at the damping basin and at the confluence, allowing normal development of flora and fauna (Blinda, 2007).

Turbined water at the damping basin has a slightly higher average conductivity of 38.75 µS/cm, but is still low. This low conductivity indicates low mineralization of salts present in the environment throughout the study area (Ben Moussa et al., 2012).

Average dissolved oxygen levels are 5.19 mg/L and 4.88 mg/L at station 1 and at the damping basin. These data show that, although the water is turbined, oxygen content varies little. However, a notable increase in oxygen content is observed at the confluence, with a value of 8mg/L. This increase seems to be linked to the abundance of vegetation and the strength of the current, a phenomenon also observed in the upper reaches of the Oued Za in Morocco (Kadri et al., 2012).

High nitrite concentrations are often indicative of the presence of toxic materials and can degrade water quality (Thomas, 1999). The presence of nitrites in the aquatic environment of fish is the result of the incomplete oxidation of ammonia into nitrates (nitrification), and occurs only exceptionally in the wild, apart from sudden and massive organic pollution. High light levels, for example, can encourage their formation by disrupting the functioning of nitrifying bacteria. (Kinkelin & Petit, 2018). The concentrations recorded are all below the WHO water quality standard (WHO, 1996).

The presence of nitrate ions in significant quantities in surface and groundwater contributes to the eutrophication of aquatic environments and the degradation of water resources (Savary, 2010). In the damping basin, the maximum nitrate content recorded is 0.5 mg/L, well below WHO guidelines (≤50 mg/L). However, average values are 0.01 mg/L at station 1, 0.01 mg/L at Bafoulabé and 0.11 mg/L at the damping basin. The levels recorded show no pollution, as the concentration of nitrates in drinking water can be classified into four categories: below 0.2 mg/L (no human influence), between 0.21 and 3.0 mg/L, (possible influence of human activities), between 3.1 and 10 mg/L, (very clear influence of human activities but no apparent impact on health), above 10 mg/L (major impact of human activities and possible effects on health) (Madisson & Brunett, 1985).

At levels above 0.1 mg/l, manganese in water can impart an undesirable taste to beverages, stain earthenware and linen, and cause deposits to build up in the distribution system. Concentrations below 0.1 mg/l are usually acceptable to consumers (WHO, Guidelines for drinking water quality: 4th ed. incorporating the first additive, WHO, 2017). The average manganese levels recorded are slightly higher than the WHO standard (0.05 mg/L): 0.51, 0.58 and 0.72 mg/L at Station 1, Bassin de d'amortissement and Bafoulabe respectively. It should be noted that the most frequent sources of manganese in water are natural, due to weathering of manganese-bearing rocks and soils. Other less frequent sources of manganese are human activities such as mining and industrial activities, leachates from landfill sites and wastewater effluents (NSNE, 2021). Given the different concentrations, we can assume that the manganese in the rocks comes from weathering.

Among the metallic mineral elements often present, iron and manganese are naturally contained in the earth's crust. These elements are dissolved in water from rocks (crystalline and sedimentary). When these metals are of anthropogenic origin, they mainly come from industrial waste (metal extraction and refining, electroplating, etc.) and from the corrosion of metal pipes (Degremont, 2005). The presence of iron in water can encourage the proliferation of certain strains of bacteria that precipitate iron or corrode pipes. Ferrous salts also contribute to water coloration (Tully, 1958). Although iron in water has no physiological disadvantages, at very high levels it affects the organoleptic quality of water (poor taste, color and flavor) (Mouaz & Bentchich, 2017). The average iron content was 0.22

and 0.06 at Bafoulabé and Station 1 respectively, in line with WHO drinking water standards. On the other hand, we note a very high level of 1.14 mg/L in turbined water from the damping basin. The high iron content is thought to be due to corrosion of the metal pipes used in the dam's equipment (Hem, 1972), (JAMES, 1977).

The presence of sulfide (in the form of hydrogen sulfide) in drinking water gives it an unpleasant taste and odor. For this reason, an organoleptic target of ≤0.05 mg/L (≤50 µg/L) (expressed as hydrogen sulfide) has been set (Santé CANADA, 1992). Relative hydrogen sulfide concentrations are a function of water pH and increase with decreasing pH (McKee & Wolf, 1963; Protection, Agency US Environmental, 1976). Consequently, in polluted waters where the pH can be neutral or acidic, the possibility of hydrogen sulfide formation is increased. During the first 4 years of the study, hydrogen sulfide was present in trace amounts. The highest content was recorded at station 1, with a value of 1.37 mg/L, corresponding to the lowest pH value at station 1. Average levels are 0.04, 0.08 and 0.27 mg/L at Bafoulabe, the retention basin and station 1 respectively. Hydrogen sulphide can be produced by the decomposition of organic matter under the soil, such as plants, or by the chemical reduction of sulphates by sulphate-reducing bacteria, which would explain the maximum value recorded at station 1. However, checks of points on the Namibian coast where levels were initially high have confirmed that the presence of hydrogen sulphide is not sedimentary. In fact, bacteria present in the water columns are responsible for the formation of hydrogen sulfide (Bisson, 2009).

Ammonium ion comes from the excreta of living organisms, nitrogenous organic matter, gaseous exchanges between water and atmosphere and the reduction and biodegradation of waste, not forgetting inputs from domestic, agricultural and industrial sources (Chapman & Kimstach, 1996). The maximum ammonium content is 0.12 mg/L, recorded at the confluence. This indicates good water quality in accordance with WHO guidelines for drinking water, which set a guide value of between 0.1 and 0.5 mg/L for ammonium (WHO, 2011). Average ammonium levels are almost identical at Station 1 and the damping basin, at 0.08 and 0.09 mg/L respectively.

Silica (Si) is a necessary element for phytoplankton growth and is used by diatoms to build their frustules, which are siliceous shells with two interlocking valves. Enrichment of the environment with silica can lead to harmful or toxic algal blooms, while a lack of silica can exacerbate eutrophication by reducing the role of diatoms in the coastal food web (Officer & Ryther, 1980). Silica is an abundant compound, present in groundwater as a result of the erosion of rocks and minerals. Silica is much more present in groundwater than in surface water. Dissolved, silica has no known harmful effects on human beings. High concentrations of dissolved silica can, however, affect the efficiency of treatment systems designed to remove dissolved iron and manganese. Extremely high concentrations of silica can lead to the formation of scale in pipes and slow down the flow of water (NSNE, 2021). In this study, the maximum silica content of 7.2 mg/L recorded at Bafoulabe, with an almost identical average content of 5.8 mg/L in the 3 measurement zones, attests to the good quality of the water.

Human activities such as agriculture, with its use of fertilizers and pesticides, contribute to the enrichment of aquatic environments with nutrients such as phosphorus, nitrates, etc. (Assougnon et al., 2017). Phosphorus is an essential nutrient for plant growth; however, above a certain concentration and under favorable conditions, it can cause excessive growth of algae and higher aquatic plants. This may be followed by an accumulation of plant biomass and detritus, generally leading to a deterioration in water quality (Ekou et al., 2011). With an average maximum content of 0.2 mg/L recorded at the confluence, the water is at a low level of degradation.

Biological parameters (Ichthyological fauna)

For the biological quality of the water, a comparative study was conducted on the fish caught at the various fishing camps upstream of the dam on the reservoir and at the Mahina market on the Bafing river side. This analysis revealed the presence of 34 species of fish belonging to 11 families in the camps and 37 species belonging to 12 families in the Bafing. Comparative studies carried out by Kantoussan between 2002 and 2003 show the same number of fish species at Manantali landings (Kantoussan, 2007).

At Mahina in the Bafing, the specific composition of catches is characterized by the presence of the Claroteidae family and four species (Alestes sp., Brycinus leuciscus, Auchenoglanis occidentalis, Distichodus engycephalus) not recorded at the camps. On the other hand, all the fish families recorded at the campsites are present at Mahina, and only one species (Hydrocynus brevis) is absent from the Mahina landings.

However, a number of families and species are widely distributed across the continent. The Cyprinidae, Characidae, Bagridae, Schilbeidae, Mochokidae and Cichlidae families are found in most African rivers (Skelton, 1988).

While we note that Cichlidae, Mochokidae, Cyprinidae, and Alestidae are the most represented families at the reservoir (camp landing) and at Mahina, in terms of species, this order does not seem to be maintained in all rivers. In fact, in the Baoulé river in Mali's Senegal river basin, Cyprinidae, Mormyridae and Mockhokidae are the most represented species (Paugy, 1994). In the Comoé river in Burkina Faso, Mormyridae, Cichlidae and Cyprinidae are the most represented (Kuela, 2002).

In terms of abundance, *Tilapia sp.* (31.98%), *Sarotherodon galilaeus* (25.08%), *Hydrocynus forskalii* (13.51%), *Synodontis schall* (7.28%), *Chrysichthys auratus* (5.21%) are the 5 most represented species at camp landings, with a percentage of 77.85%. In Mahina, *Tilapia sp.* (18.62%), *Chrysichthys auratus* (12.46%), *Synodontis schall* (12.16%), *Clarias anguillaris* (8.93%), *Labeo coubie* (7.76%), *Sarotherodon galilaeus* (6.08%) are the 6 most represented species with a percentage of 66.01%. The dominance of *Tilapia sp.* in landings is confirmed by studies carried out between 2002 and 2003 (Kantoussan, 2007).

The Shannon diversity indices calculated over the last 5 years are 2.98 at the reservoir camps and 4.07 at Mahina. This value confirms the diversity index calculated over the last 30 years since the dam was impounded (Faye, Ndao, & Sambou, Study of the Biological Quality of the Water in the Manantali Dam Reservoir: Analysis of the Fish Fauna and Plankton Communities, Faye et al., 2024). The diversity index value of 4.07 recorded at Mahina is very close to the values recorded in the middle reaches of the Baoule, the main tributary of the Bakoye, which together with the Bafing forms the Senegal River. These indices reflect average diversity and the non-dominance of one species over the others, as is the case in the rivers of the upper Niger River basin in Mali (Sanogo et al., 2012; Sanogo, 2015).

The equitability index values calculated over the last 5 years are 0.58 for camp landings and 0.78 for Mahina. The equitability index value recorded at the camp level is almost identical to that recorded during the 30-year study at the netting point (Faye, Ndao, & Sambou, Study of the Biological Quality of the Water in the Manantali Dam Reservoir: Analysis of the Fish Fauna and Plankton Communities, Faye et al., 2024). The difference is reflected in a more diverse population at Mahina than at Manantali.

This difference can be explained by the fact that the exploited population is more diversified at camp level (presence of 29 fishing camps) (Kantoussan, 2007).

The diversification index values are 3.09 and 3.08 for the camps and Mahina respectively. These values are almost identical to those recorded at the reservoir level (2.9) over the last 30 years since the dam was impounded, as well as those recorded at Lake Magui in the upper Senegal River basin (Sanogo et al., 2023), (Faye, Ndao, & Sambou, Study of the Biological Quality of the Water in the Manantali Dam Reservoir: Analysis of the Fish Fauna and Plankton Communities, Faye et al., 2024). These values indicate a theoretical number of habitats of three (Sanogo et al., 2023).

4. Conclusion

Water quality upstream (reservoir) of the dam and power plant, immediately downstream (damping basin) and at the Bafing-Bakoye confluence (Bafing side) measured with the various physico-chemical parameters shows that parameters such as temperature, pH, conductivity, dissolved oxygen, ammonium, nitrite, nitrate, iron, silica and phosphorus all comply with WHO standards, indicating good water quality and allowing normal development of fauna and flora with a low level of degradation. It should also be noted that certain parameters such as turbidity, manganese, iron and hydrogen sulphide exceeded WHO recommended standards at times, which can be attributed to the drainage of organic matter.

In addition, a study of the ichthyological fauna revealed similarities in the families and species of fish present in these areas. However, we note a greater diversity of fish species in Mahina, which could be explained by the upwelling of certain fish from the Bakoye to the Bafing at the confluence.

The overall analysis of physico-chemical and biological parameters shows that the dam and power station, together with the water turbined by the hydroelectric generating units, have no negative impact on water quality.

The study focused on the comparison of parameters measured in the sampling zones, but did not specify any statistical analysis. Given the study period (5 years), it would be necessary over a longer period to carry out a statistical analysis on all the parameters monitored, and given the number of dams along the Senegal River, to carry out a combined study along the entire Senegal River between physico-chemical parameters by calculating water quality indices, biological, bacteriological and also correlate seasonal variations, reservoir levels and planktonic and ichthyological populations to determine the factors likely to influence the health and stability of the ecosystem. Ultimately, this study will enable us to better characterize the dam's impact on water quality.

Conflicts of Interest

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

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