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Original article

Climate Change and Its Impact on Ecological Succession in Lake Trouna, Southern Libya

Ambark Mustafa[1*], Fatima Sheba[2], Abdulraof Masoud[3]

[1]*Department of Environmental Sciences, Faculty of Environment and Natural Resources, University of Wadi Al-Shatti, Libya.*
[2]*Department of Environmental and Occupational Health and Safety, Faculty of Environment and Natural Resources – University of Wadi Al-Shatti, Libya.*
[3]*Environmental Sanitation, Al-Ghreefa Municipality, Libya.*
Corresponding email. Amb.mustafa@wau.edu.ly

Abstract
Lake Trouna reflects successive environmental changes that have occurred in the Libyan Sahara over thousands of years, making it a unique model for studying climate change and ecological succession. Monitoring these changes is therefore essential to understanding the impact of climate variability on aquatic ecosystems and ensuring their sustainability. The ecosystem of Lake Trouna exhibits distinct chemical, physical, and biological characteristics and undergoes significant transformations due to both environmental and anthropogenic factors, affecting its water body, vegetation cover, and surrounding land. These influences contribute to the acceleration of ecological succession. water properties of the lake indicate very high electrical conductivity, reflecting its elevated salinity due to the high concentration of total dissolved solids (TDS). This condition is accompanied by increased levels of nutrients, such as nitrates and phosphates, which contribute to eutrophication and accelerate ecological succession. The high concentrations of sodium and potassium in the fringe soil suggest that the lake water contains these elements, originating from the geological composition of the underlying rocks. This mineral composition influences the life cycles and survival of aquatic organisms. Moreover, the soils surrounding the lake, particularly within the vegetated areas, exhibit a relatively high organic matter content, especially in regions with dense plant cover. This factor plays a supportive role in facilitating ecological succession by creating favorable conditions for its progression.
Keywords: Climate Change, Ecological Impact, Succession, Ecosystem, Saline Lakes.

Introduction

Libya is located in the tropical and subtropical regions of North Africa, where the Sahara Desert extends, covering most of the country's land under extreme arid climatic conditions. The Fezzan Desert is one of the most significant regions of the Greater Sahara, situated in southwestern Libya. The Fezzan region consists of a vast basin intersected by several depressions and valleys from the north, bordered by the southern edge of the Hamada Al-Hamra plateau and the Black Mountain region. To the east, it is bounded by the Haruj highlands, while the Tassili Mountains mark its western boundary [1].

Numerous scientific studies conducted by international research teams from various institutes and universities indicate that the lakes scattered across the Ubari Sand Sea (Adhan Ubari) are remnants of a large ancient lake that once covered extensive areas of the Libyan Desert. Between 1942 and 1952, the scientist Perofret discovered marine limestone sedimentary rocks rich in mollusk fossils, supporting the theory that the Libyan Desert was once home to a vast mythical lake that disappeared due to climatic changes over successive historical periods [2].

A scientific research team from the University of London conducted historical studies on gypsum deposits and soil in the region using radiocarbon dating and Sigma-ray analysis techniques. Their findings suggest that the lake dates back approximately 10,000 years, during which it underwent periodic evaporation due to intense solar exposure. The studies also revealed that the most severe drought occurred at the end of the Ice Age, as evidenced by sediment layers in different parts of the desert, indicating the transformation of the large lake into smaller lakes that now lie hidden among the dunes of the Ubari Sand Sea. These findings confirm the existence of a glacial-era lake [3].

Before 6,000 years ago, the Fezzan region was a massive lake during a wet climatic phase before undergoing ecological succession, eventually shrinking into smaller lakes. Over time, the area became fully desertified, leaving only a few remaining lakes, such as Lake Gaber Aoun, which represents the final stage of the Fezzan mega-lake's succession. This ancient lake once covered an area of approximately 150,000 km², with a maximum depth of 80–100 meters recorded in the Mahruqa area [4].

By tracing ancient river systems through stratigraphic studies at various desert sites, researchers have identified sedimentary deposits from the large lake, which fragmented into smaller lakes now concealed among the dunes of the Ubari Sand Sea. Several pieces of evidence, including the presence of scattered lakes such as Umm Al-Maa, Mandara, Gaberoun, Mafu, Nashnusha, and Al-Tarouna, confirm the remains of this ancient lake [5].

Lake of Trouna Al-Hamra (also known as the "Blood Lake") is located 90 km northeast of Ubari and approximately 1,180 km from Tripoli. It is considered one of the most beautiful and mysterious lakes in the

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world. Its striking red color is caused by the presence of red-pigmented crustaceans and a unique type of algae that produces a red pigment capable of absorbing light [6]. The lake is also highly saline and contains red trona (magnesium bicarbonate), also known as "Epsom salt." In Libya, it is commonly referred to as the "Lake of Blood." The sodium bicarbonate found in the lake is a valuable substance used in various industrial applications [7].
The study of aquatic systems, particularly from a biological perspective, began when research indicated the emergence of a new scientific discipline within ecology—Aquatic Ecology and Hydrobiology—pioneered by scientists such as Kestantenov, Golterman, Wetzel, and others, alongside contributions from hydrologists (Hydrology) and marine geographers (Oceanography). This field has since established fundamental principles for classifying water bodies based on research objectives, aquaculture, or water utilization for agricultural, industrial, and service-related purposes [8].
Ecological succession is a natural process that occurs within ecosystems and manifests in two primary forms: terrestrial succession and aquatic succession. Aquatic succession takes place in water-based environments such as ponds, lakes, and marshes, progressing through a series of stages [7].
This process in aquatic ecosystems is characterized by a shorter timeframe compared to terrestrial succession. Microorganisms, such as algae, diatoms, crustaceans, and floating plants, often begin to appear within just a few days due to their rapid life cycles.
In relatively stable aquatic systems, the stages of succession can be clearly observed. The process begins with the colonization of phytoplankton, which are considered pioneer species, primarily comprising algae. Following this, submerged vegetation emerges, followed by floating plants. As the process continues, the system reaches the reed-swamp stage, then the marsh-meadow stage. Subsequently, the environment evolves into the shrubland phase, ultimately reaching the climax forest stage.
In this manner, ecological succession in aquatic environments reflects the dynamic nature of life and the interactions of living organisms with their surrounding habitats [7]. This study aims to assess the current ecological status of Lake Trouna and its future implications by evaluating the physicochemical properties of the lake water, identifying the successional stage of the ecosystem, and analysing the ecological impacts of ongoing succession. Furthermore, the study provides management recommendations for ecological preservation.

Methods

Study Area

The study was conducted at Lake Trouna, located in Fezzan, southern Libya (Wadi Al-Hayat region), between longitudes 13.384447°E and latitudes 26.929086°N, near the city of Ubari, surrounded by sand dunes.

Sample Collection

Water and soil samples were collected from geographically distinct sites around the lake, including the east, north, west, south, and center. Due to environmental variability, some of these locations were further divided into sub-sites. Two sub-sites were identified in the east, three in the south, two in the west, three in the north, and one in the center.
Water samples (1 L, duplicated per site) were collected in plastic bottles for physicochemical analysis. Soil samples (lakeshore, submerged, and vegetated zones) were also collected. Field visits were conducted in winter (13/12/2022) and summer (14/07/2023).

Climatic Factors

Temperature & Humidity

Air temperature (inside/outside vegetation) was measured using a Zeal thermometer (Model B.S2841, UK). Ubari's desert climate exhibits extreme seasonal variations Winter: Max. 29°C (noon), dropping to 26°C by 6:30 PM; humidity peaked at 46% (4:30 PM). Summer: Max. 47°C (noon), dropping to 32°C; humidity ranged from 18% to 24%.

Physicochemical Water Analysis

The physicochemical properties of the lake water were analyzed using standard laboratory techniques. The pH values were measured with a HANNA pH meter (HI8314) [9], ensuring accurate readings at each sampling site. To assess salinity, electrical conductivity (EC) was determined using a JENWA conductivity meter (Model 4310), with all values corrected to 25°C to standardize the data [10]. EC25=ECt×ftEC25=ECt×ft . Total dissolved solids (TDS) were calculated based on the corresponding EC values following established conversion protocols [9]. Nutrient concentrations were evaluated through spectrophotometric analysis. Phosphate (PO_4^{3-}) levels were determined using a UV-Vis spectrophotometer operating at a wavelength of 470 nm [11], while nitrate (NO_3^-) concentrations were measured at 220 nm and corrected for organic matter interference at 275 nm [8]. These methods allowed for precise quantification of nutrient loads contributing to the lake's trophic dynamics.

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The physicochemical properties of soil samples collected from different zones around Lake Trouna—including shoreline, vegetated, and submerged areas—were assessed using established analytical procedures. Soil pH was measured using the same method applied to water samples, utilizing a calibrated pH meter to ensure consistency and accuracy. Electrical conductivity (EC) was also measured following the same technique used for water, enabling the detection of salinity levels within the soil matrix. To determine the organic matter content in the soil, samples were first dried and then combusted in a muffle furnace at a temperature range of 500–600°C for approximately seven hours. The resulting weight loss was used to calculate the percentage of organic matter, following the formula:

Organic Matter (%) = (Weight Loss / Original Weight) × 100.

Results

Climatic Conditions

Ubari's arid climate features:

Winter Daytime temps. up to 29°C; humidity 44–46%. Summer: Temps. reached 47°C; humidity <25%. (Data illustrated in Figure 1.)

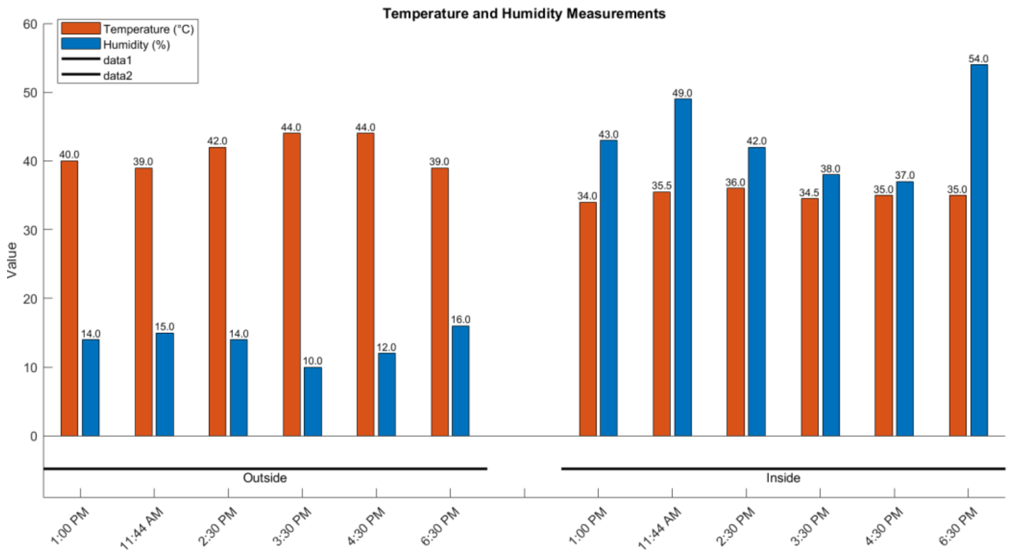

Figure 1. The temperature and humidity levels inside the lake during the winter season.

In the summer season, the temperature inside the lake reached 36°C during the afternoon, then dropped to 35°C by 6:30 PM. The humidity was 54% at 1:00 PM and decreased to 37% by 6:30 PM. Outside the lake area, the highest recorded temperature was 44°C, which gradually declined to 39°C. Meanwhile, the humidity was 16% at 6:30 PM, as illustrated in Figure 2.

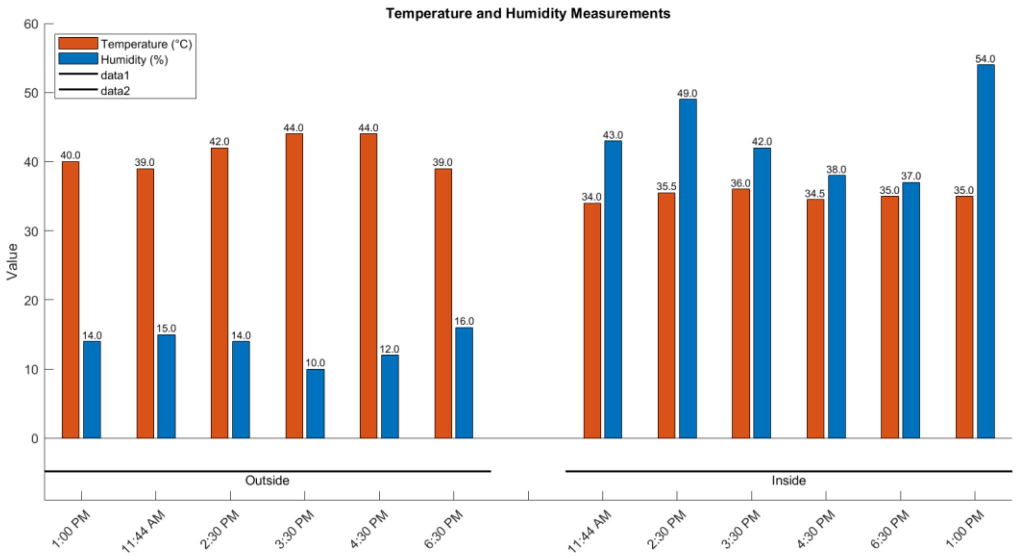

Figure 2. Illustrates the temperature and humidity levels within the lake during the summer season

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Temperature is considered one of the main environmental factors influencing many other variables, such as humidity and the rate of evaporation [12]. Consequently, the presence of favorable temperature conditions accelerates the spread of pioneer species across a wider area of the ecosystem and enhances the ecological succession process [13]. The presence of Lake Al-Tarhuna in the Ubari region plays a vital role in shaping the local climate, as the lake contributes to the creation of environments more conducive to biological growth and accelerates ecological succession. This underscores the critical importance of water in desert ecosystems.

Physical and Chemical Properties of Lake Water

pH Level

During the first phase (December), the pH values were observed to be relatively consistent across all sampling sites in the lake. The pH readings were as follows: 10.18 in the eastern part, 10.19 in the northern part, 10.04 in the western part, and 10.09 in the southern part. The sample taken from the center of the lake recorded a pH of 10.2, as shown in Figure 3-A. In the second phase, there were only minor variations in pH levels, as illustrated in Figure 3-B. The elevated pH values indicate a distinctly alkaline nature of the lake water, creating an environment unsuitable for the growth of many organisms. However, it may support specific types of algae and microorganisms that are adapted to such conditions. Although high temperatures generally reduce pH, in extremely saline environments like Lake Al-Tarhuna, this effect is minimal. This is due to the dominance of other ion concentrations such as Na^+, K^+, and HCO_3^-, which override the thermal influence and help maintain a high pH level throughout the year.

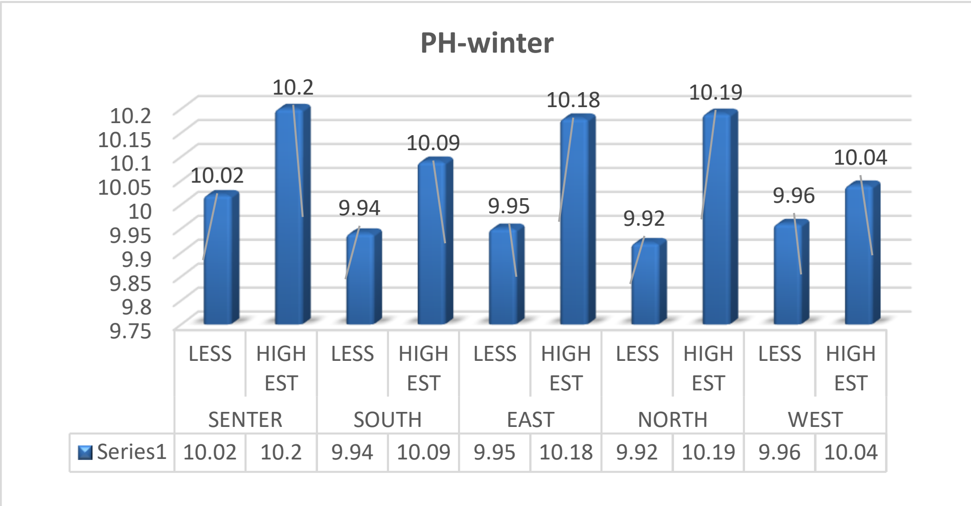

Figure 3A. The pH values of the lake water during the initial stage.

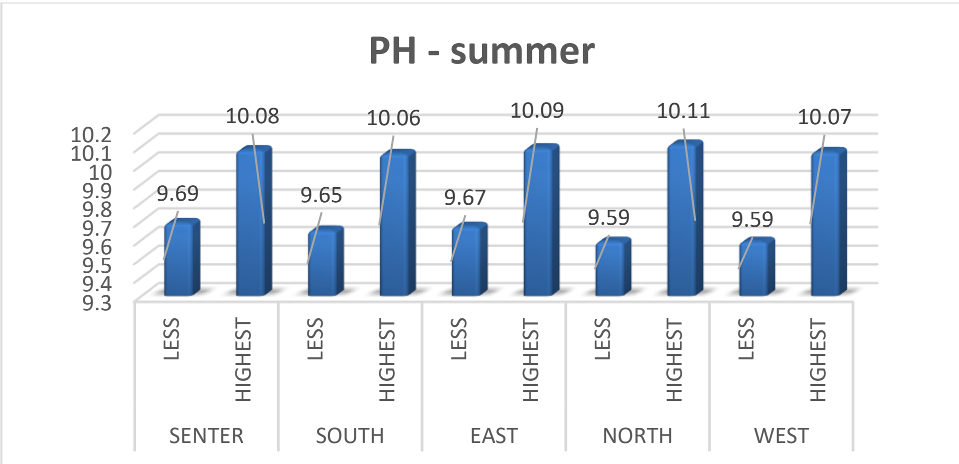

Figure 3B. The pH values of the lake water during the second phase.

Electrical Conductivity (EC)

Salinity in Lake Al-Tarhuna was assessed by measuring the electrical conductivity (EC) during two different seasons: winter and summer. In the first phase (winter season), the highest EC value was recorded at the center of the lake, reaching 351.50 µS/cm, while the lowest was observed in the eastern part at 336.90

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µS/cm. The average EC values in the western, southern, and northern parts were 350.12, 346.14, and 344.71 µS/cm, respectively, as shown in Figure (4-A). In the second phase (summer season), the highest EC value also appeared in the center of the lake, increasing to 658 µS/cm, while the northern part recorded the lowest value at 599.31 µS/cm, as shown in Figure (4-B). The presence of submerged reed plants and a significant number of algae contributed to the dark coloration of the water, indicating the occurrence of organic nutrient decomposition. The similarity in EC values across the studied sites may be attributed to the widespread distribution of algae and aquatic organisms, in addition to the growth of plants such as reeds. Vegetation around the lake helps absorb ionic salts from the water; nevertheless, the eastern sector was the only area where values rose relative to the other sectors. Elevated electrical-conductivity readings signify high concentrations of total dissolved solids (TDS) in the lake water, which have intensified salinity. This rise in salinity has clear ecological implications, playing a decisive role in determining both the composition and abundance of aquatic organisms, as noted by [14]. The present study demonstrates that salinity in Lake Al-Tarhuna is season-dependent: conductivity values differ between winter and summer, and environmental factors such as the presence of macrophytes and algae directly influence the aquatic environment and govern the quality of aquatic life in the region.

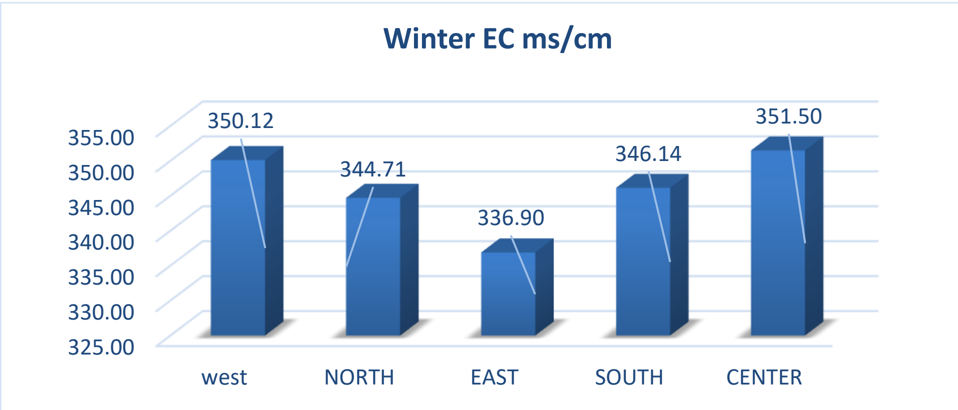

Figure 4A. The electrical conductivity (EC) values of the lake water during the initial phase.

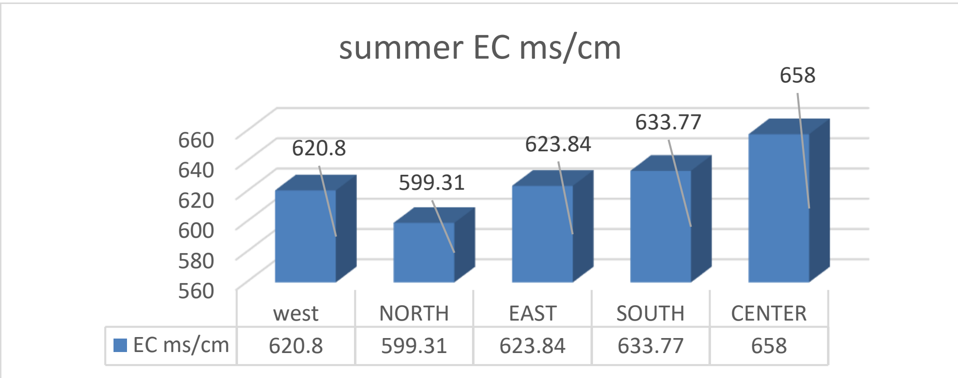

Figure 4B. The electrical conductivity values of lake water during the second phase.

Total Dissolved Solids (TDS)

The study revealed that during the first phase, representing the winter season, the highest average TDS value was recorded at the center of the lake, reaching 224.96 g/L. In contrast, the lowest value was recorded in the eastern part, at 215.62 g/L. The TDS values for the western, northern, and southern parts were 224.08, 220.62, and 221.53 g/L, respectively, as illustrated in Figure (5-A). In the second phase, representing the summer season, the highest TDS value was again observed at the center of the lake, reaching 421.12 g/L, while the lowest value was recorded in the northern part at 383.56 g/L. The southern, eastern, and western parts recorded values of 405.61, 399.26, and 383.56 g/L, respectively, as shown in Figure (5-B). The increase in TDS values during the summer may be attributed to the effect of high temperatures, in addition to other factors such as the density of algae and phytoplankton [15]. Consequently, electrical conductivity (EC) values are influenced by changes in TDS levels depending on location, which is consistent with the findings of [16].

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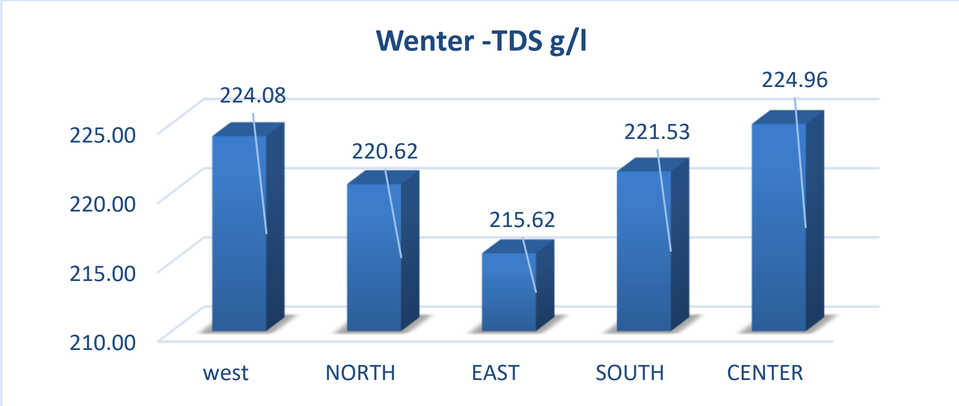

Figure 5A. Total dissolved solids (TDS) concentration in lake water during the initial phase.

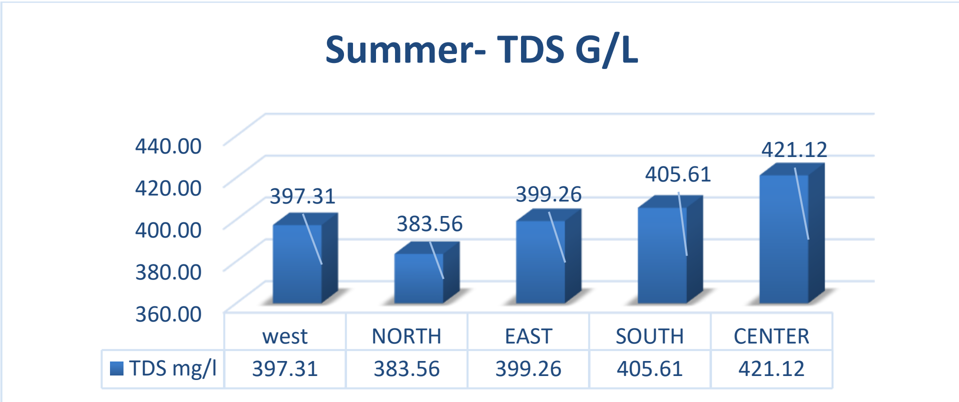

Figure 5B. The concentration of total dissolved solids (TDS) in lake water during the second phase.

Phosphate (PO_4)

The results of phosphate (PO_4) measurements during the first phase, representing the winter season, showed relatively similar averages across the different sampling sites. The highest phosphate concentration was recorded in the southern part of the lake at 74.7 mg/L, while the lowest was in the western part at 53.5 mg/L. The average phosphate concentrations in the northern part, the center of the lake, and the eastern part were 67.2, 70, and 63.6 mg/L, respectively, as shown in Figure (6-A). In the second phase, representing the summer season, there was a noticeable increase in average phosphate concentrations compared to the first phase. The southern part again recorded the highest concentration at 161 mg/L, while the lowest was in the eastern part at 80.8 mg/L. The average values in the western, northern, and central parts were 152.9, 82.4, and 81.8 mg/L, respectively, as shown in Figure (6-B). Phosphate can exist in aquatic environments in both organic and inorganic forms. The significant rise in phosphate concentration during the second phase may indicate increased organic decomposition, which could result from heightened biological activity. These findings suggest that phosphate levels in Lake Al-Tarhuna are influenced by seasonal environmental factors, with higher values observed in the summer. This increase may impact water quality and contribute to phenomena such as algal blooms, highlighting the need to monitor phosphate levels to ensure the ecological health of the lake

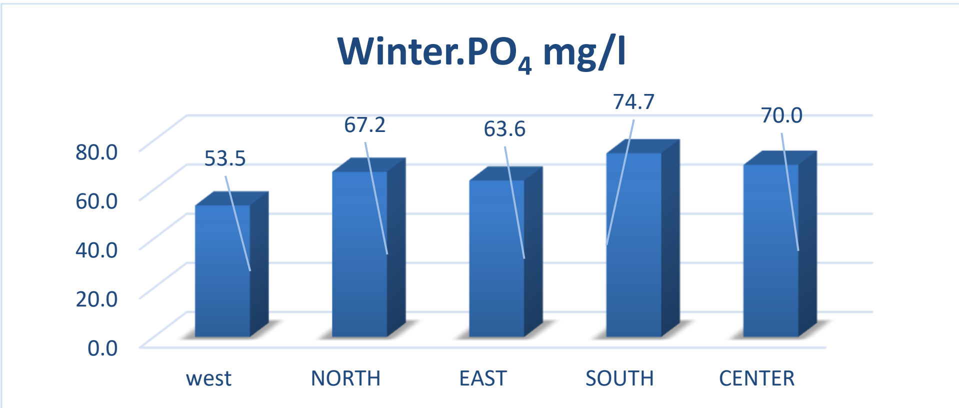

Figure 6A. The average phosphate (PO_4^{3-}) concentrations in the lake water during the initial phase.

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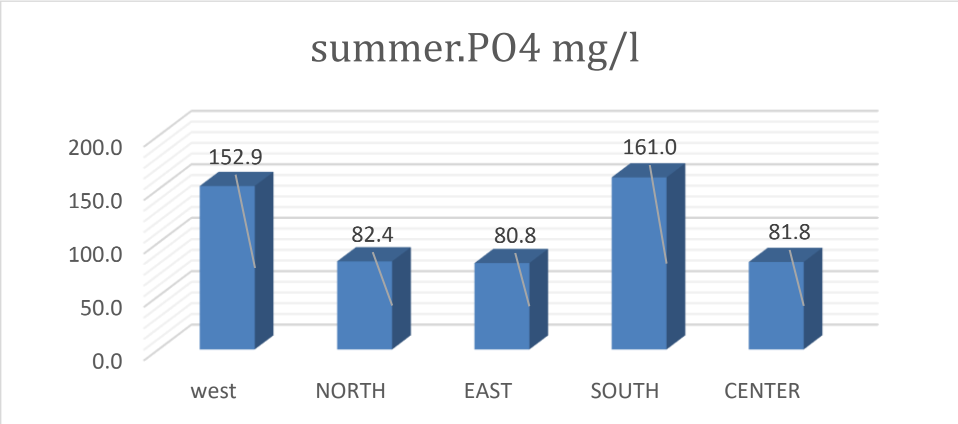

Figure 6B. The average phosphate concentrations in lake water during the second phase.

Nitrate (NO_3)

In the first phase (winter season), the average nitrate concentration in the center of the lake was 5.8 mg/L, which was the highest recorded average. Nitrate values in the southern and western parts were close, measuring 5.1 and 5.4 mg/L, respectively. The lowest values were observed in the eastern and northern parts, each recording 5 mg/L, as shown in Figure (7-A). In the second phase, the average nitrate concentration in the center of the lake increased to 6.44 mg/L, again the highest recorded value. The northern and western parts showed similar values of 6.13 and 6.15 mg/L, respectively. The lowest concentration was recorded in the eastern part, at 5.83 mg/L, as illustrated in Figure (7-B). The presence of nitrate indicates ongoing organic decomposition of plant residues. Through biochemical reactions in the water, ammonia compounds (NH_4^+) are formed, and decomposition processes intensify with rising temperatures. Waste from human activities also contributes to increased nitrate concentrations in lake water. These values are higher than those reported in the study by [17].

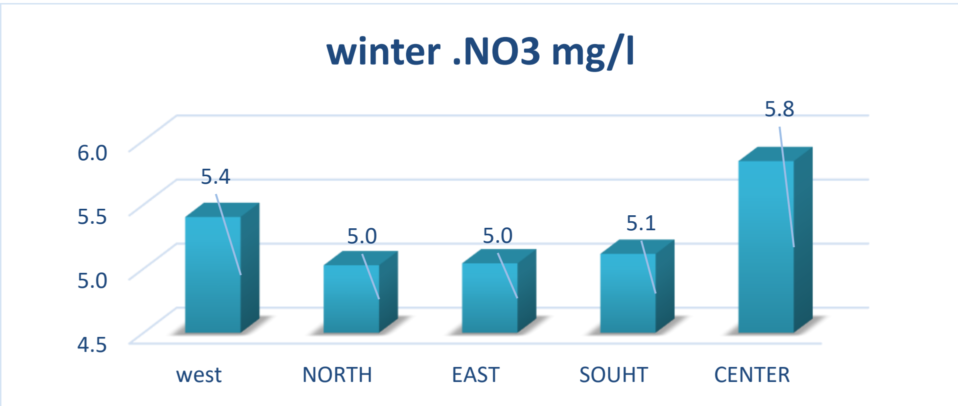

Figure 7A. Nitrate (NO_3^-) concentration in lake water during the initial phase.

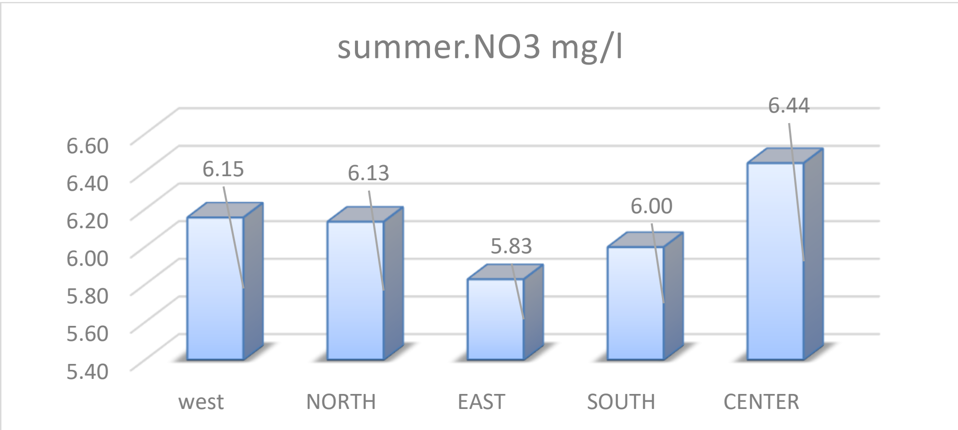

Figure 7B. The nitrate concentrations in lake water during the second phase.

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Physical and Chemical Properties of the Soil

pH *(Hydrogen Ion Concentration):*

The results indicate no significant variations in the pH values of the studied soils, except in a few locations. The eastern area recorded the lowest pH value at 7.37 in soil outside the vegetation cover. In contrast, the southern area recorded the highest pH value at 10.80 in the first site of the edge soil. For soils within the vegetation cover, pH values were relatively consistent across the other locations. In the northern area, the highest value was 10.20 at the second site of the vegetated soil. Similar values were observed between the first and second sites in the western area, ranging from 10.40 to 10.30. In the southern area, values were also close, with the second sites recording 9.78, 10.1, and 10.2 respectively, as shown in Figure (8).

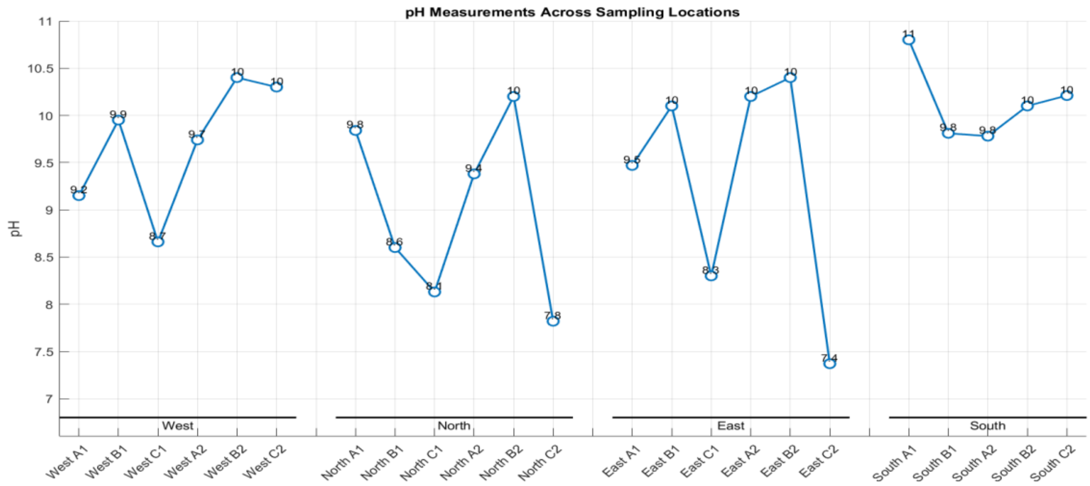

Figure 8. The pH levels of the lake's soil.

Electrical Conductivity

The results indicate elevated electrical conductivity (EC) values in the shoreline soil, with the highest average of 14.3 mS/cm recorded at two eastern sites, demonstrating severe soil salinization, as evidenced by the soil's visual characteristics. In contrast, the lowest value (5.7 mS/cm) was recorded at the first sampling point of vegetated soil in the northern sector. The values varied according to soil type and distance from the water body, with the highest readings in shoreline soil, followed by vegetated soil, and then non-vegetated soil, as illustrated in Figure (9).

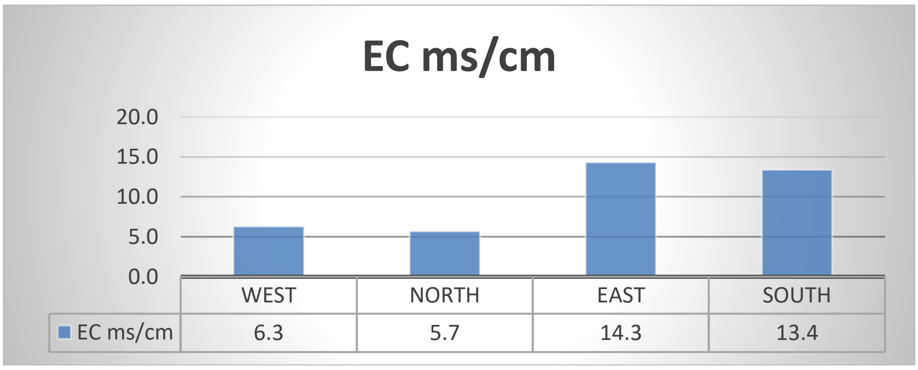

Figure 9. The electrical conductivity (EC) of the lake soil.

Organic Matter in Soil

The study revealed that the highest concentration of organic matter in the soil was recorded in the vegetated soil of the southern sector, reaching 0.096 mg/kg, while the lowest value (0.012 mg/kg) was observed in the shoreline soil of the northern sector (Site 1). The eastern shoreline soil registered an intermediate value of 0.075 mg/kg. Figure (10) illustrates the spatial distribution of organic matter across different soil types and directional sectors. Plant diversity exhibits a strong correlation with soil and water conditions, as vegetation contributes organic matter to the soil, which decomposes into nutrients upon plant senescence. This decomposition process depends on soil moisture availability and the presenc of microorganisms facilitating organic matter breakdown [8].

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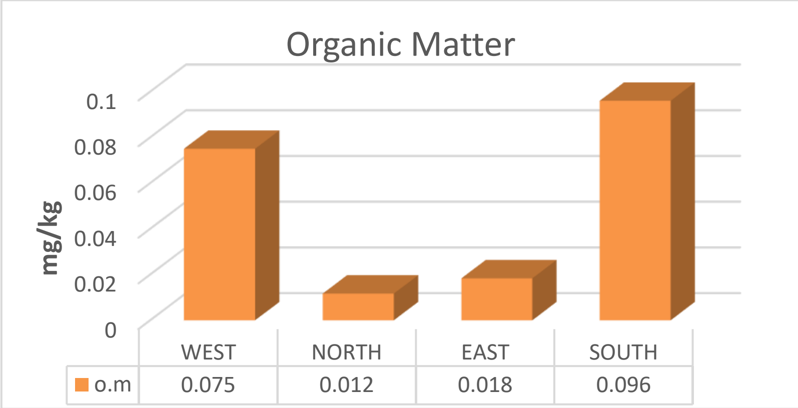

Figure 10. Organic matter content in lake soil.

Sodium and Potassium in Soil

The potassium (K^+) measurements showed elevated levels in shoreline soil at site A2, with the highest concentration (592 mg/L) recorded in the eastern sector, while the lowest value (3.3 mg/L) was observed in the northern sector. In vegetated soil, peak potassium levels (403 mg/L) were detected at site B2 in the eastern sector.

Regarding sodium (Na^+), the maximum concentration (686 mg/L) was found in vegetated soil at site B2 (eastern sector), whereas the minimum value (30 mg/L) was recorded at site C2 in the northern sector, as illustrated in Figure (11). The elevated sodium and potassium levels in shoreline soils can be attributed to High evaporation rates of water and Absence of vegetation near the water body (extending approximately 50 meters) and Formation of a surface salt-crust layer composed of crystalline deposits and Progressive expansion of this saline layer over time [18].

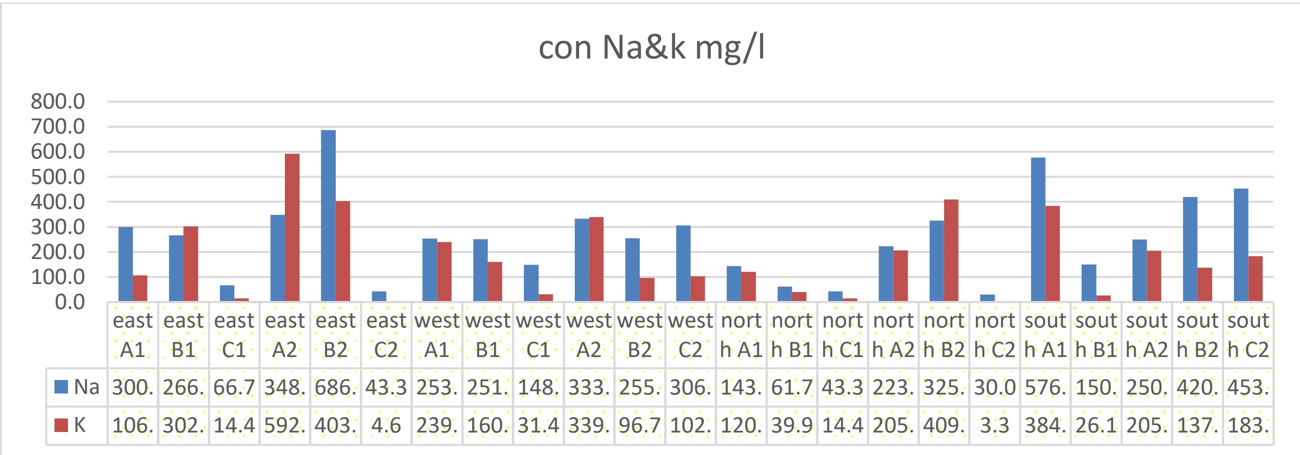

Figure 11. Sodium (Na^+) and potassium (K^+) concentrations in soils surrounding the lake.

Discussion

The findings of this study reveal a clear ecological response of Lake Trouna to both climatic conditions and physicochemical changes in its environment. The elevated pH values observed throughout the study period indicate an alkaline water body, which typically limits biodiversity but supports specialized microorganisms and algae adapted to high pH environments. The consistently high electrical conductivity (EC) and total dissolved solids (TDS), especially during the summer phase, suggest increased evaporation rates leading to elevated salinity. These conditions are known to accelerate eutrophication and ecological succession, particularly in arid regions like southern Libya.

Seasonal variations in nutrient concentrations were also evident. The phosphate and nitrate levels showed significant increases in the summer phase, implying enhanced organic matter decomposition and biological activity under higher temperatures. These nutrient surges are likely contributing to algal blooms and altering the trophic state of the lake. The strong correlation between high nutrient concentrations and temperature aligns with previous studies in similar saline environments, such as those by Al-Mathnani (2012) and Soylu & Gonulol (2010), where seasonal succession was closely tied to thermal and nutrient dynamics.

Soil analyses revealed substantial spatial variability in salinity, pH, and organic matter content. Soils near vegetated zones showed higher organic matter, supporting the hypothesis that vegetation plays a key role in sustaining nutrient cycles and promoting ecological succession. The notably high sodium and potassium

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levels, particularly in the eastern sector, may result from mineral leaching and prolonged exposure to saline water, indicating ongoing geochemical interactions between the lake and its surrounding soils.
Collectively, the results suggest that Lake Trouna is undergoing accelerated ecological succession driven by a combination of climatic stressors (e.g., extreme temperature and evaporation), nutrient loading, and mineral enrichment. If unmanaged, these processes may shift the lake toward a more eutrophic and biologically simplified state. Therefore, the findings highlight the urgency of adopting a multidisciplinary management approach to monitor, preserve, and possibly restore the ecological balance of this unique Saharan lake ecosystem.

Conclusion

Lake Trouna is a sensitive saline ecosystem significantly impacted by climate change and anthropogenic factors, accelerating ecological succession. Its waters are characterized by high salinity and nutrients, causing eutrophication, while its soils are influenced by minerals and organic matter. The lake serves as a vital model for studying the effects of climate change on saline aquatic systems in arid regions. Based on the study findings, several recommendations are proposed to support the ecological sustainability of Lake Trouna. First, regular monitoring of the lake's physicochemical properties is essential to track changes in aquatic flora and assess ecosystem health. Second, conducting comprehensive studies on benthic communities could help determine their role in mitigating lakebed overgrowth. Additionally, promoting the sustainable utilization of the lake's salt resources may offer valuable environmental applications. To control invasive plant encroachment, scientific management plans should be implemented. Seasonal nutrient analyses are also recommended to evaluate the lake's trophic status. Finally, paleolimnological studies are encouraged to reconstruct the historical patterns of ecological succession and understand long-term environmental changes.

Conflict of interest. Nil

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