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Hydrochemical and Ecological Characteristics of Hypersaline Lakes in Wau El-Namus, Sahara Southern Libya: A Baseline Assessment from 2010 Field Sampling

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ABSTRACT

Wau El-Namus, located in the Fezzan region of southwestern Libya, is a rare volcanic caldera containing inland saline lakes within a hyperarid desert environment. This study presents an environmental assessment of four sampled water bodies Lake 1, Lake 2, Lake 3, and the Red Lake based on original field sampling conducted in May 2010. The investigation integrated geomorphological observations with physicochemical, hydrochemical, and biological analyses to characterize this distinctive saline-lake system. The three main lakes differed in morphometry, with maximum depths of 16.6 m in Lake 1, 15.8 m in Lake 2, and 11.4 m in Lake 3. Surface waters of the main lakes were alkaline, with pH values ranging from 8.6 to 8.8 and water temperatures ranging from 23.3 to 23.7°C. Electrical conductivity values ranged from 20.5 to 52.3 mS/cm in the three main lakes and reached 126.0 mS/cm in the Red Lake. Total dissolved solids exceeded 50 g/L and reached 126 g/L in the Red Lake. Hydrochemical analysis showed strong ionic enrichment, with sodium concentrations ranging from 3.82 to 7.90 g/L in the three main lakes and reaching 48.46 g/L in the Red Lake, while chloride ranged from 1.20 to 4.40 g/L in the main lakes and reached 34.47 g/L in the Red Lake. The lake margins were dominated by *Phragmites australis*, with associated occurrence of *Imperata cylindrica*, *Tamarix aphylla*, and *Phoenix dactylifera*. Phytoplankton analysis identified 12 taxa, mainly diatoms and cyanobacteria, while zooplankton was dominated by *Artemia salina* and dipteran larvae. The occurrence of *Dunaliella salina* was associated with the red pigmentation of the Red Lake. Bird observations included *Egretta garzetta*, *Motacilla flava*, and *Himantopus himantopus*, indicating that the lake system also provides localized ecological habitat within the surrounding desert. These findings show that Wau El-Namus is a hydrochemically and ecologically differentiated hypersaline lake system of considerable scientific importance in the Libyan Sahara. The study provides original field-based data on one of the most distinctive inland saline environments in North Africa and establishes a basis for future limnological, ecological, and conservation-oriented research.

الخصائص الهيدروكيميائية والإيكولوجية للبحيرات شديدة الملوحة في واو الناموس، جنوب الصحراء الليبية: تقييم مرجعي مستند إلى عينات ميدانية عام 2010

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يُعدّ واو الناموس، الواقع في إقليم فزان بجنوب غرب ليبيا، من البيئات الطبيعية النادرة ذات الأهمية الجيومورفولوجية والبيئية، إذ يتمثل في كالديرا بركانية تضم مجموعة من البحيرات الداخلية الملحية ضمن نطاق صحراوي مفرط الجفاف. وتهدف هذه الدراسة إلى تقييم الخصائص البيئية لأربعة مسطحات مائية شملت البحيرة الأولى، والبحيرة الثانية، والبحيرة الثالثة، والبحيرة الحمراء، بالاعتماد على بيانات حقلية أصلية تُجمعت خلال شهر مايو عام 2010. وقد استندت الدراسة إلى منهج تكاملي جمع بين الملاحظات الجيومورفولوجية والتحليلات الفيزيائية والكيميائية والهيدروكيميائية والبيولوجية، من أجل توصيف هذا النظام الفريد من البحيرات الملحية توصيفاً علمياً شاملاً. أظهرت النتائج وجود تباين مورفومتري واضح بين البحيرات الثلاث الرئيسية، حيث بلغ أقصى عمق 16.6 م في البحيرة الأولى، و15.8 م في البحيرة الثانية، و11.4 م في البحيرة الثالثة. كما تبين أن المياه السطحية للبحيرات الرئيسية ذات طبيعة قلوية، إذ تراوحت قيم الأس الهيدروجيني بين 8.6 و8.8، في حين تراوحت درجات حرارة المياه بين 23.3 و23.7 درجة مئوية. وسجلت قيم التوصيل الكهربائي نطاقاً تراوح بين 20.5 و52.3 ملي سيمنز/سم في البحيرات الثلاث الرئيسية، بينما بلغت 126.0 ملي سيمنز/سم في البحيرة الحمراء. كذلك تجاوزت تراكيز المواد الصلبة الذائبة الكلية 50 غ/لتر، وبلغت 126 جم/لتر في البحيرة الحمراء، بما يعكس الطبيعة الفائقة الملوحة لهذا النظام المائي. وأوضحت التحليلات الهيدروكيميائية وجود إثراء أيوني مرتفع، حيث تراوحت تراكيز الصوديوم بين 3.82 و7.90 جم/لتر في البحيرات الرئيسية، وارتفعت إلى 48.46 جم/لتر في البحيرة الحمراء، في حين تراوحت تراكيز الكلوريد بين 1.20 و4.40 جم/لتر في البحيرات

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الزيتية، وبلغت 34.47 جم/لتر في البحيرة الحمراء. كما أظهرت البحيرة الأولى تبايناً مكانياً ملحوظاً في بعض المؤشرات البيئية، إذ تراوحت قيم الأس الهيدروجيني بين 8.3 و 8.9، والتوصيل الكهربائي بين 18.96 و 82.60 ملي سيمنز/سم، وتركيز الكلوروفيل-أ بين 4.31 و 130.24 ملغم/لتر، وتركيز النترات بين 0.03 و 3.55 ملغم/لتر. وعلى المستوى الحيوي، بينت الدراسة أن هوامش البحيرات كانت مهيمنة عليها نبات *Phragmites australis*، مع تسجيل وجود أنواع نباتية مصاحبة شملت *Tamarix aphylla* و *Imperata cylindrica* و *Phoenix dactylifera*. كما أسفر تحليل العوائل النباتية عن تحديد 12 وحدة تصنيفية، غلبت عليها الدياتومات والسيانوبكتيريا، في حين هيمنت *Artemia salina* ويرقات ذوات الجناحين على العوائل الحيوانية. وارتبط وجود الطحلب *Dunaliella salina* بالتصبيغ الأحمر المميز للبحيرة الحمراء. كذلك سُجلت عدة أنواع من الطيور، من بينها *Egretta garzetta* و *Motacilla flava* و *Himantopus himantopus*، مما يدل على أن هذا النظام البيئي يوفر موثلاً محلياً مهماً داخل البيئة الصحراوية المحيطة. وتلخص الدراسة إلى أن أوو الناموس يمثل نظاماً بحرياً فائق الملوحة يتميز بتباين هيدروكيميائي وبيئي واضح، وهو ما يمنحه قيمة علمية متميزة في نطاق الصحراء الليبية. كما توفر هذه الدراسة بيانات حقلية أصلية عن واحد من أكثر النظم الملحية الداخلية تميزاً في شمال أفريقيا، وتؤسس لقاعدة معرفية مهمة يمكن البناء عليها في البحوث المستقبلية المرتبطة بعلم البحيرات، والدراسات البيئية، وحماية النظم الطبيعية والمحافظة عليها.

INTRODUCTION

Hypersaline lakes in arid and hyperarid regions represent some of the most extreme inland aquatic environments on Earth. Their hydrological, chemical, and ecological characteristics are shaped by the combined effects of intense evaporation, minimal precipitation, restricted surface runoff, and localized groundwater input. Under such conditions, dissolved salts become progressively concentrated, producing water bodies with unusual ionic compositions, high salinity, and strong environmental gradients that influence both physical processes and biological communities. For this reason, saline lakes have long attracted scientific interest as natural systems for studying hydrochemical evolution, limnological adaptation, and ecological persistence under severe climatic stress (Pallas, 1980a, 1980b).

In desert environments, the persistence of lakes is especially significant because it reflects a delicate balance between water loss and water supply. Even small and isolated water bodies can provide important evidence of subsurface hydrology, geomorphological controls, and ecological tolerance. Their study contributes not only to regional environmental knowledge but also to broader understanding of how inland aquatic systems respond to aridity, salinization, and environmental isolation. In addition, hypersaline lakes often support simplified but highly specialized communities, making them useful model systems for investigating the relationship between water chemistry and biological distribution (Gajardo *et al.*, 2006; Kara, 2016).

Within the central Sahara, Wau El-Namus in southwestern Libya is one of the most distinctive examples of such an environment. The area consists of a volcanic caldera that contains a central cone and several permanent water bodies distributed across the crater floor. It is located within an extremely remote and hyperarid sector of the Libyan desert, where surface water is rare and ecological productivity is strongly constrained by climatic severity. The geomorphological configuration of the caldera, together with its volcanic origin and enclosed basin structure, creates a unique natural setting in which hydrological, chemical, and ecological processes can be examined in close spatial association (Pesce, 1960, 1968; White *et al.*, 2006).

The lakes of Wau El-Namus, (Fig. 1) are particularly important because they occur as permanent water bodies within a desert setting where long-term surface-water persistence is exceptional. Earlier studies have described the

volcanic landscape, the crater morphology, and the remarkable presence of saline lakes within this isolated depression (Pesce, 1960, 1968; White *et al.*, 2006). Other investigations have reported high salinity, alkaline conditions, and the presence of halophytic vegetation fringing parts of the lakes, together with relatively restricted aquatic biota adapted to environmental stress (Ajaili *et al.*, 1984; Almathnani & Elssaidi, 2012). These characteristics distinguish Wau El-Namus from many other inland lake systems in North Africa and increase its value as a rare Saharan hydroecological system.

From an environmental perspective, the study of Wau El-Namus is important for several reasons. First, the presence of multiple water bodies within the same volcanic caldera provides an opportunity to compare lakes that are geographically close to one another but may differ in morphology, hydrochemistry, salinity, and ecological structure. Second, the system offers an opportunity to examine how extreme aridity and evaporative concentration influence water quality and ionic balance in closed or semi-closed desert basins. Third, the associated vegetation and aquatic communities provide insight into the biological limits of tolerance under hypersaline conditions. Such observations are valuable not only for regional limnology, but also for the broader study of inland saline ecosystems subjected to climatic and hydrological stress (Gajardo *et al.*, 2006; Kara, 2016).

Despite the scientific importance of the area, detailed environmental studies integrating hydrochemical and ecological observations from the Wau El-Namus lakes remain limited. Much of the available literature has focused on the geological setting, general physical description, or isolated environmental observations rather than providing a field-based assessment that links geomorphological context, physicochemical conditions, and ecological characteristics across multiple water bodies in the caldera. In particular, there remains a need to document spatial variation among the lakes, identify the principal hydrochemical features of each water body, and relate those conditions to visible vegetation belts and aquatic biological communities.

A clearer characterization of these features is important for understanding how desert lake systems function under hyperarid climatic conditions. Variations in salinity, ionic composition, pH, temperature, and depth may strongly influence the ecological organization of each basin, including the occurrence and distribution of planktonic organisms, salt-tolerant vegetation, and other biotic components. Because the lakes coexist within the same

volcanic depression, they provide a useful environmental framework for comparative assessment. Such comparison can help clarify whether the lakes function as broadly similar parts of a single desert system or as distinct hydroecological units shaped by local differences in morphology and water chemistry.

Accordingly, the objective of this study is to provide an environmental assessment of four sampled water bodies, comprising three lakes and the Red Lake, within the Wau El-Namus caldera based on original field sampling conducted in May 2010 (Baseline Assessment). The study examines the

geomorphological setting, selected physicochemical characteristics, hydrochemical properties, and ecological features of the water bodies, with particular emphasis on water quality, ionic composition, salinity conditions, and associated biological communities. By integrating field observations with laboratory-based water analysis, this study presents original field-based data on one of the most distinctive volcanic lake systems in the Libyan Sahara and contributes to the scientific understanding of hypersaline inland waters in extreme desert environments.



Fig. (1): Lake Wau El-Namus Volcano

MATERIALS AND METHODS

Study area

Wau El-Namus (24° 55' 02.23" N, 17° 45' 55.75" E) is a volcanic caldera situated in the Fezzan region of southwestern Libya within the hyperarid central Sahara, (Fig. 2). The caldera forms an enclosed geomorphological depression containing several saline inland water bodies distributed around a central volcanic cone. The surrounding environment is characterized by extreme aridity, very limited precipitation, high evaporation, and sparse desert vegetation.



Fig. (2): Map of Libya (Wau El-Namus)

These environmental conditions strongly influence the hydrology, salinity regime, and ecological structure of the lakes. Owing to its volcanic origin, isolated location, and the persistence of saline water bodies within an arid landscape, Wau El-Namus provides a distinctive natural setting for investigating hydrochemical and ecological variation among desert lakes.

Field survey and sampling design

Fieldwork was conducted in May 2010 as part of an original environmental survey of four sampled water bodies within the Wau El-Namus caldera, namely Lake 1, Lake 2, Lake 3,

and Red Lake. The survey was designed to document the principal physicochemical and ecological characteristics of the lakes and to compare environmental variation among them.

Sampling was conducted at five stations within each of the three main lakes, with up to three field replicates collected per station when access and water depth allowed. Replicate availability therefore varied among stations and parameters. The Red Lake was sampled as a separate water body, but not all variables could be measured there because of field-access and sample-availability constraints. Consequently, the dataset should be interpreted as a spatial baseline survey rather than as a statistically balanced design across all lakes and variables.

Water depth was measured in the field using a Garmin marine GPS depth sounder. Water samples were collected from different depths according to the morphometry and accessibility of each lake, whereas near-surface samples were generally taken from approximately 0.5 to 0.75 m where conditions allowed.

Field limitations

Because shallow-water conditions restricted access in parts of the study area, several measurements could not be obtained consistently across all stations, depths, or lakes. Missing values in the tables therefore indicate parameters that were not reliably measured or not analytically available for a given site, rather than true zero concentrations. This limitation was considered during interpretation and during comparisons among lakes.

Water sample collection and preservation

Water samples were collected in 1 L glass bottles and transported to the Environmental Science Department for laboratory analysis. Sample collection, handling, and preservation followed standard procedures for water quality analysis in order to minimize contamination and maintain sample integrity prior to examination. Laboratory analyses

were carried out according to the procedures described in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association [APHA], 1998).

In situ physicochemical measurements

The principal physicochemical variables measured directly in the field were water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity. These measurements were taken to characterize the immediate environmental conditions of each sampled water body and to provide a basis for comparison among lakes. The field measurements were also used to support interpretation of the hydrochemical characteristics later determined through laboratory analysis.

Laboratory analysis of water chemistry

Laboratory analyses were conducted in the Environmental Science Department following Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Reported hydrochemical variables include the major cations sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg), together with the major anions chloride (Cl), sulfate (SO₄), and bicarbonate (HCO₃) where analytical records were available. Additional measurements included nutrients and chlorophyll-a for stations with sufficient sample volume and analytical coverage.

The purpose of these analyses was to characterize the ionic composition of the lakes, evaluate differences in water quality among the sampled water bodies, and identify the principal hydrochemical features associated with saline desert-lake conditions. The three main lakes were subjected to the full set of measured parameters, whereas some measurements were limited in the shallower parts of the study area due to field-access constraints.

Phytoplankton sampling

Phytoplankton samples were collected using fine-mesh plankton nets with a mesh size ranging from 20 to 60 µm, which is suitable for capturing microalgal forms commonly occurring in saline waters. These samples were collected to support the ecological characterization of the lakes and to document the occurrence of microscopic primary producers associated with hypersaline aquatic environments. Collected samples were preserved in formalin for subsequent examination and identification.

Zooplankton sampling

Zooplankton samples were collected using coarser plankton nets with mesh sizes ranging from 100 to 300 µm, which are appropriate for retaining larger planktonic organisms. The use of a larger mesh size allowed the collection of zooplanktonic forms present in the sampled water bodies while reducing the capture of fine suspended material. As with the phytoplankton samples, the zooplankton material was preserved in formalin for later examination.

Biological observations

In addition to plankton collection, biological observations were made during the field survey to document visible ecological characteristics of the lakes and their margins. These observations included the apparent distribution of aquatic life and shoreline-associated biological features. Such observations were used as supporting ecological information during interpretation of the hydrochemical and environmental characteristics of the sampled water bodies.

Data treatment and interpretation

The collected data were organized to allow comparison among the four sampled water bodies and among stations for which complete observations were available. Because measurement completeness differed among lakes and variables, interpretation focused on descriptive comparison of available data rather than formal hypothesis testing. Values identified as internally inconsistent were cross-checked against the narrative text and harmonized where the manuscript itself provided a consistent value; otherwise they were retained as not reported.

RESULTS AND DISCUSSION

I. Results

Geomorphological characteristics of the study area

The Wau El-Namus caldera forms an enclosed volcanic depression in the central Sahara and contains several saline water bodies distributed around a central volcanic cone. The basin includes both permanent and temporary water bodies, and field observations indicated that seasonal or shallow connections may occur between some parts of the system, particularly between Lake 2 and Lake 3, whereas Lake 1 appeared relatively more isolated, (Fig. 3).

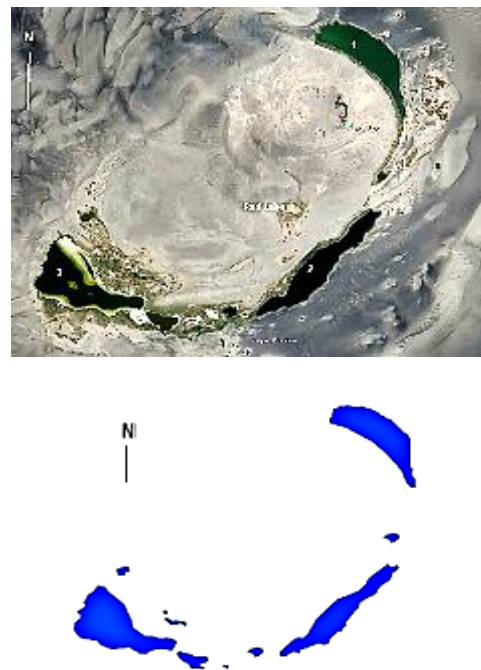
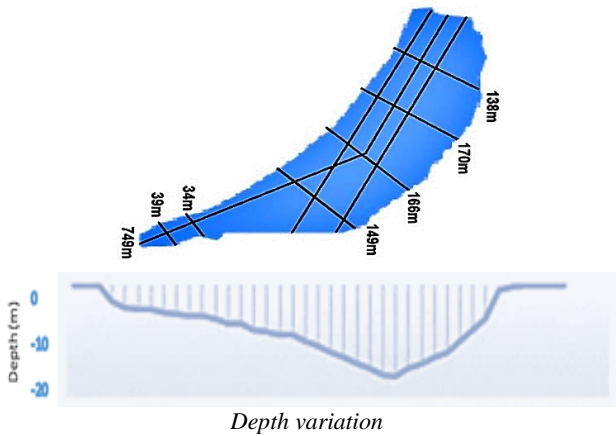


Fig. (3): Location of the Lakes around the volcano

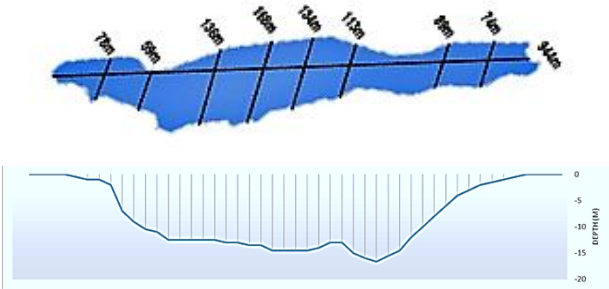
Lake 1 (24° 55' 14.46" N, 17° 46' 04.25" E)

The lake is located in the northeastern sector, with a maximum length of 490 meters and a total area of 10.5 hectares. Its shoreline has a circumference of approximately 2029 meters. The maximum water depth is 16.6 meters. The coastal area is surrounded by dense vegetation, dominated by common reed (*Phragmites australis*), which covers an estimated area of 115,062 m². The reeds reach an average height of 5.5–6.0 meters, forming a belt 5.0–6.5 meters wide along the edges and extending 4–6 meters into the water.



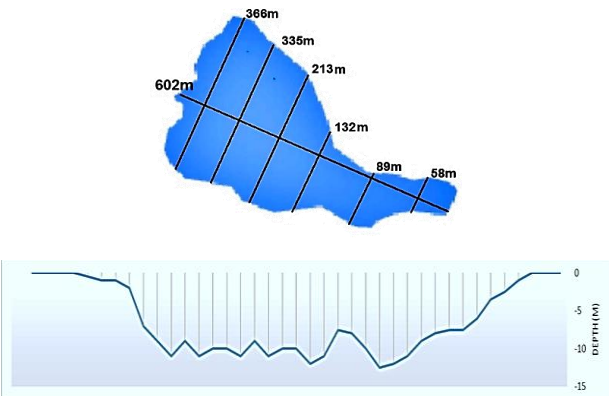
Lake 2 ($24^{\circ} 54' 32.34'' N, 17^{\circ} 45' 53.39'' E$)

The lake is located in the southeastern region, stretching 940 meters in length, with a total area of 9.2 hectares. Its circumference is approximately 2340 meters. The maximum water depth is 15.8 meters. Its shoreline is surrounded by dense vegetation consisting of various species, mostly common reeds, covering an estimated area of 115,385 m². The reeds reach an average height of 5.5–6.0 meters, forming a vegetation belt 5.0–6.5 meters wide along the edges, extending 3–5 meters into the water.



Lake 3 ($24^{\circ} 54' 30.52'' N, 17^{\circ} 45' 01.18'' E$)

The lake is located in the southwestern region, with a maximum length of 875 meters and a total area of 13.2 hectares. Its shoreline has a circumference of approximately 2830 meters. The maximum water depth is 11.4 meters. The surrounding coastal area is characterized by dense vegetation, mostly common reeds, covering an estimated 139,375 m². The reeds reach an average height of 5.0–6.0 meters, forming a belt 5.0–6.5 meters wide along the edges and extending 2–5 meters into the water.



The lakes are not directly connected; however, when the water level rises, temporary channels and small pools form, linking them together. This phenomenon is most evident between lakes 2 and 3, while lake 1 remains somewhat isolated. The red lake ($24^{\circ} 54' 30.52'' N, 17^{\circ} 45' 01.18'' E$) is completely separated and located in the northern east of the second lake, (Fig. 4).



Fig. (4): The Red Lake

All three main lakes were fringed by dense vegetation dominated mainly by common reed, *Phragmites australis*. The estimated vegetated areas surrounding the lakes were approximately 115,062 m² for Lake 1, 115,385 m² for Lake 2, and 139,375 m² for Lake 3. The marginal reed belt generally ranged from about 5.0 to 6.5 m in width and extended approximately 4–6 m into the water.

Surface-water hydrochemistry

Surface-water chemistry (Tables 1-5) differed markedly among the sampled water bodies. The three main lakes showed broadly comparable hydrochemical composition, whereas the Red Lake was chemically distinct and more concentrated. Sodium was the dominant reported cation in all sampled waters, with the highest value recorded in the Red Lake (48.46 g/L). Chloride also reached its highest concentration in the Red Lake (34.47 g/L), indicating that this water body represented the most saline and chemically concentrated environment among the four sampled sites.

In the three main lakes, sodium concentrations ranged from 3.82 g/L in Lake 3 to 7.90 g/L in Lake 1. Chloride ranged from 1.20 g/L in Lake 3 to 4.40 g/L in Lake 1. Calcium concentrations were relatively low, ranging from 0.20 to 0.31 g/L, while magnesium values were around 1.70-1.77 g/L where reported. Potassium concentrations in the three main lakes ranged from 0.37 to 0.90 g/L. For the Red Lake, sodium and chloride values were retained only where they were internally consistent between tables; other unresolved major-ion entries were left as not reported.

Trace elements, including iron, manganese, and zinc, were reported for the three main lakes. However, several values for the Red Lake were incomplete or internally inconsistent in the source tables. Therefore, the Red Lake is described quantitatively only for those measurements that could be harmonized confidently, whereas the remaining fields are presented as not reported.

Physicochemical properties of the sampled lakes

The measured physicochemical properties showed variation among the sampled water bodies. The three main lakes were consistently alkaline, with pH values ranging from 8.6 to 8.8. Water temperatures were relatively similar among them, ranging from 23.3 to 23.7°C. Electrical conductivity values, expressed in mS/cm, varied substantially across sampling

points and indicated strong mineralization of the lake waters. TDS values also differed among lakes, and the Red Lake showed the highest concentration values among the reported sites. Dissolved oxygen, biological oxygen demand, chlorophyll-a, and nitrite values varied spatially, indicating heterogeneity in both chemical and biological conditions across the lake system.

Spatial and vertical variation in Lake 1

Lake 1 showed substantial spatial variability in water quality among sampling locations and between surface and depth samples. Surface pH ranged from 8.3 at the southeast station to 8.9 at the southwest station, while surface water temperature varied more narrowly between 23.0 and 24.3°C.

Electrical conductivity ranged from 18.96 to 82.60 mS/cm, confirming strong local variation in dissolved salts across the lake. Dissolved oxygen values also varied, with reported surface values ranging from 1.58 mg/L at the center station to 4.80 mg/L at the southeast station.

Major-ion composition in Lake 1 also varied spatially. Sodium ranged from 7.03 to 9.88 g/L among the reported stations, calcium from 0.15 to 0.26 g/L, magnesium from 1.72 to 1.83 g/L, potassium from approximately 0.70 to 0.94 g/L, and chloride from 3.96 to 4.32 g/L. Trace metals also varied by station, indicating local hydrochemical heterogeneity within the lake.

Table (1): Daily change in air and soil temperature (°C) and relative humidity (Main Lake 1)

Time (hour)	air	Soil depth (cm)			Relative humidity (%)
		5	10	100	
08:00	24.5	22.0	28.0	27.0	40.0
09:00	30.5	22.0	28.0	27.0	33.0
10:00	30.8	23.0	28.5	27.5	24.3
11:00	33.5	22.8	29.8	27.5	26.3
12:00	34.5	22.0	30.0	27.5	25.0
13:00	36.5	23.0	31.5	28.0	21.0
14:00	37.3	24.0	32.5	28.0	19.3
15:00	37.5	24.5	34.5	27.5	16.0
16:00	37.3	25.8	34.5	28.3	17.5
17:00	35.0	26.3	34.5	27.8	18.5
18:00	33.8	26.5	34.5	27.8	20.0
19:00	27.0	27.0	35.0	28.5	24.5
20:00	27.0	26.5	34.0	28.0	25.0

Table (2): Physical and chemical properties of Lake 1 at different locations and depths.

Site	pH	Temperature (°C)	EC (mS/cm)	DO (mg/L)	BOD (mg/L)	Chl-a (mg/L)	NO2- (mg/L)
North (surface)	8.6	24.3	53.80	2.88		10.43	0.45
East (surface)	8.8	23.4	49.40	3.20	3.00	130.24	0.73
Center (surface)	8.5	23.5	53.80	1.58	0.48	18.90	0.42
West (surface)	8.8	23.7	53.60	2.40	2.00	32.67	0.85
South (surface)	8.7	23.9	53.70			21.96	0.03
Southeast (surface)	8.3	23.6	82.60	4.80	0.40	4.31	1.83
Southwest (surface)	8.9	23.0	18.96	2.08	0.40		0.89
North (Depth)	8.8	23.4	55.20			21.13	3.55
South (Depth)	8.5	23.5	54.40	1.92		2.78	1.72

Table 3. Major ions and trace elements in the surface waters of the studied lakes.

Site	Na (g/L)	Ca (g/L)	Mg (g/L)	K (g/L)	Cl (g/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)
Lake 1	7.90	0.20	1.70	0.90	4.40	2.40	2.50	1.90
Lake 2	6.46	0.31	NR	0.69	3.47	1.78	1.23	1.14
Lake 3	3.82	0.31	1.77	0.37	1.20	0.56	2.92	0.57
Red Lake	48.46	NR	NR	NR	34.47	NR	NR	NR

Table (4): Main ions and trace elements in Lake 1 (spatial and vertical distribution).

Site	Na (g/L)	Ca (g/L)	Mg (g/L)	K (g/L)	Cl (g/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)
North (surface)	7.03	0.23	1.72	0.93	4.32	1.78	3.85	2.44
East (surface)	7.49	0.19	1.79	0.94	3.96	1.57	4.46	1.76
Center (surface)	7.38	0.26	1.81	0.7	4.32	2.99	3.85	1.88
West (surface)	8.06	0.15	1.83	0.76	3.96	2.78	1.38	1.76
South (surface)	9.88	0.16	1.75	0.9	4.25	2.06	1.25	1.65
Southeast (surface)	7.78	0.24	1.69	0.94	8.92	2.85	2.0	1.93
Southwest (surface)	7.95	0.29	1.62	1.05	1.13	2.92	0.92	1.76

North (Depth)	8.32	0.16	1.70	0.80	4.32	2.70	8.15	1.42
South (Depth)	8.36	0.16	1.74	0.95	4.18	0.92	0.92	1.86

Table 5. Physical characteristics of the surface water of the studied lakes.

Site	pH	Temperature (°C)	EC (mS/cm)	DO (mg/L)	BOD (mg/L)	Chl-a (mg/L)	NO2- (mg/L)	Relative transparency
Lake 1	8.7	23.6	52.3	2.8	1.3	36.4	0.7	34.7
Lake 2	8.8	23.3	45.3	2.4	2.2	NR	0.62	46.3
Lake 3	8.6	23.7	20.5	2.8	NR	NR	NR	47.1
Red Lake	NR	NR	126.0	NR	0.0	NR	NR	NR

Chlorophyll-a values in Lake 1 were highly variable, suggesting uneven phytoplankton distribution or localized productivity differences among stations, (Table 6). The highest reported value was 130.24 mg/L at the east surface station, whereas lower values included 10.43 mg/L at the north surface station, 18.90 mg/L at the center surface station, 32.67 mg/L at the west surface station, and 4.31 mg/L at the southeast surface station. Nitrite concentrations also varied markedly, from 0.03 mg/L at the south surface station to 3.55 mg/L at the north depth sample.

Table 6. Estimated productivity of Lake 1 at different sites.

Site	Mid	North	West	East
Productivity (g/m ² /yr.)	1133	876	797	1076
Mean±SD	974.0 ± 138			

Biological characteristics

The Wau El-Namus lake system supported a biologically restricted yet ecologically specialized community associated with saline desert-lake conditions. Shoreline vegetation around the three principal lakes was dominated

by *Phragmites australis*, which formed the main emergent macrophyte belt. Other plant species recorded in the surrounding habitat included *Imperata cylindrica*, *Tamarix aphylla*, and *Phoenix dactylifera*, although these occurred at lower abundance than *Phragmites australis* (Table 7).

Table 7. Distribution and relative abundance of higher vegetation around the lakes.

Family	Taxon	Relative abundance
Poaceae	<i>Phragmites australis</i>	+++++
	<i>Imperata cylindrica</i>	+++
Tamaricaceae	<i>Tamarix aphylla</i>	++
Arecaceae	<i>Phoenix dactylifera</i>	++

Phytoplankton analysis identified 12 taxa: *Nitzschia palea*, *Synedra ulna*, *Gomphonema angustatum*, *Melosira granulata*, *Navicula cuspidata*, *Pinnularia aerophila*, *Cyclotella meneghiniana*, *Eucapsis alpina*, *Microcoleus steenstrupii*, *Microcystis aeruginosa*, *Anabaena variabilis*, and *Pseudanabaena africana*. The assemblage was dominated by diatoms and cyanobacteria, consistent with adaptation to elevated salinity and chemically stressed aquatic conditions (Table 8).

Table 8. Identified phytoplankton in the major lakes of Wau El-Namus.

Division	Family	Taxon	Relative abundance
Bacillariophyta	<i>Nitzschiaceae</i>	<i>Nitzschia palea</i>	+++
	<i>Fragilariaceae</i>	<i>Synedra ulna</i>	+++
	<i>Gomphonemataceae</i>	<i>Gomphonema angustatum</i>	+++
	<i>Melosiraceae</i>	<i>Melosira granulata</i>	+++
	<i>Pinnulariaceae</i>	<i>Pinnularia aerophila</i>	+++
	<i>Stephanodiscaceae</i>	<i>Cyclotella meneghiniana</i>	+++
	<i>Naviculaceae</i>	<i>Navicula cuspidata</i>	+++
Cyanobacteria	<i>Chroococcaceae</i>	<i>Eucapsis alpina</i>	++
	<i>Microcystaceae</i>	<i>Microcoleus steenstrupii</i>	+
		<i>Microcystis aeruginosa</i>	++
	<i>Nostocaceae</i>	<i>Anabaena variabilis</i>	+++
	<i>Pseudanabaenaceae</i>	<i>Pseud anabaena africana</i>	++

Zooplankton diversity was limited, with *Artemia salina* representing the principal zooplankton species recorded, in addition to dipteran larvae. This simplified assemblage indicates that only a narrow range of aquatic organisms was able to persist under the prevailing saline conditions.

A halophilic algal component attributable to *Dunaliella salina* was also observed and was associated with the red coloration of the Red Lake. This observation is consistent

with the occurrence of carotenoid-rich microalgae in hypersaline environments.

Bird species observed during the survey included *Egretta garzetta*, *Motacilla flava*, and *Himantopus himantopus*, indicating that the lake system also contributes localized habitat value within the surrounding desert environment (Figs. 5-7).



Fig. 5. Little egret (*Egretta garzetta*).



Fig. 8. Jerboa burrow (*Scarturus tetradactylus*).



Fig. 6. Yellow wagtail (*Motacilla flava*).



Fig. 9. Black garden ant (*Lasius niger*).



Fig. 7. Black-winged stilt (*Himantopus himantopus*).



Fig. 10. Evidence of fire associated with human activity.

Field surveys around the lakes indicated broader biodiversity than that represented in the plankton tables alone. In addition to the fauna already documented, the presence of hares (*Lepus* spp.) and scorpions (order Scorpiones) was confirmed, while traces of camels, snakes (suborder Serpentes), and wolves were also recorded. Active burrows of jerboas (*Jaculus* spp.) were observed (Fig. 8), together with ant colonies (family Formicidae) distributed along the dry perimeter (Fig. 9), suggesting relative stability in the surface sediments and the availability of at least minimal organic matter. Mosquitoes and their larvae were also observed, along with springtails (Collembola), which may help explain the local name El-Namus ('mosquito'). The damselfly *Ischnura saharensis* was previously reported by Aguesse (1958). No mollusks were observed during the survey. Visual inspection further revealed evidence of human activity, including charred deposits resulting from deliberate fires (Fig. 10) and the remains of rudimentary structures constructed from date palm fronds (Fig. 11).



Fig. 11. Remains of palm-frond huts (Bedouin shelters).

II. Discussion

The present study demonstrates that the Wau El-Namus caldera contains a hydrochemically and ecologically heterogeneous saline-lake system, despite the close spatial proximity of its water bodies. Differences among Lake 1, Lake 2, Lake 3, and the Red Lake indicate that these basins do not function as a chemically uniform system, but rather as distinct aquatic environments shaped by local morphometry, evaporative concentration, and shoreline conditions. This interpretation is consistent with the volcanic and structural setting of Wau El-Namus described

by Pesce (1960, 1968) and White *et al.* (2006), and with the hydrochemical contrasts recorded in the present field survey.

One of the clearest findings of this study is the marked hydrochemical distinction of the Red Lake compared with the three main lakes. The high sodium and chloride concentrations recorded in the Red Lake indicate a more concentrated saline environment, reflecting stronger evaporative enrichment than in the other sampled water bodies. By contrast, the three principal lakes, although clearly saline and alkaline, exhibited lower ionic concentrations and broadly comparable physicochemical properties. This general pattern is consistent with hydrochemical behavior described for hypersaline lakes in arid North Africa, where localized evaporation and restricted water renewal promote strong chemical differentiation among basins (Ajaili *et al.*, 1984; Abd El-Motaal *et al.*, 2020).

The observed differences among the three main lakes also indicate that hydrochemical variation occurs not only between lakes, but also within individual basins. Lake 1 showed marked spatial variation in pH, electrical conductivity, dissolved oxygen, chlorophyll-a, nitrite, and major ions. Such heterogeneity suggests that local conditions, including shallow-water concentration, shoreline influence, and limited water mixing, may affect lake chemistry at a small spatial scale. Similar fine-scale physicochemical variability has been described in other inland saline lakes, where basin morphology and evaporation gradients contribute to substantial within-lake variation (Abd El-Motaal *et al.*, 2020).

The alkaline character and elevated conductivity of the Wau El-Namus lakes confirm that these waters are strongly mineralized saline environments. This finding is consistent with earlier hydrochemical observations from the Fezzan region (Ajaili *et al.*, 1984) and with the broader pattern of saline lakes in hyperarid settings, where water loss through evaporation greatly exceeds direct precipitation input (Pallas, 1980a, 1980b; Richter, 1958). In such environments, progressive concentration of dissolved ions commonly results in sodium- and chloride-dominated waters, as observed in the present study.

From a regional perspective, Wau El-Namus is particularly important because well-documented inland hypersaline systems in Libya remain limited in the published literature. The present results therefore provide original field-based evidence for the physicochemical and ecological structure of a rare saline-lake system in the Libyan Sahara. Compared with saline depressions elsewhere in North Africa, Wau El-Namus appears distinctive in combining volcanic geomorphology, multiple permanent water bodies, and marked hydrochemical differentiation within a single enclosed caldera. This makes it more complex than many non-volcanic hypersaline basins and strengthens its value as a natural model for saline-lake research in desert environments (Pesce, 1968; White *et al.*, 2006).

The vegetation pattern recorded around the three principal lakes also reflects adaptation to strong environmental stress.

The dominance of *Phragmites australis* and the presence of *Imperata cylindrica*, *Tamarix aphylla*, and *Phoenix dactylifera* indicate that the lake margins can support a restricted belt of emergent and salt-tolerant vegetation despite the hyperarid regional setting. Similar shoreline vegetation structure has been documented in desert wetlands of southern Libya, where plant distribution is controlled by moisture availability, salinity, and microtopography (Almathnani & Elssaidi, 2012). In Wau El-Namus, differences in vegetated area among the lakes likely reflect local shoreline geometry and moisture conditions in addition to salinity gradients.

The biological findings are also consistent with the ecological filtering typical of hypersaline systems. Phytoplankton diversity was limited and consisted mainly of taxa belonging to Bacillariophyta and Cyanobacteria, while zooplankton diversity was strongly restricted and dominated by *Artemia salina*. This pattern agrees with previous work showing that inland hypersaline lakes often support low-diversity but highly specialized communities adapted to osmotic stress (Gajardo *et al.*, 2006; Kara, 2016). The occurrence of *Dunaliella salina*, especially in association with the Red Lake, is also ecologically meaningful because this species is widely associated with highly saline environments and reddish water coloration resulting from carotenoid accumulation (Kara, 2016).

Comparison with hypersaline lakes elsewhere further supports the interpretation of Wau El-Namus as a chemically concentrated but biologically selective system. In North African saline lakes, similar assemblages of halotolerant microorganisms and simplified food webs have been reported under strong salinity stress (Gajardo *et al.*, 2006; Kara, 2016). More broadly, studies of extreme aquatic environments show that salinity acts as a strong ecological filter, favoring a relatively narrow range of tolerant taxa while reducing overall biodiversity. The Wau El-Namus lakes conform to this general model, but remain distinctive because these hydrochemical and ecological patterns occur within a volcanic caldera rather than in a typical continental salt depression.

The recorded bird species, including *Egretta garzetta*, *Motacilla flava*, and *Himantopus himantopus*, indicate that the ecological significance of Wau El-Namus extends beyond aquatic chemistry alone. Even where biological diversity within the water is limited, isolated wetlands in arid landscapes can provide important habitat and stopover value for birds and other mobile organisms. This broader ecological role is consistent with the concept of arid-land refuge ecosystems emphasized by Tydecks *et al.* (2023). Therefore, the Wau El-Namus lake system should be viewed not only as a hydrochemical anomaly, but also as a localized ecological refuge within the Sahara.

At the same time, interpretation of the present dataset should remain within the limits of the field design. Some measurements could not be obtained consistently across all stations because shallow-water conditions restricted access and limited sampling in parts of the study area. Accordingly, the present work should be understood as an original field-based environmental survey rather than a

seasonal monitoring or long-term hydrological assessment. Nevertheless, the observed morphometric, hydrochemical, and biological patterns are sufficiently consistent to demonstrate that the Wau El-Namus lakes form a differentiated hypersaline system of considerable scientific importance.

Overall, comparison with hypersaline lakes in Libya and elsewhere indicates that Wau El-Namus shares several common features of saline desert lakes, including alkaline water, high ionic concentration, restricted biological diversity, halotolerant vegetation, and specialized planktonic communities (Ajaili *et al.*, 1984; Gajardo *et al.*, 2006; Kara, 2016). However, it is distinguished by its volcanic caldera setting, the coexistence of multiple permanent water bodies within one enclosed basin, and the strong hydrochemical contrast between the Red Lake and the three main lakes. These characteristics confirm the importance of Wau El-Namus as a rare inland hypersaline-lake system in the Libyan Sahara and as a valuable natural site for understanding saline-lake ecology under hyperarid conditions (Pesce, 1968; White *et al.*, 2006).

CONCLUSION

Wau El-Namus represents a rare inland hypersaline lake system in the Libyan Sahara in which volcanic geomorphology, saline-water chemistry, and biological specialization occur within a single enclosed caldera. Based on original field sampling conducted in May 2010, the present study showed that the lake system is not environmentally uniform, but consists of four sampled water bodies that differ in morphometry, hydrochemical properties, and ecological structure. This interpretation is consistent with the volcanic and geomorphological framework described by Pesca (1960, 1968) and White *et al.* (2006), and is supported by the field and laboratory results obtained in the present study.

The hydrochemical results indicate that the lakes are strongly saline to hypersaline and predominantly alkaline, with ionic composition dominated by sodium and chloride. Among the sampled water bodies, the Red Lake showed the highest degree of chemical concentration, whereas the three main lakes displayed lower but still elevated salinity values and substantial spatial variability in water quality. These findings confirm that evaporative concentration is a major control on lake-water chemistry under the hyperarid conditions of Wau El-Namus, in agreement with previous observations from saline basins in Libya and North Africa (Ajaili *et al.*, 1984; Abd El-Motaal *et al.*, 2020).

The ecological results further show that the Wau El-Namus lakes support biologically restricted but highly adapted communities. The lake margins were dominated by *Phragmites australis* and associated vegetation, while the aquatic biota included halotolerant and hypersaline-adapted organisms such as *Dunaliella salina* and *Artemia salina*. The phytoplankton assemblage was composed mainly of diatoms and cyanobacteria, whereas the zooplankton community was limited in diversity. These patterns are consistent with ecological filtering under saline stress, as described for

hypersaline systems elsewhere (Gajardo *et al.*, 2006; Kara, 2016).

The study also indicates that Wau El-Namus has ecological significance beyond its aquatic chemistry alone. The presence of bird species and shoreline vegetation suggests that the caldera functions as a localized wetland habitat and environmental refuge within the surrounding desert landscape. In this respect, the system has value not only as a hydrochemical environment, but also as an ecologically important desert wetland, consistent with broader understanding of isolated arid-zone wetlands as biodiversity-supporting habitats (Tydecks *et al.*, 2023).

At the same time, the conclusions of this study should be interpreted within the limits of the sampling design. Some parameters could not be measured consistently across all stations because shallow-water conditions limited field access in the shallowest parts of the study area. Therefore, the present work should be regarded as an original field-based environmental assessment rather than a seasonal or long-term monitoring program. Nevertheless, the results provide important baseline evidence for the hydrochemical and ecological differentiation of the Wau El-Namus lake system.

Overall, Wau El-Namus may be regarded as a distinctive hypersaline volcanic-lake system of considerable scientific importance in Libya. Its combination of multiple saline water bodies, strong hydrochemical contrast, specialized biological communities, and isolated desert setting makes it a valuable natural site for future limnological, ecological, and conservation-oriented research. Continued monitoring would be useful for clarifying temporal variation in water chemistry, biological composition, and environmental stability under ongoing arid-climate pressure.

Future studies should include seasonal and long-term monitoring of the Wau El-Namus lakes to evaluate temporal variation in salinity, hydrochemistry, and biological composition. Expanded spatial and vertical sampling is also recommended to improve understanding of within-lake heterogeneity, particularly in shallow and difficult-to-access areas. More detailed taxonomic studies of phytoplankton, zooplankton, halophilic algae, and bird use of the lake system would further clarify its ecological significance. In addition, the environmental uniqueness of Wau El-Namus suggests that it should be considered a priority site for continued limnological and conservation-oriented research in the Libyan Sahara.

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