Diagram of the hydro-trophic functioning of dam lakes in Morocco: case of the Bouhouda reservoir (Taounate)

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Abstract. Surface waters in Morocco, particularly dam lakes, are subjected to anthropogenic pressures and increasing climatic hazards, leading to an intensification of eutrophication, often with serious adverse effects on water quality. Our present study focuses on Lake Bouhouda, which is not spared from this type of pollution, a dam that was built on Oued Sra, about 18 km north of the town of Taounate. The application of the Principal Component Analysis (PCA) to understand this type of organic pollution or eutrophication is very interesting. It is in the context of such an application that 24 physico-chemical parameters, from the analysis of 32 water samples collected between March 2000 and April 2008, were studied. Axis F1 summarizes 21.42% of the information; it is representative of the variables related to seasonality. The F2 axis summarizes 16.82% of the information and it describes the gradient of mineralization, which is very particular during the winter seasons. The results obtained reveal a correlation between different indicators of eutrophication that allow the explanation of this pollution evolution. Also, this data processing methodology allows identifying the potentially interesting variables for the mathematical modeling which is used to predict the trophic state of the waters of Lake Bouhouda during future work.

Key Words: Bouhouda, eutrophication, PCA, physico-chemical parameters.

Introduction. Continental aquatic environments provide a variety of ecosystem goods and services that have an irreplaceable economic value (Gleick 1993; Oluduro & Aderiye 2007; Makhoukh et al 2011). Socio-economic development and rapid urbanization have had a negative impact on the quality of these water resources, sometimes affecting dam water quality (Kazi et al 2009; Allalgua et al 2017). Continental waters such as dam lakes attract and concentrate many populations whose activities are the source of stress for these ecosystems and, in particular, their eutrophication (Devidal et al 2007; Florence et al 2018). The lakes of the Mediterranean rim, and, in particular, those of North Africa, also suffer from this eutrophication phenomenon (Akogbeto et al 2018), resulting at the same time from natural constraints (precipitations, flows, siltation) and anthropic constraints (samplings, rejections) (El Ghachtoul et al 2005; Daeden 2015; Tremblay & Pienitz 2015). This degradation has had consequences for the economic development of several regions around the globe (Alayat et al 2013; Aumont 2016). Eutrophication is an organic pollution that has long been a problem for water managers and researchers, and one of their main tasks has been to identify the symptoms of this multifaceted pathology in aquatic environments (Pinay et al 2017; Douguet & Terreaux 2017). Eutrophication results from an increase in the fertilization of lake water by a nutrient supply, which promotes the proliferation of phytoplankton and aquatic plants. Gradually, this process accelerates sedimentation: the lake narrows, fills and eventually disappears (Ramade 2005).

In Morocco, a country with a semi-arid climate, the supply of drinking water and industrial water is mainly provided by surface water (Mehanned et al 2014). Therefore, the improvement of the quality of surface water is a general objective, especially the waters of dams intended mainly for the production of drinking water in several regions of the territory (Laouina 2006). As a result, water quality monitoring systems are essential to the success of management programs and the restoration of these aquatic environments. Reliable data, measured continuously over long periods of time, are needed to determine the trophic status of water resources, to implement effective conservation and rehabilitation programs, and to properly assess their performance (Dion 2009). To better understand the eutrophication process, it is important to study the link between the evolution of the associated environmental variables and the hydro-trophic dynamics (Sadat et al 2011).

In this perspective, an overall analysis of different parameters recorded in this lake during an eight-year follow-up, based on multivariate methods, was necessary to better identify the correlations between the variables and to determine the factors that condition their hydro-trophic dynamics in this lake.

Material and Method

***Description of the study site*.** The Bouhouda Lake is formed by a dam erected in 1999 on Oued Sra, tributary to the right bank of the Wadi Ouergha, about 18 km north of the city of Taounate (Figure 1). The structure is located in a region where geological formations limit the potential for storing underground water, despite the importance of rainfall (Jaouda et al 2018).

This roller-compacted concrete dam with a capacity of 55 Mm^3 is intended for irrigation of a perimeter of about 3000 ha and for drinking water supply until 2020 in the center of Bouhouda (3000 inhabitants) and 24 other nearby douars, with a total population of 2200 inhabitants. This work makes it possible to provide supplementary irrigation during long dry periods (from May to October) and, exceptionally, during years of drought (Ministry of Town Planning and Urban Planning 2014).

The climate of the study area is a warm semi-arid Mediterranean climate, where the seasonal contrasts are well accentuated, with a wet period and a dry period. The precipitations range from 350 to 600 mm and the temperatures oscillate between a minimum of 12.5 °C and a maximum of 37°C.

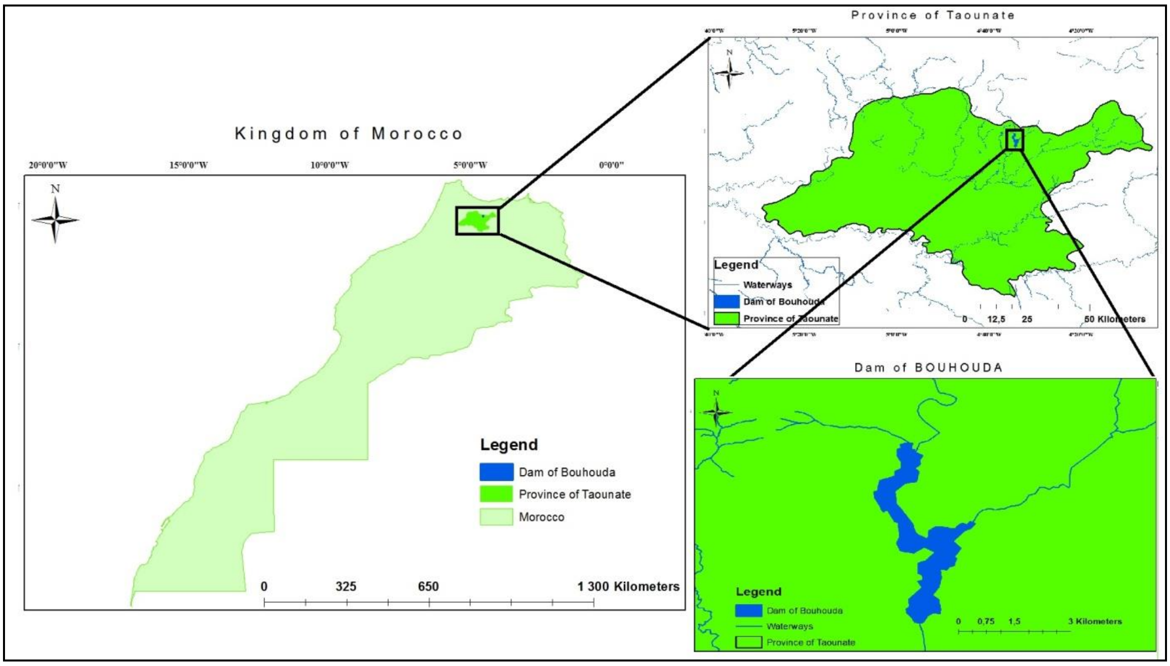

Figure 1. The geographical location of Bouhouda Lake.

Database. The database consists of 106 surveys conducted between 2000 and 2008 for the monitoring and analysis of 24 variables, which are: water supply (AppE), water temperature (Te), air temperature (Ta), pH, dissolved oxygen (O_2), oxidability (oxid), turbidity (Tur), dry residues (Rsec), suspended solids (MES), conductivity (Cond), ammonia nitrogen (NH_4^+), Kjeldal nitrogen (Nk), nitrates (NO_3^-), ortho-phosphates (PO_4^{3-}), total phosphorus (PT), iron (Fe), manganese (Mn), chlorides (Cl^-), sulphates (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium hardness (Ca^{2+}), magnesium (Mg^{2+}), chlorophyll a (Chla), and transparency (Tr).

Analyzes were carried out within the framework of an agreement between ONEP (ONEP 1996), the scientific institute of Rabat and Biodiversity consulting. The statistical software XLSTAT 2018 was used for data processing and for carrying out the PCA for the 24 variables studied in Bouhouda lake. PCA is one of the techniques whose advantage is to identify and link the different factors (or sources) to effects observed in aquatic systems. It belongs to water resource management tools allowing rapid solutions to pollution problems (Felipe-Sotelo et al 2007; Menció & Mas-Pla 2008; Ouyang 2005; Shrestha & Kazama 2007; Swaine et al 2006; Vega et al 1998).

Results and Discussion. The data obtained were processed by a statistical method (PCA) which is part of the multivariate descriptive analyses and which is widely used to interpret hydrochemical data (Abrid 2015; Toumi et al 2016). It allows analyzing tables of quantitative numerical data in order to reduce their dimensionality by constructing a new set of synthetic variables using the initial variables obtained by the matrix of bivariate correlations diagonalization (Guerrien 2003; Simenov et al 2003).

The correlation matrix obtained gives a first idea of the existing associations between the different variables such as MES and iron ($R^2=0.42$), turbidity and suspended solids ($R^2=0.34$), electrical conductivity and sodium ($R^2=0.74$). These parameters are relatively well correlated with each other (Table 1). Eigenvalues are used to measure the percentage of the variance explained by each factor. Table 1 summarizes the correlations between the various remaining variables.

The histogram of the eigenvalues shows that the first factorial plane, consisting of the axes F1 and F2, represents 38.24% of the variability and all the parameters are well represented in the plane 1-2, which means that the first two axes are sufficient to represent the information as a whole (Figure 2).

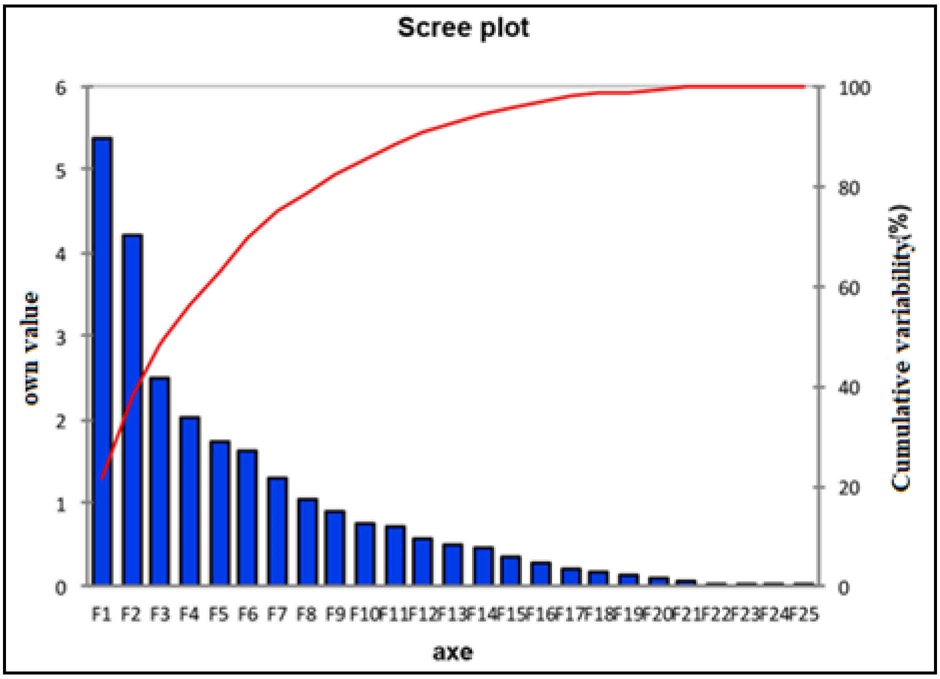

Figure 2. Distribution of the inertia between the axes.

Table 1

Correlation matrix between variables

	App E	Ta	Te	pH	O_2	Oxid	Tur	Rsec	MES	Cond	NH_4^+	NK	$NO3^-$	PO_4^{3-}	PT	Fe	Mn	Cl^-	$SO4^{2-}$	Na^+	K^+	Ca^{2+}	Mg^{2+}	Chl a	Tr
App E	1.00	0.18	0.34	0.16	0.00	0.04	0.25	0.01	0.11	0.01	0.03	0.03	0.07	0.00	0.04	0.38	0.00	0.00	0.22	0.02	0.01	0.03	0.04	0.04	0.25
Ta	0.18	1.00	0.67	0.21	0.04	0.04	0.17	0.00	0.10	0.01	0.04	0.02	0.16	0.00	0.01	0.12	0.01	0.01	0.10	0.01	0.07	0.14	0.01	0.08	0.28
Te	0.34	0.67	1.00	0.29	0.02	0.02	0.20	0.03	0.17	0.02	0.03	0.01	0.18	0.00	0.01	0.19	0.06	0.03	0.20	0.00	0.05	0.27	0.00	0.04	0.20
Ph	0.16	0.21	0.29	1.00	0.02	0.02	0.10	0.06	0.11	0.18	0.15	0.00	0.06	0.00	0.01	0.07	0.10	0.15	0.07	0.02	0.06	0.35	0.02	0.00	0.21
O_2	0.00	0.04	0.02	0.02	1.00	0.06	0.00	0.03	0.00	0.09	0.04	0.07	0.00	0.01	0.01	0.01	0.13	0.13	0.13	0.16	0.09	0.01	0.03	0.01	0.02
Oxid	0.04	0.04	0.02	0.02	0.06	1.00	0.05	0.02	0.01	0.00	0.23	0.05	0.02	0.00	0.00	0.08	0.01	0.05	0.02	0.00	0.00	0.00	0.03	0.01	0.04
Tur	0.25	0.17	0.20	0.10	0.00	0.05	1.00	0.00	0.34	0.05	0.00	0.03	0.00	0.02	0.00	0.15	0.00	0.04	0.10	0.07	0.04	0.00	0.01	0.05	0.30
Rsec	0.01	0.00	0.03	0.06	0.03	0.02	0.00	1.00	0.03	0.29	0.00	0.03	0.00	0.05	0.26	0.02	0.20	0.31	0.01	0.17	0.01	0.20	0.00	0.02	0.01
MES	0.11	0.10	0.17	0.11	0.00	0.01	0.34	0.03	1.00	0.02	0.00	0.05	0.01	0.03	0.03	0.42	0.00	0.09	0.01	0.09	0.02	0.02	0.00	0.07	0.13
Cond	0.01	0.01	0.02	0.18	0.09	0.00	0.05	0.29	0.02	1.00	0.09	0.02	0.07	0.00	0.01	0.06	0.57	0.24	0.02	0.74	0.02	0.48	0.00	0.01	0.01
NH_4^+	0.03	0.04	0.03	0.15	0.04	0.23	0.00	0.00	0.00	0.09	1.00	0.07	0.09	0.01	0.01	0.02	0.11	0.06	0.11	0.09	0.00	0.04	0.10	0.04	0.03
NK	0.03	0.02	0.01	0.00	0.07	0.05	0.03	0.03	0.05	0.02	0.07	1.00	0.00	0.01	0.03	0.01	0.00	0.08	0.02	0.08	0.20	0.01	0.15	0.05	0.07
NO_3^-	0.07	0.16	0.18	0.06	0.00	0.02	0.00	0.00	0.01	0.07	0.09	0.00	1.00	0.01	0.03	0.00	0.03	0.00	0.02	0.03	0.07	0.18	0.00	0.14	0.01
PO_4^{3-}	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.05	0.03	0.00	0.01	0.01	0.01	1.00	0.01	0.02	0.00	0.01	0.05	0.00	0.02	0.00	0.01	0.02	0.01
PT	0.04	0.01	0.01	0.01	0.01	0.00	0.00	0.26	0.03	0.01	0.01	0.03	0.03	0.01	1.00	0.01	0.01	0.01	0.02	0.02	0.01	0.00	0.02	0.10	0.02
Fe	0.38	0.12	0.19	0.07	0.01	0.08	0.15	0.02	0.42	0.06	0.02	0.01	0.00	0.02	0.01	1.00	0.02	0.09	0.18	0.04	0.00	0.00	0.02	0.00	0.12
Mn	0.00	0.01	0.06	0.10	0.13	0.01	0.00	0.20	0.00	0.57	0.11	0.00	0.03	0.00	0.01	0.02	1.00	0.31	0.00	0.56	0.01	0.30	0.02	0.00	0.00
Cl^-	0.00	0.01	0.03	0.15	0.13	0.05	0.04	0.31	0.09	0.24	0.06	0.08	0.00	0.01	0.01	0.09	0.31	1.00	0.02	0.21	0.03	0.10	0.01	0.05	0.04
$SO4^{2-}$	0.22	0.10	0.20	0.07	0.13	0.02	0.10	0.01	0.01	0.02	0.11	0.02	0.02	0.05	0.02	0.18	0.00	0.02	1.00	0.00	0.00	0.00	0.00	0.03	0.06
Na^+	0.02	0.01	0.00	0.02	0.16	0.00	0.07	0.17	0.09	0.74	0.09	0.08	0.03	0.00	0.02	0.04	0.56	0.21	0.00	1.00	0.01	0.24	0.02	0.02	0.05
K^+	0.01	0.07	0.05	0.06	0.09	0.00	0.04	0.01	0.02	0.02	0.00	0.20	0.07	0.02	0.01	0.00	0.01	0.03	0.00	0.01	1.00	0.11	0.02	0.01	0.00
Ca^{2+}	0.03	0.14	0.27	0.35	0.01	0.00	0.00	0.20	0.02	0.48	0.04	0.01	0.18	0.00	0.00	0.00	0.30	0.10	0.00	0.24	0.11	1.00	0.00	0.00	0.00
Mg^{2+}	0.04	0.01	0.00	0.02	0.03	0.03	0.01	0.00	0.00	0.00	0.10	0.15	0.00	0.01	0.02	0.02	0.02	0.01	0.00	0.02	0.02	0.00	1.00	0.01	0.12
Chl a	0.04	0.08	0.04	0.00	0.01	0.01	0.05	0.02	0.07	0.01	0.04	0.05	0.14	0.02	0.10	0.00	0.00	0.05	0.03	0.02	0.01	0.00	0.01	1.00	0.04
Tr	0.25	0.28	0.20	0.21	0.02	0.04	0.30	0.01	0.13	0.01	0.03	0.07	0.01	0.01	0.02	0.12	0.00	0.04	0.06	0.05	0.00	0.00	0.12	0.04	1.00

Note: water supply (AppE), water temperature (Te), air temperature (Ta), pH, dissolved oxygen (O_2), oxidability (oxid), turbidity (Tur), dry residues (Rsec), suspended solids (MES), conductivity (Cond), ammonia nitrogen (NH_4^+), Kjeldal nitrogen (Nk), nitrates (NO_3^-), ortho-phosphates (PO_4^{3-}), total phosphorus (PT), iron (Fe), manganese (Mn), chlorides (Cl^-), sulphates (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium hardness (Ca^{2+}), magnesium (Mg^{2+}), chlorophyll a (Chla), and transparency (Tr).

The graphs derived from multivariate analysis highlight groupings, oppositions and directional trends (Figure 3). The component C1 expresses 21.42% of the variance; it is correlated on the positive side with the water temperature (0.68%) and the pH (0.56%), and on the negative side with the water inflow (0.41%). Component C2, which expresses 16.82% of the variance, is positively related to conductivity (0.77%), Mn (0.49%), and Na^+ (0.76%) (Figure 3).

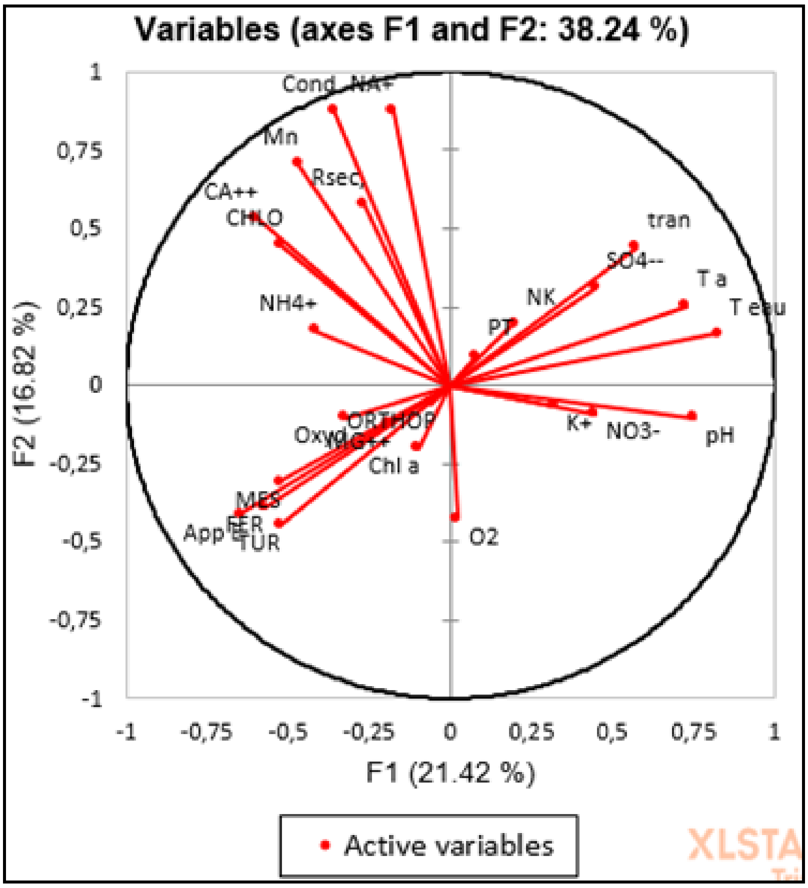

Figure 3. Circles of correlation of the variables. Notations: water supply (AppE), water temperature (Te), air temperature (Ta), pH, dissolved oxygen (O2), oxidability (oxid), turbidity (Tur), dry residues (Rsec), suspended solids (MES), conductivity (Cond), ammonia nitrogen (NH4+), Kjeldal nitrogen (Nk), nitrates (NO3−), ortho-phosphates (PO43−), total phosphorus (PT), iron (Fe), manganese (Mn), chlorides (Cl-), sulphates (SO_4^{2-}), sodium (Na+), potassium (K+), calcium hardness (Ca2+), magnesium (Mg2+), chlorophyll a (Chla), and transparency (Tr).

The correlation circle illustrating the distribution of variables (Figure 3) along the two axes F1 and F2 defines a spatio-temporal typology, determining the hydro-trophic progression of the lake (Figure 4).

The 1x2 plan makes it possible to visualize a typology that characterizes the hydrotrophic functioning of this dam lake, since it defines a seasonal gradient where we observe a succession of seasons defining two poles along this gradient (Figure 4). An autumn-summer pole characterized by low water inputs, negligible mineralization, with a hot summer and an alkaline pH; as for autumn, it is rich in nutrients such as PT, NK and NO_3^-. The winter-spring pole is represented by two stable states: a spring characterized by an enrichment in dissolved mineral elements such as Na^+ and Ca^{2+} and an acidic pH, and another state distinct by a strong solid charge dominated by the MES, Fe, an alkaline pH, which corresponds to a wet winter where very abundant water supplies have been recorded, responsible for a major sedimentation of MES and terrigenous iron; the result is the high turbidity noted during this season.

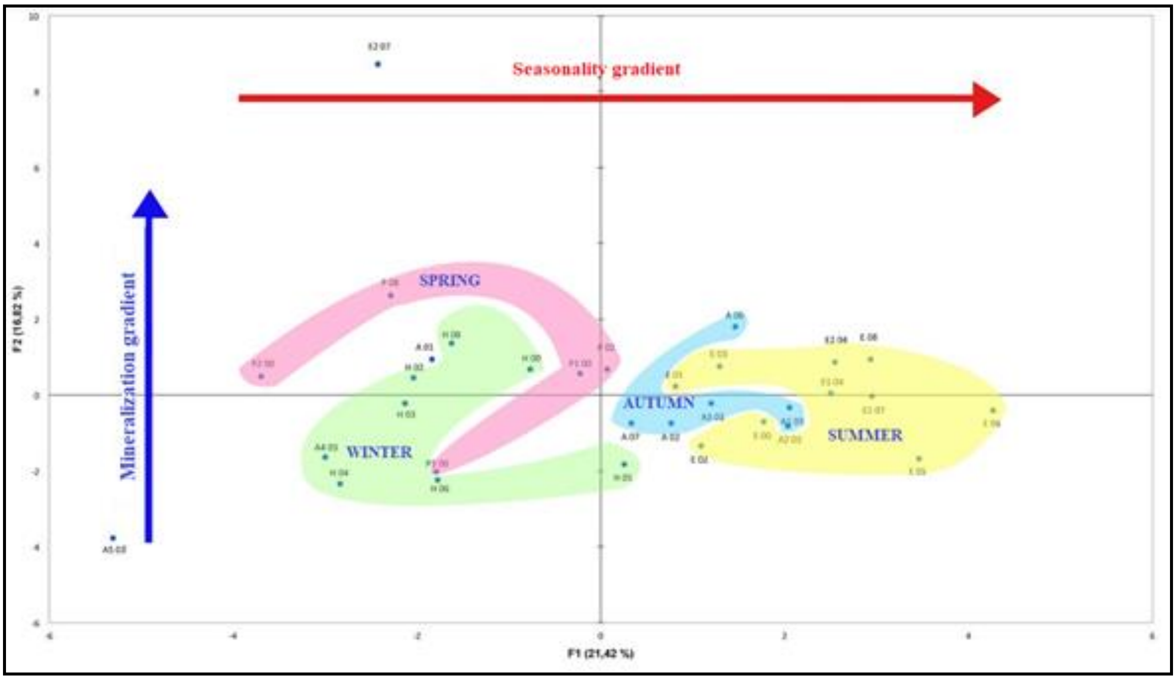

Figure 4. Factorial map of the campaigns.

The well mineralized fresh waters of Lake Bouhouda are poor in dissolved oxygen. The degradation of the biomass and the high temperatures significantly affect the quantity of dissolved oxygen, which intensifies the degree of eutrophication. This study further confirms the role of water supply in the conditioning of the water quality of lakes, since these liquid inputs increase the turbidity of the environment and thus limit planktonic development. Therefore, the evolution of the trophic state of Lake Bouhouda seems to be mainly determined by the fluctuations of the climatic conditions in a country with arid climate, similarly to several dams in Morocco, like Sehla, Smir (El Ehachtoul et al 2005), and El kanssra (Berrada et al 2000).

This study also shows the importance and the usefulness of multivariate analysis techniques as a reliable approach to obtain information on the spatio-temporal variability of the trophic state and to identify the variables that condition this state. Indeed, PCA made it possible to identify a typology dominated by four seasons and to retain key environmental variables that condition the eutrophication of lakes, such as: Te, pH, Ta, Tr, TUR, MES, and water supplies, as presented in other several studies (Cherbi et al 2008; Bouzid-Lagha & Djelita 2012; Htiti et al 2015; Mouissi & Alayat 2016).

Conclusions. The approach used in analyzing the hydro-trophic state of the Bouhouda Lake highlighted by a multivariate analysis made it possible to understand the functioning of this lake and the various factors conditioning its trophic state evolution. Thus, the physical and chemical parameters confrontation allowed the identification of a seasonality gradient with a state dominated by two phases: a spring mineral phase and a winter solid phase, opposed to a state where a nutrient-rich autumn is observed and a hot summer with alkaline pH is noted. These results further confirm the role of climate variations in the conditioning of the dam water quality and emphasize the importance of using computer tools capable of providing the necessary information to explain the major trophic trends in dam lakes. This study can also be useful for future work monitoring these ecosystems for the purpose of restoration in order to preserve biodiversity and to guarantee the survival of the population that economically depends on it.

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