

Long-Term Evolution of Water Quality and Interactions with Climate Change. Case of the Bab Louta Reservoir (Taza, Morocco)

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Abstract: Bab Louta Dam, located about 15 km from Tahla town in Morocco, has shown significant interactions between changes in water quality and climate change since it was filled in 2001. The objective is to conduct a study of the water quality, assess the effects of climate change on the ecological balance, and analyse water quality trends using appropriate technical tools. The results obtained showed a satisfactory quality of the Bab Louta reservoir for the production of water for food use, a firm thermal stratification, the occurrence of anoxic conditions in deep waters towards the end of the summer period, and the presence of undesirable elements, particularly manganese, iron, and hydrogen sulfide, requiring advanced conventional treatment. The plankton analysis shows a notable algal biomass and a marked trend towards a eutrophic state. This study made it possible to identify the mechanisms by which climate change affects the water quality of the Bab Louta dam and its ecological balance, to establish correlations between different physicochemical, hydro biological, and climatological parameters, to carry out a predictive analysis of water quality in relation to future climate changes, and to propose remedies for water quality problems related to future climate changes.

Keywords: Bab Louta, Tahla, eutrophication and climate change, water treatment, water quality

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1. Introduction

The Bab Louta Dam is located in the Sebou watershed, about 15 km from the town of Tahla in Morocco, and provides irrigation for agricultural areas downstream and water supply for food use to the towns of Tahla, Oued Amlil and Taza, and surrounding localities. A pollution survey conducted in March 2024 shows low agricultural activity in the upstream watershed of the reservoir due to the nature of the soil in the immediate dam basin and the difficulty of accessing these areas.

However, the reservoir showed early signs of water quality degradation manifested by firm thermal stratification from June to September, the appearance of anoxic conditions in the deep waters towards the end of the summer period, and the presence of undesirable elements, particularly manganese, iron, and hydrogen sulphide, which give the water a musty odour and an unpleasant taste requiring advanced treatment. Analysis of plankton populations shows a notable algal biomass in the lake and a marked trend of Lake Bab Louta towards a eutrophic state.

Corrective actions have been initiated to address these issues and their negative consequences on water treatment, notably optimising the intake level of raw water, introducing plankton-eating fish, and draining deep water layers when hydrological conditions allow. The goal is to conduct a water quality study, assess the effects of climate change on ecological balance, and analyse water quality trends.

2. Materials and Methods

2.1. Overview of the Bab Louta Watershed

The study area is located in the Sebou basin, with a focus on the Bab Louta sub-basin (Fig. 1).

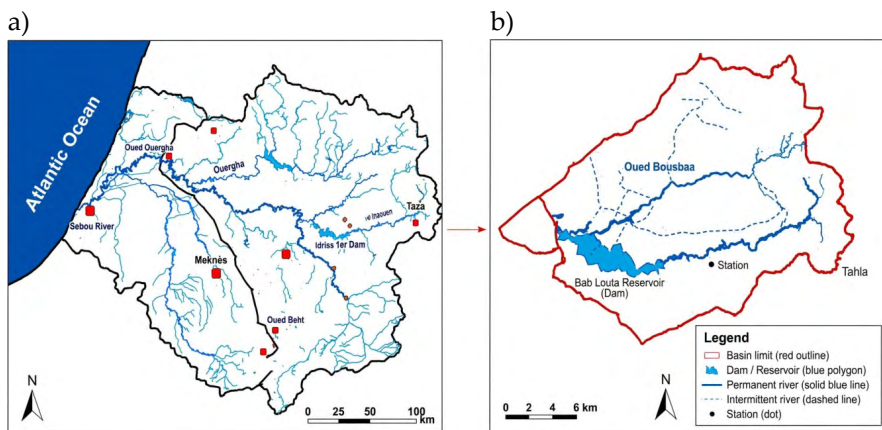


Fig. 1. Composite hydrographic map of Sebou Watershed (a) and Bab Louta sub-basin drained by Oued Bousbaa showing Bab Louta Reservoir (b)

Source: modified from [1] (panel a) and [2] (panel b)

The Bab Louta watershed is located in the Middle Atlas region. The maximum altitude reaches 1,554 m, the minimum altitude is 530 m, and the median altitude is 926 m. Four altitude classes are identified: less than 700 m covering 12.6% of the total area, between 700 and 1,100 m occupying 53.1%, between 1,100 and 1,500 m covering 33%, and greater than 1,500 m covering 1.3% of the total area [1]. The watershed of Bab Louta, drained by the Oued Bousbaa (Fig. 1), consists of two rivers: Jmaa on the Southeast side and Bni Seraj on the East side, belonging to two sub-watersheds, one of which is larger, drained by Oued Boukhaled, which in turn consists of two main intermediate basins that represent 6% and 9% of the total area of the watershed.

The lengths of the main rivers are around 14 km, and the slopes of the rivers are very variable and steep, as they can reach 16%. This variation in slopes allows for the erosion of materials along the downstream sections before reaching the dam reservoir. The temperature ranges from 20.6°C in Tahla to 11.6°C in Tazeka. The prevailing winds in this watershed are dry continental winds from the East and Southeast as well as humid oceanic winds from the West and Northeast [1].

2.2. Precipitation

The average annual rainfall in the Sebou watershed varies from 400 mm in coastal areas to 1,000 mm in mountainous regions. This variability is due to the influence of latitude, altitude, and the distance from the sea. Regarding the averages over the last 13 years (2013–2024), they were around 490 mm, whereas they were 510 mm in the previous decades, which explains why the region bordering the Bab Louta dam has experienced a decline in rainy days in recent years [1].

The monthly distribution of these precipitations is very variable. The rainy season generally spans from October to April, receiving 93% of the rain with marked maxima between November and January, whereas the dry season spans from May to September and only receives 7% of the precipitation.

The monthly average during this dry season was 40.5 mm (Fig. 2).

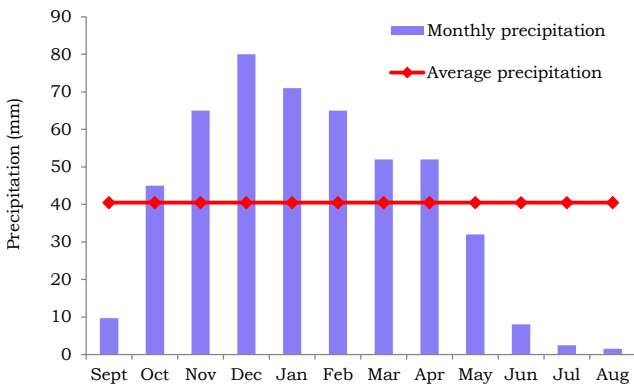


Fig. 2. Monthly average precipitation at Bab Louta station (2001–2024)

Source: own elaboration based on data from [1]

The number of rainy days per year varies from 60 to 75 depending on the location. Overall, the inter-annual irregularities in the distribution of precipitation are significant [3].

According to the classification established by the Water Directorate, based on accumulated data over several years, the Sebou watershed bordering Bab Louta is located in the rainfall range of 400–600 mm (Fig. 3)

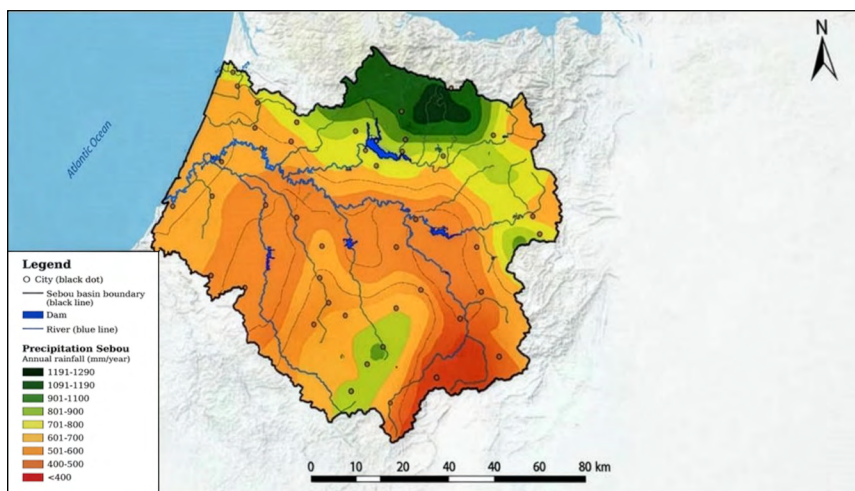


Fig. 3. Map of precipitation in the Sebou watershed [mm/year]

Source: [1], modified

2.3. Analytical Methods

The analytical methods used were standardised and validated according to the protocols of a laboratory accredited under the ISO/IEC 17025:2017 [4].

The analyses were carried out on-site for the *in situ* parameters, the rest being conducted in the laboratories of the Tahla treatment plant and that of the Water Quality Control Department in Rabat. The main parameters monitored are as follows:

- ***In situ* parameters.** These include temperature, pH, conductivity, dissolved oxygen, hydrogen sulphide, turbidity, soluble phosphorus, and light penetration.
- **Inorganic physicochemical parameters.** The parameters concerned are: nitrates, ammonium, chlorides, sulphates, metals (cadmium, lead, silver, copper, chromium, nickel, zinc, selenium, arsenic, iron, manganese, aluminium, phosphorus, and potassium analysed by inductively coupled plasma mass spectrometry (ICP-MS)), oxidizability, chlorophyll *a*, and algal toxins analysed by the protein phosphatase 2A activity assay (PP2a) method.
- **Hydrobiological parameters.** Search and counting of phytoplankton and zooplankton.

3. Results

3.1. Water Level of the Reservoir

The water inputs to the Bab Louta reservoir during the study period are assessed through the evolution of the water reserve of the lake (Fig. 4).

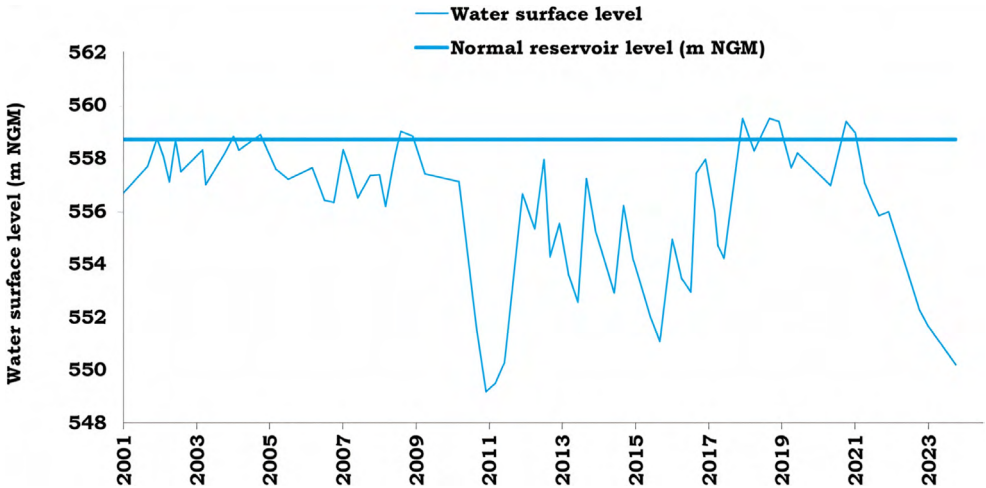


Fig. 4. Temporal evolution of water level in the Bab Louta reservoir (2001–2024). Horizontal line indicates the normal storage level (558.7 m NGM)

These data clearly show that:

- The reservoir lake did not reach its highest level of 55.5 million m³ during the extended periods of 2008–2017 and 2021–2024.
- The dam experienced a more-or-less regular hydrological regime before 2009 and from 2018 to 2021, and a very irregular regime starting from 2021.
- For seasonal variations, regular fluctuations are noted, in that the losses incurred during the dry season are partly compensated by winter contributions.

3.2. Thermal Regime

The air temperature database collected at the Bab Louta reservoir station during the study period (2001–2024) allowed us to trace its inter-annual evolution (Fig. 5). Air temperature ranged from 10.0°C (April 2, 2015) to 39.0°C (August 26, 2008), as absolute minimum and maximum daily values, respectively. The series shows a marked seasonal regularity, with less inter-annual variability compared to precipitation.

From the viewpoint of annual sunshine duration, the site records an average of over seven hours per day, with a mean annual air temperature of 15.5°C.

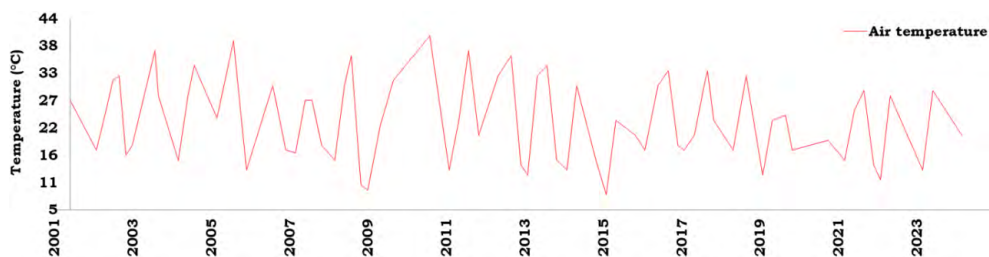


Fig. 5. Inter-annual evolution of maximum air temperature (2001–2024) at Bab Louta station

3.3. Evaporation

Evaporation is closely related to sunlight duration, high temperatures, and wind intensity. In Morocco, these conditions are generally all met, which significantly affects water resources, particularly stagnant ones. It averages around 1,600 mm/year on the coast and 2,000 mm/year inland. The maximum monthly value is recorded in summer, especially in July and August, where it can reach 300 mm. In the case of the Sebou watershed, this parameter varies annually between 1,600 and 2,000 mm. At the Bab Louta reservoir, the average monthly evaporation was 0.623 million m³.

This situation is further exacerbated by water shortages induced by the climate characterised by weak and irregular precipitation; this negatively affects the aquatic environment and consequently the quality of its water. Indeed, the evaporation rate compared to the inputs is on average 13.4% per year, which is quite significant [5].

3.4. Bioclimatic Synthesis

A separate study of the different climate factors that are insufficient to characterize the bioclimate of a given station is necessary. Indeed, it is the interaction between these parameters that determines the climate type of a given region. In order to characterize this, several indices, formulas and graphs have been proposed. Among the most commonly used are those by Debrach [6], Bagnouls and Gaussen [7], Emberger [8], and Sauvage [9].

Emberger's rainfall quotient (Q2) is considered one of the most used indices in characterizing the bioclimatic environment of a Mediterranean region. Established in 1930, it was modified in 1955 by Emberger and in 1963 by Sauvage. It is expressed as follows:

$$Q2 = \frac{2000 \cdot P}{M^2 - m^2},$$

where P is the mean annual precipitation [mm], M is the mean maximum temperature of the hottest month [K], and m is the mean minimum temperature of the coldest month [K], with:

$$T[\text{K}] = T[^\circ\text{C}] + 273.15.$$

The Emberger climatogram, modified by Sauvage [9], defines climatic zones with their thermal variants based on $Q2$ and m .

Five climatic zones of the Mediterranean bioclimate have been identified based on $Q2$. These zones have been further subdivided into variants based on the threshold's values of m (Table 1).

Table 1. Climatic zones with their thermal variants

Emberger quotient		Climate variants	
Value	Zone	Value of m [°C]	Variant
$Q2 < 20$	Saharan	$m > 7$	warm
$20 < Q2 < 30$	arid	$3 < m < 7$	temperate
$30 < Q2 < 50$	semi-arid	$0 < m < 3$	cool
$50 < Q2 < 90$	sub-humid	$-3 < m < 0$	cold
$Q2 > 90$	humid	$m < -3$	very cold

m – mean minimum temperature of the coldest month [°C].

Based on the climatic values recorded in the Bab Louta area ($P = 580$ mm, $M = 36.5^{\circ}\text{C}$, $m = 2.8^{\circ}\text{C}$), the calculated Emberger quotient $Q2$ is 58.8. According to Emberger modified by Sauvage, the study area is therefore classified in the sub-humid bioclimatic stage with a cool to temperate winter variant (Table 1). The data shows an irregular distribution of intra- and inter-annual rainfall with fluctuations ranging from 370 to 800 mm/year, based on climatic values estimated from the National Agency for Land Conservation, Cadastre and Cartography (ANCFCC) and Sebou Hydraulic Basin Agency (ABHS) meteorological records (Taza station, 1981–2010) [10, 11].

3.5. Air and Water Temperature Relationship

In order to highlight the existence of a relationship between air and water temperature, we superimposed their respective curves (Fig. 6).

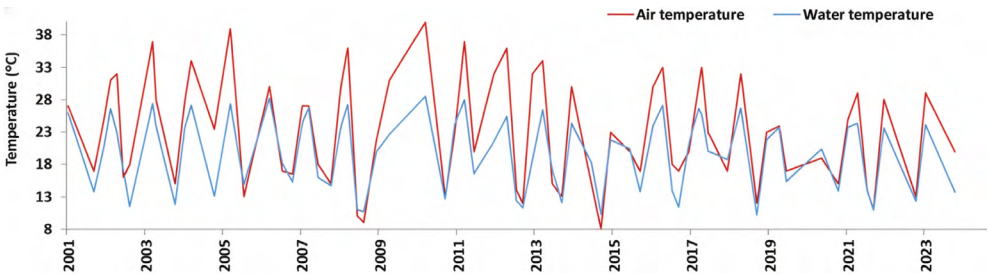


Fig. 6. Evolution of air and water surface temperatures at Bab Louta reservoir (2021–2024)

The result is evident as the water temperature follows the trend of the air temperature, which justifies the absorption of solar energy by water and its dissipation in the form of heat. The effect of this solar radiation is important in that it impacts the dynamics of photosynthesis processes and consequently the ecosystem itself, particularly through its thermal structure, stratification, mixing, as well as the production and decomposition of organic matter in the aquatic environment.

The purpose of this observation is to be able to reconstruct, to a certain extent, by analogy, the thermal life of the reservoir since it was filled, based on meteorological data, particularly air temperature. In the absence of thermal data on the water, this procedure provides a good qualitative idea of the thermal evolution of the reservoir. Indeed, this thermal quality plays an important role in the life of the reservoir, as a warm year, which is therefore sunny, stimulates and promotes the growth of plants and phytoplankton, which accentuates the phenomenon of eutrophication. Conversely, a cold year, which is reasonably often rainy and less sunny, limits this growth and consequently reduces the phenomenon of eutrophication.

3.6. Evolution of Water Temperature

The annual variation in water temperature at each depth, based on average values, is shown in Figure 7. At first glance, these curves are similar but not overlapping. The average annual variation thus takes on an almost perfect sinusoidal shape, especially for the surface layers (−0.2 m, −5 m, and −10 m).

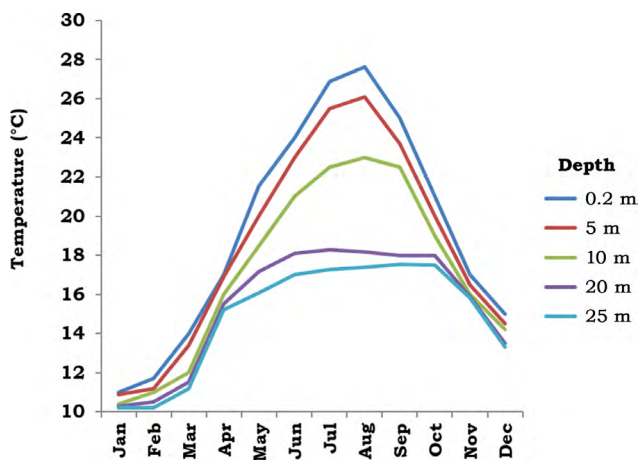


Fig. 7. Seasonal variation of water temperature along the water column (0.2–25 m) at Bab Louta reservoir

From a thermal amplitude perspective, the minimum temperature is recorded in January at the surface (11.0°C) and in February for the deep zone (10.0°C). This period generally coincides with the phase of water mixing, which is justified by the

smallest temperature difference between the surface and the bottom (Table 2). As for the average maximum surface temperature, it is reached in August (27.6°C), while at lower levels, these maxima occur between September and November. This shift is primarily due to the physical properties of water, which oppose the rapid transmission of energy to depth because of its low conductivity.

Table 2. Thermal amplitudes [°C]

Depth [m]	January	February	March	April	May	June	July	August	September	October	November	December
0.2	11.0	11.7	14.0	17.0	21.6	24.0	26.7	27.6	25.0	21.0	17.0	15.0
25	10.1	10.0	10.5	14.1	15.5	16.2	16.6	16.8	17.0	17.2	15.8	13.0
Gap	0.9	1.7	3.5	2.9	6.0	7.8	10.3	10.9	8.0	3.8	1.2	2.0

As for the average monthly deviations over the course of an annual cycle, they range from 0.9°C in January to 10.9°C in August, as shown in Table 2. This range informs us about the degree of stratification of the water column. We also observe the sinusoidal trend in the evolution of temperature deviations from year to year (Fig. 8).

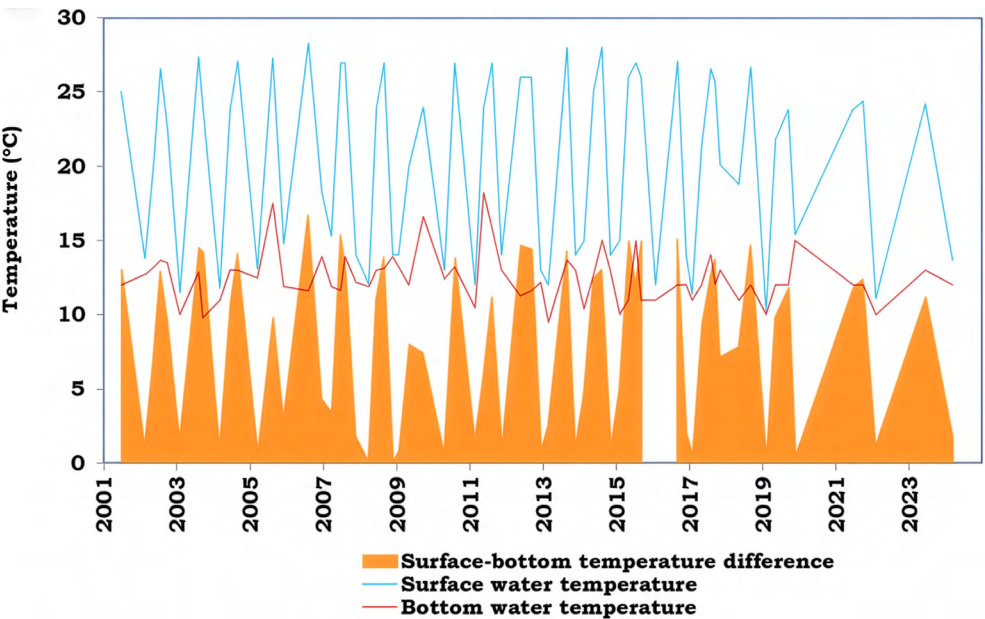


Fig. 8. Inter-annual evolution of surface and bottom water temperatures and surface-bottom thermal difference at Bab Louta reservoir (2001–2024)

Overall, the recorded values are favourable to aquatic life, particularly to fish fauna, some species of which are used in biological control against eutrophication, such as Chinese carp, which are warm-water species. The vertical temperature profiles taken during the observation period on the waters of the Bab Louta reservoir show that starting in June, the surface water temperature rises rapidly, leading to the gradual establishment of thermal stratification. This is characterised by a fairly pronounced thermocline and persists until September (Fig. 9).

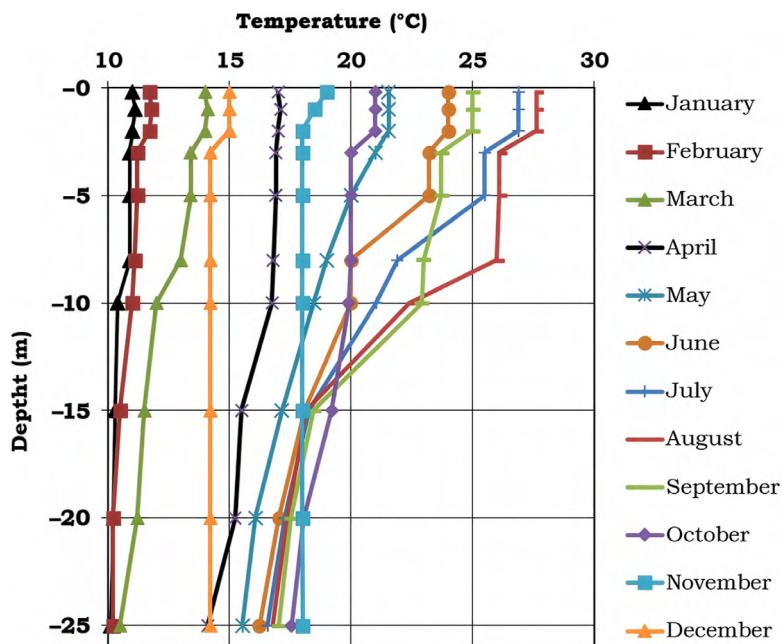


Fig. 9. Average water temperature vertical profiles in Bab Louta Reservoir (2021–2024)

3.7. Evolution of pH

Figure 10 illustrates the evolution of pH levels in Bab Louta surface and bottom waters during the period from 2001 to 2024. Thus, the waters of this lake tend to be alkaline since the hydrogen potential values range from 7.94 to 9.13 pH units (with an average of 8.51) in the surface waters and from 7.65 to 8.21 pH units (with an average of 7.94) in the deeper waters of the lake. Generally, all the studied annual cycles have shown certain regularity over time and space. On the other hand, we notice that at the surface, the minimum values were recorded during winter and the maximum values during summer. In contrast, at depth, the maximum values occur during the cold period, which is generally subjected to mixing and thus to homothermal conditions. As for the disparities between the surface and the bottom, they are higher in summer.

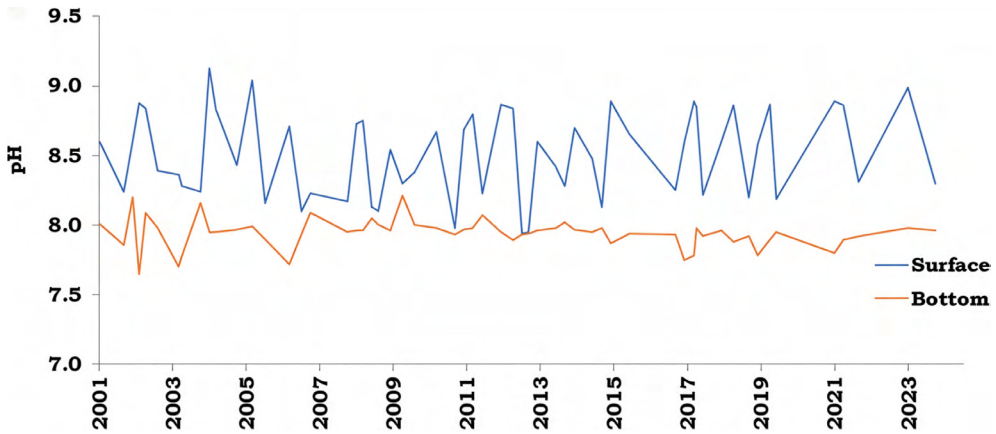


Fig. 10. Long-term evolution of surface and bottom pH in Bab Louta Reservoir (2001–2024)

This pH distribution could be explained by the photosynthetic activity of algae in the surface waters and by the mineralisation of the bottom waters by bacteria. Indeed, strong algae activity assimilates significant carbon dioxide (CO_2) from the water, which in turn leads to an imbalance in the carbonate buffering system and increases the pH level of the water. It should be noted that photosynthesis is the set of biological processes implemented by a living organism to produce its carbon matter for growth (referring to autotrophic organisms). This occurs thanks to light and the consumption of CO_2 , among other things. Some bacteria, algae, and plants are organisms capable of performing photosynthesis. To do this, they need energy provided by light energy, which they transform into chemical energy.

In summary, the relationship between the pH of water and aquatic plants is important but also complex, since pH is closely correlated with levels of calcium, magnesium, carbonate, and other constituents of water.

3.8. Dissolved Oxygen and Hydrogen Sulphide

The evolution of dissolved oxygen levels in the Bab Louta retention basin is illustrated in Figure 11. This shows that surface waters are oxygenated during almost all the samples taken, with the O_2 concentrations ranging from 3.7 to 11 mg/L, given that they present a minimum value of 3.7 mg/L (which corresponds to an oxygen saturation percentage of 38%) recorded in December 2006 and a maximum value of 11 mg/L (corresponding to a saturation of 140%) recorded in September 2003.

However, in the deep layer waters, this parameter shows remarkable seasonal fluctuations. Indeed, during the period of homogenisation of the reservoir, the lowest O_2 value recorded during the observation period is 6 mg/L at the bottom (which

is 62% saturation). Subsequently, the levels of dissolved oxygen decrease during the thermal stratification period (June–September) and reach their critical level in August and September with total anoxia.

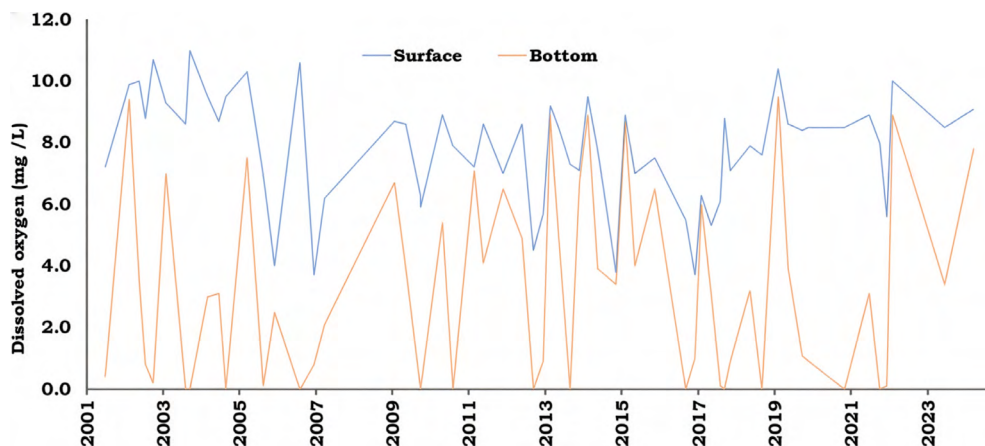


Fig. 11. Long-term evolution of dissolved oxygen at the surface and at the bottom in Bab Louta Reservoir (2001–2024)

The anaerobic conditions of the deep layer waters were observed during the following periods:

- September 2003, accompanied by the appearance of hydrogen sulphide, an undesirable element that gives the water a very unpleasant taste, starting at a depth of 20 m with a maximum S^{2-} concentration of 0.7 mg/L at a depth of 25 m;
- November 2007, with the appearance of hydrogen sulphide with an S^{2-} concentration of 0.1 mg/L at the bottom of the reservoir;
- August 2008, with the appearance of hydrogen sulphide at an S^{2-} concentration of 0.2 mg/L at the bottom of the reservoir.

3.9. Nitrate

Nitrate (NO_3) shows low concentrations at this reservoir lake during this study period, as they reach a maximum of 6.20 and 6.14 mg/L at the surface and deep waters, respectively (Fig. 12).

These values were recorded during the sampling in June 2001. A total depletion of nitrate levels in the bottom waters was observed during the samplings in September 2002 and 2003, and in August 2008. It is worth noting that in addition to their assimilation by algae in the trophogenic zone, nitrates are used by bacteria as an alternative electron acceptor after dissolved oxygen is depleted in the deep layers.

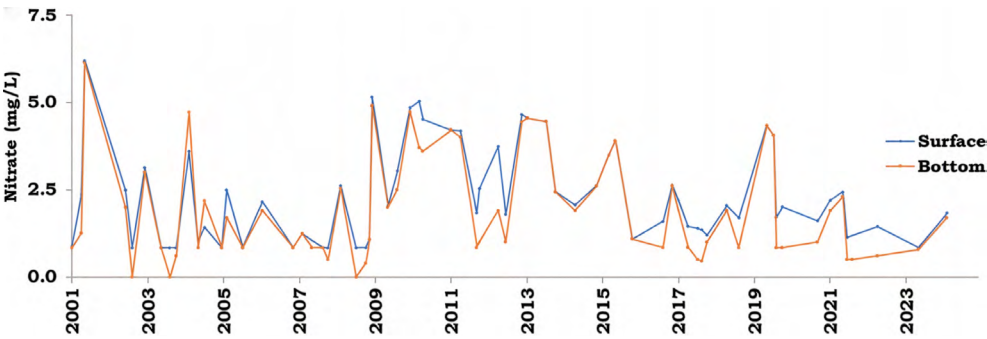


Fig. 12. Temporal evolution of nitrate concentration at the surface and bottom waters during the study period (2001–2024)

3.10. Soluble Phosphorus

The evolution of the soluble form of phosphorus (PO_4), which is preferentially used by algae for their metabolic needs, is shown in Figure 13. It is noteworthy that both in the surface and deep waters, the highest PO_4 content was recorded in September 2002, corresponding to a value of 0.37 mg/L. The other values of soluble phosphorus remained below 0.022 mg/L at the surface and 0.022 mg/L at the bottom.

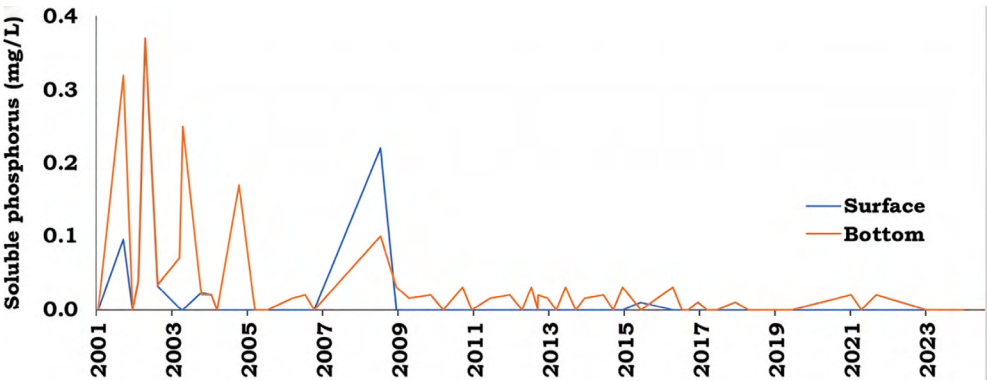


Fig. 13. Temporal evolution of soluble phosphorus concentration at the surface and bottom waters during the study period (2001–2024)

The assimilation of soluble phosphorus by phytoplankton has resulted in higher concentrations of this element in bottom waters compared to those in surface layers. The reverse situation observed during December 2008 coincides with significant inputs that affected the reservoir.

The stratification analyses show values on the same order of magnitude as those recorded at the surface or bottom waters.

3.11. Total Phosphorus

Figure 14 illustrates the evolution of total phosphorus (TP) in the Bab Louta reservoir during the period from 2001 to 2024.

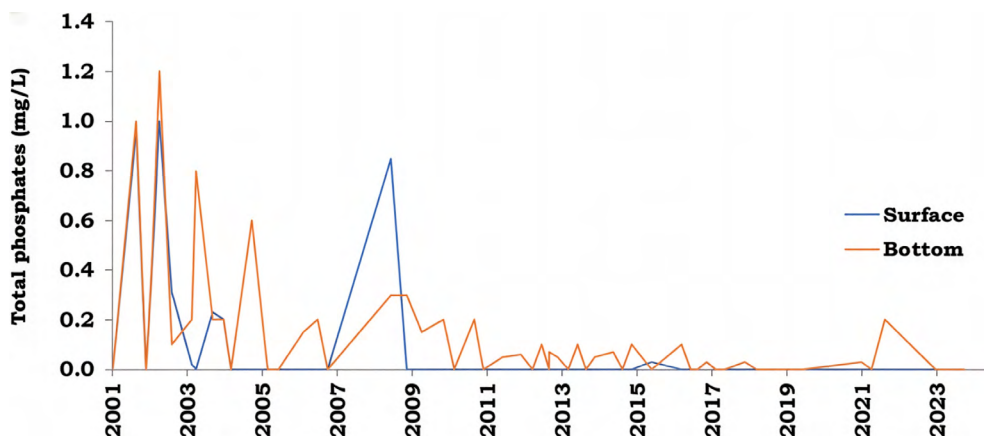


Fig. 14. Temporal evolution of total phosphorus concentration at the surface and bottom waters during the study period (2001–2024)

The concentrations of total phosphorus ranged between 0.01 and 0.96 mg/L at the surface and from 0.01 to 1.18 mg/L at the bottom (Fig. 14). The period 2001–2009 was marked by high and irregular peaks, with maximum values recorded in 2002 (1.18 mg/L at the bottom) and in 2009 (0.80 mg/L at the surface). From 2010 onwards, TP concentrations showed a marked and sustained decrease, with most values remaining below 0.10 mg/L. The long-term decline after 2009, reflects the reduction of external total phosphorus inputs to the reservoir.

3.12. Manganese Regime

Figure 15 illustrates the evolution of manganese at the Bab Louta reservoir during the study period.

The high concentrations of manganese were recorded in the bottom waters during the summer and autumn. The increase in manganese concentrations observed in the bottom waters from July to November suggests a release of manganese from the sediments. This release could be explained by the low levels of dissolved oxygen and the decrease in pH in the deep layers. Manganese concentrations in the surface waters of the reservoir range from 0.01 to 0.12 mg/L. In the bottom waters, the values range from 0.01 to 1.2 mg/L. It is noteworthy that 74% of the values recorded at the bottom of the reservoir exceed the mandatory Mn value of 0.1 mg/L set by level A2 of the water quality grid used for the production of drinking water [12].

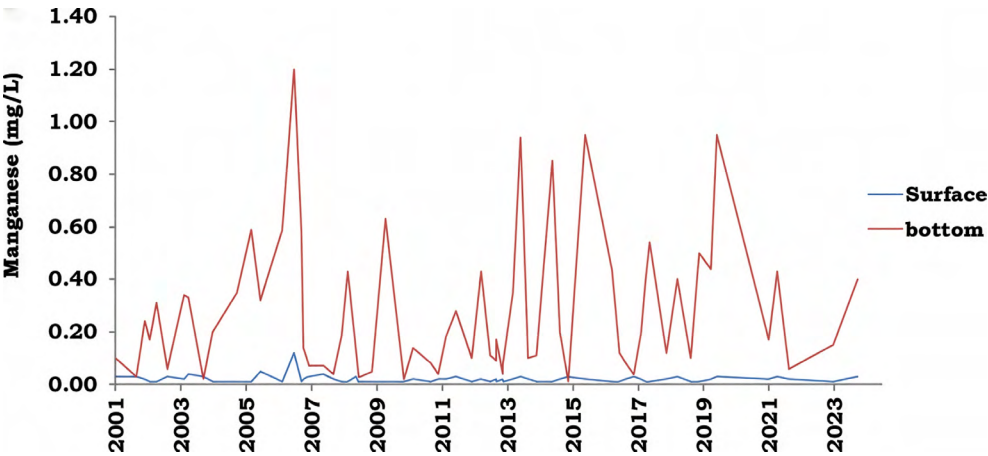


Fig. 15. Temporal evolution of manganese concentration at the surface and bottom waters during the study period (2001–2024)

For surface waters, all recorded values remain overall below the values set by Moroccan standards, with the exception of a single value recorded in December 2006.

3.13. Iron Regime

The evolution of iron during the study period is presented in the following Figure 16.

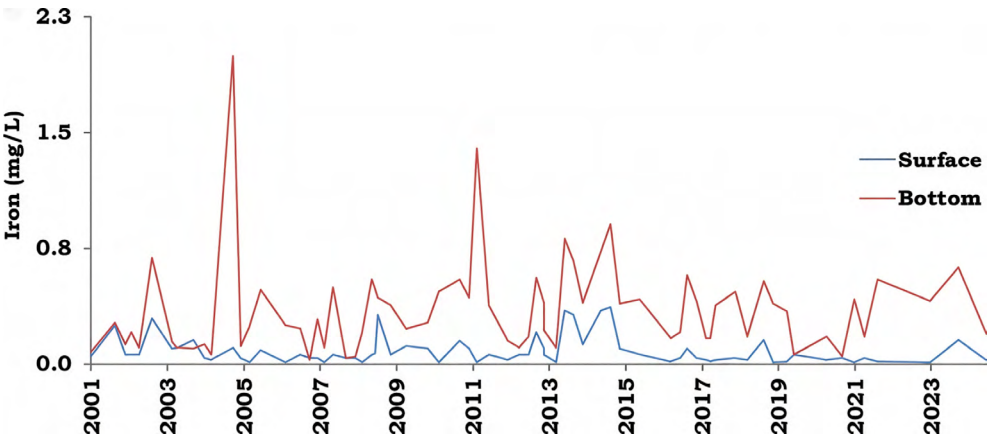


Fig. 16. Temporal evolution of iron concentration at the surface and bottom waters during the study period (2001–2024)

The iron concentrations recorded range from 0.01 to 0.35 mg/L (February 2002) for the surface and from 0.01 to 2.0 mg/L (May 2005) for bottom waters. Overall, the iron regime in this reservoir is similar to that of manganese. It is noteworthy

that 46.4% of the values recorded at the bottom of the reservoir exceed the mandatory value set by category A1 (0.3 mg/L) of the water quality grid used for drinking water production. For surface waters, 7% of the values recorded at the surface exceed the mandatory value set by the aforementioned Moroccan standard [12].

3.14. Mineralisation

The mineralisation of the reservoir waters was assessed through sulfates, chlorides, and electrical conductivity:

- **Sulfates.** Sulfate concentrations range from 11 to 95 mg/L and comply with the Moroccan standard regarding water quality for food use (400 mg/L).
- **Chlorides.** Chloride concentrations range from 9.1 mg/L in December 2006 to 96.2 mg/L in January 2016. The maximum allowable value (750 mg/L) was not exceeded during this period.
- **Electrical conductivity.** The variation in conductivity follows that of sulfates and chlorides. The latter are responsible for the observed conductivity values, which range from 250 to 427 $\mu\text{S}/\text{cm}$ at 20°C. The overall results of the mineralisation parameters indicate that the waters in the reservoir are low in minerals.

3.15. Turbidity

Turbidity provides information on the amount of suspended materials, particularly during floods that affect the Bab Louta reservoir, and varies irregularly (Fig. 17).

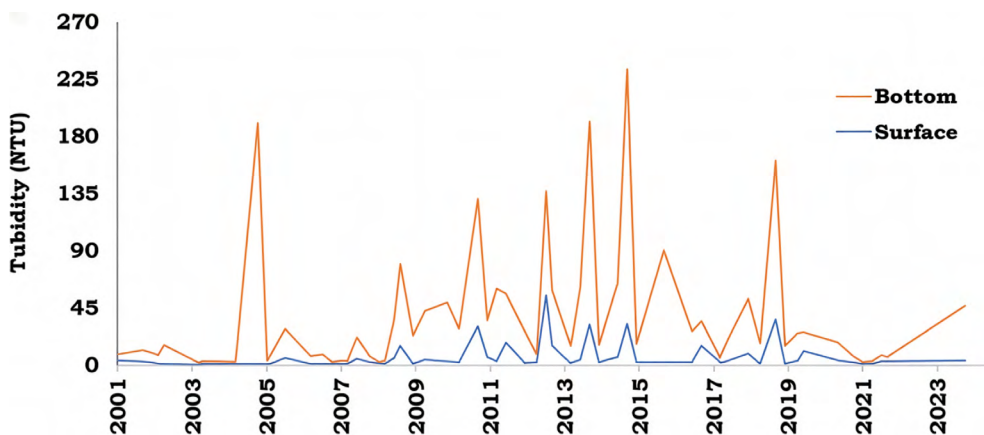


Fig. 17. Temporal evolution of turbidity at the surface and bottom waters during the study period (2001–2024)

The recorded extreme values range between 0.8 NTU (August 2003) and 55 NTU (December 2012) at the surface, and between 0.8 NTU (June 2008) and 200 NTU

(February 2015) at the bottom of the reservoir. The relatively low values are due to sedimentation occurring in the reservoir. Overall, during the study period, the turbidity of the surface waters remains lower than that of the bottom waters.

3.16. Transparency and Chlorophyll *a*

During the study period, light penetration varied between 20 cm (February 2011 and March 2024) and 640 cm (June 2021). The maximum value corresponds to a period of ecosystem stability where phytoplankton biomass is very low. The low transparency may be related to various parameters including the amounts of suspended matter, turbidity, and algal abundance.

Regarding algal development, the evolution of chlorophyll *a* seems to influence that of water transparency. Figure 18 illustrates this close relationship between these two parameters, both of which are dependent on the unstable climatic conditions that characterised this study period.

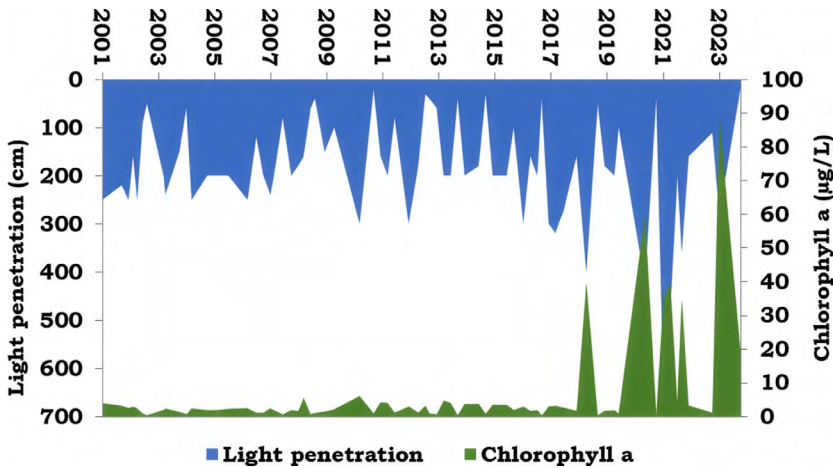


Fig. 18. Temporal evolution of light penetration and chlorophyll *a* concentration during the study period (2001–2024)

3.17. Oxidizability

In degrading, organic materials consume the dissolved oxygen in water. Therefore, if they are too abundant, they can lead to excessive oxygen consumption, causing asphyxiation of aquatic organisms. In the absence of mineral-reducing substances (Fe^{2+} , NO_2^- , SO_2^{2-} , S^{2-}), it is only the organic materials that react. This test then provides an indication of pollution by organic materials. At the reservoir level, the recorded levels were low, which characterises this water as excellent according to surface water quality standards. The recorded O_2 maxima are 7.2 mg/L at the bottom and 5.5 mg/L at the surface (December 2005). The O_2 minima are around 0.6 mg/L at the surface and at the bottom.

The inter-annual evolution is very irregular (Fig. 19), related to the instability of the climatic conditions that characterise this environment. The moderately high values would probably coincide with the autumn photosynthesis of highly active algal and zooplankton biomasses.

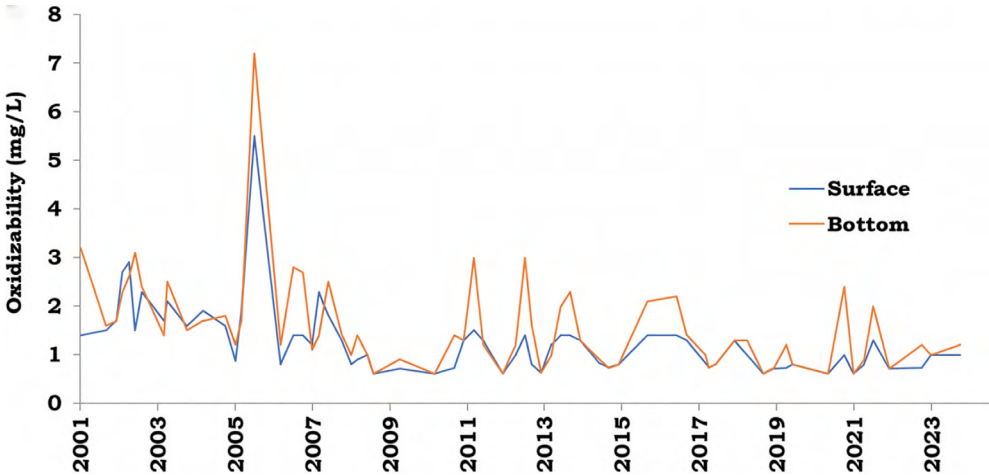


Fig. 19. Temporal evolution of oxidizability at the surface and bottom during the study period (2001–2024)

3.18. Toxic Elements

The values of inorganic toxic substances (lead, zinc, copper, arsenic, selenium, chromium, cadmium, barium, aluminium, fluorides, and silicates) analysed in the waters of the Bab Louta reservoir during this observation period show no signs of significant degradation in the water quality of this lake-reservoir and are significantly lower than the guideline values set by Moroccan standards (Table 3).

Table 3. Minimum, maximum and mean concentrations of toxic elements in Bab Louta reservoir (2001–2024)

Element	Concentrations [mg/L]						MPV* [mg/L]
	Surface			Bottom			
	Min	Max	Average	Min	Max	Average	
Zinc	0.010	0.160	0.035	0.010	0.130	0.019	3
Copper	0.010	0.020	0.014	0.010	0.020	0.012	2
Aluminium	0.040	0.550	0.290	0.020	0.019	0.050	0.2
Fluorides	0.110	0.580	0.220	0.100	0.670	0.199	1.5

Table 3. cont.

Element	Concentrations [mg/L]						MPV* [mg/L]
	Surface			Bottom			
	Min	Max	Average	Min	Max	Average	
Lead	0.0021	0.0025	0.0024	0.0026	0.0055	0.0045	0.010
Arsenic	0.0000	0.0000	0.0000	0.0020	0.0073	0.0028	0.010
Selenium	0.0001	0.0001	0.0001	0.0002	0.0003	0.0003	0.010
Chrome	0.0001	0.0020	0.0002	0.0001	0.0003	0.0002	0.050
Cadmium	0.0001	0.0001	0.0001	0.0005	0.0012	0.0008	0.003
Silicates	1.9	7.8	4.4	0.0	6.6	2.5	–
Barium	0.049	0.140	0.079	0.043	0.097	0.066	0.7

* Maximum permissible value set by the Moroccan standard for water quality (NM 03.7.001-2020) [13]

In general, the observed metal concentrations are mostly relatively low. They are all below the maximum permissible values set by the Moroccan Standard NM 03.7.001-2020 [13] for water quality, given here for indicative comparison, except for aluminium, whose levels could stem from the geology nature of watershed, particularly the aluminosilicates and clay shales.

3.19. Biological Quality

Phytoplankton

Phytoplankton plays several crucial roles in the structure and functioning of lake ecosystems. Its essential role is the production of oxygen through a direct effect and the increase of pH through an indirect effect. The source of mineral nitrogen preferentially used by algae for autotrophic production is the NH_4^+ ion. Phytoplankton participates in the transfer of matter to higher trophic compartments. It is often preferentially grazed by zooplankton compared to bacteria. The structure of its population (abundance, algal cell size) can be controlled by the grazing pressure exerted by zooplankton.

The study of phytoplankton showed moderate species diversity, comprising 40 taxa, including 55% *Chlorophyceae*, 17.5% *Bacillariophyceae*, 10% *Cyanophyceae*, 7.5% *Dinophyceae*, 7.5% *Euglenophyceae*, and 2.5% *Cryptophyceae* (Table 4) [14–16].

The temporal evolution of phytoplankton abundance represented by Figure 20 shows that the class *Chlorophyceae* is always present. Its intensive development was observed in May 2002 (584.040 ind./L), August 2005 (763.020 ind./L) and September 2019 (2.150.900 ind./L). The dominant taxa were, respectively, *Cyclotella* sp., *Oocystis crassa* and *Pediastrum simplex* associated with *Cosmarium laeve*. The class *Cryptophyceae* is not always present. Its development was observed in November 2013

(405.080 ind./L) and September 2019 (166.420 ind./L). The class *Bacillariophyceae* is always present and sub-dominant with a very low biomass; its maximum was recorded in February 2002 with 146.952 ind./L. *Cyanophyceae*, regarded as an indicator group of water quality degradation, are common in the reservoir during the study period. The peak in September 2002 (734.760 ind./L) is attributed to the proliferation of *Aphanizomenon* sp. The peak in September 2019 (163.280 ind./L) is represented by *Lyngbya* sp. and *Oscillatoria* sp. The classes *Dinophyceae*, *Euglenophyceae* and *Bacillariophyceae* are poorly represented.

Table 4. Composition of the algal community of the lake

Class	No.	Taxa
<i>Chlorophyceae</i>	1	<i>Ankistrodesmus falcatus</i> var. <i>acicularis</i>
	2	<i>Ankyra judayi</i>
	3	<i>Botryococcus braunii</i>
	4	<i>Chodatella</i> sp.
	5	<i>Closterium aciculare</i>
	6	<i>Closterium aciculare</i> var. <i>subpronum</i>
	7	<i>Coelastrum microporum</i>
	8	<i>Coelastrum reticulatum</i>
	9	<i>Cosmarium laeve</i>
	10	<i>Cosmarium</i> sp.
	11	<i>Elakatothrix gelatinosa</i>
	12	<i>Mougeotia viridis</i>
	13	<i>Oocystis borgei</i>
	14	<i>Oocystis crassa</i>
	15	<i>Oocystis lacustris</i>
	16	<i>Pandorina morum</i>
	17	<i>Pediastrum duplex</i>
	18	<i>Pediastrum simplex</i>
	19	<i>Pediastrum simplex</i> var. <i>duodenarium</i>
	20	<i>Phacotus lenticularis</i>
	21	<i>Scenedesmus arcuatus</i>
	22	<i>Scenedesmus bijugatus</i>

Table 4. cont.

Class	No.	Taxa
Bacillariophyceae	23	<i>Coscinodiscus</i> sp.
	24	<i>Cyclotella</i> sp.
	25	<i>Cymbella</i> sp.
	26	<i>Diatoma vulgare</i>
	27	<i>Melosira granulata</i>
	28	<i>Navicula</i> sp.
	29	<i>Nitzschia acicularis</i>
Cyanophyceae	30	<i>Aphanizomenon</i> sp.
	31	<i>Chroococcus</i> sp.
	32	<i>Lyngbya</i> sp.
	33	<i>Merismopedia</i> sp.
Dinophyceae	34	<i>Ceratium hirundinella</i>
	35	<i>Gymnodinium</i> sp.
	36	<i>Peridinium cinctum</i>
Euglenophyceae	37	<i>Euglena</i> sp.
	38	<i>Trachelomonas</i> sp.
	39	<i>Phacus</i> sp.
Cryptophyceae	40	<i>Chroomonas</i> sp.

Figure 20 shows the temporal distribution of the different classes of algae inventoried in Lake Bab Louta.

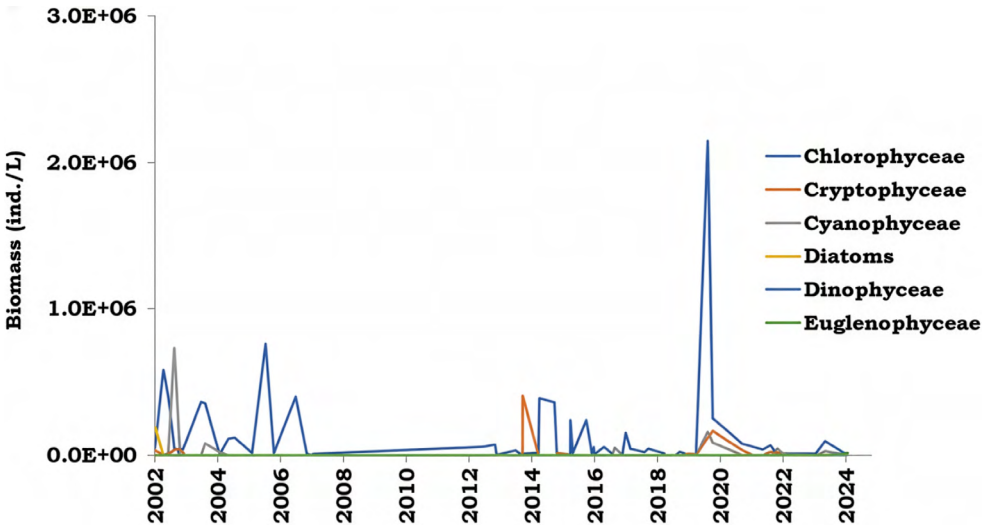


Fig. 20. Temporal evolution of phytoplankton abundance by class [ind./L]

This distribution is very heterogeneous and shows very significant seasonal and inter-annual variations. Several sawtooth peaks have been recorded. Indeed, the interaction of physical phenomena such as the morphology and depth of the lake [17], heliothermic conditions and water turbidity, and nutrient content with biological processes, such as predation and competition [18], would be factors responsible for this heterogeneous distribution in the lake. Generally, green algae and *Bacillariophyceae* are the most numerous groups. They colonise the waters throughout the entire observation cycle. The enrichment of the waters with nutrients and the reduction of water temperatures would favour these blooms.

Zooplankton

The importance of wildlife in lagoons is frequently underestimated. For several years, many authors [19, 20] have shown that certain organisms (Ciliates, Rotifers, Cladocerans, and Copepods) actively participate in purification. They concentrate and eliminate particulate matter (bacteria, algae, zooplankton, and particulate organic substances) through filtration, ingestion, or predation. Moreover, the organic matter suspended in the water, produced by algae and bacteria, resulting from the decomposition of dead organisms or originating from exogenous debris, constitutes the stock that zooplankton feeds on. All these organisms participate very actively in purification, directly through ingestion and flocculation and indirectly through the control they exert over algal populations. By thus concentrating the 'stored' substances, they contribute to the clearing of the environment. The zooplankton in the Bab Louta reservoir is represented by two groups: Crustaceans and Rotifers. The species diversity is quite low with 18 taxa, including 44.4% of Rotifers and 56.6% of Crustaceans.

Zooplankton community was composed of 18 taxa belonging to two major groups:

- 1) Crustaceans (10 taxa):
 - *Acanthocyclops* sp.;
 - *Bosmina* sp.;
 - Calanoida (unidentified copepodites);
 - *Ceriodaphnia* sp.;
 - Copepod (naupliar stages);
 - Cyclopoida (unidentified copepodites);
 - *Daphnia* sp.;
 - *Diaphanosoma* sp.;
 - *Neolovenula alluaudi*;
 - *Thermocyclops* sp.
- 2) Rotifers (8 taxa):
 - *Asplanchna* sp.;
 - *Brachionus* sp.;
 - *Filinia* sp.;

- *Keratella cochlearis*;
- *Keratella quadrata*;
- *Keratella* sp.;
- *Keratella valga*;
- *Polyarthra* sp.

The zooplankton biomass is relatively low for the various taxa recorded, except for the surge of crustaceans during the months:

- June 2001, attributed mainly to the bloom of *Neolovenula alluaudi* (48.300 ind./m³) and *Bosmina* sp. (1.380 ind./m³);
- September 2002, attributed mainly to the bloom of *Bosmina* sp. (23.500 ind./m³), *Diaphanosoma* sp. (18.800 ind./m³), and *Neolovenula alluaudi* (4.653 ind./m³);
- August 2004, attributed to the proliferation of copepod naupliar stages (28.842 ind./m³) and *Acartocyclops* (2.208 ind./m³).

In general, the zooplankton spectra obtained during the study period (Fig. 21) show the importance (in percent) of Crustaceans compared to Rotifers.

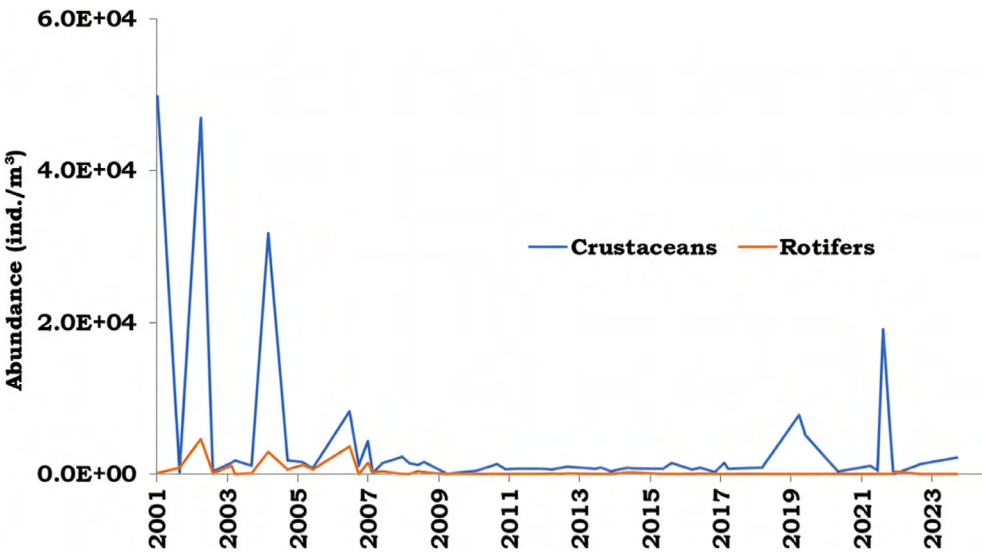


Fig. 21. Temporal evolution of zooplankton abundance [ind./m³] in the Bab Louta reservoir (2001–2024)

3.20. Physico-Chemical Drivers of Zooplankton Distribution

Among abiotic factors, temperature, light penetration, dissolved oxygen and chlorophyll *a* are the main drivers of zooplankton distribution. While temperature is a key factor in group development, its relationship with the seasonal cycle is not

straightforward due to seasonal fluctuations. Rotifers, Cladocerans and/or Copepods, which represent the majority of the fauna, were eurythermic, occurring in almost all samples and tolerating wide thermal variations. In contrast, peak rotifer abundances were recorded in summer, indicating that rotifers are eurythermic, developing at temperatures ranging from 5 to 21°C. In Bab Louta, rotifers were found at temperatures ranging from 13.4 to 29.2°C. Pearson correlation analysis between zooplankton abundance and environmental variables (Table 6) revealed no significant effect of trophic descriptors (Secchi depth, temperature, dissolved oxygen and chlorophyll *a* on zooplankton) [21–23].

Table 6. Pearson correlation coefficients (R^2) between zooplankton abundance and physico-chemical variables in Bab Louta

Zooplankton	Temperature [°C]	Dissolved oxygen [mg/L]	Secchi depth [m]	Chlorophyll <i>a</i> [µg/L]
Crustaceans	0.0129	0.0002	0.0195	0.0005
Rotifers	1.0000	0.1330	0.0044	0.0308

The zooplankton community exhibited fairly high taxonomic diversity, comprising 18 taxa. Analysis revealed a significant positive correlation between the increase in rotifer biomass during the dry season and concomitant rise in water temperature.

Furthermore, this increase was not correlated with variation in availability food at least in terms of chlorophyll *a* concentration.

3.21. Trophic Level of the Reservoir

The trophic state of the Bab Louta reservoir was assessed using mean total phosphorus (100 µg/L), mean chlorophyll *a* (6.52 µg/L), maximum chlorophyll *a* (89 µg/L) and mean Secchi depth. According to the OECD probabilistic classification (Table 7), the reservoir was classified as eutrophic based on total phosphorus (70% eutrophic, 20% hypereutrophic, 10% mesotrophic), maximum chlorophyll *a* (60% eutrophic, 30% hypereutrophic, 10% mesotrophic) and Secchi depth (60% eutrophic, 30% hypereutrophic, 10% mesotrophic), and as oligotrophic based on mean chlorophyll *a* concentration (85% oligotrophic, 15% mesotrophic).

Table 7. Probable trophic states of the Bab Louta reservoir

Parameter	Probable trophic state
Mean total phosphorus	70% eutrophic, 20% hypereutrophic, 10% mesotrophic
Mean chlorophyll <i>a</i>	85% oligotrophic, 15% mesotrophic
Maximum chlorophyll <i>a</i>	60% eutrophic, 30% hypereutrophic, 10% mesotrophic
Mean Secchi depth	60% eutrophic, 30% hypereutrophic, 10% mesotrophic

4. Conclusion

The assessment of the water quality of the Bab Louta reservoir during the study period reveals the following main conclusions:

- The reservoir is characterised by stable thermal stratification during the period from June to September.
- Conditions of anaerobiosis are observed at deeper layers during the summer and autumn period, accompanied by the presence of hydrogen sulfide at S^{2-} concentrations of up to 0.20 mg/L, giving the water a musty smell and unpleasant taste requiring significant treatment.
- A release of undesirable elements, particularly manganese and iron, was noted.
- Indicator algal species of biological quality degradation and signs of eutrophication were recorded during the study period.
- A marked trend of Lake Bab Louta towards eutrophic status was determined.
- A significant impact of climate change on the biological and physicochemical quality evolution of Bab Louta reservoir was seen.

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CRedit Author Contribution

A.Z.: conceptualization, methodology, supervision, project administration, resources, validation, writing – review & editing. As the principal investigator, he supervised the work at all stages.

J.N.: data curation, formal analysis, investigation, methodology, software, supervision, validation, visualization, writing – original draft, writing – review & editing.

K.H.: investigation, methodology, software, visualization, writing – review & editing.

L.B.: writing – review & editing.

L.L.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, writing-original draft, writing – review & editing.

M.E.A.: validation, writing – review & editing.

A.B.: funding acquisition, project administration, resources, supervision, validation.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available from the National Office of Electricity and Drinking Water (ONEE), Morocco, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon request and with permission of ONEE-Water Quality Department.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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