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RESEARCH ARTICLE

Major Constituents' Distribution as an Indicator of Water Exchange Between Lake Burullus and the Mediterranean Sea

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Abstract

Aim/objectives: **The main objective of the present study is to assess the status of Lake Burullus water quality via salinity, major ions, and chlorinity rate besides side total and specific alkalinity and evaluate the levels and the distribution pattern of different major ions and their chlorinity ratios. Produced data can help decision-makers benefit from the three different water masses with different salinities in farming different types of fish in this important Lake to meet the population's growing need for fish protein.**

Background: **Lake Burullus is a shallow brackish basin. It is the second largest natural Lake of the five coastal Lakes along the Mediterranean coast in Egypt. It is connected to the sea through a Canal 250 m long (El-Boughaz), which is shallow and saline, and connected to the western branch of the Nile by a small Canal (Brimbal Canal). The Lake is bordered by agricultural land from the south. The average volume of Lake Water (at zero mean sea level) is estimated at 328 million m^3, and the annual volume of about 3.9 billion m^3 is discharged into the Lake through the agricultural drainage system. The water level in the Lake is mostly higher than the sea level. Saline water enters the Lake from the sea through El-Boughaz during most minor irrigation requirements in the winter. The agricultural drainage waters that discharge into the Lake contain fewer salinity loads than seawater, and massive amounts of fertilizers led to creating hypertrophic levels. After the political leadership program "Rehabilitation of Egyptian lakes", the purification operations and development of the Egyptian lakes started from February 2010 till now leading to developing and increasing the quantities of water exchange between the Burullus Lake, and the Mediterranean Sea through the El-Boughaz. So, many investigators began to study the effect of these changes on Burullus Lake taking into consideration the water characteristics, climate change and their effect on the fish quality and production.**

Methods: **Sixty-two subsurface water samples were collected in 1L polyethylene bottles from 31 locations during two cruises (winter and autumn 2020) covering the different sectors of the Lake and its Drains. Salinity was measured using an inductive Salinometer Beckman model (RS-10). Chlorinity was calculated from salinity. Sodium and lithium were determined using a flame photometer (PFP JENWAY 7), Ca^{+2} and Mg^{+2} were analyzed titrimetrically against an EDTA solution. Sulphate was measured turbidimetrically. Total alkalinity was measured titrimetrically. Statistical analysis; the correlation coefficient at a confidence limit of 95% ($P \leq 0.05$) was estimated for all data ($n = 62$) using the Microsoft Office Excel program.**

Results and conclusion: **Based on salinity and specific alkalinity levels, three different water masses have been identified in Lake Burullus. The eastern sector represents a Lake-Sea connection with relatively high salinity and low specific alkalinity, the middle zone with intermediate levels, and the western part, which is far from the sea connection with low salinity and high specific alkalinity. Concerning the analyzed major ions for the two studied seasons where $n = 62$, the average concentration of the studied ions (mg/L) and their corresponding chlorinity ratios are as follows: Na^+ (788)**

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0.2740, Mg^{+2} (179) 0.0905, Ca^{+2} (74) 0.0587, SO_4^{-2} (677) 0.3461, alkalinity (336) 0.332, Li^{+} (0.135) 0.1401×10^{-3}. Salinity average concentrations were 3.783 and 2.096 for CI‰. The major cations or anions concentration in either the eastern or middle zones of the Lake follow the same order: $Na^{+}>Mg^{+2}>Ca^{+2}>Cl^{-}>SO_4^{-2}$. For the western part, the order of concentration is $Na^{+}>Ca^{+2}>Mg^{+2}>Cl^{-}>HCO_3^{-}>SO_4^{-2}$. Fortunately, the water quality of the Burullus Lake tends to be better for fish production as a positive impact was observed after the cleansing and development operations in the lake on all economic variables under study.

Keywords: Chlorinity ratios, Lake Burullus, Lithium, Major ions, Salinity

1. Introduction

Lake Burullus is a shallow brackish basin, the second largest natural lake of the five coastal lakes along the Mediterranean coast in Egypt. It is situated between the two River Nile branches; its length is ~60–70 km, and its average width is ~11 km. The Lake is separated from the Mediterranean Sea by a strip of sandy land. It is connected to the sea through a 250 m-long canal (El-Boughaz), which is shallow and saline, and connected to the western branch of the Nile by a small canal (Brimbal Canal). The lake is bordered by agricultural land from the south. The lake has economic importance as it contributes to a significant amount of fish yield, reaching 67.577 tons in 2016 in addition to about 670.000 tons from the aquaculture processes around it, representing 42.5% of the total fish production in Egypt (GAFRD, 2018) and has been designated as a Ramsar site since 1998 because of its importance for migratory foraging, refuge, and breeding of water birds (Goher, 2009). It offers opportunities to organize bird-watching tours and some simple nautical activities. Tourism can also create additional income, especially along the coastline in Baltim town. After clamming off the Nile began in 1964; a steady flow of the Nile water used for the irrigation system began to drain to the Lake and become a constant evacuator to the Mediterranean Sea. Lake water depth varies from 50 to 200 cm from west to east, with a 150 km long shoreline. Because of its central location, the lake receives most drainage water (industrial, municipal, and agricultural) through 11 drains. The average volume of Lake water (at zero mean sea level) is estimated at 328 million m^3, and the annual volume of ~3.9 billion m^3 is discharged into the Lake through the agricultural drainage system. The water level in the Lake is mostly higher than the sea level. Saline water enters the Lake from the sea through El-Boughaz during most minor irrigation requirements in the winter. The agricultural drainage waters that discharge into the Lake contain fewer salinity loads than seawater, and massive amounts of fertilizers lead to creating hypertrophic levels (Elsayed et al., 2019).

The purification operations and development of the Egyptian lakes started in February 2010 till now. These goals were undertaken after the political leadership program ‘Rehabilitation of Egyptian Lakes’ (Mehanna et al., 2023). Developing and increasing the quantities of water exchange between the Burullus Lake and the Mediterranean Sea through the El-Boughaz was one of the main objectives of the state plan.

Abd El Fatah et al. (2022) in their study divided the lake into three basins to assess the effect of seawater on the lagoon by collecting 12 stations only from the whole lake. The eastern basin (sites 1–3) receives agricultural water discharged from drains 3, 4, 5, and 7 and lies near Boughaz El-Burg. The middle of the lake (sites 4, 5, 6, 7, and 8) receives waste effluents from drains 8 and 9. The western basin represents the western side (sites 9–12), where drains 11 and 12 discharge their effluents, in addition to Brimbal Canal, which receives estuarine Nile water.

Al-Afify et al. (2023) studied the salinity and the major constituents of the Lake during 2022. Younis et al. (2024) investigated the impacts of climate change and seasonal variation on water quality and Nile Tilapia fish (*Oreochromis niloticus*) of Lake Burullus, during the four seasons of 2022 through five stations. These stations were: El-Burullus Drain, Bougaz El-Burullus Drain (7), and El-Shakhloba and Mastrou. Their results showed that the salinity % of lake water was the highest during winter and spring seasons, especially at Bougaz El-Burullus. Dissolved oxygen (DO) and ammonia (NH_3) were significantly increased during summer and autumn. The study showed seasonal changes in the level of total protein, albumin, globulin, AST, and ALT in the serum of Tilapia fish.

The main objective of the study is to assess the status of Lake Burullus water quality by analyzing the salinity, major ions, and chlorinity ratio besides total and specific alkalinity and evaluate the levels and the distribution pattern of different major ions and their chlorinity ratios. The produced data can help decision-makers benefit from the three different water masses with different salinities in farming different types of fish in this important lake to meet the population's growing need for fish protein.

2. Materials and methods

2.1. Area of study

The Lake can be divided into three sectors. The eastern sector includes 10 Sts., the middle sector contains 15 Sts, and the western sector comprises six Sts. Drainage water discharges into the Eastern Sector coming from three drains (Burullus East, Khashah, Nasser). The Middle Sector is affected by five drains (Drain 7, Drain 8, Drain 9, Maqsabah and Qudaah). Finally, the western sector receives drainage water from three drains (Drain 11, West Burullus, and Zaghloul) and one freshwater Canal (Brimbal Canal). Lake Burullus is affected mainly by agricultural drainage water mixed with different types of water from fish farms (Terra Drain, Drains 7, 8, and 11). Industrial effluents (Terra Drain, Drain 7, and El-Gharbia Drain) and domestic drainage water are being discharged mainly from El-Gharbia Drain and Drain 11.

2.2. Sampling and measurements

Sixty-two subsurface water samples were collected in 1 l polyethylene bottles from 31 locations (Fig. 1) during two cruises (Winter and Autumn, 2020) covering the different sectors of the lake and its drains. Salinity was measured using an inductive salinometer, the Beckman model (RS-10). Chlorinity was calculated from salinity according to the formula: S‰ = 1.80655 Cl‰.

Sodium and lithium were determined using a flame photometer (PFP JENWAY 7). Ca^{+2} and Mg^{+2} were analyzed through titration against an EDTA solution (APHA-AWWA-WPCF, 1995). Sulfate was measured turbidimetrically (Grasshoff, 1976). Total alkalinity was measured through titration as described by Strickland and Parsons (1977).

2.3. Statistical analysis

The correlation coefficient at a confidence limit of 95% ($P \leq 0.05$) was estimated for all data ($N = 62$) using the Microsoft Office Excel program.

3. Results and discussion

The concentrations of the studied parameters and their corresponding chlorinity ratios are tabulated in Tables 1 and 2.

3.1. Sodium (Na^{+})

Sodium is the most common monovalent cation in oceans, seas, saline, and brackish basins. It is the sixth abundant element on earth. The total average of Na-content in the lake water is 788 mg/l (Table 3), comprising ~21% of the mean salinity. Noticeable seasonal variations could be detected where the level decreased from 856 mg/l in winter to 720 mg/l

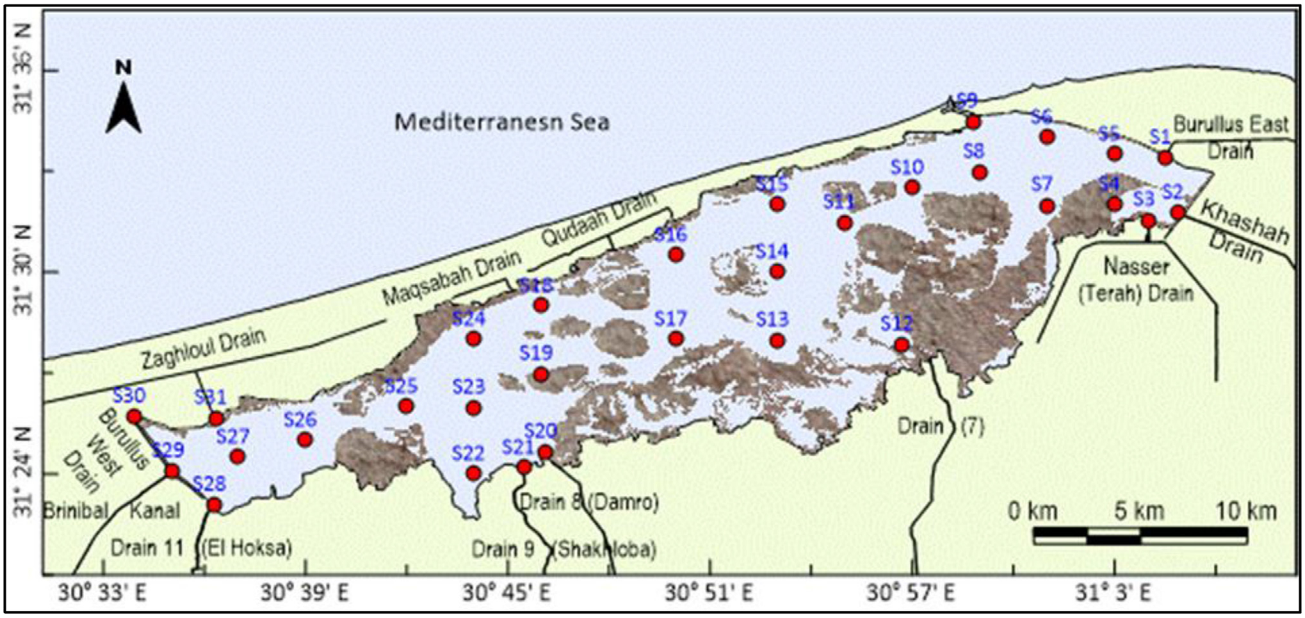

Fig. 1. Lake Burullus sampling locations.

Table 1. Major constituents and lithium concentrations in Lake Burullus water (January 2020).

Sts.	Na^+	Li	Ca^{2+}	Mg^{2+}	$SO_4{}^{2-}$	Alkalinity	S	Cl	Na/Cl	Li/Cl (10^{-3})	Ca/Cl	Mg/Cl	$SO_4{}^{2-}$/Cl	Specific alkalinity
	mg/l					$mgCaCO_3/LL$	‰							
S1	180	0.14	79	116	880	460	2.9	1.61	0.1120	0.0872	0.0492	0.0723	0.5480	0.287
S2	1100	0.13	79	161	950	305	5.27	2.92	0.3770	0.0445	0.027	0.055	0.3252	0.104
S3	600	0.12	69	137	800	325	3.68	2.04	0.2950	0.0589	0.0339	0.0672	0.3927	0.16
S4	615	0.15	69	122	810	310	3.71	2.05	0.2990	0.073	0.0337	0.0594	0.3944	0.151
S5	2200	0.14	138	364	2170	335	10.98	6.08	0.3620	0.023	0.0227	0.0599	0.357	0.055
S6	2800	0.15	138	379	1737	307.5	11.4	6.31	0.4440	0.0238	0.0219	0.0601	0.2753	0.049
S7	3200	0.13	138	349	1297	340	11.4	6.31	0.5070	0.0206	0.0219	0.0553	0.2055	0.054
S8	2950	0.17	118	406	1500	332.5	11.27	6.24	0.4730	0.0273	0.019	0.0651	0.2404	0.053
S9	3100	0.14	118	354	1030	310	10.53	5.83	0.5320	0.024	0.0203	0.0607	0.1767	0.053
S10	2900	0.12	118	384	906	320	9.86	5.46	0.5310	0.022	0.0217	0.0704	0.1660	0.059
S11	1134	0.15	89	200	880	360	5.21	2.88	0.3930	0.052	0.0308	0.0693	0.3051	0.125
S12	300	0.11	79	116	880	350	3.14	1.74	0.1730	0.0633	0.0455	0.0667	0.5063	0.201
S13	350	0.07	59	173	1010	307.5	3.64	2.02	0.1730	0.0347	0.0293	0.0854	0.5000	0.152
S14	500	0.10	69	182	1371	330	4.86	2.69	0.1860	0.0372	0.0257	0.0677	0.5096	0.123
S15	1600	0.11	128	251	1317	335	7.62	4.22	0.3790	0.0261	0.0304	0.0595	0.3122	0.079
S16	900	0.12	74	134	920	340	4.61	2.55	0.3530	0.047	0.029	0.0525	0.3605	0.133
S17	220	0.14	64	110	772	337.5	2.66	1.47	0.1490	0.0951	0.0436	0.0747	0.5243	0.229
S18	200	0.13	98	60	470	312.5	1.	1.08	0.1850	0.1204	0.0908	0.0556	0.4354	0.290
S19	200	0.15	88	65	455	310	1.85	1.02	0.1950	0.1465	0.0859	0.0639	0.4443	0.303
S20	200	0.14	88	65	445	360	1.83	1.01	0.1970	0.1382	0.0869	0.0646	0.4393	0.355
S21	200	0.14	64	58	430	380	1.74	0.96	0.2080	0.1454	0.0666	0.0602	0.4464	0.395
S22	160	0.15	103	27	400	405	1.62	0.9	0.1780	0.1673	0.1149	0.0299	0.4461	0.452
S23	215	0.14	54	79	410	355	1.78	0.99	0.2180	0.1421	0.0551	0.08	0.4161	0.360
S24	180	0.15	79	71	390	315	1.69	0.94	0.1920	0.1603	0.0844	0.0763	0.4169	0.337
S25	220	0.15	79	64	425	285	1.87	1.04	0.2130	0.1449	0.0763	0.0618	0.4106	0.275
S26	200	0.14	79	64	400	262.5	1.72	0.95	0.2100	0.147	0.083	0.0672	0.4201	0.276
S27	150	0.15	128	12	350	260	1.49	0.82	0.1820	0.1819	0.1556	0.0144	0.4244	0.315
S28	100	0.15	59	24	105	275	0.69	0.38	0.2620	0.3927	0.1551	0.0623	0.2749	0.720
S29	175	0.15	128	12	340	255	1.55	0.86	0.2040	0.1748	0.1496	0.0139	0.3963	0.297
S30	132	0.14	54	42	210	250	1.06	0.59	0.2250	0.2386	0.0926	0.071	0.3579	0.426
S31	241	0.13	54	101	644	330	2.46	1.36	0.1770	0.0955	0.0399	0.0743	0.4729	0.242
Total average	856	0.14	90	151	797	324.5	4.39	2.43	0.2770	0.1018	0.0594	0.0612	0.3839	0.229
Minimum	100	0.07	54	12	105	250	0.69	0.38	0.1120	0.0206	0.019	0.0139	0.1660	0.049
Maximum	3200	0.17	138	406	2170	460	11.4	6.31	0.5320	0.3927	0.1556	0.0854	0.5480	0.72

in autumn (Tables 1 and 2). A sharp drop could be detected westward, where the total average of both seasons for the eastern sector of 1812 mg/l dropped abruptly to 453 mg/l (25%) for the middle basin and reached only 100 mg/l (6%) for the western sector (Table 3 and Fig. 2). This lateral variation in Na-content is parallel to the reduction in salinity level from the eastern diluted seawater to the middle mixed drainage water and finally the fresh Nile and drainage water in the western end of the lake. The highest salinity levels in the eastern sector are due to seawater entering the Lake through Boughaz El-Burullus.

Stations from 5 to 10 exhibit high levels of Na (~3.000 g/l) in their water during winter (Table 1 and Fig. 1S), which is affected by the saline water of the Mediterranean Sea. Stations (27–30) at the western end of the Lake around Brimbal Canal represent the lowest Na level less than 200 mg/l for both seasons (Tables 1 and 2). The middle sector average of the Lake exhibits its water at an intermediate level of 453 mg/l (Table 3). Concerning the normal chlorinity ratio of 0.5555 reported by Nessim et al. (2015), all the computed data fluctuated widely below the normal ratio. The highest and the lowest sodium chlorinity ratios were computed during autumn (Table 2, Fig. 2). The highest ratio of 0.5552 was affected by El-Boughaz saline water (St. 10), while the lowest one of 0.0440 was detected for the western end of the Lake (St. 30) near Brimbal Canal (Table 2) with a total average ratio of 0.2740 (Table 3). Regionally, chlorinity ratios reflect substantial variations; the eastern sector, including El-Boughaz, shows the highest levels, 0.2713 and 0.2760, during autumn and winter, respectively (Table 3). These results coincided with those of Younis et al. (2024), who found that the salinity ‰ of Lake water was the highest during the winter season, especially at Bougaz El-Burullus. The ratio decreased abruptly westward to its half for the middle sector and continued dropping to reach approximately one-fourth at the western end of the basin (Fig. 2 and

Table 2. Major constituents and lithium concentrations in Lake Burullus water (October 2020).

Sts.	Na^+	Li	Ca^{2+}	Mg^{2+}	$SO_4{}^{2-}$	Alkalinity	S	Cl	Na/Cl	Li/Cl × (10-3)	Ca/Cl	Mg/Cl	$SO_4{}^{2-}$/Cl	Specific alkalinity
	mg/l					$mgCaCO_3/l$	‰							
S1	2000	0.14	80	316	772	345	7.19	3.98	0.5030	0.0352	0.0201	0.0794	0.1940	0.087
S2	550	0.13	56	173	465	340	2.85	1.58	0.3490	0.0824	0.0356	0.1094	0.2949	0.216
S3	275	0.12	80	122	436	350	2.14	1.18	0.2320	0.1013	0.0677	0.1026	0.3677	0.296
S4	1000	0.15	72	224	668	355	4.47	2.47	0.4040	0.0606	0.0292	0.0904	0.2701	0.144
S5	1550	0.14	96	331	604	340	6.43	3.56	0.4350	0.0393	0.027	0.0929	0.1697	0.096
S6	2420	0.15	96	448	975	355	8.92	4.94	0.4900	0.0304	0.0195	0.0907	0.1975	0.072
S7	2450	0.13	80	547	1876	360	11.21	6.21	0.3950	0.0210	0.0129	0.0881	0.3023	0.058
S8	2205	0.13	72	393	950	350	8.23	4.56	0.4840	0.0285	0.0158	0.0863	0.2086	0.077
S9	2330	0.14	88	371	2287	350	11.45	6.34	0.3680	0.0221	0.0139	0.0585	0.3608	0.055
S10	1810	0.13	80	679	1539	375	5.9	3.26	0.5552	0.0399	0.0246	0.2083	0.4722	0.115
S11	1100	0.15	64	265	762	350	5.1	2.82	0.3900	0.0531	0.0227	0.0938	0.2700	0.124
S12	1320	0.11	56	342	896	355	5.99	3.32	0.3980	0.0332	0.0169	0.1031	0.2702	0.107
S13	200	0.07	48	335	472	355	2.45	1.36	0.1470	0.0516	0.0355	0.2473	0.348	0.262
S14	450	0.10	64	252	460	350	2.92	1.62	0.2780	0.0619	0.0397	0.1559	0.2848	0.217
S15	100	0.11	64	240	231	355	1.32	0.84	0.1190	0.1307	0.0762	0.2852	0.2745	0.422
S16	825	0.12	56	131	287	345	3.01	1.67	0.4950	0.072	0.0337	0.0786	0.1723	0.207
S17	850	0.14	56	172	376	370	3.38	1.87	0.4540	0.0748	0.0300	0.0919	0.2011	0.198
S18	430	0.13	32	114	312	345	2.14	1.18	0.3630	0.1097	0.0271	0.0964	0.2633	0.291
S19	440	0.15	40	133	218	345	2.10	1.16	0.3790	0.129	0.0345	0.1144	0.1874	0.297
S20	435	0.14	72	114	297	355	2.11	1.17	0.3720	0.1199	0.0618	0.0978	0.2543	0.304
S21	170	0.14	64	83	400	360	1.78	0.99	0.1730	0.1421	0.0651	0.0839	0.4060	0.365
S22	20	0.15	56	100	171	350	0.67	0.37	0.0540	0.4045	0.1513	0.2687	0.4611	0.944
S23	220	0.14	64	95	275	355	1.58	0.87	0.2520	0.1601	0.0733	0.1084	0.3144	0.406
S24	230	0.15	24	107	360	340	1.74	0.96	0.2390	0.1557	0.0250	0.111	0.3738	0.353
S25	220	0.15	32	66	340	345	1.43	0.74	0.2970	0.2022	0.0432	0.0885	0.4584	0.465
S26	50	0.14	24	58	220	320	0.95	0.53	0.0950	0.2662	0.0457	0.1109	0.4184	0.609
S27	30	0.15	32	41	120	335	0.59	0.33	0.0920	0.4593	0.0982	0.1265	0.3674	1.026
S28	50	0.15	48	7	100	330	0.52	0.29	0.1740	0.5211	0.1671	0.0253	0.3474	1.147
S29	10	0.15	32	17	20	350	0.21	0.12	0.0860	1.2904	0.2758	0.1463	0.1721	3.011
S30	20	0.14	48	68	213	335	0.83	0.46	0.0440	0.3047	0.1047	0.1481	0.4636	0.729
S31	40	0.13	40	49	163	320	0.72	0.4	0.1000	0.3262	0.1006	0.122	0.4090	0.803
Total average	720	0.13	59	206	557	347.9	3.56	1.97	0.2970	0.1784	0.0579	0.1197	0.3082	0.4354
Minimum	10	0.07	24	7	20	320	0.21	0.12	0.0440	0.021	0.0129	0.0253	0.1697	0.0552
Maximum	2450	0.15	96	679	2287	375	11.45	6.34	0.5552	1.2904	0.2758	0.2852	0.4722	3.011

Fig. 2Sa). Compared with other published data, the present chlorinity ratio of Lake Burullus water is lower than those recorded in the Rosetta estuary (Aboul-Khair, 2006), Lake Edku (Okbah and Tadros, 2005/2006) and inland German water (Nessim and Schlungbaum, 1980).

3.2. Lithium (Li^+)

Lithium is a rare alkaline element in seawater as free Li^+ ions at low concentrations below 0.2 ppm and could not be considered a major cation as its concentration is below 1 ppm. Despite its low

Table 3. Total averages of the three water masses during winter and autumn seasons.

Averages	Na^+	Li	Ca^{2+}	Mg^{2+}	$SO_4{}^{2-}$	Alkalinity	S	Cl	Na/Cl	Li/Cl (10^{-3})	Ca/Cl	Mg/Cl	$SO_4{}^{2-}$/Cl	Specific alkalinity
	mg/l					$mgCaCO_3L$	‰							
E.S., Jan. 2020 (winter)	1965	0.14	106	277	1208	335	8.100	4.485	0.3932	0.0404	0.0271	0.0625	0.308	0.103
E.S., Oct. 2020 (autumn)	1659	0.14	80	360	1057	352	6.879	3.808	0.4215	0.0461	0.0266	0.1007	0.284	0.122
Total average of (E.S.)	1812	0.14	93	319	1133	343	7.490	4.147	0.4074	0.0433	0.0269	0.0816	0.296	0.112
M.S., Jan. 2020 (winter)	439	0.13	81	110	705	339	3.071	1.701	0.2261	0.1014	0.0597	0.0645	0.4315	0.254
M.S., Oct. 2020 (autumn)	467	0.13	53	170	391	352	2.515	1.396	0.2940	0.1267	0.0491	0.135	0.3026	0.331
Total average of (M.S.)	453	0.13	67	140	548	345	2.793	1.548	0.2601	0.114	0.0544	0.0998	0.3671	0.292
W.S., Jan. 2020 (winter)	166	0.14	84	43	342	272	1.495	0.827	0.2100	0.2051	0.1126	0.0505	0.3911	0.379
W.S., Oct. 2020 (autumn)	33	0.14	37	40	139	332	0.637	0.355	0.0985	0.5280	0.1320	0.1132	0.3630	1.221
Total average of (W.S.)	100	0.14	61	41.5	240	302	1.066	0.591	0.1543	0.3665	0.1223	0.0819	0.377	0.800
Total winter average	856	0.14	90	151	797	325	4.222	2.2	0.2760	0.1018	0.0594	0.0612	0.3839	0.229
Total autumn average	720	0.13	59	206	557	348	3.343	4.485	0.2713	0.1784	0.0579	0.1197	0.3082	0.435
Total Lake average	788	0.135	74	179	677	336	3.783	3.808	0.2740	0.1401	0.0587	0.0905	0.3461	0.332

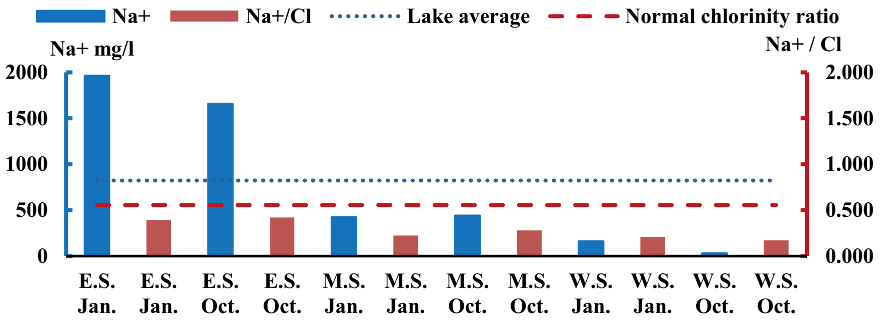

Fig. 2. Sodium and its chlorinity ratio during January and October 2020.

content, the oceans exhibit ~5000 times more lithium than the land. The total average content of lithium in Lake Burullus water is 0.135 mg/l. The winter average is slightly higher than that of autumn, 0.14 and 0.13 mg/l, respectively (Table 3). The highest level of 0.17 mg/l was recorded at St. 8 affected by saline water coming from El-Boughaz during winter, while the lowest level of 0.07 mg/l was found at St. 13 near the middle of the Lake during both seasons (Tables 1 and 2 and Fig. 1Sb). The Li/Cl ratio of the Sts. under study varied between a minimum of 0.021 × 10^{-3} at St. 7 in the eastern sector during both seasons and a maximum of 1.29 × 10^{-3} computed for St. 29 in the western sector during autumn (Tables 1 and 2) with a total average of 0.14 × 10^{-3} (Table 3 and Fig. 2Sb). All the data for both seasons deviated positively above the normal chlorinity ratio of 0.0202 × 10^{-3} (Table 3, Fig. 3). Only St. 29 gave a strong positive chlorinity ratio deviation influenced by the low salinity (0.21). The lateral variation in chlorinity ratio parallel to salinity reduction toward the west could be detected, where the ratio of the total average rose from 0.0433 × 10^{-3} for the eastern part to 0.114 × 10^{-3} in the middle sector and raised to 0.3665 × 10^{-3} in the western sector of Lake Burullus (Table 3, Fig. 3).

3.3. Calcium (Ca^{+2})

As in sodium, remarkable regional and seasonal variations in Ca-content parallel to salinity could be detected through these two cruises. The Ca-content in Lake water was found to be between 54 mg/l at Sts. (23, 30, 31) in the western end of the Lake and 138 mg/l at Sts. (5, 6, 7) in the eastern sector with a total average of 90 mg/l (Table 1 and Fig. 1Sc). A relatively lower level was recorded during autumn, where the values vibrated between 24 mg/l at Sts. (24, 26) and 96 mg/l at Sts. (5, 6) with a total average of 59 mg/l (Table 2). The total Lake average of the two cruises is 74 mg/l (Table 3).

Different rates of seasonal variations among the three sectors of the Lake could be observed; the winter level of the eastern sector is 1.33 times greater than that of autumn. For the middle sector, the rate increased to 1.53 while that for the western sector reached 2.27 fold (Table 3 and Fig. 4). This increase in Ca level may be related to the weathering and overturning of water that facilitates the release of $CaCO_3$ from the bottom sediments during winter (Abdo, 2004; Okbah and Tadros, 2005/2006). Concerning the normal chlorinity ratio of calcium (0.0216) computed by Nessim et al. (2015), most of the calculated data are positive and found above normal (Fig. 4). The chlorinity ratio average of the eastern sector of 0.0269 is nearly doubled for the middle sector (0.0544) and reached up to 0.1223 for the western one (Table 3 and Figs 2Sc, 4). Only one sample at St.8 near El-Boughaz gave a negative chlorinity ratio during winter (Table 1). The area with negative ratios increased during autumn to cover the area between Sts. 6 and 9 (Table 2). In

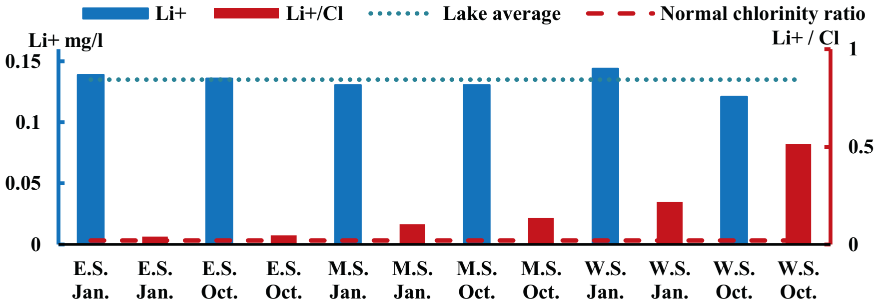

Fig. 3. Lithium and its chlorinity ratio during January and October 2020.

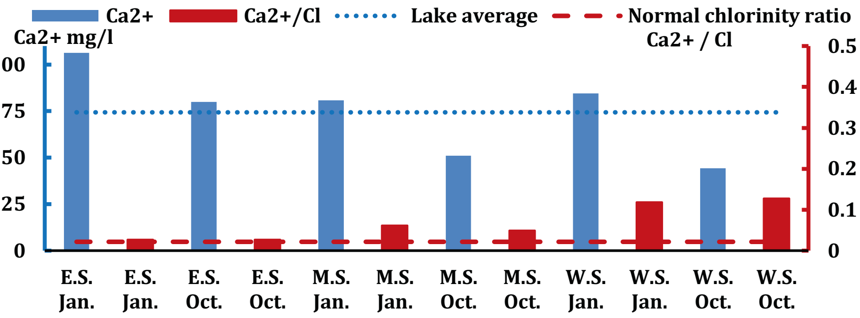

Fig. 4. Calcium and its chlorinity ratio during January and October 2020.

addition to St. 1, all of these locations (below normal) were found in the eastern sector of the Lake subjected to seawater. In comparison between the values reported in Lake Mariout (El-Wakeel et al., 1970) or in the Rosetta estuary (Aboul-Khair, 2006), the present data is relatively higher. Recently, Saad (2017) recorded higher levels during their study of two seasons in Lake Mariout than our data.

3.4. Magnesium (Mg^{+2})

Magnesium is the eighth most abundant element in the earth's crust. In oceans and seas, magnesium is the second cation after sodium. In typical freshwater, calcium, magnesium, sodium, and ammonium are the most important positively charged cations. Magnesium and calcium are responsible for water hardness. The total average concentration of Mg in Lake Burullus (179 mg/l, Table 3) is about 14% of its amount in seawater.

Mg ions showed extensive spatial and seasonal variations if compared with calcium ions, where the values dropped from 679 mg/l recorded at St. 10 to only 7 mg/l at St. 28, both levels were during autumn (Table 2) with a total average of 179 mg/l (Table 3, Fig. 1Sd). Magnesium content showed a very pronounced decrease westward, where the level dropped to less than half for the middle or even one-eighth in the western sector, being 319, 140, and 41.5 mg/l (total average of both seasons) at the eastern, middle, and western sectors, respectively (Table 3, Fig. 5). This lateral variation could be expected from the effect of saline water rich in Mg ions reaching the eastern sector and the relative poorness of freshwater contributing to Brimbal Canal at the western end of the Lake, this results agree with a study of Zaghloul et al. (2022). Their study showed that the deepening of the connection between the seawater and the lake has resulted in a relative increase in salinity and subsequent changes in the water quality and phytoplankton community structure particularly in the eastern sector of the lake. Contrary to calcium, the autumn average is higher than the winter one, 206 and 151 mg/l, respectively (Tables 1 and 2). These averages are too high compared to their corresponding averages of Lake Mariout (Saad, 2017).

Concerning the normal Mg/Cl ratio of 0.0669 reported by Nessim et al. (2015), about one-third of the winter samples fluctuated their ratios positively above normal, the rest of the samples with ratios below normal. Most of the autumn ratios were found above normal except in two locations (Sts. 9 and 28) affected by water drainage through El-Boughaz and Brimbal Canal (Table 2, Figs 2Sd, 5).

3.5. Sulfate (SO_4^{2-})

Wide fluctuations in sulfate content either regionally or seasonally could be detected where the

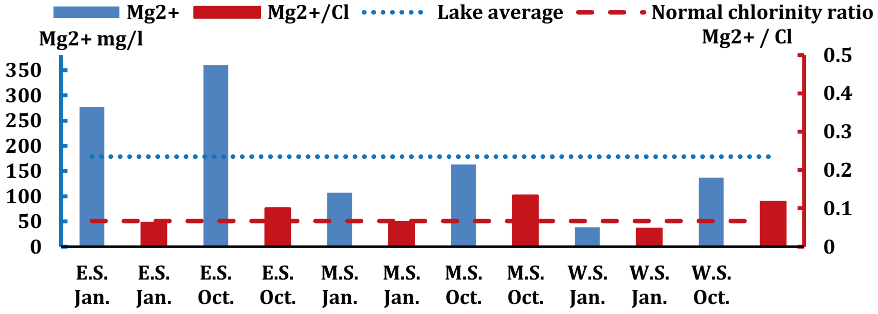

Fig. 5. Magnesium and its chlorinity ratio during January and October 2020.

values varied between 105 mg/l (St. 28) and 2170 mg/l (St. 5) during winter (Table 1) and from 20 mg/l (St. 29) to 2287 mg/l (St.9) during autumn (Table 2, Fig. 1Se) with a total average of 677 mg/l (Table 3), which is higher than that recorded for Lake Mariout either observed by Mahlis et al. (1970) or Saad (2017). It is too high if compared with that of Lake Edku (Okbah and Tadros, 2005/2006). Similar to sodium and calcium ions, the winter SO_4^{2-} values and their average are relatively higher than those for autumn.

Like the other studied ions, SO_4^{2-} reached its maximum concentration at different locations in the eastern sector of the Lake, which may be attributed to the effect of saline seawater entering the Lake from the El-Boughaz Canal (Fig. 6).

Zak et al. (2021) stated that sulfate (SO_4^{2-}) concentrations in freshwaters have increased globally over the last decades even though a strong reduction in atmospheric sulfur (S) deposition has occurred across large parts of North America and Europe. However, the extent and effects of increased SO_4^{2-} concentrations in freshwater and terrestrial ecosystems remain poorly understood regarding many aspects of ecosystem structure and functioning. SO_4^{2-} concentrations typically range from 0 to 630 mg/l in rivers, from 0 to 250 mg/l in lakes, and from 0 to 230 mg/l in groundwater (1985–1987; UNEP, 1990); in seawater SO_4^{2-} concentrations are typically 2.7 g/l (Hitchcock, 1975). For this reason, as the eastern part is connected to the Mediterranean Sea through El-Boughaz, this part showed higher SO_4^{2-}concentrations, which is nearly half its value in the sea and then decreased gradually till it reached 139 mg/l in the western part.

The sulfate/chlorinity ratio for the Lake water varies from an absolute maximum of 0.5480 detected at St. 1 to a minimum of 0.1660 at St. 10; both were calculated for winter samples (Table 1), with a total average ratio of 0.3461 (Table 3, Fig. 2Se). The normal sulfate/chlorinity ratio for seawater is 0.1400 (Morris and Riley, 1966). Bather and Riley (1954) obtained an average sulfate/chlorinity ratio of 0.1399 for the Irish Sea. For Baltic seawater, Thompson et al. (1931) determined the sulfate/chlorinity ratio to be 0.1414. The Nile water has a sulfate/chlorinity ratio of 1.6878, much greater than 12 times that of seawater (Morcos, 1967). For river waters flowing into the eastern Irish Sea, Bather and Riley (1954) reported a very high range of sulfate/chlorinity ratio (11.51–1.32). The sulfate/chlorinity ratio increases in regions where seawater is diluted by river or drainage waters (Mahlis et al., 1970). Elster and Jensen (1960) obtained an average sulfate/chlorinity ratio of 0.206 for Lake Mariout water of chlorinity 1.69‰, while Wahby (1961) obtained an average ratio of 0.26 for the same Lake.

3.6. Alkalinity

Alkalinity measures the Lake's ability to buffer or neutralize acidity. It is essential for fish and aquatic life because it protects or buffers against rapid pH changes. Fish production generally is higher in alkaline waters (pH 7.1–9.0). Freshwater usually has 20–200 mg/l levels of alkalinity. Alkalinity in natural waters is produced mainly by bicarbonate and carbonate (Hem, 1978). The lowest total alkalinity of 250 mg $CaCO_3$/l was measured during winter at St. 30 in front of Burullus west drain, while the highest level of 460.0 mg $CaCO_3$/l was recorded at the eastern sector St. 1 (Table 1), both extremities were

Table 4. Correlation coefficient between the measured major ions during both seasons.

Parameter	Na^+	Li^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Alkalinity	S‰
Na^+	1						
Li^+	0.04	1					
Ca^{2+}	0.62	0.10	1				
Mg^{2+}	0.84	−0.21	0.40	1			
SO_4^{2-}	0.77	−0.14	0.58	0.75	1		
Alkalinity	0.06	−0.08	−0.17	0.25	0.13	1	
S‰	0.97	−0.03	0.65	0.84	0.88	0.08	1

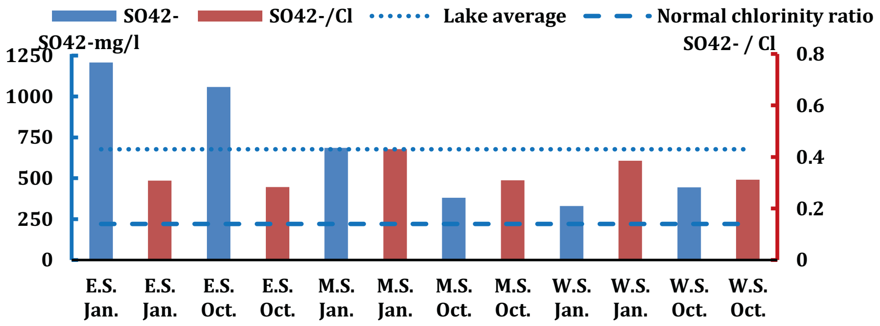

Fig. 6. Sulfate and its chlorinity ratio during January and October 2020.

Table 5. Comparison between the averages or ranges of the obtained major constituents and previous major constituents and physicochemical parameters data

Sampling collection	Na^+	Li	Ca^{2+}	Mg^{2+}	$SO_4{}^{2-}$	Alkalinity	Salinity	DO	NH_3	NO_2^-	NO_3^-	PO_4^{3-}	SiO_3^-	Reference
	mg/L					mg/L	‰	mg/L	µg/L					
E.S. Jan. 2020 (winter)	1965	0.14	106	277	1208	335	8.1							This study
E.S. Oct. 2020 (autumn)	1659	0.14	80	360	1057	352	6.879							This study
M.S., Jan. 2020 (winter)	439	0.13	81	110	705	339	3.071							This study
M.S., Oct. 2020 (autumn)	467	0.13	53	170	391	352	2.515							This study
W.S., Jan. 2020 (winter)	166	0.14	84	43	342	272	1.495							This study
W.S., Oct. 2020 (autumn)	33	0.14	37	40	139	332	0.637							This study
E.S. Jan. 2020 (winter)								14.4	95.6	9.87	27	7.75		Zaghloul et al., 2022
E.S. Oct. 2020 (autumn)								9.55	44.5	19.4	5.21	6.16		Zaghloul et al, 2023
M.S., Jan. 2020 (winter)								10.1	42.5	4.02	22.3	5.62		Zaghloul et al, 2024
M.S., Oct. 2020 (autumn)								8.41	22.9	12.6	2.59	3.18		Zaghloul et al, 2025
W.S., Jan. 2020 (winter)								8.95	69.9	13.5	32.5	6.97		Zaghloul et al, 2026
W.S., Oct. 2020 (autumn)								7.71	19.1	23.9	3.37	3.26		Zaghloul et al, 2027
Winter 2021	132.05-5.375		39.28-329.46	105.55-894.46	140.80-300.60	132.05-375								Al-Afify et al., 2023
Summer 2021	163-425		24.05-236.47	99.85-676.10	71.09-255.75	163-425								Al-Afify et al., 2024
Winter 2022					187.3-208.9	CO_3^{2-} 5.0-9.3 HCO_3^- 110-281		4.8-7.1	899.6-1772.9	78.2-124.7	150.9-201.7	184.9-394.5	9.5-11.2	Abd El Fatah et al, 2022
Summer 2022					94.3-137.1	CO_3^{2-} 30-44.2 HCO_3^- 160-313		8.3-15.2	321.4-935.4	30.5-72.6	58.5-114.9	178.9-324.8	7.3-10.5	Abd El Fatah et al, 2023

recorded during both seasons near El-Boughaz salt water (Tables 1 and 2, Fig. 3Sa). The specific alkalinity is the ratio of total alkalinity to chlorinity and could be used to differentiate between variable water masses of Lake Burullus. Concerning salinity and specific alkalinity averages, the Lake could be identified as three different water masses as follows:

(1) The eastern sector (Sts. 1–10) showed diluted seawater mixed with drainage water of the lowest specific alkalinity of 0.1125 and the highest salinity of 7.490 (Table 3, Fig. 3Sa and b) and characterized by its highest concentrations of major ions (Table 3). In this sector, marine fish can be cultured.
(2) The middle zone of the Lake (Sts. 11–25) with drainage water showed intermediate levels of specific alkalinity (0.3015) and salinity of 2.705 and major ions (Table 3, Fig. 3Sa and b).
(3) The western sector (Sts 26–31) represented freshwater of the Rosetta branch mixed with drainage water, exhibits the highest specific alkalinity (0.7985) and lowest salinity of 1.900 and consequently lowest major ion content (Table 3, Fig. 3Sa and b). In this sector, freshwater fish farms can be established.

Tayel and Shriadah (1992) attributed the low and high specific alkalinities in Abu-Qir Bay to the high variations in the chemistry of the water, either spatial or temporal, which do not differ from the present study. Riley and Chester (1975) refer to the high production in surface water associated with low specific alkalinity and vice versa. Halim et al. (1976) recorded low values after the flourishing of phytoplankton in the Egyptian Delta Lakes.

3.7. Relationship between the averages of the different cations during January and October 2020

Referring to the total averages (Table 3), the ratios calculated for the studied cations follow the order: Na/Ca (11.12) > Na/Mg (4.598) > Mg/Ca (2.419). Na/Ca (19.44 eastern sector 6.55 middle zone, 1.47 western sector, Mg/Ca (3.42 eastern sector, 2.05 middle zone, 1.36 western sector), and Na/Mg (5.69 eastern sector, 3.20 middle zone, 1.09 western sector). Ratios between the studied cations tend to decrease westward parallel to the salinity and cation content.

3.8. Correlation coefficient between the different measured major ions during both seasons ($n = 62$)

The concentration of sodium ions exhibits a linear correlation with the salinity of water, $r = 0.97$, and to a lesser extent with each of Mg^{+2} ($r = 0.84$), SO_4^{-2} ($r = 0.77$), and Ca^{+2} ($r = 0.62$). Magnesium ions show weaker correlation with S‰ and SO_4^{-2} content, $r = 0.84$ and 0.75, respectively. Calcium ions are the least correlated with salinity ($r = 0.65$) and SO_4^{-2} ($r = 0.58$) (Table 4).

3.9. Comparison between the data obtained with other previous physicochemical parameters

Table 5 presents the data obtained in this study and the other previously obtained data as follows:

4. Conclusion

(1) Sodium, calcium, and SO_4^{2-} averages (878, 90, and 797) during winter are relatively higher than those for autumn (768, 58.7, and 206.2), respectively. Magnesium ion concentrations showed extensive spatial and seasonal variations compared with calcium ions. The average concentration of lithium ions in winter is slightly higher than in autumn, 0.14 and 0.13 mg/l, respectively.
(2) The total averages of Na/Cl, Li/Cl, Ca/Cl, Mg/Cl ratios, and specific alkalinity (0.2713, 0.1784, 0.0579, 0.1197, 0.4354), respectively, during autumn were greater than their corresponding values during winter (0.276, 0.1018, 0.0594, 0.0612, 0.229, respectively). The total average of SO_4^{2-}/Cl showed the opposite trend: 0.3839 during winter and 0.3082 during autumn.
(3) The total cations' average ratios are calculated to follow the order: Na/Ca > Na/Mg > Mg/Ca. These ratios tend to decrease westward parallel to salinity and cation content.
(4) The Lake is divided into three different water masses according to salinity and specific alkalinity averages: the eastern sector (Sts. 1–10), the middle zone (Sts. 11–25), and the western sector (Sts. 26–31).
(5) Fortunately, the water quality of Burullus Lake tends to be better for fish production as mentioned by Mehanna et al. (2023). Their statistical study was carried out over a period of 10 years from 2000 to 2009 and 10 years from the beginning of the development project (2010–2020) to find its impacts on fish production and catch composition of the lake. Their analysis results showed a positive impact of the cleansing and development operations in the lake on all economic variables under study.

Ethical approval

Details and aims of the study were explained to all the participants.

Conflicts of interest

There are no conflicts of interest.

Acknowledgments

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