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Physicochemical Characterization of Pond Waters in the Kanem Region, Republic of Chad

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Abstract— *The physicochemical properties of ten water samples from ponds in the Kanem region and a sample from the southern part of Lake Chad were analyzed. Surface water samples were collected in October 2007. The following parameters were determined: temperature, pH, electrical conductivity, the major ions (Ion Chromatography),* SiO_2 *and* HCO_3^- *(UV-visible Spectrophotometer) and trace elements (Li, Rb, Cs, Be, Sr, Ba, Al, V, Cr, Mn, Co, Ni, Cu, Zn, Mo, Ag, Cd, Sn, Pb, Bi, As, Sb, U) (ICP-MS). Based on pH the waters are neutral or alkaline. The waters exhibited low, medium, and high salt enrichments based on conductivity. Compared to Lake Chad, the concentrations of major ions vary significantly. Salinity, defined by Total Dissolved Solids, ranged from fresh, brackish, and saline to brine waters. Water chemistry is predominantly influenced by the evaporation-crystallization process. In the Piper and Chadha diagrams, the pond waters are mainly of the Na-HCO3 type. Trace element concentrations are either enriched or depleted compared to Lake Chad and resemble those of soda or saline lakes. Occasionally elevated concentrations of As (0.20–0.70 mg/L) could impact the quality of harvested spirulina from the Kanem ponds.*

Keywords—*Chad, Kanem, Pond, Water, Major and Trace Elements, Arsenic, Spirulina.*

I. INTRODUCTION

To the northeast of Lake Chad, the Kanem region is occupied by a fossil erg composed of dunes-oriented NE-SW. The climate is sub-desertic with annual rainfall of less than 300 mm. Temperatures are high, with an average of around 28°C annually. The interdunal depressions are often occupied by permanent or temporary ponds locally referred to as "ouadi." The term "ouadi," derived from "oued," is improper as it implies temporary surface drainage, whereas the ouadis of Kanem have neither watershed nor outlet. The ponds are solely supplied by sources from the shallow groundwater table and rainfall. In Chad, the term "lake" is used for large permanent ponds. Similar to the ponds, lakes are shallow, with depths of about a meter. This renders the term lake incorrect as per Touchart's (2000) terminology, but it has been commonly used since early studies (Iltis, 1969), in agreement with Dussart's (1966) nomenclature. The sub-desert climate leads to the precipitation of evaporitic minerals in the ouadis, primarily gaylussite and trona (Maglione, 1968), as well as Mg-calcite, natron, nahcolite, thermonatrite, halite, northupite, gypsum, mirabilite, thenardite, bloedite, magadiite, kenyaite, kanemite, mordenite (Maglione, 1971, 1976; Maglione and Karn, 1975). Under favorable water salinity conditions (Iltis, 1968, 1969), spirulina develops in the ponds of the ouadis. The ouadis are centers of intense activity for subsistence farming and sometimes for trona exploitation and spirulina harvesting. In the 1950s–1970s, the Kanem region was the subject of numerous scientific studies, but the chemical analyses of ouadi waters conducted during these studies (Iltis, 1971a, 1971b; Maglione, 1969; 1976) only focused on major ions. In this paper, we present and discuss new geochemical results regarding the analysis of major ions and trace elements in the waters of ten ouadis that have not been studied previously.

II. GEOLOGICAL SETTING

The Kanem region is occupied by a Quaternary fossil erg. The aeolian sand formations were deposited during the Pleistocene Last Glacial Maximum approximately 200,000 years ago (Servant, 1983; Maley, 2010; Sylvestre, 2014). During the Holocene, between ca. 12,000 and ca. 5,000 years BP (Amaral et al., 2013; Sylvestre et al., 2019), the climate becomes wetter. Lake Chad then extended to a coastline at 325 meters and formed the Mega Lake Chad (Fig. 1a), covering an area of 350,000 km2 (Schuster et al., 2005; Leblanc et al., 2006a, b). During this transgression, the Mega Lake Chad partially covered the aeolian sand formations, and the lacustrine Labdé series (Servant and Servant, 1970) was deposited in interdunal depressions. This series consists of clay and silts (Dupont, 1967). After around ca. 5,000 years BP, the climate becomes more arid, resulting in a reduction in the surface area of Lake Chad (Sylvestre et al., 2019), which is today estimated at around 25,000 km^2 (CBLT 2023). The Labdé series now outcrops, forming the bottom of the ouadi ponds.

The existence of the ponds depends on rainfall and groundwater levels. The persistence of the ponds is possible when water inputs from the shallow groundwater compensate for the deficit between precipitation and evaporation. The piezometric surface of the groundwater is marked by a depression (Fig. 1b) along the northeast border of Lake Chad (Schneider, 1967 a, b). The ouadis located southwest of this depression are fed by the Lake Chad aquifer; their water levels depend on Lake Chad's water level, which is influenced by rainfall in its watershed. The ouadis located in the northeast of the piezometric depression are fed by the Chitati aquifer, with the underground water divide located about fifty kilometers northeast of Lake Chad. Their water level depends solely on the local rainfall regime that feeds the Chitati aquifer in the studied region.

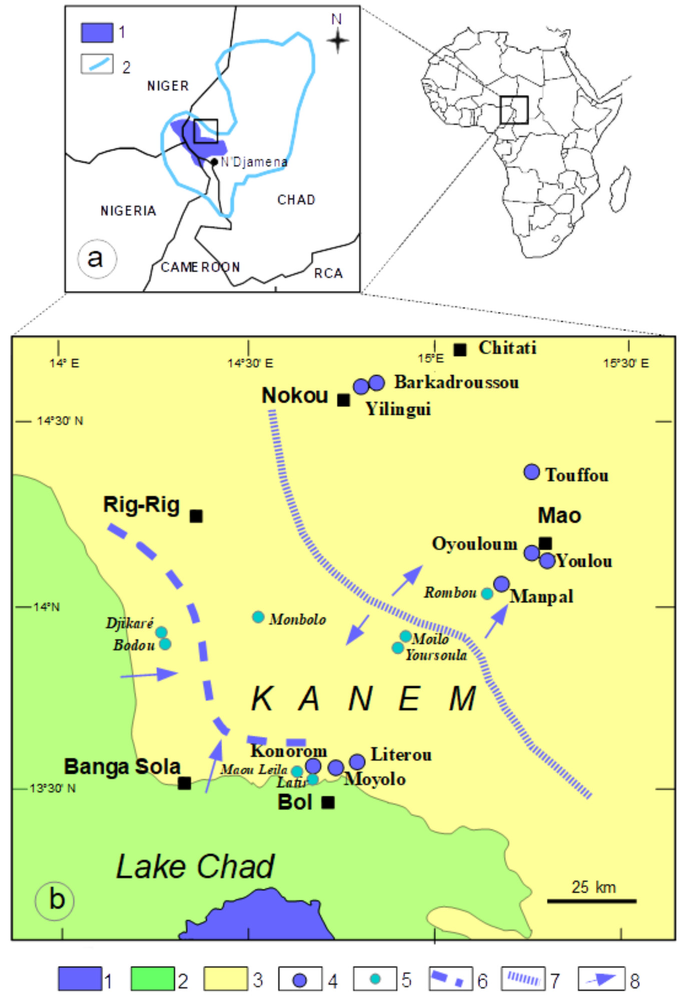

Fig.1. Schematic map of the study area. (**a**) Mega Lake Chad. 1: Current Lake Chad. 2: Holocene Mega Lake Chad. (**b**) Location map of the ouadis. 1: Lake Chad, permanent open water. 2: Lake Chad, polders. 3: Aeolian sand formations and undifferentiated Quaternary deposits. 4: Studied ouadis. 5: Ouadis mentioned in the text. 6: Hydrogeological depression. 7: Groundwater divide. 8: Groundwater flow direction.

Over the past 5,000 years, the transition to a more arid climate in the Lake Chad basin has not been linear and has shown alternating wet and dry periods (Maley, 2010). The current period is characterized by significant irregularities in the annual precipitation regime (Maglione, 1969), leading to cycles of drying and refilling of the ouadi ponds. As such, the ouadis have a complex history marked by several hydrogeological cycles.

Among the ouadis that have been the subject of previous studies (Iltis, 1971a, 1971b; Maglione, 1969; 1976), only the Monbolo and Yoursoula lakes are still in water. The Bodou, Rombou, Djikaré, and Moilo lakes and the Latir and Maou-Leila ponds are currently dried up.

III. SAMPLES COLLECTION AND ANALYSIS

Water samples for analysis were collected in October 2007. The samples were taken from the Oyouloum, Mampal, Moyolo, Rombou, Literou, Youlou, Konorom, Barkadroussou, Touffou, and Yilingui ouadis. The locations of the ouadis are shown in Figure 1b. For comparison, a sample was also taken from the southern part of Lake Chad at Lat 12.996198° N and Long 14.576358° E.

The physicochemical parameters, pH, and temperature were measured in situ using the pH 323 / Set B mixed electrode, and conductivity was measured using the Lf 318 / Set electrode. Several water samples were collected at each site for analysis, and the following sample preparation protocols were conducted in the field. The waters were initially filtered using Millipore mixed cellulose 0.45 µm filters through a pressure vessel and a Millipore Swinnex filter holder. The samples were stored in pre-cleaned high-density polyethylene bottles. Samples for trace element analysis were then filtered at 0.22 µm. Water samples for cations and trace elements analysis were acidified with ultra-pure nitric acid.

Major ions analysis was performed at the Laboratory of Hydrogeology at the University of Avignon, France. Major ions were analyzed using Ion Chromatography. The overall detection limit for ions was 0.04 mg/L. SiO_2 and HCO_3^- were analyzed using a UV-visible Spectrophotometer. Trace element analyses were conducted at the Hydro-Sciences Laboratory, University of Montpellier II (France) using Inductively Coupled Plasma-Mass Spectrometry with a relative uncertainty of less than 5%. Quality control was performed using international water standards

IV. RESULTS AND DISCUSSION

The physical and chemical characteristics of the ouadi waters are presented in Table 1.

4.1 Physical Parameters

The temperature of the ouadi waters is variable. The Barkadroussou and Konorom ouadis have temperatures of 24.30°C and 24.40°C, respectively, similar to Lake Chad measured at 23.40°C. The other ouadis have higher temperatures ranging from 27.40°C to 33.30°C.

The pH values of the ouadi water samples range from 7.45 to 10.17. According to the WHO classification (2017), the waters of Oyouloum and Manpal ouadis with pH values between 6.5 and 8.5 are neutral. The waters of the other ouadis, with pH values above 8.5, are alkaline.

The electrical conductivity (EC) ranged from 227 to 14,800 µS/cm. EC is a measure of the ionic concentration (i.e., salinity) of the water. EC is classified according to Sarath Prasanth et al. (2012) into Type I (EC < 1,500 µS/cm), Type II (1,500 < EC < 3,000 µS/cm), and Type III (EC > 3,000 µS/cm). According to this classification, the Oyouloum and Manpal ouadis fall under Type I (low enrichment of salts). The Moyolo and Rombou ouadis fall under Type II (medium enrichment of salts), and the other ouadis fall under Type III (high enrichment of salts).

4.2 Major ions

The Oyouloum ouadi has a low Na^+ concentration (16.67 mg/L), similar to that of Lake Chad (17.50 mg/L). The other ouadis have highly variable Na^+ concentrations. The Manpal,

TABLE 1. Physicochemical parameters of ouadi waters and a sample from the Southern part of Lake Chad.

		Oyouloum	**Mampal**	**Moyolo**	**Rombou**	**Literou**	**Youlou**	**Konorom**	**Barkadroussou**	**Touffou**	**Yilingui**	**Lake Chad**
T°C		30.70	28.60	27.40	32.70	26.60	33.30	24.40	24.30	29.00	29.90	23.40
pH		7.45	7.73	9.36	9.30	9.61	9.39	9.97	10.09	9.87	10.17	7.60
c 25°C		227	460	2,170	2,700	5,870	21,500	57,000	72,400	75,600	94,800	335
Na+	mg/L	16.97	55.92	441.60	565.50	1,252	5,365	21,840	25,630	27,950	35,550	17.50
K+	mg/L	5.13	12.83	124.40	146.30	334.80	1,276	1,292	6,053	6,273	11,050	8.60
Ca++	mg/L	24.07	32.49	11.33	3.00	2.80	15.80	8.75	7.25	10.25	8.25	16.20
Mg++	mg/L	1.79	1.82	3.79	2.02	8.10	15.60	57.00	55.50	98.75	44.50	7.50
HCO3-	mg/L	105.75	184.18	968.93	1,130	2,120	7,596	16,604	30,715	40,715	27,534	121.40
CO3	mg/L	0.12	0.41	91.02	92.45	354.12	764.50	6,354	15,494	12,376	16,699	1.80
NO3-	mg/L	<0.03	0.52	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	28.36	<0.03	-
NO2-	mg/L	0.55	9.25	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	-
Cl-	mg/L	3.91	7.50	112.57	117.96	470.90	1,789	874.88	6,841	6,027	16,653	4.30
SO4--	mg/L	19.43	52.94	13.51	135.14	146.17	2,869	19,578	784	2,557	4,414	6.20
PO4--	mg/L	<0.03	0.66	11.12	12.42	37.31	204.52	254.56	674.58	572.14	1,247	4.27
Br-	mg/L	<0.03	0.18	1.53	2.31	9.38	31.53	45.55	100.92	86.68	296.13	-
F-	mg/L	0.07	0.19	0.48	0.33	1.20	1.20	2.00	130.87	533.43	7.84	0.90
SiO2	mg/L	58.57	87.21	115.04	79.91	101.41	198.59	209.95	248.00	315.58	333.91	48.54
ionic B		-0.01	-0.01	0.01	0.01	0.00	0.01	0.03	0.01	0.01	0.07	-0.01
Li	µg/L	1.26	0.92	3.08	1.07	1.83	1.81	1.89	16.54	27.75	20.05	0.30
Rb	µg/L	1.83	1.65	16.58	51.20	238.40	383.50	148.10	3,691	4,437	7,642	6.56
Cs	µg/L	0.003	0.01	0.01	0.02	0.06	0.07	0.02	0.95	1.25	1.37	0.02
Be	µg/L	<0.003	<0.003	<0.003	<0.003	<0.003	0.03	0.03	0.05	0.05	0.05	<0.003
Sr	µg/L	89.74	120.30	256.40	44.10	137.00	97.97	395.10	181.90	141.70	144.10	91.23
Ba	µg/L	32.76	29.82	176.80	22.75	255.80	63.22	157.70	196.70	226.90	228.70	70.38
Al	µg/L	<0.129	<0.129	0.13	<0.129	0.13	5.68	2.33	8.16	15.04	8.48	47.87
V	µg/L	1.33	0.42	7.83	30.85	26.25	95.78	228.70	85.40	21.05	245.90	3.88
Cr	µg/L	<0.012	<0.012	1.69	1.11	9.67	41.92	33.40	65.65	92.12	100.80	1.00
Mn	µg/L	<0.003	0.01	0.63	0.58	2.31	9.30	6.07	23.77	64.65	9.91	3.43
Co	µg/L	0.09	0.07	0.14	0.08	0.41	2.21	1.22	1.53	9.98	1.03	0.28
Ni	µg/L	0.08	0.26	0.15	0.45	5.73	51.66	78.61	3.20	10.02	18.00	1.89
Cu	µg/L	0.08	0.81	0.48	3.26	4.09	7.93	25.64	29.78	24.25	60.51	2.18
Zn	µg/L	<0.159	<0.159	0.97	<0.159	5.27	7.18	14.99	5.57	9.94	9.77	16.41
Mo	µg/L	0.75	2.11	2.77	3.64	16.26	206.00	483.90	378.10	82.91	691.90	0.43
Ag	µg/L	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	<0.009	0.04	<0.009	<0.009
Cd	µg/L	<0.003	<0.003	0.003	<0.003	0.84	0.25	1.65	1.64	0.64	0.49	0.13
Sn	µg/L	0.68	0.46	0.29	0.80	0.94	3.63	7.80	11.17	47.38	2.26	5.00
Pb	µg/L	<0.003	<0.003	0.003	<0.003	0.38	<0.003	0.96	1.10	6.13	<0.003	0.19
Bi	µg/L	25.59	35.29	100.40	141.80	774.60	2,939	3,018	7,054	5,905	11,400	5.69
As	µg/L	0.49	0.61	1.51	11.49	18.54	201.30	697.70	377.90	322.10	640.10	0.04
Sb	µg/L	0.04	0.002	0.04	0.12	0.24	1.98	8.42	2.22	1.57	3.55	0.06
U	µg/L	0.03	0.03	0.09	1.02	3.49	6.89	201.40	28.26	15.30	32.18	0.27
TDS	mg/L	237	446	1,896	2,288	4,846	20,129	67,127	85,222	97,556	113,858	190

Moyolo, Rombou, Literou, and Youlou ouadis have concentrations (55.92–5,365 mg/L) lower than that of seawater estimated at 10,784 mg/L (UNESCO, 1994), while the other ouadis have significantly higher concentrations (21,840–35,365 mg/L) than that of seawater.

The Oyouloum and Manpal ouadis have K^+ concentrations of 5.13 mg/L and 12.83 mg/L, respectively, similar to that of Lake Chad (8.6 mg/L). The other ouadis have higher and more variable K^+ concentrations (124.4–11,050 mg/L).

The Ca^{2+} concentrations in the Oyouloum and Manpal ouadis are 24.07 and 32.49 mg/L, respectively, higher than that of Lake Chad (16.20 mg/L). The other ouadis have lower Ca^{2+} concentrations (2.80–15.80 mg/L).

The Oyouloum, Manpal, Moyolo, and Literou ouadis have Mg^{2+} concentrations (1.79–2.02 mg/L) lower than that of Lake Chad (7.50 mg/L). The other ouadis have higher Mg^{2+} concentrations (8.10–98.75 mg/L).

The concentrations of HCO_3^- (105.75–40,715 mg/L) and CO_3^{2-} (0.12–5,494 mg/L) are highly variable. The HCO_3^- concentrations in the Oyouloum and Manpal ouadis, 105.75 and 184.18 mg/L, respectively, are similar to that of Lake Chad (121.4 mg/L). The other ouadis have significantly higher HCO_3^- concentrations (968.93–40,715 mg/L). The CO_3^{2-}

concentrations in the Oyouloum and Manpal ouadis, 0.12 and 0.41 mg/L, respectively, are lower than that of Lake Chad (1.80 mg/L). The other ouadis have significantly higher CO_3^{2-} concentrations (91.02–16,699 mg/L).

NO_3^- concentrations are below the detection limit (0.03 mg/L), except for the Manpal ouadi (0.52 mg/L) and the Touffou ouadi (28.36 mg/L). Nitrate concentrations in the Touffou ouadi are high compared to the other ouadis, where concentrations are similar to most saline lakes (< 1 mg/L) (Jirsa et al., 2013). Nitrate (NO_3^-) and nitrite (NO_2^-) concentrations result from the nitrification of ammonium ions (NH_4^+) derived from incomplete degradation of organic matter in the water. Ammonium ions are oxidized to nitrites and then to nitrates. The elevated NO_3^- values in the Touffou ouadi may be attributed to the high density of spirulina during sample collection (Doumnang Mbaigane, 2008), as spirulina has high rates of decomposition and subsequent nitrification (Hammer, 1986).

NO_2^- concentrations in the ouadis are below the detection limit (0.02 mg/L), except for the Oyouloum and Manpal ouadis, which have concentrations of 0.55 mg/L and 9.25 mg/L, respectively. Nitrites are unstable and naturally occur in low quantities in waters (Appelo and Postma 1996; OEHHA, 1997). The presence of nitrites may be attributed to a significant influx of nitrogen (Forrest et al., 2006; Dubrovsky et al., 2010). We attribute the presence of nitrites in the Oyouloum and Manpal ouadis to recent pollution from the excreta of livestock drinking in these ouadis.

The Cl^- concentrations in the Oyouloum and Manpal ouadis are low, 3.91 and 7.5 mg/L, respectively, similar to that of Lake Chad (4.30 mg/L). The other ouadis have significantly higher Cl^- concentrations (112.57-16,653 mg/L).

SO_4^{2-} concentrations are highly variable (13.51-1,958 mg/L) and higher than that of Lake Chad (6.2 mg/L). The presence of SO_4^{2-} in waters is due to gypsum deposits in the ouadis.

The Oyouloum and Manpal ouadis have very low PO_4^{2-} concentrations, <0.03 and 0.66 mg/L, respectively, lower than that of Lake Chad (4.27 mg/L). The other ouadis have highly variable PO_4^{2-} concentrations (11.12-1,247 mg/L), higher than that of Lake Chad. The PO_4^{2-} concentrations are attributed to the use of phosphate fertilizers for agricultural activities in the ouadis.

The Oyouloum and Manpal ouadis have low Br^- concentrations, <0.03 and 0.18 mg/L, respectively. The other ouadis have higher concentrations (2.31–296.13 mg/L).

The Barkadroussou and Touffou ouadis have high F^- concentrations, 130.87 and 533.43 mg/L, respectively, much higher than that of Lake Chad (0.90 mg/L). The other ouadis have lower (0.07-0.33 mg/L), similar (1.2-2 mg/L), or higher (7.84 mg/L) F^- concentrations than that of Lake Chad.

SiO_2 concentrations range from 58.57 to 333.91 mg/L and are higher than that of Lake Chad (48.54 mg/L).

4.3 Salinity and Total Alkalinity

There are numerous descriptive terms in the literature for describing water salinity, and there are several different classification systems. Typically, Total Dissolved Solids (TDS) is used to define salinity. According to TDS (Kharaka and Hanor, 2003), waters are classified as freshwater (TDS < 1 g/L), brackish (1 < TDS < 10 g/L), saline (10 < TDS < 35 g/L), and brine (TDS > 35 g/L). The TDS values of the ouadi waters (Table 1), calculated by adding the total ion concentration of the water, are highly variable (205 to 11,386 mg/L). According to the above classification, the Oyouloum and Manpal ouadis, similar to Lake Chad (TDS = 167 mg/L), are classified as freshwater. The Moyolo, Rombou, and Literou ouadis are Brackish, the Youlou ouadi is Saline, and the Konorom, Barkadroussou, Touffou, and Yilingui ouadis are Brines.

The ouadi waters exhibit an excess of total alkalinity (TA = $HCO_3^- + 2(CO_3^{2-})$ i.e., the sum of the charges of the bicarbonate ion plus carbonate ion) over the charges of the alkaline earth ions magnesium and calcium: $(HCO_3^-) + 2(CO_3^{2-}) > 2(Mg^{2+}) + 2(Ca^{2+})$. According to Kempe and Kazmierczak (2011), this characterizes "soda lakes" where evaporation of the waters will lead to an increase in pH, and eventually, sodium carbonates will precipitate.

4.4 Mechanisms Controlling Water Chemistry

The Gibbs (1970) diagram is an effective tool for identifying the major mechanisms controlling natural water chemistry, including precipitation, rock-water interaction, and evaporation.

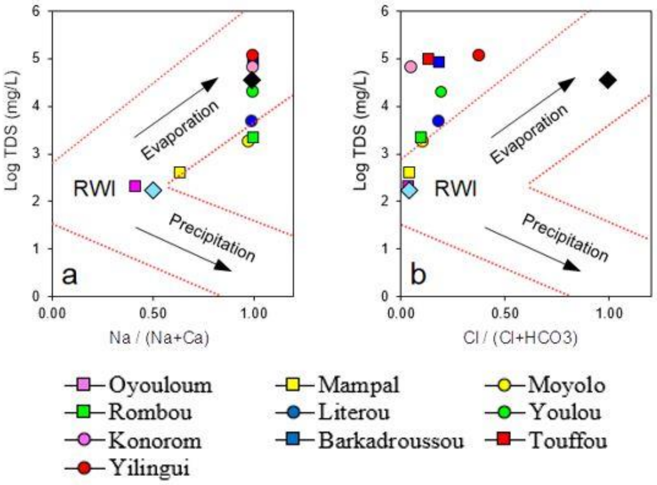

Fig. 2. Gibbs (1970) plots, a and b, showing the dominant factors controlling the ouadi water chemistry. RWI: Rock-Water interaction. Blue diamond: Lake Chad. Black diamond: Sea Water (UNESCO, 1994).

In the Gibbs diagram TDS vs $N/(Na^+ + Ca^{2+})$ (Fig. 2a), the waters of Oyouloum and Manpal fall, as Lake Chad, within the rock-water interaction dominant zone. The waters of the other ouadis fall within the evaporation dominance zone. This indicates that water chemistry is primarily controlled by the evaporation-crystallization process. The evaporation process increases from the Moyolo ouadi to the Youlou ouadi, with the TDS being slightly lower than that of seawater. The Konorom, Barkadroussou, Touffou, and Yilingui ouadis have TDS values higher than that of seawater.

In the Gibbs diagram TDS vs $Cl^-/(Cl^- + HCO_3^-)$ (Fig. 2b), the waters of Oyouloum, Manpal, and Lake Chad also fall within the rock-water interaction dominant zone. The water chemistry of the other ouadis falls above the evaporation dominance zone defined by Gibbs (1970), which does not take into account soda lakes.

The Pearson correlation coefficient, r, shows a strong positive correlation ($p < 0.05$) of Na^+ ($r = 1$), CO_3^{2-} ($r = 0.97$), HCO_3^- ($r = 0.95$), SiO_2 ($r = 0.96$), K^+ ($r = 0.92$), PO_4^{2-} ($r = 0.92$), Mg^{2+} ($r = 0.88$), Cl^- ($r = 0.84$), and Br^- ($r = 0.84$) with TDS. The concentration of these ions depends on the water concentration, which increases with the progression of evaporation. The other major ions show no correlation with TDS. Therefore, their concentrations are not influenced by evaporation.

4.5 Type Waters

The chemical analysis results of major ions have been plotted on the diagram proposed by Piper (1944) and Chadha (1999) to identify water types. We have also included the average concentrations of analyzed waters available in the literature (Iltis 1971a, 1971b; Maglione 1969, 1976). The diagrams were made using Simler's (2023) software.

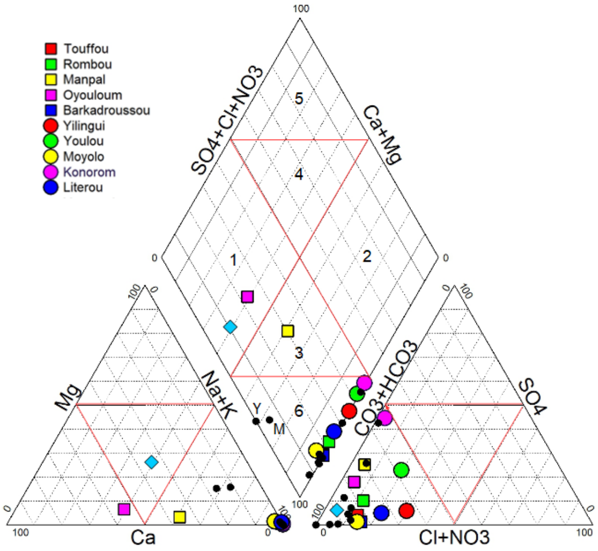

Fig.3. Piper diagram. Water types: 1, Ca-HCO3; 2, mixed Na-Cl-SO4; 3, mixed Ca-Na-HCO3; 4, mixed Ca-Mg-SO4-Cl, 5, Ca-Cl; 6, Na-HCO3. Blue diamond: Lake Chad. Analyze available in the literature: Y, Yoursoula; M, Moilo; Black solid circles, other ouadis (Iltis 1971a, 1971b; Maglione 1969; 1976).

The Piper diagram (Fig. 3) shows that the ouadi waters are predominantly of sodium bicarbonate type except for the freshwaters of Oyouloum, which is of calcium bicarbonate type, and Manpal, which is a mixed type of calcium bicarbonate and sodium bicarbonate.

The Chadha diagram divides water into eight types, as illustrated in Fig. 4. In this diagram, weak acidic anions (HCO_3^- and CO_3^{2-} exceed strong acidic anions (Cl^- and SO_4^{2-}) and, except for the Oyouloum ouadi, alkali metals (Na^+ and K^+) exceed alkaline earths (Ca^{2+} and Mg^{2+}). The freshwater of the Oyouloum ouadi and Lake Chad belong to the Ca-Mg-HCO3 type. The other ouadis belong to the Na-HCO3 type.

These results are consistent with the older analyses available in the literature, which show that the ouadi waters are predominantly of sodium bicarbonate type (Figs. 3 and 4). In the Piper and Chadha diagrams, the freshwater of Oyouloum, Manpal, Yoursoula (Maglione 1969), and Moilo (Maglione 1976) stand out from the other ouadis due to their lower sodium content. The low salinity of certain ouadis can be explained by leakage of salts into the underlying groundwater, as is the case for Lake Chad, and also by a significant salinity gradient from the edge of the ponds fed by freshwater sources to center, saltier due to evaporation (Maglione 1976).

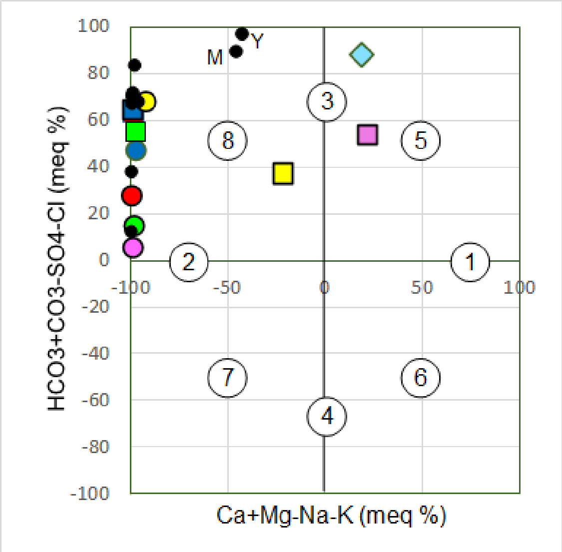

Fig. 4. Chadha diagram. Same legend as Fig.3. (1) Alkaline earths exceed alkali metals, (2) alkali metals exceed alkaline earths, (3) weak acidic anions exceed strong acidic anions, (4) strong acidic anions exceed weak acidic anions, (5) Ca–Mg–HCO3 water type, (6) Ca–Mg–Cl water type, (7) Na–Cl water type, (8) Na–HCO3 water type.

4.6 Trace Elements

The concentrations of trace elements are presented in Table 1. To assess the enrichment of trace elements during the evaporation of ouadi waters, we compare the trace element concentrations to those of freshwater from the Southern part of Lake Chad. The normalized trace element profiles of ouadi waters (Fig. 5) reveal diverse enrichments and depletions depending on the elements and the considered ouadis.

The lithium (Li) concentrations (0.92–27.75 µg/L) are higher than that of Lake Chad (0.30 µg/L). Most ouadis have concentrations <10 µg/L, comparable to the soda Lake Turkana (Otachi et al., 2015). However, the ouadis of Barkadroussou, Touffou, and Yilingui have higher concentrations (16.54–20.05 µg/L), which are still much lower than those of Li-exploited salt lakes (Labbé and Daw, 2012).

Rubidium (Rb) concentrations in Oyouloum (1.83 µg/L) and Manpal (1.65 µg/L) are lower than that of Lake Chad (6.56 µg/L) and comparable to the soda Lake Turkana (<10 µg/L) (Otachi et al., 2015). Other ouadis exhibit more variable Rb concentrations (16.58–7,242 µg/L), some of which are lower or within the range of salt lake concentrations (300–16,900 µg/L) (Gao et al., 2020).

Cesium (Cs) concentrations in ouadis are either lower or equal (0.01–0.02 µg/L) to that of Lake Chad (0.02 µg/L) or higher (0.06–1.37 µg/L). These concentrations are low compared to salt lakes (34–2,500 µg/L) (Gao et al., 2020).

Beryllium (Be) concentrations in ouadis (<0.003–0.05 µg/L) are very low.

Strontium (Sr) concentrations in Oyouloum (89.74 µg/L) and Rombou (44.10 µg/L) are lower than that of Lake Chad (91.23 µg/L). Other ouadis show higher concentrations (97.97–395 µg/L), comparable to soda lakes Turkana, Nakuru, and Bogoria (10–286 µg/L) (Jirsa et al., 2013; Otachi et al., 2015).

Barium (Ba) concentrations in Oyouloum (32.76 µg/L), Manpal (29.82 µg/L), and Rombou (22.75 µg/L) are lower than that of Lake Chad (70.38 µg/L). Other ouadis have higher concentrations (157.70–255.80 µg/L), which fall within the range of soda lakes Turkana, Nakuru, and Bogoria (<10–643 µg/L) (Jirsa et al., 2013; Otachi et al., 2015).

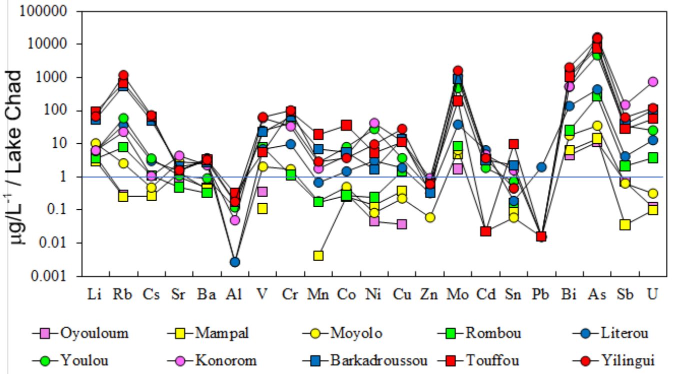

Fig. 5. Profiles of trace elements normalized with the values of the Southern part of Lake Chad.

Aluminum (Al) concentrations (<0.129–15.04 µg/L) are lower than that of Lake Chad (47.87 µg/L). These concentrations are low compared to the soda Lake Turkana (860 µg/L) (Otachi et al; 2015), the salt lakes of South Africa (>150 µg/L) (Melho et al., 2023), and the Altai region (170–720 µg/L) (Leonova et al., 2007).

Vanadium (V) concentrations in Oyouloum (1.33 µg/L) and Manpal (0.2 µg/L) are lower than that of Lake Chad (3.88 µg/L). Other ouadis exhibit higher concentrations (7.83–245.90 µg/L) compared to Lake Chad. These values are comparable to those of South African salt lakes (5–147 µg/L) (Melho et al., 2023).

Chromium (Cr) concentrations in Oyouloum and Manpal are lower than the detection threshold of 0.012 µg/L. Other ouadis show concentrations (1.69–100.80 µg/L) higher than that of Lake Chad (1.00 µg/L). These concentrations are comparable to those of the Altai salt Lakes (11-16 µg/L) (Leonova et al., 2007) and the Urubu salt Lake (50 µg/L) (Akubugwo et al., 2007).

Manganese (Mn) concentrations in Oyouloum are below the detection threshold (0.003 µg/L). Ouadis of Manpal, Moyolo, Rombou, and Literou exhibit lower concentrations (0.01–2.31 µg/L) than that of Lake Chad (3.43 µg/L). Other ouadis show higher concentrations. These concentrations are within the range of soda lakes Lonar (0.07 µg/L) (Surve et al., 2020) and Turkana (28 µg/L) (Otachi et al., 2015).

Cobalt (Co) concentrations are diverse. Ouadis of Oyouloum, Manpal, Moyolo, and Rombou have concentrations (0.07–0.14 µg/L) lower than that of Lake Chad (0.28 µg/L). Other ouadis show concentrations (0.41–9.98 µg/L) higher. These concentrations are low compared to the Sambhar soda lake (2,450–9,100 µg/L) (Cherakar and Pathak, 2016; Pathak and Cherakar, 2015).

Nickel (Ni) concentrations are varied. Ouadis of Oyouloum, Manpal, Moyolo, and Rombou have concentrations (0.08–0.45 µg/L) lower than that of Lake Chad (1.89 µg/L). These low concentrations are comparable to those of the soda lake Turkana (<5 µg/L) (Otachi et al., 2015). Other ouadis exhibit concentrations (5.73–78.61 µg/L) higher than Lake Chad and within the range of South African salt lakes (2–8,000 µg/L) (Melho et al., 2023).

Copper (Cu) concentrations are varied. The ouadis of Oyouloum, Manpal, and Moyolo have concentrations (0.08–0.81 µg/L) lower than that of Lake Chad (2.18 µg/L) and comparable to those of the soda Lake Turkana (<0.2 µg/L) (Otachi et al., 2015) and Lonar (0.45 µg/L) (Surve et al., 2021). Other ouadis show higher concentrations (4.09–60.51 µg/L), comparable to those of salt lakes in the Altai region (8–13 µg/L) (Leonova et al., 2007) and the Urubu Salt Lake (15 µg/L) (Akubugwo et al., 2007).

Zinc (Zn) concentrations (0.97–14.99 µg/L) are lower than that of Lake Chad (16.41 µg/L). These concentrations fall within the range of soda lakes Nakuru and Sambhar (<10–600 µg/L) (Jirsa et al., 2013; Pathak and Cherakar, 2015).

Molybdenum (Mo) concentrations show diversity (0.75–691.90 µg/L) and are higher than that of Lake Chad (0.43 µg/L). These concentrations are within the range of soda lakes Van and Nakuru (0.02–1,712 µg/L) (Reimer et al., 2009; Jirsa et al., 2013).

Silver (Ag) concentrations are below the detection limit (0.009 µg/L).

Cadmium (Cd) concentrations in Oyouloum, Manpal, Moyolo, and Rombou (<0.003–0.003 µg/L) are lower than that of Lake Chad (0.13 µg/L). Other ouadis exhibit higher concentrations (0.25–1.65 µg/L). These low concentrations are similar to those of unpolluted lakes for Cd, such as the soda lake Turkana (<5 µg/L) (Otachi et al., 2015) or the Urubu salt lake (3 µg/L) (Akubugwo et al., 2007).

Ouadis of Konorom, Barkadroussou, and Touffou have tin (Sn) concentrations (7.8–47.38 µg/L) higher than that of Lake Chad (5.00 µg/L). Other ouadis exhibit lower concentrations (0.29–3.63 µg/L) than that of Lake Chad.

Ouadis of Literou, Konorom, Barkadroussou, and Touffou have lead (Pb) concentrations (0.38–6.13 µg/L) higher than that of Lake Chad (0.19 µg/L). Other ouadis exhibit very low concentrations (<0.003–0.003 µg/L) of Pb.

Bismuth (Bi) concentrations (25.59–11,400 µg/L) show significant variability and are higher than that of Lake Chad (5.69 µg/L).

Arsenic (As) concentrations (0.49–697.70 µg/L) show considerable variability and are higher than that of Lake Chad (0.04 µg/L). Arsenic concentrations in Youlou, Konorom, Barkadroussou, Touffou, and Yilingui (201.30–697.70 µg/L) are elevated compared to those of soda lakes of Sambhar (20 µg/L) (Pathak and Charaka, 2015), Nakuru (9–103 µg/L), and Bogoria (18–132 µg/L) (Jirsa et al., 2013). These high concentrations of As pose problems for spirulina harvested in the ouadis due to the ability of spirulina to absorb heavy metals as well as toxic elements such as As (Gershwin and Belay 2008; Doshi et al., 2009; Ahmad et al., 2010). Arsenic concentrations exceeding the tolerable limit of 1 ppm for human consumption (USP, 2015) have been reported in spirulina from Chad (Vicat et al., 2014).

Antimony (Sb) concentrations in Oyouloum, Manpal, and Moyolo (0.002–0.04 µg/L) are lower than that of Lake Chad (0.04 µg/L). Other ouadis show concentrations (0.12–3.55 µg/L) which are low compared to those of salt lakes in South Africa (5–200 µg/L) (Melho et al., 2023).

Uranium (U) concentrations in Oyouloum, Manpal, and Moyolo (0.03–0.049 µg/L) are lower than that of Lake Chad (0.04 µg/L). Other ouadis exhibit concentrations (3.49–201.40 µg/L) higher and comparable to those of the Sambhar salt lake (8–1,400 µg/L) (Yadav and Sarin, 2009).

The Pearson correlation coefficient, r, shows a strong positive correlation ($p < 0.05$) with the TDS for Bi ($r = 1$), Cu ($r = 0.98$), Rb ($r = 0.94$), Cr ($r = 0.93$), Cs ($r = 0.89$), Mo ($r = 0.88$), As ($r = 0.84$), Li ($r = 0.79$), and a good positive correlation for V ($r = 0.74$) and Al ($r = 0.67$). These elements tend to be conserved in the ouadi waters throughout the evapoconcentration process. The other trace elements do not show a correlation with the TDS.

V. CONCLUSION

The chemical composition of the waters of the Kanem ouadis is that of soda lakes with varying salinity and alkalinity levels. The concentrations of major ions show high variability compared to Lake Chad. Water chemistry is primarily influenced by the process of evapoconcentration. The predominant water type is sodium bicarbonate, consistent with historical analyses.

This study presents the initial data on trace element contents. Trace elements display varying degrees of enrichment or depletion when compared to Lake Chad. Trace element concentrations are similar to those found in soda lakes or saline lakes.

The concentrations of Na^+, K^+, Mg^{2+}, HCO_3^-, CO_3^{2-}, Cl^-, PO_4^{2-}, Br^-, SiO_2, Li, Rb, Cs, Cr, Cu, Mo, Bi, As, Al and V are positively correlated with the evapoconcentration process.

Due to sometimes high concentrations of As in water, this study recommends that spirulina development projects in the Kanem region include monitoring this toxic element in spirulina harvested in the ouadis.

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