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Modified Water Quality Index and Multivariate Analysis for Water Quality Assessment in El-Mex Bay, Alexandria, Egypt: A Study of the Largest Drain in the Southeastern Mediterranean Sea

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ABSTRACT

El-Umum Drain has been identified as a significant pollution source, consistently discharging drainage water into the southeastern Mediterranean Sea at El-Mex Bay in Egypt. Hence, El-Mex Bay water and its drain were extensively studied. Nevertheless, the previous assessments did not consider the relative weights of the measured variables, which would overlook the seasonality and potential improvements of the water quality due to the enhancement of wastewater treatment techniques. In this study, a modified water quality index (WQI) and multivariate analysis were applied to accurately assess water quality of El-Mex Bay and El-Umum Drain. Water quality parameters at nine stations were measured during 2020-2021. Most of the parameters showed significant spatial and temporal variations, indicating the influence of anthropogenic activities. The WQI values ranged from "poor" in El-Umum Drain to "medium" in El-Mex Bay open water. The cluster analysis (CA) was employed to categorize the nine survey sites into three distinct groups. Specifically, the analysis revealed highly polluted stations at El-Umum Drain and moderately polluted stations in the El-Mex open water area. In addition, the CA classified the sampling months into two groups: highly polluted in March, May and August, and less polluted in January, indicating the variation of the volume of the discharged wastewater. Principal component analysis/factor analysis revealed that the parameters responsible for water quality variations were mainly associated with the inorganic dissolved nutrients, salinity and organic matter (anthropogenic). The application of the modified Water Quality Index (WQI) enabled an accurate and scientifically rigorous evaluation, even when individual variables experienced deterioration or improvement. This approach addresses the limitations of previous evaluation methods that relied on single-factor assessments, providing a more comprehensive and nuanced understanding of water quality conditions. For future water quality monitoring, it is recommended to apply the modified Water Quality Index (WQI) and include additional variables such as heavy metals and fecal bacteria. This approach would result in more comprehensive and scientifically sound evaluations

INTRODUCTION

According to **UNEP/MAP (2019)**, about 85% of sewage water goes into the Mediterranean Sea without adequate treatment, creating several health risks. The coastal pollution in developing countries is rising rapidly because of urbanization and industrial development. The sewage effluent from Alexandria City is the main pollution source in the southeastern Mediterranean Sea **(UNEP/MAP, 2019)**.

El Umoum Drain is located in the west of Nile Delta and is the largest drain in the southeastern Mediterranean Sea. It conveys annually about 2.50 billion m^3 of drainage water into the Mediterranean Sea **(Shreadah *et. al.*, 2019)**. Consequently, several studies investigated the water quality of El-Mex Bay **(Emara *et. al.*, 1992; Alam El-Din, 2001; Mahmoud *et. al.*, 2005; El-Rayis & Abdallah, 2006; Abdallah, 2007; Masoud *et. al.*, 2007; Abdallah & Abdallah, 2008; Farag, 2009; El-Naggar *et al.*, 2013; El Nemr *et. al.*, 2013; Okbah *et al.*, 2013; Aboul Ezz *et. al.*, 2014; Shreadah *et al.*, 2014; 2015a; 2015b; Nasr *et al.*, 2017; Said *et al.*, 2017; Soliman *et al.*, 2017; Hassaan & El-Rayis, 2018; Abdallah & Mohamed, 2019; Dorgham *et. al.*, 2019)**. In addition to the investigation of the water treatments, solutions by **Masoud *et al.* (2016)** and **Abdallah *et al.* (2017)** were recommended.

Lately, a national plan has been directed towards the diversion of the sewage water from El-Umum Drain for irrigation, which urges for an adequate water quality assessment prior and post the execution of the plan. Multivariate analysis and water quality indices (WQI) are widely applied in water quality assessment, playing a vital role in water resources management **(El Sayed *et al.*, 2020; Gradilla-Hernández *et al.*, 2020; Ma *et al.*, 2020; Varol, 2020; Zaghloul *et al.*, 2022)**. WQI and multivariate analysis should be applied together to increase the accuracy of water quality assessment **(Varol, 2020)**. According to **Ma *et al.* (2020)**, the application of the modified WQI overcomes the deficiency of previous evaluation methods of considering single-factor evaluations **(Ma *et al.*, 2013)**. Modified WQI is based on principle component analysis (PCA) and factor analysis (FA) to create weights for the measured parameters **(Mitra *et al.*, 2018; Gradilla-Hernández *et al.*, 2020; Ma *et al.*, 2020)**. In this study, modified WQI and multivariate analysis were applied in order to accurately assess water quality of El-Mex Bay and El-Umum Drain and estimate the main factors controlling the spatial and temporal variation in the water quality.

MATERIALS AND METHODS

2. Study area

El-Mex Bay is a relatively large urban estuary located at the west of Alexandria City along the Mediterranean Coast of Egypt. It has an average depth of 10.2m and surface area of about 15.56Km^2. Despite being an important fishing area, El-Mex Bay is highly polluted, where it receives tremendous amounts of agricultural, industrial and sewage discharges from El Umum Drain **(Aboul Ezz *et al.*, 2014)**. According to Drainage Research Institute, the volume of the untreated wastewater varied between 7×10^6 and $8\times 10^6 m^3$/day, which is expected to increase with the growing population. Sampling was set at nine stations, in March, May, September 2020, and January, August

2021. Stations 1 and 2 were chosen at E-Umum Drain, stations 3, 5, 8, 6 were inside El Mex Bay, and stations 4, 7, 9 were at the exchange between the Mediterranean Sea and the bay (Fig. 1).

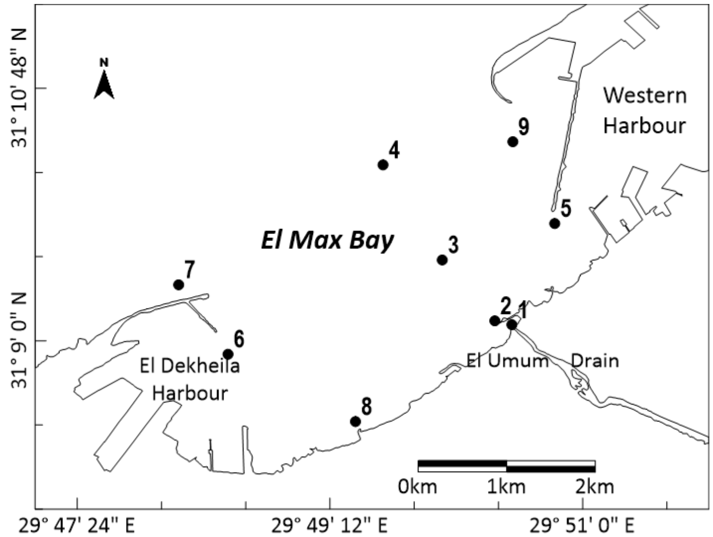

Fig. 1. Map of El Mex Bay showing sampling stations during 2020-2021

2.1 Sampling and analysis

The samples were collected in 5l cleaned plastic bottles at a depth of 0.5cm. A portable water quality multiparameter (model, YSI 556) was used to measure temperature (T) and salinity (SAL). In the laboratory, dissolved oxygen (DO) and dissolved inorganic nutrients (NO_2-N, NO_3-N, NH_4-N, PO_4-P, and SiO_4-Si) were determined according to **Grasshoff *et al.* (1999)**. The oxidizable organic matter (OOM) was measured according to **FAO (1976)**.

2.2. Water quality index

WQI was calculated by using the methods of **Mitra *et al.*, (2018), Gradilla-Hernández *et al.* (2020)** and **Ma *et al.*, (2020)**. WQI is based on principle component analysis (PCA) and factor analysis (FA) to create weights for the measured parameters. Before conducting the multivariate analysis, the dependency of all variables should be tested **(Ma *et al.*, 2020)**. All nine variables were analyzed using Spearman's rank correlation coefficient, and the variable that had non-significant correlation with the other variables was excluded from subsequent analysis process. All the selected variables (X) were transformed to $\log_{10}$ (X+1) to stabilize the variance, and standardized to avoid biased classification resulting from dimensions differences **(Duan *et al.*, 2016; Ma *et al.*, 2020).** The statistical analysis was performed using Statistica 14.0. The following formula was applied to calculate the WQI in El-Mex Bay:

$$\text{WQI} = \sum_{k=1}^{n} (W_k \; VF_k)$$

Where, k is the number of varifactors resulting from the FA after conducting varimax rotation to the PCs to increase their interpretation; VF_k is the value of the kth PC, and W_k is the weight of each variable (% of variance).

2.3. Statistical analysis

The statistical analysis was conducted on 405 total observations (nine stations * nine variables * five months), using Statistica Software (Ver.14). The data was tested for normality using Leven's test, variables with non-normal distribution were $\log_{10}$ (X+1) to stabilize the variance. Main-effect ANOVA test was conducted to measure the spatial and temporal variation of the variables. The similarity among the stations and sampling months was tested using Hirarichal Cluster Analysis (HCA). The HCA enabled grouping the stations and months using Euclidean distance as a measure of similarity, and Ward's method was used as an agglomerative hierarchical technique **(Alves *et al.*, 2018; Passos *et al.*, 2021)**. The HCA enabled grouping the stations and months using Euclidean distance as a measure of similarity in relation to water quality **(Razmkhah *et al.*, 2010; Bertossi *et al.*, 2013; Alves *et al.*, 2018; Passos *et al.*, 2021)**.

RESULTS AND DISCUSSION

3. Spatiotemporal distribution of the environmental parameters

The concentrations of the nine parameters are shown in Fig. (2). The variables showed significant temporal (P= 0.00; F= 24.80) (except salinity), and spatial variations (except DO and NO_3-N) (P= 0.00, F= 3.50), indicating the influence of anthropogenic activities **(Shreadah *et al.*, 2015a)**. Surface water temperature ranged between 16.84 and 28.60°C, and the annual average was 23.25± 4.77°C. The mean temperature values were significantly lower in January and March (P= 0.00, F= 1182.43). Salinity values ranged between 2.67 and 39.06, with an annual average of 28.64±13.70. Surface water salinity showed significant spatial variation (P= 0.00, F= 268.30), where the lowest salinity was recorded at stations 1 and 2, representing the wastewater flux from El-Umum Drain. The volume of discharged wastewater from El-Umum Drain to the Mediterranean Sea through El-Mex Bay ranged between 2207 and 2784 million m^3 during 2020-2021 (Drainage Research Institute) (DRI).

DO concentrations ranged between 2.59 and 20.41mg/l, with an annual average of 8.68±3.64mg/l. DO concentrations showed significant temporal variation, May and August had the highest mean concentrations (P= 0.00, F= 9.62), indicating the water turbulence and mixing at this time of the year. OOM concentrations varied from 0.64 to 31.04mg/ l, and averaging 7.52±6.23mg/l. The highest mean OOM concentration was recorded in August, and the lowest value in January (P= 0.00, F= 7.01). Station 1 had significantly higher mean OOM concentration than the other stations, while St.7 had the lowest values (P= 0.00, F= 6.09).

For the dissolved inorganic nutrient, NH_4-N concentrations ranged between 1.32 and 173.57µM, with an annual average of 50.83±50.22µM. March and August had significantly higher mean NH_4-N concentrations than September and January (P=0.00, F= 7.23). Station 1 had the highest mean NH_4-N concentrations, which was significantly higher than St.7 (P=0.04, F= 2.32). NO_2-N concentrations varied between 0.15 and 31.04µM, with an annual average of 9.09±9.06µM. August had significantly the highest mean NO_2-N concentrations, while January had the lowest mean values (P= 0.00, F= 17.26). Stations 1 and 2 had significantly higher NO_2-N concentrations than the other stations (P= 0.00, F= 9.11). NO_3-N concentrations varied between 1.61 and 64.77, with an annual average of 25.42±16.06µM. January had the highest mean NO_3-N concentration (P= 0.00, F= 12.28). PO_4-P concentrations varied between 0.16 and 19.03µM, with an annual average of 4.49±5.59µM. August and March significantly had the highest mean PO_4-P concentrations, while May had the lowest mean values (P= 0.00, F= 17.72). Stations 1 and 2 had significantly higher PO_4-P concentrations than the other stations (P= 0.00, F= 7.52). SiO_4-Si concentrations ranged between 0.16 and 250.58µM, with an annual average of 63.48±67.61µM. August and March significantly had the highest mean SiO_4-Si concentrations, while January had the lowest mean values (P= 0.00, F= 9.18). Stations 1 and 2 significantly had higher SiO_4-Si concentrations than stations 6, 7 and 9 (P= 0.00, F= 5.69). The elevated concentrations of inorganic nutrients, particularly NH_4-N associated with increasing of OOM at El-Umum Drain indicates organic pollution from point-sources, such as domestic sewage, industrial wastewater and non-point sources from agriculture drainage water associated with fertilizers **(Aboul Ezz *et al.*, 2014; Duan *et al.*, 2016; Varol, 2020)**.

The temporal and spatial variation of the environmental parameters was further clarified by HCA. HCA has been widely used for water quality assessments to contribute to the spatial discriminant analysis **(Ma *et al.*, 2020)**. Fig. (3a, b) display the dendrograms resulting from hierarchical cluster analysis (HCA), showcasing the grouping of stations and months in El-Mex Bay, based on their similarities in relation to water quality parameters. The cut-off lines, which determine the number of clusters, grouped stations and months into three distinct categories. This grouping illustrates the impact of anthropogenic stressors and seasonality on the qualitative characteristics of the water.

Regarding the grouping of the stations (Fig. 3a), stations 1 and 2 were represented in group I, which showed the lowest number of stations. Groups II and III were heterogeneous, with group III showing the largest number of stations. In addition, St.7 was represented only in group III. This indicates that St.1 and St.2 had different water quality than other stations, which has affected neighboring stations. However, St.7 located in the Mediterranean Sea had different water quality characteristics since it is located at the farthest distance from El-Umum Drain.

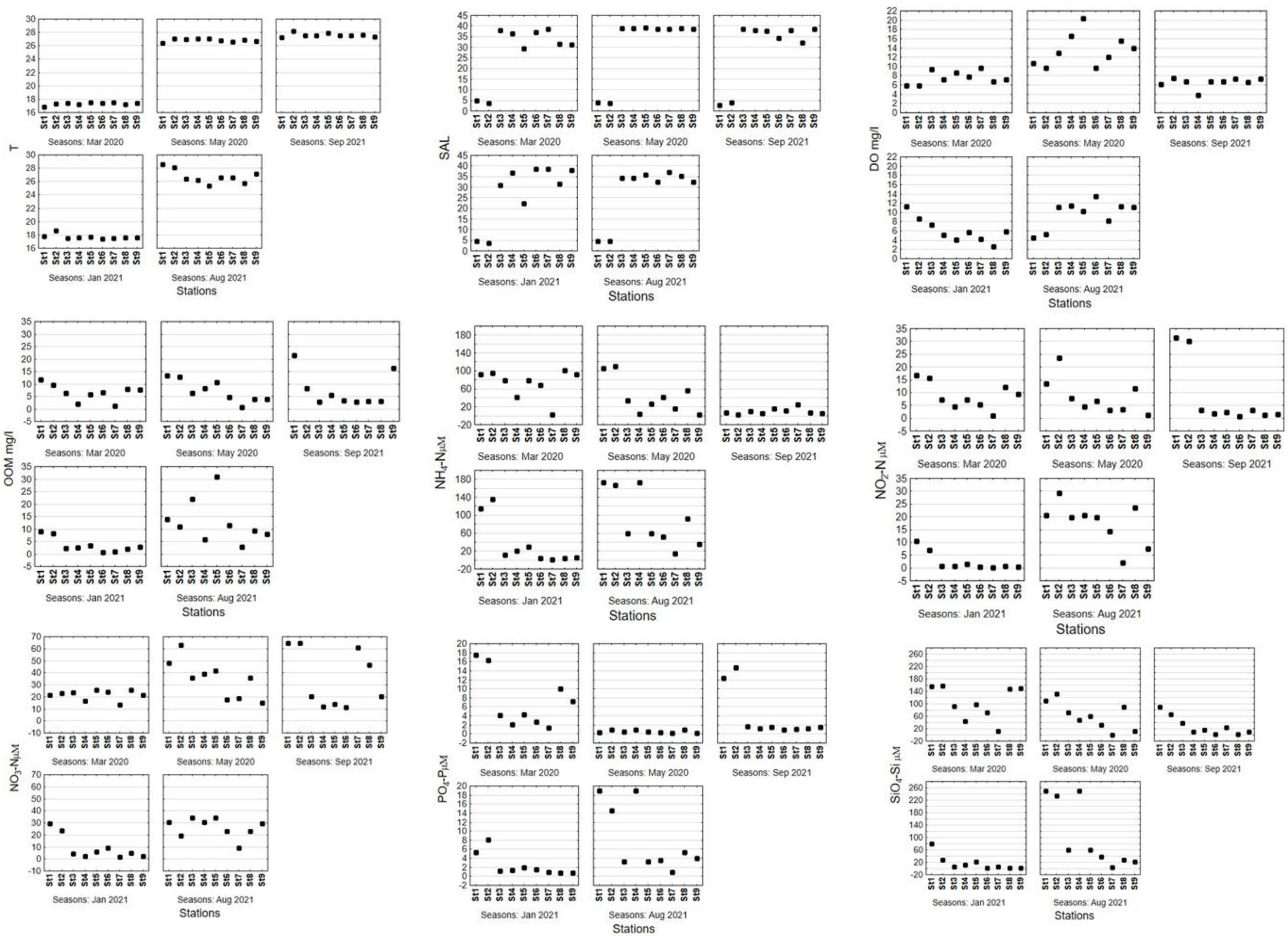

Fig. 2. Concentrations of physicochemical parameters in El-Mex Bay. during the period from Mar 2020 to August 2021.

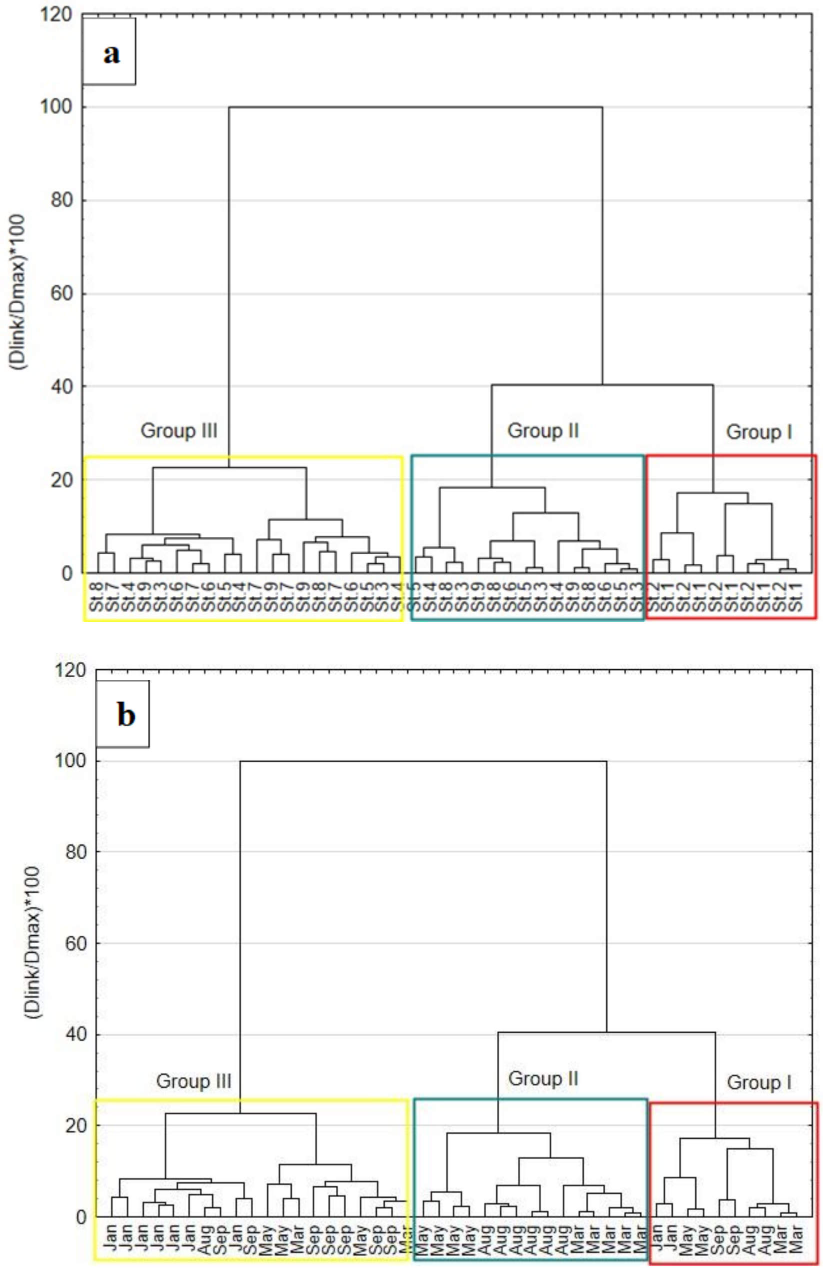

Fig. 3. Dendrogram from the HCA for the environmental parameters of the El-Mex Bay, grouped by (a) stations and (b) months

On the other hand, grouping by sampling months showed that the groups were heterogeneous, indicating the significant seasonal changes in water quality (Fig. 3b). Group II showed that March, May and August had similar water quality, where the highest mean concentrations OOM and dissolved nutrients were recorded during these months, while January, which is represented in group III, had the lowest concentrations.

3.1. Multivariate statistical analysis of water quality

Spearman correlation analysis was conducted to eliminate irrelevant variables and improve the accuracy of the subsequent multivariate analysis. The results showed that surface water temperature showed non-significant correlation with the other variables

(Table 1). However, the temperature was excluded from the subsequent analysis since it is not a limiting variable to the water quality. The significant negative correlation between the salinity and dissolved inorganic nutrients and OOM signifies the impact of freshwater-carrying pollutants from E-Umum Drain, since increasing of the dissolved nutrients concentrations leads to elevated OOM **(Abdelsalam *et al*., 2020)**.

Table 1. Correlation among the variables using Spearman's rank correlation coefficient as a nonparametric test. Significant at the 0.05 level

Variable	T	SAL	DO	OOM	NH4-N	NO2-N	NO3-N	PO4-P	SiO4-Si
T		0.07	0.10	0.22	-0.18	0.16	0.35	-0.16	-0.08
SAL	0.07		0.32	-0.45	-0.50	-0.49	-0.24	-0.62	-0.42
DO	0.10	0.32		0.26	0.18	0.32	0.49	-0.22	0.18
OOM	0.22	-0.45	0.26		0.55	0.80	0.65	0.47	0.67
NH4-N	-0.18	-0.50	0.18	0.55		0.68	0.38	0.53	0.75
NO2-N	0.16	-0.49	0.32	0.80	0.68		0.72	0.61	0.82
NO3-N	0.35	-0.24	0.49	0.65	0.38	0.72		0.24	0.58
PO4-P	-0.16	-0.62	-0.22	0.47	0.53	0.61	0.24		0.59
SiO4-Si	-0.08	-0.42	0.18	0.67	0.75	0.82	0.58	0.59	

A standardized set of the eight selected variables was used to conduct PCA. To determine the characteristics of water quality, FA with Varimax rotation was performed on the PCs to identify the main factors that contribute to water quality in El-Mex Bay and to extract eigenvalues. The results showed that two sets of VFs were obtained for El-Mex Bay (Table 2).

Table 2. Loading of selected variables on significant PCs for El-Mex Bay

Variables	VF_1	VF_2
SAL	**-0.80**	0.12
DO	-0.15	**0.93**
OOM	**0.70**	0.46
NH_4-N	0.68	0.33
NO_2-N	**0.83**	0.49
NO_3-N	0.47	**0.72**
PO_4-P	**0.88**	-0.14
SiO_4-Si	**0.81**	0.39
Eigenvalue	4.58	1.50
% Total variance	57.24	18.70
Cumulative	4.58	6.08
El-Umum Drain		
SAL	**0.75**	0.22
DO	0.02	**-0.94**
OOM	-0.65	0.30
NH_4-N	**0.78**	0.02
NO_2-N	-0.66	0.60
NO_3-N	**-0.87**	-0.35
PO_4-P	0.11	**0.73**
SiO_4-Si	0.07	**0.77**
Eigenvalue	2.81	2.65
% Total variance	35.19	33.11
Cumulative	2.81	5.46
El-Mex Bay		
SAL	-0.41	**0.74**
DO	0.35	**0.82**
OOM	**0.71**	0.31
NH_4-N	**0.90**	0.03
NO_2-N	**0.89**	0.36
NO_3-N	0.58	0.62
PO_4-P	**0.83**	-0.30
SiO_4-Si	**0.85**	0.21
Eigenvalue	4.44	1.68
% Total variance	55.44	21.02
Cumulative	4.44	6.12

VF_1 accounted for 57.24% of the total variance with a strong negative loading (> 0.70) of SAL, and positive loading of NO_2-N, PO_4-P, and SiO_4-Si. VF_2 accounted for 18.70% of the total variance with a strong positive loading of DO and NO_3-N. The same procedure was separately conducted for El-Umum Drain and the open water of El-Mex Bay. The results showed that two sets of VFs were obtained for El-Umum Drain (Table 2). VF_1 accounted for 35.19% of the total variance with a strong positive loading (> 0.70) of SAL, NH_4-N, and negative loading of NO_3-N. VF_2 accounted for 33.11% of the total variance with a strong negative loading of DO and positive loading of SiO_4-Si, and PO_4-P. Similarly, two sets of VFs were obtained for the open water of El-Mex Bay, VF_1 accounted for 55.44% of the total variance with a strong positive loading (> 0.70) of OOM, NH_4-N, NO_2-N, PO_4-P, SiO_4-Si. VF_2 accounted for 21.22% of the total variance, with a strong positive loading of DO and SAL.

In general, the first VF captured the relation between freshwater discharge and the inorganic dissolved nutrients and OOM, while the second VF showed the reduction of DO in response to the increase of PO_4-P and SiO_4-Si, which probably indicates eutrophic conditions particularly near El-Umum Drain, where the eutrophication has been excessively reported **(Ma *et al*., 2020)**.

3.2. Spatiotemporal variation of water quality

The WQI values in El-Mex Bay, El-Umum Drain, and the open water of El-Mex Bay are shown in Fig. (4). The application of the modified WQI provided an accurate and scientific evaluation, even if one variable deteriorated or enhanced **(Ma *et al*., 2013)**, which overcomes the deficiency of previous evaluation methods of considering single-factor evaluations **(Alam El-Din, 2001; Farag, 2009)**. El-Max Bay exhibited “medium” water quality when including all stations and months (Fig. 4). El-Umum Drain has “poor” water quality, while El-Mex open water exhibited “medium” condition.

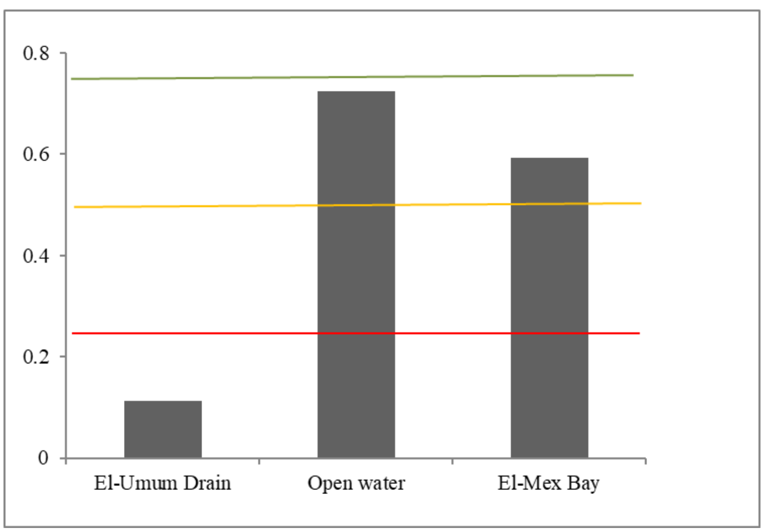

Fig. 4. Modified WQI for El-Mex Bay and El Umum Drain in 2020-2021

The volume of discharged water from El Umum Drain to El Mex Bay was the lowest in the spring and the highest in the winter. However, the level of pollution is subjected to seasonal variations (Table 3). The dynamics of water masses and circulation in El-Mex Bay control the accumulation, distribution, and flux of wastewater **(Alam El-Din, 2001; Farag, 2009)**, which are in turn affected by the continuous alteration in the morphology of the bay due the extensive constructions of new infrastructures.

Table 3. Volumes of water discharged to El Mex Bay through El Umum Drain (million m^3)

Season	Previous study				Present study	
	1982- 1983	1988	1995-1996	2003-2004	2020	2021
Summer	230	520.978	207	588.73	816.36	509.5
Autumn	257	450.704	207	705.44	647.76	638.2
Winter	222	744.381	205	658.98	816.16	708.6
Spring	246	490.528	185	510.45	504.1	353.5
Total	2865	2206.591	2412	2452.65	2784.38	2209.8

According to some previous studies **(Emara *et al.*, 1992; Mahmoud *et al.*, 2005; Aboul Ezz *et al.*, 2014; Shreadah *et al.*, 2014; 2015a)**, the winter-closure period (in January and February) leads to accumulation of pollutants in the drain, and the wastewater in the canals is subjected to strong unsteady flow, while a relatively stable flow occurs from June to October.

CONCLUSION

The water quality of El-Mex Bay has always been considered as poor. However, the assessments did not consider the relative weights of the measured variables, which would overlook the seasonality or the potential improvements of the water quality due to the enhancement of wastewater treatments or the closure of other drains. We recommend the application of the modified WQI for future monitoring of the water quality of El-Mex Bay. In addition, including more variables such as heavy metals and fecal bacteria would result in sound scientific evaluations.

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