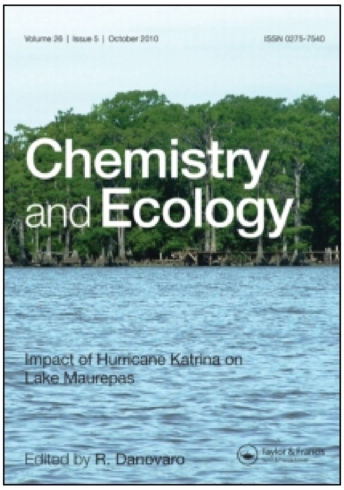

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Bioavailability of phosphorus in Abu Qir Bay and Lake Edku sediments, Mediterranean Sea, Egypt

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The aim of this study is to investigate the distribution of phosphorus bioavailability (total phosphorus, organic, and inorganic phosphorus) in the sediments from two areas (Abu Qir Bay and Lake Edku) located east of Alexandria City. Abu Qir Bay is a very important productive area of the Mediterranean Sea off Egypt, since it receives nutrient-rich brackish water from Lake Edku as well as El-Tabia pump station. The release of phosphorus from the sediment is generally important for eutrophication, which influences the sea-water quality of the study area. Sediment samples from 10 sites of Abu Qir Bay and eight sites of Lake Edku were subjected to a seven-step extraction procedure to determine organic, inorganic, and total phosphorus as well as phosphorus bioavailability: water-soluble phosphorus (WSP), readily desorbable phosphorus (RDP), algal available phosphorus (AAP), and $NaHCO_3$-extractable phosphorus. Our results indicate low recovery of available phosphorus extracted by $CaCl_2$ for the sediments of the lake and the bay. The sediments of Lake Edku were richer in organic and inorganic phosphorus. The range and mean concentration ($\mu g\,g^{-1}$) of the organic P were 17–260 (129) for Abu Qir Bay, and 84–930 (349 $\mu g\,g^{-1}$) for Lake Edku. The accumulation of fresh macrophyte debris in Lake Edku sediments plays an important role in organic-matter enrichment (average 9%) and phosphorus bioavailability. The inorganic P was higher than the organic P for the study area, and its content ($\mu g\,g^{-1}$) ranged from 127 to 446 (mean; 252) and from 515 to 947 (mean; 682) for Abu Qir Bay and Lake Edku sediments, respectively. The distribution of both total P and organic P content in the lake sediments revealed a decreasing level from the eastern to the western region, towards the opening of Boughaz El-Maadia, while the inorganic phosphorus increased from 598 $\mu g\,g^{-1}$ in the eastern side to 875 $\mu g\,g^{-1}$ in the western region of the lake. In general, the rank order of extraction efficiency was the same in the two regions, and the amount extracted was in the sequence AAP > Olsen-P > WSP > RDP.

Keywords: Phosphorus; Bioavailability; Sediments; Abu Qir Bay; Lake Edku

1. Introduction

Phosphorus (P) plays a key role in the structural and biochemical functional components for the growth of plants including algae [1]. It is also often the most important factor in managing ecosystem productivity. Phosphorus is regarded as a key factor responsible for eutrophication problems in surface waters; its concentration in sea water, lakes, and rivers results from both external inputs such as rainfall, runoff and soil leaching, industrial and municipal effluents,

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and the internal loading from the system itself such as aquatic plants, algae, and sediments. The internal loading of P by sediment plays an important part in the phosphorus status of the study area. Its release depends on the form of phosphorus in the sediment. The application of selective chemical extraction methods for speciation has been documented by many authors [2–5] and is a better tool for estimating the potential phosphorus release from sediments to the overlying water and the bioavailability of phosphorus for algal uptake than estimating total phosphorus [6–8]. Total phosphorus concentrations in sediments cannot predict the potential ecological danger. The available phosphorus fraction is an important factor for predicting future internal P loading. This internal P loading may become a possible phosphorus source that will support the trophic status of the lake, even after a reduction of external loading [9, 10].

Methods for the partitioning of phosphorus have been well studied in view of the potential importance of the bioavailability of phosphorus accumulated in superficial sediments. Phosphorus may be adsorbed to the sediments accumulated at the bottom of seas or lakes. These sediments may accumulate over long periods and can act as new phosphorus sources to the overlying water for many years after the water quality has improved [11, 12]. Phosphorus may be transferred from the water column to sediment by biochemical and physical reactions such as ion exchange, adsorption, and precipitation [13]. It may be released from the sediments if the overlying water quality changes [14]. Therefore, it is believed that controlling phosphorus is the best approach to reducing eutrophication [15]. Both areas in the present study (Abu Qir and Lake Edku, figure 1) receive urban runoff, which further increases phosphorus concentrations. Release of phosphorus from sediments may be caused by environmental changes (a decrease or increase in pH, change in water temperature) and may be associated with the other pollutants such as metals. Metal ions such as iron and manganese oxidized to their higher states [Fe (III) and Mn (IV)] precipitate phosphorus with metal hydroxide [16]. Phosphorus solubility is therefore also a function of pH and redox potential. Under reducing conditions, the iron and manganese precipitates become more soluble and release PO_4^{2-} [11, 13]. The aim of this study is to investigate the distribution of phosphorus bioavailability in the sediments

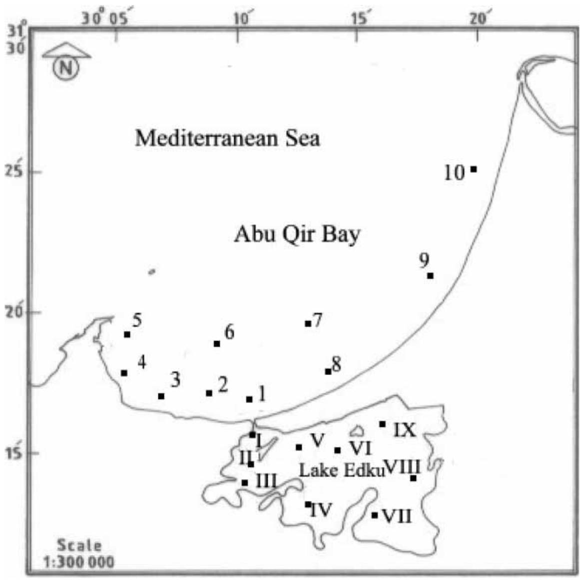

Figure 1. Sampling stations.

of Abu Qir Bay and Lake Edku (located to the east of Alexandria City), and their possible contribution to the P-bioavailability of the two systems.

2. Materials and methods

2.1 *Study areas*

Lake Edku is one of the northern Nile Delta Lakes; it is a reservoir of wastewaters discharged from domestic sewage systems as well as industrial and agricultural drains before flowing to the Mediterranean Sea. The Lake is considered the least affected delta lake by anthropogenic impacts [17].

Abu Qir Bay is a shallow basin lying 35 km east of Alexandria City. The Bay receives various types of wastewaters from three sources, namely El-Tabia Pumping station, Boughaz El-Maadia, and Rosetta at the mouth of the Nile River. It has an area of 500 km^2 with an average depth of 12 m and a shore line of 50 km long. Approximately 3.3 million $m^3\ d^{-1}$ of brackish water is introduced into the Bay from Lake Edku through Boughaz El-Maadia [18].

2.2 *Sediment sampling and analysis*

Nineteen surface sediment samples were taken to a depth of 10 cm from Lake Edku and Abu Qir Bay, using a van Veen grab. Samples were stored at 4 °C in a refrigerator. A sub-sample was taken to determine chemical and physical characteristics of the sediments such as particle size distribution, total organic matter, and calcium carbonate contents. Wet sieving was carried out to define the particle-size distribution. Water-content, organic-matter content, and carbonate-content measurements were based on ignition and weight losses after drying and combustion of the sediments at 105, 550, and 900, respectively. The loss in weight was calculated.

Total organic carbon (TOC) was assessed for oxidizable matter after treatment of the sample with chromic acid/H_2SO_4 according to the Walkley–Black method [19]. The concentrations of Ca, Mg, Fe, Mn, and Al were determined in the sediment after wet digestion with aqua regia for 2 h [20]. The determination of these elements was performed by AAS.

Total phosphorus was extracted by ashing the sample at 550 °C for 2.5 h and subsequent shaking with 1 mol l^{-1} HCl for 16 h [21]. Inorganic phosphorus was extracted by shaking the oven-dried sediment with 1 mol l^{-1} HCl for 16 h, and then phosphorus concentrations in the two extracts were determined using the acidic molybdate–ascorbic acid (AMAA) method [20]. Organic phosphorus was calculated from the difference between the total and inorganic phosphorus concentrations.

2.3 *Phosphorus bioavailability*

According to Zhou *et al.* [10], the chemically extractable phosphorus that is closely related to bioavailability of phosphorus in the sediments includes water-soluble phosphorus (WSP), readily desorbable phosphorus (RDP), algal available phosphorus (AAP), and $NaHCO_3$-extractable phosphorus (Olsen-P). Their analytical procedures were as follows.

2.3.1 Water-soluble phosphorus (WSP). One gram of wet sediment was placed into bottle and shaken in 100 ml of deionized water for 2.0 h on a reciprocating shaker at 25 °C [6].

2.3.2 Readily desorbable phosphorus (RDP). Two grams of wet sediment was placed into a bottle and shaken for 1.0 h with 50 ml of 0.01 mol l^{-1} $CaCl_2$ solutions [22].

2.3.3 Algal available phosphorus (AAP). Wet sediment (0.80 g) was placed in a bottle, and 200 ml of 0.1 mol l^{-1} NaOH solution was added; the bottle was then covered, and the sample was shaken for 4.0 h on a shaker [1, 23].

2.3.4 $NaHCO_3$ extractable phosphorus (Olsen-P). Wet sediment (2.50 g) was placed in a bottle, and the sample was shaken for 0.5 h with 50 ml of 0.5 M $NaHCO_3$ solution (pH 8.5) [8]. The suspensions in the four steps (WSP, RDP, AAP, and Olsen-P) were filtered through 0.45-μm-pore-size membrane filters. The filtrates were analysed spectrophotometrically for the soluble reactive phosphate in each fraction using the AMAA method [20]. The analytical results were normalized to air-dry weight.

2.4 *Multivariate statistical assessment*

Multivariate approaches (matrix correlation and principal-components analysis) were employed to interpret the data and to explore the relationships among the bioavailability of different phosphorus forms. The STATGRAPH plus 4.0 software package was employed for data analysis.

3. Results and discussion

3.1 *Sediment characteristics*

The particle-size distribution and the chemical component concentrations in Lake Edku and Abu Qir Bay sediments are presented in table 1. The sand fraction dominated in the sediments of the western region of Abu Qir Bay (85.5%) and the western area of Lake Edku (average 47.7%). Organic matter in the sediments ranged from 0.6 to 2.7% in Abu Qir Bay, and from 4.5 to 14.6% in the Lake sediments. The range and mean content of calcium carbonate were 4.2–14.3% (7.6%) for the Bay sediments, and 12.6–33.8% (21.4%) for the Lake. Total calcium concentrations were higher in sediments from Lake Edku, ranging from 1.12 to 2.34%, compared with those found in the Bay (0.47–0.87%).

3.2 *Total phosphorus, organic, and inorganic P concentrations*

The total phosphorus, organic, and inorganic P concentrations in Abu Qir Bay and Lake Edku sediments are shown in table 1. The results revealed considerable variation among sediments of the study areas. The total phosphorus concentration ranged between 257 and 1388 $\mu g\, g^{-1}$ (average 591 $\mu g\, g^{-1}$) and from 791 to 1451 $\mu g\, g^{-1}$ (average 1048 $\mu g\, g^{-1}$) for Abu Qir Bay and Lake Edku sediments, respectively. Generally, there was a high content of total-P in Lake Edku sediments. The mean value exceeded that reported by El-Sabrouti *et al.* [24], who showed that the majority of phosphorus fertilizer added to the soil is recovered in solution upon soil flooding and eventually finds its way to the lake through drainage water.

Table 1 shows the contents of organic and inorganic forms of phosphorus for the sediments of Abu Qir Bay and Lake Edku. In general, more phosphorus was found in both forms in the western area of Abu Qir Bay (Stations 2, 3, 4, and 5) compared with the eastern area

Table 1. Grain-size analysis, organic matter, $CaCO_3$, and total phosphorus concentrations in Abu Qir Bay and Lake Edku sediments.

	Grain-size distribution											
Site	Sand (%)	Silt (%)	Clay (%)	Organic carbon (%)	$CaCO_3$ (%)	Total Al (%)	Total Fe (%)	Total Ca (%)	Total Mn ($\mu g\,g^{-1}$)	Total P ($\mu g\,g^{-1}$)	Inorganic P ($\mu g\,g^{-1}$)	Organic P ($\mu g\,g^{-1}$)
Abu Qir Bay sediments												
1	92	6	2	1.18	5.69	0.33	2.6	0.63	214	249	179	70
2	89	8	3	1.52	4.93	0.39	3.3	0.48	240	446	249	197
3	75	17	8	1.13	5.29	1.45	3.0	0.56	217	530	318	212
4	80	15	5	1.42	14.32	1.69	3.2	0.87	312	688	428	260
5	90	6	4	1.08	10.50	1.55	3.0	0.72	220	651	446	205
6	87	8	5	1.25	7.58	1.36	3.1	0.61	254	449	229	220
7	78	12	10	0.32	6.35	0.42	2.8	0.59	265	205	188	17
8	65	23	12	0.51	7.54	0.53	2.7	0.47	216	187	160	27
9	69	21	10	0.48	5.98	0.39	2.9	0.52	247	157	127	30
10	73	19	8	0.54	4.23	0.41	2.7	0.75	208	162	132	31
Min.	65	6	2	0.32	4.23	0.33	2.6	0.47	208	157	127	17
Max.	92	23	12	1.52	14.32	1.69	3.3	0.87	312	688	446	260
Average	80	14	7	0.94	7.58	0.88	2.9	0.63	242.75	381	252	129
Lake Edku sediments												
I	53	30	17	3.2	12.6	2.06	3.1	1.31	135	837	753	84
II	47	25	28	4.8	14.3	2.28	3.2	1.24	141	1246	926	320
III	43	30	27	3.5	15.6	3.35	2.9	1.12	126	1070	947	123
IV	19	51	30	2.5	25.4	3.19	4.2	2.34	130	791	515	275
V	65	22	13	2.7	30.7	2.84	3.9	2.09	127	811	611	199
VI	14	65	21	6.2	33.8	2.76	3.6	2.16	233	840	594	245
VII	10	61	29	7.3	23.5	2.89	3.8	1.98	246	1386	681	705
VIII	13	42	45	7.1	16.8	3.05	4.7	1.78	276	856	593	262
IX	20	39	41	8.2	19.5	3.15	4.3	2.24	253	1451	521	930
Min.	10	22	13	2.5	12.6	2.06	2.9	1.12	126	791	515	84
Max.	65	65	45	8.2	33.8	3.35	4.7	2.34	276	1451	947	930
Average	32	41	28	5.1	21.4	2.84	3.7	1.81	185	1032	682	349

(Stations 7, 8, 9, and 10), and these high phosphorus contents were related to the direct impact of wastewater and solid materials from El-Tabia Pumping station as well as the drainage water from Lake Edku through Boughaz El Maadia. The sediments of Lake Edku were richer in organic and inorganic phosphorus; the range and average concentrations in $\mu g\,g^{-1}$ of organic P were 16.70–260 (129) for Abu Qir Bay and 84–930 (349) for Lake Edku. The inorganic P concentrations exceeded the organic P concentrations for the study area; this agrees with results of Moussa *et al.* [25]. Inorganic P ranged from 127 to 446 $\mu g\,g^{-1}$ (mean; 252 $\mu g\,g^{-1}$) and from 515 to 947 $\mu g\,g^{-1}$ (mean; 682 $\mu g\,g^{-1}$) for Abu Qir Bay and Lake Edku sediments, respectively.

The eastern side of Lake Edku was characterized with fine particles (silty clay; around 85%) and higher organic carbon content (7.53%). These results agree with those of El-Sabrouti *et al.* [24], who showed that the decomposition and excreta of indigenous organisms should contribute a significant portion of organic phosphorus. It is clear that the inorganic phosphorus in the lake sediments increased towards the open sea, and its concentration was greater (875 $\mu g\,g^{-1}$) in the western side of the lake than in the eastern region (598 $\mu g\,g^{-1}$). Phosphorus concentration in the sediments is controlled by a number of variables, including texture, Fe, Al, $CaCO_3$, organic matter, and pH [26]. These factors may affect the adsorption of inorganic P. In the eastern part of the lake, the decomposition of organic matter and release of CO_2 led to the decrease in pH and dissolution of $CaCO_3$. On the other hand, the western area was characterized by low organic carbon content (3.83%) and a relatively high pH (around 8.15). This may lead to phosphorus to combine with $CaCO_3$ to form apatite, and the solubility tends to decrease with increasing pH [27].

3.3 *Bioavailability of phosphorus forms*

Phosphorus in sediments can be considered as unavailable, potentially available and immediately available. Zhou *et al.* [10] showed that immediately available phosphorus in sediments is the most accessible form of phosphorus to algae, which equates to soluble inorganic phosphorus and almost exclusively orthophosphate. The concentrations of phosphorus in bioavailability forms in the sediments and their relative percentage from the total are shown in table 2 and figures 2–5.

3.3.1 Water-soluble phosphorus (WSP). Water-soluble phosphorus (WSP) is the fraction not retained by the sediments and is the best estimate of bioavailable phosphorus [3, 10]. This fraction comprised less than 1.5% of the total P. The WSP fraction was higher in Lake Edku sediments, ranging from 3.35 to 17.95 $\mu g\,g^{-1}$ with a relative percentage 0.39–1.49% compared with 0.72–6.50 $\mu g\,g^{-1}$ (0.14–1.46%) for Abu Qir Bay sediments.

3.3.2 Readily desorbable phosphorus (RDP). This fraction refers to phosphorus readily released from the sediments. The results revealed a low desorbable phosphorus extracted by $CaCl_2$ solution from the sediments of the lake and the bay. Phosphorus concentration in this form ranged between 0.30 and 1.63 $\mu g\,g^{-1}$ for Abu Qir Bay, and between 0.40 and 3.53 $\mu g\,g^{-1}$ for the Lake, and these values represent 0.05–0.73% of the total P for the two regions. This low recovery reflects the low extractability by $CaCl_2$ of sediment phosphorus and low content of phosphorus adsorbed on the sediment surfaces, and possibly the high calcium concentration is depositing the solubility of calcium phosphate. The phosphorus concentrations extracted by water are two to 20 times greater than those of the extracted by $CaCl_2$ solution.

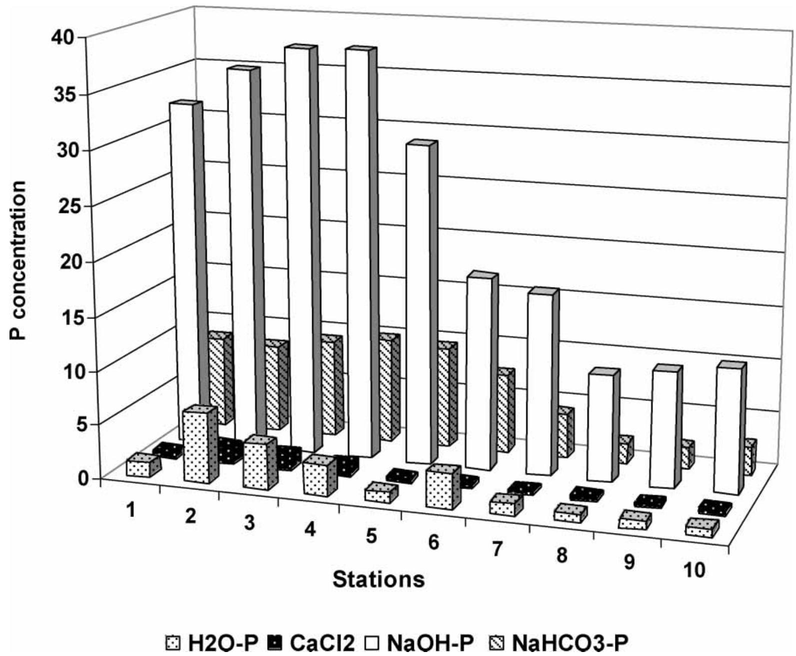

Figure 2. Distribution of bioavailable phosphorus forms ($\mu g\,g^{-1}$) in Abu Qir Bay sediments.

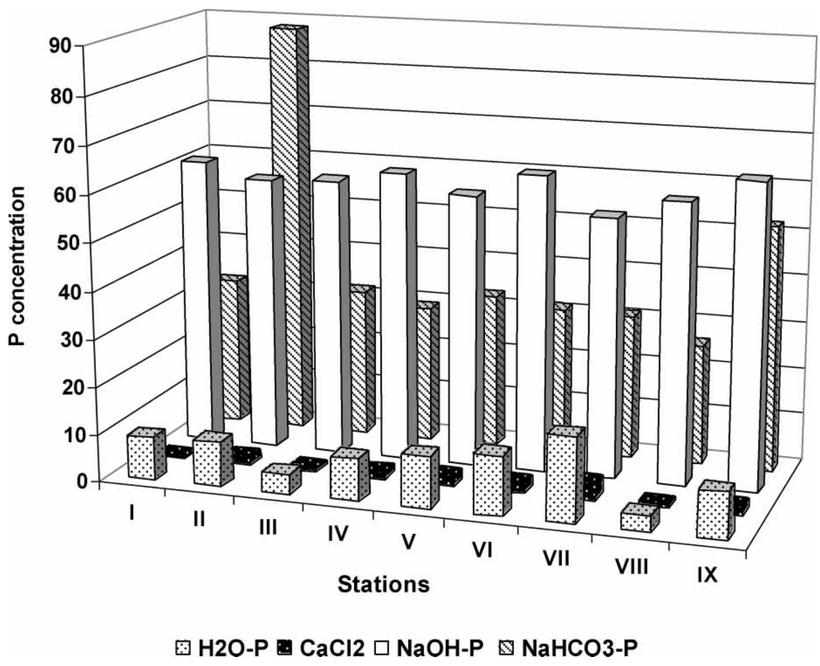

Figure 3. Distribution of bioavailable phosphorus forms ($\mu g\,g^{-1}$) in Lake Edku sediments.

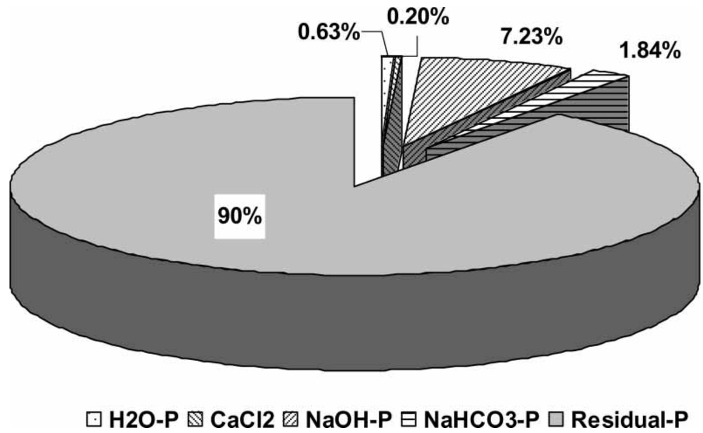

Figure 4. Average percentage of phosphorus forms in Abu Qir Bay sediments.

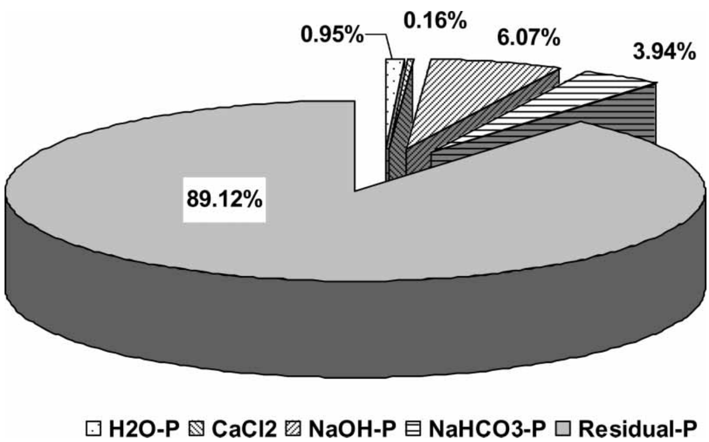

Figure 5. Average percentage of phosphorus forms in Lake Edku sediments.

3.3.3 Algal available phosphorus (AAP). NaOH-extractable phosphorus can be used for estimation of both short-term and long-term available phosphorus in sediments and is a measure of algal available-P [1, 10, 28]. Available phosphorus extraction by NaOH also represents phosphorus bound to metal oxides, mainly of Al and Fe, which is exchangeable with OH and inorganic P compounds soluble in bases [29]. NaOH solution gave the highest values compared with the other available fractions, ranging from 9.97 to 37.97 $\mu g\,g^{-1}$ for Abu Qir Bay, and from 54.9 and 64.3 $\mu g\,g^{-1}$ for Lake Edku (table 2). The range and the mean proportion of AAP to Total-P in sediments of Abu Qir Bay were 4.00–12.95% (7.23%) and in Lake Edku 3.96–7.76% (6.07%). Ting and Appan [30] showed that NaOH-extractable phosphorus could be released for the growth of phytoplankton when anoxic conditions prevail at the sediment–water interface. The premise that the fraction of NaOH contained organic *P* and associated with high-molecular-weight of humic components, this is substantiated by the correlation between the AAP and both organic matter content and the concentrations of the organic phosphorus ($r = 0.885$ and 0.862, respectively, significant at $P < 0.05$). This suggested that much of the NaOH-P is associated with the organic matter of the sediments.

A typical feature of Lake Edku is abundant vegetation which binds large amounts of nutrients; the P is removed by plant uptake, but after the growing season, vegetation decay occurs with subsequent release of phosphorus. The study by Carignan and Kalff [31] implied that 72% of the phosphorus needed for the growth of macrophytes originated from sediment. *Potamogeton pectinatus* L., *Ceratophyllum demersum* L., and *Phragmites communis* L. are common plants in the lake [32]. The markedly lower values of the relative percentage of the bioavailability of phosphorus obtained from Lake Edku compared with those in Abu Qir Bay may be related partly to the high total phosphorus content in Lake Edku. It is clear that the organic-matter enrichment in the sediments of the lake (4.46–14.6%) results from the accumulation of fresh macropyte debris and plays an important role in the bioavailability of phosphorus.

3.3.4 $NaHCO_3$ extractable phosphorus (Olsen-P). Olsen-P is a good index by which to represent the status of nutrients in soils and sediments. Thus, Olsen-P can also be regarded as a quantitative index of available phosphorus for algae to a certain extent [10]. Table 2 shows the amount of phosphorus extracted by $NaHCO_3$ solution from the sediments of the study area. The range and the mean concentrations of Olsen-P in Abu Qir Bay and Lake Edku sediments were 1.93–9.8 $\mu g\,g^{-1}$ (6.3 $\mu g\,g^{-1}$) and 25.7–88.2 $\mu g\,g^{-1}$ (42.2 $\mu g\,g^{-1}$), respectively. The proportion of Olsen-P to total-P in sediments of the Lake and the Bay was relatively high compared with those of WSP and RDP.

3.4 *Statistical analyses*

3.4.1 Principal-component analysis (PCA). The principal-component analysis (PCA) is a method of investigation of the structure of the data. Its aim is to exhibit the underlying

Table 2. Distribution of phosphorus bioavailability forms ($\mu g\,g^{-1}$) and relative percentage in Abu Qir Bay and Lake Edku sediments.

Site	H_2O-P	%	$CaCl_2$	%	NaOH-P	%	$NaHCO_3$-P	%	Total P
Abu Qir Bay sediments									
1	1.39	0.56	0.56	0.23	32.23	12.95	8.51	3.42	249
2	6.50	1.46	1.63	0.37	35.67	7.99	8.24	1.85	446
3	4.19	0.79	1.49	0.28	37.94	7.16	9.18	1.73	530
4	2.88	0.42	1.12	0.16	37.97	5.52	9.83	1.43	688
5	0.93	0.14	0.33	0.05	29.76	4.57	9.49	1.46	651
6	3.26	0.73	0.42	0.09	17.95	4.00	7.37	1.64	449
7	1.12	0.55	0.31	0.15	16.88	8.25	4.18	2.04	205
8	0.75	0.40	0.37	0.20	9.97	5.34	1.93	1.03	187
9	0.81	0.52	0.30	0.19	10.78	6.87	2.10	1.34	157
10	0.72	0.44	0.42	0.26	11.52	7.09	2.73	1.68	162
Min.	0.72	0.14	0.30	0.05	9.97	4.00	1.93	1.03	157
Max.	6.50	1.46	1.63	0.37	37.97	12.95	9.83	3.42	688
Average	2.48	0.63	0.74	0.20	24.05	7.23	6.28	1.84	381
Lake Edku sediments									
I	9.11	1.09	0.40	0.05	61.11	7.30	31.68	3.78	837
II	9.49	0.76	1.75	0.14	57.87	4.64	88.15	7.07	1246
III	4.19	0.39	0.81	0.08	58.75	5.49	31.42	2.94	1070
IV	8.93	1.13	1.48	0.19	61.34	7.76	28.93	3.66	791
V	10.93	1.35	2.11	0.26	57.51	7.09	32.78	4.04	811
VI	12.49	1.49	2.05	0.24	62.70	7.47	31.06	3.70	840
VII	17.95	1.30	3.53	0.25	54.88	3.96	30.75	2.22	1386
VIII	3.35	0.39	0.74	0.09	59.14	6.91	25.73	3.01	856
IX	9.77	0.67	1.95	0.13	64.25	4.43	52.00	3.58	1451
Min.	3.35	0.39	0.40	0.05	54.88	3.96	25.73	2.22	791
Max.	17.95	1.49	3.53	0.26	64.25	7.76	88.15	7.07	1451
Average	9.77	0.95	1.70	0.16	59.70	6.07	42.40	3.94	1048

dimensions in a data set and explore the relationships among individuals. PCA determines a small number of principal components that recover as much variability in the data as possible. These components are linear combinations of the original variables. In the present study, a PCA was used to extract the factors influencing the variance of P forms in the sediments of the study area. It is a powerful pattern-ecognition technique that attempts to explain the variance of a large set of intercorrelated variables with a smaller set of independent variables. Hopke [33] showed that the elimination of factors with eigenvalues less than 1 can lead to the exclusion of meaningless factors. The PCA was performed on the original data using the STATGRAPH plus-4 software package. The results are presented in table 3 for the sediment data set of the lake and the bay.

Two principal components accounted for 82.9% of the variance of data in Abu Qir Bay. The first PC_1 accounting for 68.8% of the total variance was correlated with NaOH-P, $NaHCO_3$-P, organic matter, and organic P. This revealed the important role of the organic matter in regulating of NaOH-P and $NaHCO_3$-P forms in Abu Qir Bay sediments. The second PC_2 accounting for 14.2% of the variance was correlated with total aluminium (T-Al), $CaCO_3$, and inorganic P. This factor might control the presence of the RDP form, probably represents the autochthonous precipitation of P, and could represent the sedimentary phosphorus due to erosion processes [28, 34].

Three PCs accounting for 85.4% of the total variance were identified in Lake Edku (table 3). The first, PC_1, accounts for 48.6% of the variance and was correlated with NaOH-P and $NaHCO_3$-P forms and organic matter, $CaCO_3$, organic P, total Al, and total Fe. The forms of NaOH-P and $NaHCO_3$-P seem to be the most reactive fraction in Abu Qir Bay and Lake Edku sediments. This could be interpreted in terms of the processes influencing the release of bioavailable phosphorus. These processes may include the settlement of plankton and fine-particle deposition where phosphorus is associated with organic matter, carbonates, and oxides [28, 35, 36]. The second PC_2, accounting for 20.6% of the variance, positively correlated with H_2O-P, $NaHCO_3$-P, and both organic matter and organic P. This is interpreted in terms of the relationships between the algal bioavailable phosphorus forms. The third, PC_3, accounting for 16.2% of the variance, was negatively correlated with H_2O-P and inorganic P (HCl-P). This showed that terrigenous phosphorus extracted with strong acids contains phosphorus forms

Table 3. Principal-components analysis showing component loading of available phosphorus forms and chemical characteristics of the sediments.

	Abu Qir Bay		Lake Edku		
Parameters	PC1	PC2	PC1	PC2	PC3
Eigenvalue	6.88	1.42	3.47	1.85	1.45
Percentage variance	68.81	14.15	48.56	20.59	16.18
H_2O-P	0.29	0.49	0.03	0.57	0.62
$CaCl_2$-P	0.29	0.54	0.18	0.26	0.12
NaOH-P	0.74	−0.06	0.82	0.21	0.35
$CaHCO_3$-P	0.68	0.13	0.71	0.51	0.42
Clay	−0.27	0.06	−0.42	0.08	0.49
Organic matter	0.76	−0.11	0.79	0.66	0.11
Total Al	0.26	0.54	0.41	0.32	0.9
Total Fe	0.31	−0.09	0.47	0.15	0.13
$CaCO_3$	0.28	0.65	0.73	0.32	0.08
Organic P	0.86	0.15	0.89	0.74	0.04
Inorganic P	0.31	0.82	0.39	0.19	0.82

that could be a possible source of bioavailable phosphorus, probably due to bacterial activity that could solubilize P compounds [28, 34].

4. Conclusions

The study of phosphorus forms and their bioavailability is a good way to understand the origins and transformations in the sediments of the study area. These forms of phosphorus may be released into the water column of the bay or the lake with changes in environmental conditions. Also, the results proved that Lake Edku is a source of organic phosphorus to Abu Qir Bay. In general, the high proportion of organic phosphorus in the lake sediments may be an important source of phosphorus release to the bay. The PCA showed that the NaOH-P and $NaHCO_3$-P extractable forms were the most reactive fractions in Abu Qir Bay and Lake Edku sediments, and these could be related to processes influencing the release of bioavailable of phosphorus. These processes may include the settlement of plankton and fine-particle deposition where phosphorus is associated with organic matter.

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