Aquatic ecosystem health and trophic status classification of the Bitter Lakes along the main connecting link between the Red Sea and the Mediterranean

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Abstract

The Bitter Lakes are the most significant water bodies of the Suez Canal, comprising 85% of the water volume, but spreading over only 24% of the length of the canal. The present study aims at investigation of the trophic status of the Bitter Lakes employing various trophic state indices, biotic and abiotic parameters, thus reporting the health of the Lake ecosystem according to the internationally accepted classification criteria. The composition and abundance of phytoplankton with a dominance of diatoms and a decreased population density of 4315–7376 ind. l⁻¹ reflect the oligotrophic nature of this water body. The intense growth of diatoms in the Bitter Lakes depends on silicate availability, in addition to nitrate and phosphate. If the trophic state index (TSI) is applied to the lakes under study it records that the Bitter Lakes have an index under 40. Moreover, in the total chlorophyll-a measurements of 0.35–0.96 µg l⁻¹ there are more indicative of little algal biomass and lower biological productivity. At 0.76–2.3 µg l⁻¹, meanwhile, the low quantity of Phosphorus is a further measure of low biological productivity. In the Bitter Lakes, TN/TP ratios are high and recorded 147.4, and 184.7 for minimum and maximum ratios, respectively. These values indicate that in Bitter lakes, the limiting nutrient is phosphorus and confirm the oligotrophic status of the Bitter Lakes. The latter conclusion is supported by Secchi disc water clarity measurements, showing that light can penetrate, and thus algae can photosynthesize, as deep as >13 m. This study, therefore, showed that the Bitter Lakes of the Suez Canal exhibit oligotrophic conditions with clear water, low productivity and with no algal blooming.

1. Introduction

The quality of the water and the health of the aquatic ecosystem of lakes are very sensitive issues and lakes in different regions of the world particularly in developing countries are facing a variety of problems associated with anthropogenic activities and unsustainable use of their resources.

Monitoring and assessing the aquatic environment for eutrophication is essential to mitigate or prevent adverse environmental and economic impacts (Devlin et al., 2011; Napiórkowska-Krebiel and Hutorowicz, 2014). To ensure the environmental health of aquatic ecosystem including lakes, different regulatory instruments are in place across the regions and the world. The Water Framework Directive 2000/60/EC is one such example demanding the European Union (EU) member states to assess the ecological state of their lake waters, and it has become the guiding principle in other countries as well (Mischke et al., 2008; Kaiblinger et al., 2009; Hutorowicz et al., 2011; Phillips et al., 2013), although it is adopted with some modifications in other areas (Hutorowicz and Pasztaleniec, 2009, 2014). The environmen-
tal health of any lake system is essentially determined through its trophic status; basically on a classification scale for how productive the lake is. Such a trophic status is calculated by exploiting a combination of quality parameters like water clarity, and light penetration; chlorophyll-α concentration, as a measure of algal activity and phosphorus concentration, an essential nutrient needed by aquatic plants and algae to grow. The protocol classifies lakes as eutrophic, mesotrophic or oligotrophic (Gholizadeh et al., 2016). The dynamic nature of the productivity and eutrophication due to natural and anthropogenic factors leaves no single assessment variable as a true measure of the eutrophication status of a given water body (Xu et al., 2001; Padisák et al., 2009) and a combination of physical and chemical parameters are widely used in determining the health of a lake ecosystem (Phillips et al., 2013).

The bitter lake has attracted the attention of researchers and many studies have focused on different aspects of natural, biological and socio-economic aspects of the lake (Ghazzawi, 1939; Heimdal et al., 1977; Dorgham, 1985; Nassar and Shams El-Din, 2006; Hamed et al., 2012; El-Serehy et al., 2014; Nassar and Fahmy, 2016). The lake system together with the Suez canal are not merely an ecosystem on environmental value, rather these are efficient shipping routes (Schøyen and Bråthen, 2011; Baccelli et al., 2015; Galal, 2015; Galil et al., 2015) greatly shortening the voyage and contributing to the nature conservation on a broader environmental spectrum. In the wake of new and emerging needs and development, activities and potential biological impact to the water volume, although only spreading over 24% of the canal length. The lakes have exhibited somewhat unusual hydrological regimens since the canal was opened for navigation (Thorson, 1971).

Table 1 summarizes the limnological parameters of the little and the Great Bitter Lakes of the Suez Canal. At the time when the canal was excavated and operational, in 1869, a massive salt deposit was found spread over the bottom of the Great Bitter Lake (Heimdal et al., 1977) that later covered the Little Bitter Lake as well, and subsequently has been gradually dissolved by the overlying water. The later has become high saline from surface salinity of 50–52‰ and at the bottom even higher (68–80‰) in 1869. Today salt deposit layered at the bottom has been washed away thus reducing the level of salinity to 43–44‰ at the surface and 45–46‰ at the bottom (El-Serehy et al., 2014).

2. Material and methods

2.1. Study area

Red Sea in the south is connected directly with the Mediterranean in the north via the Suez Canal. The Suez Canal water system, about 164 km long stretch of sea-level waterway includes several natural lakes. The Bitter Lakes (Great Bitter Lake and Little Bitter Lake) (Fig. 1) are considered significant, representing 85% of the water volume, although only spreading over 24% of the canal length. The lakes have exhibited somewhat unusual hydrological regimens since the canal was opened for navigation (Thorson, 1971). Table 1 summarises the limnological parameters of the little and the Great Bitter Lakes of the Suez Canal.

| Parameter | Little Bitter Lake | Great Bitter Lake |
|-----------|--------------------|-------------------|
| Surface area (m²) | 40 × 10³ | 194 × 10³ |
| Maximum depth (m) | 28 | 28 |
| Mean depth (m) | 11 | 18 |
| Maximum length (m) | 15,000 | 24,000 |
| Maximum width (m) | 2760 | 13,000 |
| Maximum Secchi disc depth (m) | 11.81 | 14.83 |

Fig. 1. The location of the three sampling sites in the Bitter Lakes on the Suez Canal. The inset shows the position of the Suez Canal as a link between the Mediterranean and the Red Sea.
the limnological parameters of the little and the Great Bitter Lakes of the Suez Canal.

2.2. Sampling

Surface water samples were collected at three stations in the Bitter Lakes each month from November 2010 to October 2011. The locations of the sampling stations are shown in Fig. 1. Secchi disc (SD) was used to determine the transparency of lake water. Surface water salinity at a depth ranging from 50 to 75 cm was recorded with an electronic salinometer (MC Salinity/Temperature Bridge); temperature at the same level was determined by using a mercury-in-glass thermometer while a pre-calibrated digital pH meter was used to record the pH.

Total phosphorus (TP) was analysed by the molybdenum blue method (Standard methods, 1960) after mineralization in perchloric acid in unfiltered water samples. Total nitrogen was determined using the CEAEQ (2006) protocol. Unfiltered samples were tested to give total nitrogen which includes nitrate, nitrite, ammonia and organic nitrogen. The acetone extraction method (Golterman, 1969) was applied to determine the chlorophyll a concentration.

Samples for the microscopic determination of phytoplankton were collected by horizontal phytoplankton hauls using plankton nets with a mesh size of 33 μm, and fixed with acetic Lugol solution with final concentration of 1% (Throndsen, 1978). Phytoplankton taxa were identified using an inverted microscope (Nikon TMS, magnification: 200×, 400× and 600×). The most commonly used literature was consulted to ascertain the taxonomy of the phytoplankton (Krammer and Lange-Bertalot, 1986, 1988; Sournia, 1986; Popowski and Pfiester, 1990; Cox, 1996; Komarek and Anagnostidis, 1999; John et al., 2002). Taxa and authors names were confirmed following standardized databases for phytoplankton taxonomy (Guiry and Guiry, 2013).

2.3. Trophic state determination

The trophic state was determined on the basis of Trophic State Indices (TSI) using a logarithmic transformation (Ln) of the chlorophyll a concentration (Chl. a) in microgram per liter, Secchi disc depth (SD) in meters and the total phosphorus (TP) in microgram per liter according the following equation (Carlson, 1977):

$$CTSI = \frac{\left( TSI(\text{SD}) + TSI(\text{CHL}) + TSI(\text{TP}) \right)}{3}$$

where

$$TSI(\text{SD}) = 60 - \frac{14}{44} \ln(\text{SD}) \text{ (m)}$$

$$TSI(\text{CHL}) = \frac{9}{81} \ln(\text{chl.a}) + \frac{30}{6} \text{ (μg/L)}$$

$$TSI(\text{TP}) = \frac{14}{42} \ln(\text{TP}) + \frac{4}{15} \text{ (μg/L)}$$

Vollenweider's method for assessing a water body's trophic state was also applied, as it is accepted protocol by the Organization for Economic Co-Operation and Development (OECD) (Ryding and Rast, 1994); Environment Canada (2004); and the Ministry of Sustainable Development in Quebec, MDDEP (2007), and is based on the average values of selected parameters (Vollenweider, 1989).

3. Results

3.1. Physico-chemical properties of the Bitter Lakes

The minimum and maximum values of different physico-chemical parameters measured at the three sampling sites chosen at the Bitter Lakes are listed in Table 2. The surface water temperature varied between 17.2 °C in winter at station 3 and 31 °C in summer at station 1. Salinity levels ranged between 41.1% (During Winter, at station 2) and 44.6% (During Summer at station 1); while the nutrient concentration (P) remained extremely low, fluctuating between 0.76 and 2.3 μg l⁻¹ at the three sampling stations with no apparent differences. The present study recorded pH around slightly alkaline mean values of 8.04–8.30 (Table 2). Although generally low, the concentrations of total chlorophyll a showed pronounced temporal and spatial variation (Table 2). The highest concentration of 0.96 μg l⁻¹ was measured at station 3 during spring, while the lowest concentration of 0.35 μg l⁻¹ was measured at station 1 during summer. Total nitrogen concentration ranged between 112 and 425 μg l⁻¹ for the minimum and the maximum values, respectively.

3.2. Planktonic algae of the Bitter Lakes

The present study reports a total of 104 species of phytoplankton (Table 3) from the Bitter Lakes belonging to 5 families: Bacillariophyceae (65 species); Dinoflagellate (15 species); Chlorophyceae (11 species); Cyanophyceae (11 species) and Euglenophyceae (2 species). The percentage contribution of 62, 14, 11, 11 and 2% to the phytoplankton community was recorded for Bacillariophyceae, Dinoflagellate, Chlorophyceae, Cyanophyceae and Euglenophyceae, respectively (Fig. 2). Characteristic phytoplankton groups and algal indicator species for the trophic status classification of the Suez Canal Bitter Lakes are shown in Table 4. The level and value of the standing crop of species was generally poor reaching a highest density (7376 ind. l⁻¹) at station 3 in the northern part of the Great Bitter Lake, and a visible decline in the algal density southwards reaching 4315 ind. l⁻¹ at station 1. Overall, the Bacillariophyceae was the most abundant group of phytoplankton, followed by the Dinoflagellate rank and the Chlorophyceae and the Cyanophyceae. While the Bacillariophyceae formed the largest group in almost every month, the Dinoflagellate group represented a large part of the phytoplankton community during the study period, although the population varied during the sampling seasons. The members of the family Chlorophyceae were recorded largely around the year. On the other hand, members of Cyanophyceae were present in the samples received in some seasons and the numbers tend to remain low, a fact contrary to the other groups of phytoplankton. For example, presence of the members of blue-green algae was recorded in summer months only. No algal blooms were noticed during the sampling period.

3.3. Trophic status classification

Data contained in the Table 5 exhibits the complete spectrum of the trophic state index (TSI) and its associated parameters (Carlson, 1977). The values calculated for TSI in the water of the Bitter Lakes are shown in Fig. 3. The latter shows that the Bitter Lakes have an Index under 40. Table 6 compares the internationally accepted criteria accepted by the OECD (1982), Environment Canada (2004), MDDEP (2007), Nurnberg (2001), and University of Florida (1983) for the trophic status classification of lakes.

4. Discussion

4.1. Phytoplankton species composition and community structure in the Bitter Lakes

The need for the present study aroused because of the significance of fragile lake ecosystem of the Suez Canal and the proposed development activities in the area (El-Serehy, et al., 2014). The con-
Table 2

| Parameter                     | Min     | Max     | Average | SD     |
|-------------------------------|---------|---------|---------|--------|
| Secchi disc transparency (m)  | 5.65    | 14.83   | 6.13    | ±2.11  |
| Temperature (°C)               | 17.2    | 31.0    | 25.1    | ±3.32  |
| Salinity %                    | 41.1    | 44.6    | 41.2    | ±5.74  |
| pH                            | 8.04    | 8.3     | 8.08    | ±0.38  |
| Total Phosphorus (µg L⁻¹)     | 0.76    | 2.3     | 1.61    | ±0.56  |
| Chlorophyll a (µg L⁻¹)        | 0.35    | 0.96    | 0.55    | ±0.07  |
| Total Nitrogen (µg L⁻¹)       | 112     | 425     | 195     | ±28.60 |
| TN/TP ratio                   | 147.4   | 184.7   | 168.1   | ±18.75 |

Table 3

List of planktonic taxa and species collected from the coastal water of the Bitter Lakes during the present study.

**Bacillariophyceae**

1. Amphipora alata Kützing
2. A. paludosa Smith
3. Asterionella japonica Cleve
4. Bacillaria paradoxa (Müller) Grunow
5. Biddulphia favae (Ehrenberg) Van Heurck
6. B. longicuris Greville
7. B. mobilisem (J.W. Bailey) Grunow
8. B. obtusa (Kützing) Rafls
9. Campylocephalus noricus var. hibernicus (Ehrenberg) Grunow
10. Cerataulina bergonii (H. Peragallo) F. Schütt
11. Chaetoceros anastomosans Grunow
12. C. curvisetus Cleve
13. C. decipiens Cleve
14. C. lorentzianus Grunow
15. C. peruvianus Brightwell
16. C. tortissimus Grunow
17. Chlamidocystis biconcavum Cleve
18. Chlamidocystis moniliger Ehrenberg
19. Cocconeis placentula var. hibernicus Ehrenberg
20. Coscinodiscus grani Gough
21. C. radiatus Ehrenberg
22. Cyclotella meneghiniana Kützing
23. Cymbella ventricosa Kützing
24. Diploneis interrupta (Kützing) Cleve
25. Frigilaria capucina Desmazières
26. Guinardia flacciola (Castracane) H. Peragallo
27. Gyrosigma attenuatum (Kützing) Rabenhorst
28. G. balticum (Ehrenberg) Rabenhorst
29. Hemiaulus hebergeri Cleve
30. Lauderia borealis Grunow
31. Leptocylindrus danicus Cleve
32. Licmophora abbreviata Agardh
33. L. flabellata (Greville) Agardh
34. L. gracilis (Ehrenberg) Grunow
35. Melosira granulata (Ehrenberg) Rafls
36. M. sulcata (Ehrenberg) Kützing
37. M. varians Agardh
38. Navicula cryptocephala Kützing
39. N. cuspidate Kützing
40. N. dicephala Ehrenberg
41. N. gracilis Cleve
42. Nitzschia closterium (Ehrenberg) Smith
43. N. kützingiana Hülse
44. N. longissima (Brébisson) Rafls
45. N. pacifica Cupp
46. N. pungens var. atlantico Cleve
47. N. sula (Castracane) Hustedt
48. N. sigma (Kützing) W. Smith
49. Pleurosigma angulatum (Quekett) Smith
50. Rhizosolenia alata f. gracillima (Cleve) Grunow
51. R. alata f. indica Nothig
52. R. calcic-avis Schultz
53. R. imbricata Brightwell
54. R. stolterfothii H. Peragallo

**Bacillariophyceae continued**

55. R. styloides Brightwell
56. Schroederella delicatula (Peragallo) Pavillard
57. Skeletonema costatum (Greville) Cleve
58. Stephanopyxis nipponica Gran & Yendo
59. Surirella ovata Kützing
60. S. robusta Ehrenberg
61. Synedra crystalloides (Agardh) Kützing
62. S. ulna (Nitzsch) Ehrenberg
63. Thalassionema nitzschioides (Grunow) Meschchkovsky
64. Thalassiosira frauenfeldii (Grunow) Grunow
65. T. longissima Cleve & Grunow

**Diaphyceae**

1. Ceratium egyptiacum Halim
2. C. furca (Ehrenberg) Claparède & Lachmann
3. C. fusus (Ehrenberg) Dujardin
4. C. trichoceras (Ehrenberg) Kofoid
5. C. tripos (Müller) Nitzsch
6. Dinophyced caudata Savielle-Kent
7. D. rotundata Claparède & Lachmann
8. Oxytoxum scolopes Stein
9. Phalacroma rapa Jörgensen
10. Procentrum marinum (Cienkowski) Loeblich
11. P. micans Ehrenberg
12. Proterothecis cerasus (Paulsen) Balech
13. P. depressum (Bailey) Balech
14. P. diversum (Ehrenberg) Balech
15. Pyrophacus horologium Stein

**Chlorophyceae**

1. Actinomitra hantzschii Lagerheim
2. Chlorodesmus sonorus. Sp.
3. Chlorella vulgaris Beijerink
4. Closterium gracile Brébisson ex Rafls
5. Pediasstrum clathratum (Schröder) Lemmermann
6. Scenedesmus bijugus (Turpin) Lagerheim
7. S. dimorphus (Turpin) Kützing
8. S. obtusus (Turpin) Kützing
9. S. quadracauda (Turpin) Brébisson
10. Staurodiscus gracile Rafls ex Rafls
11. Stigodiscus sp.

**Cyanophyceae**

1. Chroococcus turgidus (Kützing) Nägeli
2. Gomphosphaeria aponia Kützing
3. Lyngbya major Meneghini ex Comont
4. Merismopedia punctata Meyen
5. Oscillatoria constricta Száler
6. O. erythraea (Ehrenberg) Geitler
7. O. immetica Lemmermann
8. O. tenuis Agardh ex Comont
9. Phormidium ambiguum Comont
10. Spirulina major Kützing & Comont
11. S. platensis (Comont) Geitler

**Euglenophyceae**

1. Euglena baltica Schüler
2. Phacus sp.

*Fresh water form.*

*b Benthic forms.*

Savation community remained cautious of the proposed development agenda in the presence of impact of past anthropogenic activities and spread of biological invasion (Gunnar, 1979; Elton, 2000; Galil et al., 2015). Among the algal communities, diatom taxa are considered as a group sensitive to water chemistry and specific ecological conditions, and thus are used as an indicator for...
The completed trophic state index and its associated parameters as set out in Carlson classification of the Suez Canal Bitter Lakes. Characteristic phytoplankton groups and algal indicator species for the trophic status classification of the Suez Canal Bitter Lakes. 

**Table 5**
The completed trophic state index and its associated parameters as set out in Carlson (1977).

| TSI | Secchi disk (m) | Surface phosphorus (mg/m$^2$) | Surface chlorophyll $a$ (mg/m$^2$) |
|-----|----------------|-------------------------------|-----------------------------------|
| 0   | 64             | 0.75                          | 0.04                              |
| 10  | 32             | 1.5                           | 0.12                              |
| 20  | 16             | 3                             | 0.34                              |
| 30  | 8              | 6                             | 0.94                              |
| 40  | 4              | 12                            | 2.6                               |
| 50  | 2              | 24                            | 6.4                               |
| 60  | 1              | 48                            | 20                                |
| 70  | 0.5            | 96                            | 56                                |
| 80  | 0.25           | 192                           | 154                               |
| 90  | 0.12           | 384                           | 427                               |
| 100 | 0.062          | 768                           | 1183                              |

Fig. 2. The percentage contribution of Bacillariophyceae, Dinophyceae, Chlorophyceae, Cyanophyceae and Euglenophyceae to the phytoplankton community at the Bitter Lakes during the present study.

A total of 104 phytoplankton taxa were recorded in the water of the Bitter Lakes (Table 3). It is very interesting to compare the list of phytoplankton species identified in the present investigation with the earlier literature (Ghazzawi, 1939; Kimor, 1972; Lipkin, 1972; Heimdal et al., 1977; Nassar and Shams El-Din, 2006). An early investigation reported a small number of phytoplankton species (Ghazzawi, 1939) and fifty years later, similar results were obtained by Kimor (1972) and Lipkin (1972) for the entire water system of the Suez Canal. As Kimor’s data was related to the entire Suez Canal, it cannot be considered, with certainty, representative of the planktonic populations in the Bitter Lakes. The marked differences in the findings reported by Ghazzawi (1939) and the results of the present investigation might stem from the marked differences in the sampling gear: plankton hauls (with a 50–60 μm mesh size of sampling gear) carried out during 1934–1936 formed the basis of Ghazzawi’s samples and the present study employed net with a mesh size of 33 μm. Further, the differences might also be real, on account of natural and anthropogenic activities in the whole Suez Canal ecosystem. With this background, the phytoplankton list of the Bitter Lakes exhibit interesting characteristics when compared with information in the available literature (Ghazzawi, 1939; Kimor, 1972; Nassar and Shams El-Din, 2006; Nassar and Fahmy, 2016). Ghazzawi (1939) reported the diatom species *Nitzschia seriata* to be abundant in the samples and a similar pattern in Lipkin’s and Nassar and Shams El-Din’s samples (Lipkin, 1972; Nassar and Shams El-Din, 2006). Contrarily, the species was not reported by Kimor (1972) and Heimdal (1977) and is not recorded during the present study. *N. seriata* is believed to be a typical cold-water form (Hasle, 1976). So, *N. seriata* ia a pan thalassic species, it could be affected by changes in the temperature or by the dissolution in salinity (from 80‰ earlier to 46‰ at present) and/or any other competing organism in the Bitter Laces ecosystem. This sporadic pattern of the appearance of this species needs further investigation. The present research reports *Rhizosolenia alata* as very abundant diatom species in the Bitter Lakes and was considered among the most common diatom in the waters of the lakes (Heimdal et al., 1977; Nassar and Shams, El-Din 2006; Nassar and Fahmy, 2016). Earlier, it was, however, not recorded from the Bitter Lakes by Ghazzawi (1939). A similar discontinuous pattern of existence of fresh or brackish water diatom species is also noticed: The species listed by Heimdal (1977) have not been reported in previous studies (Ghazzawi, 1939; Kimor, 1972; Lipkin, 1972). Most of the freshwater species recorded are unlikely to grow in seawater and were probably brought to the site water-quality in many aquatic systems (Stevenson and Smol, 2003). The species are also useful parameters to monitor changes temporally and spatially.
of the Bitter Lakes from other localities by wind (Heimdal et al., 1977). The later supposition can be used to interpret the presence of the freshwater diatom Cocconeis placentula Ehrenberg to the Bitter Lakes reported by the earlier studies (Nassar and Shams El-Din, 2006; Nassar and Fahmy, 2016), and as well as during the present investigation. The changing scenarios of algal communities over time raise a question of environmental health from these changes. Movement of the species (Por, 1978; El-Serehy et al., 2014; Galil et al., 2015) from Mediterranean to the Red Sea and vice versa remains subjected to further investigation.

The occurrence of the littoral or benthic diatoms, for example: Diploneis; and Surirella in the phytoplankton net hauls reported by Kimor (1972) and Heimdal (1977) cannot be surprising as the canal is open for navigation and the traffic of course agitates and whirls up the sediments in the navigational pass way and of the Bitter Lakes. This phenomenon might be the explanation of existence of the benthic diatoms observed in the net hauls used in the present study (Table 3). It is, however, somewhat surprising that the benthic diatom species were seldom observed in the samples collected by Ghazzawi (1939) and Lipkin (1972). The latter investigator reported that many benthic diatom species in the Suez Canal were attached to the higher algae (seaweeds) and were missing from the net samples.

This difference in composition of the phytoplankton community of the Bitter Lakes as reported by authors does not however reflect a significant change in the community structure; yet, the results discussed above indicate some changes in the phytoplankton community structure of the Bitter Lakes during the eighty years and it denies the static nature of the planktonic biodiversity. Some kind of transport of phytoplankton species to the Bitter Lakes is more likely occurs, from both the eastern Mediterranean and the Red Sea through the canal system (El-Serehy et al., 2014; Galil et al., 2015). The later suggestion is supported by the inhabitation of the planktonic species and maintaining at least some self-sustaining isolated populations, a phenomenon strongly suggesting Suez Canal and Bitter Lakes system as a habitat of its own characters, rather than merely a funnel or corridor for planktons passing like ships from one end to the other (Por, 1978; El-Serehy and Al-Rasheid, 2011; El-Serehy, et al., 2014). Diatoms formed the dominant component of phytoplankton in Bitter Lakes representing 62% of the total phytoplankton composition (Fig. 2). Owing to the relatively short life cycle, the diatoms respond rapidly to the physico-chemical changes and eutrophication thus indicating information on nutrient changes (Rahmati et al., 2011; Darling, 2015). Moreover, diatoms are strongly correlated to total phosphorus (TP) concentrations (Wang et al., 2014). In the areas with lower concentration of phosphorus (TP: 0.76–2.3 μg l⁻¹), diatom species such as Amphipora alata, A. paludosa, Chaetoceros anastomosans, C. curvisetus, C. decipiens, C. tortissimus, Coscinodiscus grani, Hemisphaerium heibergii, N. Kütingiana, N. longisima, Nitzschia sigma, N. pungens, Rhizosolenia alata, Skeletonema costatum were dominant diatom species. These dominant diatom species can be suggested as indicators to oligotrophic status of the Bitter Lakes ecosystem, a phenomenon used as potent indicator of trophic status in the water of many lakes (Phillips et al., 2013; Napiórkowska-Krzebietke and Hutorowicz, 2014). On the other hand, Euglenophyceae, represented only by two species and constituting 2% of the total algal community, are rightly represented in this manner owing to the absence of organic matters in the Bitter Lakes water. Euglenoids are the more dominant protists in habitats rich in organic matter (Sleigh, 1989).

Pattern of the spatial and temporal distribution and taxonomic composition of phytoplankton in study area was generally uniform, a phenomenon reflecting more homogenous hydrographic characteristics of the three sites. The amount of the standing crop of planktonic algae attained a lower density of between 4315 and 7376 ind. l⁻¹ (Table 4) a fact attributed to the very poor nutrients availability (0.76–2.3 μg l⁻¹ Table 2), and also to the Lakes’ proximity to red sea in its northern end, the later in its turn provokes an increasing level of oligotrophy (Almogi-Labin, 1984). The phyto-
plankton community in the Bitter Lakes, therefore, is characterized by low population density but a high number of algal species diversity (104 species), a combination that can be associated with low levels of nutrients, low values of chlorophyll \( a \), low productivity, thus suggesting the oligotrophic nature of the Bitter Lakes.

### 4.2. Trophic status classification of the Bitter Lakes

Efforts have been made to establish an accepted criteria and levels of thresholds to classify lakes based on trophic status, nutrients, total phosphorus as well as on certain other physical (e.g., transparency, dissolved oxygen) and biological (e.g., algal pigments) characteristics (OECD, 1982; Galvez-Cloutier and Sanchez, 2007; Zebez, 2009). A nutrient ratio (N/P) has been used to explain specific algal populations, or identify a nutrient limiting factor (Redfield, 1958; Hecky and Kilham, 1988). Redfield Ratio (Nitrogen to Phosphorus in molecular weights: 224/30 = 7.46) is considered as an established baseline for nutrient availability (Wetzel, 1983) and it has been suggested that Phosphorus becomes limiting nutrient in water bodies containing TN/TP value greater than 7, whereas a ratio below 7 is a reflection of nitrogen as limiting factor for algal growth (Meybeck et al., 1989; Chapman, 1996). For practical purposes, TN/TP value less than 10 indicates a nitrogen deficiency, and value greater than 20 as phosphorus deficiency. Lower TN/TP ratios are observed in eutrophic lakes and high in mesotrophic and oligotrophic lakes. The present study reports TN/TP ranging between 147.4 and 184.7, while the average ratio is 168.1, a fact indicating that in the Bitter lakes, phosphorus remains the limiting nutrient (Table 2).

The presence of cyanobacteria is a major risk to human and ecosystem health, and is frequently associated with eutrophic conditions, a situation not encountered during the present study where no algal blooms were detected in the study area. Since many bloom-forming cyanobacteria can fix atmospheric \( N_2 \), it has been reasoned, based on resource ratio theory, that cyanobacteria should dominate at low TN/TP ratios, and these species become rare when the TN/TP ratio is greater than 29 (Smith, 1983; UNEP, 2006). Based on the results of the present investigation, Bitter Lakes can be considered as ultraoligotrophic and presented TN/TP as more greater than 29. Apart from the ratios, Downing et al. (2001) showed that individual concentrations of TP and TN can also be correlated with the presence of cyanobacteria. They predicted that the probability of cyanobacteria dominance is about 40% when TP is between 30 and 70 \( \mu g/l \), and rises asymptotically to around 80% at a value of TN near 100 \( \mu g/l \).

Use of various protocols is largely determined by the scope of the work and the objectives of such analyses. The present study employs Carlson’s Trophic State Index (TSI) with the understanding that it is a well-tested robust quantitative method and replicable methodology considering biological and physical parameters.

### Table 6

The internationally accepted criteria are used for trophic state classification of the water bodies.

| Trophic status      | TP (\( \mu g \) l\(^{-1} \)) | Chlorophyll \( a \) (\( \mu g \) l\(^{-1} \)) | Transparency\(^a\) (m) |
|---------------------|-----------------------------|---------------------------------|----------------------|
|                     | Mean | Maximum | Mean | Maximum |
| Ultra-oligotrophic  | <4   | <1      | <2.5 | >6      | >12     |
| Oligotrophic        | <10  | <2.5    | <8   | >3      | >6      |
| Mesotrophic         | 10–35 | 2.5–8  | 8–25 | 1.5–3   | 3–6     |
| Eutrophic           | 35–100 | 8–25   | 25–75 | 0.7–1.5 | 1.5–3   |
| Hyper-eutrophic     | >100 | >25     | >75  | <0.7    | <1.5    |
| **Canadian criteria\(^b\)** |     |         |      |         |         |
| Oligotrophic        | 4–10 | <2.5    | <8   | >3      | >6      |
| Mesotrophic         | 10–20 | 2.5–8  | 8–25 | 1.5–3   | 3–6     |
| Eutrophic           | 35–100 | 8–25   | 25–75 | 0.7–1.5 | 1.5–3   |
| Hyper-eutrophic     | >100 | >25     | >75  | <0.7    | <1.5    |
| **Quebec criteria\(^c\)** |     |         |      |         |         |
| Oligotrophic        | 4–10 | <1      | <2.5 | >6      | >12     |
| Mesotrophic         | 10–30 | 3–8    | 8–25 | 2.5–5   | –       |
| Eutrophic           | 30–100 | 8–25   | –    | 1–2.5   | –       |
| Hyper-eutrophic     | –    | –       | –    | –       | –       |
| **Nürnberg criteria\(^d\)** |     |         |      |         |         |
| Oligotrophic        | <10  | <3.5    | –    | –       | –       |
| Mesotrophic         | 10–30 | 3.5–9  | –    | –       | –       |
| Eutrophic           | 31–100 | 9.1–25 | –    | –       | –       |
| Hyper-eutrophic     | –    | –       | –    | –       | –       |
| **Swedish criteria\(^e\)** |     |         |      |         |         |
| Oligotrophic        | <15  | <3      | –    | –       | >3.96   |
| Mesotrophic         | 15–25 | 3–7    | –    | 2.43–3.96 | –   |
| Eutrophic           | 25–100 | 7–40   | –    | 0.91–2.43 | –   |
| Hyper-eutrophic     | >100 | >40     | –    | <0.91   | –       |
| **Bitter Lake results\(^g\)** |     |         |      |         |         |
| Ultra-oligotrophic  | 0.76–2.3 | 0.36   | 0.96 | >5      | >13     |
| Oligotrophic        | –    | –       | –    | –       | –       |
| Mesotrophic         | –    | –       | –    | –       | –       |
| Eutrophic           | –    | –       | –    | –       | –       |

\(^a\) Transparency by Secchi disk depth.

\(^b\) Ryding and Rast (1994).

\(^c\) Environment Canada (2004).

\(^d\) MDDEP (2007).

\(^e\) Nurnberg (2001).

\(^f\) University of Florida (1983).

\(^g\) Present study.
and the findings are presented in Table 5. A TSI value between 40 and 50 is usually associated with mesotrophic (moderate productivity); values greater than 50 are associated with eutrophic (high productivity), and values less than 40 are associated with oligotrophic nature (low productivity) of the water body (Murthy et al., 2008). If the TSI is calculated using Carlson’s method, measuring Secchi disk depth, chlorophyll a and total phosphorous values, the present study reveals that the Great Bitter Lake, and Little Bitter Lake of the Suez Canal each have an Index under 40 (Fig. 3) and are thus considered to be oligotrophic lakes.

Scientific Studies have been carried out to establish a quality criteria and thresholds for classification of lakes according to their trophic status on the basis of nutrient concentrations, and certain physical and biological characteristics (OECD, 1982; Galvez-Cloutier and Sanchez, 2007; Hutorowicz et al., 2011, Phillips et al., 2013). Estimation of trophic level largely based on levels of phytoplankton biomass seems effective; however, the results are hard to compare especially when the information originates through the use of different methods (Kasprzak et al., 2008) and sampling gear. The protocol employs largely enumerating planktonic particles, measurement of chemical constituents and/or combination of both, although over the past decades the protocols are refined, standardized and modified (See Kasprzak et al., 2008). For Suez Canal Lakes, the classification of trophic level in relation to total phosphorus, chlorophyll a and transparency was employed as a predictor of trophic structure according to the rules adopted by the OECD (1982), Environment Canada (2004) and MDDEP (2007) (Table 6). Overall, these criteria are similar and can be used to indicate a specific trophic level for the Bitter Lakes. On these scales, trophic status is categorized as being ultra-oligotrophic, oligotrophic, mesotrophic, meso-eutrophic, eutrophic and hyper-eutrophic respectively. The classification—in respect to the trophic levels reported through the present study is given in Table 6, these data indicate that the Bitter Lakes can be considered as ultra-oligotrophic. The microscopic evaluation of phytoplankton samples and calculation of algal biomass remain significant in studies focusing on biological parameters but are, however, labour-intensive as well as demanding taxonomic skills of the investigators. An alternate is chlorophyll a concentration, though with limitations, has gained interest of the researchers as a quick and easy-to-measure index of phytoplankton biomass.

5. Conclusions

Bitter Lakes can be regarded as among the most oligotrophic of marine habitats when considering the magnitude of the standing crop of plankton, especially to the phytoplankton groups. Species composition and community structure of the phytoplankton group of the Bitter Lakes showed some changes during the last decades, suggesting dynamic nature of the trophic status of the lakes (El-Serehy et al., 2014). The source of such changes could be aided by some kind of transport of species to the lake through the use of different methods (Kasprzak et al., 2008) and SAMPLING gear. The protocol employs largely enumerating planktonic particles, measurement of chemical constituents and/or combination of both, although over the past decades the protocols are refined, standardized and modified (See Kasprzak et al., 2008). For Suez Canal Lakes, the classification of trophic level in relation to total phosphorus, chlorophyll a and transparency was employed as a predictor of trophic structure according to the rules adopted by the OECD (1982), Environment Canada (2004) and MDDEP (2007) (Table 6). Overall, these criteria are similar and can be used to indicate a specific trophic level for the Bitter Lakes. On these scales, trophic status is categorized as being ultra-oligotrophic, oligotrophic, mesotrophic, meso-eutrophic, eutrophic and hyper-eutrophic respectively. The classification—in respect to the trophic levels reported through the present study is given in Table 6, these data indicate that the Bitter Lakes can be considered as ultra-oligotrophic. The microscopic evaluation of phytoplankton samples and calculation of algal biomass remain significant in studies focusing on biological parameters but are, however, labour-intensive as well as demanding taxonomic skills of the investigators. An alternate is chlorophyll a concentration, though with limitations, has gained interest of the researchers as a quick and easy-to-measure index of phytoplankton biomass.

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