

1 **Potentially Toxic Elements in Saltmarsh Sediments and Common Reed (*Phragmites australis*) of**
2 **Burullus Coastal Lagoon at North Nile Delta, Egypt: A Survey and Risk Assessment**

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33 **Abstract**

34 Burullus Lagoon is the second largest lake in Egypt. However, there has never been a comprehensive
35 survey which studied nineteen potentially toxic elements in sediments and plants and evaluated the
36 associated potential risk. Thus, we aimed to study the total and potentially available content of As, Al,
37 Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Sb, Se, Sn, Tl, V, and Zn in the sediments and common reed
38 (*Phragmites australis*) at thirty two sites along the entire lagoon and connected drains. Contamination
39 Factor (CF), Pollution Load Index (PLI), Geo-accumulation Index (I_{geo}), and Enrichment Factor (EF)
40 were calculated to assess the grade of contamination. Element accumulation factor (AF) and bio-
41 concentration ratio (BCR) were also calculated. Aluminium showed the highest median (mg kg^{-1}) total
42 content (41,200), followed by Fe (30,300), Mn (704.7), V (82.0), Zn (75.5), Cr (51.2), Cu (47.8), Ni
43 (44.3), As (31.9), Tl (24.6), Co (21.4), Se (20.3), Sb (17.6), Sn (15.6), Mo (11.3), and Hg ($16.6 \mu\text{g kg}^{-1}$).
44 Values of the EF, CF, and I_{geo} showed that the sediments were heavily contaminated with As, Sb, Se, Tl,
45 Mo, Sn, Co, Ni, and Cu. The drained sediment had significantly higher values of total and potentially
46 available element content than the lagoon sediments. Sediments of the middle and western area showed
47 significantly higher contents of total and available elements than the eastern section. The BCR and AF
48 values indicate that the studied plant is efficient in taking up high amounts of Zn, Fe, As, Sn, Tl, Ni, Mo,
49 Mn; then Co, Cu, and V. The results exhibit a dramatic contamination at certain sites of the lagoon, and
50 the studied PTEs have a predominant role in contamination-related ecological risk. Further investigations
51 concerning redox-induced mobilization of PTEs in sediments, the risk of fish contamination and the
52 potential health hazards are highly recommended.

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54 Keywords: Wetlands; Toxic metal(loid)s; Contamination indices; Accumulation factors.

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59 1. Introduction

60 Burullus lagoon is a UNESCO-protected Area in the north of Nile Delta, Egypt. This lake supplies a
61 considerable percentage of the annual Egyptian fish yield. Thus, there is a considerable health risk when
62 these lagoon sediments have high levels of potentially toxic elements (PTEs). The lagoon receives
63 drainage water through several drains (El-Badry and Khalifa, 2018). The water sources for the lake are
64 mainly derived from agricultural drainage, municipal sewage, and industrial wastewater (Gu et al., 2012).
65 Therefore, the lake environment is vulnerable to environmental changes particularly related to enhanced
66 anthropogenic pressure (Eid and Shaltout, 2004; Nassar and Gharib, 2014) such as agricultural, industrial
67 and sewage discharge and fishing activities (Okbah and Hussein, 2006; Abukila, 2015).

68 Wetland sediments are important sinks for PTEs and play a significant role in the remobilization of
69 contaminants in aquatic ecosystems under certain conditions (Ali and Fishar, 2005; Ghosh et al., 2018).
70 Information on PTEs, in particular some emerging contaminants such as Se, Sb, Sn, Th, and V in coastal
71 lagoon sediments and plants, is still limited. Although some authors (e.g., Chen et al., 2010; Gu et al.,
72 2012; El-Badry and Khalifa, 2018) studied partially a few elements at certain sites in the Burullus lagoon,
73 there is no comprehensive study which would link nineteen PTEs in sediments and plants in this lake
74 with the associated potential risk. Therefore, we aim 1) to study the total and potentially available content
75 of As, Al, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Sb, Se, Sn, Tl, V, and Zn in the sediments and common
76 reed in the Burullus lagoon, 2) to assess the grade of contamination and the associated eco-toxicological
77 risk using different contamination indices such as Contamination Factor (*CF*), Pollution Load Index
78 (*PLI*), Geo-accumulation Index (I_{geo}), and Enrichment Factor (*EF*), and 3) to investigate the suitability of
79 common reed as a hyperaccumulator of the studied PTEs using the accumulation factor (*AF*) and bio-
80 concentration ratio (*BCR*) indices.

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85 **2. Materials and methods**

86 **2.1 Study area and sampling**

87 The Burullus Lake is located in the Kafr El-Sheikh governorate at the north of the Egyptian Nile Delta
88 (31° 14' 60" N and 31° 14' 60" E) (Appleby et al., 2001). The lagoon extends between 31° 22' - 31° 26' N
89 and 30° 33' – 31° 07' E (Fig. 1). The entire lake is 47 km long and about 5 km wide, and has a water
90 surface area of about 440 km² (Chen et al., 2010). The lagoon is connected to the Mediterranean Sea with
91 a small waterway called Al-Bughaz (Fig. 1). In the southern part of the lagoon, many drains are connected
92 the Burullus lagoon. Through these drains, untreated agricultural, domestic, and industrial drainage from
93 the local towns and villages directly flow into the lagoon. We divided the studied area into six sections as
94 follows: 1) all (include the lake and the drains), 2) drains (include the drains connected with the lake), 3)
95 lake (include the lake without the drains), 4) eastern sector (include the lake and drains in the eastern part
96 of the studied area), 5) middle sector lake (include the lake and drains in the middle part of the studied
97 area), and 6) western sector (include the lake and drains in the western part of the studied area) (Fig.1).

98 Thirty-two sampling sites were selected across the lagoon and its main drainage water supplies during the
99 period from March 1 to June 1, 2014. Samples of sediments and common reed (*Phragmites australis*)
100 plants were collected in triplicates of each site resulting in ninety six samples in total. The sediment
101 samples were collected from the surface layer (0-10 cm) using polyvinylchlorid (PVC) cores. The
102 sediments were morphologically described; thereafter the samples were placed into plastic bags. Whole
103 plants of common reed were collected, washed using the lake water, and placed into plastic bags.

104 [Insert Figure 1]

105 **2.2 Preparation and characterization of studied samples**

106 The sediment samples were homogenized, air-dried, crushed, and passed through a 2-mm sieve. Salinity,
107 pH, and total organic carbon of the ninety six sediment samples were analysed. Sediment pH was
108 measured in 1:1 (w/v) suspension using a calibrated pH-meter (JENWAY 3510). The salinity was
109 measured using EC-meter (MI 170, Italy). Organic carbon was determined by loss on ignition using a
110 muffle furnace at 500°C for 5 hours (Cambardella et al., 2001). The sediment texture was identified by

111 finger test (Whiting et al., 2016). The plant biomass of the common red was thoroughly washed with 1 M
112 HCl; thereafter deionized water, and dried to constant weight at 70 °C with a force-drought oven. The
113 samples of the dry biomass were grounded to fine powder in a stainless steel grinder.

114

115 **2.3 Extraction and analysis of PTEs in sediment and plant samples**

116 Sediment samples were digested in an advanced microwave digestion system (Milestone; ETHOS EASY,
117 Germany) to determine the pseudo-total element concentrations (US EPA 3051a, 2007). Total content of
118 Hg in sediment samples were measured using a direct mercury analyzer (DMA-80, Milestone Inc.,
119 Sorisole, Italy). The potentially available form of the elements (except for Hg) was extracted using a
120 solution of ammonium bicarbonate (1M NH₄HCO₃) - diethylene tri amine penta acetic acid (0.005 M
121 DTPA) (AB-DTPA) according to Soltanpour and Schwab (1977).

122 One gram of the plant material was dry-ashed in a muffle furnace at 450°C for five hours, extracted with
123 20% hydrochloric acid (Jones et al., 1991) to analyse the plant tissue concentrations of the studied
124 elements. The element concentrations in the sediment and plant samples were measured by ICP-OES
125 (Ultima 2, Horiba Jobin Yvon, Unterhaching, Germany).

126

127 **2.4 Quality control and statistical analyses**

128 Quality control of the extraction efficiency of the pseudo-total element concentrations was performed
129 using certified soil reference materials (CRM051 and CRM042) obtained from the Labmix24 GmbH,
130 Germany. The average recovery of the studied elements ranged between 86 and 101%. To ensure that the
131 results were reliable, blank and triplicate measurements were employed during the analyses. Standard
132 solutions (Merck) of the elements were used to guarantee high-quality results. The maximum allowable
133 relative standard deviation (RSD) among replicates and was set to 15 % for sediments and plant analyses.
134 The detection limits were 28 µg L⁻¹ for Al, 10 µg L⁻¹ for As, 2.7 µg L⁻¹ for Cd, 7.0 µg L⁻¹ for Co, 7.1 µg L⁻¹
135 ¹ for Cr, 5.4 µg L⁻¹ for Cu, 12 µg L⁻¹ for Mo, 10 µg L⁻¹ for Ni, 1.5 µg L⁻¹ for Se, 6.25 µg L⁻¹ for Sn and
136 Sb, 12.5 µg L⁻¹ for Ag and Tl, 7.5 µg L⁻¹ for V, and 1.8 µg L⁻¹ for Zn. Values below the detection limit

137 were as equal to 1/8 of the detection limit for statistical purposes. The statistical analyses were carried out
138 using IBM SPSS Statistics 23 (NY, USA). The means for the variables were tested using a one-way
139 ANOVA with Duncan's multiple range tests at a significance level of 0.05. OriginPro 9.1 b215
140 (OriginLab Corporation, Northampton, USA) was used to create the figures.

141

142 **2.5 Sediment contamination and risk assessment indices**

143 We calculated the following indices to assess the risk by the PTEs studied:

144 **2.5.1 Contamination Factor (CF):**

145 The CF is calculated according to the following equation as reported in [Islam et al. \(2015a,b\)](#) and
146 [Antoniadis et al. \(2017a,b\)](#):

$$147 \quad CF = C_s / C_{ReIS}$$

148 where C_s is total element concentration in the sediments; C_{ReIS} is the background reference element
149 concentration in uncontaminated sediments. The background reference concentrations were obtained from
150 [Kabata-Pendias \(2011, p. 41\)](#) as “crustal average“(Table 1). We have used these background reference
151 concentrations due to the lack of local element background information and also to have a uniform scale
152 for all elements studied, because some emerging contaminants such as Se, Sb, Sn, and Tl have no
153 reported background value in sediments ([Birch , 2017](#)). The contamination level according to the CF
154 value may be classified as follows: low degree ($CF < 1$), moderate degree ($1 \leq CF < 3$), considerable degree
155 ($3 \leq CF < 6$), and very high degree ($CF \geq 6$) ([Luo et al., 2007](#); [Shaheen et al. 2017a](#); [Ghosh et al., 2018](#)).

156

157 **2.5.2 Pollution Load Index (PLI)**

158 The *PLI* is defined as the n^{th} root of the multiplications of the contamination factor of elements ([Bhuiyan](#)
159 [et al., 2010](#); [Islam et al., 2015a,b](#); [Shaheen et al., 2018](#)):

$$160 \quad PLI = (Cf_{s,1} \times Cf_{s,2} \times \dots \times Cf_{s,n})^{1/n}$$

161 where $Cf_{s,1}, Cf_{s,2}, Cf_{s,n}$ are the element CF; 1, 2, ..., n , and n is the number of measured elements.

162

163 **2.5.3. Enrichment Factor (EF):**

164 The enrichment factor (EF) is calculated by normalizing the given elements concentration in sediments to
165 concentration of Al (Islam et al., 2015a; Antoniadis et al., 2017a,c):

166
$$EF = (C_S/AI_S)/(C_{RefS}/AI_{RefS})$$

167 where AI_S is total Al concentration in the sediments, and AI_{RefS} is the background reference value of Al
168 (taken as equal to 20000 mg/kg). We have used 20,000 mg kg⁻¹ as reference value of Al because
169 Salminen et al. (2004) reported that the value 0.2% (20,000 mg kg⁻¹) is the lowest median total content of
170 Al in the stream and floodplain sediments. In addition the lowest value of total Al in the studied lake
171 sediments (except for three sandy texture samples) is 21,100 mg kg⁻¹; thus we considered 20,000 mg kg⁻¹
172 as background value of Al in the studied sediments. Generally, an EF value of 1.0 suggests that a given
173 PTE may be entirely from crustal materials or natural processes of weathering (Rashed, 2010). The EF
174 value ranges of 1.5–3, 3–5, 5–10 and > 10 is considered as evidence of minor, moderate, severe, and very
175 severe contamination, respectively (Islam et al., 2015b).

176

177 **2.5.4. Geo-accumulation Index (I_{geo}):**

178 The I_{geo} is calculated according to the following equation:

179
$$I_{geo} = \log_2 (C_S/1.5C_{RefS})$$

180 The level of contamination as recorded by I_{geo} is indicated by Latin numbering, as follows:

181 Class I: $I_{geo} < 0$, class II: $I_{geo} = 0-1$, class III: $I_{geo} = 1-2$, class IV: $I_{geo} = 2-3$, class V: $I_{geo} = 3-4$, class VI: $I_{geo} = 4-5$,

182 and class VII: $I_{geo} > 5$ (as per Kasa et al., 2014; Li et al., 2014; Yakun et al., 2016; Ghosh et al., 2018).

183

184 **3. Results and discussion**

185 **3.1. Characterization of studied sediments**

186 The studied sediments were alkaline with pH values ranging from 7.1 to 9.1, with a median value of 8.1.

187 The median pH value of the sediments in the middle section of the studied lake and drains was lower than

188 that of the other parts (Fig. 2). The sediment alkalinity might be explained by its high content of

189 carbonates originating from the carbonaceous broken shells and the high salinity, in particular water
190 soluble and exchangeable sodium content (Shaheen et al., 2013). The sediment salinity showed high and
191 significant variety and ranged between 0.8 dS m⁻¹ and 14.5 dS m⁻¹. The highest values of sediment salinity
192 were recorded in the middle section, while the lowest were in the western section (Fig. 2). The sites close
193 to the Mediterranean Sea (e.g., sites No. 8 and 15) showed higher salinity than the other sites, which
194 might be due to the seepage of the highly saline sea water. The lake receives high amounts of saline
195 drainage water from the agricultural drains, which might be also another reason for the high salinity of
196 lake sediments. The sediments were poor in their organic matter content (0.2-2.7%; Fig. 2). The
197 sediments of the middle section showed the highest percentages of organic matter, while the lowest ones
198 were in the eastern part. The higher value of OM in the middle section of the lake might be explained by
199 the higher growing biomass in this section than the other margins sections. The high content of organic
200 matter in the middle part may be probably assisted by the expected biological activity in the upper
201 sediment part caused by the establishment of grown plants. Plant residues especially contribute
202 considerably high organic matter levels. The sediments had a silty / clayey texture in all sites except for
203 sites number 5, 25, and 29, which had a sandy texture (data not shown). Our findings corroborate with
204 those of Chen et al. (2010) and El-Badry and Khalifa (2017), who conducted work in the same area.

205 [Insert Figure 2]

206 The sediments (except for the sandy texture sites number 5, 25, and 29) were rich in the total content of
207 Al and Fe. Iron showed higher total content (2.2 g kg⁻¹ to 61.2 g kg⁻¹) than Al (1.4-58.3 g kg⁻¹) (Fig. 2).
208 The middle section sediments contained the highest median value of total Al and Fe content, while the
209 eastern section sediments contained the lowest median concentrations of both elements (Fig. 2). This
210 likely indicates differences in sediments concerning (hydr)oxides contents. Mean values of total Al
211 differed significantly only between the middle and the eastern part, while Fe content was without
212 significant differences between the sections. The high contents of total Fe and Al in the lake clayey
213 sediments could be explained by the dominance of phyllosilicate minerals and the hydrous oxides of iron
214 and aluminum. High values of total contents of Al and Fe in the lake sediments are in agreement with

215 those reported by [Chen et al. \(2010\)](#) and [Gu et al. \(2012\)](#) in works that have been conducted in the same
216 area. Consequently, the large differences in the above mentioned properties are expected to affect the total
217 and potentially available PTE concentrations among the lake sites.

218

219 **3.2. Total content of PTEs in the sediments**

220 Total content (mg kg^{-1}) of the studied PTEs (As (2.4-59.7), Co (1.4-37.3), Cr (1.4-37.3), Cu (2.2-103.5),
221 Mn (100.3-1897.8), Mo (0.51-19.8), Ni (2.4-82.2), Sb (0.82-32.9), Se (1.2-39.3), Sn (≤ 0.07 -30.7), Tl (1.1-
222 50.1), V (8.4-154.5), and Zn (5.8-156.8)) ranged widely in the studied lake and drains sediments (Fig. 3).
223 Mercury showed the lowest concentrations and varied from $1.6 \mu\text{g kg}^{-1}$ to $65.5 \mu\text{g kg}^{-1}$. The order of the
224 elements based on their total median content (mg kg^{-1}) was as follows: Manganese showed the highest
225 median content value (704.7), followed by V (82.0 mg kg^{-1}), Zn (75.5 mg kg^{-1}), Cr (51.2 mg kg^{-1}), Cu
226 (47.8 mg kg^{-1}), Ni (44.3), As (31.9), Tl (24.6), Co (21.4), Se (20.3), Sb (17.6), Sn (15.6), Mo (11.3), and
227 Hg ($16.6 \mu\text{g kg}^{-1}$) (Fig. 3). Total content of Cd was lower than the detection limits ($2.7 \mu\text{g L}^{-1}$) in all sites
228 except for drain 9 (site no. 16).

229 The drains sediments contained higher median concentrations of all studied elements (except for Hg) than
230 the lake sediments (Fig. 3). Among the studied drains, sediments of drain 9 (site 16) and drain 8 (site 19)
231 contained the highest total concentrations of all studied elements (except for Hg). High concentrations of
232 these elements in the drains, in particular drains 9 and 8, are closely related to domestic and industrial
233 wastewater discharges in these drains, particularly in densely populated catchments ([Chen et al., 2010](#);
234 [Ali, 2011](#); [Abukila, 2015](#); [El-Badry and Khalifa, 2017](#)). Among the lake sections, the middle and western
235 sections showed higher median concentrations of As, Cu, Mo, Sb, Se, Sn, Tl, V, and Zn than the eastern
236 section (Fig. 3). Thus, the significant increases in PTEs pollution recorded in the western part of the lake
237 can be attributed to the increase of the pollutant load to the lake from these drains ([Abukila, 2015](#);
238 [Shaheen and Tsadilas, 2009](#)).

239 The sandy sites (sites No. 5, 25, and 29) contained lower concentrations of all elements than the clayey
240 sites, which may indicate the significant contribution of geogenic sources in element enrichment in the

241 clayey sediments. The close elemental and clay mineralogical association in different sediments is well
242 reported (e.g., Hooda, 2010; Kabata-Pendias, 2011; Vuba et al., 2015). Positive relations between clay
243 content and total element concentrations in sediments and soils were reported in many studies (e.g.,
244 Shaheen et al., 2017b; Shaheen and Rinklebe, 2017).

245 [Insert Figure 3]

246 The total content of all elements (except for Hg) correlated positively with total Fe (with r values ranged
247 between 0.79** and 0.96**) and all elements with total Al (r = 0.79** - 0.94**). Chromium, Co, Ni, V, and
248 Zn were more closely correlated with total Fe than Al, while As, Cu, Sb, Se, Sn, Tl, and Hg had better
249 correlation with total Al. The substantial impact of total Fe and Al and their oxides on the studied
250 elements indicates that these elements are strongly associated (bounded and/or occluded) with Fe-Al
251 oxides and tends to replace Fe and Al in crystal structures. For example, elements such as V, Cr, and Fe
252 are reported to be closely associated and usually co-exist in sediments/soils (Edwards et al. 1995; Aide
253 2005; Rinklebe et al., 2016; Shaheen and Rinklebe 2017).

254 Also, the positive correlations between the elements (except for Hg) and sediment organic matter (r = 0.64
255 – 0.82; $P \leq 0.05$) point to the association of those elements with sediment organic carbon and their
256 possible distribution in the organic fraction as suggested by Shaheen and Rinklebe (2014) for Cu and Zn,
257 and by Shaheen et al. (2017b) for As. Also, Shaheen et al. (2017a) found that the total concentrations of
258 Al, Cd, Cr, Cu, Fe, Mn, Ni, and Zn were higher in a soil rich in organic carbon than in an adjacent soil
259 poor in organic carbon. Moreover, Zhou et al. (2018) supported the crucial role of OM in the distribution
260 of Cd and Zn. The maximum total content of all PTEs (except for Hg) in the studied sediments was
261 higher than the average crustal content (Table 1). Maximum values of total As, Cu, Hg, Ni, V, and Zn
262 were higher than the upper continental crust composition. Also, maximum values of total Cu, Mn, Ni, V,
263 and Zn in the studied sediments were higher than their content in the shales (Table 1).

264 [Insert Table 1]

265 The level of PTEs in sediments at the studied sites was evaluated by the ERL (effects range low) and
266 ERM (effects range medium) analysis (Table 1) as described by Long et al. (1995) and reported in Coynel

267 [et al. \(2016\)](#) and [DeLaune et al. \(2016\)](#) . [Long et al. \(1995\)](#) identified nine PTEs (Ag, As, Cd, Cr, Cu, Hg,
268 Ni, Pb, Zn) that were observed to have ecological or biological effects on organisms (in sediments). The
269 ERL values are defined as the lowest concentration of an element that produced adverse effects in 10% of
270 the data reviewed whereas the ERM data designates the level at which half of the studies reported harmful
271 effects. Element concentrations below the ERL value are not expected to elicit adverse effects, while
272 levels above the ERM value are like to be very toxic. Based on the ERL and ERM values, total Hg and Cr
273 contents were lower than the ERL values resulting in no eco-toxicological effects. Arsenic, Cu, and Zn
274 was below the ERM values, but greater than the ERL values, which would perhaps suggest that there
275 could be some toxicity under certain conditions. Nickel total content was higher than the ERM, which
276 indicates high toxicity of Ni under certain conditions ([US EPA, 2002](#)). Evaluation of the level of PTEs
277 based on the ERL and ERM indicates that the studied sediments are more contaminated by Ni, As, Cu,
278 and Zn than other marsh sediments in the Wax Lake Delta ([DeLaune et al., 2016](#)) and the Loire Estuary,
279 France ([Coynel et al., 2016](#)).

280 A large area of the studied lake was drained and used as a cultivated soil. Therefore, to assess the
281 contamination of the studied sediments as a soil, we compared the total content of the studied PTEs with
282 the world-soil average as reported in [Kabata-Pendias \(2011\)](#), and found that the total content of all PTEs
283 (except for Cr and Hg) in the studied sediments was clearly higher than the world-soil average content.
284 Also, the total content of all PTEs (except for Hg) in the studied sediments was clearly higher than the
285 maximum allowable concentrations of these elements in soils as reported in [Kabata-Pendias \(2011\)](#). This
286 is an indication of enrichment of these PTEs in the studied sediments.

287

288 **3.3 Contamination indices**

289 Sediment contamination indices may help in identifying the level of enrichment of a sediment/soil with
290 PTEs ([Birch, 2017](#)). We calculated the Contamination Factor (CF), Pollution Load Index (*PLI*),
291 Enrichment Factor (EF), and geo-accumulation index (I_{geo}). The sediments were enriched and
292 contaminated by the studied PTEs as indicated by the values of EF (Appendix A in Table S1), CF

293 (Appendix A in Table S2), I_{geo} (Appendix A in Table S3), and PLI (Fig. 4). A conclusion of the sediments
294 contamination degree based on the EF, CF, and the I_{geo} is included in Table 2.

295 [Insert Table 2]

296 [Insert Figure 4]

297 An EF value of 1.0 suggests that a given PTE may be entirely to sediments/soils from geogenic sources
298 (Rashed, 2010), while samples having $EF > 1.5$ are considered under human influence (Islam et al.,
299 2015a; Antoniadis et al., 2017a,c). The studied PTEs (except for Cr, Cu, Hg, and V) showed EF values
300 higher than 1.5. Values of the EF, CF, and I_{geo} (Table 2) showed that the sediments were severe/heavily
301 contaminated by As, Sb, Se, Tl, Mo, Sn; then these were followed by Co and Ni. Such results of high EF,
302 CF, and I_{geo} values exhibit a clear indication of dramatic contamination at certain sites as also agreed by
303 others (e.g., El-Badry and Khalifa, 2017; Ghosh et al., 2018).

304 To assess the pollution load in the sediments by all studied PTEs, the PLI was calculated and presented in
305 Figure 4. The high PLI is generated as a result of a multi-contamination by the studied elements
306 (Antoniadis et al., 2017a,b; Birch, 2017). The PLI values ranged between 0.27 and 8.4 with a median
307 value of 4.85 in the studied sediments. The PLI indicated that the studied sediments especially the drain
308 sediments were contaminated by the studied elements as shown by its values which were higher than
309 unity. However, As, Sb, Se, Tl, Mo, Sn contributed the highest CF values, followed by Co and Ni, and
310 Zn. Therefore, the contribution of As, Sb, Se, Tl, Mo, Sn to the sediment pollution was higher than that of
311 the other studied elements. This shows that sediment contamination of the studied areas constituted a
312 multi-element contamination case. Higher PLI values were observed in the drain sediments than the lake
313 sediments, in particular in the eastern area. Comparing the lake sections, the PLI values in the western and
314 middle parts were higher than in the eastern part (Fig. 4). The lower pollution load in the eastern section
315 might be due to the dilution of the contaminated water in the lake by the sea water, where the eastern part
316 of the lagoon is connected to the Mediterranean Sea with a small waterway called Al-Bughaz (Fig. 1).
317 The higher pollution load in the middle and western sections of the lake might be linked to down-stream
318 industrial activity discharged and deposited when the drains water/sediments (in particular drains No. 8

319 and 9) enter into the western and middle parts of the lake. The wastewater sources is encompassing all
320 discharge in the entire catchment area and it covers also industrial and domestic activities, agricultural
321 sources, discharge of wastes, and discharge of communal wastes. The connected drains with the lake
322 collect different types of agricultural, sewage, and industrial wastewaters through the industrial cities
323 north of Nile delta and also from the rural domestic activities along these drains.

324 The high EF, CF, I_{geo} , and *PLI* values indicate the significant contribution of the anthropogenic sources in
325 increasing these elements, in particular As, Sb, Se, Tl, Mo, Sn, Co, Ni, Cu, and Zn (Table 2), in the lake
326 and drain sediments. On other hand, the low EF, CF, and I_{geo} values of Cr, Hg, and V indicate that the
327 geogenic source might be the main source of these elements in the studied sediments (Rashed, 2010). As
328 for anthropogenic inputs, the industrial, municipal, and farm wastewater are the main sources of PTEs-
329 contaminated waters/sediments (Sorme and Lagerkvist, 2002; Houhou et al., 2009; Barakat, 2011). For
330 instance, widespread use of PTEs in electroplating, metal finishing, pigments, textile and dyeing, and leather
331 tanning industries, wood treatment using mixture of copper-chromium-arsenate, and electrical and electronic
332 equipment may increase the level of these elements in the industrial wastewaters. In this respect, Shaheen et
333 al. (2013) also found that the textile and dyeing factories wastewater contains high Cu and Zn contents.
334 Contamination of the wastewater and sediments by trace elements such as Sn might be due to using this
335 element in many industrial activities such as alloys and steels, coating layer for major industrial materials
336 made of iron and steel, polymer stabilizer, various medical uses, and in soap or food additive (Clifford et
337 al., 2010; Jennings 2013). The main sources of PTEs in municipality wastewater are institutions,
338 households and commercial buildings which could discharge large amounts of PTEs (Bolan et al., 2009;
339 Abe et al., 2012). The farm wastewater or effluents (for example, those coming from poultry, piggeries
340 and dairy farms) is contaminated with PTEs and used as irrigation water and discharged from the drainage
341 to the lake as mentioned above, which increase the levels of PTEs (Fig. 3) and organic matter (Fig. 2) in
342 the lake sediments (Bolan et al., 2009; Abe et al., 2012).

343

344

345 **3.4 Potential availability of the studied elements**

346 The potential availability of the studied elements was assessed using AB-DTPA according to [Soltanpour](#)
347 [and Schwab \(1977\)](#). The elements potential availability differed significantly among the elements and
348 studied sites (Table 3). The AB-DTPA- extractable concentrations of Cd, Cr, Sb, and Se were lower than
349 the detection limits in all sites. (Table 3). Iron showed the highest median potential availability, followed
350 by Mn, Cu, V, Ni, Co, and Mo (Table 3). The potential availability of all elements (except for As, Mo,
351 Sn, and Tl) was obviously higher in the drains than the lake sediments, and was also higher in the western
352 part than in the eastern part of the studied area.

353 **[Insert Table 3]**

354 The main reason for the high potential availability of Fe and Mn in the sediments might be due to their
355 high total content (Fig. 2). In addition, the continually flooded conditions in the lake and thus low redox
356 potential of the lake sediments (-1.2 to -52.5 mV) may cause reductive dissolution of Fe-Mn oxides and
357 consequently release of Fe and Mn in dissolved form, which increase their mobilization and potential
358 availability ([Shaheen et al., 2014a](#)). Also, increasing the mobilization of some other elements such as V,
359 Co, Ni, and Mo might be due to their high total content and their association to Fe and Mn oxides;
360 therefore, their release after the assumed reductive dissolution of the oxides ([Rinklebe and Shaheen,](#)
361 [2017a,b](#)). The AB-DTPA-extractable amounts of Mo, Ni, and V were positively correlated with the total
362 amounts of Fe ($r = 0.28^*$ for Ni; $r = 0.23^*$ for Mo; $r = 0.35^{**}$ for V) and Mn ($r = 0.29^*$ for Ni; $r = 0.57^{**}$ for
363 Mo; $r = 0.49^{**}$ for V). Also, the AB-DTPA-extractable amounts of Co, Mo, Ni, and V were positively
364 correlated with the AB-DTPA-extractable amounts of Fe ($r = 0.30^*$ for Co; $r = 0.41^{**}$ for Ni) and Mn ($r =$
365 0.65^{**} for Co; $r = 0.68^{**}$ for Ni; $r = 0.41^{**}$ for V). In this respect, [Shaheen et al. \(2014a\)](#) found that release
366 and mobilization of Fe, Mn, Co, Ni, and V were increased in lacustrine soil originated from similar
367 sediments around the studied lake. Also, [Shaheen et al. \(2014b\)](#) indicated the close association between
368 dissolved Fe, Mn, and Mo in fluvial sediments. During flooding of wetland sediments, formation of iron
369 oxyhydroxides is important in retaining PTEs in surface sediments/soils. When sediments become

370 reducing, the PTEs bound to Fe and Mn oxides are transformed into readily available forms due to
371 dissolution of Fe and Mn oxides (Rinklebe, 2017a,b).
372 The lower portion of available form of the studied PTEs in comparison to the total content may indicate
373 that the AB-DTPA was not able to extract a significant part from the mobile fraction of some elements
374 such as Cr and Se, which in agreement with what was reported before in similar sediments of the Nile
375 Delta by Shaheen et al. (2017b). Also, the lower portion of available form of the studied PTEs in
376 comparison to the total content may be explained by the high alkalinity (Fig. 2) of the studied sediments.
377 Negative relations between solubility of PTEs (except for Mo and V) are well-documented (Hooda, 2010;
378 Kabata-Pendias, 2011). On the other hand, increasing the potential availability of some elements such as
379 Mo and V might be explained by the higher pH, where these two elements have positive relations with
380 sediment pH as reported in other studies (e.g., Evans and Barabash, 2010; Shaheen et al., 2017b; Shaheen
381 and Rinklebe, 2017). For example Shaheen et al. (2017b) explained the higher relative mobilization of
382 Mo in sediments of the Nile River by the alkaline pH of these sediments. Sediment pH affects solubility
383 of PTEs, since H⁺ is a reactant in redox reactions. In addition, pH affects surface charge characteristics
384 and speciation of metal ions; thus, it influenced adsorption-desorption process of the involved ions of
385 those elements. Also, sediment pH may regulate other processes such as sulfide formation, which
386 indirectly influence the solubility of PTEs (Rinklebe, 2017a,b).

387

388 **3.5 Concentrations of the studied PTEs in common reed**

389 Plant tissue concentrations of the studied elements differed significantly based on each element and
390 between the studied sites (Fig. 5). The median plant tissue concentrations (mg kg⁻¹) of the elements were
391 1242.2 for Fe, 194.2 for Mn, 9.24 for Zn, 6.8 for Ni, 5.5 for Cu, 5.3 for V, 3.5 for As, 3.1 for Cr, 1.1 for
392 Sb, 0.85 for Mo, 0.67 for Co, and 0.61 for Tl (Fig. 5). The plant tissue concentrations of Al, As, Co, Cu,
393 Mn, Mo, S, Se, Tl, V, and Zn did not show significant variation among plants grown in the studied
394 sections. However, the concentrations of Cr, Fe, Ni, and Sb differed significantly among the plants grown
395 in the different lake sections (Fig. 5). The plants grown in the middle lake sections showed significantly

396 higher concentrations of Fe, and Sb than those in the other lake sections. The plants grown in the eastern
397 lake sections showed significant higher concentrations of Cr than the other lake sections. The plant
398 concentrations of all elements did not show significant correlations with the total element content.

399 [Insert Figure 5]

400 Plants showed higher As and Cu concentrations than the critical levels (1-10 for As and 15-20 for Cu) as
401 reported by [Kabata-Pendias \(2011\)](#). These results may indicate that common reed can grow on sediments
402 contaminated with As and Cu; therefore this plant seem to tolerate these elements to the given levels.
403 However, the common reed revealed element concentrations less than 1,000 mg kg⁻¹ of all studied
404 elements; thus, it is not considered as a hyperaccumulator of these elements ([Baker and Brooks 1989](#)).

405 The sediment-to-plant transfer factors, termed accumulation factor (AF) or bio-concentration ratio (BCR),
406 are indices for evaluating the transfer PTEs from sediment to plants ([Cui et al. 2004](#); [Twining et al., 2004](#);
407 [Kabata-Pendias, 2004](#)). Sediments-to-plant transfer factor can be used to estimate a plant's potential for
408 phytoremediation purpose ([Yoon et al. 2006](#); [Tomovic et al. 2013](#); [Shaheen and Rinklebe, 2015](#)). The bio-
409 concentration ratio was calculated according to [Wang et al. \(2006\)](#) as follows: $BCR = \text{mg element kg}^{-1}\text{plant} / \text{mg AB-DTPA-element kg}^{-1}\text{sediment}$. Plants exhibiting BCR values less than 1 are considered to
410 be unsuitable for phytoextraction ([Baker and Brooks 1989](#)). The studied plant BCR values were higher
411 than 1 with all detected elements and the median values were 1.15 for Cu, 1.03 for V, 1.85 for Co, 5.03
412 for Mn, 5.31 for Mo, 9.31 for Ni, 1936 for Fe, 20.2 for Tl, 33.2 for Sn, 1092.5 for As, and 2283.6 for Zn,
413 which means a high ability of these elements to be accumulated by the common reed.

415 We also calculated the accumulation factor (AF) as follows: $AF = \text{mg element kg}^{-1}\text{plant} / \text{mg Total-}$
416 $\text{element kg}^{-1}\text{sediment}$ ([Wang et al., 2006](#); [Shaheen and Tsadilas, 2009](#)). The AF values ranged between
417 0.03-18.7 for Mn, 0.1-17.2 for S, 0.04-2.33 for Ni, 0.0-2.2 for Cu, 0.02-1.59 for Zn, 0.0-1.22 for Tl,
418 0.010.99 for Mo, 0.01-0.84 for As, 0.0-0.71 for Sb, 0.01-0.51 for V, 0.0-0.51 for Co, 0.01-0.44 for Al,
419 and 0.01-0.27 for Fe, which means a high ability of the common reed to accumulate these elements .

420 Thus, based on the BCR and AF values, the studied plant was efficient in taking up many of the studied
421 elements as mentioned by [Eid and Shaltout \(2004\)](#).

422 **4. Conclusions**

423 We conclude that the sediments were severely contaminated by As, Sb, Se, Tl, Mo, and Sn, followed by
424 Co and Ni. The PLI indicated that the studied sediments, especially the drain sediments, were
425 contaminated by the studied elements, as exhibited by its values which were higher than unity. Evaluation
426 of the eco-toxicological effects of the studied PTEs based on the ERL (effects range low) and ERM
427 (effects range medium) indicated potential eco-toxicological effects of As, Cu, and Zn; also high toxicity
428 of Ni and no eco-toxicological effects of Cr and Hg under certain conditions in these sediments. The
429 portion of the potential availability of the elements of the total content was low, which might be due to the
430 alkalinity of the studied sediments. Based on the high values of BCR and AF, the common reed is
431 considered efficient in taking up many of the studied elements. Future studies elucidating the temporal
432 kinetics and release of PTEs from the sediments to solution under flooding conditions will offer a range
433 of scientific opportunities for a comprehensive understanding of the processes determining the dynamics
434 of these pollutants in wetland ecosystems. Also, further investigations concerning the risk of fish
435 contamination of this lake and the potential health hazards are highly recommended. Additionally,
436 mitigation strategies and routine monitoring programs should be developed so that necessary remediation
437 approaches may be employed to ameliorate these PTE-contaminated sediments.

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626 **Figure captions**

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628 Figure 1. Map of the studied area.

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630 Figure 2. Sediments pH, redox potential, salinity, organic matter content and total content of Fe
631 and Al in the studied lake and drains. Significance between values of the sediment properties and
632 element concentrations in the studied sections is indicated with the Duncan letters.

633

634 Figure 3. Total concentrations of the studied PTEs in the studied lake and drain sediments.
635 Significance between element concentrations in the studied sections is indicated with the Duncan
636 letters.

637

638 Figure 4. Pollution load index (*PLI*) of the sediments of 32 sites of the studied lake and drain
639 sediments. Significance between *PLI* values in the studied sections is indicated with the Duncan
640 letters.

641

642 Figure 5. Concentrations of the studied PTEs in the common reed grown in the studied lake and
643 drain sediments. Significance between element concentrations in the studied sections is indicated
644 with the Duncan letters.

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