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Assessment of Water Quality, Bacteria, and Plankton Diversity at Thermal Pollution Sites along the River Nile, Egypt

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ABSTRACT

The Nile River is exclusively Egypt's freshwater supply and is used to cool steam turbines in power plants, most of which are located along its course. An investigation was conducted to address the water quality in six areas affected by thermal discharge along the Nile and to monitor the potential effects of temperature fluctuations on the biodiversity of bacteria, phytoplankton, and zooplankton communities. Samples were collected from the upstream, downstream, and discharge zones of each power plant. Temperatures increased more at the mixing points than in the upstream and downstream locations, while transparency and dissolved oxygen levels were the lowest at the mixing points. The water quality index for the Nile ranged from 68 (medium) to 93 (excellent), with the lowest values found near the thermal discharge points. Fecal coliform and fecal streptococci counts ranged from 3 to 1100 and 3 to 1200 MPN/100 ml, respectively, with the mixing points showing the lowest levels of pollution-related bacterial markers. Our results indicate that plankton abundance and dominance were influenced by temperature at the mixing points. Seasonal changes in zooplankton composition and density were observed, with rotifers consistently being the dominant group. It is recommended to regularly monitor the condition of the Nile water, especially after the completion of the Grand Ethiopian Renaissance Dam and the decrease in Egypt's share of the Nile water, as these changes could lead to increased water temperatures near the power plants.

INTRODUCTION

Freshwater constitutes an essential resource for human life, and its quality is a pressing global concern **(Abdel-Satar *et al*., 2024)**. The River Nile supplies most of the country's freshwater resources for agricultural and drinkable uses. The quality of the water in the River Nile has been declining as a result of human inputs and the disposal of untreated wastewater **(Abdel-Satar *et al*., 2022)**. Water, sediment, and biota act as key indicators for monitoring environmental pollution and the toxicological effects of contaminants **(El-Anwar *et al*., 2021)**.

Thermal pollution refers to water quality degradation arising from any process capable of elevating or reducing the surrounding water temperature. The presence of heat becomes a form of water pollution when it stems from heated industrial discharges or wastes from power plants **(Speight, 2020)**. The utilization of water as a coolant in industrial enterprises and power plants significantly contributes to thermal pollution. The abrupt alteration in temperature arising from the discharge of water, previously employed as a coolant, back into the environment at an elevated temperature can have substantial ramifications on the ecosystem. This sudden shift in water temperature, commonly referred to as thermal shock, can potentially result in the mortality of fish and other organisms adapted to specific temperature ranges **(Alaa & Jaeel, 2019)**. The solubility of gases in water exhibits an inverse relationship with temperature. Consequently, the presence of heated effluents diminishes the quantity of dissolved oxygen in water accessible to aerobic (oxygen-dependent) species. Moreover, heat augments the metabolic rate of aquatic organisms, thereby exacerbating the reduction in dissolved oxygen levels. This occurs because respiration intensifies until the water temperature surpasses a critical threshold, resulting in the mortality of the organism **(Speight, 2020; Xiong *et al*., 2020)**.

Thermal pollution, characterized by the discharge of heated water from thermal power plants into aquatic environments, can exert detrimental effects on aquatic life. The combination of elevated temperature and oxygen depletion has the potential to curtail the activity of aerobic decomposers, thereby precipitating a reduction in the availability of nutrients within the water bodies. Additionally, the temperature-induced suppression of enzyme activity can impede the photosynthetic rate of aquatic plants, resulting in a diminished primary productivity and a decline in species diversity among aquatic flora. Reduced dissolved oxygen can cause direct mortality in living organisms or sub-acute effects such as reduced growth and reproductive success **(Mahmoud *et al*., 2020; Jovcevski *et al*., 2022)**.

An increase in the water temperature in aquatic systems can lead to an increase in organic matter, fecal bacteria, and toxic substances, where the presence of high levels of fecal bacteria restricts the suitability of the water for various uses. Thermal pollution may enhance bacterial abundance and reduce bacterial diversity **(Bhasin *et al*., 2020)**.

Water temperature exerts both direct and indirect influences on phytoplankton. Directly, it impacts the physiology and metabolic rates of individual phytoplankton cells. Indirect effects encompass alterations to the aquatic growth environment and interactions with other members of the phytoplankton community. The fundamental metabolic processes of a phytoplankton cell, including photosynthesis, respiration, growth, and nutrient uptake, are all contingent on temperature **(Chisholm, 1992, Zohary *et al*., 2021)**.

Thermal pollution can induce alterations in community structure, potentially facilitating the establishment of exotic species while leading to the local extinction of native species. The temperature has an impact on the survival, growth rates, morphology, reproduction, metabolism, and behavior of numerous aquatic organisms. Additionally, temperature fluctuations can serve as a crucial factor in shaping the behavior of aquatic organisms, including their migration patterns and predator-prey interactions **(Xiong *et al*., 2020; Gozdziejewska & Kruk, 2023)**.

The River Nile is the valued natural and exclusive source of fresh water in Egypt, where the drinking water supply is limited to the river **(Al-Afify & Abdel-Satar, 2020)**. Moreover, its flow rate relies on the available water stored in Nasser Lake to achieve needs within Egypt's annual water budget. Stresses are coming from the upstream dam projects on the Nile River, water usage by neighboring countries, population growth, and potential climate change **(Abdel-Satar *et al*., 2022)**. The quality of the Nile water is a matter of serious concern due to the expansion of industrial, agricultural, and recreational activities in addition to the poorly structured drainage and sewerage system **(Abdel-Satar *et al*., 2017)**. The Nile branches receive pollution loads from several drains and waste from industrial and power plants **(Mostafa & Peters, 2015; Hasaballah *et al*., 2019; Eldourghamy, 2024)**. Thermal power plants constitute the primary source of energy generation in Egypt. They comprise about 36 stations, accounting for 88.9% of the nation's total power generation. There are about 23 of them spread out over Cairo and the two branches. The power generation is categorized into four distinct groups corresponding to the four electricity-producing companies: Cairo, East Delta, West Delta, and Upper Egypt. The annual range of water withdrawn from Egypt's Quota for cooling purposes is estimated to be 2.7% in Upper Egypt, 1.6% in the East Delta group, 2.16% in the West Delta group, and 3.96% in the Cairo group **(Eshra, 2020)**.

The objectives of the present study were to evaluate the physical, chemical, and microbiological qualities of water in selected locations within the River Nile that have been impacted by thermal pollution and to assess the phytoplankton and zooplankton biodiversity in these locations.

MATERIALS AND METHODS

Study area

The current study focused on six specific locations along a 200-kilometer stretch of the Nile River that are affected by the discharge of waste from power plants. These locations include El-Taben, Shoubra El-Khima, and Saqel, which are situated in the Greater Cairo. Additionally, Benha, Talkha, and Damietta are located within the Damietta Branch of the Nile River (Fig. 1). Table (1) lists the site descriptions of the six Nile locations.

Samples collection and analysis

Eighteen water samples were collected during 2022 on a seasonal basis (with a total of 72 samples). The samples were collected from the upstream, downstream, and discharge zones of each individual power plant (mixing point) using a Ruttner water sampler. Duplicate co-located samples were obtained from each site, ensuring that the percentage of variation in laboratory results remained below 5%. In the field, several physical variables, namely water temperature (WT), electrical conductivity (EC), total dissolved solids (TDS), pH and transparency were promptly assessed using a combined meter pH/EC/TDS/temperature (Mi 805) and Secchi-disc. A well-mixed sample volume was evaporated to determine the total solids (TS) according to **APHA (2012)**.

Chemical parameters were assessed following the procedure outlined in **APHA (2012)**. The water samples were processed to measure various parameters including dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), chloride, sulphate, silicate, carbonate bicarbonate, orthophosphate (ortho-P), total phosphorus (TP), nitrogen forms (nitrite, nitrate, and ammonia), as well as major cations (Na, K, Ca, and Mg). Three readings were collected for each variable, and the mean value was calculated, ensuring that the relative standard deviations were below 5%.

Water samples were manually collected in sterile brown bottles (200mL) for bacteriological examination. Samples were kept at 4°C until the bacteriological analysis was finished within 48 hours. The most probable number (MPN) procedure was used to count the total number of coliforms, faecal coliforms, and faecal streptococci **(APHA, 2012)**.

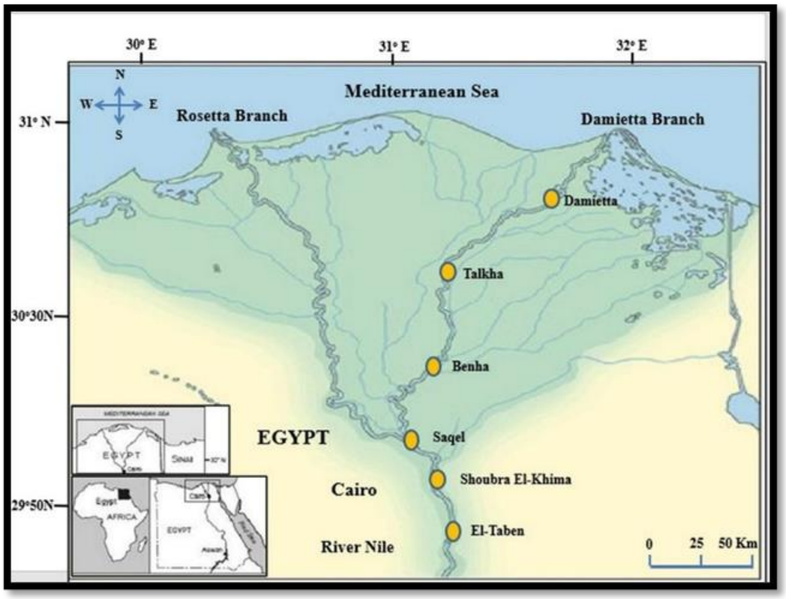


Fig. 1. Map of Egypt showing the selected Nile River areas

Fecal coliforms were cultured in EC broth media (44.5 ± 0.5°C at 24 ± 2h), total coliforms were cultured in lauryl tryptose broth (37 ± 0.5°C at 48 ± 2h), and fecal streptococci were cultured in azide dextrose broth (35 ± 0.5°C at 48 ± 2h). Using the pour plate method, total bacteria were counted on a nutrient agar medium at incubation temperatures of 22, 37, and 55°C for thermophile bacteria **(APHA, 2012)**.

Table 1. The GPS coordinates of the selected River Nile locations

Location	**Latitude**	**Longitude**
El-Taben	31°29'30.08" E	29°77'67.41" N
Shoubra El-Khima	31°23'54.41" E	30°12'35.82" N
Saqel	31°16'48.81" E	30°14'19.19" N
Benha	31°22'50.38" E	30° 49'72.94" N
Talkha	31°39'97.36" E	31°06'27.67" N
Damietta	31°72'04.87" E	31°37'99.42" N

The water quality index (WQI) was used as an indicator of the environmental quality of the Nile River water. WQI was calculated according to **Pesce and Wunderlin (2000)** method during different seasons at each site using the means of triplicate readings for each variable. The water quality variables including TS, DO, BOD, COD, Cl^-, SO_4^{2-}, Mg, ortho-P, TP, NH_3-N, NO_2-N, NO_3-N, and total coliform were used for WQI calculation (Text S1, Table 1S). The classification of WQI scores was illustrated by 5 categories of water quality as very bad (0–25), bad (26–50), medium (51–70), good (71–90) and excellent (91–100) **(Pesce & Wunderlin, 2000)**.

For phytoplankton community analysis, approximately 1 liter of water samples were promptly preserved by adding 4% neutralized formalin and transferred to glass cylinders with a capacity of 1000ml, and Lugols iodine solution was added to the samples **(APHA, 2012)**. Phytoplankton enumeration, expressed as cells/L, was conducted using an inverted microscope with magnification powers of 40 and 100x. Algal identification was performed with algae base following established references, including works by **Lebour (1926)**, **Hendey (1964)**, **Bourrelly (1981)**, **Sheath and Wehr (2003)** and **Taylor *et al*. (2007)**.

Zooplankton samples were collected following the procedures described by **Mageed (2005)** and **Tahoun *et al.* (2021)**. Water was collected from various points using a standard 15-liter plastic bucket. A total of 30 liters of water were subsequently filtered through a plankton net with a mesh diameter of 55µm. Zooplankton samples were characterized and enumerated using a binocular microscope, following the protocols outlined by **Shiel and Koste (1992)**, **Einsle (1996)**, and **Smirnov (1996)**. Each replicate was identified at various magnifications using a counting cell **(El-Shabrawy *et al*., 2015)**.

Statistical analysis

The data obtained from the water samples for the variables were subjected to analysis of variance (ANOVA) and Fisher's least significance difference (LSD) at a significant level of $P<0.05$ using STATISTICA v10 (Statsoft, OK, USA). Furthermore, the Pearson correlation index was utilized to determine the correlations between the examined variables in the water of Nile River. The PAST software was used to calculate Shannon-Wiener diversity, species richness, evenness, similarity index, and multivariate analysis of variance. Whereas, the canonical correspondence analysis (CCA) was examined using Canoco 4.5 software **(Ter Braak & Smilauer, 2002)** to evaluate seasonal and spatial patterns of environmental factors.

RESULTS

Assessment of water quality

The recorded surface water temperature ranged from 23.0 to 35.0°C in autumn, 15.0 to 22.8°C in winter, 24.8 to 34.1°C in spring, and 28.4 to 38.1°C in summer (Fig. 2). The Nile water temperature varied significantly between the seasons, with the highest temperature range was observed in summer and the lowest in winter. Additionally, the WT was higher in the mixing point locations than upstream and downstream locations. Transparency ranged from 30.0 to 200cm, where the mixing point locations had lower transparency than the upstream and downstream sites (Fig. 2). The pH values ranged from 7.6 to 8.0 in autumn, 7.8 to 8.2 in winter, 7.2 to 8.1 in spring, and 7.5 to 8.2 in summer, with no seasonal variation. TDS and EC exhibited a consistent distribution pattern across all sampling sites, with higher values observed at the mixing points compared to the upstream and downstream sites (Fig. 3). Their values ranged between 206 and 329mg/ L for TDS and 300 and 490µS/ cm for EC, where the maximum levels for both variables were observed during winter, and the lowest values were recorded during summer (high flood) season. DO concentrations displayed variations within the ranges of 4.5-8.6, 6.0-8.5, 4.8-9.6, and 5.4-9.2mg/ L for autumn, winter, spring, and summer, respectively, with no temporal variation (Fig. 4). The mixing point locations exhibited lower DO values compared to the upstream and downstream locations.

Both BOD and COD exhibited significant seasonal variation, with ranges of 0.8-7.6 mg/L and 6.0-20.0 mg/L, respectively (Fig. 4).

Inorganic nitrogen forms displayed a wide range of values, with higher levels of nitrite (2.34-130.9µg/ L), nitrate (16.84-416.0µg/ L), and ammonia (10.40-794.2µg/ L) observed in the Damietta Branch locations compared to the Cairo locations (Tables 2, 2S). The average concentrations of ortho-P were 29.4, 33.9, 23.9, and 19.5µg/ L for autumn, winter, spring, and summer, respectively. The winter season exhibited the highest levels of ortho-P, with significant temporal and spatial variations.

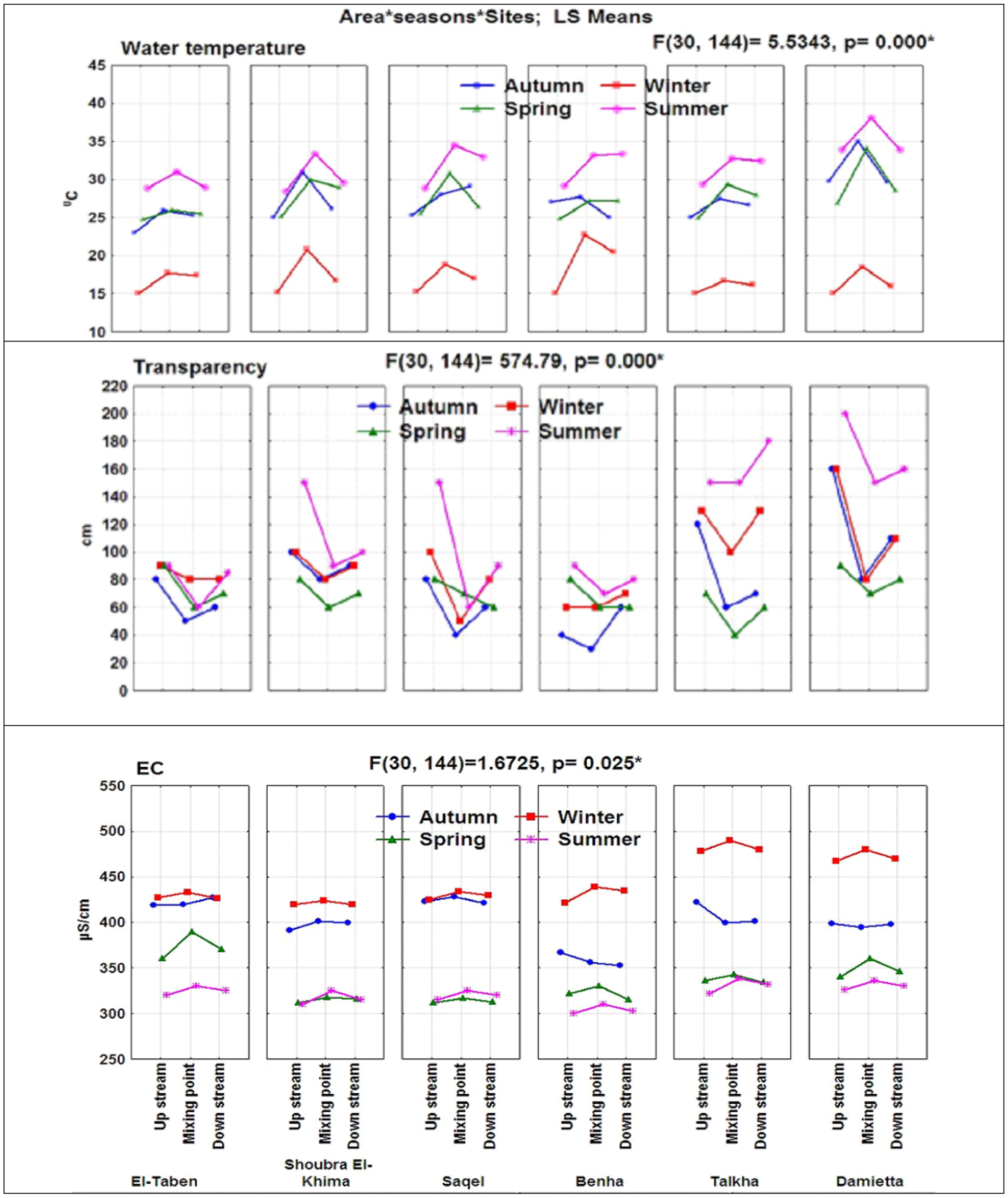


Fig. 2. Seasonal variations of WT, transparency and EC in the Nile waters along different sites in the Nile River during 2022

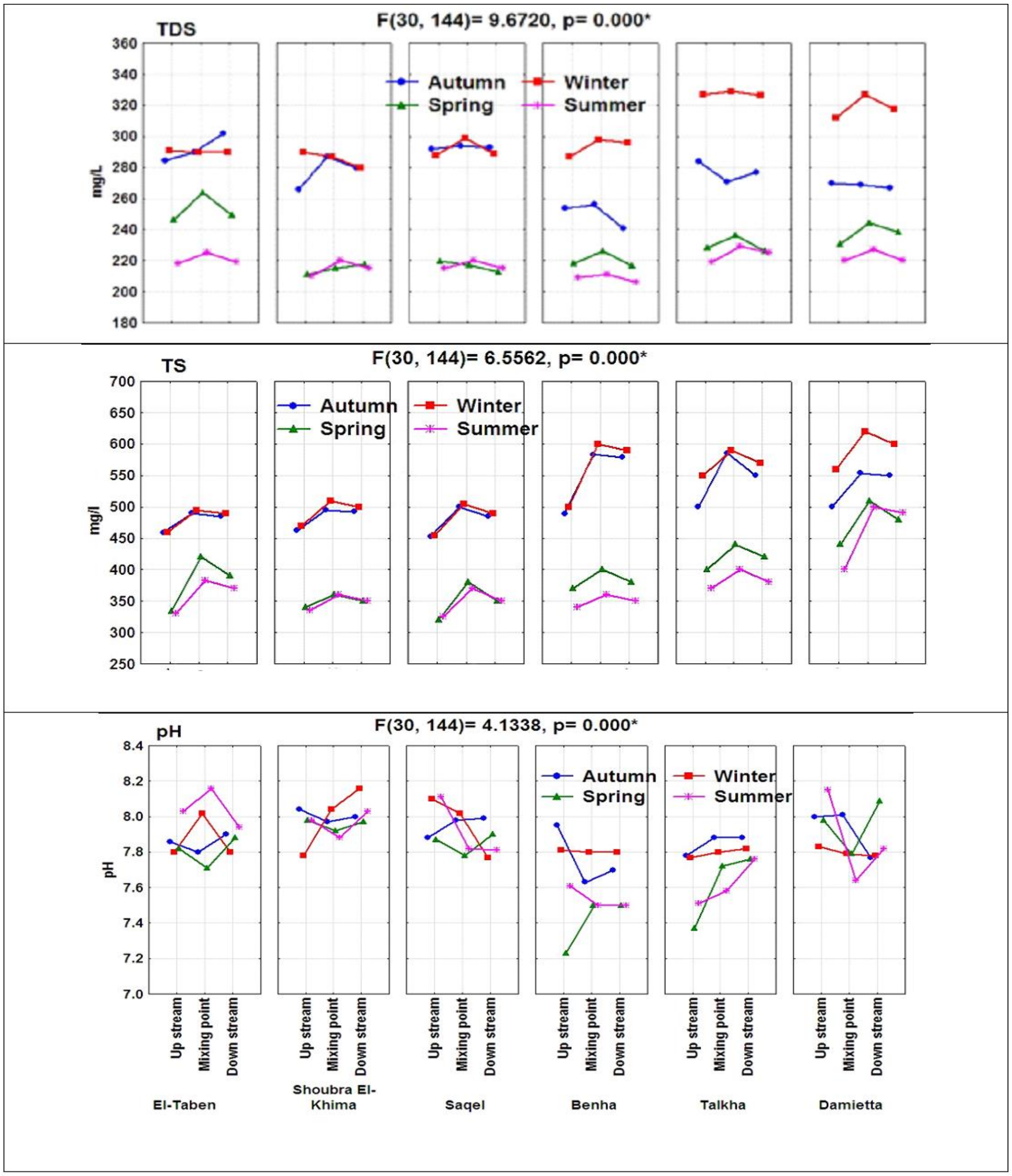


Fig. 3. Seasonal variations of TDS, TS and pH in Nile waters along different sites in the Nile River during 2022

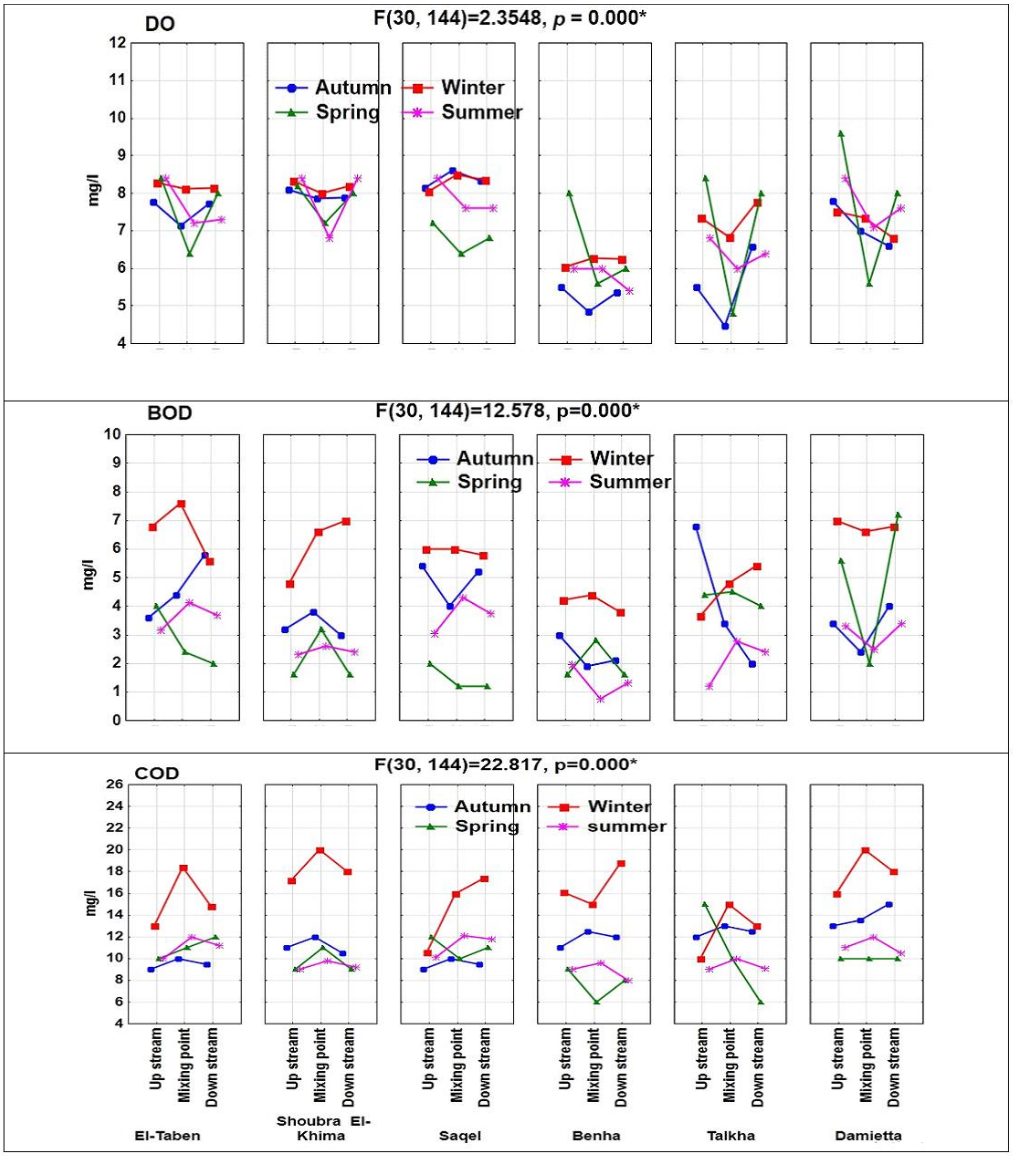


Fig. 4. Seasonal variations of DO, BOD, COD in the Nile waters along different sites in the Nile River during 2022

While the average levels of total-P were 133.0, 235.7, 118.2, and 58.7µg/ L, with the lowest values recorded during the summer season, demonstrating significant temporal variation (Tables 2, 2S). Silicate concentrations demonstrated notable seasonal variations, with higher mean values of 6.2mg/ L observed during the spring season and the lowest values of 3.3mg/ L detected during the summer (Tables 2, 2S). In general, there was an increase in nutrient salt levels in the Damietta Branch locations compared to the Cairo locations. The analysis of anions revealed lower concentrations of chloride and sulphate compared with bicarbonate. Carbonate values exhibited large amplitude with random distribution across different seasons and sites (Tables 2, 2S).

The average levels of the dominant anions, namely HCO_3^-, Cl^-, and SO_4^{2-}, were 164.9, 29.3, and 26.1mg/ L, respectively (Fig. 5). While, the average levels of major cations, including Na, K, Ca, and Mg, were 29.5, 7.2, 32.2, and 19, respectively (Tables 2, 2S). Anions and cations generally displayed higher levels in mixing point locations and in winter, with notable seasonal variations.

Assessment of bacterial diversity

Fig. (6) depicts the fluctuations in total bacterial population counts developed at either 22 or 37°C, representing autochthonous and allochthonous bacteria, respectively.

ANOVA analysis revealed significant differences attributed to seasons and sites (including the upstream, mixing point, and downstream locations). Notably, the mixing point locations exhibited lower bacterial counts compared to the up-and downstream sites. In general, the total bacteria count developed at 37°C was very high in summer, reaching up to 10^5 cfu /mL, while it was relatively low in the winter season, whereas in the spring, the total bacteria count developed at 22°C was the highest. The counts of thermophilic bacteria ranged from 0.02×10^2 to 3.20×10^2 cfu /mL, with the mixing point locations recording higher loads than the up-and downstream locations for most selected stations. Additionally, for pollution-related bacterial markers, ANOVA analysis revealed significant differences attributed to area, seasons and sites and interaction between them (Table 3). The total coliform counts ranged from 4 to 1200 MPN/100 mL, while the counts of fecal coliforms and fecal streptococci ranged from 3 to 1100 and from 3 to 1200 MPN/100 mL, respectively. Notably, the spring season exhibited a distinct enrichment of pollution-related bacterial markers.

The aquatic WQI indicated that the Nile water in the studied area extended from 68 (medium) to 93 (excellent) (Fig. 7). The minimum values were recorded at Talkha site (Damietta Branch), while the maximum values were recorded at Cairo sites.

Assessment of phytoplankton diversity

The phytoplankton communities observed at the present sites exhibited varying patterns of diversity and abundance across different seasons (Fig. 8). The phytoplankton samples collected from the Nile River belong to several classes, including Bacillariophyceae, Chlorophyceae, Cyanobacteria, Cryptophyceae, Euglenophyceae, and

Chrysophyceae (Table 3S). These groups were arranged based on their respective percentage abundance within the total phytoplankton crops.

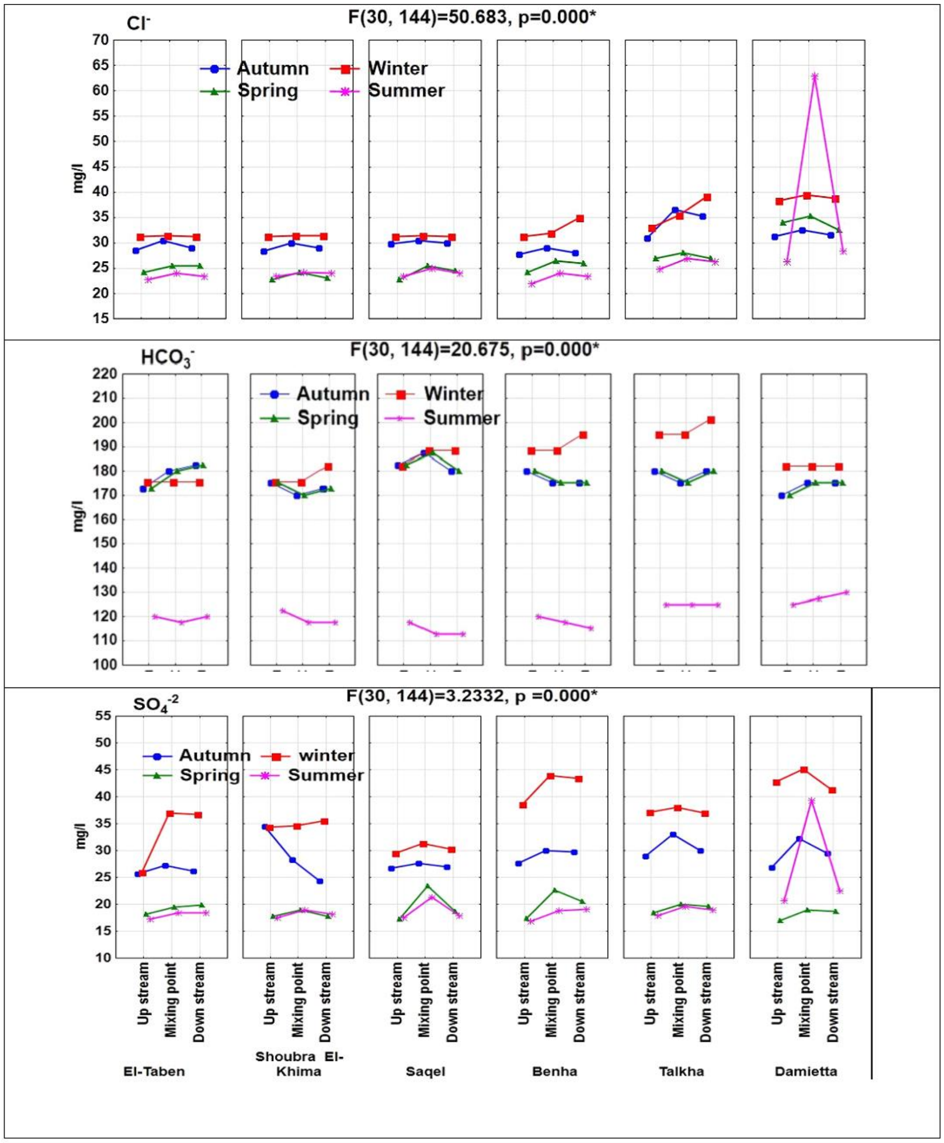


Fig. 5. Seasonal variations of major anions in the Nile waters along different sites in the Nile River during 2022

Table 2. Basic statistics of some chemical variables in the Nile water along different seasons during 2022

		El-Taben	**Shoubra El-Khima**	**Saqel**	**Benha**	**Talkha**	**Damietta**
CO$_3^-$ (mg/L)	**Range**	**1.00-9.00**	**1.25-9.50**	**1.25-9.00**	**0.50-5.00**	**0.90-5.00**	**1.40-15.00**
	Mean±SD	**5.92^{a}±2.74**	**6.27^{a}±2.84**	**5.77^{a}±2.67**	**1.66^{b}±1.22**	**2.10^{b}±1.32**	**6.28^{a}±4.26**
NO$_2^-$ -N (µg/l)	**Range**	**2.34-15.45**	**2.44-11.37**	**2.47-10.83**	**3.77-53.00**	**8.48-130.85**	**24.57-57.81**
	Mean±SD	**7.80^{d}±5.36**	**6.80^{d}±4.17**	**6.24^{d}±3.62**	**21.52^{c}±16.30**	**63.85^{a}±36.33**	**38.12^{b}±10.78**
NO$_3^-$ -N (µg/l)	**Range**	**32.89-195.00**	**16.84-196.00**	**18.26-101.75**	**64.61-280.11**	**116.60-416.01**	**110.49-370.23**
	Mean±SD	**81.71^{c}±52.61**	**68.17^{cd}±59.66**	**52.11^{d}±25.53**	**122.68^{b}±78.65**	**210.39^{a}±98.89**	**222.61^{a}±87.29**
NH$_3$ -N (µg/L)	**Range**	**12.89-244.64**	**10.40-275.50**	**12.20-501.20**	**15.92-637.22**	**13.20-794.20**	**14.00-382.79**
	Mean±SD	**83.38^{c}±73.81**	**81.16^{c}±78.44**	**125.34^{c}±145.08**	**207.55^{ab}±213.67**	**257.55^{a}±273.58**	**150.26^{bc}±108.57**
Ortho-P (µg/L)	**Range**	**12.22-38.22**	**7.26-24.62**	**6.91-27.28**	**12.04-35.25**	**26.04-65.00**	**28.16-65.50**
	Mean±SD	**20.19^{b}±7.44**	**14.77^{c}±5.05**	**14.45^{c}±5.81**	**24.01^{b}±8.33**	**42.02^{a}±12.55**	**44.62^{a}±11.72**
TP (µg/L)	**Range**	**36.14-207.24**	**44.28-215.50**	**43.58-225.00**	**46.00-236.20**	**54.56-265.50**	**54.92-335.15**
	Mean±SD	**114.42^{c}±59.55**	**132.26^{bc}±56.36**	**120.78^{bc}±63.51**	**134.06^{bc}±61.88**	**148.32^{ab}±73.09**	**168.50^{a}±97.34**
SiO$_3^{-2}$ (mg/L)	**Range**	**1.09-6.20**	**1.00-5.80**	**1.15-6.17**	**1.00-5.90**	**1.76-5.60**	**2.62-5.30**
	Mean±SD	**2.80^{b}±1.91**	**2.46^{b}±1.92**	**2.66^{b}±1.97**	**2.59^{b}±1.98**	**3.02^{b}±1.51**	**3.98^{a}±1.02**
Na (mg/L)	**Range**	**22.98-34.41**	**23.54-34.10**	**23.83-36.00**	**23.81-36.24**	**26.00-40.00**	**28.78-62.00**
	Mean±SD	**26.46^{c}±4.15**	**27.29^{c}±4.27**	**27.24^{c}±4.36**	**28.36^{bc}±5.13**	**31.02^{b}±5.09**	**36.62^{a}±9.51**
K (mg/L)	**Range**	**5.80-8.20**	**5.50-8.97**	**5.48-8.29**	**6.03-8.74**	**6.16-8.60**	**6.76-9.98**
	Mean±SD	**6.72^{c}±1.05**	**7.22^{bc}±1.23**	**7.01^{bc}±1.11**	**7.36^{ab}±1.12**	**7.28^{b}±0.84**	**7.81^{a}±1.12**
Ca (mg/L)	**Range**	**22.10-36.00**	**25.65-36.55**	**27.00-38.48**	**25.65-37.00**	**27.00-37.03**	**26.00-43.29**
	Mean±SD	**31.74^{a}±4.10**	**32.09^{a}±3.89**	**32.42^{a}±4.31**	**31.72^{a}±4.38**	**31.93^{a}±3.85**	**33.09^{a}±5.34**
Mg* (mg/L*)	**Range**	**11.67-29.50**	**10.41-28.20**	**10.00-27.24**	**11.77-28.00**	**12.55-26.00**	**12.21-33.08**
	Mean±SD	**19.73^{a}±5.89**	**18.73^{a}±6.31**	**19.22^{a}±5.97**	**20.06^{a}±6.15**	**20.14^{a}±4.93**	**20.77^{a}±6.25**

SD: standard deviation; ANOVA: Different letters indicate significant differences among area (*P*<0.05).

Table 3. Seasonal variations of bacterial indicators of pollution (MPN/100 ml) in the Nile water along different seasons during 2022

		El-Taben	**Shoubra El-Khima**	**Saqel**	**Benha**	**Talkha**	**Damietta**
Total coliform			**F (30, 144) =18.516, p=0.00***				
Autumn	Up stream	4^{i}	10^{i}	240^{efg}	88^{ghi}	460^{d}	15^{i}
	Mixing point	14^{i}	7^{i}	24^{i}	42^{i}	17^{i}	18^{i}
	Down stream	9^{i}	33^{i}	24^{i}	37^{i}	460^{d}	7^{i}
Winter	Up stream	27^{i}	15^{i}	319^{def}	50^{hi}	20^{i}	112^{ghi}
	Mixing point	28^{i}	7^{i}	31^{i}	33^{i}	673^{c}	135^{ghi}
	Down stream	13^{i}	42^{i}	142^{ghi}	357^{def}	37^{i}	22^{i}
Spring	Up stream	887^{b}	1200^{a}	1200^{a}	1200^{a}	460^{d}	1100^{a}
	Mixing point	673^{c}	240^{efg}	1200^{a}	210^{fgh}	240^{efg}	240^{efg}
	Down stream	460^{d}	1200^{a}	1200^{a}	673^{c}	36^{i}	460^{d}
Summer	Up stream	1100^{a}	1100^{a}	1100^{a}	460^{d}	22^{i}	23^{i}
	Mixing point	387^{de}	93^{ghi}	240^{efg}	93^{ghi}	240^{efg}	9^{i}
	Down stream	23^{i}	460^{d}	460^{d}	1100^{a}	75^{hi}	9^{i}
Fecal coliform			**F (30, 144) = 466.82, p = 0.00***				
Autumn	Up stream	4^{mn}	7^{mn}	$23^{hijklmn}$	35^{ghijk}	120^{e}	4^{mn}
	Mixing point	4^{mn}	3^{n}	9^{lmn}	15^{klmn}	20^{jklmn}	4^{mn}
	Down stream	4^{mn}	11^{lmn}	9^{lmn}	28^{hijkl}	9^{lmn}	4^{mn}
Winter	Up stream	7^{mn}	7^{mn}	15^{klmn}	21^{ijklmn}	9^{lmn}	15^{klmn}
	Mixing point	11^{lmn}	7^{mn}	4^{mn}	7^{mn}	460 b	43^{gh}
	Down stream	3^{n}	7^{mn}	43^{gh}	10^{lmn}	24^{hijklm}	9^{lmn}

Spring	Up stream	150^{d}	36^{ghij}	1100 a	1100 a	36^{ghij}	22^{ijklmn}
	Mixing point	21^{ijklmn}	240^{c}	1100 a	41^{ghi}	142^{d}	43^{gh}
	Down stream	93^{f}	53^{g}	237^{c}	460 b	29^{hijkl}	15^{klmn}
Summer	Up stream	51^{g}	22^{ijklmn}	36^{ghij}	460 b	3^{n}	3^{n}
	Mixing point	21^{ijklmn}	21^{ijklmn}	240^{c}	15^{klmn}	240^{c}	3^{n}
	Down stream	3^{n}	21^{ijklmn}	36^{ghij}	460 b	39^{ghij}	3^{n}
Fecal streptococci			**F (30, 144) =35.352, *p*= 0.00***				
Autumn	Up stream	535^{bc}	29^{ef}	1200^{a}	240^{d}	1200^{a}	93^{def}
	Mixing point	16^{f}	4^{f}	13^{f}	240^{d}	240^{d}	93^{def}
	Down stream	1200^{a}	1100^{a}	1200^{a}	240^{d}	3^{f}	15^{f}
Winter	Up stream	23^{ef}	15^{f}	3^{f}	96^{def}	460^{c}	23^{ef}
	Mixing point	23^{ef}	170^{de}	14^{f}	460^{c}	150^{def}	460^{c}
	Down stream	21^{ef}	9^{f}	15^{f}	93^{def}	240^{d}	240^{d}
Spring	Up stream	1200^{a}	1200^{a}	1200^{a}	1100^{a}	1200^{a}	1200^{a}
	Mixing point	1200^{a}	1200^{a}	1200^{a}	1200^{a}	1200^{a}	1200^{a}
	Down stream	1100^{a}	1200^{a}	1200^{a}	1100^{a}	1100^{a}	673^{b}
Summer	Up stream	240^{d}	460^{c}	460^{c}	9^{f}	29^{ef}	53^{ef}
	Mixing point	1200^{a}	36^{ef}	460^{c}	24^{ef}	94^{def}	29^{ef}
	Down stream	460^{c}	460^{c}	460^{c}	24^{ef}	1100^{a}	93^{def}

ANOVA: means followed by the same letter are not significantly different ($P < 0.05$).

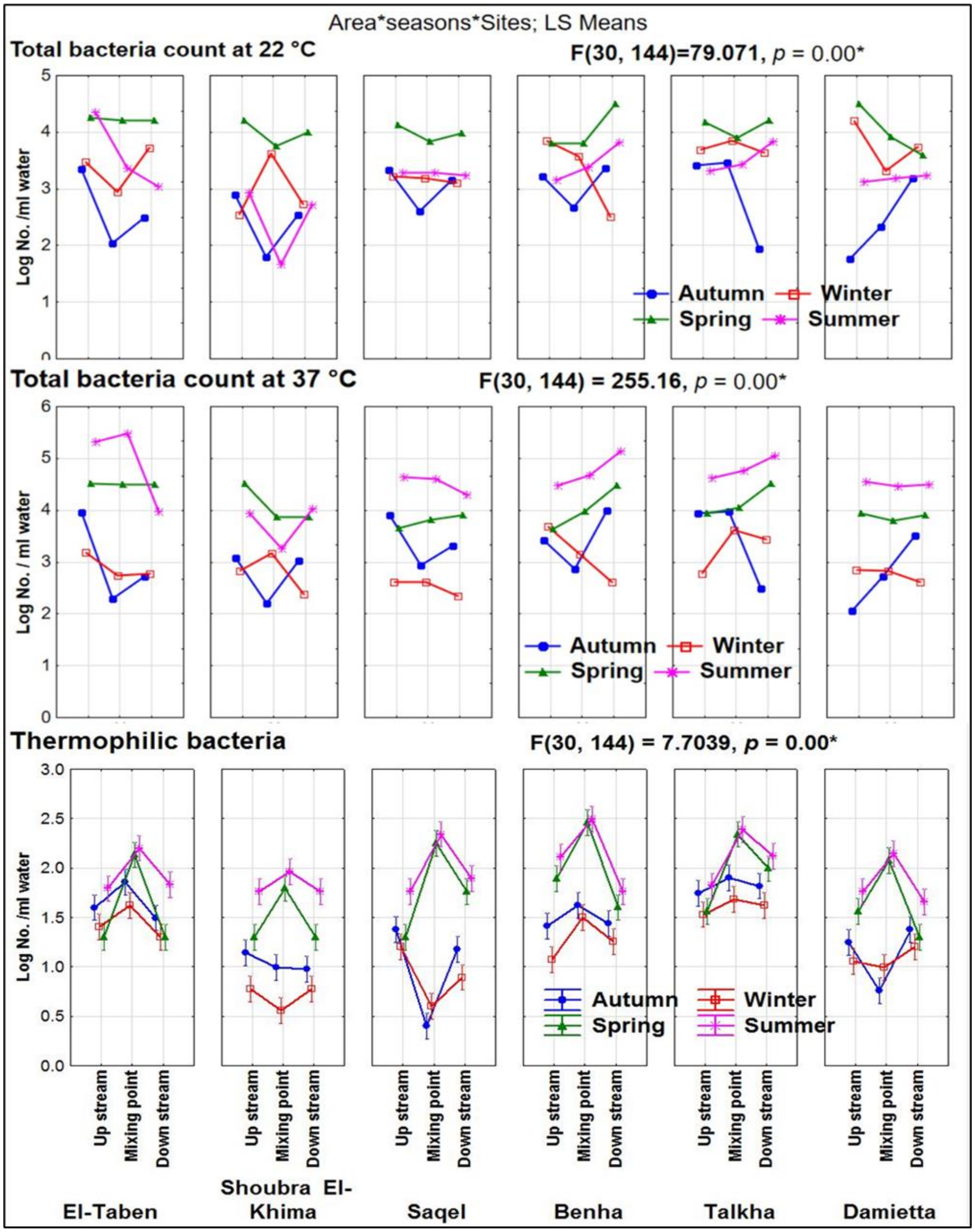


Fig. 6. Seasonal variations of total bacteria developed on 22^0C, total bacteria developed on 37^0C, and thermophilic bacteria developed on 55^0C in waters along different sites in the Nile River during 2022

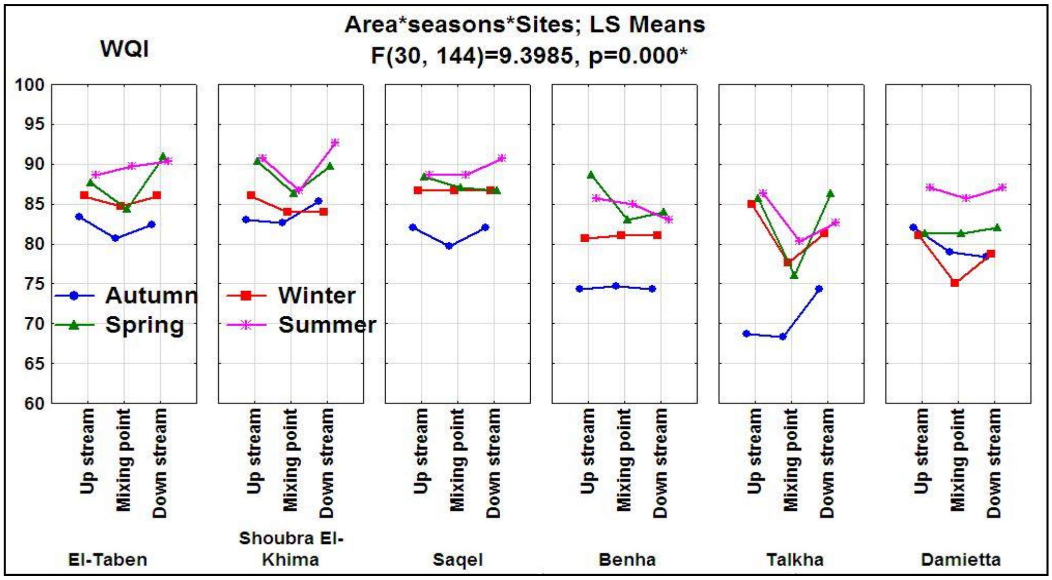
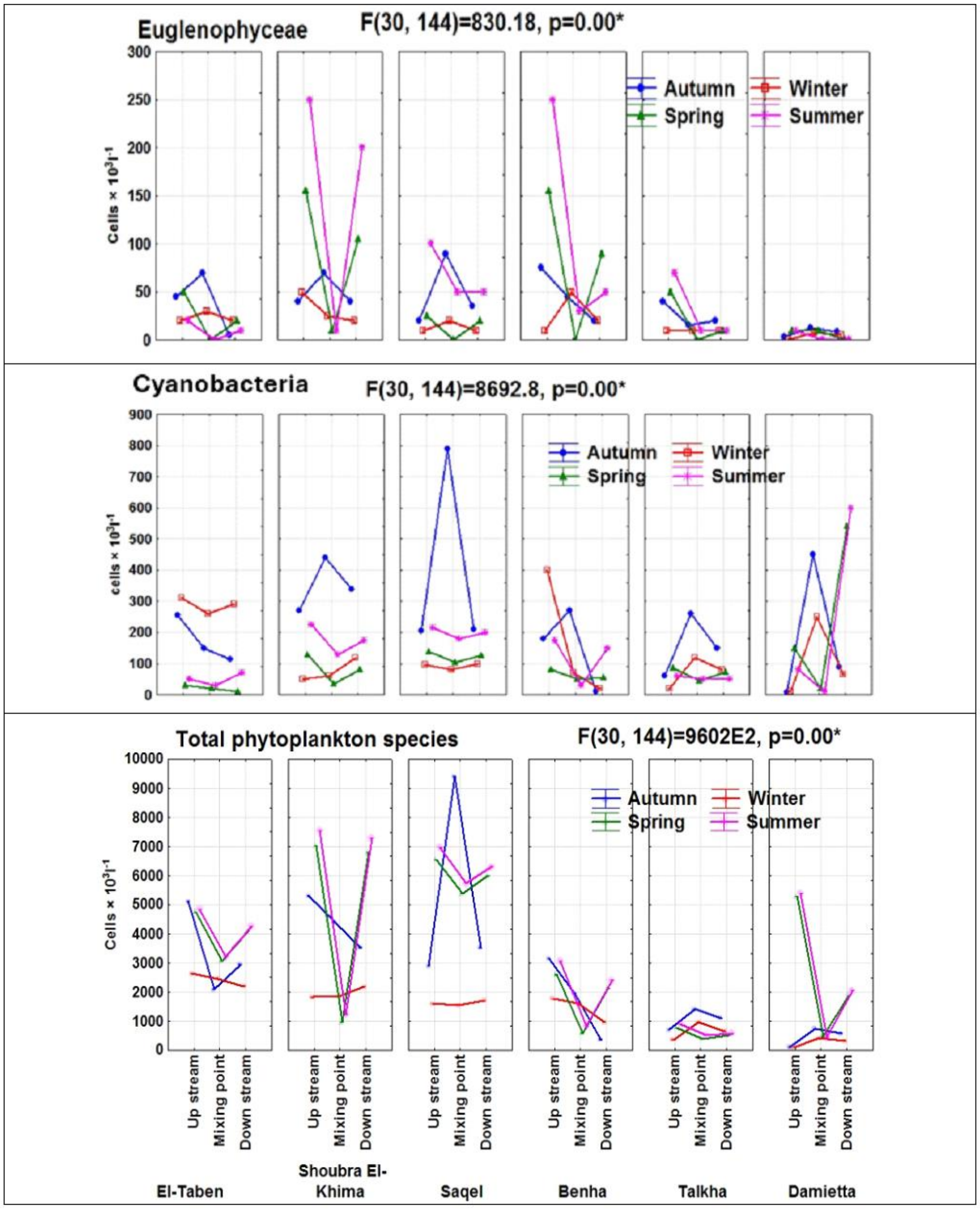


Fig. 7. Seasonal variations of WQI in the Nile waters along different sites in the Nile River during 2022

Diatoms were the most dominant group, comprising diverse species, followed by Chlorophyceae and Cyanobacteria. Members of Euglenoides and Cryptophyceae were scarce, while Chrysophyceae were very rare, only detected at the upstream of Shoubra El-Khima (30 cells × 10^3/L) and Saqel (50 cells × 10^3/L) power plants during summer.

Diatoms were mainly dominated by *Aulacoseira granulata* (Ehr.) Sim., *Aulacoseira granulata var. angustissima* (O. Müller) Simonsen, *Stephanocyclus meneghinianus* (Kützing) Kulikovskiy, Genkal & Kociolek, *Epithemia operculata* (C. Agardh) Ruck & Nakov, *Pantocsekiella ocellata* (Pantocsek) K. T. Kiss & Ács, *Lindavia glomerata* (H. Bachmann) Adesalu & Julius and *Lindavia bodanica* (Eulenstein ex Grunow) T. Nakov. There was a distinct difference in the dominant phytoplankton groups in front of the Damietta power plant compared to the other sites, with Chlorophyceae (126 cells ×10^3/L & 210 cells ×10^3/L) dominating rather than Bacillariophyceae during winter and autumn seasons, respectively. This site contains a record of *Pediastrum* sp. (green algae species) with a high number and diversity. Chlorophyceae were dominated by *Scenedesmus quadricauda* (Trup.) de Brebisson, *S. dimorphus* (Turpin) Kuetzing, *S. quadricauda var. maximus* W& G.S. West, *S. bijuga var. major*, *S. bicaudatus* Dedusenko, *S. quadricauda var. longispina* Chodat, *S. ecornis* (Ehr.) Chodat and *Pediastrum duplex* Meyen.

The area in front of Shoubra El-Khima exhibits the highest phytoplankton diversity among the selected power plants, with a list of species comprising up to 220 phytoplankton species both upstream and downstream. However, the mixing point location exhibits a decrease in species diversity compared to the upstream and downstream locations. The highest number of phytoplankton cells was recorded during the spring and summer seasons, whereas the lowest counts were observed in winter throughout the course of this study.



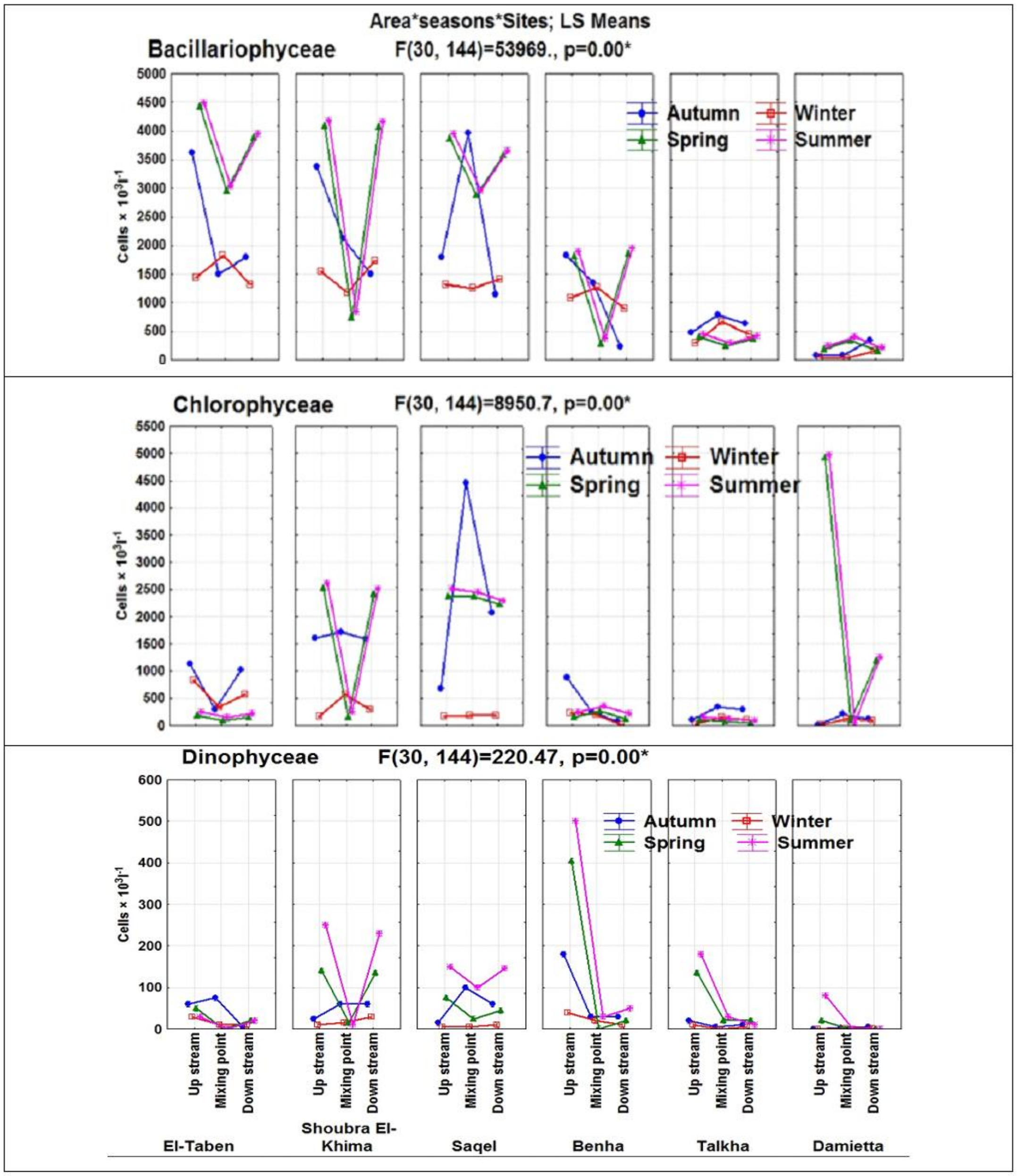


Fig. 8. Phytoplankton class's distribution and total phytoplankton abundance along different sites in the Nile River

In terms of total phytoplankton species, except for the area in front of El-Taben power plant, an increase was observed during the autumn season compared to other seasons in the mixing point sites where total phytoplankton reached 4405 cells ×10^3/L in Shoubra El-Khima, 9410 cells ×10^3/L in Saqel, 1950 cells ×10^3/L in Benha, 1408 cells ×10^3/L in Talkha and finally 754 cells ×10^3/L at Damietta sites.

The Bi-plot representing the two axes of CCA of the environmental variables and the phytoplankton classes along different sites in the Nile River is presented in Fig. (9).

Assessment of zooplankton diversity

Across all stations, a comprehensive evaluation of zooplankton groups was conducted, encompassing five groups: Rotifera, Cladocera, Copepoda, Meroplankton, and Protozoa. Across various seasons, Rotifera group dominated the total zooplankton abundance, representing 78.42-93.85%, followed by Protozoa (2.65-19.82%), Copepoda (0.45-1.83%), Cladocera (0.76-1.41%) and Meroplankton (0.07-0.91%). The distribution of various zooplankton taxa in each evaluated season is presented in Table (4). Concerning the zooplankton density in the autumn season, some stations (such as in front of Talkha) did not record any organisms, whereas others exhibited varying numbers of zooplankton species.

The highest number of species (24 species) was observed at Saqel station (4100000 Org./m^3). During the winter season, the number of zooplankton taxa exhibited variation, ranging from four species upstream of Talkha site (with a density of 580,000 Org./m^3) to 20 species upstream of Shoubra El-khima site (with a density of 7,240,000 Org./m^3). No zooplankton taxa were recorded in front of Shoubra El-khima area during the spring season, where the number of zooplankton taxa observed at other stations varied, ranging from one species in the mixing point location in front of Damietta site (20000 Org./m^3) to 19 species downstream of Shoubra El-Khima site (4850000 Org./m^3). The number of zooplankton taxa in the summer ranged from zero (at mixing points and downstream of Talkha site) to 19 species upstream of Saqel site (2480000 Org./m^3). The correlation analysis between zooplankton density and water temperature was conducted. Annually, there is a negative correlation between the zooplankton density and water temperature (r= -0.43, p= 0.0001).

The multivariate analysis of variance values detailing the relations among the zooplankton groups and individual zooplankton species with various environmental factors during each season were estimated. The diversity indices including the Margalef index, Shannon diversity index and equitability during different seasons are presented in Table (5). Both the Shannon diversity index (P = 0.0001) and the Margalef index (P = 0.0001) showed significant differences at the seasonal level in the two-way analysis of variance. Multivariate analysis of variance at the annual level was used to assess the environmental factors that influence the density and diversity indices of zooplankton taxa. Zooplankton density values were significantly affected by transparency (P=0.009) and NH_3-N concentrations (P=0.02), the Shannon diversity index was significantly impacted by both water temperature (P=0.03) and NO_2-N (P=0.01), while equitability values exhibited significant associations with pH (P=0.03), NO_2-N (P=0.00), and NO_3-N (P=0.00). Additionally, the Margalef index values were associated with EC (P=0.01) and ortho-P (P=0.02) (Table 6). These findings declare the interaction between environmental factors with density and diversity of zooplankton, and several indices.

The Bi-*plot* representing the two axes of CCA of the environmental variables and the zooplankton groups along different sites in the Nile River is presented in Fig. (10).

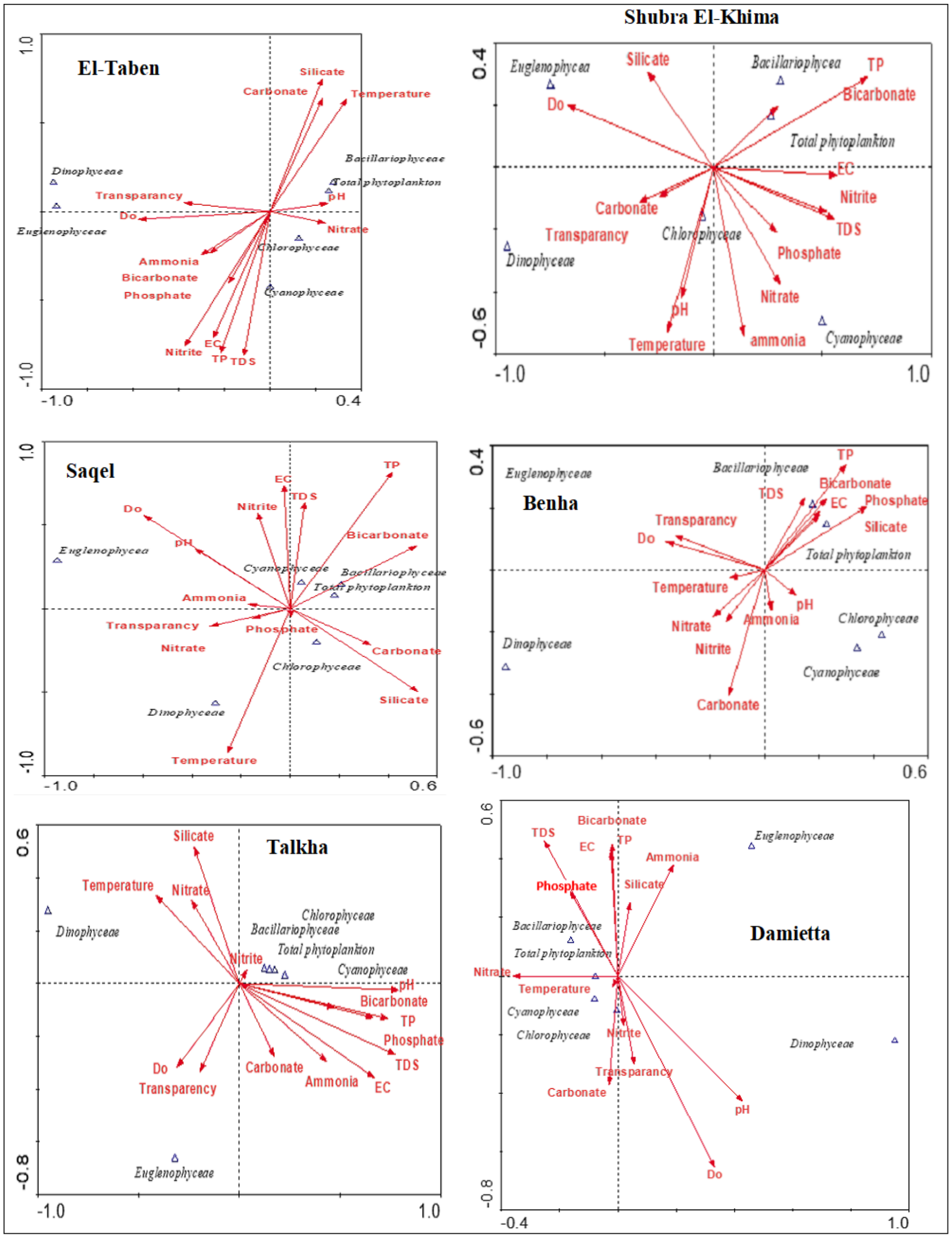


Fig. 9. Bi-*plot* representing the two axes of CCA of the environmental variables and the phytoplankton classes along different sites in the Nile River

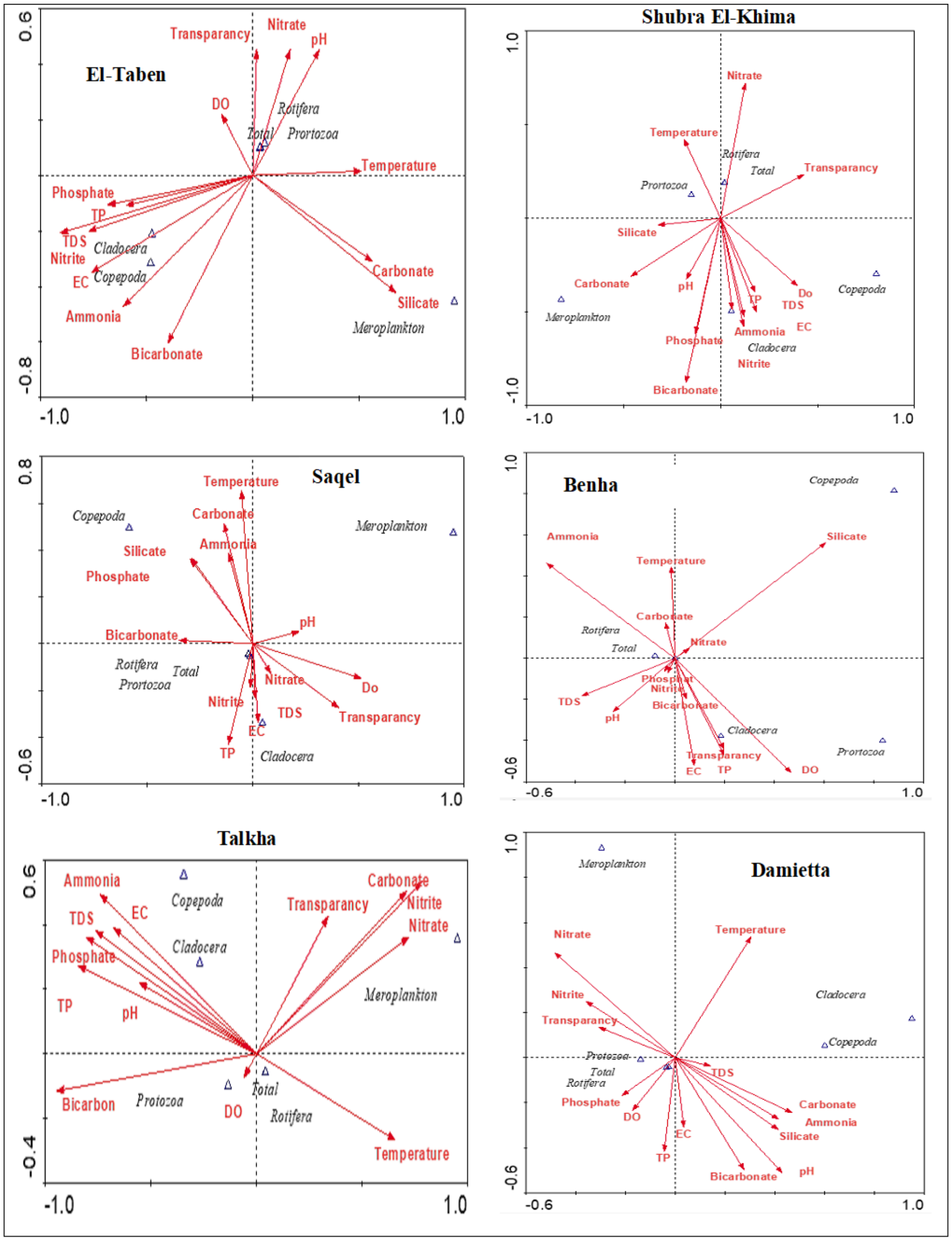


Fig. 10. Bi-*plot* representing the two axes of CCA of the environmental variables and the zooplankton groups along different sites in the Nile River

Table 4. Distribution of various zooplankton taxa across different seasons in the Nile River during 2022

	AU	SP	WI	SU		AU	SP	WI	SU
Rotifera									
Anuraepsis fissa	1	1	1	1	*Scaridium longicaudum*	1	0	0	0
Ascomorpha saltans	0	1	1	1	*Synchaeta sp.*	1	0	0	0
Asplanchnella sieboldi	1	1	1	1	*Trichocerca cylindrica*	1	1	1	1
Brachionus angularis	1	1	1	1	*Trichocerca longiseta*	1	0	0	0
B. budapestinesis	0	0	0	1	*Trichocerca pusilla*	1	1	1	1
B. calyciflorus	1	1	1	1	*Trichocerca rattus*	1	0	0	0
B. caudatus	1	1	0	1	*Trichocerca similis*	1	1	1	1
B. leydigii	0	0	0	1	*Trichotria tetractis*	0	1	0	0
B. patulus	0	0	0	1	*Trichotria curta*	0	0	1	0
B. falcatus	1	0	0	0	**Copepoda**				
Brachionus plicatilis	1	0	0	0	*Acanthocyclops americanus*	1	0	1	0
Brachionus quadridentatus	1	0	1	1	*Cyclopid copeoda*	1	0	1	0
Brachionus urceolaris	1	1	1	1	*Nauplius larva*	1	1	1	1
Cephalodella gibba	1	0	1	1	**Cladocera**				
Collotheca sp	1	0	1	0	*Alona rectangula*	1	1	1	1
Colurella adriatica	0	0	1	0	*Bosmina longirostris*	1	1	1	1
Epiphanes macroura	1	1	1	1	*Ceriodaphnia quadrangula*	1	1	1	0
Filinia longiseta	1	0	1	1	*Chydorus sphaericus*	0	1	1	0
Hexarthra mira	1	1	1	1	*Diaphanosoma excisum*	1	0	0	0
Keratella cochlearis	1	1	1	1	Meroplankton				
Keratella tropica	1	0	1	1	*Cercaria*	0	1	0	1
Lecane calcaria	1	0	0	0	*Free living nematodes*	0	1	0	0
Lecane luna	1	1	0	0	*Insect larvae*	0	0	0	1
Lecane monostyla	1	1	1	1	*Oligochaeta larvae*	1	1	1	1
Lecane bulla	1	0	0	0	**Prortozoa**				
Lepadella patella	1	1	1	0	*Arcella* sp	1	0	0	1
Notholca sp	0	1	1	0	*Cercaria*	1	0	0	0
Notholca caudata	1	0	0	0	*Paramecium* sp	1	0	0	0
Paracolurella longima	1	0	1	1	*Pseudo dileptus* sp	1	0	0	0
Philodina acuticornis	1	1	0	1	*Didinium* sp	0	0	0	1
Prompholicus sp	0	0	1	0	*Stentor* sp	0	0	0	1
Polyarthra vulgaris	1	1	1	1	*Oscracoda* sp	0	0	0	1
Proales daphnicola	1	0	0	0	*Acanthocystis aculeata*	0	1	1	0
Pseudohrringia similis	0	0	1	0	*Arcella* sp	0	1	1	0
Proales daphnicola	0	0	1	1	*Vorticella* sp	0	1	1	0
Proalides sp	1	1	1	1					

1 = Present; 0 = Absent; AU = Autumn; SP = Spring; WI = Winter; SU = Summer

Table 5. Number of zooplankton species (sp.), species density (Org./m^3), Shannon diversity index (H), Margalef index (M) and Equitability (E) in different seasons during 2022

		Autumn					**Winter**				
		Sp.	**Org./m^3**	**H**	**M**	**E**	**Sp.**	**Org./m^3**	**H**	**M**	**E**
Ta	**U**	16	2480000	2.114	1.019	0.76	17	5100000	1.994	1.036	0.7
	Mi	18	2660000	2.208	1.149	0.76	13	4740000	1.149	0.781	0.45
	D	21	4260000	2.096	1.31	0.69	14	2660000	1.662	0.879	0.63
	U	21	4700000	2.355	1.302	0.77	20	7240000	1.438	1.203	0.48
Sh	**Mi**	19	3180000	2.161	1.202	0.73	18	4180000	1.468	1.115	0.51
	D	21	5220000	2.131	1.293	0.7	18	4600000	1.319	1.108	0.46
	U	10	700000	1.883	0.669	0.82	19	7960000	1.315	1.133	0.45
Sa	**Mi**	13	1720000	1.825	0.836	0.71	18	5460000	1.333	1.096	0.46
	D	24	4100000	2.391	1.511	0.75	18	4660000	1.213	1.107	0.42
	U	7	360000	1.692	0.469	0.87	10	1620000	1.082	0.63	0.47
Be	**Mi**	16	1100000	2.046	1.078	0.74	10	1880000	1.129	0.623	0.49
	D	15	2660000	1.985	0.946	0.73	7	1440000	0.977	0.423	0.5
	U	0	0	0	0	0	4	580000	0.545	0.226	0.39
Ta	**Mi**	0	0	0	0	0	9	1160000	1.121	0.573	0.51
	D	0	0	0	0	0	5	820000	0.821	0.294	0.51
	U	15	600000	2.468	1.052	0.91	5	600000	1.153	0.301	0.72
Da	**Mi**	4	100000	1.332	0.261	0.96	5	360000	1.268	0.313	0.79
	D	0	0	0	0	0	4	640000	0.987	0.224	0.71
		Spring					**Summer**				
	U	14	990000	1.927	0.9417	0.73	14	1800000	2.065	0.903	0.78
Ta	**Mi**	18	4940000	1.794	1.103	0.62	12	880000	2.185	0.804	0.88
	D	16	3860000	1.877	0.989	0.68	13	1220000	2.174	0.856	0.85
	U	0	0	0	0	0	4	220000	1.121	0.244	0.81
Sh	**Mi**	12	860000	1.943	0.805	0.78	12	820000	2.139	0.808	0.86
	D	19	4850000	1.813	1.169	0.62	14	1320000	2.18	0.922	0.83
	U	14	4840000	1.926	0.8446	0.73	19	2480000	2.177	1.223	0.74
Sa	**Mi**	13	4920000	1.949	0.7788	0.76	18	1640000	2.271	1.188	0.79
	D	18	3660000	2.08	1.125	0.72	17	860000	2.485	1.171	0.88
	U	4	80000	1.386	0.2657	1	9	340000	2.038	0.628	0.93
Be	**Mi**	5	120000	1.561	0.342	0.97	12	300000	2.396	0.872	0.96
	D	6	180000	1.735	0.4132	0.97	3	120000	0.868	0.171	0.79
	U	3	60000	1.099	0.1818	1	4	100000	1.332	0.261	0.96
Ta	**Mi**	6	160000	1.667	0.4173	0.93	0	0	0	0	0
	D	2	80000	0.693	0.0886	1	0	0	0	0	0
	U	2	80000	0.562	0.0886	0.81	2	260000	0.271	0.08	0.39
Da	**Mi**	1	20000	0	0		8	360000	1.879	0.547	0.9
	D	2	140000	0.41	0.0844	0.59	5	360000	1.08	0.313	0.67

Ta=El-Taben, SH=Shoubra El-Khima, Sa=Saqel, Be=Benha, Ta=Talkha, Da=Damietta, U=Up stream, Mi=Mixing point, D=Downstream, Org= Organism, H=Shannon diversity index, species Sp.= species, M=Margalef index and E=Equitability.

Table 6. Associations between zooplankton diversity indices and environmental variables revealed by multivariate analysis of variance (annual level)

	Individuals		**Shannon**		**Equitability**		**Margalef**	
Factors	p	R^2	p	R^2	p	R^2	P	R^2
Constant	0.168		0.324		0.0127		0.5243	
Temperature	0.343	0.191	0.0307	0.0108	0.211	0.055	0.126	0.024
Transparency	0.0098	0.0101	0.723	0.0856	0.797	0.040	0.0855	0.067
EC	0.103	0.0877	0.195	0.0241	0.750	0.104	0.018	0.011
pH	0.173	0.120	0.241	0.0094	0.030	0.030	0.841	0.099
DO	0.160	0.132	0.421	0.0646	0.132	0.034	0.293	0.12
BOD	0.314	0.040	0.961	0.0035	0.153	0.002	0.967	0.0003
NO_2-N	0.160	0.213	0.0104	0.328	6.87E-07	0.168	0.517	0.363
NO_3-N	0.0751	0.341	0.198	0.126	0.0006	0.0001	0.973	0.304
NH_3-N	0.0247	0.0208	0.992	0.0378	0.571	0.068	0.33	0.021
Ortho-P	0.3603	0.353	0.064	0.2008	0.969	0.016	0.0202	0.382

P= probability of the observed results; R^2= coefficient of determination

DISCUSSION

Water physicochemical parameters are the primary indicators of its nature, quality, and type **(Rashad *et al*., 2020)**. Water quality dynamics were influenced by environmental variables, particularly temperature, which exhibited distinct seasonal fluctuations between dry and rainy periods **(Mondragon-Diaz *et al*., 2022)**. The results indicated that most chemical variables have significant seasonal variations ($P<0.05$) with a significant increase in macro- and micronutrients in winter. Moreover, elevated EC and TDS concentrations were observed during the winter closure period compared to the summer.

Temperature is a crucial variable that affects most of the physical and biological characteristics of the aquatic environment. It has a significant impact on food web cycles and ecosystem functioning **(Mohanty *et al*., 2021)**. There are increases in temperature in the mixing points than up and downstream points at all studied sites; these fluctuations in temperature can stress the aquatic organisms becoming harmful to fauna and flora **(Vyravsky *et al*., 2023)**. Water transparency is a crucial parameter for assessing the productivity potential of water bodies. It is influenced by various factors, including the inflow of silt-laden surface runoff, resuspension of bottom sediments due to physical disturbances, and elevated phytoplankton abundance **(Haugen *et al*., 2003)**.

The decrease in transparency at the mixing point is attributed to the turbulent conditions created by the confluence of the Nile waters with the influx of heated water discharged from the power plants. This is confirmed by the elevated TS at the mixing point compared to upstream and downstream locations, further supported by the inverse correlations between transparency and TS (r=-0.3; n=18, *P*<0.2). Additionally, the water's pH values in the mixing point locations remained within the alkaline range, consistently falling within the acceptable range (6.5 to 9.0) throughout the study period **(CCME, 2007)**. DO is a crucial variable for evaluating water quality, reflecting the environment's oxidative or reductive state. In aquatic systems, DO levels undergo substantial fluctuations due to physical processes like photosynthesis, atmospheric re-aeration, and organic matter degradation **(Mohanty *et al*., 2021)**. The relationship between temperature and the concentration of DO helps explain why wintertime concentrations are higher than summertime ones **(Hussein *et al*., 2021)**. The lower DO levels observed in the mixing point locations in front of all the power plants, as compared to the upstream and downstream sites, are likewise explained by this association. Except for the mixing point at Talkha site, the Nile water in the investigated locations exhibited an adequate oxygenation, with DO levels exceeding 5mg/ L throughout all seasons.

BOD values exhibit considerable variability across different water bodies, where the BOD level was below 1mg/ L in pristine waters, while moderately polluted waters generally exhibit BOD values ranging from 2 to 8mg/ L **(Wilhelm, 2009)**. Consequently, the Nile water in the studied area (1.0-7.6mg/ L) was classified as ranging from low to moderately polluted. However, the Nile water was classified as unpolluted, with COD values less than 20mg/ L **(Jain & Singh, 2003)**. It is noticeable that, concentrations of major cations (Na, K, Ca, Mg) and anions (Cl^-, SO_4^{2-}) were observed to be elevated at the mixing point with the rise in water temperature compared to upstream and downstream locations. Additionally, concentrations of major cations and anions were higher at all Damietta Branch sites compared to those in Cairo, reflecting the anthropogenic wastes discharged along the Nile branches **(Hasaballah *et al*., 2019; El Sayed *et al*., 2020; Abdo *et al*., 2022)**.

Generally, anions and cations in the Nile water differ naturally depending on the climatic and geographic conditions **(Rashad *et al*., 2020)**. In addition, the nutrient salts (nitrogen and phosphorus forms and silicate) were increased significantly in the mixing point locations across all seasons with clear temporal variations, where summer season (high flood) registered the lowest levels. Similar findings were reported by **Othman *et al*. (2021)**, **Hussein *et al*. (2023)** and **Abdel-Satar *et al*. (2024b)**.

Primary pollutants, such as nitrogen and phosphorus, can form secondary pollutants, where a high concentration of these compounds would cause eutrophication and adversely affect aquatic life **(Giao *et al*., 2021)**.

WQI provides a comprehensive assessment of the condition of the aquatic environment, including the water column, sediments, and the associated aquatic life. It is a useful tool for evaluating the suitability of water for various purposes including the aquatic life **(Kaur *et al*., 2023)**. The average WQI showed the lowest values in the mixing point locations for all studied areas, reflecting the thermal pollution effect (Fig. 7).

The release of heated water into aquatic systems presents a complex issue with potentially contrasting ecological consequences. While in some cases such thermal additions may not cause harm or even benefit local conditions **(Bobat, 2015)**. Water temperature displayed positive correlations (n=72, $P<0.01$) with both TBC at 37°C and thermophilic bacteria, (r = 0.33 and 0.49, respectively) and other bacterial groups, except with TBC at 22°C (Table 3 and Fig. 6). Water bodies naturally self-purify through various physical, chemical, and biological processes **(Oketola *et al.*, 2006)**. Numerous bacterial groups in the present study showed negative correlations with several water quality variables, including EC, NH_3-N, TP, Cl, SO_4^{2-}, Na, and K, indicating that bacteria are involved in self-purification.

The survival and even the growth of coliform bacteria can be enhanced under certain environmental conditions, such as pH, temperature, solar radiation, salinity, abundant nutrients, and suspended particles **(Juhna *et al.*, 2007; Hong *et al.*, 2010)**. There was a high prevalence of fecal streptococci at most sampling sites due to their resistance to environmental fluctuations compared to coliforms **(Rosenfeld *et al.*, 2006)**.

Water quality deterioration cannot be solely attributed to the high abundance of viable bacteria. A low ratio of total bacterial counts (TBC) at 22°C to TBC at 37°C, specifically falling below 10, serves as a key indicator of water pollution, as reported by the **Ministry of Health (1939)**. For most water samples, this ratio fell below 10, confirming pollution at the investigated sites, except for those upstream and downstream of the Damietta power plant during winter.

It is well established that heterotrophic microbial communities, along with phytoplankton, play crucial roles in structuring and maintaining the function of freshwater ecosystems. However, these communities can undergo significant and rapid changes over time in response to both biotic and abiotic factors **(Song *et al.*, 2017)**.

The fecal coliform to fecal streptococci (FC/FS) ratio serves as a qualitative indicator of pollution source **(Al-Afify *et al.*, 2023)**. Domestic human wastes typically yield ratios exceeding 4.0, while values below 0.7 indicate contamination from animal wastes **(Geldreich & Kenner, 1969)**. Most water samples displayed low ratios, implying non-human pollution sources. However, at Benha site (both upstream and downstream) in summer and the upstream of Saqel site in winter exhibited ratios more than 4, suggesting human sewage influence. Additionally, Talkha (downstream-autumn and mixing point-winter) and Saqel (downstream-winter) sites recorded ratios between 0.7 and 4, suggesting a potential mixture of pollution sources.

While the dynamics of environmental abiotic conditions exert the main influence on bacterial load fluctuations, specific phytoplankton assemblages may also play a role. Certain bacterial groups might exhibit associations with specific phytoplankton, potentially influencing the dynamic patterns of the microbial community (**Niu *et al.*, 2011; Schweitzer-Natan *et al.*, 2019**). Notably, total coliform bacteria displayed significant positive correlations (n=72, $P<0.01$) with Chlorophyceae, Euglenophyceae, Dinophyceae, Bacillariophyceae, and total phytoplankton (r = 0.34, 0.39, 0.36, 0.53, and 0.52, respectively). While Cyanobacteria exhibited negative correlations (n=72, $P<0.05$) with fecal streptococci, TBC at 37°C, and thermophilic bacteria (r = -0.25, -0.28, and -0.30, respectively).

Phytoplankton total abundance and diversity exhibited higher values during the spring and summer seasons, while the lowest values were observed in winter. This seasonal pattern is attributed to the influence of water surface temperature **(Bergkemper & Weisse, 2017)**, varied environmental perturbations **(Palijan, 2017)** and nutrient concentrations **(Burford *et al*., 2023)**. The confluence of Shoubra El-Khima Power Plant discharge with the Nile water exerted a detrimental impact on phytoplankton diversity, confining the community to dominant species.

According to **Ye *et al*. (2019)**, the combined effects of mechanical stress, elevated temperature, high pressure, and residual chlorine from the nuclear power plant could have damaged or eliminated phytoplankton cells. Where the abundance and diversity of phytoplankton species were lower in the drainage outlet area compared to the other stations.

Canonical correspondence analysis (CCA) results at Shoubra El-Khima site revealed a strong association between total phytoplankton and Bacillariophyceae abundance with TP and bicarbonate concentrations (Fig. 9). Cyanobacteria occurrence was significantly influenced by the availability of major nutrients, including NO_2-N, NO_3-N, NH_3-N, ortho-P, in addition to TS. Chlorophyceae distribution was primarily controlled by temperature, pH, and carbonate content. At Saqel site, diatoms dominated the phytoplankton community, accounting for over 60% of the species composition in the Nile water. The high relative abundance of diatoms suggests that silica was not a limiting factor **(Mancuso *et al*., 2021)**.

CCA revealed that TP and bicarbonate concentrations were the primary limiting parameters. At Benha site, CCA indicated that HCO_3^-, ortho-P, TP, and silicates levels were the limiting factors for both total phytoplankton abundance and Bacillariophyceae growth in the Nile water (Fig. 9). At Talkha site, the mixing zone exhibited elevated total phytoplankton counts during the autumn and winter seasons, surpassing those observed at upstream and downstream locations. This pattern reversed during the spring and summer seasons. As confirmed by **Liu (2018)**, elevated temperature exerted an impact on both phytoplankton and zooplankton communities. Phytoplankton growth rates exhibited a positive association with temperature, showing an approximate doubling effect with every 10°C rise in temperature. CCA results at Talkha site confirmed that total phytoplankton and the three major dominant groups were less affected by all physicochemical variables (Fig. 9).

At the Damietta site, the order of dominant phytoplankton classes deviated from the pattern observed at the other sites, where Chlorophyceae attained the first predominant position instead of Bacillariophyceae. A unique record of *Pediastrum* sp., a green algae species, was observed with high number and diversity at Damietta site. As algae are sensitive indicators of water quality, the predominance of green algae and *Pediastrum* suggests a eutrophication of the water body. This observation aligns with the simultaneous rise in average temperature and water eutrophication, suggesting the potential occurrence of sewage discharge at the Damietta site **(Jankovska & Komarek, 2000; Tang *et al*., 2013)**. CCA results at the Damietta site showed high positive correlations between Chlorophyceae and various water variables, including NO_2-N, NO_3-N, CO_3^{2-}, DO, pH, and water transparency (Fig. 9). These suggest the connection between nutrient availability and phytoplankton abundance **(Burford *et al*., 2023)**.

Zooplankton abundance and diversity were chosen as key indicators for assessing environmental variations in the River Nile due to their sensitive responses to changes in water quality at both spatial and temporal scales **(Mohammad *et al*., 2021; Idam *et al*., 2023)**. The composition and density of zooplankton groups displayed significant seasonal fluctuations throughout the year, with the rotifers consistently dominating. This observation was consistent with the results of **El-Shimy *et al.* (2009)** about thermal pollution affecting the Nile water and disagrees with the finding of **Mohammad *et al*. (2021)** for the Nile water at Qena. **Elfeky and Sayed (2014)** examined the distribution of Rotifer populations along the Nile River and revealed a notable increase in their abundance downstream. Inconsistencies between our study and the others may result from differences in the ecological conditions in different areas of the Nile. The prominent Rotifers identified in the present study were primarily from the planktonic groups *Keratella*, *Brachionus*, *Polyarthra*, *Asplanchna*, and *Anuraeopsis* **(Elfeky & Sayed, 2014)**. The existence of *Brachionus*, *Keratella cochlearis*, and *Filinia* species within a water body signals eutrophication, while *Filinia longiseta* specifically serves as an indicator of pollution **(Elfeky & Sayed, 2014)**. At all primary mixing points assessed in all seasons, *Brachionus calyciflorus* was notably high as a pollution-tolerant species, reflecting thermal influences.

The absence of zooplankton in autumn samples collected both at Talkha site at all points and downstream of Damietta samples may be attributed to elevated levels of NO_2-N, NO_3-N, NH_3-N, ortho-P, and water temperature that were recorded at these samples, where significant negative correlations ($P< 0.05$) were observed between the total number of zooplankton and these environmental variables. These reflect the anthropogenic wastes discharged along the Nile branches **(Hasaballah *et al*., 2019; El Sayed *et al*., 2020; Abdo *et al*., 2022)**.

Multivariate analysis of variance indicated that copepod density, including Nauplius larvae shown at mixing points, exhibited significant changes with temperature fluctuations in autumn (P=0.008 and 0.02, respectively).

In winter, Rotifera species, including *Keratella cochlearis* (P=0.02), *Lecane monostyla* (P=0.000), *Prompholicus* sp. (P= 0.000) and *Proalides* sp. (P= 0.002), as well as Cladocera species, including Chydorus sphaericus (*P*=0.03), exhibited significant responses to temperature variations.

Finally, Rotifera species, including *Brachionus budapestinesis* and *Trichocerca similis*, showed significant variation with temperature in the summer season (*P*=0.01). These varying sensitivities suggest species-specific adaptations or dependencies on temperature fluctuations for their population dynamics during different seasons **(Gauthier *et al*., 2014; Rogozin *et al*., 2015)**.

The impact of temperature on community structure and diversity can influence the physiological and metabolic processes of zooplankton taxa, through changes in the rate and pathway of uptake and elimination **(Tsui & Wang, 2004)**. **Omori and Ikeda (1984)** reported that zooplankton taxa growth and feeding rates were affected by temperature. Additionally, the temperature gradients influence the biocenosis composition and the structure of the food chain **(Gozdziejewska & Kruk, 2023)**.

Shannon diversity index is frequently employed to assess biodiversity by considering both the abundance and evenness of species within a community **(Elsebaie *et al*., 2023; Olivera *et al*., 2023)**. Notably, the index assigns greater weight to rare species. Species richness (reflected by Margalef index) and species evenness (reflected by equitability) were quantified to investigate the effects of environmental changes on zooplankton species diversity **(Tahoun *et al*., 2021)** at the Nile River stations (Table 5).

The number of zooplankton species and estimated zooplankton taxa in addition to the species richness, species evenness, and Shannon diversity indices varied spatially within each season. Multivariate analysis of variance revealed that Shannon diversity values are affected by fluctuations in measured environmental factors, specifically temperature (P = 0.03) and NO_2-N (P = 0.01) (Table 6). This indicates that the temperature and NO_2-N levels play a significant role in shaping the zooplankton community.

CCA results at El-Taben indicated that total zooplankton species and the dominant groups Rotifera and Protozoa were significantly influenced by WT, pH, and NO_3-N (Fig. 10). While Cladocera and Copepoda groups were strongly affected by ortho-P, TP, NO_2-N, TDS, and bicarbonate. At the Shoubra El-Khima site, NO_3-N exerted a substantial impact on both the total zooplankton community and the dominant Rotifera group. Concurrently, NH_3-N, TP, TDS, DO, and EC significantly influenced Copepoda and Cladocera. At Saqel site, the total zooplankton community, Rotifera, and Protozoa were affected by TP and NO_2-N. The Copepoda group was influenced by WT, NH_3-N, carbonate, ortho-P and silicate.

The zooplankton community and Rotifera group at the Benha site exhibited positive correlations with WT, carbonate, and NH_3-N. At Talkha station the total zooplankton species and Rotifera group were negatively impacted by NH_3-N, ortho-P, TP, TDS, EC, and pH. Finally, at the Damietta site, total zooplankton species and the groups Rotifera, and Protozoa were positively influenced by ortho-P, TP and DO, while negatively correlated with WT.

CONCLUSION

The thermal discharges in the Nile are mostly localized, and their impact is not observable on a larger scale. Consequently, the self-purification capacity of the Nile River plays a vital role in mitigating these effects. The water quality index (WQI) showed the lowest levels near thermal discharge points, where dissolved oxygen (DO) decreases, harming aquatic biota. A high prevalence of fecal streptococci was found at most sampling sites, likely due to their greater resistance to environmental fluctuations compared to coliforms.

Certain bacterial groups may be associated with specific phytoplankton, potentially influencing the dynamic patterns of the microbial community. The absence of zooplankton at some stations indicates the potential impact of environmental factors, including water temperature, NO2-N, NO3-N, NH3-N, and ortho-P. Fluctuations in water temperature and nitrite levels play significant roles in shaping zooplankton diversity.

At the Talkha site, the predominant phytoplankton was not affected by environmental variables; however, a complete absence of zooplankton was recorded, reflecting the high pollution load and thermal shock in this location. This study highlights the importance of ongoing monitoring of water quality variables, bacterial loads, and phytoplankton/zooplankton diversity, as well as the impact of water temperature on these factors.

A reduction in Egypt's share of the Nile water is likely to lead to further increases in temperature near power plants after the completion of the Grand Ethiopian Renaissance Dam. Therefore, routine monitoring of the Nile water is essential for assessing and mitigating potential ecological impacts.

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Supplementary Materials

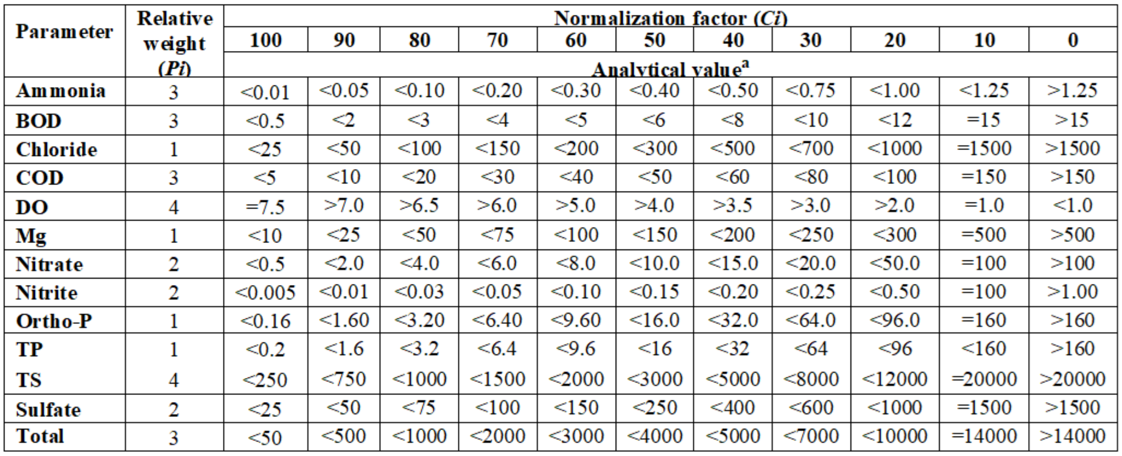
Text S1 Water quality index

Water quality index (WQI) is done by transforming each parameter into 0 to 100 scale (Pesce and Wunderlin, 2000). These sub-indices are then averaged to give a water quality index value by applying suitable weighting factors that reflect the importance of each parameter as an indicator of the water quality. The water quality index was calculated as the following empirical equation (Pesce and Wunderlin, 2000).

$$WQI = {\sum_{i=1}^{n} CiPi}\Big/{\sum_{i=1}^{n} Pi}$$

where, n is the total number of parameters, Ci is the value assigned to parameter i after normalization and Pi is the relative weight assigned to each parameter. Pi values range from 1 to 4, with 4 assigned to a parameter that has the most importance for aquatic life preservation (e.g. dissolved oxygen) and value of 1 assigned to the parameter that has a smaller impact (e.g. chloride). According to which, WQI in the range of 0–25 is very bad, 26–50 is bad, 51–70 is medium, 71–90 is good and 91–100 is excellent. Table 1S gives the different parameters that were used in the evaluation process, as well as their relative weights and the normalization factors

Table 1S. Values suggested for the parameters Ci and Pi, used in the calculation of WQI.



Parameter	Relative weight (*Pi*)	Normalization factor (*Ci*)										
		100	**90**	**80**	**70**	**60**	**50**	**40**	**30**	**20**	**10**	**0**
		Analytical value[a]										
Ammonia	3	<0.01	<0.05	<0.10	<0.20	<0.30	<0.40	<0.50	<0.75	<1.00	<1.25	>1.25
BOD	3	<0.5	<2	<3	<4	<5	<6	<8	<10	<12	=15	>15
Chloride	1	<25	<50	<100	<150	<200	<300	<500	<700	<1000	=1500	>1500
COD	3	<5	<10	<20	<30	<40	<50	<60	<80	<100	=150	>150
DO	4	=7.5	>7.0	>6.5	>6.0	>5.0	>4.0	>3.5	>3.0	>2.0	=1.0	<1.0
Mg	1	<10	<25	<50	<75	<100	<150	<200	<250	<300	=500	>500
Nitrate	2	<0.5	<2.0	<4.0	<6.0	<8.0	<10.0	<15.0	<20.0	<50.0	=100	>100
Nitrite	2	<0.005	<0.01	<0.03	<0.05	<0.10	<0.15	<0.20	<0.25	<0.50	=100	>1.00
Ortho-P	1	<0.16	<1.60	<3.20	<6.40	<9.60	<16.0	<32.0	<64.0	<96.0	=160	>160
TP	1	<0.2	<1.6	<3.2	<6.4	<9.6	<16	<32	<64	<96	<160	>160
TS	4	<250	<750	<1000	<1500	<2000	<3000	<5000	<8000	<12000	=20000	>20000
Sulfate	2	<25	<50	<75	<100	<150	<250	<400	<600	<1000	=1500	>1500
Total	3	<50	<500	<1000	<2000	<3000	<4000	<5000	<7000	<10000	=14000	>14000

[a] **value in mg/L; bacteria is expressed as MPN/100 ml.**

Table 2S Seasonal variations of some chemical variables in Nile River at the selected sites

Parameters	Seasons	El-Taben			Saqil			Shoubra El-Khima			Benha			Talkha			Kafr Saad		
		Up stream	Mixing point	Down stream	Up stream	Mixing point	Down stream	Up stream	Mixing point	Down stream	Up stream	Mixing point	Down stream	Up stream	Mixing point	Down stream	Up stream	Mixing point	Down stream
CO_3^- (mg/L)	Autumn	7.00	5.00	6.50	5.00	5.00	5.00	8.00	7.50	5.50	5.00	1.00	1.00	2.50	5.00	3.75	8.00	10.00	2.50
	Winter	1.00	6.50	1.50	6.50	6.50	1.25	1.25	6.50	6.50	1.50	1.50	1.25	1.20	1.25	1.30	1.50	1.40	1.40
	Spring	8.50	8.00	9.00	9.00	9.00	9.00	9.50	9.20	9.10	0.50	0.90	0.90	0.90	0.90	0.90	9.50	8.00	15.00
	Summer	7.50	8.00	2.50	8.00	2.50	2.50	2.50	2.00	7.70	2.00	2.10	2.25	2.50	2.50	2.50	8.00	2.50	7.50
NO_2^- -N (µg/L)	Autumn	13.13	15.45	14.40	9.56	10.83	10.50	10.35	11.37	10.65	16.84	11.50	16.84	42.99	93.77	78.86	32.07	33.49	32.80
	Winter	10.16	12.00	11.37	8.18	9.00	8.33	10.50	10.70	10.54	14.85	15.73	15.70	32.61	43.43	42.42	40.81	57.81	42.93
	Spring	3.07	3.52	3.04	2.47	2.91	2.50	2.44	3.50	3.45	3.77	10.87	8.80	8.48	49.05	36.60	24.57	25.00	24.60
	Summer	2.34	2.41	2.69	2.69	5.16	2.79	2.69	2.72	2.70	37.61	53.00	52.74	91.68	130.85	115.46	47.33	48.50	47.50
NO_3^- -N (µg/L)	Autumn	55.41	105.06	42.42	29.10	37.80	35.00	60.50	78.67	68.95	68.21	98.11	90.21	116.60	173.47	160.00	110.49	165.80	140.55
	Winter	69.29	73.20	72.51	46.90	62.30	49.55	55.79	60.93	56.30	64.61	76.80	72.00	120.53	191.85	130.96	256.61	368.63	190.22
	Spring	32.89	33.00	32.90	18.26	44.27	36.21	16.84	18.00	17.16	71.63	88.00	86.89	116.77	259.23	196.46	127.30	274.10	190.66
	Summer	113.29	195.00	155.50	75.66	101.75	88.50	70.92	196.00	118.00	225.20	280.11	250.38	345.88	416.01	296.95	221.20	370.23	255.50
NH_3 -N (µg/L)	Autumn	149.33	244.64	197.65	269.09	501.20	280.00	133.60	275.50	180.50	477.16	637.22	560.33	598.63	794.20	688.80	122.61	285.20	235.36
	Winter	47.00	58.20	56.85	60.64	61.59	61.00	61.02	63.00	61.50	101.66	143.20	110.55	16.33	285.95	259.50	158.99	382.79	179.33
	Spring	66.33	68.00	67.10	66.70	83.38	77.60	71.44	10.40	78.20	113.89	150.50	144.78	133.98	135.50	134.50	129.67	130.00	129.80
	Summer	12.89	19.17	13.37	12.20	16.11	14.59	11.50	14.10	13.18	15.92	17.81	17.62	13.20	15.73	14.27	14.00	20.28	15.16
Ortho-P (mg/L)	Autumn	18.24	38.22	27.10	9.74	27.28	21.96	17.36	24.62	17.71	27.63	35.25	25.51	36.84	42.50	40.12	36.31	41.80	40.30
	Winter	12.22	25.75	23.03	12.40	16.12	13.11	13.82	15.59	14.53	26.04	35.00	30.29	56.15	65.00	62.70	58.81	65.50	64.12
	Spring	12.58	16.22	14.35	13.46	16.47	13.11	15.59	18.07	16.00	20.50	28.50	22.32	34.72	39.68	38.97	28.16	44.81	37.02
	Summer	17.54	19.00	18.00	6.91	15.23	7.62	7.26	8.67	8.00	12.04	13.00	12.10	26.04	31.00	30.47	37.02	41.20	40.39
TP (µg/L)	Autumn	114.42	145.00	133.91	114.78	122.22	100.96	122.22	143.20	128.02	123.99	130.20	124.70	145.95	150.20	148.35	157.29	163.67	125.05
	Winter	180.68	202.28	207.24	204.40	225.00	218.22	205.46	215.50	210.50	207.94	236.20	230.62	231.68	265.50	262.16	274.18	335.15	329.82
	Spring	60.00	98.14	86.42	102.74	112.30	105.20	100.40	120.80	104.40	109.12	128.00	127.00	121.80	148.50	135.68	132.50	199.44	135.00
	Summer	36.14	55.00	53.84	43.58	54.92	45.00	44.28	137.10	55.26	46.00	90.00	55.00	54.56	60.00	55.50	54.92	60.00	55.00
SiO_3^{-2} (mg/L)	Autumn	1.20	2.01	1.73	1.36	2.04	1.80	1.00	1.37	1.20	1.50	1.57	1.44	2.23	2.92	2.55	3.49	4.93	4.27
	Winter	1.09	1.95	1.90	1.15	1.90	1.23	1.00	1.65	1.20	1.00	1.21	1.12	1.89	2.10	2.09	3.75	3.98	3.65
	Spring	5.60	6.20	6.10	6.03	6.17	5.66	5.60	5.80	5.60	5.81	5.90	5.63	5.40	5.48	5.60	5.10	5.30	5.16
	Summer	1.49	2.20	2.15	1.51	1.60	1.52	1.38	1.90	1.85	1.10	3.32	1.50	1.76	2.20	2.07	2.62	2.80	2.70
Na (mg/L)	Autumn	22.98	23.83	23.83	23.83	24.68	25.53	23.83	25.60	25.53	24.68	25.53	25.53	28.94	29.79	29.79	28.94	29.79	29.79
	Winter	30.13	34.41	31.76	31.76	36.00	32.30	32.78	34.10	33.19	35.22	36.24	35.80	37.26	40.00	37.87	40.10	43.10	42.70
	Spring	24.75	27.00	26.21	26.03	27.00	26.76	26.58	27.00	26.60	27.50	28.04	30.00	26.00	31.50	30.60	34.09	35.50	34.64
	Summer	23.41	25.20	24.00	23.94	25.00	24.00	23.54	25.15	23.60	23.81	24.07	23.90	26.55	27.00	26.94	28.78	62.00	30.00
K (mg/L)	Autumn	6.28	7.84	7.62	7.84	8.29	8.07	8.29	8.97	8.74	8.52	8.74	8.52	6.76	7.00	6.90	6.76	6.91	6.91
	Winter	7.20	8.20	8.14	7.60	8.14	8.00	7.87	7.90	7.88	7.80	8.47	8.00	8.34	8.60	8.27	8.80	8.94	8.90
	Spring	5.80	5.90	5.84	5.84	6.16	6.00	6.16	6.81	6.50	6.16	6.80	6.49	6.16	7.13	7.00	7.13	7.50	7.30
	Summer	5.88	6.00	5.90	5.48	6.52	6.18	5.50	6.18	5.80	6.03	6.67	6.13	6.60	7.30	7.24	6.80	9.98	7.80
Ca (mg/L)	Autumn	22.10	32.20	30.30	27.00	29.20	28.50	27.25	32.06	25.65	25.65	29.00	27.00	27.00	30.00	29.00	26.00	29.00	27.00
	Winter	35.27	36.00	35.59	35.75	35.91	35.80	36.23	36.39	36.55	36.60	37.00	36.55	36.47	36.71	37.03	37.35	43.29	37.60
	Spring	32.06	33.00	32.10	28.86	38.48	36.87	32.00	33.60	32.06	33.67	34.00	33.70	32.06	33.00	32.50	32.06	33.00	32.10
	Summer	30.46	31.26	30.50	30.46	31.26	31.00	30.46	31.50	31.26	28.86	29.66	29.00	28.86	30.46	30.00	30.45	38.00	31.20
Mg (mg/L)	Autumn	15.56	21.40	21.40	15.56	20.48	20.43	13.62	17.59	14.55	13.62	22.10	21.00	20.60	22.70	20.92	19.00	21.90	20.00
	Winter	19.46	20.00	19.50	20.43	21.89	20.50	17.51	23.00	22.86	22.37	23.00	22.50	20.43	22.00	21.00	18.50	33.08	23.35
	Spring	25.29	29.50	27.50	24.30	28.20	26.00	26.27	27.24	27.00	25.29	28.00	27.24	24.32	26.00	25.29	24.32	26.00	25.00
	Summer	11.67	13.00	12.45	10.41	11.28	11.19	10.00	13.10	12.00	11.77	12.00	11.87	12.89	13.00	12.55	12.35	13.50	12.21

Table 3S. Phytoplankton distribution (no of cells X 10^3/L) in Nile River during different seasons

El-Taben

Season	Sites	Bacillariophyceae	Chlorophyceae	Cyanobacteria	Euglenophyceae	Dinophyceae	Total phytoplankton
Autumn	**Up stream**	3630	1125	255	45	60	5115
	Mixing point	1500	300	150	70	75	2095
	Down stream	1800	1025	115	5	5	2950
Winter	**Up stream**	1440	840	310	20	30	2640
	Mixing point	1820	340	260	30	10	2460
	Down stream	1320	569	290	20	10	2209
Spring	**Up stream**	4435	185	30	50	50	4750
	Mixing point	2960	95	20	0	0	3075
	Down stream	3885	155	10	20	20	4090
Summer	**Up stream**	4500	250	50	20	30	4850
	Mixing point	3025	160	30	0	0	3215
	Down stream	3950	220	70	10	20	4270

Shoubra El-Khima

Season	Sites	Bacillariophyceae	Chlorophyceae	Cyanobacteria	Euglenophyceae	Dinophyceae	Total phytoplankton
Autumn	**Up stream**	3370	1605	270	40	25	5310
	Mixing point	2115	1720	440	70	60	4405
	Down stream	1502	1590	340	40	60	3532
Winter	**Up stream**	1550	165	50	50	10	1825
	Mixing point	1175	570	60	25	15	1845
	Down stream	1730	290	120	20	30	2190
Spring	**Up stream**	4080	2530	130	155	140	7035
	Mixing point	745	155	35	10	15	960
	Down stream	4065	2420	80	105	135	6805
Summer	**Up stream**	4175	2625	225	250	250	7555
	Mixing point	840	250	130	10	10	1240
	Down stream	4160	2515	175	200	230	7300

Table 3S. Continued.

Saqel

Season	Sites	Bacillariophyceae	Chlorophyceae	Cyanobacteria	Euglenophyceae	Dinophyceae	Total phytoplankton
Autumn	Up stream	1800	860	205	20	15	2900
	Mixing point	3970	4460	790	90	100	9410
	Down stream	1140	2080	210	35	60	3525
Winter	Up stream	1320	175	96	10	5	1606
	Mixing point	1250	190	80	20	5	1545
	Down stream	1415	180	100	10	10	1715
Spring	Up stream	3875	2440	140	25	75	6555
	Mixing point	2875	2375	105	0	25	5380
	Down stream	3575	2225	125	20	45	5990
Summer	Up stream	3950	2515	215	100	150	6980
	Mixing point	2950	2450	180	50	100	5730
	Down stream	3650	2300	200	50	120	6320

Benha

Season	Sites	Bacillariophyceae	Chlorophyceae	Cyanobacteria	Euglenophyceae	Dinophyceae	Total phytoplankton
Autumn	Up stream	1830	885	180	75	180	3150
	Mixing point	1350	255	270	45	30	1950
	Down stream	230	80	10	20	30	370
Winter	Up stream	1090	240	400	10	40	1780
	Mixing point	1270	200	70	50	20	1610
	Down stream	900	20	20	20	10	970
Spring	Up stream	1805	155	80	155	405	2600
	Mixing point	280	265	50	0	0	595
	Down stream	1855	120	55	90	20	2140
Summer	Up stream	1900	250	175	250	500	3075
	Mixing point	375	360	30	30	30	825
	Down stream	1950	215	150	50	50	2415