Assessment of physico-chemical and biological parameters of Aguelmam Sidi Ali Lake, a threatened Ramsar Site, Morocco

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Abstract. The objective of this work is to study the physicochemical and biological quality of the waters of Aguelmam Sidi Ali from 2015 to 2016. The Kruskal-Wallis nonparametric ANOVA test was used to detect any variability in water temperature, oxygen concentration, pH, electrical conductivity, salinity, turbidity, concentration of solid solvents, ammonia nitrogen, nitric nitrogen, total nitrogen, orthophosphates, total phosphorus, chlorophyll a, b and c and carotenoids between seasons and lake depths. Analysis of variance (ANOVA, Tukey's test) was used to detect any difference in depth determined by Secchi disc. Principal Component Analysis (PCA) was used to describe the relationships between environmental variables and sample distribution. The results showed significant differences ($p<0.05$) between seasons for the majority of variables. All variables tested, except ammonia nitrogen, total nitrogen and carotenoids, differed at least from season to season ($p\leq0.05$). On the other hand, there were statistically significant differences between depths and months for Chl-a and pH, while the values of temperature, dissolved oxygen, and pH differed considerably ($p\leq0.01$) between depths and seasons. The results obtained reveal that the dynamics of the physicochemical and biological parameters of Lake Sidi Ali undergo spatiotemporal variations, which are governed by exogenous (watershed) and endogenous (in the lake) factors.

Key Words: Lake Sidi Ali, Morocco, spatial temporal variability, water quality.

Introduction. Due to the climatic and hydrogeological conditions of Morocco, lentic ecosystems are exposed to high risks of eutrophication. These water bodies are in the majority of the cases built on watersheds subjected to a strong pressure of anthropic origin, particularly agricultural and pastoral activities. They receive large quantities of nutrients from their tributaries, particularly nitrogen and phosphorus, which disturb their ecological balance. The first consequence of this dysfunction is the excessive proliferation of algae and particularly cyanobacteria. Many studies have shown that the biogeochemical composition of these aquatic ecosystems is also influenced by the hydrological and climatic disturbances, which are characterized by the irregularity and the decrease of pluviometry involving the fluctuations of water level, influencing the physicochemical and biological quality of these water bodies (Bahhou 2001; Bouhaddioui 2003; Sadani et al 2004; Etebaai et al 2012). Due to its geographical position, Morocco has been confronted in recent decades with a real rainfall deficit (Sebbar et al 2010; El Ajhar et al 2018), resulting in severe droughts that have had dramatic consequences linked to significant imbalances in water resources, both quantitatively and qualitatively. Morocco is among the richest countries in wetlands. Currently, it has 38 sites classified in the list of RAMSAR sites. The Middle Atlas, oriented from southwest to northeast, is located in central Morocco between the Rif and the High Atlas. It is home to a very large number of wetlands that play crucial hydrological, socio-economic and ecological roles on the national level (Azeroual et al 2000; Chillasse et al 2001; Chillasse & Dakki 2004). Its location in an area with very high rainfall rate gives it the character of a "water tower". It is also characterized by the existence of dozens of lakes (dayets) that base their water supply on the heavy precipitation during wet periods, and snow melting in spring. These lakes are of different origins, and their water supply depends on the position of each lake, either a watershed specific to the lake, or a supply by the rise of the water table. Aguelmam Sidi Ali, of volcanic origin, is part of these lakes. It is located in the middle of a cedar forest in the eastern part of the central Middle Atlas. This lake has been classified as a site of biological and ecological interest since 1996 and as a RAMSAR site in 2005. It is a wintering and resting place for several migratory waterbirds (Chillasse 2004; Khaffou et al 2013). This gives it an international importance. Currently, this lake is confronted with many dysfunctions, mainly manifested by a decrease in water level and ecological disruptions generated by human activities and accentuated by drought (Chillasse & Dakki 2004; Sayad et al 2011; Menjour et al 2016). Thus, it seems that the recourse to a continuous monitoring and the evaluation of the quality of its waters are indispensable tools for the implementation of an integrated protection system and sustainable management of this lake. In this context, the present work aims to characterize the physicochemical and biological quality of Aguelmam Sidi Ali during the hydrological year 2015-2016, a particularly dry period, to highlight the evolution of the trophic status of the lake.

Material and Method

Description of the study site. Aguelmam Sidi Ali is located at an altitude of 2100 m in the central Moroccan Middle Atlas, next to the national road number 13, about 55 km south of the town of Azrou and about 70 km north of the town of Midelt (33°03'N, 5°00'W) (Figure 1).

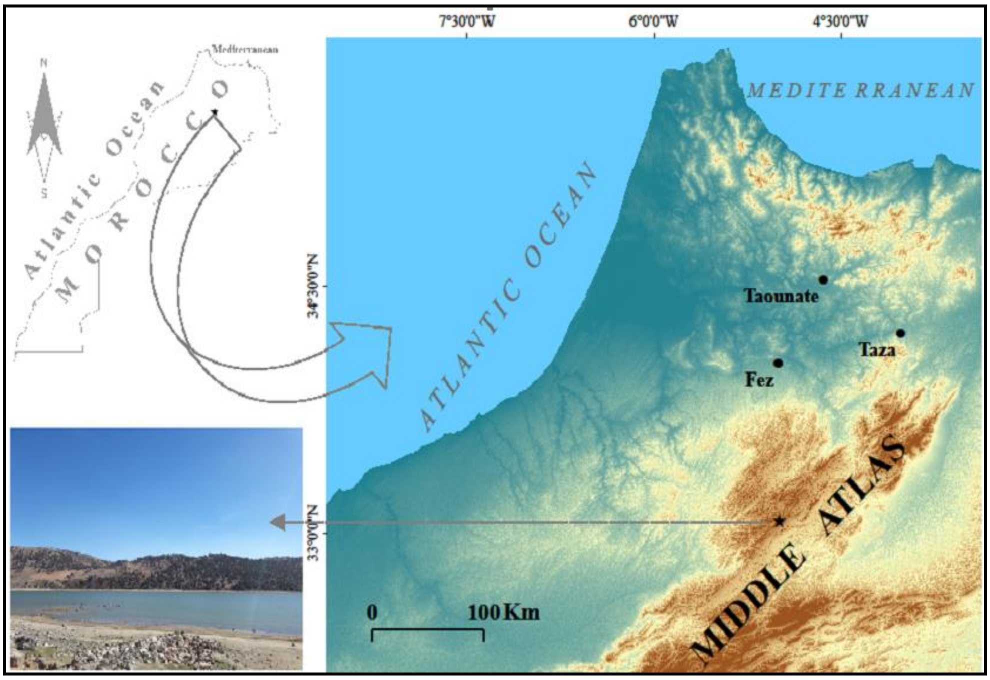

Figure 1. Geographical location of Lake Sidi Ali.

The lake is of volcanic and also karstic origin. It has an average depth of 1.9 m and a maximum depth of 37 m with an area of 300 ha (Martin 1981; Chillasse et al 2001; Chillasse & Dakki 2004). Its watershed is made up of limestone and liasic dolomites, marls, Bajocian limestone, and plio-quaternary basalts (Martin 1981; Baali 1998). It is fed by runoff and karst springs. This wetland is characterized by a subhumid climate with cold winter (Morgan 1982), with an annual precipitation rate that can exceed 500 mm and a snowfall that can be prolonged throughout the year (ABHS 2010).

On the basis of climatic data recovered from the Sebou Hydraulic Basin Agency and collected at the level of the meteorological station of Aguelmam Sidi Ali over a period of 7 years (2006-2013), the area appears to be characterized by a subhumid bioclimate with very cold winters according to the Emberger quotient ($Q2=38.33$), and a dry season that extends from mid-May to September (Khaffou 2014).

Water sampling. The lake studied was the subject of a physicochemical and biological follow-up during a period spanning from November 2015 to November 2016. The water samples were taken at the vertical of the deepest point using the van Dorn bottle. After collection, the samples were placed in polyethylene bottles previously treated according to the Rodier procedure (Rodier et al 2009) and stored in a refrigerated cooler for transportation to the Biotechnology, Conservation and Valorisation of Natural Resources Laboratory, Faculty of Sciences Dhar El Mehraz, Morocco. The sampling was carried out on a bi-monthly frequency at 0 m, 5 m, 10 m, 15 m, 20 m and 25 m depth.

***Physico-chemical and biological analyses of water**.* The physico-chemical analyses were conducted following the standard procedures described by Rodier et al (2009). Parameters measured *in situ* using WTW MultiLine P4 portable equipment included temperature, pH, concentration of solid solvents, electrical conductivity and salinity. The turbidity was measured by means of a turbidimeter LOVIBOND TB 211 IR. Dissolved oxygen (DO) concentration was determined using the Winkler titrimetric method, while ammonium (NH_4^+), nitrate (NO_3^-), total nitrogen, orthophosphate (PO_4^-) and total phosphorus concentrations were determined by spectrophotometry. Quantification of chlorophyll pigments, used to estimate total phytoplankton biomass, was performed using the Lorenzen method (Lorenzen 1967).

***Statistical analysis**.* The distribution of normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene test) were tested for all data obtained. This allowed the selection of appropriate statistical tests. The non-parametric Kruskal-Wallis ANOVA test was used to detect any variability in water temperature, oxygen concentration, pH, electrical conductivity, salinity, carotenoids, and chlorophyll a, b, and c between seasons and lake depths. The same test was used to detect any variability in concentration of solid solvents, ammonia (NH_4^+), nitrate, total nitrogen, orthophosphate, and total phosphorus rates between seasons, while an analysis of variance (ANOVA, Tukey's test) was used to detect any difference in Secchi depth (SD). Sampling months were hierarchically clustered according to the environmental variables studied in the lake water using the Bray-Curtis dissimilarity method.

Principal Component Analysis (PCA) was used to describe the separation of monthly samples during the study period and the distribution of environmental variables. When there were no statistically significant differences for some variables in terms of lake depth, samples for nutrient concentrations were collected from the first three water layers (0, 5, and 10 m). The results obtained for samples taken at these depths were considered reliable for the analyses. All statistical analyses were carried out using R software.

Results and Discussion. The ranges of values of physicochemical parameters obtained during this study are presented in Table 1. An increase in data fluctuation with depth was observed in the majority of parameters. Also, as confirmed by statistical analysis, significant seasonal differences were found for most of the parameters studied. The temperature of the waters of Aguelmam Sidi Ali varies with an amplitude of about 19.6°C passing from 1.6°C in winter to 21.2°C in summer. The homogenization of the waters was spread out from autumn to the end of winter. Following the spring warming of surface waters, a stratification sets in separating a hot epilimnion with a maximum temperature of 21.2°C and a cold hypolimnion with a temperature of 9.8°C.

Table 1

Ranges of values of physico-chemical parameters, minimum-maximum ± standard deviation (SD)

			Study period			
Depth	*WT (°C)*	*DO (mg L^{-1})*	*pH*	*EC (μs cm^{-1})*	*Sal (‰)*	*SSC (g L^{-1})*
0 m	1.6-21.2±6.47	6.32-13.46±1.91	8.32-9.54±0.28	500-1600±266.09	0-0.7±0.17	0.48-0.79±0.09
5 m	1.6-20.4±6.12	6.02-12.24±1.7	8.28-9.51±0.3	500-1600±266.43	0-0.7±0.18	0.5-0.78±0.09
10 m	1.6-19±5.88	5.48-11.42±1.49	8.4-9.5±0.29	500-1500±257.42	0-0.7±0.18	0.48-0.77±0.09
15 m	1.6-15±4.42	3.51-11.39±2.29	8.42-9.42±0.25	500-1600±264.84	0-0.7±0.18	0.48-0.8±0.09
20 m	1.6-12±3.32	1.63-11.4±2.76	8.4-9.38±0.22	500-1500±257.26	0-0.7±0.18	0.48-0.81±0.09
25 m	1.6-9.8±2.67	0-11.36±3.13	8.4-9.24±0.19	500-1500±257.26	0-0.7±0.18	0.48-0.79±0.09
			water column			
Winter	1.6-5±0.8	6.93-11.42±1.65	8.28-9.24±0.29	500-1000±169.72	0-0.5±0.19	0.51-0.62±0.03
Spring	3.5-20±4.21	5.04-13.46±1.89	8.97-9.44±0.13	1100-1250±55.29	0.2-0.7±0.15	0.54-0.81±0.07
Summer	8-21.2±4.02	1.41-10.81±2.94	8.89-9.54±0.2	750-1600±292.86	0.1-0.6±0.18	0.6-0.8±0.06
Autumn	3.4-14.5±3.1	0-9.18±1.92	8.4-9.42±0.25	800-1500±232.67	0.2-0.7±0.14	0.48-0.79±0.09
			Study period			
Depth	*Turb (NTU)*	*A-amm (mg L^{-1})*	*A-nitr (mg L^{-1})*	*Az-Tot (mg L^{-1})*	*Orthoph (mg L^{-1})*	*Ph-Tot (mg L^{-1})*
0 m	0.93-23.8±5.53	0.01-0.18±0.05	0.31-0.84±0.12	0.02-5.45±1.56	0-0.03±0.01	0-0.08±0.02
5 m	1.51-25.8±5.61	0.01-0.2±0.06	0.31-1.91±0.32	0.08-6.79±1.54	0-0.03±0.01	0-0.09±0.02
10 m	1.57-25.2±6.45	0.01-0.28±0.07	0.31-0.91±0.16	0.59-4.33±1.13	0-0.02±0.01	0-0.11±0.02
15 m	1.75-28.3±6.84	0.01-0.19±0.05	0.31-0.84±0.13	0.02-5.37±1.59	0-0.02±0.01	0-0.18±0.04
20 m	1.4-25.4±6.67	0.01-0.38±0.09	0.31-2.49±0.42	0.02-6.07±1.73	0-0.05±0.01	0-0.11±0.02
25 m	1.43-25.3±6.81	0.01-0.71±0.2	0.31-2±0.33	0-5.06±1.51	0-0.04±0.01	0.01-0.18±0.03
			water column			
Winter	2.19-20.3±5.5	0.01-0.24±0.05	0.31-2.49±0.46	0-6.79±1.84	0-0.05±0.01	0-0.11±0.02
Spring	2.21-22±7.65	0.01-0.28±0.09	0.31-0.54±0.06	0.13-5.37±1.48	0-0.01±0	0-0.09±0.02
Summer	0.93-14±3.56	0.01-0.49±0.14	0.31-0.48±0.04	0.02-5.06±1.43	0-0.01±0	0-0.05±0.01
Autumn	3-28±6.81	0.01-0.71±0.16	0.31-0.96±0.18	0-5.59±1.47	0-0.03±0.01	0.01-0.18±0.04

		Study period		
Depth	*Chl-a (μg L^{-1})*	*Chl-b (μg L^{-1})*	*Chl-c (μg L^{-1})*	*Carot (MSPU m^{-3})*
0 m	1.88-26.46±6.79	0-11.02±2.65	0.31-50.12±10.05	3.31-60.23±13.41
5 m	1.43-25.03±6.46	0-9.02±2.06	0-54.12±10.35	1.8-63.13±14.75
10 m	1.49-23.95±6.62	0-8.41±1.98	0-49.18±10.03	1.1-64.72±12.07
15 m	0.89-21.85±4.9	0-22.16±6.25	0.07-42.86±8.35	1.2-51.12±10.81
20 m	0-15±3.98	0-21.62±6.25	0-39.22±8.55	1.3-57.36±11.17
25 m	0-10±2.92	0-8.86±2.04	0-13.21±3.81	1.01-25.07±5.66
		water column		
Winter	0-21.85±5.55	0-20.16±4.68	0.07-27.47±5.84	3.9-28.62±5.25
Spring	0-11.85±3.43	0-22.16±4.56	0.75-13.18±2.83	1.01-28.79±7.18
Summer	1.55-25.41±6.91	0-13.84±2.39	0-23.45±5.08	3.3-37.7±7.86
Autumn	1-26.46±5.75	0-21.62±4.22	0-54.12±13.81	1.1-64.72±18.42

Note: WT - water temperature; DO - dissolved oxygen; EC - ; Sal - salinity; SSC - concentration of solid solvents; Turb - turbidity; A-amm - ammonia; A-nitr - nitrate; Az-Tot - total nitrogen; Orthoph - orthophospate; Ph-Tot - total phosphorous; Chl-a - chlorophyll a; Chl-b - chlorophyll b; Chl-c - chlorophyll c; Carot - carotenoids.

DO showed high concentrations during water mixing, but especially in the epilimnion in spring, where the maximum was 13.46 mg L^{-1}. These values decreased with depth during the stratification period. This decrease continued gradually to reach 0 mg L^{-1} in autumn, at the bottom of the lake. The highest pH values were observed during spring and summer, especially in the surface layers. Conductivity showed homogeneous values throughout the water column. Furthermore, they evolved with time according to an increasing gradient from the winter period to the summer period. The elevated concentrations of ammonia were observed in the hypolimnion during the thermal stratification period. Nitrate concentrations were generally higher than ammonia concentrations (NH_4^+). For total phosphorus, its evolution was relatively homogeneous, with values ranging from 0 to 0.18 mg L^{-1}. During periods of thermal stratification, high concentrations were registered at the bottom of the lake. On the other hand, the lowest concentrations of total phosphorus were observed in the surface layers, where high concentrations of chlorophyll a have been recorded.

The variability of many of the parameters depended on the season. Winter was a season with the most stable water temperature (SD=0.8) and DO (SD=1.65) (Table 1). The highest pH stability (SD=0.13) was observed in the spring, during which chlorophyll a and c also showed fairly low variability.

Statistically significant differences (Kruskal-Wallis and Conover-Iman test, $p<0.05$) between seasons were found for most variables. All the variables tested, with the exception of ammonia, total nitrogen and carotenoids, differed at least from one season to another ($p \leq 0.05$). On the other hand, there were statistically significant differences between depths and months for Chl-a and pH, while the values of temperature, DO, and pH differed considerably ($p \leq 0.01$) between depths and seasons.

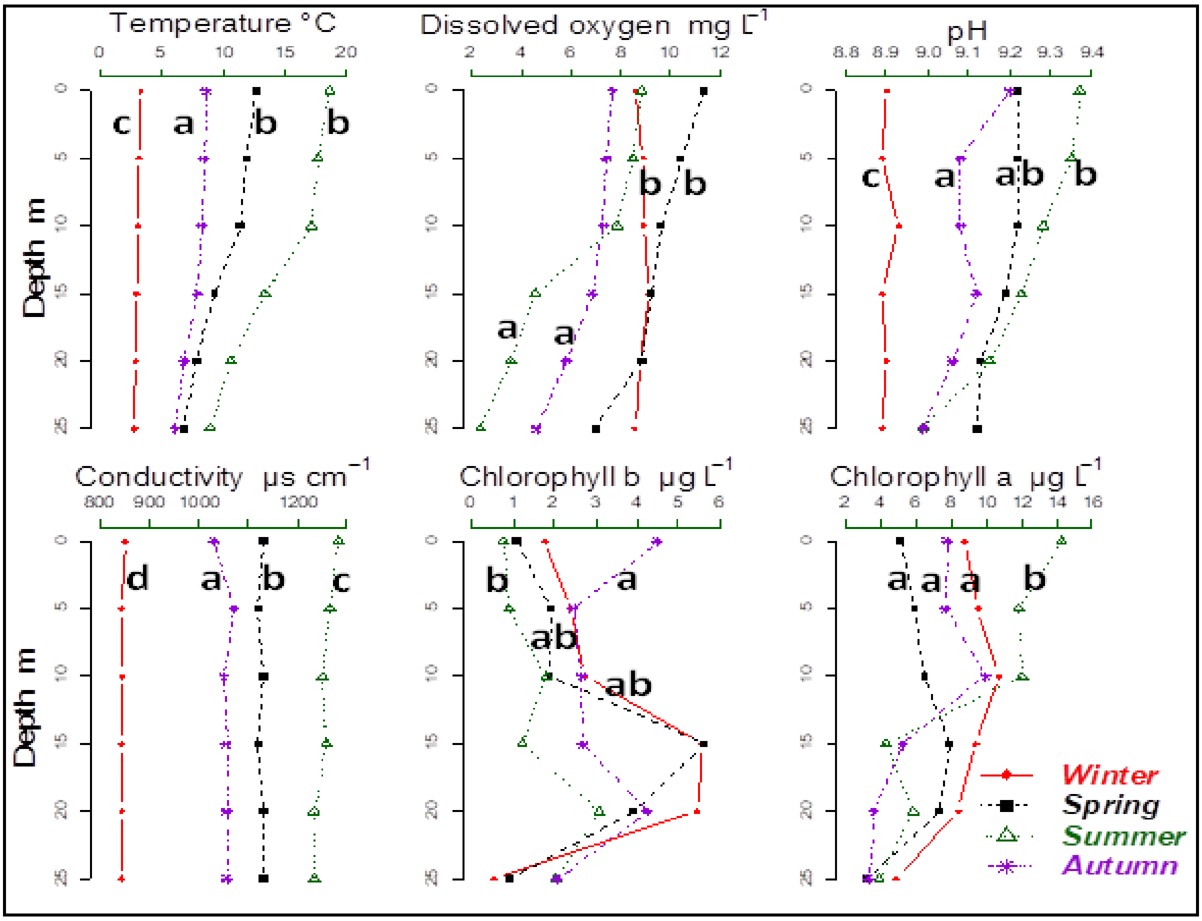

Figure 2. Seasonal changes of some physicochemical and biological parameters of the lake water. Different letters show significant differences ($p<0.05$).

The months were classified according to their environmental similarity by hierarchical clustering using the Bray-Curtis dissimilarity method (Figure 3). The results separate the months into two groups, one representing the hot season with the two driest months (July and August) and the other representing the cold season with two mild months.

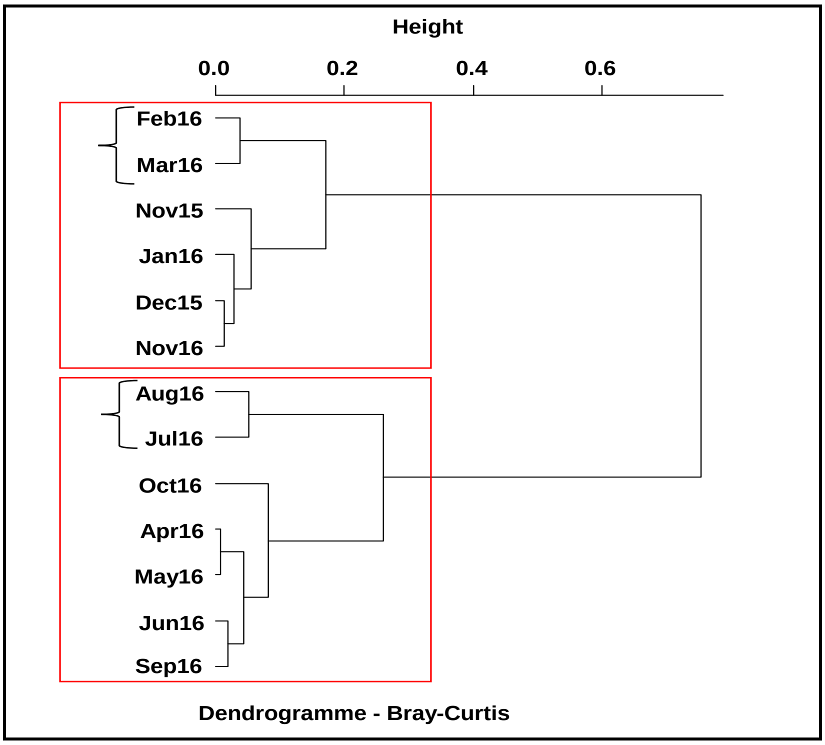

Figure 3. Clustering dendrogram showing the four groups obtained.

The analysis of the environmental parameters in principal components shows that the first two axes F1 and F2 (Figure 4) hold most of the information, since they represent 55.08% of the total inertia. The examination of the correlations between the axes and the different mesological components studied makes it possible to explain the meaning of each axis in the structured distribution of the cloud of months and the relationship between the typological structure and the variables of the environment. The F1 axis (34.44% of total inertia) shows a very good correlation with temperature and DO. The F1 axis expresses a temperature gradient, and separates the months into two groups, a group on the left with low temperatures, and a group on the right with high temperatures. The F2 axis (20.64% of total inertia) is positively correlated with orthophosphate, chlorophyll b and c. It mainly expresses the extremes of the two groups identified on the F1 axis, and separates the cold season into the colder months at the bottom (December and January) and the others at the top (November, February and March). For the dry season, the months are also separated into two sub-groups, one bringing together the two driest and hottest months (July and August), the other the hot and less dry months (April, May, June, September and October).

Principal Component Analysis (PCA) showed that the samples collected during the months of the study were separated into cold winter and hot summer. The analyses showed some differences in the distribution and correlation of variables between months. During the cold period of the study, DO and nitrate were strongly correlated with the winter season. Chlorophyll b, c, carotenoids and conductivity were strongly correlated with the spring and summer seasons.

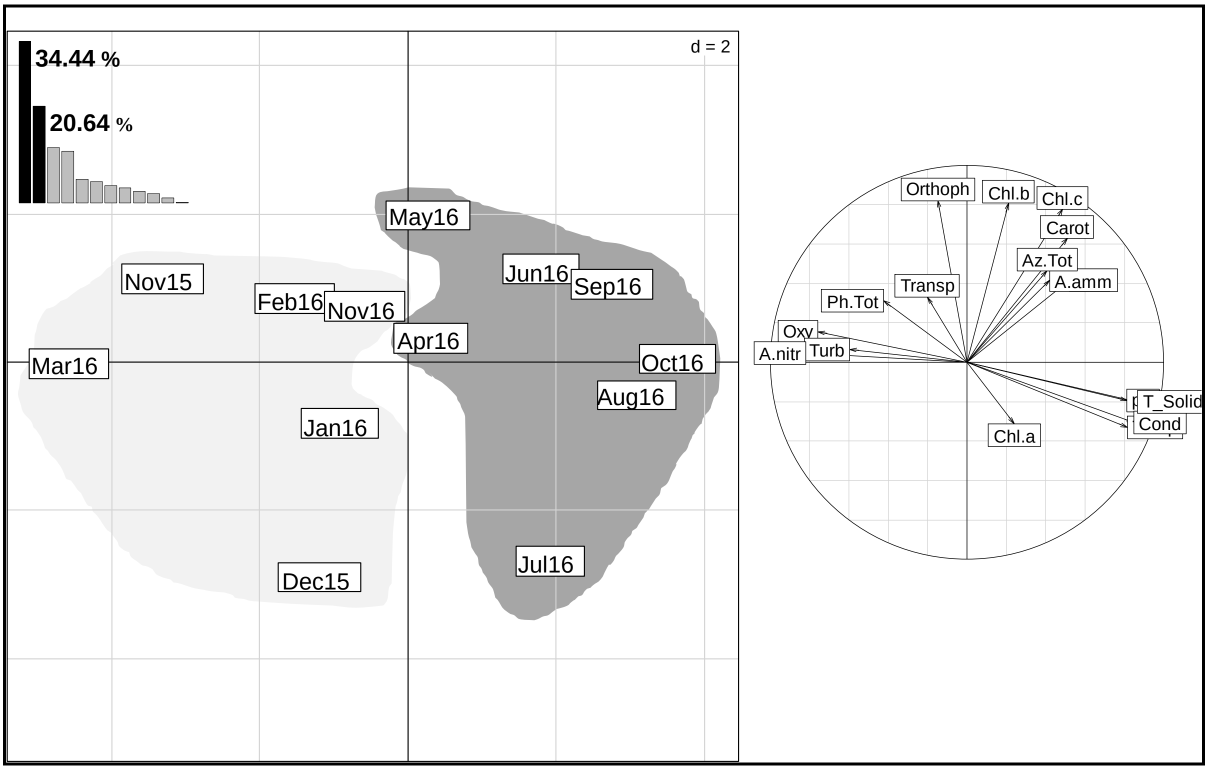

Figure 4. Principal component analysis in the F1-F2 plane presenting the correlation circle of the physico-chemical parameters and the plot of the sampling months.

These results confirmed the results of previous studies (Gayral 1954; Dumont et al 1973; Sadani et al 2004; Etebaai et al 2012), where the watershed, hydrological and climatic conditions influence the majority of limnological variables of the lake. The study on the physico-chemical and biological characterization of the lake Sidi Ali shows that the parameters considered generally vary both in time (seasons) and space (water column). The temperature of the waters of Sidi Ali Lake depends closely on the seasonal variability of the climate, and it is conditioned simultaneously by the morphology of the lake basin and its depth. The thermal regime of the lake was characterized during the study period by a single winter mixing period and a single thermal stratification period. This makes it possible to classify Aguelmam Sidi Ali in the category of monomictic lakes (Lewis 1983; Wetzel 2001).

DO is essential for the maintenance of aquatic life and the self-purification of lakes (Haritash et al 2016; Kumar et al 2018). It depends on many physical, chemical, and biological factors (Ouali et al 2018). The high concentration of DO found in the winter period was the result of the decrease in temperature to which was added the mixing of the waters under the influence of atmospheric disturbances (Belaud 1996; Etebaai et al 2012). While high concentrations of DO found in the surface layers of the waters of Aguelmam Sidi Ali during thermal stratification were due to the strong photosynthetic activity during phytoplanktonic growth. On the other hand, low oxygenation was recorded in the same period at the bottom of the lake. This decrease has been linked not only to increased temperature that limits oxygen solubility, but also to microbial activity that breaks down organic matter at the water column and sediment level (Ahangar et al 2012).

The aquatic alkalinity observed at Aguelmam Sidi Ali could be due to the influence of the dissolution of the geological substrate limestone, dolomitic and basaltic (Sayad et al 2011), and the strong precipitation of carbonates caused by evaporation (Zielhofer et al 2017). The period of winter mixing induced a homogenization of pH throughout the water column. During thermal stratification, the pH of the bottom waters did not show a lowering trend. The temporal variation of pH was marked by an increase in summer, being related to the degassing of waters under the effect of the high phytoplanktonic productivity and the precipitation of carbonate minerals (Bapst 1987; Bouchard 2004; Zeng et al 2019).

As for the electrical conductivity of Aguelmam Sidi Ali, it was generally homogeneous over the entire water column, with high values resulting from the contents of magnesium and bicarbonates, which are the most abundant ions in the lake (Gayral 1954; Zielhofer et al 2017).

The temporal evolution of the conductivity has known the same trend as the pH. It was marked by an increase in the summer. This was due to the predominance of mineralization processes of organic matter and the evaporation of water causing the concentration of alkaline elements. In winter, the conductivity decreased slightly as a result of the contributions of poorly mineralized rainwater, which causes a slight decrease in electrical conductivity.

The increase in nitric nitrogen in the waters of lake Sidi Ali in winter seemed to be linked to the effect of water laden with this element, which enters the lake by the drainage of runoff from the watersheds through precipitation (Ouattara 2000; El Qryefy et al 2021). The low ammonia concentrations (NH_4^+) of Aguelmama Sidi Ali come from the gradual oxidation of this element into nitrites and nitrates, and its preferential consumption compared to nitrates by algae, if the latter have them simultaneously (Galvez-Cloutier et al 2002; Procházková et al 1970; Chahboune et al 2013). In summer, the increase in ammonia from the surface to the bottom was due to the decrease in DO concentrations in the deep layers, which is regularly accompanied by the simultaneous release of ammonia and organic nitrogen from the sediments on the one hand, and the bacterial degradation of organic matter, and, in particular, cyanophyceae on the other hand (Bahhou 2001).

The waters of Aguelmam Sidi Ali are poor in orthophosphates and total phosphorus. Relatively low concentrations in surface water were observed compared to that at the bottom. This would be due to the high consumption by phytoplankton biomass. Previous works by Ravera et al (1986) and Abdellaoui et al (1998) detected this relationship between phosphorus concentrations and plankton flora. According to Pomero et al (1965) and Satpathy et al (2010), the release of phosphorus from sediment by various processes such as phosphorus desorption and the buffering action of sediments under variable environmental conditions, as well as that of bacterial regeneration, were the main factors in the relatively high concentrations observed at the bottom of a lake. For chlorophyll a, the high values recorded in summer were attributed to the increase in the temperature of this period, which affected metabolic activity and accelerated the development of phytoplankton (Khan et al 2012). Based on their physico-chemical and biological characteristics, and the classification recommended by the OECD model (OECD 1982), Aguelmam Sidi Ali can be classified in the category of mesotrophic lakes.

Conclusions. The drop in water levels due to climate change and the succession of drought periods will have negative consequences on the survival and balance of Aguelmam Sidi Ali. An in-depth study over a long period becomes essential in order to be able to highlight the impact of this reduction on the trophic state of this water environment. There is no doubt that the results of this study are incomplete, as they relate to a limited period. However, the data acquired provide a first illustration of the limnological variables during an annual cycle (2015-2016), constituting an important entry in the ecological model for a sustainable management of Aguelmam Sidi Ali, and a basis for comparison with future studies at the level of water dynamism. To fully understand the waters dynamism of the lake, more detailed studies are needed on the phytoplankton composition and the biogeochemical cycle of the sediments.

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Conflict of Interest. The authors declare that there is no conflict of interest.

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