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PHYTOPLANKTON RESPONSE TO CHANGES OF PHYSICOCHEMICAL VARIABLES IN LAKE NASSER, EGYPT

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Abstract

Seasonal and spatial changes of phytoplankton in relation to environmental variables affecting the water quality were investigated along the main channel of Lake Nasser throughout 2013. In total, 104 phytoplankton species, belonging to 7 classes, were identified. Phytoplankton assemblages were dominated by Bacillariophyceae, Cyanophyceae and Chlorophyceae, whereas Dinophyceae, Euglenophyceae, Chrysophyceae and Cryptophyceae were infrequent. *Cyclotella glomerata*, *C. ocellata* and *Aulacoseira granulata* represented the most abundant species among Bacillariophyceae. Cyanophyceae was dominated by *Planktolyngbya limnetica* and *Eucapsis minuta*, and Chlorophyceae by *Ankistrodesmus fusiformis* and *Staurastrum paradoxum*. The water column was thermally stratified during summer, while being mixed throughout winter. Phytoplankton features and physicochemical variables were analyzed with the principal component analysis. Electrical conductivity and water temperature were the most common factors negatively controlling phytoplankton density. Phytoplankton density was positively associated with NO_3, whereas it was negatively correlated with PO_4 and HCO_3. Cyanophyceae were strongly adapted to the environmental variables and NO_2 was limiting their growth. Chlorophyceae were more dependent on PO_4 than NO_3. The vertical distribution of Chl *a* was associated with the summer thermal stratification and its concentration increased southwards. Chl *a* was affected by NO_2 and linked to Chlorophyceae. The regional variations of phytoplankton reflected its response to varying environmental conditions. The annual average of the trophic state index indicated eutrophic waters of Lake Nasser.

Keywords: Lake Nasser, nutrients, chlorophyll *a*, diatoms, phytoplankton, density.

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INTRODUCTION

Lake Nasser was formed after the construction of the High Dam (1968) at a distance of 17 km south of Aswan (Egypt) on the Nile River. The quality of its aquatic ecosystem became very important, as it is the main source of drinking and irrigation water, but also one of the main fishing resources, weighing on the national economic growth. Fish production is mostly dependent on plankton (phytoplankton, zooplankton), as a natural food. In African lakes, fish yield is well-correlated with the corresponding primary production (Melack 1976). However, primary production was also found to be rather poorly related to the global fishery, in contrast to chlorophyll *a* and mezozooplankton productivity (Friedland et al. 2012). Fish presence may positively affect the phytoplankton biomass either directly or indirectly, through grazer -predator control (Lacerot et al. 2013).

Physicochemical and biological factors can affect the temporal distribution of phytoplankton in a lake. In turn, the density, biomass and composition of phytoplankton can indicate the lake's trophy status. Historically, the aquatic environment in Lake Nasser was quite rich in phytoplankton (Latif 1984), which suggested its eutrophic state. During the period of 1971--1993, it was differentiated spatially, vertically and seasonally (e.g. Gaber 1982, Mohamed 1993, Abd El-Monem 1995, Bishai et al. 2000). Phytoplankton was then fairly diverse. Bacillariophyceae (*Cyclotella*, *Aulacoseira* and *Melosira*) and Cyanophyceae (*Phormidium* and *Anabaenopsis*) were the main components, while Dinophyceae, Chlorophyceae and Euglenophyceae were infrequent. During the highest flood season, Bacillariophyceae even consitituted the most important group (Gharib, Abdel-Halim 2006). The chlorophyll *a* concentration found to be an effective variable, approximately indicating the eutrophy of an aquatic ecosystem, while also serving as the best proxy of phytoplankton biomass (Huot et al. 2007). The evident seasonal, vertical and regional variability of its concentrations were previously recorded in Lake Nasser and some khors (e.g. Habib et al. 1987, Habib, Aruga 1996, Mohamed 1996b, Abd El-Monem 1995).

The purpose of the present study was to evaluate the main characteristics of phytoplankton in the seasonal, vertical and regional distributions in Lake Nasser and the extent of their response to physicochemical factors throughout the year.

MATERIAL AND METHODS

The High Dam Lake as the headwater of the Nile River (formed after the construction of the High Dam) is one of the largest man-made lakes in Africa and in the world (length about 496 km and area about 6275 km^2).

This lake comprises two parts: Lake Nasser – the largest part of it located in Egypt (292 km long) and Lake Nubia – a smaller water body in Sudan (204 km long). Lake Nasser is situated in a subtropical arid region. Its area is about 5248 km^2, with the mean depth changing between 21.5 and 25.5 m and width of 8.9-18.0 km; the two water bodies lie at 160 and 180 m above the main sea level, respectively (ABD EL-MONEM 2008).

The present study was conducted at nine stations selected in the deepest middle sites along the main channel of Lake Nasser (Figure 1). The name of each station, position (latitude and longitude) and its distance from the High Dam are given in Table 1. Water samples were collected seasonally from 4 depths (subsurface, mid-depth of the photic zone, compensation point depth and near the bottom) at each station throughout the year 2013, using a 1.5 dm^3 Ruttner sampler. A predefined volume of water was filtered through

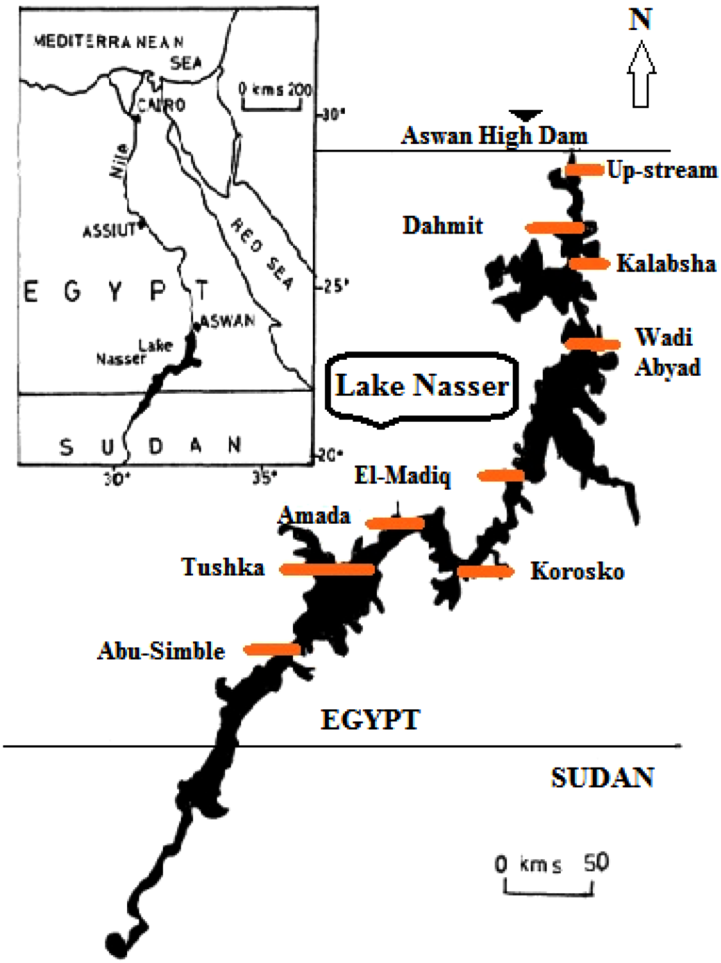

Fig. 1. The map with selected sampling sites in the main channel of Lake Nasser

Table 1

The selected sampling sites, their positions and distance from the High Dam, in the main channel of Lake Nasser

No.	Sampling sites	Latitude	Longitude	Distance from High Dam (km)
1.	High Dam	23º 56.24′	32º 51.89′	2.9
2.	Dahmit	23º 51.1′	32º 53.78′	21
3.	Kalabsha	23º 33.41′	32º 52.04′	47.7
4.	Wadi-Abyad	23º 20.08′	32º 56.12′	74.3
5.	El-Madiq	22º 56.47′	32º 37.68′	130.1
6.	Korosko	22º 37.65′	32º 24.14′	167.2
7.	Amada	22º 43.97′	32º 5.45′	199
8.	Tushka	22º 36.32′	31º 55.21′	240
9.	Abu-Simble	22º 19.71′	31º 37.14′	268.8

a glass microfiber filter (GF/F), and the filter with residue was foiled and refrigerated for pigments analyses. The remainder of the sampled water was subdivided into 2 parts, one preserved with 4% neutral formalin and Lugol's iodine solution (Margalef 1974) for phytoplankton analysis and the other one refrigerated for chemical analysis. During water sampling, pH using Orion Research Ion Analyzer (399A), electrical conductivity using a conductivity meter (S.C.T.33 YSI), transparency with a black-white Secchi disc and water temperature with an ordinary thermometer were measured. CO_3^{2-} and HCO_3^- were measured titrimetrically, with standard H_2SO_4 (0.02 N) using phenolphthalein and methyl orange as indicators. The dissolved oxygen content was determined with the azide modification method (APHA 1996).

Water samples were analyzed according to the APHA (1996) procedures. Colorimetric techniques were used for the analysis of nutrients: formation of a reddish purple azo-dye for NO_2, Cd reduction for NO_3, phenate method for NH_4 and stannous chloride reduction for PO_4. Calcium and magnesium were determined by the EDTA titrimetric method and biochemical oxygen demand (BOD) by 5-day incubation methods. The chlorophyll *a* (Chl *a*) concentration retained on filters was extracted in acetone (90%) overnight, prepared, measured spectrophotometrically and calculated applying the trichromatic equation. The Chl *a* was chosen as a proxy of total phytoplankton biomass.

For quantitative and qualitative analyses of phytoplankton, the preserved samples were transferred into a glass cylinder. Phytoplankton cells were allowed to settle for 5 days (APHA 1996), siphoned and concentrated to a fixed volume and transferred to plastic vials for microscopic examination. The drop method was applied for counting and identification of phytoplankton species. Triplicate samples (5 μl) were taken and examined under an inverted microscope at magnifications of 400 and 1000x. The latest references were used for identification.

The trophic state index – TSI (Carlson 1977) was employed to assess the trophic state of Lake Nasser. Originally, TSI values range from 0 to 100. The average values of TSI classify the lakes to oligotrophic (<40), mesotrophic (40-50), eutrophic (50-70) or hypertrophic (>70) water bodies. TSI values in this study were calculated based on Secchi disc visibility, chlorophyll *a*, and total phosphorous.

The Pearson's correlation was performed to evaluate the phytoplankton-environment relationships. These relations were also examined with a normalized principal component analysis (PCA).

RESULTS AND DISCUSSION

Phytoplankton is a useful tool to assess changes in the water quality. The plankton (phyto- and zooplankton), mainly its abundance and species composition, can be an excellent indicator because of its sensitivity to environmental changes (Varadharajan, Soundarapandian 2014). Phytoplankton provides unique information concerning an ecosystem's conditions and plays a vital role in maintaining the balance of an aquatic ecosystem (Field et al. 2007). Phytoplankton can be used as a water bioremediation agent (Oswald, 1992), to feed fish and its fry in aquaculture (De Pauw, Persoone 1992), as food for humans and invertebrates (Roslin 2003), in pigment and oil production (Johnson, An 1991), and in the bioremoval of heavy metals (Wilde, Benemann 1993). However, it is extremely difficult to gain good understanding of biological phenomena which occur in a water ecosystem without having the knowledge of its chemistry, which would reveal much about the metabolism and explains general hydrobiological interrelationship (Sithik et al. 2009). Furthermore, physicochemical variables tend to express only the causes of water quality changes, while living organisms have to deal primarily with the effects of these changes.

Environmental variables

In the main channel of Lake Nasser, the water depth fell to 110 m, near the High Dam, and gradually decreased upstream to 46 m at Korosko (Table 2). Water transparency also gradually decreased southwards. The Secchi disc visibility ranged between 1.5 m (Tushka) and 5.2 m (Dahmit) during different seasons. Water turbidity stemmed mostly from the turbidity of flood water loaded with suspended inorganic maters at the southern stations, whereas at the northern ones it was mainly caused by suspended living organisms. This is consistent with Abd El-Monem's (1995) findings.

Lake Nasser was thermally stratified during warm seasons, and turbulently mixed during winter. Entz and Latif (1974, cited in Abd El-Monen 2008) reported that the total circulation ended in March or April, i.e. when

Table 2

Annual averages of physicochemical variables studied in Lake Nasser throughout the year 2013

Parameters	Water layer	Stations								
		1	2	3	4	5	6	7	8	9
Physical variables										
Depth (m)		110	89	80	76	80	46	65	57	61
Secchi disc (m)		3.50	3.88	4.03	3.88	3.08	2.38	2.36	2.57	1.90
pH	S	7.80	7.86	8.29	8.33	8.36	8.69	8.47	8.39	8.39
	M	7.66	7.97	8.32	7.98	8.20	8.22	8.10	8.22	8.37
	C	7.77	7.84	8.31	7.98	8.07	8.24	8.02	8.04	8.31
	B	7.57	7.82	7.92	7.71	8.16	7.93	7.97	7.85	8.28
Temperature (°C)	S	23.1	23.6	25.4	25.7	26.4	27.0	26.7	25.7	26.6
	M	22.2	23.0	22.9	23.8	24.6	23.0	22.9	22.8	23.3
	C	21.7	22.1	23.5	23.9	24.4	24.3	23.9	23.8	22.9
	B	20.5	20.4	21.2	21.4	21.3	21.4	21.8	21.5	21.6
EC (µS cm^{-1})	S	230	214	212	207	215	221	215	215	210
	M	207	205	205	201	201	201	196	199	196
	C	214	202	206	201	206	208	207	200	195
	B	209	201	201	196	197	199	200	199	190
Chemical variables										
NH_4 (µg dm^{-3})	S	153	93.3	78.0	58.3	76.0	25.8	42.7	62.0	43.7
	M	74.3	29.8	83.5	38.3	74.7	66.1	36.2	59.4	10.7
	C	288	66.3	108	43.2	56.3	51.5	46.0	30.2	28.0
	B	233	199	203	242	241	189	258	339	54.1
NO_2 (µg dm^{-3})	S	12.5	7.13	10.2	3.8	5.93	7.56	17.6	20.1	20.3
	M	11.5	7.18	13.5	5.35	9.2	4.66	17.6	16.2	40.3
	C	12.9	6.88	12.4	2.85	6.85	10.1	16.6	14.2	18.6
	B	15.2	8.68	13.1	3.45	6.83	15.1	29	15.1	29.2
NO_3 (µg dm^{-3})	S	265	262	131	405	174	608	607	328	855
	M	188	275	95.2	287	390	547	893	712	368
	C	306	560	345	841	551	547	371	605	387
	B	257	190	233	441	352	560	433	165	385
PO_4 (µg dm^{-3})	S	102	107	67.9	74	78.1	60.1	49	82.9	91.6
	M	91.5	72.6	76.5	71.7	79.5	41.8	50.8	38.6	59.9
	C	83.1	89.5	72.9	69.4	86.5	29.1	59.9	90.9	59.9
	B	102	96.6	86.1	105	114	104	104	152	74.9
CO_3 (mg dm^{-3})	S	13.9	13.9	19.9	13.2	17.3	10.0	13.3	12.2	18.6
	M	7.4	18.3	16.2	16.2	12.0	12.0	14.0	8.0	20.0
	C	10.8	13.4	13.9	11.2	10.0	10.0	12.0	9.5	12.0
	B	10.8	13.4	11.7	8.4	6.0	-	-	5.4	-
HCO_3 (mg dm^{-3})	S	121	116	108	109	109	109	112	110	109
	M	123	110	112	110	113	105	104	100	104
	C	122	115	114	110	113	118	114	110	107
	B	126	121	121	117	115	115	122	117	106
DO (mg dm^{-3})	S	5.7	5.3	6.0	5.6	5.7	6.2	6.2	6.4	6.6
	M	5.1	5.2	5.0	4.9	5.3	5.4	5.3	6.3	6.7
	C	5.0	4.7	4.5	4.8	5.0	5.0	4.6	6.3	6.5
	B	4.8	3.2	2.4	2.5	3.0	2.6	2.8	3.5	5.5
BOD (mg dm^{-3})	S	3.37	1.87	1.63	1.43	2.03	2.83	1.60	1.27	1.80
	M	1.33	1.17	1.45	2.10	1.00	1.80	1.90	0.85	1.00
	C	2.17	1.33	1.25	1.40	0.70	1.20	1.15	1.07	0.80
	B	1.40	1.00	0.70	0.55	0.35	0.80	0.60	0.60	0.45

S – subsurface, M – mid-depth of the photic zone, C – compensation point depth at light intensity 1%, B – near the bottom, - no data the stratification usually started to form. During summer, the temperature amplitude peaked at about 8°C, with a distinct decline downward into the water column and the maximum variance of 5.6°C at Korosko (Table 2). The thermal amplitude was statistically significantly correlated with the depressing effect of water depth (r = -0.26, $p \leq 0.05$). Water temperature as an extremely important factor that bears certain ecological consequences, e.g. it affects water chemistry including the solubility of important gases such as oxygen in a water body. The water temperature increase was associated with a significant dissolved oxygen decrease (r = -0.545, $p < 0.001$). As well as that, temperature positively correlated with Chl *a* (r = 0.35, $p < 0.001$), which affected the phytoplankton growth.

The concentrations of NO_3 were higher than NO_2, with annual averages of 414.4 and 13.0 μg dm^{-3}, respectively (Table 2). High levels of NO_3 were recorded in the southern stations, with the maximum at Amada, but they decreased at the northern sites, with the minimum at Kalabsha. Similarly, the NO_2 distribution followed an identical trend as NO_3. The horizontally differentiated distribution of N-nutrients could have been due to the reception of nutrient-rich flood water in the southern region. In the vertical distribution (attributed to microbial and biological activities), the highest content of NO_3 was found at the compensation depth (501.4 μg dm^{-3}, on average), whereas the lowest (335.1 μg dm^{-3}, on average) appeared near the bottom. The NO_3 content increased with the water transparency increase (r = 0.36). The NO_2 content was irregular in its vertical distribution and opposite to the other variables in the aquatic ecosystem. A general trend of the horizontal distribution of NH_4 was opposite to that of the other N-nutrients. Low values were recorded at the southern stations (with minimum of 34.1 μg dm^{-3}) and higher values at the northern stations, with a maximum of 187.1 μg dm^{-3} near the High Dam. In the vertical distribution, a low content was in the upper layers, grossly increasing (217.6 μg dm^{-3}) near the bottom, with anoxic conditions. It was mainly attributed to the organic matter decaying in the sediment through anaerobic condition initiated with thermal stratification and oxygen depletion (Bolalak, Frankowski 2003). Slight spatial variations were also recorded in PO_4 distribution, whereas the vertical distribution showed obvious increase near the bottom, with an average of 104.3 μg dm^{-3}. It was positively correlated with water temperature, EC and HCO_3 (r = 0.60, 0.51 and 0.65, respectively).

Phytoplankton

The phytoplankton composition and density can be good indicators of trophy. In Lake Nasser, 104 phytoplankton species were recorded (Table 3). Phytoplankton assemblages were formed by species belonging to 7 classes: Bacillariophyceae (38), Chlorophyceae (32), Cyanophyceae (21), Dinophyceae (5), Cryptophyceae (3), Euglenophyceae (3) and Chrysophyceae (2). Thus, the phytoplankton community was dominated by three classes, while the other classes were poorly represented. This agrees with the findings of Abou

Table 3

List of phytoplankton taxa recorded in the main channel of Lake Nasser during the study period

Bacillariophyceae	**Chlorophyceae**
Achnanthes exilis Kütz.	*Actinastrum hantzschii* Lagerh.
Achnanthes minutissma Kütz.	*Ankistrodesmus convolutus* Corda
Amphora ovalis Kütz.	*Ankistrodesmus fusiformis* Corda
Amphora rostrata Van Heurck	*Ankistrodesmus nitzschioides* G.S.West
Aulacoseira granulata (Ehr.) Sim.	*Asterococcus superbus* (Cienk.) Scherff.
Aulacoseira granulata var. *angustissima* (O.F. Müll.) Sim.	*Cardiomonas* sp.
Biddulphia antediluviana (Ehr.) Van Heurck	*Chlorella vulgaris* Beyer.
Cocconeis placentula Ehr.	*Closterium venus* Kütz. ex Ralfs
Cocconeis scutellum Ehr.	*Coelastrum microporum* Näeg.
Coscinodiscus lacustris Grun.	*Cosmarium* sp.
Cyclotella bodanica Eul. ex Grun.	*Crucigenia quadrata* Morr.
Cyclotella comta (Ehr.) Kütz.	*Crucigenia tetrapedia* (Kirch.) Kuntze
Cyclotella glomerata Bachm.	*Dictyosphaerium pulchellum* Wood
Cyclotella kuetzingiana Thwait.	*Elakatothrix gelatinosa* Wille
Cyclotella meneghiniana Kütz.	*Eudorina elegans* Ehr.
Cyclotella ocellata Pant.	*Eudorina unicocca* G.M. Smith
Cyclotella operculata (C.Agardh) Bréb.	*Golenkinia paucispina* West & G.S. West
Cyclotella stelligera Cl. & Grun.	*Golenkinia radiata* Chod.
Cymbella amphicephala Näeg.	*Kirchneriella lunaris* (Kirch.) Möb.
Cymbella cuspidata Kütz.	*Lagerheimia ciliata* (Lag.) Chod.
Cymbella naviculiformis (Auers. ex Heib.) Cl.	*Monoraphidium contortum* (Thuret) Kom.-Legn.
Diatoma hiemale (Lyngb.) Heib.	*Oocystis borgei* J.W. Snow
Dimeregramma minor (Greg.) Ralfs ex Pritch.	*Oocystis solitaria* Wittr.
Fragilaria construens var. *venter* (Ehr.) Grun.	*Pediastrum simplex* Meyen
Melosira tenella Nyg.	*Scenedesmus dimorphus* (Turp.) Kütz.
Navicula cryptocephala Kütz.	*Scenedesmus* sp.
Navicula dicephala Ehr.	*Schroederia setigera* (Schröd.) Lemm.

Navicula lanceolata var. *arenaria* (Donk.) Van Heurck	*Selenastrum gracile* Reinsch
Navicula placentula (Ehr.) Kütz.	*Staurastrum paradoxum* Meyen ex Ralfs
Navicula pusilla W. Smith	*Staurastrum sebaldii* var. *ornatum* Nordst.
*Navicula viridula (*Kütz.) Ehr.	*Tetmemorus brebissonii* Ralfs
Nitizschia acicularis (Kütz.) W. Smith	*Tetraedron minimum* (A. Br.) Hansg.
Nitizschia longissima (Bréb.) Ralfs	
Nitzschia fonticola (Grun.) Grun.	**Cyanophyceae**
Nitzschia apathulata W. Smith	*Anabaena constricta* (Szaf.) Geitl.
Nitzschia frustulum (Kütz.) Grun.	*Anabaena fertilissima* C.B. Rao
Ulnaria ulna (Nitzsch) P. Comp.	*Aphanocapsa elachista* var. *conferta* West & G.S. West
Ulnaria ulna var. *subaequalis* (Grun.) M. Aboal	*Chroococcus dispersus* (Keissl.) Lemm.
	Chroococcus turgidus (Kütz.) Näg.
Dinophyceae	*Cylindrospermopsis raciborskii* Wolosz.
Ceratium hirundinella O.F. Müll.	*Eucapsis minuta* Fritsch
Gymnodinum aeruginosum Stein	*Gomphosphaeria aponina* Kütz.
Peridinium pusillum (Pén.) Lemm.	*Gomphosphaeria compacta* (Lamm.) Ström
Peridinium umbonatum Stein	*Gomphosphaeria lacustris* Chod.
Peridinium volzii Lemm.	*Gomphosphaeria lacustris* f. *compacta* (Lemm.) Elenk.
Chrysophyceae	*Leptolyngbya laminosa* (Gom. ex Gom.) Anagn. & Kom.
Mallomonas sp.	*Lyngbya versicolor (*Wartm.) Gom.
Ochromonas mutabilis Klebs	*Merismopedia punctata* Meyen
Cryptophyceae	*Microcystis aeruginosa* (Kütz.) Kütz.
Chroomonas acuta Uterm.	*Myxosarcina spectabilis* Geitl.
Cryptomonas erosa Ehr.	*Phormidium interruptum* Kütz. ex Forti
Pyramimonas sp.	*Planktolyngbya limnetica* (Lemm.) Kom.-Legn. & Cronb.
Euglenophyceae	*Pseudanabaena limnetica* (Lemm.) Kom.
Trachelomonas volvocina var. *derephora* Conr.	*Pseudanabaena* sp.
Trachelomonas planctonica Svir.	*Synechococcus aeruginosus* Näg.
Trachelomonas pulcherrima Playf.	

El-Kheir et al. (2000). During 1993, Bacillariophyceae and Cyanophyceae represented the main components of phytoplankton, Chlorophyceae created the third dominant group (2.1% in winter to 20.6% in spring), while the other classes were scarcely represented (Abd El-Monem 1995). According to Latif (1984), Cyanophyceae were sometimes even more common than diatoms. The increase in diatoms can be seen as an ecological advantage, supplying energy for the planktonic food web (Gorczyca, London 2003), hence diatoms have been used to investigate the natural and anthropogenic influences on biodiversity (Ormerod et al. 1994).

The highest species richness (97) was recorded during spring while the lowest one (71) occurred in summer (Figure 2). The seasonal fluctuation in

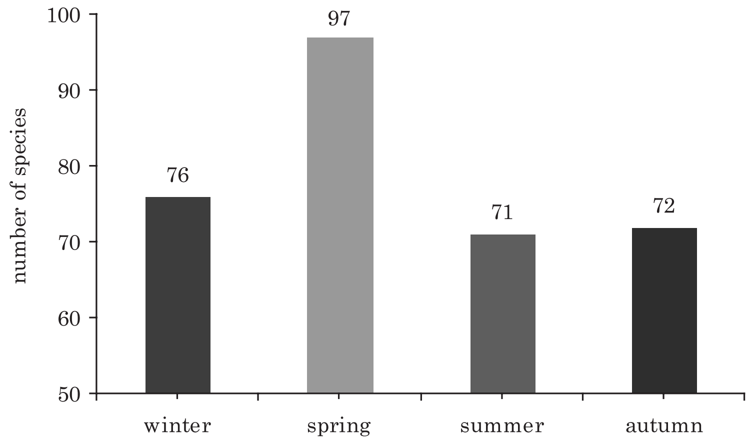

Fig. 2. Seasonal fluctuation of the phytoplankton species number in Lake Nasser

the species number can be linked to changes in physicochemical variables of the lake water. Harper (1986) found that the species number can decrease to half due to high nutrient concentrations. Regarding the phytoplankton abundance, the highest density occurred during winter, whereas the least density was observed in autumn (Figure 3). The vertical distribution of the phytoplankton density reached its climax in the surface layer during winter compared with the other seasons, when it was about 508 x 10^4 cell dm^{-3}, decreasing downward. This can be related with the spatial differentiation in temperature and light, which are the most important physical variables in the primary productivity control (Abd El-Monem 2001). The spatial distribution of phytoplankton revealed the highest density at station 5 (on average 255 x 10^4 cell dm^{-3}) only during exceptionally warm conditions (Figures 3, 4). Bishai et al. (2000) mentioned that phytoplankton standing crop increased southwards. Whereas according to Latif (1984), the northern sites in the main channel had a higher number of phytoplankton than the southern ones. The regional variation of phytoplankton can reflect its response to varying environmental conditions and it can be affected, for example, by advection, turbulence or grazing (Chang, Bradford 1985).

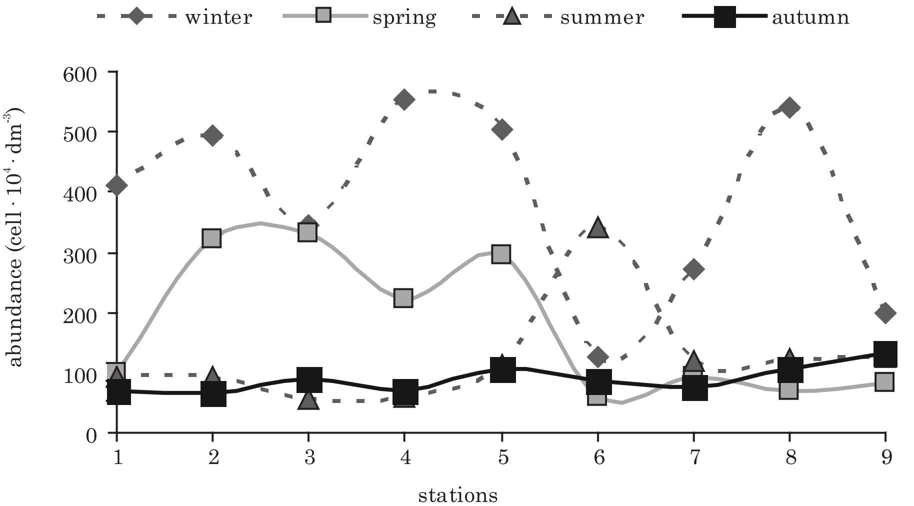

Fig. 3. Annual distribution of phytoplankton density in the main channel of Lake Nasser at different stations, the stations' codes are given in Table 1

The most abundant phytoplankton groups were diatoms, cyanobacteria and chlorophytes (Figure 4). Bacillariophyceae were dominated by *Cyclotella glomerata* Bachm., *Aulacoseira granulata* (Ehr.) Sim. and *Cyclotella ocellata* Pant. Generally, these species have low nutrient requirements and low temperature optima (Reynolds et al. 2002, Brettum, Andersen 2005). *Cyclotella* and *Aulacoseira* (previously *Melosira*) might be used as bioindicators of the oligo-mesotrophic status (Gharib, Abd El-Halim 2006). Furthermore, they reported that *Aulacoseira granulata* and *A. granulata* var. *angustissima* (O.F.Müll.) Sim. were the most dominant species in Lake Nasser and there was a spatial tendency towards an increase in their abundance upstream.

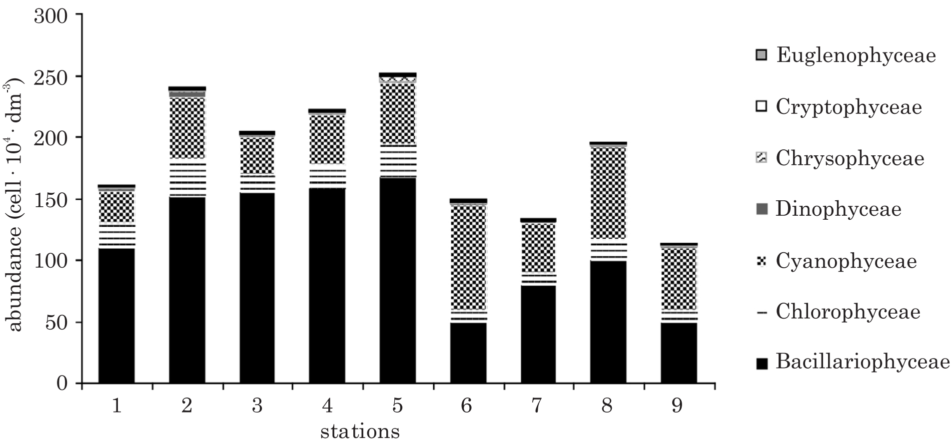

Fig. 4. Geographical distribution of class-based phytoplankton density during the study period (an annual average)

Cyanophyceae, as the second predominant class, was mostly composed of *Planktolyngbya limnetica* (Lemm.) Kom.-Legn. & Cronb. and *Eucapsis minuta* Fritsch. The filamentous *Lyngbya* sp. was the main species in Lake Nasser (El-Otify 2002). Chlorophytes were dominated by *Ankistrodesmus fusiformis* Corda and *Staurastrum paradoxum* Meyen ex Ralfs throughout the year. Similar findings were reported by El-Otify (2002) and Gharib and Abd El-Halim (2006).

Chlorophyll *a* content is considered to be the best descriptive parameter to indicate phytoplankton biomass in freshwater lakes (Vörös, Padisák 1991). Furthermore, it is one of the most effective variables influencing the trophic status of aquatic ecosystem and the analysis of Chl *a* has long been regarded as a very good indicator for monitoring and assessment (Heinonen et al. 2000). A significant spatial variation in Chl *a* was determined among the different stations in Lake Nasser (Figure 5). Its content increased south-

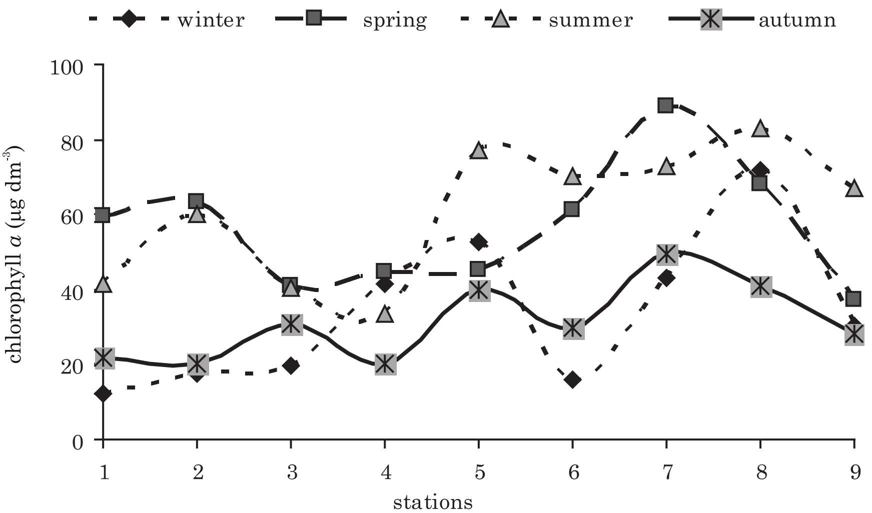

Fig. 5. Annual average chlorophyll *a* concentrations in the main channel of Lake Nasser at different stations

wards to the highest values at Amada (in spring) and Tushka (in summer). That was strictly associated with physicochemical variables and biological activities in the water budget. Mohamed (1996*a*) also recorded an increase in Chl *a* during the warm period and its decrease during the cold period. Vertically differentiated distribution of Chl *a* was associated with the thermal stratification, while being more or less homogeneous during winter (Habib, Aruga 1996).

Physicochemical and biological interrelations

The phytoplankton species composition, growth and abundance are collectively influenced by environmental variables, especially nutrient enrichment, water transparency and temperature (Dayala et al. 2014). In Lake Nasser, the trophic state index (TSI 56.4-66.1, on average 61; Figure 6) indicated eutrophic conditions according to Carlson (1977).

The statistical analysis used a dataset of phytoplankton characteristics and physicochemical variables, which determined the environmental-phytoplankton relationships. Nitrates were a limiting factor for the phytoplankton density, and especially for diatoms and cyanobacteria (r = 0.577 and 0.350, respectively). NO_3, as the most reactive form of N-nutrients, was con-

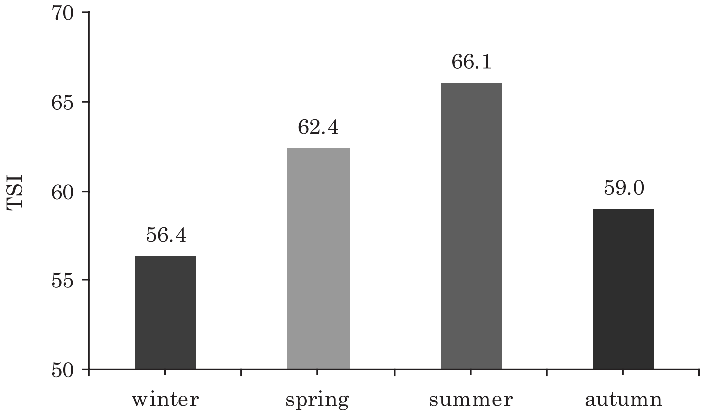

Fig. 6. Seasonal distribution of TSI values in Lake Nasser

nected (positively or negatively) with other physicochemical variables. PCA demonstrated that NO_3 significantly positively correlated with pH, CO_3 and DO (Figure 7) while being strongly negatively related to EC, water temperature and HCO_3. A significant negative correlation was between PO_4 and phytoplankton density (r = -0.460), especially with diatoms (r = -0.490), but the relation to Chl *a* was insignificant. According to Gharib and Abd El-Halim's (2006), phosphate concentrations in Lake Nasser increased southward and were weakly negatively correlated with phytoplankton biomass. Such negative relations were also found in some European temperate lakes (e.g. Napiórkowska-Krzebietke et al. 2013, Napiórkowska-Krzebietke, Hutorowicz 2015). EC and water temperature were the most common physical parameters negatively influencing the phytoplankton densities (r = -0.754 and -0.711, respectively), similarly to HCO_3 (r = -0.367). They significantly increased along with the increase of water transparency (r = 0.512) and Mg and Ca concentrations (r = 0.492 and 0.459, respectively).

The abundance and distribution of Bacillariophyceae were significantly controlled by various physical and chemical variables of the lake water (Figure 7). PCA indicated that diatoms were negatively correlated with EC, water temperature and HCO_3. They were positively associated with water transparency and CO_3 content. Similar relations were found regarding Ca and Mg concentrations (r = 0.404 and 0.442, respectively). The relation be-

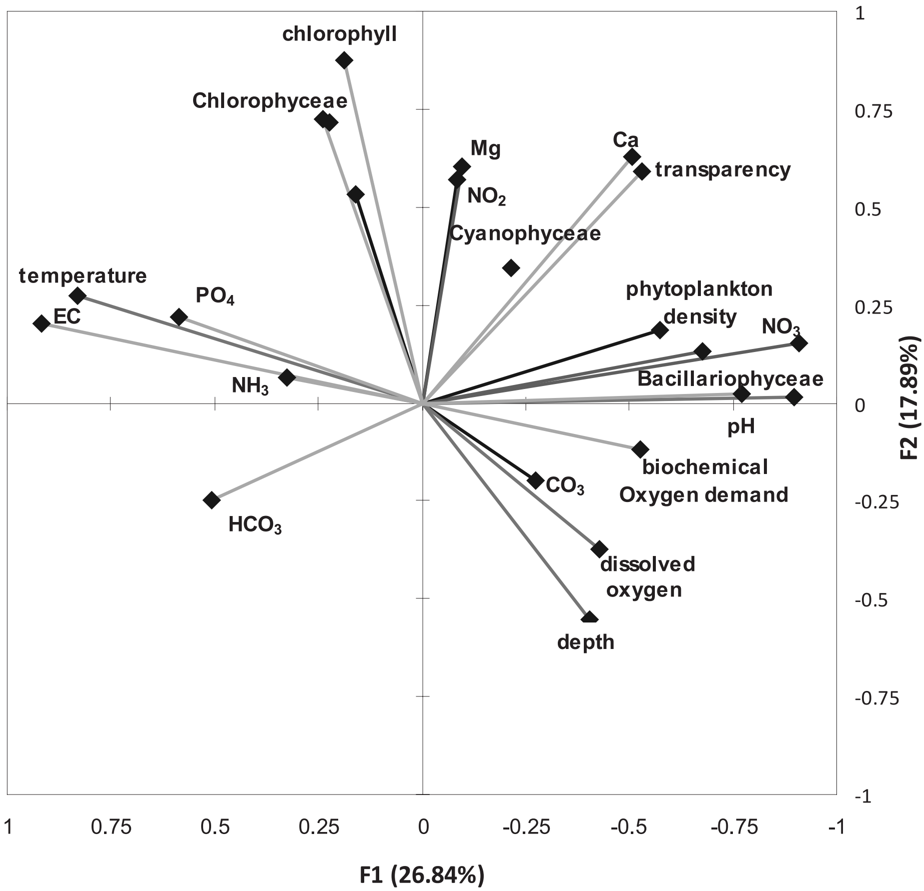

Fig. 7. PCA performed on total phytoplankton density, dominant phytoplankton classes and some physicochemical variables

tween diatoms and PO_4 content was negative (r = -0.489). Cyanophyceae density significantly increased along with the NO_2 and NO_3 increase. They were sensitive to EC with a significant negative correlation (r = -0.346), and their relations to Ca, Mg and pH were insignificant. Chlorophyceae density corresponded, albeit insignificantly, with water temperature, EC, PO_4 and NH_4. Only Chl *a* content was significantly associated with Chlorophyceae (r = 0.388). Water temperature was the most effective variable shaping the Chl *a* distribution in the lake, with a positive significant relation (r = 0.351). The release of NO_3 was also significantly associated with increasing Chl *a* (r = 0.599), while the relationship with NO_2 was non-significant. Chl *a* was related to PO_4 and NH_4, but statistically non-significantly.

The understanding of relationships between phytoplankton and the environment is essential for desinging management strategies of Lake Nasser. Proper functioning of this lake's ecosystem should fulfill the main purposes including water supply for drinking and irrigation, hydropower generation and fish production, which rose to 34,206 ton during 1981 (Bishai et al. 2000). The most common freshwater fish in Egypt is Nile tilapia (*Oreochromis niloticus* L.), and recently, its relative percentage has increased up to 80% of the total catch in Lake Nasser. Microalgae in fish guts of Nile tilapia consisted of diatoms (47%), with *Aulacoseira granulata* as the most frequent and abundant species, followed by chlorophytes (31%), cyanoprokaryotes (19%) and dinophytes (2%) (Abd El-Karim et al 2009). In the future, the research projects designed to enhance the planktonic production (phytoplankton and zooplankton as natural food for fish) would be helpful in increasing the fish production.

CONCLUSIONS

Lake Nasser, as a man-made fresh water lake, has not reached a stable state yet. The phytoplankton structure and density were strongly dependent on the seasonal changes in physicochemical variables, regulated with the flooded water in the southern region, and by nutrients at the north. The vertical distribution of phytoplankton was caused by thermal stratification during the warm seasons. The trophic state of this lake indicated that it contained quite eutrophic waters.

The monitoring of the lake should continue in order to investigate further changes in water quality and biological activities. The risk of algal bloom including dominant species should herald potential hazards or/and toxicity. Such collective environmental information can be helpful for further water management, including research projects planned especially to increase of the fish production, where phytoplankton and zooplankton are fish's natural food.

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