PAN
POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2022.141572
2022, No. 54 (VII–IX): 194–200

Salinisation process of Lake Sidi Boughaba, Kenitra, North Western, Morocco: A statistical approach

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RECEIVED 21.11.2020 ACCEPTED 18.09.2021 AVAILABLE ONLINE 28.09.2022

Abstract: In order to determine the nature of the high salinisation rate of the waters of Lake Sidi Boughaba, which has been listed in the Ramsar list since 1980, 23 samples that were taken during four sampling operations were subjected to physicochemical analyses. The obtained results were processed using a combination of bi-varied methods (correlation tests) and multivariate statistical methods (principal component analysis – PCA). The physicochemical analyses reveal that they are alkaline waters with a pH ranging between 8.38 and 9.03, an electrical conductivity (*EC*) of the order of 12.4 to 17.4 $mS \cdot cm^{-1}$, and high levels of Na^+ and Cl^-, up to 3700 and 6630 $mg \cdot dm^{-3}$ respectively, indicating a marine origin of these waters. In addition, the statistical treatment revealed that the mineralisation of the waters of this ecosystem is controlled by four main mechanisms of the salinisation; the main mechanism underlying this strong mineralisation is due to the impact of the marine spray. The second-order processes are about the phenomenon of the ion exchange, the dissolution/precipitation of evaporitic and carbonate formations, the oxidation–reduction processes, notably the reduction of sulphates as well as biochemical phenomena due to the selective absorption of certain ions by fauna and flora.

Keywords: Kenitra, marine aerosols, Morocco, salinisation, Sidi Boughaba Lake

INTRODUCTION

Salinisation is one of the leading causes of water quality degradation in the world [Vengosh 2003]. In the marine domain, marine intrusion is one of the most common salinisation mechanisms affecting coastal water quality [Jones *et al.* 1999]. However, the sea spray that is a kind of aerosol removed by the wind at the crest of the waves, in turn, constitutes a potential natural source of salinisation for coastal waters [Younsi 2001]. In Morocco, the conditions of the arid climate and their hydrological consequences are the fundamental factors behind the formation of salty waters. The salinity of the waters of Sidi Boughaba Lake and the overlying groundwater have been the subject of a number of previous studies to explain the origin, causes, and the evolution of this phenomenon [Ben Kabbour 2002; Margat 1961; Ramdani 1981; Zouhri *et al.* 2010]. The classic approach to interpreting hydrochemical variables is limited to analysing hydrochemical processes and classifying hydrochemical facies using various graphic methods. In contrast, multivariate statistical techniques are the best and, most often, the only effective solution for analysing a large body of information generated from hydrochemical data [Join *et al.* 1997]. In this respect, principal component analysis (PCA) was performed to better constrain the interpretation of data using the XLSTAT 2019 statistical analysis software.

MATERIALS AND METHODS

SITE DESCRIPTION

The Sidi Boughaba reserve occupies a coastal interdune basin of 6 km long and 300–800 m wide parallel to the Atlantic coast, over an area of 650 ha. It consists of a succession of dunes oriented from N–NE to S–SW (Fig. 1) separated in the middle by a depression occupied by a lake [Cherkaoui, Bouchafra 2003]. The formation of this lacustrine environment dates back to 6520 ±110 before present [Reille 1979]. This age corresponds to the Mellahian phase of the Moroccan Quaternary (Flanders of Europe) [Atbib 1983]. The southern part is locally colonised by chenopods. The dune ridges bordering the water body are occupied by *Eucalyptus* sp., *Juniperus phoenicea*, *Pistacia lentiscus*, *Retama monosperma*, *Populus alba*, *Phillyrea angustifolia*, *Chamaerops humilis*, *Tamarix gallica* and *Olea europaea* are relatively undisturbed [Ramdani *et al.* 2001]. The climate of this area is characterised by the influence of the Atlantic Ocean. The rainfall pattern is characterised by a seasonal distribution of precipitation. The annual average rainfall height is 557.2 mm. The average levels of temperature in August and January are approximately 23.8 and 12.2°C, respectively. Weak white frosts can occur in winter. The annual mean evapotranspiration value is 837.11 mm. It is greater than the precipitation value [Belghazi, Mounir 2016; Najy *et al.* 2021]. The lake is fed mainly by the water table [Cherkaoui, Bouchafra 2003]. Its water is brackish with salinity ranging from 3 to 27 g·dm^{-3} depending on the season [Lachhab *et al.* 2013].

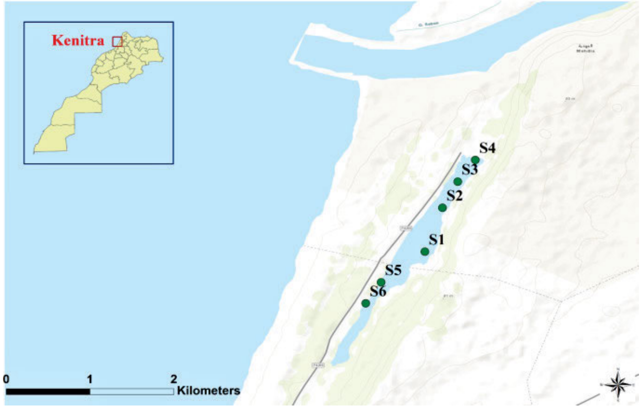

Fig. 1. Descriptive map of the Lake Sidi Boughaba wetland; source: own elaboration

SAMPLING AND ANALYSIS METHODS

The data presented in this study come from four water sampling campaigns carried out on six stations from July, 2009 to May, 2010 (Tab. 1).

Table 1. Description of sampling stations

Station	Description
S1	located in the north of the permanent part
S2	located in the middle of the permanent part
S3	located in the south of the permanent part
S4	located in the northern part of the lake and separated from the permanent water body by a road that leads back to the center of education
S5	located at the south end of the lake in a semi-permanent biotope
S6	located outside the reserve in a temporary biotope

Source: own elaboration.

The samples were filtered through a 0.45 μm filter and were collected in polyethylene bottles with a capacity of 2 dm^3 without air bubbles, and those for cation determination were acidified using nitric acid to prevent adsorption and precipitation of the chemical elements and were stored in portable coolers (+4°C) [Rodier 2009]. Then, they were analysed on their arrival at the National Institute of Hygiene's (INH) (Fr. Institut National d'Hygiène) hydrology laboratory in Rabat. The analyses of various physicochemical parameters were carried out according to the method described by Rodier [2009]. Reaction (pH), temperature (*T*), dissolved oxygen (*DO*), electrical conductivity (*EC*) and were total dissolved solids (*TDS*) measured *in situ* by the use of a portable pH meter, type (WTW pH 330i/SET), thermometer incorporated in the pH meter, Orion Model 607A Oximeter, Portable Conductivity Meter, type (WTWcond330i/SET) and salinometer incorporated in the conductivity meter. Furthermore, the major cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) were determined by the VARIAN atomic absorption spectrophotometer model, the two anions (Cl^- and SO_4^{2-}) were measured by Dionex 2000 ionic chromatography, the biological oxygen demand (BOD_5) by BOD meter, the total alkalinity (*TA*) and bicarbonates (HCO_3^-) with a volumetric dosing of 0.1 N HCl and colour by Nessleriser Comparator.

STATISTICAL METHODS OF DATA PROCESSING

The classical approach to the interpretation of hydrochemical variables considers hydrochemical variables as limited to interpreting hydrochemical processes and classifying hydrochemical facies using various graphical methods [Aboubakar 2012]. Multivariate statistical techniques such as principal component analysis are better and often the only effective solution for analysing a large mass of information [Join *et al.* 1997].

Principal component analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of uncorrelated variables called principal components [Qin *et al.* 2013]. It reduces a large number of variables to a small number of main components by linearly combining measurements made on the original variables [Guler *et al.* 2012]. The first step is to calculate the correlation coefficients between the variables. Subsequently, the projection axes are assimilated to the eigenvectors of the correlation matrix [Ben Alaya *et al.* 2014]. The number of components to be extracted is determined by the variance accumulation test commonly called "Scree test", where the extraction of the components at the location of the slope change in the eigenvalue graph [Aw *et al.* 2011]. This statistical technique has been widely applied to investigate environmental phenomena and hydrogeochemical processes around the world [Aw *et al.* 2011; Ben Alaya *et al.* 2014; Eblin *et al.* 2014; Mouissi, Alayat 2016; Reggam *et al.* 2015] and in Morocco [El Yaouti *et al.* 2009; Fadili *et al.* 2015; Najib *et al.* 2016; 2017].

The PCA has 6 descriptors and 15 variables which are: *EC*, pH, *T*, *DO*, *TA*, colour, BOD_5, *TDS*, and ions such as HCO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, Ca^{2+} and Mg^{2+}. It was carried out by using the software XLSTAT 2019. The combination of all the methods used in this study makes it possible to know the origin of the salinisation process of the Sidi Boughaba Lake waters.

RESULTS AND DISCUSSION

DESCRIPTIVE STATISTICS

The results of physicochemical analyses carried out on the waters of Sidi Boughaba Lake (Tab. 2) reveal that the *T* varies between 19.46 and 21.55°C, with an average of 21.04 ±0.78°C. The pH values are ranging between 8.38 and 9.03, with an average of 8.72 ±0.3. The *EC* ranges from 12.4 to 17.4 mS·cm^{-1}, with an average value of 14.12 ±2.19 mS·cm^{-1}.

Table 2. Descriptive statistics of the physicochemical parameters of the waters of the Lake Sidi Boughaba

Parameter	Unit	Value			
		min.	max.	mean ±*SD*	*CV*
T	°C	19.46	21.55	21.04 ±0.78	0.04
DO	mg·dm^{-3}	4.81	8.58	6.86 ±1.28	0.19
pH	pH unit	8.38	9.03	8.72 ±0.30	0.03
EC	mS·cm^{-1}	12.4	17.4	14.12 ±2.19	0.16
Colour	mg Pt·dm^{-3}	71.25	475.00	141.60 ±163.41	1.15
TDS	g·dm^{-3}	7.59	11.23	8.91 ±1.62	0.18
BOD_5	mg·dm^{-3}	5.00	7.50	6.21 ±1.05	0.17
TA	meq·dm^{-3}	5.12	18.29	8.29 ±4.95	0.60
Na^+	mg·dm^{-3}	2526	3700	3019.67 ±506.72	0.17
Ca^{2+}	mg·dm^{-3}	46.69	163.2	97.47 ±49.47	0.51
Mg^{2+}	mg·dm^{-3}	271.33	485.05	340.50 ±81.72	0.24
K^+	mg·dm^{-3}	38.64	57.66	45.72 ±7.27	0.16
Cl^-	mg·dm^{-3}	5007	6630	5595.00 ±678.12	0.12
SO_4^{2-}	mg·dm^{-3}	139.95	1091.07	502.79 ±397.60	0.79
HCO_3^-	mg·dm^{-3}	303.18	1001.96	484.86 ±257.82	0.53

Explanations: *SD* = standard deviation, *CV* = coefficient of variation, *T* = temperature, *DO* = dissolved oxygen, *EC* = electrical conductivity, *TDS* = total dissolved solids, BOD_5 = biological oxygen demand, *TA* = total alkalinity.
Source: own study.

DO levels range from 4.81 to 8.58 mg·dm^{-3}, which is considered as an average of 6.86 ±1.28 mg·dm^{-3}. The *TDS* rate varies between 7.59 and 11.23 g·dm^{-3}, which is considered an average of 8.91 ±1.62 g·dm^{-3}. The BOD_5 has a minimum of 5 mg·dm^{-3} and a maximum of 7.5 mg·dm^{-3}, with an average value of 6.21 ±1.05 mg·dm^{-3}. The *TA* oscillates between 5.12 and 18.29 meq·dm^{-3}, which is considered an average of 8.29 ±4.95 meq·dm^{-3}. The colour varies between 71.25 and 475 mg Pt·dm^{-3}, with an average of 141.60 ±163.41 mg Pt·dm^{-3}. Sodium and magnesium appear to be the dominant cations ($Na^+ > Mg^{2+} > Ca^{2+} > K^+$), while chlorides and bicarbonates are the dominant anions ($Cl^- > HCO_3^- > SO_4^{2-}$). Concentration of Na^+ ranges from 2526 to 3700 mg·dm^{-3} with an average of 3019.67 mg·dm^{-3}. Mg^{2+} levels range from a high rate of 485.05 mg·dm^{-3} to a low rate of 271.33 mg·dm^{-3} with an average of 340.50 mg·dm^{-3}. Ca^{2+} ions have a maximum of 163.2 mg·dm^{-3} and a minimum of 46.69 mg·dm^{-3} with an average of 97.47 whereas K^+ values range from 38.64 mg·dm^{-3} to 57.66 mg·dm^{-3} with an average value of 45.72 mg·dm^{-3}. In addition, Cl^- concentrations range from 5007 to 6630 mg·dm^{-3} with an average of 5595 mg·dm^{-3}; HCO_3^- concentrations vary between a maximum of 1001.96 mg·dm^{-3} and a minimum of 303.18 mg·dm^{-3} with an average value of 484.86 mg·dm^{-3} while the SO_4^{2-} values are between 139.95 mg·dm^{-3} and 1091.07 mg·dm^{-3}.

CORRELATION BETWEEN VARIABLES

The study of bi-variate linear correlations between the studied physicochemical parameters proves the solid associations between them. The different relations between the parameters controlled by the estimation of the correlation coefficient can be determined on the basis of the theoretical critical coefficient drawn from the table of Bravais–Pearson according to the number of couples put into play. On this basis, the critical coefficient is 0.4134 for the number of pairs 21, and the values, the absolute values of which are greater than said critical coefficient, are written in bold (Tab. 3).

The *T* shows a slight positive correlation with the BOD_5 of 0.596, which could be explained by a decomposition of organic matter [Négrel *et al.* 2001]. It also shows a negative correlation successively with Ca^{2+} (–0.672) and *DO* (–0.634), this can be explained by a strong precipitation of calcium carbonates under the impact of evaporation and the decrease of the oxygen solubility. *DO* is positively correlated with pH (0.437) and Ca^{2+} (0.468). It also has a negative correlation with *TDS*, Mg^{2+}, Na^+, HCO_3^-, Cl^-, colour, *TA*, and BOD_5.

The correlation between pH and *DO* is one of the essential characteristics of eutrophic environments both for phytoplankton development and for macrophytes [Aw *et al.* 2011]. The colour is positively correlated with *TA*, HCO_3^-, SO_4^{2-}, Na^+ and Cl^- as well as a negative correlation with Ca^{2+}. BOD_5 is positively correlated with *TA* and HCO_3^- and negatively with Ca^{2+}.

Strong correlations have been observed between *TDS* and *EC* with a value of Na^+, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and HCO_3^-. This strong correlation implies that these ions participated in the mineralisation of the waters of this lacustrine environment [Askri *et al.* 2016]. They also demonstrate a slight positive correlation with colour.

HCO_3^- ions are positively correlated with Na^+ and SO_4^{2-}. The association with Na^+ could be explained by chemical reactions and mineral dissolution [Ganyaglo *et al.* 2010], whereas the correlation with SO_4^{2-} could be explained by the reduction of SO_4^{2-} ions to HCO_3^-, according to the following reaction [De Montety *et al.* 2008]:

$$\mathrm{SO_4^{2-}} + 2\frac{1}{n}(\mathrm{CH_2O})_n \rightarrow \mathrm{H_2S} + 2\mathrm{HCO_3^-}$$

They also have a negative correlation with calcium. This can be explained by the complexation of $Ca–HCO_3$ and saturation with

Table 3. Correlation matrix for all data (n = 23)

Para-meter	***T***	***DO***	**pH**	***EC***	**Colour**	***TDS***	***BOD*₅**	***TA***	Na^{+}	Ca^{2+}	Mg^{2+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
T	1														
DO	**–0.634**	1													
pH	0.372	**0.437**	1												
EC	–0,008	**–0.611**	**–0.892**	1											
Colour	0.168	**–0.776**	**–0.586**	**0.497**	1										
TDS	–0,082	**–0.581**	**–0.927**	**0.996**	**0.514**	1									
BOD_5	**0.596**	**–0.676**	0.061	–0.005	**0.584**	–0.022	1								
TA	0.320	**–0.818**	**–0.448**	0.403	**0.984**	0.408	**0.683**	1							
Na^{+}	0.057	**–0.705**	**–0.882**	**0.974**	**0.581**	**0.972**	0.198	**0.501**	1						
Ca^{2+}	**–0,672**	**0.468**	**–0.423**	0.368	**–0.479**	0.393	**–0.768**	**–0.619**	0.252	1					
Mg^{2+}	–0,257	–0.271	**–0.832**	**0.909**	0.132	**0.913**	–0.337	0.007	**0.840**	**0.715**	1				
K^{+}	–0,374	–0.198	**–0.855**	**0.877**	0.141	**0.892**	–0.293	0.002	**0.830**	**0.742**	**0.976**	1			
Cl^{-}	0.296	**–0.687**	**–0.670**	**0.922**	**0.458**	**0.890**	0.081	**0.415**	**0.882**	0.165	**0.766**	**0.702**	1		
SO_4^{2-}	–0,371	–0.465	**–0.961**	**0.792**	**0.744**	**0.834**	0.039	**0.616**	**0.794**	0.226	**0.657**	**0.691**	**0.580**	1	
HCO_3^{-}	0.354	**–0.827**	**–0.419**	0.386	**0.977**	0.390	**0.700**	**0.999**	**0.487**	**–0.644**	–0.015	–0.022	0.411	**0.588**	1

Explanations: *T*, *DO*, *EC*, *TDS*, BOD_5, *TA* as in Tab. 2.
Source: own study.

$CaCO_3$ [Ketata *et al.* 2011]. Chlorides show a strong positive correlation with the major components of seawater (Na^{+} and SO_4^{2-}) whereas Cl–Na (r = 0.882) and Cl–SO_4 (r = 0.580) indicate that seawater influenced the lake water mineralisation [Askri *et al.* 2016]. The above-mentioned significant correlation between Na^{+} and Cl^{-} as well as the association between Mg^{2+} and Cl^{-} (r = 0.766) takes place due to seawater intrusion [Mtoni *et al.* 2013]. The strong correlation between K^{+} and Cl^{-} (r = 0.702) and the moderate correlation between K^{+} and SO_4^{2-} (r = 0.691) could be explained by marine intrusion [Askri *et al.* 2016; Mtoni *et al.* 2013; Najib *et al.* 2017]. The low correlation observed between Ca^{2+} and Cl^{-} results from the removal of calcium following precipitation of calcite [Mtoni *et al.* 2013]. The strong correlation between Mg^{2+} and Ca^{2+} (r = 0.715) can be attributed to the dissolution of calcite and dolomite minerals [Askri *et al.* 2016; Ketata *et al.* 2011; Najib *et al.* 2017; Qin *et al.* 2013] and the exchange of cations resulting from the intrusion of seawater [Najib *et al.* 2017; Qin *et al.* 2013]. The ions are strongly correlated with Mg^{2+} (r = 0.840). This result would be attributed to ion exchange reactions [Askri *et al.* 2016]. The correlation of potassium with sodium, magnesium, and calcium is explained by the phenomenon of inverse ionic exchange between water and aquifer and which is resulting from the adsorption of Na^{+} or K^{+} and the release of Ca^{2+} or Mg^{2+} [Askri *et al.* 2016; Capaccioni *et al.* 2005; Ibrahim *et al.* 2018; Najib *et al.* 2016;]. Sulphate ions are correlated with sodium and magnesium. The lack of correlation between Ca^{2+} and SO_4^{2-} seeks an origin for calcium other than a dissolution of gypsum [Aboubakar 2012; Ganyaglo *et al.* 2010].

PRINCIPAL COMPONENT ANALYSIS (PCA)

The results obtained with principal component analysis (PCA) are reported in Tables 4 and 5. Based on the variance accumulation test commonly known as Scree test [Aw *et al.* 2011], two main factors were extracted, the sum of the variances

Table 4. Neat values and percentages expressed by the main axes

Parameter	**Value for factor**				
	F1	**F2**	**F3**	**F4**	**F5**
Eigenvalue	8.244	4.899	1.427	0.349	0.081
Variability (%)	54.962	32.663	9.512	2.324	0.539
Cumulative (%)	54.962	87.625	97.137	99.461	100.000

Source: own study.

Table 5. The contribution of variables in the determination of factors

Parameter	**Value for factor**				
	F1	**F2**	**F3**	**F4**	**F5**
T	0.007	–0.685	0.721	–0.089	–0.056
DO	–0.721	0.612	–0.281	–0.020	0.164
pH	–0.922	–0.266	0.271	–0.042	0.065
EC	0.961	0.209	0.175	–0.041	0.011
Colour	0.710	–0.603	–0.355	–0.080	0.021
TDS	0.967	0.233	0.096	–0.022	0.001
BOD_5	0.186	–0.855	0.077	0.473	0.073
TA	0.623	–0.731	–0.266	–0.082	0.014
Na^{+}	0.975	0.073	0.156	0.142	–0.004
Ca^{2+}	0.172	0.981	0.006	0.086	–0.032
Mg^{2+}	0.784	0.586	0.191	0.018	–0.065
K^{+}	0.771	0.609	0.077	0.155	0.060
Cl^{-}	0.863	0.037	0.428	–0.198	0.176
SO_4^{2-}	0.887	0.081	–0.452	–0.043	–0.019
HCO_3^{-}	0.606	–0.754	–0.240	–0.082	0.013

Explanations: *T*, *DO*, *EC*, *TDS*, BOD_5, *TA* as in Tab. 2.
Source: own study.

expressed is 87.625% (Tab. 4). These factors truly reflect the variance expressed and explain the information sought. The representation using these two factors accounts for the structure of the scatter plots satisfactorily. The results of the PCA make it possible to choose the different necessary elements for the interpretation of the different data. The analysis of the space graphs of the variables in the factorial plane F1–F2 (Fig. 2) shows that this plane alone represents 87.62% of the researched information as well as the expressed variance. The circle of community (Fig. 2) shows that the factor F1, the most important, is positively correlated with *EC*, *TDS*, Mg^{2+}, Na^+, K^+, Cl^- and SO_4^{2-} (Tab. 5), which can also be attributed to the intrusion of sea water [Askri *et al.* 2016]. Elevated levels of *TDS*, Cl^- and Na^+ are generally from marine sources, either seawater intrusion into aquifers or marine aerosols carried by precipitation [Qin *et al.* 2013]. It is also positively correlated with colour, *TA*, and HCO_3^- ions as well as a negative correlation with *DO* and pH (Tab. 5). Factor F2 shows a negative correlation with *T*, pH, colour, BOD_5, *TA*, and HCO_3^- ions, as opposed to *DO* and cations Ca^{2+}, Mg^{2+} and K^+, which could take place due to a rise in temperature which is responsible for the precipitation of calcite; this precipitation has an influence on a variety of chemical parameters: bicarbonates, dissolved CO_2, Ca^{2+}, and consequently salinity, conductivity, alkalimetric title (AT), complete alkalimetric title (CAT), hydrotimetric title (HT) and hardness [Roche 1979]. The opposite evolution of Ca^{2+} and HCO_3^- indicates another source in addition to carbonate alteration, such as gypsum dissolution and cation exchange, which increases the Ca^{2+} content [El Yaouti *et al.* 2009]. The positive correlation between the three cations (Mg^{2+}, Ca^{2+}, and K^+) could be explained by the absorption of these elements by the plants during this period which knows a great photosynthetic activity. Seasonal growth of molluscs, which is faster in warmer waters, is expected to result in higher calcium absorption from April to October, especially during the low water level period [Roche 1979]. It may also take place due to the uptake of these elements by vegetation [Roche 1979]. The graphical representation in the factorial space of the statistical units (Fig. 3) is due to the distribution of the water points according to the different factors F1–F2. The analysis of this graph shows a single grouping of the water points, which reflects the homogeneity of the physicochemical characteristics of the waters of this lacustrine environment.

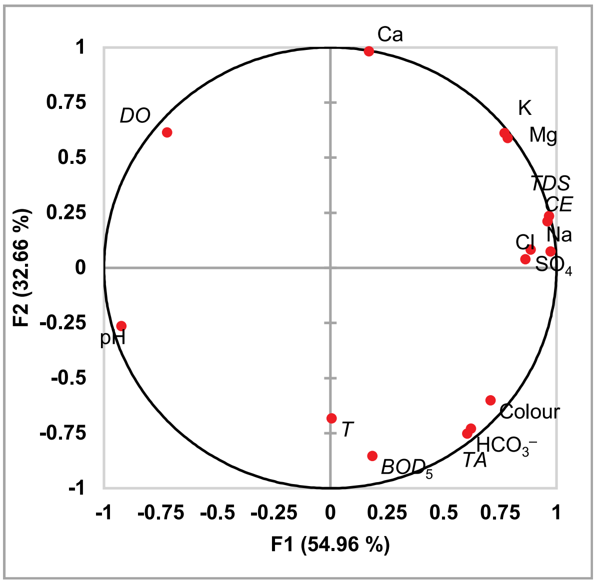

Fig. 2. Space of the variables in the factorial plane F1–F2; source: own study

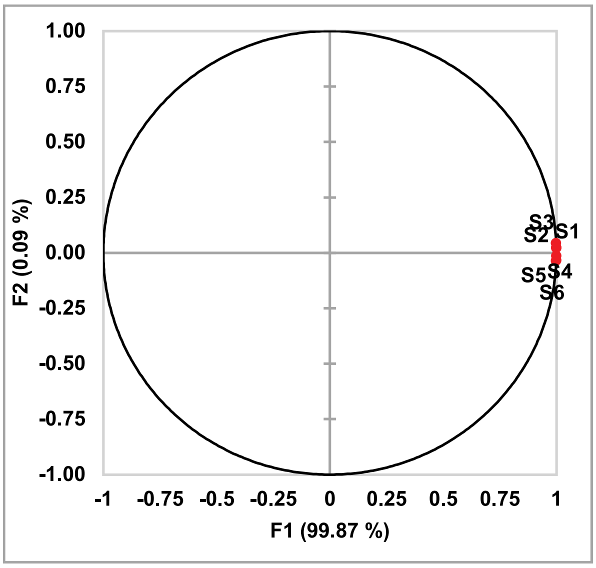

Fig. 3. Space of individuals in the factorial plane F1–F2; source: own study

CONCLUSIONS

The statistical study carried out on the hydrochemical variables resulting from the analysis of the waters of the Lake Sidi Boughaba made it possible to classify this lake environment as a eutrophic medium. It also revealed high levels of *TDS*, Cl^- and Na^+ on the one hand, and their correlation indicating a marine source, be it the intrusion of seawater into the aquifers or the marine aerosols carried by the precipitations on the other hand. It identified four main mechanisms that are responsible for the evolution of the mineralisation of the waters in the area. The mechanism at the base of the mineralisation in major elements of the waters is the effect of sea spray. The second-order processes are the ion exchange phenomenon, the dissolution/precipitation of evaporitic and carbonate formations, the oxidation-reduction processes, notably the reduction of sulphates as well as biochemical phenomena due to the selective absorption of certain ions by fauna and flora.

ACKNOWLEDGMENTS

The authors would like to thank Miss Soukaina AROUB for the assistance in the field of computing and Mr. Miloud CHAKIT and Mr. Mohamed HA-NINE for the assistance in the field of sampling.

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