Effects of pollution on hydrogeochemistry and water quality of the Damietta branch (Nile River, Egypt)

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ABSTRACT

Currently, different sources of contamination threaten water quality in Damietta, Egypt. The aim of this study was to assess the pollution, hydrogeochemistry and suitability for use in agriculture of water collected at seven stations along the Damietta branch of the Nile River. In addition to pH, temperature, dissolved oxygen (DO), and electrical conductivity (EC), levels of Mg$^{2+}$, Ca$^{2+}$, K$^+$, Na$^+$, Cl$^-$, HCO$_3^-$, SO$_4^{2-}$ and CO$_3^{2-}$ were measured. From the highest to the lowest, the concentrations of cations were Na$^+$, Ca$^{2+}$, Mg$^{2+}$, K$^+$, whereas those of anions were HCO$_3^-$, SO$_4^{2-}$, Cl$^-$ in water samples collected at seven stations along the Damietta branch. Moreover, water quality indexes, such as sodium percentage (Na%) ranged between 21.6 and 71.4, Kelly’s ratio from 0.37 to 3.85, sodium adsorption ratio (SAR) varied from 1.73 to 61.8, residual sodium carbonate (RSC) found to be in range of 0.2 to 3.8. Also, the potential salinity (PS) and permeability index (PI), magnesium hazard (MH), were calculated. Most samples (71%) belonged to the Mg–Ca–Na–HCO$_3$ watertype. Fertilization wastes were identified as the main contributors of alkaline earth metals, whereas ion exchange was the main source of alkali metals. This work also provides information on distinguishing geochemical behaviors and the pollution of water samples.

Key words: Damietta branch, hydrogeochemistry, pollution, water quality

INTRODUCTION

The Nile River is the main source of fresh water in Egypt (Abdel-Dayem 2011). Classified as a dry country, Egypt depends on a very limited availability of fresh water. Water availability might be further restricted after the construction of the El Nahda Dam in Ethiopia, which can exacerbate problems related to the lack of water in Egypt (El-Ezaby et al. 2010). The Nile River splits into two branches: the Rosetta branch and the Damietta branch. The Damietta branch flows through five governorates, where it is the only source of water for domestic, agricultural, municipal and industrial activities (Abdel-Dayem 2011). Contamination in the Nile is the biggest water-related challenge currently faced by Egypt, mainly because of population growth, urbanization and fast industrial development (Abdel-Wahaab & Badawy 2004; Redwan & Elhaddad 2016). As industrial development and economic growth advances, problems related to water contamination are aggravated (Ali et al. 2011). Environmental degradation caused by water contamination has a quite high cost with impacts on the quality of life and human health (Danyliuk et al. 2021; Tatarchuk et al. 2021). Water contamination not only reduces water quality, it threatens the health of aquatic organisms and disrupts the integrity of aquatic ecosystems (Mostafa & Abdelazim 2017). Closed freshwater systems, such as the delta of the Nile River, are especially susceptible to water quality deterioration. In the
delta, the use of water for irrigation and the flow from drainage canals reduce water quality to alarming levels (Said & Hamed 2006; Redwan and Elhaddad 2020). Furthermore, the Damietta branch receives contaminated water from domestic effluents and industrial sewages (Abdel-Wahaab & Badawy 2004). Therefore, monitoring water quantity and quality, as well as controlling the pollution of water resources, is one of the national goals for reaching sustainable progress in Egypt (Ibrahim & Elhaddad 2020). To adequately assess contamination, it is essential to describe the characteristics of water in the Damietta branch and evaluate its quality. Hence, the aim of this study was to evaluate water quality parameters of samples collected along the Damietta branch of the Nile by measuring their physicochemical and geochemical characteristics.

MATERIALS AND METHODS

Water samples were collected in clean polyethylene bottles (Al-Sabahi et al. 2009) during the winter of 2019 from seven stations: S1 (north of the delta barrage), S2 (near Banha City), S3 (Kafreshoukr), S4 (near MitGahamr), S5 (Talkha City), S6 (near Sherbeen City) and S7 (Damietta outlet). The first station, S1, was considered as the reference (control) sample (Figure 1), three samples from every station were taken.

After collection, samples were placed in insulated boxes and immediately transported to the lab. Temperature, pH, dissolved oxygen (DO) levels, and electrical conductivity (EC) were measured by a multi-probe system model Hydrolab Surveyor multi-probe system model Hydrolab Surveyor. Levels of potassium (K⁺), sodium (Na⁺), magnesium (Mg²⁺), and calcium (Ca²⁺) were determined using atomic absorption spectroscopy (AAS) (Perkin-Elmer Corp.). The levels of chloride (Cl⁻) and bicarbonate (HCO₃⁻) were assessed by titration, whereas that of sulfate (SO₄²⁻) was measured calorimetrically. Hydrogeochemical calculations based on the results were conducted using AquaChem software (Waterloo Hydrogeologic).

RESULTS AND DISCUSSION

The concentration of ions in samples collected along the Damietta branch varied widely among stations (Table 1). Levels of Na⁺, Mg²⁺, K⁺ and Ca²⁺ were the highest in samples from station S7, probably due to the proximity to seawater. From the highest to the lowest, the concentrations of cations were Na⁺ > Ca²⁺ > Mg²⁺ > K⁺, whereas those of anions were HCO₃⁻ > SO₄²⁻ > Cl⁻. The pH of water samples varied from 7.8 to 8.7. Electrical conductivity varied from 250 to
25,045 μS/cm. The simple measurement of the concentrations of individual ions is not sufficient for evaluating the suitability of water for use in agriculture irrigation. Therefore, we accounted for the effect of interactions among ions by calculating several water quality parameters.

**Water quality indexes**

The following water quality indexes were computed to assess the suitability of water samples for use in agriculture (Table 2): sodium percentage (Na%), permeability index (PI), sodium adsorption ratio (SAR), potential salinity (PS), magnesium hazard (MH), and residual sodium carbonate (RSC). These are key factors for defining the quality of water for irrigation.

**Sodium percentage (Na%)**

The content of sodium in water supplies for irrigation is usually expressed as sodium percentage (Na%). According to Wilcox (1955), Na% is a commonly used factor to evaluate the suitability of water for use in agriculture. Here, Na% was calculated using the following equation:

\[
Na\% = \frac{Na^+}{(K^+ + Na^+ + Ca^{2+} + Mg^{2+})} \times 100
\]

Based on the equation above, Na% in water samples from the seven stations ranged from 21.6 to 71.4%. Water with Na% below 60% is considered safe for irrigation purposes, whereas that with Na% >60% is not safe for irrigation. The reason is that high Na% levels cause soil deflocculation and reduces soil permeability (Arveti et al. 2011). Thus, the water collected at

| Stations | Na% | RSC | SAR | MH | Kiely ratio |
|----------|-----|-----|-----|----|-------------|
| 1        | 21.6| 0.2 | 1.73| 42.2| 0.37        |
| 2        | 31.6| 0.6 | 2.78| 43.89| 0.45       |
| 3        | 38.7| 0.8 | 2.78| 45.90| 0.56       |
| 4        | 42.8| 0.9 | 9.89| 50.98| 0.9        |
| 5        | 45.6| 1.8 | 13.89| 55.82| 1.8        |
| 6        | 60.8| 2.6 | 25.8| 57.34| 2.6        |
| 7        | 71.4| 3.8 | 61.8| 63.4 | 3.58       |

RSC, residual sodium carbonate; SAR, sodium adsorption ratio; MH, magnesium hazard.
S7 was unsuitable for irrigation, since its Na% reached 71.4%. Such a high Na% at station S7 is probably the result of the interaction with seawater.

**Sodium adsorption ratio (SAR)**

The evaluation of sodium hazard is essential for understanding the suitability of water for irrigation uses. In addition to Na%, sodium adsorption ratio (SAR) is one of the key parameters to measure sodium hazard (Brindha & Elango 2012), since sodium-affected soils are known to have low permeability (Todd & Mays 2005). Here, SAR values were calculated using the following equation (Hem 1992):

\[
SAR = \frac{Na^+}{[(Ca^{2+} + Mg^{2+})/2]^{1/2}}
\]

Richards (1954) classified water samples into four quality categories: excellent (SAR < 10), good (SAR = 10–18), fair (SAR = 18–26), and poor (SAR > 26). The SAR values of water samples collected at seven stations along the Damietta branch varied from 1.773 to 61.8. Since the highest value was observed at S7, the water from station cannot be safely used for irrigation.

Kelly (1940) and Wilcox (1958) used another approach to predict the hazardous effects of irrigation water containing sodium calculating the Kelly’s ratio (KR), which is the result of the following equation:

\[
Kelly\text{'}s \text{ ratio} = \frac{Na^+}{Ca^{2+} + Mg^{2+}}
\]

Kelly’s ratios above 1 indicate an excess of sodium in the sample. Hence, water is suitable for irrigation if its Kelly’s ratio is lower than 1, whereas it is unsuitable if the ratio is higher than 1. The Kelly’s ratios of water samples analyzed in this study varied from 0.37 to 3.85.

**Potential salinity (PS)**

The suitability of water for irrigation does not depend exclusively on the content of soluble salts (Doneen 1964). Since soluble ions, even at low concentrations, precipitate and accumulate in the soil, they can raise the salinity of the soil over time. In this context, the potential salinity (PS) of water is calculated using the following equation:

\[
PS = Cl^- + \frac{1}{4} SO_4
\]

The PS of water samples collected at seven stations along the Damietta branch varied from 1.12 to 217.23. These values are high, especially for S7, whose water is not suitable for irrigation purposes based on its PS value.

**Residual sodium carbonate (RSC) and permeability index (PI)**

Waterborne CO$_3^{2-}$ and HCO$_3^{-}$ interacts with Mg$^{2+}$ and Ca$^{2+}$ in soil, producing magnesite and calcite precipitates. The sodium adsorbed on soil particles causes harmful effects associated with sodium hazard, including soil aeration, reduced soil permeability and increased pH (Doneen 1964). Two water quality parameters have been used to evaluate the interaction between these ions (Ca$^{2+}$, Mg$^{2+}$, Na$^+$, HCO$_3^{-}$ and CO$_3^{2-}$): residual sodium carbonate (RSC) and permeability index (PI), which are calculated using the following equations:

\[
RSC = (CO_3^{2-} + HCO_3^{-}) - (Mg^{2+} + Ca^{2+})
\]

\[
PI = \frac{Na^+ + \sqrt{HCO_3^{-}}}{Mg^{2+} + Ca^{2+} + Na^+} \times 100
\]

The RSC values of water samples collected at seven stations along the Damietta branch varied from 0.2 to 3.833. Water can be categorized into three classes based on its PI: class I (PI > 75% maximum penetrability, suitable), class II (PI = 25–75%, good), and class III (PI < 25%, unsuitable). The first two classes are adequate for irrigation purposes.
The PI values of water samples collected at seven stations along the Damietta branch varied from 21.5 to 71.950%, and, thus, most were classified in class II as good for use in irrigation.

Generally, the values of RSC, PI, and SAR offer several insights into the quality of irrigation water, including information on the probability of the formation of magnesite and calcite precipitate in soil, and the occurrence of problems associated with salinity and alkalinity hazards. We analyzed the interplay between these parameters building a United States Salinity Laboratory (USSL) diagram (Figure 2). Salinity and alkalinity hazard category of water samples were distributed in C2–S1 (42.8%), C3–S1 (48.8%) and C4–S3 (14.2%). As expected, the water from S7 was placed in the C4–S3 section of the diagram, which was caused by its high sodium content and high salinity. Magesh & Chandrasekar (2011) highlight the deleterious effects of high salinity on cultivated plants, including ion toxicity, osmotic stress, and nutrient deficiency. Thus, according to the high salinity hazard evidenced by the USSL diagram, the water samples analyzed in this study are not suitable for use in agriculture, unless salinity monitoring systems are used. Considering that most samples were classified in class C3–S1, the continuous use of water from these sources will eventually raise the salinity and alkalinity of the soil.

**Magnesium hazard (MH)**

Magnesium and calcium are essential ions for agriculture and maintain a state of equilibrium in the aquatic environment. However, excessive magnesium levels in the ecosystem have adverse effects on crop yield. For this reason, magnesium hazard (MH) has been commonly calculated for water intended for irrigation using the following equation:

$$\text{MH} = \left[ \frac{\text{Mg}^{2+}}{[\text{Ca}^{2+} + \text{Mg}^{2+}]} \right] \times 100$$

The MH values of water samples collected at seven stations along the Damietta branch varied from 42.2 to 63.40. Some samples had MH levels higher than 50%, which are expected to have negative effects on harvest due to increased alkalinity (Jalali 2008). Such high MH values in water from the Damietta branch can be explained by the occurrence of dolomite in this region. Joshi et al. (2009) reported that high SAR values harmfully influence soil and harvest yield as soil salinity increases.

**Hydrogeochemical assessment**

Piper diagrams have been widely used to depict the chemical composition of water samples and graphically represent the association between ions in samples. This kind of graph can be used to identify differences and similarities between water samples (Todd 1980). The water samples collected at seven stations along the Damietta branch (Figure 3) fell in the Mg-Ca-Na-HCO3 type (71%) and Mg-Ca-Na-HCO3-Cl type (14%). Moreover, water from the last station (S7) was classified

**Figure 2** | United States Salinity Laboratory (USSL) diagram showing the relationship between sodium hazard, measured as sodium adsorption ratio (SAR), and salinity hazard, measured as electrical conductivity (EC).
as Na–Cl type (14%) due to its high salinity caused by the contact with seawater (Sharma et al. 2016). The main feature of water samples from the Damietta branch was the presence of HCO$_3$ as the main hydrochemical component. This indicates an important contribution of weathering in dissolving carbonates into the water, whereas magnesium, calcium, and sodium would come from various sources of mixed wastes (Ibrahim et al. 2017).

The availability of minerals, anthropogenic activities, and weathering are the main drivers of variation in the chemical composition of water (Keesari et al. 2014). The contribution of these processes is evident in the mixed water types, such as the Mg–Ca–Na–HCO$_3$ type. Considering that the Damietta branch region is muddy and has high availability of clay, ion exchange would be an important factor determining water quality (Manjusree et al. 2009). The main geochemical processes underlying the chemical composition of water in the Damietta branch are discussed below.

**Cation exchange**

The reactions between soil and water include ion exchange, which plays a major role in defining water quality (Hem 1985; Chidambaram et al. 2013). Plotting the content of (Ca$^{2+}$ + Mg$^{2+}$) versus (SO$_4^{2-}$ + HCO$_3^-$) revealed that the relationship between these two parameters has a slope lower than that of the equimolar line (Figure 4(a)). An equimolar distribution would indicate a major contribution of dolomite, calcite, and gypsum dissolution. However, most samples were below the equimolar line, indicating a higher concentration of SO$_4^{2-}$ and HCO$_3^-$ than that of Ca$^{2+}$ and Mg$^{2+}$. This could be caused by additional sources of sulfate (pyrite oxidation) and carbonate (organic matter oxidation), or cation exchange (Pant et al. 2019).

A similar approach was used to evaluate the relationship between (Na$^+$ + K$^+$) and Cl$^-$ (Figure 4(b)). All samples were above the equimolar line, indicating that Na$^+$ and K$^+$ would have an additional source, such as the weathering of silicate. Given that Cl$^-$ has a higher affinity for K$^+$ and Na$^+$ than that for Mg$^{2+}$, it is possible that Cl$^-$ may be found in the form of alkali chlorides and other alcalis. The high concentration of Na$^+$ and Cl$^-$ detected in water from S7 might be the result of the dissolution of chloride from seawater. Another source would be the dissolution of halite in water, which introduces equivalent amounts of Na$^+$ and Cl$^-$ into water.

**Evaporation**

Water evaporation increases the concentration of ions in the percolating water. If evaporation is the dominant geochemical process in a system, one should observe increases in EC without any change in Na$^+$/Cl$^-$ ratio (Reddy & Kumar 2010). Our data had a nearly linear relationship with a small inclination when Na$^+$/Cl$^-$ ratio was plotted against EC (Figure 5(a)). Such
Figure 4 | Relationship between the content of selected ions. (a) (Ca$^{2+}$ + Mg$^{2+}$) versus (SO$_4^{2-}$ + HCO$_3^{-}$). (b) (Na$^{+}$ + K$^{+}$) versus Cl$^{-}$.

Figure 5 | Relationship among the content of selected ions and electrical conductivity (EC). (a) Na$^{+}$/Cl$^{-}$ ratio versus EC. (b) Na$^{+}$ versus Cl$^{-}$. (c) (Ca$^{2+}$ + Mg$^{2+}$) versus HCO$_3^{-}$. 
pattern indicates a major role of evaporation, as well as the contribution of waste and drainage from agriculture. One well-known source of Na\(^+\) is NaNO\(_3\), which is a key ingredient of fertilizers and also found in domestic wastes (Jankowski & Acworth 1997; Kumar et al. 2007). The dominant contribution of evaporation is also corroborated by the relationship between the concentrations of Na\(^+\) and Cl\(^-\) (Figure 5(b)). Moreover, it indicates that Na\(^+\) and Cl\(^-\) are from a similar source (Elhaddad & Al-Zyoud 2017).

The influence of carbonate weathering was evaluated by plotting the content of (Ca\(^{2+}\) + Mg\(^{2+}\)) versus HCO\(_3\) (Figure 5(c)). The results from all samples were above the equilibrium line, indicating that the concentration of (Ca\(^{2+}\) + Mg\(^{2+}\)) does not depend on that of HCO\(_3\). Thus, a significant portion of (Ca\(^{2+}\) + Mg\(^{2+}\)) would have a non-carbonate origin, such as Cl\(^-\) and SO\(_4\)^{2-} salts (Abdalla & Shamrukh 2016).

**CONCLUSION**

In this study, we assessed hydrogeochemical parameters and water quality indexes of samples collected along the Damietta branch, Nile River, Egypt. The findings were used to identify major geochemical processes underlying water quality and characterize the suitability of the water for irrigation purposes. As evidenced in the Piper trilinear diagram, there was a wide variability in water quality across the sampling stations. Calcium and bicarbonates were identified as the most abundant ions. The high salinity of water from station 7 makes it unsuitable for irrigation or drinking. Water samples from S6 and S7 had high levels of RSC and Na\(_\%\), which can be explained by different sources of contaminated water streams that run into the river, making it unsuitable for irrigation. Mg–Ca–Na–HCO\(_3\) was the domain type of water in the Damietta branch. Cation exchange and evaporation were identified as the major geochemical processes affecting water quality in the area. Sources of Ca\(^{2+}\) and Mg\(^{2+}\) in this region include dolomite, calcite, and gypsum dissolution. The prominent sodium hazard of the water can affect crop yield and threatens local agricultural production.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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