Trophic status and impact of the filling rate on eutrophication of the MBAK dam

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Abstract. The Mohammed Ben-Abdelkrim Khattabi (MBAK) dam contributes to the growing need for water for irrigation, electricity production and drinking water supply in the province of Al Houciema. In order to gain a better understanding of the mechanisms involved and the factors that condition eutrophication, a study was conducted on this dam. A monthly sampling of water from the dam was carried out between spring 2005 and winter 2015 at the level of the National Office of Electricity and Drinking Water (ONEP) intake to determine the degree of stratification, the trophic status, and some trace elements (iron and magnesium) of the reservoir. Principal component analysis (PCA) was performed to process information on some of the most important physical and chemical tracers in the eutrophication of the dam. Trophic status, according to Trophy State Index (TSI) and Vollenweider classification, classifies the lake as mesotrophic. The stratification and mixing regime of the water mass presents a warm monomictic water body with a thermal stratification that generally extends between April and November. Physico-chemically, the water of the MBAK dam has a relatively high concentration of total phosphorus, a very reduced transparency per phase and a significant oxygen deficit in the hypolimnion. As for nitrates (NO^{3-}), they present relatively high levels in the winter-spring period in relation to the good oxygenation of the water combined with the importance of liquid inputs. The PCA showed a state dominated by waters rich in chlorophyll-*a*, helped by the good oxygenation, leading to a strong turbidity of the waters and an opposite state, marked by a deficit in dissolved oxygen but with a high mineral load (manganese, iron) and which generally corresponds to the summer and autumnal period.

Key Words: eutrophication dynamics, MBAK dam, state index, stratification, water supply.

Introduction. Eutrophication of dams has become an inevitability in arid climate countries. It is a ubiquitous phenomenon that occurs in different types of climate, including equatorial (Galvez-Cloutier & Sanchez 2007), tropical (Janjua et al 2009; Quevedo-Castro et al 2019), arid (Al-Taani et al 2018; Shekha et al 2017), temperate (Zbierska et al 2015; Dumitran et al 2020) and even polar climates (Kaup et al 2005). This threat has become increasingly severe due to climate change. Furthermore, the interactive impacts of warming and eutrophication have been widely established and documented in the literature (Ansari et al 2010; Binzer et al 2016).

In the context of the Mediterranean climate dominated by the semi-arid bioclimate, Morocco's water resources, which can be mobilized mainly for drinking water production and agriculture, have become subject to water quality degradation during drought years. This state of affairs certainly impacts the water heritage stored in almost all the dams' reservoirs (Laouina 2019). Therefore, the improvement of water quality, particularly those of the dams, is a major challenge for our country.

In particular, the central Rif on the Mediterranean shore, especially in the Nekor watershed in the province of Al Hoceima, is characterized by a rugged relief totally gullied, a friable lithological formation, a vegetation cover scattered or even almost absent on several slopes and by the irregularity of rainfall. This state of affairs has a negative impact on the proper hydrobiological functioning and water quality of the Mohammed Ben-Abdelkrim Khattabi (MBAK) dam.

To determine the trophic status of water resources and better understand the eutrophication process, it is important to study the link between the evolution of associated environmental variables and hydro-trophic dynamics (Sadat et al 2011).

A global analysis of the key parameters of the monitoring database, conducted during ten years (2005-2015), was necessary to better identify correlations between variables and determine the factors that condition their hydro-trophic dynamics in this dam.

Material and Method

Study site. The MBAK dam is located in the Nekor watershed in the northeast of Morocco, in the eastern part of the Rif mountains (35°5'32.48"N; 3°48'28.61"). It is the only source of water for the city of Al Hoceima and neighboring urban centers (Imzouren, Beni Bouayach, etc.). The climate is typically Mediterranean with a semi-arid trend (Figure 1). It is cold and wet in winter and hot and dry in summer. The average interannual rainfall of the basin is estimated at 340 mm (Arrebei et al 2019). The water regime of the main tributary (Oued Nekor) is characterized by intermittent flow and does not reach ten floods per year (Dimane et al 2017).

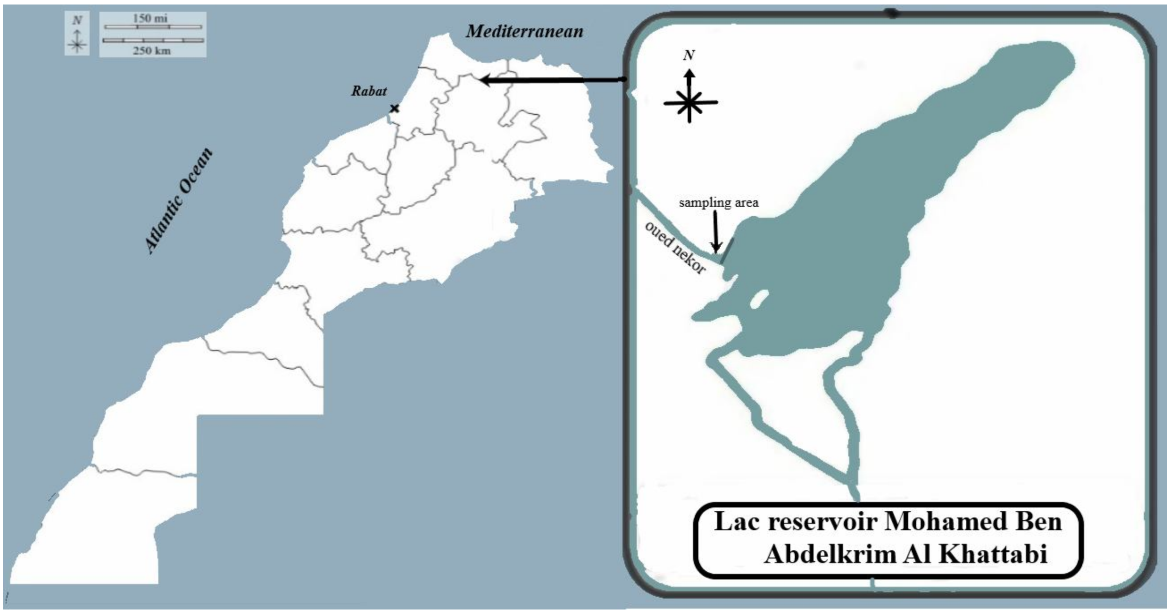

Figure 1. Geographical location of the Mohamed Ben Abdelkrim Al Khattabi (MBAK) dam.

Topographically, the dominant relief is rugged with an average altitude of 1500 m (Lahlou 1990). It rests on sedimentary formations of schistous type, soft, fractured, without coherence. The soil consists mainly of debris of alteration of the substrate, are superficial and the organic matter content is low (Arrebei et al 2019). The near absence of vegetation cover and the advanced state of gullying of the slopes surrounding and upstream of the MBAK reservoir accelerate its siltation and compromise its life span (5000 t year^{-1} of soil loss). According to the bathymetry of 2020, the storage capacity is about 11.8 Mm^3 representing a quarter of its capacity when it was first filled in 1981 (43 Mm^3) (Murcia et al 2021). As for the morphometric and hydrological characteristics, they are illustrated in Table 1.

Table 1

Morphometric and hydrological characteristics of Lake MBAK

Parameters	*Values*
Date of impoundment	1981
Normal reservoir elevation	140 NGM
Overall capacity of the reservoir	43.3 Mm^3
Surface area of the reservoir	3.86 Km^2
Function	Drinking water
Stream	Oued Nekor
Nearby city	Al Houceima

Water sampling and analysis. The temporal sampling plan for this study spans from spring 2005 to summer 2015 (4 times/year). In the water column vertical, the water samples were taken at the National Office of Electricity and Drinking Water (ONEP) outlet (Figure 1) at the surface of the water body and vertically at a depth of 15 m in the same point after the dam spillway. Thus, the sample size is of the order of 80 observations.

In order to calculate the trophic status index (TSI) of MBAK lake waters, physicochemical and biological parameters such as: pH, temperature (T^o), electrical conductivity (Ec), nitrates (NO^{3-}), iron (Fe^{2+}), manganese (Mn^{2+}), dissolved oxygen (DO), total phosphorus (TP), transparency (Secchi disk), and chlorophyll-*a* were measured according to standard methods (Cooke et al 2016; Le Moal et al 2019).

Water samples were collected in a clean 1L polyethylene bottle at the sample site below with two levels and were transferred to the ONEP laboratory at 4°C for measurement of chemical (DO, TP, Iron, Manganese, nitrate) and biological (Chl-*a* extraction) parameters. While physical parameters (T°C, pH, EC and transparency) were measured in situ (Table 2).

Table 2

Methods and techniques used in the physico-chemical parameters measurements

Measurements	*Parameter*	*Method or technique*
In situ	Temperature (T°C)	Thermometer
	pH	pH Philips 4014
	Electrical conductivity (Ec)	EC Philips 4025 counter
	Transparency	Secchi disk
Laboratory	Dissolved oxygen (DO)	Nitrogen method in modification of the Winkler method
	Total phosphorus	Colorimetric (after mineralization of persulfate in an acid environment)
	Iron (Fe)	Atomic absorption spectrometry
	Manganese (Mn)	Atomic absorption spectrometry
	Nitrate	Colorimetry
	Chl-*a* extraction	Using 80% acetone extraction procedure, which was determined at 663 and 645 nm

The TSI (Carlson 1977) was developed based on transparency as a relative indicator of algal biomass and is the most appropriate and acceptable method for inland lake eutrophication (Duan et al 2007).

The formula for the TSI is as follows:

$$TSI\ (Tr) = 10[6 - \ln (Tr)/\ln(2)]$$

Based on the averages used in the parameter measurements, we calculated the Carlson indices according to the formulae:

$$\mathbf{TSI\ (CHL) = 9.81\ ln\ (Chl) + 30.6}$$

$$TSI\ (CHL) = 9.81 \ln (3.11) + 30.6$$

$$\mathbf{TSI\ (TP) = 14.42\ ln(PT) + 4.15}$$

$$TSI\ (TP) = 14.42 \ln (394) + 4.15$$

In order to determine the degree of stratification of the lake, a monthly average over ten years was taken; a profile of temperature, pH, and oxygen was obtained using time-lapse measurements recorded at each meter over an annual cycle.

Statistical analyzes. The parameters were assessed by Pearson correlation ($p < 0.05$) using SPSS 20.0 software (Kuperman et al 2002; Van Belle et al 2006). All data were tested for normality and homogeneity of variance prior to parametric statistical analysis. Variability between sampling sites was analyzed for each water parameter by one-way ANOVA. To check the differences between the means of the parameters, we used Duncan's test between the tested parameters.

The principal component analysis (PCA) performed allowed to classify and process the information related to some of the most important physical and chemical tracers in the dam eutrophication during the years 2005 and 2015 by establishing a typological structure able to explain the quality water evolution during this period and to identify the correlations between the variables.

This PCA was carried out with a data matrix consisting of 41 samples (41 campaigns) in which the nine variables (water temperature, pH, DO, Ec, Chl-*a*, transparency, TP, Fe and Mn).

Results and Discussion

Dam water stratification

Temperature. The presence of a seasonal cycle in this data set is noticeable. This cycle shows that the surface water temperature is minimal during the cold season and maximum in the warm season. However, bottom temperatures are lower than surface temperatures with a small thermal difference. This thermal difference (TD) is significant in spring.

At the surface, the lowest value 10.70°C was observed in winter 2014, the maximum value 31.60°C was observed in summer 2009. However, at the bottom, the lowest value measured in winter 2014 is 10.60°C, while the maximum value 27.20°C was obtained in summer 2014 (Figure 2a).

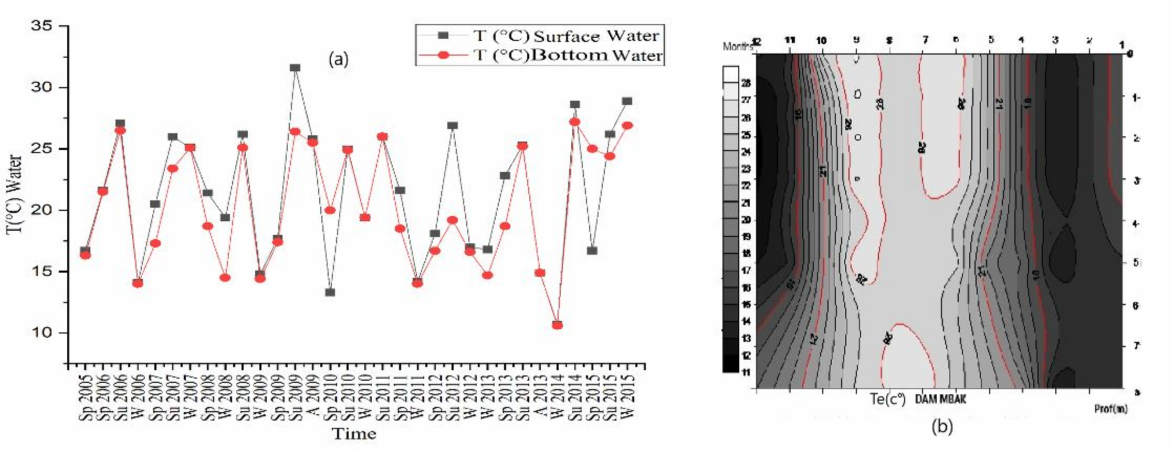

Figure 2. (a) The interannual temperature variation of the MBAK reservoir. (b) The vertical profile and the diagram of the monthly variation of the MBAK reservoir.

The low minimum temperatures and the large temperature range observed seasonally, especially in spring in the reservoir, and a thermal stratification induce important changes in the stability of the water column (Wu et al 2021) on a seasonal scale.

Indeed, stratification begins to set in from April due to the increase in surface water temperatures followed by a decrease that starts around October and is diffuse until total mixing towards the end of November (Figure 2b). The duration and volume of water isolated during the summer can affect the duration and depth of temperature stratification (Dumitran et al 2020). However, an episode of homothermy was recorded during the December-February period of each year, the winter mixing phase (Figure 2b). The figure shows the presence of several phases where significant temperature differences between the surface and the bottom were maintained continuously from a period of significant stratification (summer season). The reservoir is divided into a lower part called cold hypolimnion and an upper part called warm epilimnion separated by a thermocline located at a depth of 3-6 m. From November onwards, the dam begins its late autumn-winter mixing. These periods are all associated with wet periods (precipitation).

The duration and depth of thermal stratification can also affect the time and volume of water stored during the summer (Dumitran et al 2020). These observations have been found in an arid climate (Asadian et al 2020) and those made in a humid subtropical climate (Jin et al 2019).

Another factor influencing stratification is climate change which contributes to rapid warming of waters and stronger stratification (O'Reilly et al 2015; Yin et al 2018; Woolway & Merchant 2019; Firoozi et al 2020; Valerio et al 2021).

Note the disruption of the thermal structure of the water column noted in the months of April, May, October, and November of each year is marked by an abrupt shift of warm surface water to the bottom. This phenomenon can only be related to a large-scale mechanical action namely the opening of the reservoir gates (Zbierska et al 2015) or a very strong wind (Firoozi et al 2020). Thus, the thermal and dynamic stratification pattern observed at the lake level of the MBAK dam is typical and can be classified as warm monomictic

Also, the magnitude of precipitation, water level, and climatic variations in air and water temperature appear as key factors in stratification (Jin et al 2019; Liu et al 2020).

pH. In general, the pH of surface waters is always alkaline, with values generally ranging from 7.45 to 8.7 (Figure 3a). At the surface, the lowest value 7.88 is observed in winter 2013 and the maximum value 8.7 was observed in summer 2010. However, the pH decreases from the surface to the bottom to 7.45 (lowest value measured in summer 2012), while the maximum value 8.45 is obtained in summer 2011. These values are all within the minimum required value range (ONEP 1989). Surface-to-bottom pH differences are higher in summer than in spring and winter with an average decrease of 0.80 and 0.2 respectively.

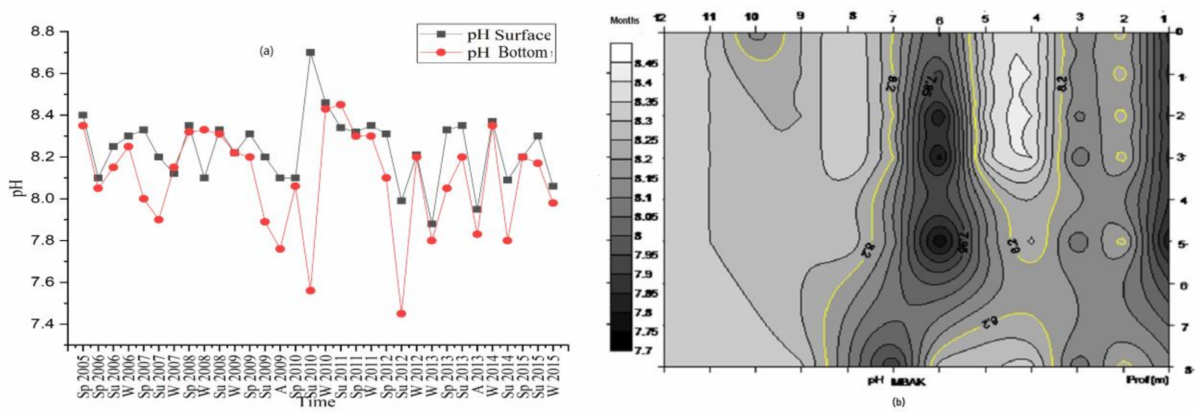

Figure 3. (a) Interannual pH variation of the MBAK reservoir.
(b) Vertical profile and diagram of the monthly pH variation of the MBAK reservoir.

From the data collected, it is possible to appreciate the existence of a state of pH stratification, depending on depth and season (Figure 3b). The monthly variations show a stratification from January to July with the highest values in summer and autumn.

This distribution of pH could be explained by photosynthetic activity of surface algae and mineralization of bottom waters by bacteria. The increase in pH results solely from the photosynthetic activity of green algae. The high algal activity allows high CO_2 uptake by the waters, which leads to the imbalance of the carbonate buffer system and increases the pH level of the waters (Labrecque & Milne 2012; Ihnken et al 2014).

Dissolved oxygen. The maximum DO value recorded at the surface and at the bottom was 12 and 10.5 mg L^{-1} respectively in winter 2009, while the minimum value at the surface was around 5 mg L^{-1} in winter 2012 and at the bottom was 0 mg L^{-1} in summer 2013 (Figure 4a).

For the bottom waters, the contents are marked by two states:
1 - state of anoxia: mostly during the summer and autumn seasons;
2 - state of good oxygenation mainly in winter seasons with peaks that can reach 12 mg L^{-1} (case of winters 2009; 2011 and 2013).

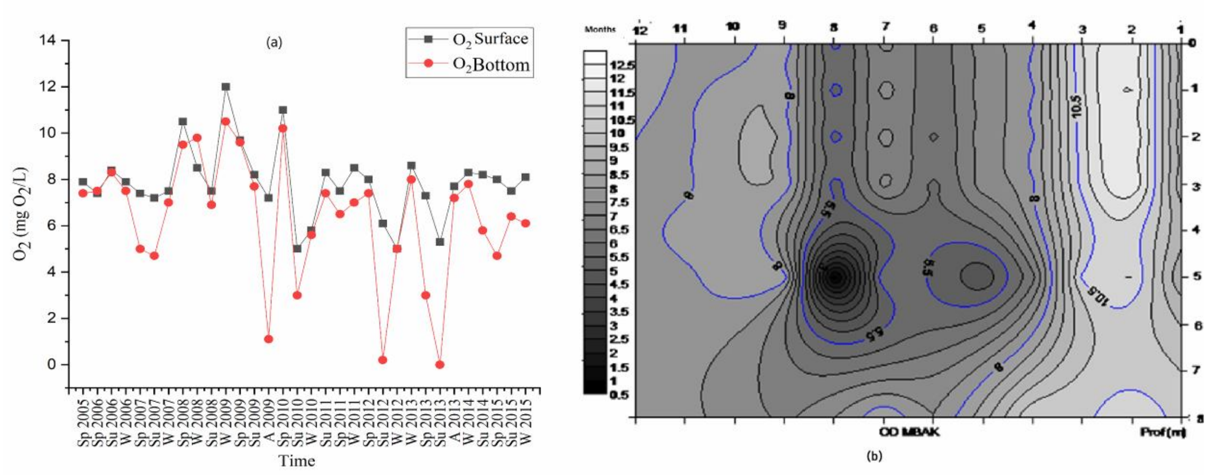

Figure 4. (a) Interannual variation of oxygen in the MBAK reservoir. (b) Vertical profile and the diagram of the monthly variation of oxygen of the MBAK reservoir.

The vertical oxygen profile is characterized by winter mixing, allowing partial reoxygenation of the bottom with DO concentrations of 10.50 and 8 mg L^{-1} respectively between January and March (Figure 4b). A reduction of reoxygenation starts in the water column to reach in June and August a value of 5.5 mg L^{-1} at the bottom, this situation characterizes all the surface layers in relation with the excessive use of O_2 by aquatic organisms and bacterial oxidation (Tifnouti & Pourriot 1989; El Hamouri et al 1995). The detailed analysis of the vertical profile shows that in winter period, the whole water column is totally homogeneous only during one month of January; with average DO levels of 10.50 mg L^{-1}. This observation suggests that the water-sediment interface of the lake is quasi-anoxic, but that the hypolimnion holds a sufficient amount of DO in the summer period. Reservoir mixing is particularly important to provide oxygen to the deep waters and to transport nutrients from the hypolimnion to the epilimnion (Yankova et al 2017; Duvil et al 2018).

In addition, a recent study showed that oxygen levels in 45,148 samples from 393 temperate lakes in surface and deep waters declined by an average of 5.5% and 18.6% respectively (Jane et al 2021). Our study estimates that the main driver of this oxygen loss in surface waters is the overall increase in temperature that decreases the solubility of oxygen in water. While for deep waters, the increase in thermal stratification, in intensity and duration, leads to a decrease in oxygen concentrations in the deep layers of dams (Jane et al 2021). Notably, eutrophication of deep waters is related to the decomposition of organic matter in combination with oxygen consumption (Yan et al 2015).

From spring onwards, there is a drop in the deep layers from a depth of 6 m, which accelerates to reach the superficial layers during the summer season (6-7 m) (aphotic zone) and reaching an anoxic phase from the higher depths, continuing until the beginning of autumn, to know a beginning of reoxygenation of the deep layers from mid-autumn.

This oxygen deficit is indicative of extensive biodegradation at depth. The average difference between surface and bottom oxygenation is important. It is sometimes noted that the stratification is not stable (case of May), probably due to stirring caused by winds (Firoozi et al 2020) or flushing operations (Zbierska et al 2015). Water transparency plays a prominent role in DO stratification. Indeed, with high levels of organic matter settling to the bottom of reservoirs, it is clear that the oxygen demand at the water-sediment interface is very high. This could explain the development of anoxic conditions at depth in these types of aquatic ecosystems (Boehrer et al 2008; Bhagowati et Ahamad 2019; Winton et al 2019; Liu et al 2021). On the other hand, the evolution of DO concentration in the Stanca-Costesti reservoir showed large variations correlated mainly with the evolution of water temperature (Dumitran et al 2020).

The thermocline forms a barrier that prevents the transit of well-oxygenated water from the epilimnion to the hypolimnion. This is due, on the one hand, to the increase in the deficit as a function of the consumption of oxygen in the waters of the hypolimnion and, on the other hand, to the richness of nutrients in the epilimnion, which provides a very favourable environment for the development of phytoplankton at the beginning of the summer. The production of the phytoplankton in the superficial layers is due to the penetration of light which, in the presence of nutrients, leads to an excessive sedimentation of detritus, which allows the deoxygenation of the hypolimnion where conditions of anaerobiosis are established which tend to rise very high in the water column, particularly in the summer season.

Trophic state. The maximum recorded concentrations of TP were about 2.7 mg L^{-1} at the surface on spring 2006 and 2.40 mg L^{-1} at the bottom on winter 2007 (Figure 5a). For the rest of the surveys, they hardly exceed 1 mg L^{-1}. Except for 2005, 2006 and 2009 samples, phosphorus concentrations are significantly higher at the bottom than at the surface, which demonstrates that bacterial activity in the hypolimnion is less intense. In fact, the values recorded classify these waters as poor quality according to the lake water quality grid (Meybeck et al 1998).

For Chl-*a*, the interannual evolution is marked by a very significant seasonal variability during the whole study period (2005-2015). The highest concentration of 7 mg m^{-3} at the surface and 8.6 mg m^{-3} at the bottom were obtained in winter 2010 and spring 2014 respectively and the lowest are around 0.9 mg m^{-3} (Figure 5b). On the other hand, this high level of Chl-*a* recorded during 2008/2010 could be the result of phytoplankton activity and nutrient enrichment of the water column. The overall data analysis shows a stable productivity of the water body. This lack of trend is due to the lack of change observed for phosphorus concentrations.

On the other hand, the concentration of Chl-*a* in the reservoir was lower during the stratification period, probably due to nutrient limitation and intense water fluxes related mainly to low filling rate, responsible for the observed high chlorophyll-*a* levels. This was found at two reservoirs in Brazil (Coulliette & Noble 2008).

In addition, the level of Chl-*a* in the water can vary due to turbidity and other factors unrelated to algal growth. The highest Chl-*a* values corresponded to lower transparencies. The strong direct correlation between total phosphorus and Chl-*a* presented supports this conclusion (Galvez-Cloutier et al 2007).

The interannual evolution of transparency is marked by a very marked seasonal variability during the 2008/2009 period. The highest values (250 cm) were recorded in the spring 2008 and summer 2015 seasons (Figure 5c). Indeed, comparison of the Chl-*a* variation profiles with that of transparency shows some correlation except for a few points. This suggests that the productivity of the dam is the factor responsible for this condition, not the winter and autumn floods which are highly charged with suspended matter.

Water transparency varies irregularly and depends on hydrological cycles but especially on phytoplankton and algal productivity. Indeed, seasonal variations show that the waters of the dam are weakly transparent especially in Winter and relatively transparent in Summer and Autumn. Consistent with our study, transparency correlates with increased phytoplankton density indicating higher chlorophyll (a) content (Shekha et al 2017).

As for nitrate, which has an impact on trophic status, it has a low variability except for some peaks where we found a value of 0.04 mg L^{-1} in summer 2006 at the bottom and surface. On the other hand, the maxima are recorded respectively 7.24 mg L^{-1} in winter 2014 and 5.87 mg L^{-1} in winter 2009 at the bottom and surface (Figure 5d).

Nitrate (NO^{3-}) levels show significant seasonal and cyclical interannual variations. They are relatively high in the winter-spring period in relation to the good oxygenation of the water combined with the importance of liquid inputs (Figure 5d). These levels respect the water quality standards (excellent class) (< 10 mg L^{-1}).

Thanks to the presence of nitrates in sufficient quantities, which act as additional oxidizing material, the bacteria do not need to use sulfates in the decomposition processes of the organic matter, but iron and manganese are present. The decomposition of these organic residues and the decrease in temperature can contribute to lower nitrate levels in the water (Abdelhay et al 2018).

Mixing processes can alter the vertical concentration of ions and influence the presence of nitrate in the hypolimnion nutrients (Liu et al 2020). Indeed, the importance of denitrification at the bottom (Bonin et al 1989), the low allochthonous contributions and the algal assimilation would lead to the depletion of this element in the water column in summer period. Nitrates would be the limiting factor for algal production in the reservoir during this period.

Conductivity data from the dam reveal a very high mineralization (> 1170-1180 µS cm^{-1}) especially during the period 2011 and 2013 with however (Figure 5e), a difference between surface and bottom is very small. According to Thornton et al (2013), a difference of less than 80 µs cm^{-1} is not very significant and allows a single point to provide a realistic description of water quality. Indeed, this sudden increase may be an indication of a release of minerals by the decomposition of organic matter at the bottom. However, the conductivity seems to be conditioned by the filling rate, evaporation is no longer compensated by lateral inputs

The higher conductivity values were observed during the winter season due to the erosion process in the basin. Indeed, seasonal differences in dilution/concentration seem to have an impact on this parameter such as conductivity and nitrates (Chanudet et al 2016).

Average iron levels range from 0.09 mg L^{-1} (fall 2013) to 1.20 mg L^{-1} (spring 2005) at the surface and from 0.13 mg L^{-1} (spring 2008) to 0.2 (winter 2012) at the lake bottom (Figure 5f). The significant values were recorded during the wet period, with the maximums systematically observed at the bottom of the reservoir. In contrast, all values recorded at the surface do not exceed the guide values (ONEP 1989). For manganese, the phenomenon of seasonality is more pronounced, particularly at the bottom (Figure 5f), where levels are well above the guide value, except at a few points. These values range from 0.02 mg L^{-1} (spring 2006) to 0.2 mg L^{-1} (winter 2007). At the surface, manganese levels vary between 0.01 mg L^{-1} (spring 2010; 2013 and summer 2012) and 0.2 mg L^{-1} (summer 2007). The increase in concentrations begins in summer and reaches its maximum in late autumn for the whole cycle. This situation coincides with the conditions of fall of oxygen at the bottom of the lake (conditions of anoxia). Indeed, in this period, we record, simultaneously with the decrease of the dissolved oxygen contents, an increase of the iron and manganese concentrations of the deep layers of the lake (phenomenon of release of iron by the sediments of the bottom). The high phosphorus, iron, and manganese loads recorded at the dam, are explained simultaneously with the phenomena of fine sediment release. Indeed, this high content in a eutrophic reservoir supports an increased level of primary production until nitrogen limitation (Shekha et al 2017). Spatial and temporal variations show lower concentrations of iron in high water periods than in low water periods, higher concentrations in the bottom waters than in the surface waters and an increasing gradient according to the number of days after a flood (Niazi et al 2005). The variation of manganese concentrations according to hydrological conditions, found in the mass balance and estimated in the first 10 centimeters by Niazi et al (2005), is explained by the effects of climates changes on the lake hydrological conditions and water physicochemical properties.

If the total phosphorus concentrations in the waters dam are maintained at around the current load and provided there are no long periods of poor water mixing and prolonged bottom water anoxia. This would cause a strong release of phosphorus from the sediment (decrease of the sedimentation constant) which could cause the dam to fall into a hyper-eutrophic state and a strong erosion and the availability of a large stock of mobilizable particles in the watershed make the solid load of the Wadi Nekkor considerable.

The accumulation of soluble phosphorus through nutrient release in the hyplimnion layer depends on oxygen concentration, microbial decomposition, hypolimnetic temperature, and thermocline depth (Benateau et al 2019; Pitoi et al 2019; Dumitran et al 2020). However, the rate of water filling intensifies vertical mixing of the water, moving phosphorus from the bottom (hypolimnion) to the epilimnion (Dumitran et al 2020).

In fact, the accentuation of the drought that the country has experienced and consequently the scarcity of inputs from the Wadi Nekkor, have favored the mobilization of Mn and its diffusion from the pore waters causing the contamination of the waters of the reservoir. The mobilization of chemical elements stored in soils or sediments in response to changes necessarily anthropogenic - of the environment (Stigliani & Ravasi 2012).

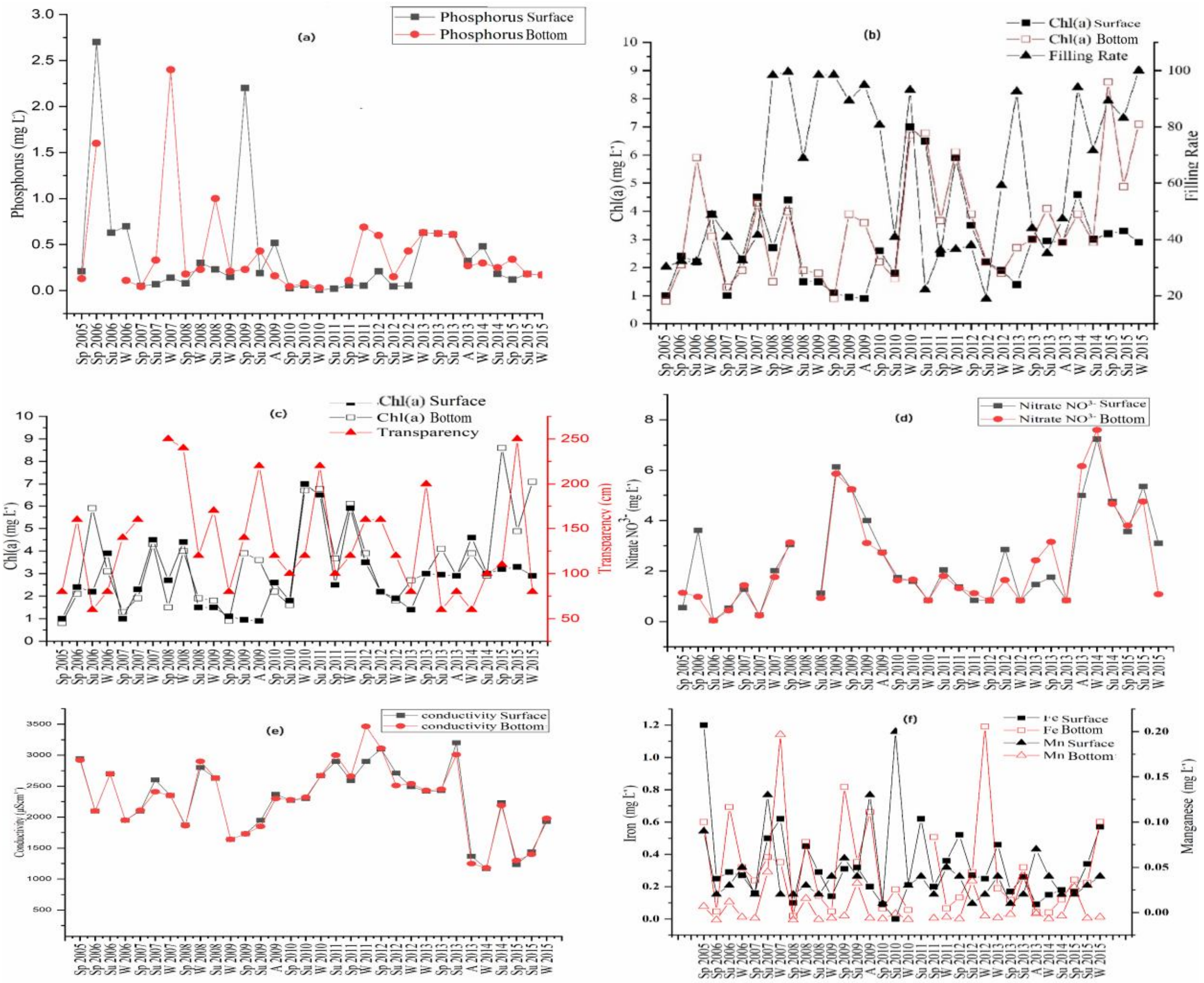

Figure 5. Interannual evolution of the parameters of the MBAK reservoir: (a) variation of phosphorus as a function of time; (b) variation of Chl-*a* and filling rate with time; (c) variation of Chl-*a* and transparency; (d) variation of nitrate with time; (e) seasonal variation of surface and bottom conductivity; (f) seasonal variation of surface and bottom iron and manganese.

Indeed, when the reservoir is stratified, an increase in Mn and Fe in the Lake hypolimnion coincides with lower oxygen concentrations, which was demonstrated in the study (Munger et al 2017). Thus, oxygen resupply leads to some oxidation of manganese and iron in the epilimnion to achieve vertical oxygen homogenization through brazing and flushing operations, which was confirmed by (Munger et al 2016). Otherwise, Mn and Fe concentrations are significantly lower during the stratification period (Munger et al 2017). Other similar studies, concerning other reservoirs, have observed elevated Iron concentrations during winter and spring due to increased water inputs (Blakar & Hongve 1997; Giles et al 2016).

Overall, the bottom contents are similar to those of the surface. This situation is related to the importance of hydrological and biological processes taking place in the dam (Asadian et al 2020).

A similarity of variation between the surface and the bottom is to be noted. According to Trenhaile (2000), the MBAK dam waters are very productive. As such, the transition from one trophic state to another is based on the conversion of the degree of nutrient input and reservoir productivity (Odagiri et al 2020).

Carlson's (1977) TSI is based on the fact that the degree of eutrophication of a dam is a function of increasing nutrient concentration, particularly phosphorus. Generally, the increase in the concentration of phosphorus leads to an increase in the amount of microscopic algae, as revealed by measurements of the chlorophyll (a) parameter, and a decrease in transparency.

The average values of the three parameters, namely transparency (Secchi), chlorophyll (a) and TP and their TSI, considered in the index are reported in Table 3.

Table 3

Mean, TSI, mean index and status of TP, transparency and chl-*a*

	Transparency (m)	*Total phosphorus (µg L^{-1})*	*Chlorophyll-a (µg L^{-1})*	*TSI mean*
Mean	1.24	394	3.11	
TSI	57	90.23	41.68	62.97
Status	Eutrophic	Eutrophic	Mesotrophic	Eutrophic

The TSI index for the transparency of the impoundment corresponds to eutrophic trophic status (Table 3). The index for total phosphorus also suggests eutrophic status while the chlorophyll (a) biomass index obtained reveals a mesotrophic status. However, the average index of 62.97 classifies the lake as eutrophic.

In summary, the trophic status of the lake corresponds to a eutrophic stage. This conclusion is based on the three indices that show low water transparency, average phytoplankton biomass and high total phosphorus concentrations.

However, the trophic status approach of the MBAK reservoir lake based on the overall average chlorophyll (a) and according to classification of Vollenweider et al (1998), classifies it as a mesotrophic lake (Table 4). Nevertheless this trophic state is only an average situation which can change according to the season.

Table 4

MBAK dam classification according to Vollenweider et al (1998)

Trophic category	*Chlorophyll-a (mg L^{-1})*
Ultra-oligotrophic	< 1
Oligotrophic	< 2.5
Mesotrophic	2.5-8
Eutrophic	8-25
Hypereutrophic	> 25

Eutrophication dynamics. The typology of eutrophication showed a seasonal trend between the eleven variables (water temperature, DO, EC, chl-*a*, transparency, TP, turbidity, NO3-, N, iron and manganese), the eigenvalues of the PCA in the factorial map are represented in Figure 6.

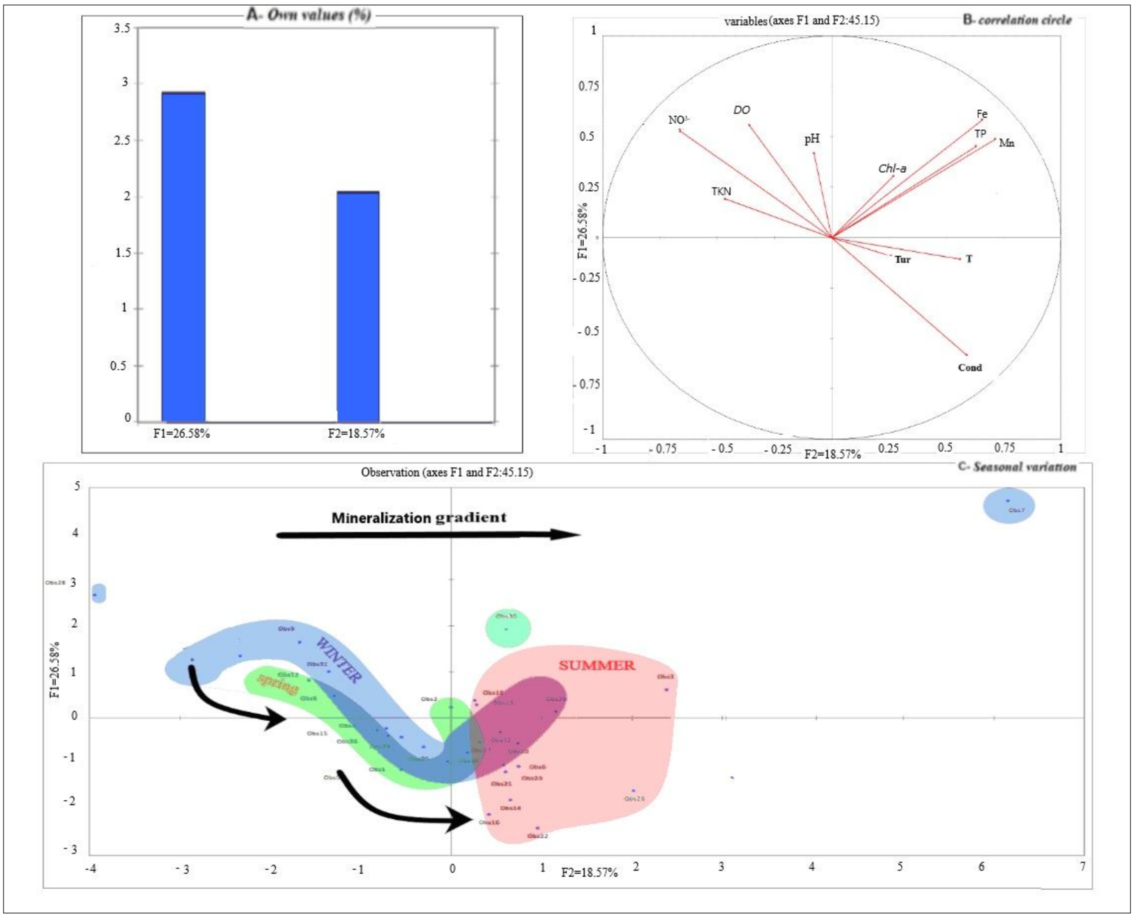

Figure 6. Graphical approach to PCA: (A): distribution of the inertia between the axes; (B): correlation circles of variables; (C): factual map of the campaigns.

The codes of the variables with high correlation and their coordinates are represented in Table 5.

Table 5

Correlation matrix (Pearson (n)) of PPC in waters

Variable	*Chl-a*	*T°*	*pH*	*EC*	*DO*	*Turb*	*TKN*	NO^{3-}	*TP*	*Fe*	*Mn*
Chl-*a*	1										
T°	0.331	1									
pH	0.283	-0.252	1								
EC	-0.114	0.128	-0.058	1							
DO	-0.077	-0.357*	0.488*	-0.370*	1						
Turb	0.020	0.059	0.043	0.144	-0.102	1					
TKN	-0.082	-0.154	-0.173	-0.377*	-0.038	-0.137	1				
NO^{3-}	-0.028	-0.297	0.023	-0.776*	0.286	-0.157	0.482*	1			
TP	0.332	0.244	0.127	0.185	0.084	0.028	-0.105	-0.235	1		
Fe	0.072	0.185	0.037	0.047	0.037	0.153	-0.143	-0.073	0.515*	1	
Mn	0.107	0.286	-0.077	0.114	-0.135	0.072	-0.110	-0.106	0.513*	0.911*	1

Starred values (*) are significantly different from 0 at the alpha=0.05 significance level. T°, water temperature; CE, electrical conductivity; DO, dissolved oxygen; Chl-*a*, chlorophyll-*a*; transparency; TP, total phosphorus, TKN, total Kjeldahl nitrogen; Turb, turbidity; NO^{3-}, nitrates; Fe, iron; Mn, manganese.

Examination of the correlation matrix between variables reveals the presence of: A first set of variables, made up of descriptors that are well correlated with each other: pH/DO, TP/Fe, TP/Mn and Fe/Mn (Table 5).

The results obtained (Table 5 and Figure 6A) allow a first typological approach of the different variables according to their affinities and their groupings on the first two principal components based on their contribution. The first two axes determine 45.14% of the total information (26.58% for axis 1 and 18.57% for axis 2).

In the first factorial plane Axis 1*2, the qualitative state 1 (EQ1) is mainly determined by phosphorus (0.629), iron (0.65) and manganese (0.713) coupled with water temperature (0.55) and conductivity (0.53), opposite to nitrate (-0.66). It thus defines a gradient of mineralization from left to right that results in an increase of iron, manganese, total phosphorus, conductivity and a reduction of nitrogenous elements (Figure 6B).

The variation of this mineralization appears to be more related to the release of iron, manganese and phosphorus by bound sediments in relation to dissolved oxygen which presents a hypoxic state at the level of the deep layers.

The global analysis allows to define a typology dominated by the individualization of two groups of clear seasons, namely winter (H)/spring and summer (E) (Figure 6C), which have a dominant and determining tendency in view of the importance of the changes taking place during the temporal evolution of the seasons. In relation to the fall season, the evolution does not follow a particular trend.

The qualitative state 2 (EQ2) has a lesser importance, by a passage of a pole rich in nitrogenous elements, particularly nitrate, in relation to a good oxygenation and a weak mineralization. At the level of this pole, we note a significant presence of elements (iron, manganese and phosphorus) and their resuspension in relation to a state of anoxia recorded at the level of the deep layers. Between the two poles, there is an intermediate situation marked by an average quality of the water of the dam.

The global typology was marked by an individualization of a particular state observed during the winter of 2007 and which is characterized by a very strong mineralization of the waters related to the presence of chemical elements such as iron, manganese and total phosphorus. This particular situation is correlated to an exogenous contribution and a leaching of agricultural land with a rainy winter. During this period, the overall analysis is correlated with the factor of filling rate, but the emphasis on the preponderant influence of the latter on the hydro-trophic conditioning of the dam and underlines the interest of monitoring this factor, in order to define a critical threshold that conditions the quality of the water of the dam and its socio-economic impact.

According to the typology, the variation seasonal average of the quality is observed, notably from an average state recorded in 2005 to a concentrated state in 2007.

Conclusions. The study of chemical and biological tracers allows us to qualify the warm monomictic dam, whose trophic state showed a very marked seasonal variation of total phosphorus, chlorophyll (a), conductivity, transparency, and nitrate in relation to the filling rate.

The stratification and temperature mixing regime shows two bottom water states, one state of anoxia in the summer and fall period and another state of good oxygenation during the winter period. The parameters of total phosphorus and transparency classify the dam in a eutrophic state, while chlorophyll (a) classifies it in a mesotrophic state. Generally, the trophic status of the MBAK dam corresponds to a eutrophic state.

In fact, the trophic status recorded evolves between mesotrophic and eutrophic and seems to be influenced by the filling rate, questioning the importance of the latter in the modification of the water quality and consequently the cost of drinking water treatment to be learned in these similar climatic and hydrological situations.

The seasonal and vertical analysis of the evolution of the different parameters in this dam have allowed to conclude these main characteristics both qualitative and quantitative such as a strong mineralization of the water, a ionic overload (Fe and Mn) coupled with a high phosphate content of the dam were recorded in summer, reduction of dissolved oxygen levels with installation of summer stratification and total anoxia at depth during a certain period of the year in relation to the filling rate, rapid denitrification, favored by a reduction of dissolved oxygen at the surface and at the bottom in the case of a low water mass, contrary to the behavior of the phosphate concentration.

The reduction of the water mass favors a marked increase of phosphate and trace element (iron and manganese) contents resulting from the high sediment release.

The typology and the diagram of the functioning of this dam highlighted by an analysis allowed to approach the model of functioning dominated by the individualization of several qualitative states according to the season and the lateral contributions (winter 2007).

The PCA analysis showed an individualization of two clear groups of seasons, namely winter (H)/spring and summer (E), which have a dominant and determining tendency in view of the importance of changes taking place during the temporal evolution of the seasons. Thus, a correlation with the factor of filling rate, emphasized on the preponderant influence of the latter on the hydro-trophic conditioning of the dam and underlines the interest of monitoring this factor, in order to define a critical threshold that conditions the quality of dam water and its socio-economic impact.

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