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ARTICLE

Study of Chemical and Biological Indicators of Saline Pollution of the Coastal Lake Sidi Boughaba (Kenitra, Morocco)

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ABSTRACT

For around fifty years, the regression and degradation of wetlands were considered so worrying that they were the subject of an international Convention signed on 2 February 1971, in Iran (RAMSAR). This treaty aims to conserve wetlands meeting criteria of international importance through the notion of rational use of these spaces and their biodiversity. The national and even international value of Lake Sidi Boughaba (Kenitra, Morocco) lies in its biodiversity which allowed its inclusion on the Ramsar list in 1980. This importance motivated us to begin an ecological assessment of the level of its pollution through spatiotemporal monitoring and analysis of physicochemical tracers from surface waters at seven sampling stations between January and December 2023. The waters of Lake Sidi Boughaba are relatively basic (pH = 8.63), cold (15.14 °C), very hard (64 meq/L), quite turbid (7.65 NTU), very salty (1935.85 µs/cm) and well saturated with Calcium ions = 312; Magnesium = 605; Chlorides = 5892; Sulfates = 944; Silicates = 26 (mg/l). Other elements including nitrates (1.29 mg/l), ammonium (1.56 mg/l), fluorides (410 µg/l), iron (350 µg/l) and manganese (35 µg/l) are low. This study concludes that Lake Sidi Boughaba is classified in the category of oligomesotrophic lakes and that it is too threatened by the progressive transformation of its fresh water into brackish water and consequently the change in its benthic and planktonic fauna necessary for food of avian fauna. The study further concludes that this wetland is under significant threat, and to protect its biodiversity, innovative approaches to hydrological development are necessary.

Keywords: Ecosystem; Lake; Pollution; Physicochemistry; Biodiversity; Sidi Boughaba; Mehdia; Morocco

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1. Introduction

The degradation of water resources and aquatic ecosystems is a global and complex problem. The problem arises under both quantitative and qualitative aspects, often interdependent in arid and semi-arid areas [1]. This problem has attracted the attention of several researchers. Among the multitude of significant threats to water resources, salinization influences these qualities. Also, toxic elements, including heavy metals and pesticides, can cause the disappearance of certain animal and/or plant species and consequently, lead to the dysfunction of the trophic chain.

Water salinity is one of the major problems in Morocco, given its devastating effect on water quality. It is often linked to the dissolution of geological formations, the effect of evaporation and the effect of marine intrusion [2–4]. Aware of the increasing degradation of national biodiversity, particularly that of wetlands, Morocco was one of the first signatories of the International Convention on Biodiversity in 1992. Three years later, it ratified this convention, demonstrating its commitment and willingness to contribute to the international effort aimed at reducing threats to various components of global biological diversity. Morocco has also signed, ratified and included some of its wetlands in the RAMSAR convention, which is one of the most specific international conventions in this area.

The Convention on Wetlands is an intergovernmental treaty that was adopted on 2 February 1971 in the Iranian city of Ramsar [5]. This convention is an international treaty for the conservation and sustainable use of wetlands. It aims to halt the degradation and loss of these areas today and tomorrow by recognizing their fundamental ecological functions. In recent years, these areas, subject to increasing exploitation pressures, have attracted the attention of international biodiversity and environment programs.

Ramsar is the first global convention on the protection of nature. This convention was ratified by Morocco in 1980 [6].

Concerning wetlands, it has recently been strengthened from the point of view of the rational exploitation of all these areas. The Ramsar Convention's mission is: "The conservation and wise use of wetlands through local, regional and national actions and through international cooperation, as a contribution to achieving sustainable development throughout the world. The Secretariat of the Ramsar Convention is located in Switzerland.

Under the impetus of various international conventions for the protection of nature [7–12], wetlands are attracting increasing interest from the international scientific community. In Morocco, this interest is particularly oriented towards avifauna, and mainly concerns the Atlantic coast. Indeed, four wetlands on the Atlantic coast have been included on the Ramsar convention list: Merja Zerga in Moulay Bouselham (280 ha), Merja Sidi Boughaba in Mehdia-Kenitra (650 ha), Lake Afennourir near Ifrane (280 ha) and the Khenifiss lagoon near Tarfaya (6500 ha). In the case of the Mediterranean coast, despite the diversity of wetland types and the recognition of five sites (Moulouya mouth, Bou Areg sebkha, Tahaddarte wadi, Smir lagoon and dam) as sites of biological and ecological interest [13], no site currently benefits from the status of a nature reserve.

Despite their ecological interest, continental ecosystems continue to be considered primarily for their socio-economic values, by decision-makers, managers and the local population. Nearly half of Mediterranean wetlands have been drained and transformed into agricultural, urban and industrial land [14]. The pollution and degradation of these ecosystems has direct consequences in the decline, or even the disappearance, of its endemic fauna, of great importance for biodiversity, which is sometimes replaced by banal opportunistic species.

Lake Sidi Boughaba constitutes, by its location, its size (650 ha) and its biotic and abiotic characteristics, one of the most important links in this network. The ornithological interest earned this site a RAMSAR site classification in 1980 and also allowed it to be selected in the master plan for protected areas in Morocco (AEFCS) by decree no. 638-80 of 7/5/1980 and as a site of biological and ecological interest (SIBE). In 1992, a partnership agreement between the Ministry of Water and the Society for the Protection of Animals and Nature (SPANA) allowed the creation, on the scale of the reserve, of a National Center for Environmental Education (CNEE) with the financial support of SPANA/Great Britain, BirdLife International and the European Union.

Aquatic ecosystems, particularly lake ecosystems or wetlands, are increasingly threatened by pollution, which risks reducing their ecological and economic potential and having harmful repercussions on human health. The choice to study the waters of the Lakes is motivated by their important roles in supporting low water levels, recharging water tables, regulating floods, a filter for water purification and a source for biodiversity with more than 171 migratory bird species.

This study aims to determine the origin of the mineralization of the waters of Lake Sidi Boughaba and to study the impact of the quality on aquatic biodiversity. For this, a sampling plan including several field campaigns was set up to characterize the chemistry of the lake waters by determining the physicochemical parameters, the chemical facies, the origin and processes of water mineralization, the calculation of water saturation with respect to carbonate and evaporite minerals as well as the study of pollutants and their origins.

Highlighting the physicochemical mechanisms that govern the evolution of aquatic species in time and space in Lake Sidi Boughaba.

2. Materials and Methods

2.1. Study Area

2.1.1. Lake Sidi Boughaba

This work concerned the wetland of Lake Sidi Boughaba. It is an ecological study of the waters and its aquatic biodiversity. The first step concerns the physicochemical analysis of the water through the monitoring of seasonal variations in the main parameters.

Lake Sidi Boughaba is located on the Atlantic coast in northwest Morocco. It is oriented NNE-SSW (**Figure 1**) and located in an interdunal depression. The lake extends over 5.5 km in length with a variable width of 100 to 350 meters and a depth that varies between 0.5 and 2.50 meters at most.

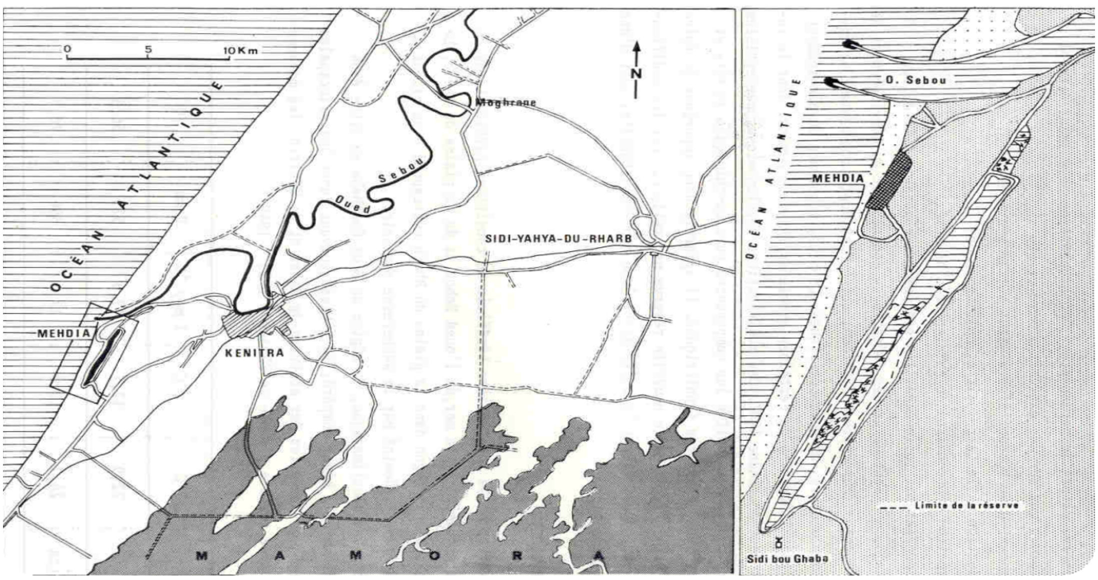

Figure 1. Geographical location of Lake Sidi Boughaba near Mehdia beach (Kenitra, Morocco).

The Sidi Boughaba Biological Reserve is located in the Atlantic coastal zone of Morocco, 13 km from the city of Kenitra, 35 km from Rabat, and less than one km from the sea, and is oriented NNE-SSW with coordinates of 34°15′ N - 06°39′ W.

The Mamora is a vast quaternary platform which extends from the Ocean between Rabat and Kenitra, up to 70 km towards the interior of the country, limited to the South by the Bou Regreg valley and the foothills of the Central Plateau and to the North by the Gharb plain.

The geological formations of the coastal zone of the Mamora are essentially composed of sandstones and quaternary marine or dune sands. They are indistinguishable from the Pliovillafranchian formations and are topped with more or less clayey red silt. These silts separate several sandstone levels and cover the ground in this coastal sector up to 3 or 4 km from the current shoreline. The conglomerate layers are located from 33 to 48 m deep.

The dune cordon that delimits the furrow towards the west can reach several meters in thickness. It separates the marine domain from the continental peaty marshland domain. It has favored the establishment of wetlands in the hinterland by concentrating the flow towards the ocean of rainwater and runoff. It is a still mobile dune formed by the accumulation of elements brought by erosion and marine sedimentation, consisting of shell sands and silts.

To the east of the merja, an older, consolidated dune system presents a cliff, probably shaped by the sea, and offers a relatively gentle slope compared to that of the west which is steeper.

The wide furrow separating the two dune systems is occupied by a deposit of red sand of continental origin called soltanian red silts.

To the north of the merja the soils are accidentally flooded and have a very weakly clayey-silty humus-sandy texture, with little humus.

In the south, they are of clayey-sandy-silty texture and rich in fine organic matter; this type of very hydromorphic soil is designated under the name of vertisols (tirs). Further inland from the merja, the soils are clearly organic and very rich in fine particles: clays and decomposed organic matter of gray to black color. The upper and underlying horizons present 20 to 60% of fresh organic matter.

2.1.2. Floristic Diversity

Information on vegetation is taken from previous research in the field [15–17].

Algal Vegetation

The algal flora is dominated in its shallow parts of the northern end and the entire southern zone by a luxuriant development of characeae to which are added a flora of floating or fixed macroscopic algae and a microscopic flora rich in Diatoms. The planktonic flora is present in the deep northern part of the lake, which does not have macroscopic algal vegetation, with the exception of some filamentous algae and Cyanophyceae on these edges [15].

Hygrophilous Vegetation

Four vegetation zones are clearly distinguished in the merja, by their locations, their micro-topographic positions and their different ecological and water requirements [17]:

(1) Riparian Forest: Composed of *Populus alba* L., this forms a narrow edge on the eastern bank to the south of the merja. It likely corresponds to the final stage of the evolution of hygrophilous vegetation, remaining unaffected by submersion. This scrubland is associated with *Tamarix* species and shelters the bracken fern (*Pteridium aquilinum* L.) in the undergrowth, alongside notable bramble species such as *Rubus ulmifolius* Schott.

(2) Wet Meadows: These areas are characterized by dense herbaceous vegetation, largely composed of *Gramineae* and *Cyperaceae*. They mainly occupy micro-elevations (ridges) within the merja and extend to the edges. Sometimes, they form islets that are often submerged at their edges during winter and spring.

(3) Marshy Vegetation: Dominated by tall, aquatic or semi-aquatic plants, including reeds (*Phragmites*), *Typha* species, and *Scirpus* species. This vegetation is found in lowland areas, following the wet meadows or in regions completely submerged in water. *Iris pseudacorus* L. is also found here, but it is highly localized in the northeastern part of this area.

(4) Reed Grass Elevation: A few centimeters above the general floor level, this area is occupied by Reed Grass, forming a transition between the water and the surrounding dune environment.

Terrestrial Vegetation Covering the Slopes of the Lake

Lake Sidi Boughaba is one of the rare coastal wetlands whose perimeter is wooded. Apart from the Eucalyptus plantation located on the northeastern shore, the rest is made up of spontaneous vegetation. On the western shore, a very dense Juniperus is difficult to penetrate, to the east, degraded, giving way to a scrubland with *Retama monosperma* or *Chamaerops humilis*.

The sea spray and winds have vigorously shaped the Juniperus, although this climax forest resembles a scrubland [18]. It has a height of 5 to 6 meters. The upper stratum besides the Juniperea includes other species, mostly ornithocorous: *Phillyrea angustifolia*, *Ephedra fragilis*, *Pistacia lentiscus*, *Rhammus lycoides*, *Jasminus fruticans*, *Silax aspera*, and *Olea europea*.

The herbaceous stratum is made up of sciaphilous and nitrophilous species including, among others, *Mercurialis annua* and *Parietaria mauritanica*. In the empty degraded parts, the flora is different and includes, among others, *Retama monosperma* with *Gandinia fragilis*, *Trisetaria panicea*. Since 1975, the merja has been given the status of a nature reserve with the development of an Eucalyptus grove around the perimeter and the introduction of leather carp and black bass.

These developments have influenced the environment and its plant groups. The cessation of grazing and mowing has favored the development of large helophytes (*Fragmites gigantea*) and grasses (*Panicum repens*).

These physiognomic changes have certainly led to physicochemical and faunistic changes in Lake Sidi Boughaba. It is therefore important to make an ecological assessment of this biological reserve.

The existence of this body of water is due to the fact that the topographic surface is located at a lower elevation than that of the piezometric surface of the coastal water table, rainwater, and runoff[16]. The water height is maximum at the end of winter (March) and minimum just before the return of the rains (August). Due to the significant variation in level (nearly 1 m), only a part of this lake, sufficiently deep, remains in water all year round (well less than half of the surface)[18–22].

Lake Sidi Boughaba has a surface area varying according to the seasons and the intensity of the rains from 150 to 200 hectares[16], a length between 5.5 and 6 km, and a width that varies between 100 and 350 m (**Figure 2**). This body of water, which has no direct opening onto the ocean, is mainly fed by groundwater; thanks to its topographic surface which is located at a lower level than that of the piezometric surface of the coastal water table, but also, to a lesser extent, directly from precipitation and runoff water.

Figure 2. Illustration of Sidi Boughaba lake- Mehdia Kenitra (Morocco).

2.1.3. Climatic Data

Total rainfall across the entire Moroccan territory is estimated at approximately 150 billion m^3 in an average year, of which nearly 29 to 30 billion m^3 (approximately 20%) are considered effective rainfall, divided into runoff water (20 billion m^3) and infiltrated water feeding the water tables (9 billion m^3).

Following population growth, the mobilizable volume per inhabitant, which was 833 m^3 per year in 1994, would be reduced to less than 500 m^3 in 2020, which places Morocco in the category of water-poor countries (high water stress). They are thus unevenly distributed across the national territory. The northern regions and the Sebou basin, although occupying only 8.5% of the country's total area, receive more than 59.5% of the total rainfall, while the Moulouya basin, which occupies 8.2% of this area, receives only 4.8% of the total rainfall.

Gaussen's work is one of the most important attempts to relate vegetation cover and climate data. Since the annual water balance is considered to be a determining factor for vegetation, it is important to know the length of the dry season. By definition, any month will be biologically dry when the total precipitation P (mm) is equal to or less than twice the average monthly temperature expressed in degrees centigrade [19]. The graphic representation of this diagram shows that the dry period extends over five months (May, June, July, August and September) while the wet period extends from October to April. January is the wettest month of the year with an average of 67 mm.

The climatic data collected at the Mehdia rainfall station (**Table 1**, **Figure 3**) span the period from 1969 to 2015, allowing us to see the local climatic characteristics of the study region and also to see the average monthly, seasonal, and annual distributions of this region.

Table 1. Precipitation at Mehdia station.

Months	S	O	N	D	J	F	M	A	M	J	J	A
P (mm)	10.80	42.43	98.51	114.45	90.06	73.97	60.46	62.19	31.99	4.24	0.36	0.83
Seasons		Autumn			Winter			Spring			Summer	
P (mm)		151.74			278.48			154.64			5.43	

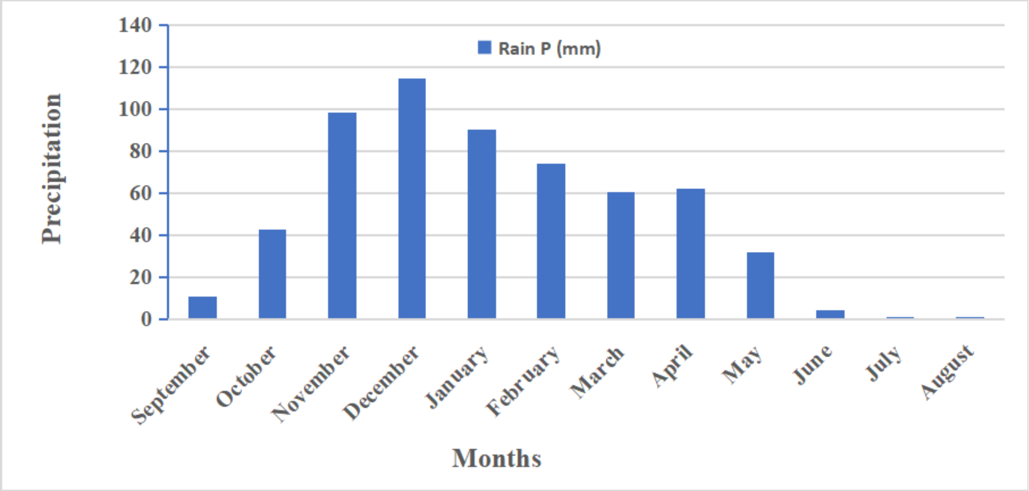

Figure 3. Variation of monthly average precipitation at Sidi Boughaba.

The analysis of monthly precipitation variation shows that the maximum is recorded in December, while the minimum is recorded in July and August.

The analysis of **Table 1**, relating to the seasonal variations in precipitation, shows that the seasonal distribution of rainfall for this region indicates a maximum recorded only during Spring, while the minimum is recorded in Summer.

Rainfall in Morocco increased to 260.62 mm in 2022 from 249.43 mm in 2021. Rainfall in Morocco averaged 333.99 mm from 1901 to 2022, reaching a historical record of 555.05 mm in 1996 and a record minimum of 186.27 mm in 1981 (**Figure 4**).

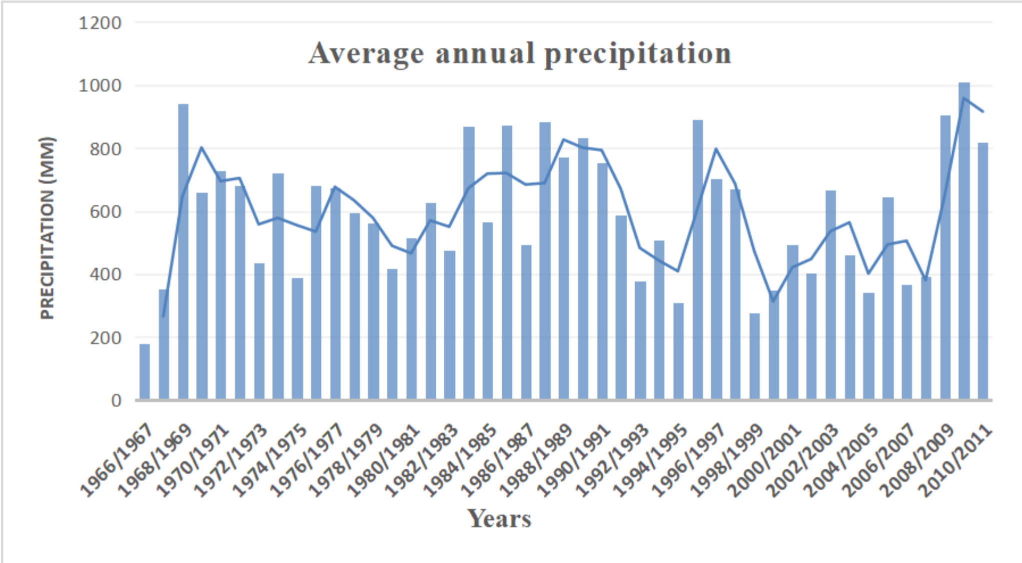

Figure 4. Variation of average annual precipitation in Sidi Boughaba.

Aridity is an expression qualifying the qualitative or quantitative dryness of a region. Knowing that the latter is characterized by low annual precipitation, with a very irregular distribution in time and space, and notably lower than the annual potential evaporation [24].

The gradients of these indices are also used to delimit zones according to their rainfall. Two indices can be used, as a factor that can allow a classification of the climate. The Emberger Pluviothermic Quotient and the De Martonne Aridity Index.

The Quotient allows the classification of the region according to its bioclimatic stage. It gives an exact overview of the climate of the targeted region. It was developed by Emberger. The average of the minima of the coldest month is plotted on the x-axis, and the Emberger rainfall quotient (Q2) is plotted on the y-axis, defined as

$$\mathrm{Q2} = \frac{2000P}{M^2 - m^2} \tag{1}$$

where P signifies average annual precipitation in (mm), M represents average temperatures of the maximums of the hottest month in °C, and m stands for average temperatures of the minimums of the coldest month in °C.

The Emberger Climagram is used to classify Mediterranean stations into five (06) bioclimatic stages: Perhumid, humid, sub-humid, semi-arid, arid, and Saharan. The Climagram considers that a region is drier when the quotient is smaller. The Q2 index of the Kenitra and Mehdia stations was calculated.

In 1926, Emmanuel De Martonne developed a climate classification system using a statistical method [25]. He used an index combining hydrometric and thermal data, defined as:

$$\mathrm{I} = \frac{P}{(T+10)} \tag{2}$$

where I represents the annual aridity index, P stands for average annual precipitation (mm), and T indicates average annual temperature in (°C).

Climate classifications based on the index are as follows:

- $20 < I < 30$: temperate climate
- $10 < I < 20$: semi-arid climate
- $7.5 < I < 10$: steppe climate]
- $0.5 < I < 7.5$: desert climate
- $I < 5$: hyperarid climate

Vegetation levels based on winter temperatures are classified as:

- Very cold winter: $-5 < m < -3$ °C (Mediterranean mountain vegetation level)
- Cool winter: $-3 < m < 0$ °C (Supra-Mediterranean vegetation level)
- Cool winter: $0 < m < 3$ °C (Meso-Mediterranean vegetation level)
- Temperate winter: $3 < m < 7$ °C (Thermo-Mediterranean vegetation level)
- Warm winter: $7 < m < 10$ °C (Infra-Mediterranean vegetation level)

- Very warm winter: m > 10 °C (Infra-Mediterranean vegetation level

The application of this formula yields the results summarized in **Figure 5**.

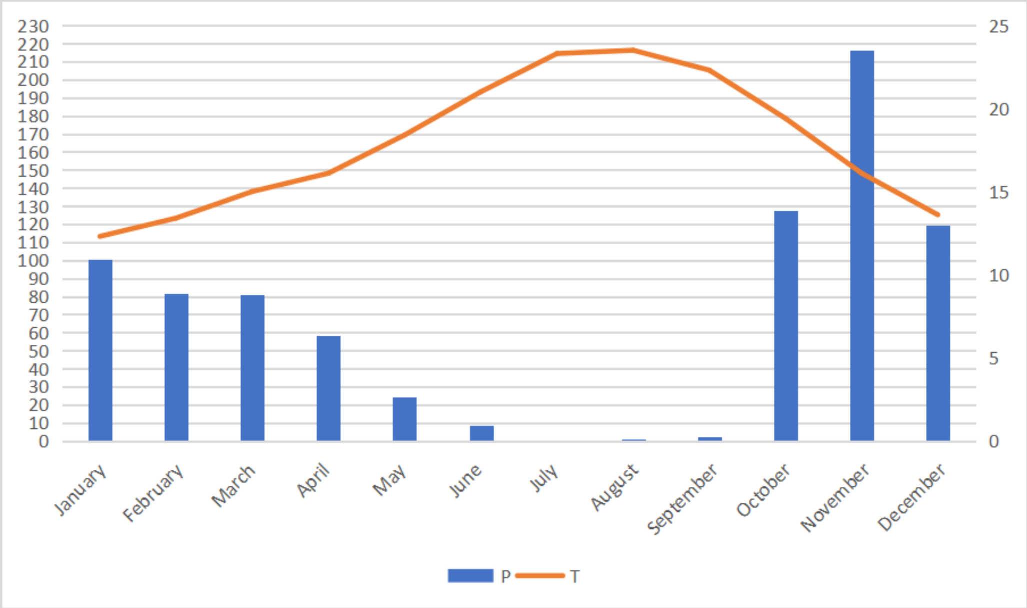

Figure 5. Ombrothermic diagram in Sidi Boughaba.

The average annual rainfall in Kenitra is 590.29 mm and the average annual temperature is 17.86 °C. From there, we have an Emberger coefficient of the order of 22 and a De Martonne aridity index of 21.18. The ombrothermic diagram (**Figure 5**) shows that the dry months extend between June and August.

2.1.4. Faunal Diversity

(1) Invertebrates

Lake Sidi Boughaba has 156 species belonging to 6 Orders [26]. Some species, in turn, are dominant according to the seasons, giving the population of the body of water very contrasting aspects. Invertebrates enter in large proportions in the diet of the birds of the lake.

(2) Vertebrates Other than Birds

* Fish

- *Cyprinus carprio* (common carp was introduced in 1924).
- *Gambusia affifinis* holbricki, also introduced.
- *Atherina boyeri* Risso, reported by Furnestin et al. (1958) [27], under the binomial *Atherina caspia* Eichwald, common in Sidi Boughaba.

* Amphibians

- At least four species of anuran amphibians are found in Sidi Boughaba.
- *Hyla arborea* L. (Southern tree frog)
- *Discoglossus pictus* Otth. (Painted disgloss)
- *Bufo mauritanicus* Sch. (Mauritanian toad)
- *Rana ridibunda* P.P. (Green frog)

* Reptiles

- *Clemmys caspica* Leposa, the leopard turtle is commonly found in the lake Sidi Boughaba.
- *Chamaelo chameoleon* (common chameleon).
- *Testudo graeca* is quite common in the merja.
- *Natrix maura* L. (Viperine snake).

* Mammals

- *Erinaceus algirus* lereboullet. (Algerian hedgehog). Nocturnal. Observed several times in the reserve during the present study.
- *Rattus rattus* L. (Black rat). Very common.
- *Rattus norvegicus* Berkenhout (Murkey). Very common.
- *Mus musculus* L. (Grey mouse). Very common.
- *Gerbillus campestris* Levaillant. (Rural gerbil). Common in the reserve and its surroundings.

- *Oryctolagus cuniculus* L. (European rabbit). Very common.
- *Mustela nivalis* L. (Weasel). Very common in the Juniperaie woodland. The Weasel is practically the only carnivorous mammal existing in the reserve.
- *Lepus capensis* L. Much rarer than the Rabbit, the Hare has been noted in the reforested dunes.

2.2. Methodology

2.2.1. Methods of Physico-Chemical Study of Lake Sidi Boughaba

In general, water sampling must be homogeneous and representative. Before sampling, the bottle is rinsed with distilled water and then three times with the water to be analyzed. The bottles are filled two meters from the bank. The sampling of each campaign is carried out at the same time and in the same place of the seven sampling sites along the banks of the lake. The water samples collected were transported at low temperatures (+4 °C) in portable coolers to the laboratory for physicochemical analysis.

Some physicochemical parameters require field measurements, such as water temperature, air temperature, electrical conductivity, salinity, dissolved oxygen, redox potential and pH.

The pH, temperature, electrical conductivity and dissolved oxygen were measured using a multiparameter analyzer Consort - Model 835 and a portable multiparameter device model Hanna HI 9828. In this context the parameters to be analyzed calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), potassium (K^{+}), carbonate and bicarbonate, chlorine (Cl^{-}), Sulfates, Silicates, Fluorides, Ammonium (NH_4), nitrate (NO_3), Nitrites, Iron and Manganese[28]. Cl, CO_3, HCO_3, TH parameters were measured by the colorimetric method according to standard techniques[28], SO_4 by atomic emission spectrometry (ultraviolet-visible), major cations (Na, K, Ca, Mg) by the flame atomic absorption method and atomic absorption and Mass Spectrometry Inductively Coupled Plasma (ICP-MS) methods were used for the determination of heavy metal concentrations.

Turbidity is an organoleptic parameter and an expression of the optical property of water to absorb or diffuse light. It is due to the more or less cloudy condition of water, due to the presence of fine suspended matter (silt, clay, microorganisms, etc.). Turbidity is measured by nephelometry, it is expressed in Nephelometric Turbidity Unit (NTU).

Method for measuring calcium and magnesium by complexometry (EDTA N/50) using the same principle as for measuring calcium hardness, but the use of two indicators makes it possible to measure them successively on the same sample.

The dosage of sodium and potassium by flame photometer. Dosage of chloride combined with the chloride state by silver nitrate 0.05N, in the presence of potassium chromate solution K_2CrO_4. Determination of sulfates by colorimetry by precipitation of sulfate ions in the presence of barium chloride in a hydrochloric medium in the state of barium sulfate and measurement at a wavelength of 420 nm and determination of the concentration using a calibration curve.

Determination of nitrates and ammoniums by distillation in the presence of a catalyst respectively magnesium oxide and DEVA RDA alloy, $NH_4{}^{+}$ and $NO_3{}^{-}$ are collected in a boric acid solution and measured by H_2SO_4.

The alkalinity of water corresponds to the presence of basic species such as hydroxide ions (OH^{-}), carbonate ions ($CO_3{}^{--}$), hydrogen carbonate ions ($HCO_3{}^{-}$), phosphate ions ($PO_4{}^{---}$) and silicates ($SiO_3{}^{--}$). The alkaline titer (TA) corresponds to the neutralization of all of the OH^{-} hydroxide ions and the transformation of half of the carbonate ions into hydrogen carbonates by a strong acid (HCl). The complete alkaline titer (TAC) corresponds to the neutralization of all the hydroxide, carbonate, and hydrogencarbonate ions by a strong acid (HCl).

Fluorides are determined by potentiometer using a fluoride-selective electrode and a single or double junction reference electrode connected to an electrometer. Molybdic acid, in the presence of silicate ions at a pH = 1.2, produces a yellow color due to the silico-molybdic complex capable of colorimetric determination at a wavelength of 410 nm. Dosage by atomic absorption spectrometry of the elements: manganese, iron.

2.2.2. Methods for Studying Biological Indicators of Pollution

The assessment of the quality of an aquatic environment using biological methods is based on the application of a general principle according to which a given environment corresponds to a particular biocenosis. As a result, the populations of a habitat can be considered as the synthetic expression of all the ecological factors that condition the system. The alterations of the environment, which result in the evolution of some of these factors, then cause more or less marked modifications of the living communities that it hosts. Also, the analysis of the composition of a faunal repertoire considered in isolation makes it possible to define the state of the environment while the comparative upstream-downstream or before-after analysis makes it possible to evaluate the effect of the changes in the environment that affect the communities.

In the field of running waters, diagnoses are most often based on the analysis of populations of benthic macroinvertebrates dependent on the substrate. Indeed, the benthos combines a large number of advantages in the overall assessment of the quality of environments compared to other faunal or floral groups. However, other communities are also used.

The biological analyses developed throughout the world are very numerous and can be grouped into two types.

The first includes all the analyses based on the comparison of biocenoses belonging to different stations of the same watercourse or on the comparison of a biocenosis of a site with a control or potential biocenosis established for a given biogeographical area. The second type of analysis includes the methods that provide for each river station studied a level or index of quality.

The principle of these methods is to combine an indication of diversity on the basis of the taxonomic groups observed with an indication of pollution concerning particular taxonomic groups, to obtain an index or score [29]. The conceptual scheme is based on the consideration of two effects of pollution.

Firstly, the reduction of community diversity, and secondly, the progressive loss of certain groups living in good quality waters called indicator organisms [30].

Beck first spoke of a biotic index (BI) in 1955 [31], by classifying macroscopic invertebrates according to their tolerance to organic pollution in a class I which does not tolerate it and in a class II which tolerates it more. He obtained a "biotic index" by adding the number of species in class II and twice the number of species in class I. However, this index cannot correspond to the previous definition since it does not take diversity into account.

The assessment of the biological quality of fresh water is based on the study of benthic macroinvertebrates according to a method derived from that of the Biotic Indices [32].

In Lake Sidi Boughaba, the harvesting process is based on the sweep net and the plankton net with a 45 µm mesh size and a hand spade. To extract the benthic fauna, the collected sediments are immediately washed with lake water through a series of sieves with mesh sizes of 315, 500 and 630 µm.

The calculation of the BI is carried out using a double-entry table whose rows correspond to the systematic groups classified in order of decreasing sensitivity and the columns to the total number of groups collected. The intersection of a row and a column determines the station index (**Table 2**) [32]. The ten indices are grouped into five quality classes (**Table 3**), each corresponding to a level of organic pollution [33].

Table 2. Determination of the modified biotic index.

I Fauna Groups		II US Systematic Unit	III Total Number of US Systematic Units Presented				
			0 à 1	2 à 5	6 à 10	11 à 15	16 et +
			Biotic Index				
Plecoptera	1	+ than one U.S	-	7	8	9	10
Ecdyonuridae	2	1 only U.S	5	6	7	8	9
Trichoptera with	1	+ than one U.S	-	6	7	8	9
Sheaths	2	1 only U.S	5	5	6	7	8
Ancylidae Ephemeroptera	1	+ of 2 U.S	-	5	6	7	8
Except Ecdyonuridae	2	2 or – than 2 U.S	3	4	5	6	7
Aphelocheirus or Odonates Gammaridae or Molluscs (except Sphaeridae)	0	All U.S. above absent	3	4	5	6	7

Table 2. *Cont.*

I Fauna Groups		II US Systematic Unit	III Total Number of US Systematic Units Presented				
Asellus or Hirudinae or Sphaeridae or Hemiptera (except Apherocheirus)	0	All U.S. above absent	2	3	4	5	-
Tubificidae or Chironomidae of the Thumniplumosus Groups	0	All U.S. above absent	1	2	3	-	-
Eristalinae		All U.S. above absent	0	1	1	-	-

Table 3. Correspondence between values of biotic indices (BI) and classes of pollution levels.

Index	Pollution Level Classes	Color
0–1–2	1: Very high pollution	Red
3–4	2: High pollution	Orange
5–6	3: Medium pollution	Yellow
7–8	4: Low pollution	Green
9–10	5: Low to no pollution	Blue

2.2.3. Methods of Ornithological Study of Lake Sidi Boughaba

In late summer and early autumn and after the breeding season, nearly a quarter of the birds in the Palearctic zone (European and Asian birds) migrate to Africa to winter south of the Sahara. Morocco is located on one of the two main bird migration routes between Europe and Africa and the Strait of Gibraltar is an important crossing point between these two continents[16, 34–36].

The study of the aquatic avifauna of Lake Sidi Boughaba was carried out at several observation points chosen to allow the most exhaustive coverage of each sector of the Lake. The observation timing with a telescope and a pair of binoculars began at sunrise going from the North to the South of the Lake[34–36].

During the study of birds, the first problem we faced was the precise taxonomic determination of the species observed and their enumeration. After establishing the list of avifauna, we can then consider an in-depth ecological or biological study such as census, migration, ringing, nesting, etc.

Systematic determination. As for the identification of the species of the site, the equipment used consists of an illustrated ornithological guide, a pair of binoculars and a telescope;

For the determination and systematics of birds, we based ourselves on morphological, behavioral and other characters. Among the morphological characters, we note the size of the bird; the shape and size of the beak; the shape and size of the legs and the plumage and general color.

Also, ethological characters include Swimmer, diver, terrestrial; bird song; flight; fishing bird; wader; and bird of prey.

3. Results

3.1. Physicochemical Diagnosis

Generally, and following annual variations during the study years, the average water temperature of Lake Sidi Boughaba ranges from 12 °C in winter to 30 °C in summer (**Table 4**).

These fluctuations reflect the real state and nature of the waters studied. The pH levels recorded in the study area vary between a minimum of 7.75 and a maximum of 8.98. The average is (8.63). These values are therefore not different and reflect waters close to neutral but slightly alkaline. The waters of Lake Sidi Boughaba are relatively basic (pH = 8.63) (**Table 4**).

The measured values oscillate between 7.7 and 8.99 pH units, which indicates a slight alkalinity favorable to fish life[37]. This alkaline trend could be related to the petrographic nature of the terrain crossed, with a limestone dominance[38].

Table 4. Physicochemical analysis of Sidi Boughaba waters.

Sampling Points/Date of Sampling	**29/01/2023**				**19/02/2023**		
Sampling points	P 1	P 2	P 3	P 4	P 5	P 6	P 7
Temperature of water (°C)	14	15	15	14	14	17	17
Temperature of air (°C)	13	13	13	14	14	20	20
pH	7.75	8.85	8.68	8.81	8.98	8.53	8.83
Turbidity (NTU)	11.80	5.29	9.23	5.10	1.88	17.8	2.50
Conductivity (µs/cm)	1940	2515	1594	1589	1633	2650	1630
Alkalimetric titer (meq/l)	0.0	2.0	0.0	0.0	0.0	0.0	1.0
Full alcaline titer (meq/l)	12.0	17.0	7.0	7.0	7.5	15	7.2
Hardness (meq/l)	46.4	46.0	79.2	83.2	82.0	69.2	42.0
Calcium (mg/l)	512	240	288	272	288	344	240
Magnesium (mg/l)	260	425	810	870	845	650	375
Chlorides (mg/l)	5005	4899	4544	5503	5857	9159	6283
Iron (mg/l)	1.60	0.20	0.40	0.10	0.06	0.06	0.03
Manganese (mg/l)	0.04	0.10	0.10	0.00	0.00	0.01	0.00
Silicates (mg/l)	13.2	33.4	37.2	32.6	16.3	34.6	15.8
Sulfates (mg/l)	452	1529	367	394	384	3018	468
Fluorides (mg/l)	0.52	0.39	0.41	0.40	0.38	0.43	0.35
Nitrites (mg/l)	0.03	0.06	0.01	0.02	0.00	0.04	0.01
Nitrates (mg/l)	1.31	1.25	1.02	1.75	1.28	1.42	1.03
Ammonium (mg/l)	2.25	1.26	4.23	0.52	0.65	1.53	0.51

The waters of Lake Sidi Boughaba are relatively cold (15.14 °C), very hard (64 meq/l), quite turbid (7.65 NTU), very salty (1935.85 µs/cm) and well saturated with Calcium ions = 312; Magnesium = 605; Chlorides = 5892; Sulfates = 944; Silicates =26 (mg/l).

The high hardness values recorded in winter and spring are due to runoff water during precipitation which causes the leaching of limestone watersheds.

Other elements are low such as nitrates (1.29 mg/l), ammonium (1.56 mg/l), fluorides (410 µg/l), iron (350 µg/l) and manganese (35 µg/l). Low nitrate and nitrite values show the absence of an influence of agricultural activity on the lake.

Measurements of the water conductivity of Lake Sidi Boughaba do not show large variations during the year of study. The only remark is that the northern part of the Merja is characterized by significant values of conductivity. Monitoring the quality of the sampled waters made it possible to observe that the spatiotemporal evolution of the physicochemical parameters of the Lake waters varies from one station to another.

The salinity of the waters of the Lake expressed in µs/cm oscillates between a minimum of 1589 and a maximum of 2650, with an average of 1935. These variations are under the influence of periodic changes in climate and temperature the flood period and low flow period; precipitation and evaporation.

The low conductivity values were recorded in winter at 1589 µs/cm, the average values in spring at 2650 µs/cm, and the highest values were observed during the low-water period at 29,600 µs/cm. These strong variations in salinity are due to precipitation in winter and strong evaporation in summer, accentuated by marine intrusion.

Lake Sidi Boughaba is only affected by seasonal salinization and an increase in pollution from organic matter, which can lead to summer eutrophication.

3.2. Inventory of Macroinvertebrate Fauna

Lake Sidi Boughaba is one of the last natural expanses of permanent water on the northwest coast of Morocco. This Merja, with its variety of natural biotopes (freshwater, brackish, temporary, permanent, and those little or not influenced by Humans), presents a particularly interesting site for hydrobiological and ecotoxicological work. Indeed, except for the very old work of Thévenot devoted to avifauna and those on the physicochemical study and faunistic analysis in this site, no work has been published on the use of biological methods (biological index IB) to evaluate the quality of the water of Lake Sidi Boughaba [16, 26]. The assessment of the biological quality of freshwater is based on the study of benthic macroinvertebrates using a method derived from Biotic Indices [32].

In this work, we have focused, more particularly, on drawing up an exhaustive taxonomic inventory of zoobenthic groups indicating pollution of the waters of Lake Sidi Boughaba (**Table 5**), along with the use of a biological method, simple, fast, and effective for determining water quality.

Table 5. Inventory of zoobenthos at the level of Lake Sidi Boughaba classified by Phyllum, Order, family and species.

Crustacea Amphipods	**Insects**	**Insects Coleoptera**
Gammarus sp.	Diptera	Helodidae
CrustaceaIsopods	Tipulidae	Helophoridae
Asellus sp.	Psychodidae	Hydrophilidae
Mollusca Gastropods	Ceratopogonidae	Dytiscidae
Physa acuta	Chironomidae	Hydraenidae
Annelids Oligochaetes	Stratiomyiidae	Elmidae
Lumbricidae	Tabanidae	
Lumbriculidae	Athericidae	Insects Trichoptera
	Culicidae	Hydropsychidae
Insects Odonata	Syrphidae	Insects Orthoptera
Agrion sp.	Tanypoidae	Gryllides
Cordulida sp.	Insects Heteroptera	
Sympetrum sp.	*Corixa* sp.	
	Notonecta sp.	

At the end of our study, we can conclude that Lake Sidi Boughaba exhibits a diverse array of macroinvertebrates across the four stations throughout the year. The examination of the faunal inventory table shows the presence of groups with a wide distribution, which appear in all the stations and exclusive groups located in one or two stations. Oligochaetes (Lumbricidae and Lumbriculidae) are present only at the level of S1 and S2 for the four seasons (**Table 6**).

Table 6. Result of the seasonal count of macroinvertebrates at Lake Sidi Boughaba.

Season	**Summer**				**Autumn**				**Winter**				**Spring**			
Taxa/Stations	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Amphipods																
Gammarus sp.	-	-	-	-	-	-	+	-	-	-	+	-	-	-	+	-
Isopods																
Asellus sp.	-	-	-	-	-	+	-	-	+	-	+	-	+	-	-	-
Gastropods																
Physa acuta	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+
Melanopsis praemorsa	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+
Oligochaetes																
Lumbricidae	+	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
Lumbriculidae	+	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
Insects																
Diptera																
Tipulidae	-	+	+	-	-	-	+	+	-	+	-	-	+	+	-	-
Psychodidae	+	+	-	-	+	+	+	-	-	-	+	-	-	-	+	-
Ceratopogonidae	+	+	+	-	+	+	+	+	+	+	+	-	+	+	+	+
Chironomidae	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+
Stratiomyiidae	+	+	+	-	+	+	+	+	-	+	-	+	-	-	-	-
Tabanidae	-	-	-	-	+	-	+	+	-	-	-	-	+	+	-	-
Athericidae	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
Culicidae	-	-	-	-	-	-	+	+	-	-	+	+	+	+	-	+
Syrphidae	+	+	-	-	-	-	+	+	-	+	-	+	+	-	+	+
Tanypoidae	-	-	-	-	-	-	-	-	+	+	+	-	-	+	+	-
Coleoptera																
Helodidae	-	-	-	-	+	+	-	-	+	-	-	-	-	-	-	-
Helophoridae	+	+	-	-	+	+	+	+	+	-	+	+	-	+	+	-
Hydrophilidae	-	-	-	-	+	-	-	-	+	+	+	+	-	+	-	-

Table 6. *Cont.*

Season	Summer				Autumn				Winter				Spring			
Dytiscidae	-	-	-	-	-	-	-	-	-	+	+	+	+	+	-	+
Hydraenidae	-	-	-	-	-	-	-	-	-	+	-	-	+	+	+	+
Elmidae	-	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-
Odonata																
Agrion sp.	-	+	+	+	+	+	-	+	+	+	+	+	+	+	+	-
Cordulida sp.	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+
Sympetrum sp.	+	+	+	-	+	-	+	-	-	-	-	-	-	-	-	-
Heteroptera																
Corixa sp.	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+
Notonecta sp.	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+
Trichoptera																
Hydropsychidae	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Orthoptera																
Gryllidae	+	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
Number of Systematic Units	11	13	7	1	16	16	16	13	14	16	14	14	18	19	14	11
Biotic Index (BI)	6	6	5	3	7	7	7	6	6	7	6	7	7	7	6	6
Classe	3	3	3	2	4	4	4	3	3	4	3	4	4	4	3	3

Gastropods (*Physa acuta* and *Melanopsis praemorsa*) are present in the fourteen stations during the fall, winter and spring and are absent during the summer.

Insects (Chironomidae and Ceratopogonidae) were observed at all fourteen stations throughout the study period.

In Lake Sidi Boughaba, we noted the almost general absence of Plecoptera and Ephemeroptera, groups most sensitive to pollution. On the other hand, Odonata and Gammaridae crustaceans are quite abundant. But we especially note the predominance of Diptera larvae (mainly Chironomidae and Ceratopogonidae) and Oligochaetes (lumbricidae and lumbriculidae).

Which allowed us to deduce that the BI presents values varying from 5 to 7 (classes 3 and 4), which shows an average to low organic pollution. On the other hand, during the summer season, it has a value of 3 (class 2), implying a high pollution by organic matter.

3.3. Bird Inventory

Thanks to its privileged coastal location on the bird migration route, Lake Sidi Boughaba showed great ornithological richness (**Table 7**). Totally, 171 species were observed, of which 95 are regular, 34 occasional, 35 accidental, and seven pelagic [16]. Currently, due to the degradation of the environment and human disturbances, only 61 species of aquatic birds were observed during the present study, of which 50 are regular, eight occasional, and three accidental.

Anatidae constitute the most dominant group in species all year round, including 15 species encountered during the study period. The predominant species are the Mallard *Anas platyrhynchos*, Marbled Teal *Marmaronetta angustirostris* and the Northern Shoveler *Anas clypeata*.

Waders are in second position in terms of actual numbers, but in first position in terms of species richness: 29 species including 22 observed during the study period, the Black-winged Stilt *Himantopus himantopus*, Kentish Plover *Charadrius alexandrinus*, Common Snipe *Gallinago gallinago* and Eurasian Curlew *Numenius arquata* being the most dominant.

Laridae 13 species including seven recorded during the study period. Laridae are mainly represented by the Lesser Black-backed Gull *Larus fuscus*, the Black-headed Gull *Larus ridibundus*, the Little Tern *Sterna albifrons* and the Black Tern Chlidonias niger also have remarkable numbers. Ardeidae and Rallidae are each represented by five species with the dominance of two species each: the Grey Heron *Ardea cinerea* and the Little Egret *Egretta garzetta* for Ardeidae and the Eurasian Coot *Fulica atra* and the Crested Coot *Fulica cristata* for Rallidae. In Podicipedidae, and even though the specific richness does not exceed three species, the Little Grebe *Tachybaptus ruficollis* is by far among the most dominant species in Lake Sidi Boughaba.

The other families, with low specific richness, total eight species recorded during the study period, among which are the Great Cormorant *Phalacrocorax carbo*, the Eurasian Spoonbill *Platalea leucorodia* and the Greater Flamingo *Phoenicopterus ruber*.

Table 7. Results of waterbird observations in Lake Sidi Boughaba during the year 2023.

Species	Species	Species
Tachybaptus ruficollis	*Tadorna tadorna*	*Calidris alpina*
Podiceps cristatus	*Marmaronetta angustirostris*	*Calidris minuta*
Podiceps nigricollis	*Netta rufina*	*Gallinago gallinago*
Phalacrocorax carbo	*Aythya ferina*	*Limosa limosa*
Phalacrocorax aristotelis	*Aythya nyroca*	*Limosa lapponica*
Nycticorax nycticorax	*Aythya fuligula*	*Numenius phaeopus*
Bubulcus ibis	*Aythya marila*	*Numenius arquata*
Ardea cinerea	*Circus aeruginosus*	*Tringa erythropus*
Ardea purpurea	*Rallus aquaticus*	*Tringa totanus*
Egretta garzetta	*Gallinula chloropus*	*Tringa nebularia*
Platalea leucorodia	*Porphyrio porphyrio*	*Tringa ochropus*
Ciconia Ciconia	*Fulica atra*	*Tringa hypoleucos*
Ciconia nigra	*Fulica cristata*	*Larus audouinii*
Phoenicopterus ruber	*Haematopus ostralegus*	*Larus cachinnans*
Tadorna tadorna	*Himantopus himantopus*	*Larus fuscus*
Casarca ferruginea	*Recurvirostra avosetta*	*Larus ridibundus*
Anas Penelope	*Burhinus oedicnemus*	*Sterna sandvicensis*
Anas strepera	*Vanellus vanellus*	*Sterna albifrons*
Anas crecca	*Pluvialis squatarola*	*Chlidonias niger*
Anas platyrhynchos	*Charadrius hiaticula*	*Asio capensis*
Anas acuta	*Charadrius alexandrinus*	
Anas querquedula	*Charadrius dubius*	
Anas clypeata	*Calidris ferruginea*	

4. Discussion

The hydrochemical investigation made it possible to define facies of sodium chloride-type waters with a salinity between 7 and 14.8 g/l. This mineralization is essentially evaporitic and is controlled by various processes, such as evaporation and marine influence by aerosols, sea spray and problems by marine intrusion at depth.

Water salinity presents one of the major problems in Morocco, given its devastating effect on water quality. It is often linked to the dissolution of geological formations, the effect of evaporation, and the effect of marine intrusion [34, 39].

Lake Sidi Boughaba is a closed reservoir located in an interdune depression. The geographical location of the lake is at a level lower than that of the piezometric surface of the coastal water table. Therefore, it is fed more particularly by the water table. Contrary to what one might believe, the lake has no communication with the ocean waters of Mehdia beach or with salty groundwater. But during the drop in the water table level in summer and the increase in evaporation and marine intrusion the lake becomes salty.

Our present results of the summer salinization of the waters of Lake Sidi Boughaba confirm and complete the results reported by several previous studies [20–22, 34]. However, unlike our previous work, the present study, by its multi-criteria nature, made it possible to explain the seasonality of salinization and linked the scarcity of macroinvertebrates to the increase in salinity.

The qualitative variations of invertebrate fauna can be due to the influence of the physicochemical factors of the environment in particular the temperature and dissolved oxygen. As well as the discharge of organic waste and the leaching of soils from forests in neighboring regions.

Indeed, the groups most sensitive to pollution are relatively absent and we obtained: ten Genera (one of Amphipod, one of Isopod, two of Gastropod, three of Odonata, two of Heteroptera and one of Orthoptera), nineteen Families (ten of Diptera, six of Coleoptera, two of Oligochaeta and one of Trichoptera). The calculated BI varies from 5 to 7, and which classifies these waters in classes 2 to 4 which shows an average to low pollution by organic matter (**Table 5**).

5. Conclusions

This work has focused, more particularly, on drawing up an exhaustive taxonomic inventory of zoobenthic groups indicating pollution of the waters of Lake Sidi Boughaba, together with the use of a biological method, simple, fast and effective for determining water quality.

Our study, on the one hand, confirms the importance of the coastal lake to provide a calm and vast refuge for migratory and sedentary birds and also a habitat for several species of global importance.

On the other hand, it concludes that Lake Sidi Boughaba is classified in the category of oligomesotrophic lakes and that it is too threatened by the progressive transformation of its fresh waters into brackish waters and consequently the modification of its benthic and planktonic fauna necessary for the feeding of avian fauna.

This study further concludes that this wetland is also threatened by siltation due to erosion of the dune slopes and the transport and deposition of clays in the lake. This phenomenon threatens the long-term sustainability of the lake and its biodiversity. Innovative hydraulic developments will be necessary.

Author Contributions

Conceptualization, D.B.; methodology, D.B., S.A.-S., M.A., and F.A.; software, E.H.; validation, D.B. and H.E.; formal analysis, E.H.; investigation, M.M.; resources, D.B.; data curation, E.H.; writing—original draft preparation, M.M., K.E.K., and D.B.; writing—review and editing, M.M., K.E.K., and D.B.; visualization, E.H.; supervision, D.B.; project administration, D.B and B.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article. The research was conducted independently, and no financial or personal relationships exist that could have influenced the work reported in this study.

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