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Long-term changes of physicochemical parameters and benthos in Lake Qarun (Egypt): Can we make a correct forecast of ecosystem future?

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Abstract – Biotic changes and a salinity increase (from 13 to 40 g.L^{-1}) occurred in Lake Qarun (Egypt) since 1901. Was salinity increasing a cause of observed biotic changes? To answer this question we used benthos as a model group. Benthos and water sampling was conducted in different seasons (2008−2013). Comparing our and literature data, we discuss the long-term trends and possible causes of benthos changes. Salinity reached 3 g.L^{-1} in middle of 19th century; and biotic changes caused by this were started. From middle 19th century to 1928 a biotic transformation was driven by the salinity increase; after 1928 a regular alien species introduction caused that a marine community formed. In 1970−2000 eutrophication played a main role in species composition changes. In 2014 ctenophore *Mnemiopsis leidyi* introduced in the lake; eutrophication, chemical pollution, and a population dynamics of this ctenophore may be main drivers of the ecosystem change now. Benthos biomass gradually decreased during interval 1975−2013 without any correlation with salinity change. A variety of other factors than salinity may be significant in determining the structure and dynamics of communities, and we conclude that we have a small chance to make a correct forecast of possible future ecosystem changes in Lake Qarun.

Key-words: Saline lake / long-term changes / alien species / eutrophication / *Mnemiopsis leidyi*

Résumé – Les changements à long terme des paramètres physico-chimiques et du benthos dans le lac Qarun (Égypte) : peut-on faire une prévision correcte du futur de l'écosystème ? Des changements biotiques et une augmentation de la salinité (de 13 à 40 g.L^{-1}) ont été observés dans le lac Qarun (Égypte) depuis 1901. L'augmentation de la salinité a-t-elle été une cause des changements biotiques observés ? Pour répondre à cette question, nous avons utilisé le benthos en tant que groupe modèle. Le benthos et l'eau ont été échantillonnés à différentes saisons (2008-2013). En comparant nos données à celles de la littérature, nous discutons des tendances à long terme et des causes possibles de l'évolution du benthos. La salinité a atteint 3 g.L^{-1} au milieu du 19e siècle ; et les changements biotiques causés par cette salinité ont débuté. À partir du milieu du 19e siècle jusqu'à 1928 une transformation biotique a été causée par l'augmentation de la salinité ; à partir de 1928 une introduction régulière d'espèces exotiques a fait qu'une communauté marine s'est formée. En 1970−2000 l'eutrophisation a joué un rôle principal dans les changements de la composition des espèces. En 2014 le cténophore *Mnemiopsis leidyi* a été introduit dans le lac ; l'eutrophisation, la pollution chimique, et la dynamique de la population de ce cténophore peuvent être les principaux moteurs de l'évolution actuelle de l'écosystème. La biomasse du benthos diminue progressivement pendant l'intervalle 1975−2013 sans aucune corrélation avec le changement de salinité. Une diversité d'autres facteurs que la salinité peuvent être importants dans la détermination de la structure et de la dynamique des communautés, et nous concluons que nous avons peu de chance de faire une prévision correcte des possibles changements écosystémiques futurs dans le lac Qarun.

Mots-clés : Lac salé / changements à long terme / espèces exotiques / eutrophisation / *Mnemiopsis leidyi*

1 Introduction

Lakes are integrators and mirrors for the effects of climate change and human activity on watersheds, airsheds, and other landscape components. In recent decades an acceleration of lake ecosystem changes are observed worldwide; the reasons include the climate change, human population growth, and an intensification of human activities (O'Reilly *et al.*, 2003; Smol *et al.*, 2005; Anneville *et al.*, 2007; Abbaspour *et al.*, 2012; Shadrin and Anufriieva, 2013). We need to study the ongoing long-term changes of lake ecosystems to predict their further

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changes and mitigate unwanted impact on human well-being and activities. Lack of data on the long-term lake changes is a bottleneck in ecology of long-term changes, which does not allow to adequately understanding the causes and mechanisms ongoing changes. There are a lot of different papers on changes in Lake Qarun during last century (Naguib, 1958,1961; Abdel-Malek and Ishak, 1980; Ishak and Abdel-Malek, 1980; El-Shabrawy and Dumont, 2009); Lake Qarun may serve as one important lake for a deeper understanding of the interconnections of causes and consequences of the long-term lake changes.

Lake Qarun, the third largest lake in Egypt, is located the northern Fayum (Faiyum), a natural depression extending over 12 000 km^2, and was formed by wind erosion ca 1.8 million year ago (Ball, 1939). The depression is bounded by sandy hills, broken in the south, where Canal Bahr Yousef enters the depression. This canal is main source of water for the lake, and received fresh water from the Nile since early Pharaonic times, *i.e.*, before 2500 BC (Hassan, 1986). Terraced lands allow a use of masonry weirs for the distribution of irrigation waters. Lake Qarun collects agricultural water through two drainages – El-Bats and El-Wadi systems. Since 1973, about 30% of this water has been diverted to a second depression, Wadi El Rayan, south-west of the Fayum (El-Shabrawy and Dumont, 2009). In 1952–1954 the annual average drainage waters entering into the lake were about 349.2 mln.m^3 (Naguib, 1958) and in 2000s – about 400 mln.m^3 (Abdel-Satar *et al.*, 2010).

Archaeologists showed that the modern Lake Qarun is the shrunken remnant of Lake Moeris, which known from since 450 BCE. Herodotus, visited Egypt, saw a large water expanse, Lake Moeris, assumed artificial (Brown, 1892). At that time the lake was 75 m deep (20 masl), covered more than 2000 km^2 and maintained by a seasonal supply of Nile water (Ball, 1939; Shafei, 1960). Different studies showed that the lake level has varied from relatively high levels in its early history to lower levels in later years, although there have been numerous changes in water level over the past 7000 years (Shafei, 1960; Mehringer *et al.*, 1979; Nicoll, 2004). Lake Qarun has been profoundly affected by a combination of human activities and climatic changes over the past 5000 years (Mehringer *et al.*, 1979; Nicoll, 2004; Baioumy *et al.*, 2010). During last 2000 years, there were several periods of low water level; some of them were: 17 mbsl or lower in the third century A.D.; in 1245 AD, when Nabulsi gave a description of the Fayum area, the lake level fell to 30 mbsl; in 1805–1848, when Mohamed Ali ruled Egypt, – averaged 40 mbsl; in 1933–1934 – 45–46 mbsl (Baioumy *et al.*, 2010). Dropping the lake level and an accumulation of salts increased salinity; Lake Qarun was only slightly brackish up until about 1884, and later salinity increased from 8.5 g.L^{-1} in 1905 to 38.0 g.L^{-1} in 1980 due to three factors (El-Shabrawy and Dumont, 2009; Baioumy *et al.*, 2010). The first factor – evaporative losses increased; second – increased quantities of water were loss to the lake through groundwater outflow; and third – saline groundwater intruded into the lake (Ball, 1939; Meshal and Morcos, 1984; Flower *et al.*, 2006; Baioumy *et al.*, 2010). To reduce salinity in the lake, the Egyptian Salts and Minerals Company (EMISAL) was established on the southern coast of Lake Qarun in 1986 to extract salts and minerals (EMISAL, 1996). Its activity contributes to salt balance regulation in the lake now. Current salt balance in the lake (annual average) includes: (i) salt discharge via the main drains of 419.56 mln kg, (ii) ground water provide of 70.36 mln kg, and (iii) salts extracted by the EMISAL plant are of 416 mln kg. Concerning salt budget, during the last years (to 2007) Lake Qarun accumulated 70–85 mln.kg.year^{-1}. This may lead to obvious increase of its salinity by 0.07 g.L^{-1}.year^{-1} (Abd Ellah, 2009). Could such a salinity increase lead to the catastrophic changes in the lake ecosystem?

During last 100 years there were pronounced changes in structure and functioning of biota in the lake; many researchers explained these changes by the salinity increase (Naguib, 1958; Abdel-Malek and Ishak, 1980; Ishak and Abdel-Malek, 1980; Mageed, 2005; El-Shabrawy and Dumont, 2009). There is another point of view that salinity variation is not a main cause of zooplankton changes in the lake during the last decades (El-Shabrawy *et al.*, 2015). Is fluctuating salinity the main determinant of biotic changes in Lake Qarun? The question remains open. To answer these questions we used benthos as a model group. Changes in biota occur on different temporal scales (diurnal, seasonal, and inter-annual). Plankton species are more sensitive to environmental changes than benthos due to their small sizes; sometime their seasonal and other short-term fluctuations exceed the inter-annual differences. Thus benthos may be used more successfully than plankton to assess the inter-annual changes and their causes in ecosystems.

Aims of our paper are to provide new data (2008–2013) on current changes of chemical parameters and benthos in Lake Qarun, and comparing them with data available in literature to discuss the long-term trends and causes of benthos changes.

2 Materials and methods

2.1 Study area

Lake Qarun is a closed saline lake in the northern part of El-Fayum Depression (Middle Egypt, ~80 km southwest of Cairo, at the margin of the Nile Valley). The studied lake lays on 29° 30' N, 30° 30′ E (Figure 1) and is 43–43.5 mbsl now (Abdel-Satar *et al.*, 2010). The lake length from east to west is about 40 km, and the maximal width is about 6.7 km. The lake has a surface area of 243 km^2 and a volume of 924 mln.m^3 (El-Shabrawy and Dumont, 2009). Maximum depth (~8.3 m) is in the northwest part. Non-irrigated northern shores of the lake are actually devoid of vegetation and mark the beginning of the Western Egyptian Desert. The lake has no connection to the sea, being located 320 km south of the Mediterranean coast of Egypt, and is sustained directly by the Nile River via Canal Bahr Yousef.

2.2 Sample collection

Benthos and water sampling was conducted during different seasons from March 2008 to February 2009 and from August 2011 to November 2013 on ten stations in Lake Qarun

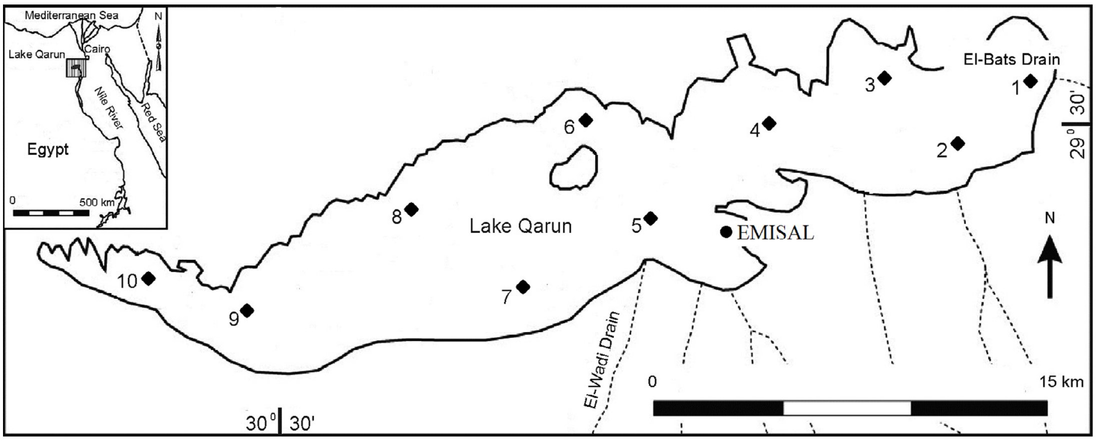

Fig. 1. Scheme of sampling stations in Lake Qarun (Egypt).

(Figure 1). Macrobenthos samples were collected by Ekman grab (0.023 m^2 opening area). The samples were sieved using a bolter of 0.4 mm mesh diameter, and washed with lake water to remove mud or other fine particles. The organisms retained in the bolter were preserved in 10% neutral formalin solution. In the laboratory, the samples were rewashed with tap water to remove any silt remains. Sorting of the specimens was carried out by taking successive small sub-samples and examining them under a stereomicroscope (×40 magnification). The bottom organisms were sorted into main groups. Each group was examined and sorted into genera or species (Lincoln, 1979; Brown, 1980; Ruffo, 1982; Fischer *et al.*, 1987; Shiganova and Malej, 2009). Both the number and wet weight of each species were measured after retaining the organism on filter paper for 3 min before weighing. All mollusk species were weighed with shell. Additionally, to analyze changes in chemical composition during 2002–2013, we sampled water every day at one point near EMISAL pumping station (29° 28′ N, 30° 41′ E) (Figure 1).

Water samples were taken by 1 L bathometer. Water temperature (°C) and pH were in-situ measured using Hydrolab (Multi Set 430i WTW). Transparency was measured using a white/black Secchi disk (0.3 m in diameter). Salinity (g.L^{-1}) was determined as Total dissolved solids (TDS) by filtrating a sample with glass micro fiber filter (GF/C) and a known volume of filtrate was evaporated at 180 °C. Dissolved oxygen (DO, mg.L^{-1}) was carried out using modified Winkler method. Biological oxygen demand (BOD) was determined by using 5 days incubation method. Chemical oxygen demand (COD) was carried out using potassium permanganate method. Water alkalinity was determined immediately after sampling collection using phenol-phthalein and methyl orange indicators. Nitrogen-Ammonia (N-NH_3) was determined by phenate method. Nitrogen-Nitrite (N-NO_2) was determined using colorimetric method with formation of reddish purple azo-dye. Nitrogen-Nitrate (N-NO_3) was measured as nitrite after cadmium reduction. Orthophosphate (P-PO_4) was estimated by using ascorbic acid molybdate method. Reactive silicate (SiO_4) determined using molybdate methods. Total nitrogen (TN) and total phosphorus (TN) were measured as nitrate and orthophosphate respectively, after persulphate digestion (APHA, 1995).

2.3 Statistical analysis

Data were subjected to standard statistical processing (Sokal and Rohlf, 1995). Variability of parameters in the samples was qualified by the coefficient of variability (CV). Pair coefficients of correlations (R) were calculated. Significance of differences in average values was evaluated by a Student's t-test, and confidence level of correlation coefficients (p) was determined by comparison with parameter critical values (Müller *et al.*, 1979).

3 Results

During 2008–2013, there were pronounced seasonal and inter-annual changes of abiotic characteristics in Lake Qarun (Tables 1 and 2). The levels of spatial variability of measured parameters were very different; temperature (CV = 0.028–0.071) and pH (CV = 0.011–0.041) were parameters with lowest spatial variability in the lake; highest variability was observed in concentrations of NO_2(CV = 0.525–2.091), NO_3 (CV = 0.752–1.751), NH_3 (CV = 0.565–1.635), and PO_4 (CV = 0.171–1.071). CVs in Table 1 show that the levels of spatial variability of abiotic parameters fluctuated in time. Stations that had smallest salinity and highest nutrient concentrations and turbidity were most closed to the discharges of waters from El-Bats and El-Wadi drainage systems (Figure 1). To analyze salinity changes after 2000, we used annual average data (2002–2013) for one point near EMISAL pumping station. After 2002, salinity fluctuated without any positive or negative trend (Figure 2); average salinity was 36.1 g.L^{-1} (CV = 0.06).

Ion composition changed over the period from 2002 to 2013. The proportion of SO_4/Cl slightly increased from 2002 to 2013. The proportion of CO_3^{2-}/HCO_3^{1-} decreased; this decrease may be approximated by (R = –0.636, p = 0.025):

$$CO_3^{2-}/HCO_3^{1-} = 13.27e^{-0.02x}, \quad (1)$$

where x – a year number since 2001.

During period of our study (2008–2013) 16 macrobenthic species were found in total (Table 3). In 2008–2013 Polychaeta *Polydora hoplura* Claparède, 1869 and *Ficopomatus*

Table 1. Physico-chemical parameters and their variability in Lake Qarun during 2008−2013 (Seasonal average/CVs)*.

Season	Temp., °C	Transp., cm	Salinity, g.L^{-1}	pH	DO, mg.L^{-1}	BOD, mg.L^{-1}	COD, mg.L^{-1}	CO_3, mg.L^{-1}	HCO_3, mg.L^{-1}
2008									
Spring	25.7/0.02	–	34.4/0.02	8.4/0.01	8.5/0.20	5.1/0.19	19.5/0.07	18.1/0.23	284.8/0.01
Summer	29.0/0.06	–	34.5/0.02	8.4/0.01	6.7/0.15	4.9/0.13	19.7/0.10	16.6/0.17	277.1/0.03
Autumn	15.5/0.02	–	34.4/0.03	8.3/0.01	8.6/0.07	6.6/0.09	13.5/0.05	9.2/0.10	234.0/0.05
2009									
Winter	20.7/0.02	–	32.8/0.03	8.4/0.01	8.7/0.10	5.2/0.20	14.1/0.06	14.6/0.10	252.9/0.02
2011									
Summer	27.8/0.03	106.0/0.42	32.7/0.24	8.4/0.02	9.1/0.11	4.1/0.27	14.2/0.21	34.9/0.31	158.3/0.28
Autumn	17.8/0.04	98.0/0.39	33.1/0.24	8.3/0.01	7.4/0.10	3.7/0.21	14.2/0.19	13.5/0.70	203.4/0.18
2012									
Spring	25.7/0.04	55.0/0.22	30.6/0.18	8.2/0.01	10.1/0.13	8.2/0.18	9.8/0.15	38.3/0.37	204.7/0.12
Summer	28.6/0.06	81.5/0.49	34.4/0.19	8.1/0.04	6.5/0.23	4.9/0.11	19.3/0.11	36.8/0.43	224.5/0.08
Autumn	21.0/0.03	116.5/0.27	32.9/0.21	8.3/0.02	8.1/0.31	4.0/0.46	6.6/0.05	25.9/0.23	176.3/0.11
2013									
Winter	15.4/0.07	77.5/0.34	32.7/0.04	8.7/0.03	12.2/0.3	4.4/0.60	9.8/0.14	48.0/0.39	214.7/0.12
Spring	21.8/0.04	65.5/0.24	31.4/0.10	8.5/0.02	7.8/0.17	5.1/0.28	7.3/0.18	42.3/0.23	246.4/0.11

Note: *Seasonal average – average value for all ten stations; CVs – coefficient of spatial variability.

Table 2. Nutrient concentrations and their variability in Lake Qarun during 2008−2013 (Seasonal average/CVs).

Season	NH_3, mg.L^{-1}	NO_2, μg.L^{-1}	NO_3, μg.L^{-1}	TN, mg.L^{-1}	PO_4, μg.L^{-1}	TP, μg.L^{-1}	SiO_2, mg.L^{-1}
2008							
Spring	0.13/0.17	9.86/0.29	77/0.12	–	13.7/0.25	125.6/0.11	4.6/0.13
Summer	0.09/0.15	5.35/0.74	79/0.38	–	7.6/0.70	86.6/0.13	3.3/0.09
Autumn	0.12/0.12	1.56/1.34	45/0.15	–	13.8/0.14	102.5/0.21	8.7/0.09
2009							
Winter	0.10/0.26	8.74/0.25	59/0.44	–	15.3/0.11	117.2/0.09	6.1/0.10
2011							
Summer	0.42/0.57	9.96/1.97	214/1.75	3.85/0.35	31.9/0.98	257.6/0.77	5.1/0.20
Autumn	0.22/1.20	25.37/2.58	239/1.44	6.15/0.58	53.9/1.07	179.2/0.83	5.9/0.19
2012							
Spring	0.28/1.64	33.00/1.98	275/1.64	3.13/0.15	43.0/0.68	380.2/0.19	7.2/0.15
Summer	0.32/0.60	12.01/1.65	87/1.60	4.69/0.12	80.2/0.19	187.9/0.20	12.3/0.11
Autumn	0.17/0.61	29.56/1.17	118/0.75	1.61/0.24	12.5/1.04	82.9/0.26	11.6/0.08
2013							
Winter	0.20/0.58	8.03/0.53	191/1.05	9.21/0.52	15.2/0.17	100.9/0.25	7.1/0.24
Spring	0.46/0.57	16.14/2.09	54/1.30	6.21/0.06	13.1/0.39	156.6/0.20	7.8/0.21

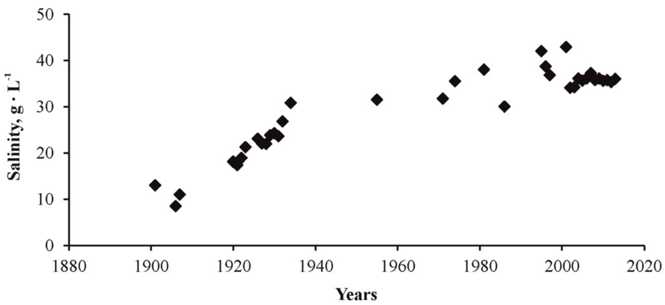

Fig. 2. Diagram showing salinity changes in Lake Qarun between 1901 and 2013.

enigmaticus (Fauvel, 1923), Gastropoda *Nassarius cuvierii* (Payraudeau, 1826), found in the lake at first time in 2006, were the common species. Frequencies of common species occurrence (FO) changed from 2006 to 2013 (Table 4); during this time there was a trend of FO decrease of several species. The correlation coefficients (R) between FO and the numbers of year since 2006 were calculated. This negative trend was significant for *P. hoplura* ($R = -0.935$, $p = 0.01$) and for Amphipoda *Monocorophium acherusicum* (Costa, 1853) ($R = -0.855$, $p = 0.05$).

Total annual average abundance of macrozoobenthos fluctuated between 536 and 1229 ind.m^{-2} (average 840 ind.m^{-2}; $CV = 0.310$) (Table 5).There is a negative temporal trend of total benthos abundance change. Total annual average zoobenthos biomass fluctuated from 26.5 g fresh wt.m^{-2} to 70.3 g fresh wt.m^{-2} (Table 6); there was no directed trend of its change. In benthos, Bivalvia dominated (in biomass) (Table 3); *Cerastoderma glaucum* (Bruguière, 1789) contributed in total biomass 12.2−44.6%, *Polititapes aureus* (Gmelin, 1791) −20.8−71.4%, and both species − 51.7−83.6%. In 2012 the contribution of Bivalvia in total biomass was lowest − 51.7% and the contributions of other animal groups were highest:

Table 3. Species composition and parts of the different species in total macrozoobenthos biomass g (wet weight) m^{-2} in Lake Qarun during 1974–2013.

Species	1974–1977*	1989**	1994**	1995**	1999/2000**	2006***	2008	2011	2012	2013
Coelenterata										
Aiptasiogeton cf. *pellucidus* (Hollard, 1848)	0	1.3	3.4	1.2	1.9	3.0	1.1	1.3	0.2	0.3
Obelia sp.	+	0	0	0	0	0	0	0	0	0
Arthropoda										
Brachynotus sexdentatus (Risso, 1827)	0	3.3	2.9	1.5	17.3	1.3	1.4	9.5	15.1	4.2
Fistulobalanus pallidus (Darwin, 1854)	4.8	29.9	44.1	32.5	7.9	7.7	3.4	3.7	2.0	4.6
Gammarus aequicauda (Martynov, 1931)	?	<0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.2	0
Monocorophium acherusicum (Costa, 1853)	0	1.7	1.0	0.5	0.1	0.1	2.2	0.4	0.6	1.4
Palaemon elegans Rathke, 1837	+	?	?	?	?	?	?	?	?	?
Platorchestia platensis (Krøyer, 1845)	+	?	?	?	?	?	?	?	?	?
Sphaeroma serratum (Fabricius, 1787)	+	+	0.4	0.1	0.4	1.0	0.8	0.5	0.6	0
Chironomidae, larvae	?	?	?	<0.1	<0.1	0.3	<0.1	<0.1	1.6	0.1
Annelida										
Ficopomatus enigmaticus (Fauvel, 1923)	0	0	0	0	0	2.4	3.9	4.0	0.9	1.8
Hediste diversicolor (O.F. Müller, 1776)	1	10.7	11.3	3.0	4.9	4.0	5.9	1.7	19.3	7.9
Hydriod sp.	0	0	0	0	3.2	0	0	0	0	0
Polydora cornuta Bosc, 1802	0	0	0.4	0.3	0.7	0	0	0	0	0
Polydora hoplura Claparède, 1869	0	0	0	0	0	0.3	0.2	0.1	0.3	0.5
Tubificidae spp.	?	?	<0.1	0.1	0.6	0.1	0.1	0.1	1.0	0.4
Mollusca										
Bulla ampulla Linnaeus, 1758	0	0	0	0	1.6	5.5	7.4	1.1	3.5	3.7
Cerastoderma glaucum (Bruguière, 1789)	69.8	30.7	22	34.7	31.3	41.5	12.2	25.2	30.9	44.6
Cleopatra bulimoides (Olivier, 1804)	+	0	0	0	0	0	0	0	0	0
Melanoides tuberculata (O. F. Müller, 1774)	+	0	0	0	0	0	0	0	0	0
Monodonta sp.	0	0	0	0	0	0	0	1.1	2.1	0
Nassarius cuvierii (Payraudeau, 1826)	0	0	0	0	0	0.1	0	1.3	1.2	2.9
Physa acuta Draparnaud, 1805	+	0	0	0	0	0	0	0	0	0
Polititapes aureus (Gmelin, 1791)	8.0	18.5	10.0	23.0	27.6	28.4	71.4	47.7	20.8	25.6
Potamides conicus (Blainville, 1829)	10.5	?	0.7	1.8	1.4	1.0	8.8	0.6	0.4	0.6
Hydrobia aponensis Martens, 1855	5.2	0	0	0	0	0	0	0	0	0
Semisalsa sp.	0	0	1.5	0.3	0.3	0.1	0.4	2.5	1.2	1.7

Note: * Abdel-Malek and Ishak (1980); ** El-Shabrawy and Dumont (2009); *** El-Shabrawy and Khalifa (2007).

Table 4. Frequencies of different species occurrence in samples in different years (%).

Species	2006*	2008	2011	2012	2013
Hediste diversicolor (Müller, 1776)	67	75	55	63	70
Polydora hoplura Claparède, 1869	50	38	35	33	30
Tubificidae spp.	38	42	35	28	35
Ficopomatus enigmaticus (Fauvel, 1923)	29	38	40	25	25
Monocorophium acherusicum (Costa, 1853)	63	63	55	48	30
Fistulobalanus pallidus (Darwin, 1854)	29	17	30	13	20
Cerastoderma glaucum (Bruguière, 1789)	75	54	65	65	55
Polititapes aureus (Gmelin, 1791)	50	50	80	55	50

Note: *El-Shabrawy and Khalifa (2007).

Table 5. Total average macrozoobenthos abundances and their variability in the Lake Qarun during 2006–2013 (ind.m^{-2}).

Season	2006*		2008		2011		2012		2013		2006–2013	
	average	CVs	average	CVs	average	CVs	average	CVs	average	CVs	average	CV
Winter	757	0.66	1064	0.77	–	–	856	1.45	648	1.39	831	0.21
Spring	567	0.79	2513	0.98	–	–	900	1.03	424	0.95	1101	0.87
Summer	869	1.19	760	1.04	1236	0.80	176	0.79	–	–	440	0.58
Autumn	1073	0.46	577	0.86	600	0.99	860	1.84	–	–	–	–
Ann. average	817	–	1229	–	–	–	698	–	–	–	–	–
CVt	0.26	–	0.72	–	–	–	0.50	–	–	–	–	–

Note: * El-Shabrawy and Khalifa, 2007; CVs – coefficient of spatial variability; CVt – coefficient of temporal variability.

Table 6. Total macrozoobenthos biomass g (wet weight) m^{-2} in Lake Qarun during 2006–2013.

Season	2006*		2008		2011		2012		2013		2006–2013	
	average	CVs	average	CVs	average	CVs	average	CVs	average	CVs	average	CV
Winter	22.64	0.97	9.51	0.84	–	–	63.04	1.34	33.26	1.40	32.11	0.71
Spring	34.66	0.96	40.74	1.16	–	–	59.99	0.94	29.60	1.56	41.25	0.32
Summer	76.41	0.67	23.68	1.38	99.64	0.62	16.02	1.24	–	–	53.94	0.75
Autumn	29.62	0.39	32.20	1.03	41.00	0.66	33.63	1.10	–	–	34.11	0.14
Ann. average	40.84	–	26.53	–	–	–	43.17	–	–	–	36.84	0.25
CVt	0.59	–	0.50	–	–	–	0.52	–	–	–	–	–

Note: * El-Shabrawy and Khalifa (2007).

Table 7. Annual average individual wet weight (g) in populations of the different species in Lake Qarun during 1989–2013.

Species	1989*	1993*	1994*	1995*	1999*	2006*	2008	2011	2012	2013	CV
Cerastoderma glaucum (Bruguière, 1789)	0.61	0.81	0.44	0.76	0.85	0.22	0.12	0.26	0.17	0.15	0.67
Polititapes aureus (Gmelin, 1791)	0.31	0.23	0.61	0.61	0.80	0.22	0.22	0.24	0.14	0.13	0.67
Hediste diversicolor (Müller, 1776)	0.04	0.06	0.04	0.03	0.11	0.02	0.03	0.03	0.09	0.04	0.58
Fistulobalanus pallidus (Darwin, 1854)	0.11	0.20	0.16	0.21	0.39	0.09	0.09	0.07	0.08	0.08	0.67
In total zoobenthos	0.05	0.04	0.03	0.06	0.08	0.05	0.03	0.07	0.07	0.06	0.31

Note: * Calculated from data in El-Shabrawy and Dumont (2009).

Crustacea *Brachynotus sexdentatus* (Risso, 1827) – 15.1% and Polychaeta *Hediste diversicolor* (Müller, 1776) – 19.3%. Individual annual average wet weight in macrobenthos fluctuated between 0.029 and 0.074 g (average = 0.057 g, $CV = 0.307$) (Table 6).

Populations of abundant species also demonstrated inter-annual differences in individual annual average wet weight (Table 7). There are temporal trends of individual average weight changes. For *P. aureus* the trend was negative, and for *H. diversicolor* it was positive, but both trends were insignificant. The negative trend for Crustacea *Fistulobalanus pallidus* (Darwin, 1854) was significant ($R = -0.086$, $p = 0.05$). Calculated CVs (coefficients of spatial variability) show that a spatial distribution of macrobenthos biomass was not homogenic; annual average CVs changed between 0.640 and 1.479 (Table 6). Seasonal variability of biomass (CVt) in 2006–2012 was close in different years (Table 6); CVt fluctuated between 0.502 and 0.593 over this interval.

4 Discussion

4.1 Long-term changes of abiotic characteristics

Totality of available data on salinity since 1901 (Naguib, 1958; Ishak and Abdel-Malek, 1980; Meshal and Morcos, 1984; Soliman, 1991; Sabae and Ali, 2004; Abd Ellah, 2009; El-Shabrawy and Dumont, 2009; Abdel-Satar *et al.*, 2010; El-Shabrawy *et al.*, 2015) was summarized (Figure 2). We see that there was strong salinity increase since 1901 (13 $g.L^{-1}$) to approximately 2000, which may be approximated by the equation ($R = 0.935$, $p = 0.0001$):

$$S = 0.275t + 14.07, \quad (2)$$

where S – salinity, $g.L^{-1}$, t – a number of year (since 1901).

Later there were only small fluctuations. Taking into account a range of observed current fluctuations salinity may reach 44–45 $g.L^{-1}$ in 2100. If we take into account that EMISAL increases salt extraction to 535 thousand tons now and plans to increase its production more, a real salinity increase in future would be less.

Study of sediment cores from Lake Qarun showed that benthic foraminifera first appeared at 0.314 m depth, ca. AD 1550; this depth marks the beginning of colonization of the lake by foraminifera and indicates a change in lake water salinity, as foraminifera cannot tolerate freshwater (Abu-Zied *et al.*, 2011). Comparing this result with calculated by equation (2) we may conclude that the salinity increase before middle 19th century was very slow and fluctuating. Study of sediment cores demonstrates such fluctuations; salinity was highest around AD 1700 and after AD 1990 (Abu-Zied *et al.*, 2011). There is some superposition of natural rhythms in salinity fluctuation; we need to interpret these accurately to predict of further salinity changes in the lake.

There were the significant temporal trends for changes of other abiotic parameters. Using own and published data (Sabae and Ali, 2004; Abd Ellah, 2009; El-Shabrawy and Dumont, 2009; Abdel-Satar *et al.*, 2010; El-Shabrawy *et al.*, 2015) we found that some changes in ion composition occurred; proportion SO_4/Cl grew. This growth may be approximated by equation ($R = 0.558$, $p = 0.001$):

$$SO_4/Cl = 0.556e^{0.018x}, \quad (3)$$

where x – a number of year since 1995.

We used data from literature (Sabae and Ali, 2004; Abd Ellah, 2009; El-Shabrawy and Dumont, 2009; Abdel-Satar *et al.*, 2010; El-Shabrawy *et al.*, 2015) and analyzed a long-term change of K concentration in the lake. Proportion K/Na decreased and its inter-annual dynamics may be approximated ($R = -0.888$, $p = 0.001$):

$$K/Na = 0.105e^{-0.343x}, \quad (4)$$

where x – a number of year since 1995.

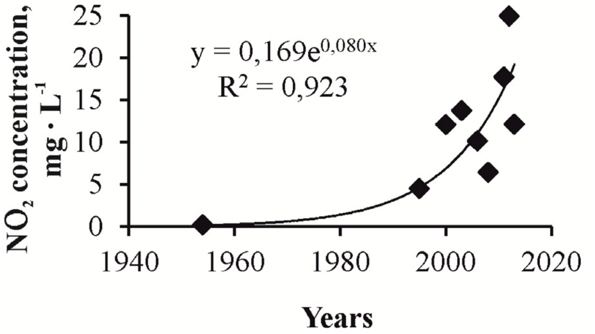

Fig. 3. Diagram showing changes of average NO_2 concentration in Lake Qarun in 1954–2013 (x – number of years from 1954).

K plays a very important role in functioning of cells; its part in total salt content decreased over this time interval; and it may affect biota. Ionic composition may influence the composition of the biota but the mechanisms of those influences on an animal composition in saline lakes remain obscure (Williams, 1998).

More pronounced current long-term changes were found for concentrations of biogenic elements in Lake Qarun. From 1954 to 2013, there was high exponential growth of concentrations of NO_2 – from 0.16 $\mu g.L^{-1}$ in 1954–1955 to 18.5–22 $\mu g.L^{-1}$ in 2012–2013 (Figure 3) as well as for NO_3 – from 34.84 $\mu g.L^{-1}$ in 1954–1955 to 122.5–226.5 $\mu g.L^{-1}$ in 2011–2013. For PO_4 there was a significant ($p = 0.001$) gradual increase from 0.38 $\mu g.L^{-1}$ in 1954 to 94.0 $\mu g.L^{-1}$ in 2003 and a significant ($p = 0.001$) decrease to 14.2–42.9 $\mu g.L^{-1}$ in 2011–2013. For SiO_4 a significant ($p = 0.001$) gradual decrease from 17.7 $mg.L^{-1}$ in 1954 to 2.1 $mg.L^{-1}$ in 2013 was recorded. Average-annual transparence in the lake decreased from 2.39 m in 1975 (Mageed, 1998) to 0.85 m during studied period. Those are signs of eutrophication development in the lake with all associated events. Lake Qarun is the largest reservoir of agricultural and sewage drainage of Fayoum province as well as the drainage from fish farms established around the lake, which cause eutrophication. However, there is one more cause, which intensifies eutrophication, – global climate warming. Climate change, by intensifying storms, affecting rainfall patterns, warming soils, and others, may increase diffuse nutrient loading (Jeppesen *et al.*, 2011). People can control nutrients in wastewaters, but those nutrients that run from the land are seemingly intractable (Moss *et al.*, 2011). As a result of eutrophication, recurrent microalgae blooming phenomenon was recorded in the last years (2008–2012) at autumn or winter seasons with remarkable water discoloration to red; mass mortality of animals occurs (Abou El-Geit *et al.*, 2013). There is no thermal stratification in the lake, but there is chemocline during most part of a year; increased salinity, depletion of oxygen concentration, and H_2S were observed near the bottom as early as in 1954 (Naguib, 1958, 1961). This creates a possibility of "dead" zones on the bottom and mass mortality events in benthos.

4.2 Changes in species composition

With increasing salinity above 3 $g.L^{-1}$, the composition of the biota of salt lakes increasingly diverges from that of fresh waters; but in waters with salinities between 3 and 20 $g.L^{-1}$, most taxa present are also found in freshwater (Williams, 1998). In Lake Qarun, salinity reached 3 $g.L^{-1}$ in middle of 19th century; and biotic changes caused by this were started. Changes occurred in plankton and benthos among all taxa. Many saline lake species have dormant stages, which can be transported for long-distance by birds, flying insects and winds (Caceres and Soluk, 2002; Figuerola *et al.*, 2003; Anufriieva and Shadrin, 2014). Birds may serve as a transportation vector also for some mollusks that known long time (Darwin, 1859). In 1907 two Bivalvia species were found in the lake: *Corbicula fluminalis* (Müller, 1774) and *C. africana* (Krauss, 1848) and 9 Gastropoda species (Table 8). All these species are the Nilotic freshwater forms (Smith, 1908) but there was also a marine hydrozoan species *Cordylophora* (Cunnington and Boulenger, 1907) At same time in 1907 some typical freshwater animals that were common in Nile and connected fresh water bodies, were apparently not presented in Lake Qarun (Cunnington and Boulenger, 1907). A successive settlement of a primarily marginal marine bottom fauna has begun in Lake Qarun. *C glaucum* introduced to the lake between 1907 and 1927 (Gardner, 1932; Kowalke, 2005) In 1974–1977 only three mollusk species: *Hydrobia aponensis* (Martens, 1855), *Melanoides tuberculata* (Müller, 1774), and *Cleopatra bulimoides* (Olivier, 1804) from 11 species, found in 1907, were rarely presented in the lake. Those three species have not been detected after 1977. In 1952–1955 three genera of marine mollusks dominated in the lake – Bivalvia *Cerastoderma* and *Mactra*, Gastropoda *Potamides* (Naguib, 1958). In 1974 and later *Mactra* was not recorded in the lake, and *Polititapes aureus* replaced it in the lake benthos (Table 2).

In 1907 14 fish species inhabited in the lake, the overwhelming majority of these are two species of *Tilapia*; fishes occurred "in astonishing abundance" (Cunnington and Boulenger, 1907). Fishery was very important for local people. After 1907 there was a dramatic decrease of fish productivity due to salinity increased; it gradually eliminated all fish species except one species *Tilapia* and *Anguilla* (Faouzi, 1936). We suppose that from middle 19th century to 1928 there was first stage of a modern biotic transformation in Lake Qarun when a salinity increase drove the biotic changes.

Due to extinction of native fish fauna in Lake Qarun, the commercial catch dropped from 4000 t in 1920 to 1000–2000 t in 1925–1926, affecting the livelihood of the fishery community around the lake (Faouzi, 1936). To improve fishery a decision was made about intentional introduction of marine fishes and crustaceans into the lake. Mullet species: *Mugil cephalus* (Linnaeus, 1758), *Liza ramada* (Risso, 1827), *L. saliens* (Risso, 1810), *L. aurata* (Risso, 1810) and other fishes such as *Atherina boyeri* (Risso, 1810), *Anguilla anguilla* (Linnaeus, 1758), *Solea aegyptiaca* (Chabanaud, 1927), as well as several prawn species: *Metapenaeus stebbingi* (Nobili, 1904), *Palaemon elegans* (Rathke, 1837) and *Penaeus semisulcatus* (De Haan, 1844) were transplanted to the lake in 1928 (Mageed, 2005; El-Shabrawy and Dumont, 2009). Some of the introduced species can reproduce in the lake. *M. cephalus*,

Table 8. Mollusk species in Lake Qarun in 1907 (Smith, 1908).

Species name as given in (Smith, 1908)	Accepted species name
Gastropoda	
Melania tuberculata Müller	*Melanoides tuberculata* (Müller, 1774)
Cleopatra bulemoides (Olivier)	*Cleopatra bulemoides* (Olivier, 1804)
Valvata nilotica Jickeli	*Valvata nilotica* (Jickeli, 1852)
Neritina nilotica Reeve	*Neritina nilotica* Reeve, 1856
Planorbis cornu Ehrenbergi	*Planorbis cornu* Brongniart, 1810
Vivipara unicolor (Olivier)	*Vivipara unicolor* (Olivier, 1804)
Lanistes carinatus (Olivier)	*Lanistes carinatus* (Olivier, 1804)
Paludestrina peraudieri (Bourguignat)? (*Hydrobia peraudieri*)	*Hydrobia aponensis* Martens, 1855
Isidora contorta (Michaud)	*Bulinus contortus* (Michaud, 1829)
Bivalvia	
Corbicula fluminalis Müller	*Corbicula fluminalis* (Müller, 1774)
Corbicula radiata Philippi	*Corbicula africana* (Krauss, 1848)

L. ramada and *L. aurata* cannot breed; they are continuously transported in the lake since 1928. About two million of fry were annually released during 1928–1964 (El-Zarka and Kamel, 1965), 55 million between 1971 and 1978, and more than 100 million of fry later (El-Shabrawy and Dumont, 2009). This transplantation led to an occasional introduction of different marine species, both planktonic and benthic.

In 1928 there was a start of second stage of modern changes in the lake biota. Now there is a marine community in the lake, which continues to change. Main driver of this were a regular introduction of alien species and a press of aliens on the existent species. Almost all of introduced fishes and prawns in the lake are bottom feeders impacting on structure and dynamics of zoobenthos (El-Shabrawy and Khalifa, 2007). In addition, bottom fishing gears impact on the lake floor, causing mortality and injury to surface-living and shallowly buried fauna. The towed fishing gears, used for prawn, greatly affect macrobenthos structure in Lake Qarun (El-Shabrawy and Khalifa, 2007).

We assume that after 1970 eutrophication played a main role in the changes of species composition in the lake (third stage of the change). Table 3 shows a change in species structure during that stage. Intermittent hypoxia/anoxia in the lake's bottom waters, caused by human eutrophication, may account for these most recent changes.

Last alien species, occasional introduced in Lake Qarun, was the warty comb jelly *Mnemiopsis leidyi* (Agassiz, 1865) was first reported at Lake Qarun in March 2014 (El-Shabrawy *et al.*, 2015). Large numbers of the ctenophore was reported by many fishermen and the researchers of National Institute of Oceanography and Fisheries. Probably, *M. leidyi* was accidentally introduced in the lake through the mullet fry transportation. *Mnemiopsis leidyi* was recorded also in the second lake of the Fayum depression – Lake Wadi el Rayan, where large swarms had been recorded (El-Shabrawy *et al.*, 2015). *Mnemiopsis leidyi* was introduced in the Black Sea in the 1980s, with catastrophic results for the Black Sea ecosystem and fishery industry (Gomoiu *et al.*, 2002). It was supposed that eutrophication and ecosystem destabilization promoted the successful occupation of the Black Sea and other seas by *M. leidyi*. This introduction may lead to start a new stage of the change of biotic structure in Lake Qarun when eutrophication, chemical pollution and a population dynamics of this ctenophore may be main drivers of the ecosystem change.

4.3 Quantitative changes in benthos

We used the data published since 1974 (Abdel-Malek and Ishak, 1980; El-Shabrawy and Khalifa, 2007; El-Shabrawy and Dumont, 2009) to analyze long-term trend of benthos biomass change (Table 9, Figure 4). Best approximation gives an equation ($R = -0.969$, $p = 0.0005$):

$$Y = 3322.5t^{-1.214}, \tag{5}$$

where Y – biomass, g.wt.w.m^{-2}, t – year number (since 1974).

No correlation was found between changes of benthos biomass and salinity; salinity did not significantly influence on biomass changes from 1974. No significant correlations were found between inter-annual changes of benthos biomass and NO_3 or PO_4; there was linear slight positive influence of NO_2 on benthos biomass in 1974–2013 ($R = 0.885$, $p = 0.01$). We conclude that changes of biogenic element concentrations did not directly cause of long-term benthos biomass changes but, probably, their high concentration led to the benthos biomass decrease causing episodically microalgae blooms and mass mortality events in the lake.

Inter-annual fluctuations of individual average weight in macrozoobenthos do not demonstrate any directed trend since 1989 (Table 7). Individual annual average weight in the populations of some single species changed very much. Annual average weight (AAW) of *C. glaucum* fluctuated between 0.440 and 0.845 g (average = 0.694, $CV = 0.241$) in 1989–2000, and – between 0.115 and 0.261 g (average = 0.183, $CV = 0.316$) in 2006–2013. Differences are high significant ($p = 0.001$). Similar trends were also found for *P. aureus* and *F. pallidus*. For *P. aureus* in 1989–2000 AAW was 0.510 g ($CV = 0.464$) and in 2006–2013 AAW was 0.189 g ($CV = 0.266$). For *F. pallidus* in 1989–2000 AAW was 0.214 g ($CV = 0.492$) and in 2006–2013 AAW was 0.082 ($CV = 0.109$). *H. diversicolor* did not demonstrate such AAW change. We think that there was shortening of life span of above noted species due to microalgae blooms causing mass mortality of animals. It

Table 9. Long-term changes of total macrobenthos average biomass in Lake Qarun during 1974–2013 g (wet weight) m^{-2}.

Season	1974*	1975*	1989**	1993**	1994**	1995**	1999-2000**	2006***	2008	2011	2012	2013	Av	CV
Winter	2112.2	2170.3	–	–	111.6	132.3	75.7	22.6	9.5	–	63.0	33.3	32.1	0.710
Spring	3309.4	2328.9	–	–	58.5	143.8	122.8	34.7	40.7	–	60.0	29.6	41.3	0.322
Summer	2020.0	2061.7	–	–	49.3	154.0	84.6	76.4	23.7	99.6	16.0	–	53.9	0.753
Autumn	2668.3	2383.3	–	–	70.9	112.2	52.1	29.6	32.2	41.0	33.6	–	34.1	0.143
Ann. average	2527.5	2223.3	81	76.7	72.6	135.6	83.8	40.8	26.5	70.3	43.2	31.4	40.4	–
CVt	0.235	0.066	–	–	0.379	0.132	0.351	0.593	0.502	–	0.519	–	0.245	–

Note: * Abdel-Malek and Ishak (1980); ** El-Shabrawy and Dumont (2009); ***El-Shabrawy and Khalifa (2007).

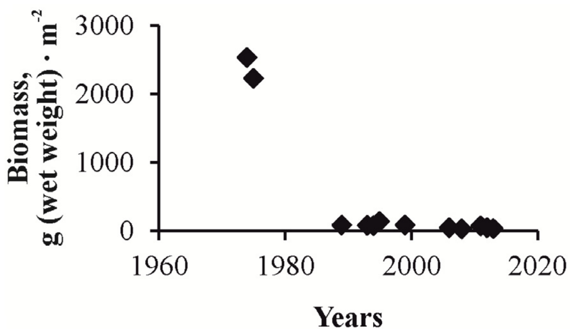

Fig. 4. Diagram showing benthos biomass changes in Lake Qarun in 1974–2013.

is known that older invertebrates, including mollusks, demonstrate less resistance to stressing factors than younger individuals (Shadrin *et al.*, 1993). An observed decrease of occurrence frequency may be also explained by episodical microalgae blooms and mass mortality of benthic species. Probably, this may also explain an increase of spatial heterogeneity (*CVs*) in total benthos biomass distribution; development of microalgae blooms may lead to formation of local anoxic dead zones on bottom.

Discussing changes in Lake Qarun we must include pollution by heavy metals, pesticides, and other pollutants (Mansour and Sidky, 2003; Authman and Abbas, 2007). Because Lake Qarun is terminal with an intensive evaporation the salts, heavy metals and pesticides, carried by agricultural and municipal drainage waters, accumulate in the lake. A current level of pollutants in the lake also contributes to increased mortality of the different species, and diminished immunity and reproduction (Mansour and Sidky, 2003; Authman and Abbas, 2007). We conclude that multiple factors contribute to current changes in Lake Qarun benthos with different chain, domino, top-down and up-down effects. So it is very difficult task to isolate the specific causes of modern long-term changes in Lake Qarun ecosystem.

Williams (1998) concluded that, irrespective of whatever factors determine community structure; salinity may have rather little impact over wide ranges of salinity in salt lakes with salinities generally in excess of 50 g.L^{-1}. Same conclusion was made for zooplankton changes in the lake (El-Shabrawy *et al.*, 2015). So since 1928 salinity had rather little impact on benthic changes in Lake Qarun. Most common and abundant species in the lake are high halotolerant. As example, Bivalvia *C. glaucum* can live under salinity up to 70–80 g.L^{-1}, Crustacea *Gammarus aequicauda* (Martynov, 1931) – to 80–100 g.L^{-1} and *Sphaeroma serratum* (Fabricius, 1787) – to 85 g.L^{-1}, the most abundant species in Lake Qarun meiobenthos Ostracoda *Cyprideis torosa* (Jones, 1850) – to 150 g.L^{-1} (Neale, 1988; Kowalke, 2005). According with the current trend, salinity will not reach 50 g.L^{-1} in 21 century in Lake Qarun; increasing salinity will not be a key driver of changes in Lake Qarun ecosystem in 21 century.

5 Conclusions

A variety of other factors than salinity (hydrological patterns, chemical pollution, modern and past climatic dynamics, ecosystem memory – a bank of resting stages, chance, human activities, and various forms of biotic interactions) may, in various combinations, be significant in determining the structure and short- and long-term dynamics of communities in Lake Qarun. Taking into account all above as well the shapes of poor-known natural rhythms and multiplicity of ecosystem stable states in saline lakes (Shadrin, 2013), we conclude that we have a very small chance to make a correct forecast of possible ecosystem changes in Lake Qarun. And this chance is dropping further due to enhanced climate instability (McElroy and Baker, 2012). "When sorrows come, they come not single spies, but in battalions" (Shakespeare, "Hamlet"); violating natural landscape and ecological connectivity we multiply the problems, including a prediction of future changes. However, this does not mean that we should lose heart; we need to pay more attention to stabilize the lake ecosystem and regulate concentrations of N, P, and various pollutants in the lake. An intelligent use of artificial reefs may be one of the tools to go to regulation of nutrient and pollutant concentrations, and stabilization of biotic composition in the lake (Canfield *et al.*, 2000).

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