



## Changes in Alluvial Soil Quality under Long-Term Irrigation with two Marginal Water Sources in an Arid Environment



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**T**HE CURRENT work aimed at verifying the modifications in chemical, physical, fertility, and environmental quality of alluvial soils south east of the Nile Delta of Egypt following 25-years irrigation using two marginal water sources; agricultural drainage water (ADW) and sewage effluent water (SEW). Two sites irrigated with ADW and SEW were chosen and compared with a nearby site irrigated with the Nile freshwater. At each site, ten samples of irrigation water and adjacent (around 50m) top soil (0 – 30 cm) were collected and analyzed. Marginal water irrigation caused slight changes in soil properties. The soil chemical quality index was adversely affected through increasing the pH, electrical conductivity, and exchangeable sodium percentage. Available micro-nutrients (Fe, Mn, Zn, and Cu) and P in SEW-irrigated soils were increased. The physical quality index was also increased, but mainly due to inherent soil properties (particle size distribution) rather than irrigation water. Parent materials governed soil total contents of Cr, Co and Ni, while contents of Cd, Cu, Pb, and Zn were closely related to irrigation water. The environmental quality index showed increasing trend in the ADW-irrigated soils, while a decrease in the SEW-irrigated soils. The marginal water irrigation resulted in positive changes in soil quality index exhibiting increases of 14 and 21% in the ADW- and SEW-irrigated soils over the Nile freshwater-irrigated soils, respectively. It is recommended to perform periodic monitoring for irrigation water and soil quality in the studied area. Proper in-situ remediation scenarios and on-farm practices should be considered in future management.

**Keywords:** Soil quality index, Marginal water irrigation, Alluvial soils, Nile Delta.

### Introduction

Soil is one of the most vital natural resources affecting human life (Iskan and Guler, 2021). It contributes to ecosystem services through several functions, including biomass production, improving ground - and surface water quality, carbon capture for climate mitigation, limiting emissions of the greenhouse gas, and biodiversity protection and enhancement (Chalhoub et al., 2020). The term “soil quality” is a concept describing soil competence to perform those functions. Thus, securing soil quality is essential for future planning due to its importance in achieving land-related sustainable development goals (Bouma, 2020).

In Egypt, the total cultivated area is 3.6 million ha, of which 89% are alluvial soils in the Nile Valley (43%) and Delta (65%) (Mohamed, 2019). However, water availability remains the major constraint for sustainable agricultural production (Zohry and Ouda, 2020). Egypt is one of the most arid regions of the world, where nearly 86% of its total land is hyper-arid and 14% is arid and semi-arid (Embabi, 2020). Thus, the country depends entirely on irrigated agriculture which consumes more than 85% of the available freshwater (Abdelhafez et al., 2020). This accelerates the dependence on alternative water sources in irrigation, including agricultural drainage water and treated sewage water (Elbana et al., 2019; Bassouny et al., 2020; Farid et al., 2020)

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Reusing drainage water has been adopted since the early seventies of the last century through mixing agricultural drainage water with the Nile freshwater in main and branch canals (El-Quosy, 2019). Unofficial reuse of drainage water by farmers is also done by direct pumping of such water without blending with freshwater (Elshemy, 2019). The quantity of annual reuse of drainage water is 13.1 billion cubic meters (BCM)(CAPMAS., 2019) that provides an integral supplement to the country's water supply. However, this water contains high soluble salts, nutrients, agro-chemicals, and pollutants (Abou-Elela, 2019). Salinity is one of the major challenges facing drainage water reuse in the Nile Delta, and thus uncontrolled irrigation using this water leads to soil salinity (El-Agha et al., 2020). El-Ramady et al. (2019) stated that the reuse of more than 10 BCM of saline drainage water coupled with poor drainage would lead to high salinity and sodicity of the Nile Delta alluvial soils.

Treated sewage effluent is a promising water supply in Egypt. According to FAO (2016), the total annual wastewater produced in Egypt is 7.1 BCM. Only, 4.0 BCM is subjected to treatments (primary, secondary, and/or tertiary), while 3.1 BCM does not receive any treatment. Elbana et al. (2019) reported that most treatment plants occur mainly in urban and to a some extent in peri-urban areas, while many rural communities in the Nile Delta lack such facilities. As a result, using raw or partially treated sewage effluent is practiced in irrigated arable lands. Abuzaid (2016) and Omran (2016) reported that using raw sewage effluents in irrigating alluvial soils increased their organic matter and nutrient contents. However, bioaccumulation of pathogens and toxicants remained a main drawback of such practice (Bassouny et al., 2020).

Changes in quality indicators of the Nile Delta alluvial soils under prolonged marginal-water irrigation have been increasingly studied (Elbana et al., 2017; Abuzaid 2018; Abd-Elwahed, 2019). These indicators were investigated separately with little attention to quantify the overall status of soil health; thereby performing its vital services. Soil quality index (SQI), as reported by Bhaduri et al. (2020), is a common methodology to gather individual parameters (indicators) in a single value representing soil function. It provides integrated information for temporal and spatial changes in soil performance in response to farming practices, e.g. irrigation. In this context,

the present study aimed at using SQI as a tool for investigating the impacts of irrigation using two marginal water sources; agricultural drainage water and sewage effluent on alluvial soils in the Nile Delta compared with the Nile freshwater. The study depended on integrating key soil properties determining chemical, physical, fertility, and environmental quality indices to develop an SQI representing the overall status of soil health.

## **Materials and methods**

### *The area of study*

The studied area (36.29 km<sup>2</sup>, 3629 ha) is located in Qalubiya Governorate, southeast of the Nile Delta of Egypt between latitude 30° 13' 24.66" to 30° 17' 34.08" N and longitude 31° 17' 12.24" to 31° 20' 10.16" E (Fig. 1). The climatic condition is dominated by a hot arid summer and little rain in winter. The mean annual temperature is 21 °C and the annual precipitation is 55 mm.

According to Soil Survey Staff (2014a), the soil temperature regime is "Thermic" and the soil moisture regime is "Torric". The young alluvial plain landscape with terrace landform dominate the area (EEAE, 2007). Based on the ASTER digital elevation model (DEM), the buffering zones in the studied area have elevation varying from -3 to 40 m a.s.l. The slope maps (Fig. 2) show that the slope of the buffering zones ranges from 0 (flat) to 3.24% (gently sloping). The area is underlain by Quaternary sediments of the Nile silt deposits (EEAE, 2007). Soils taxonomy is *Typic Torriorthents* (Abd El-Hameed et al., 2013). The crop pattern is dominated by wheat and clover in the winter and maize in the summer (Abuzaid, 2013).

### *Collection of samples*

During the summer of 2020, ten water samples were collected from each of two marginal water sources, i.e., agricultural drainage water (ADW) from Sindwah drain and sewage effluent water (SEW) from Shebein El-Kanater drain. For comparison, ten samples were collected from a nearby Nile freshwater canal (Fig. 1). Samples were collected at about 1 km intervals between every two subsequent points. At each sampling site, composite water samples with three-subsamples were collected in acid-washed high-density polypropylene bottles (1 L) at 50 cm below the water surface. Another set of samples was collected for potentially harmful elements (PHEs) using 500 mL polypropylene bottles previously washed with 50% HNO<sub>3</sub> then with double

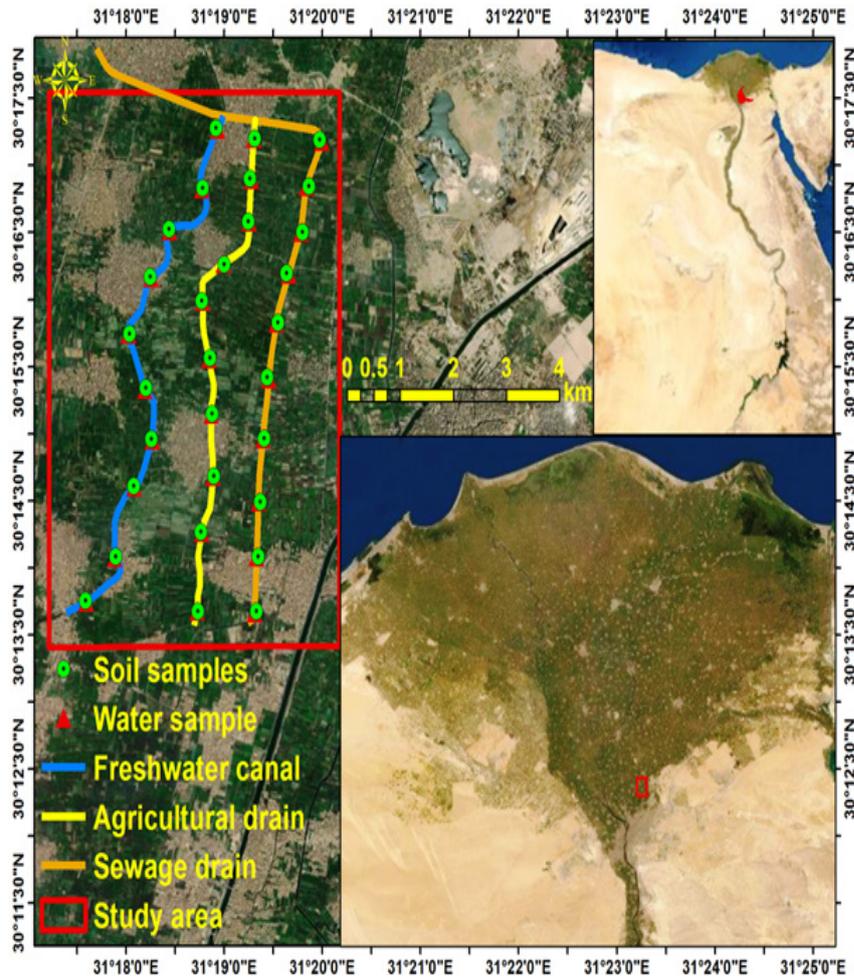


Fig. 1. Map of the studied area and sample locations

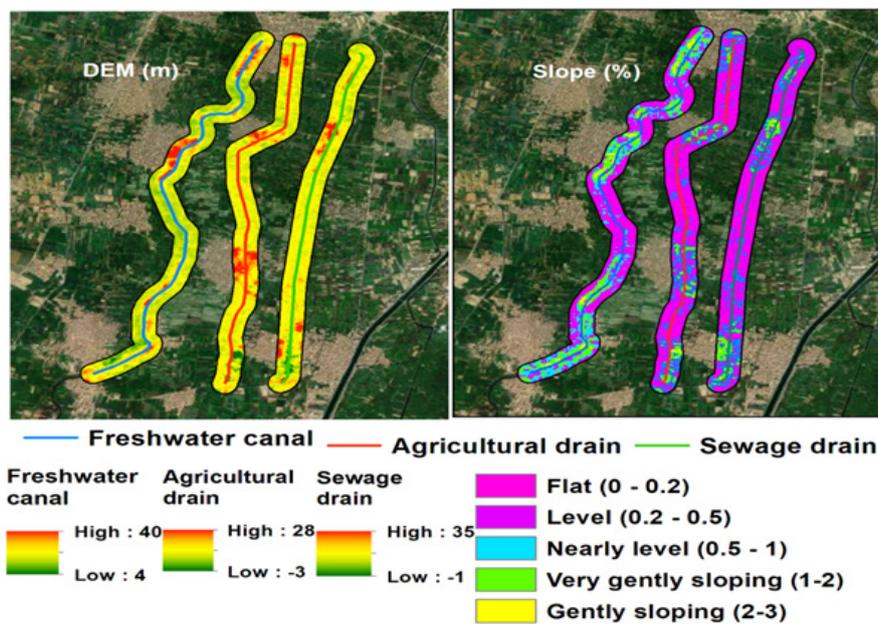


Fig. 2. Maps of the digital elevation models (DEMs) and slope (%) of the studied area

deionized water, and acidified with 5 mL HNO<sub>3</sub>. The collected samples were then transported in iceboxes to the laboratory within 24 h and kept at 4 °C until analyzed. Adjacent to the points of water sampling, thirty surface soil samples (0 – 30 cm) were collected from the three irrigated sites (ten samples from each site). At each site, composite soil samples with five sub-samples were collected using a stainless steel auger, kept in plastic bags, and transported to the laboratory. A further set of soil cores (100 cm<sup>3</sup>) were collected to determine soil bulk density (BD).

#### Laboratory analysis

Water analyses were performed according to the standard methods of APHA (2017). Samples to be analyzed for PHEs were digested (method 3030 E: nitric acid digestion) and measured using Inductively Coupled Plasma-Optical Emission Spectrophotometer (ICP-OES, Perkin Elmer Optima 5300, USA). The chemical oxygen demand (COD) was determined using Method 5210 B open reflux method, while the biochemical oxygen demand at 5 days (BOD<sub>5</sub>) was determined using Method 5210 B 5-Day BOD test.

Soil samples were air-dried, grounded, passed through a 2-mm mesh, and kept for analysis. The soil analyses, including pH, electrical conductivity (EC), cation exchange capacity (CEC), exchangeable sodium percentage (ESP), soil organic matter (SOM), particle size

distribution, water holding capacity (WHC), and hydraulic conductivity (HC) were performed according to standard methods of the Soil Survey Staff (2014b). Mineral N was extracted by KCl and determined using Micro-Kjeldahl apparatus (Mulvaney, 1996). Available P, K, Fe, Mn, Zn, and Cu were extracted by the AB-DTPA (ammonium bicarbonate diethylene triamine penta acetic acid) solution at pH 7.6 and measured by ICP-OES (Soltanpour, 1991). Total forms of PHEs were extracted based on US EPA (1995); method 3052: microwave-assisted acid digestion using concentrated HNO<sub>3</sub>, HF, and HCl, and measured by ICP-OES.

#### Development of soil quality index (SQI)

The procedure included three steps; indicator selection, scoring and indexing (Fig. 3). Twenty-five indicators were chosen to quantify four indices; chemical quality index (CQI), physical quality index (PQI), fertility quality index (FQI), and environmental quality index (EQI) (Table 1). The most common indicators affected by prolonged wastewater irrigation were considered based on expert knowledge and literature review (Abuzaid 2018; Abd-Elwahed, 2019; Elcosy et al., 2020; Farid et al., 2020). A score ranging from 0.1 to 1.0 was calculated for each indicator based on the linear procedure using three functions (Rezaee et al., 2020); more is better (Eq. 1), less is better (Eq. 2) and optimum range as follows:

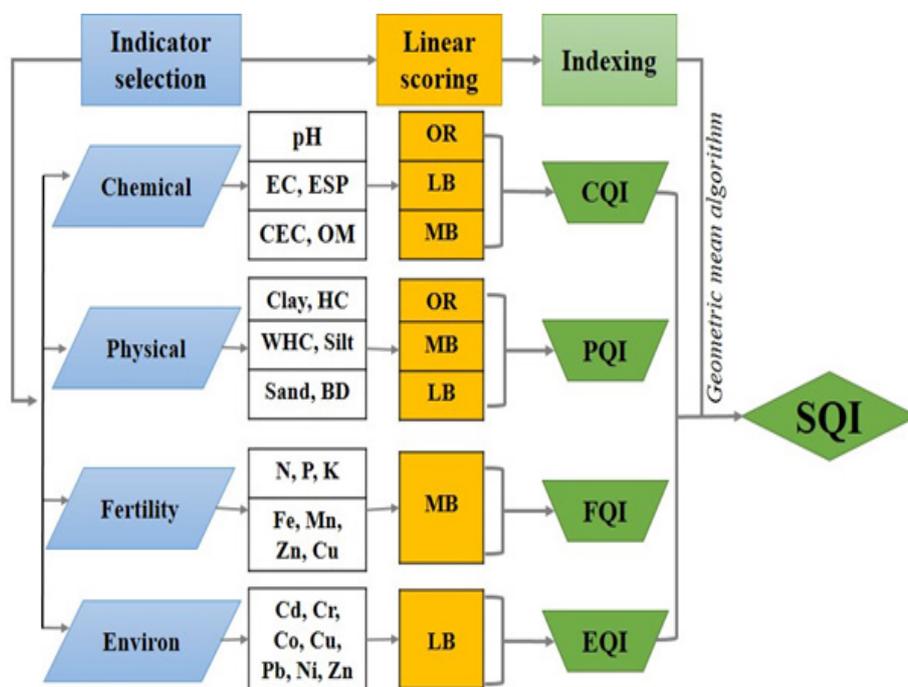


Fig. 3. Flowchart of the methodology used for developing soil quality index

**TABLE 1. Dataset used in soil quality assessment**

Indicator	Associated soil function	SSF	OR	Limit reference
Chemical quality index (CQI)				
pH	Microbial activity and rooting relations	OR	7	Nabiollahi et al. (2017)
EC	Microbial activity and plant growth	LB		
ESP	Water infiltration and movement	LB		
CEC	Total amount of exchangeable cations that soil can absorb	MB		
OM	Biological activity and diversity	MB		
Physical quality index (PQI)				
Sand		LB		
Silt	Soil structure, erosion & water retention	MB		
Clay		OR	25%	(Armenise et al., 2013)
BD	Soil structure	LB		
WHC	Water storage and availability	MB		
HC	Water movement	OR	0.20 cm hr <sup>-1</sup>	Hazelton and Murphy (2016)
Fertility quality index (FQI)				
Nutrient availability	Plant growth and development	MB		
Environmental quality index (EQI)				
Toxic metal	Biodiversity and environmental safety	LB		

EC, electrical conductivity; ESP, exchangeable sodium percentage; CEC, cation exchange capacity; OM organic matter; BD, bulk density; WHC, water holding capacity; HC, hydraulic conductivity; SSF, standard scoring function; OR, optimum range; LB, less is better; MB, more is better.

$$Y = 0.1 + \left[ \left( \frac{x-b}{a-b} \right) \times 0.9 \right] \quad \text{Eq. (1)}$$

$$Y = 1 - \left[ \left( \frac{x-b}{a-b} \right) \times 0.9 \right] \quad \text{Eq. (2)}$$

where Y is the linear score, x is the measured value of the soil property (indicator), b and a are the minimum and maximum values of each indicator.

More is better function was applied to indicators being preferred when in high values, while less is better function was applied to indicators restrict good soil functionality when in high values. For optimal range function, indicators were scored as more is better up to a threshold value then scored as low is better above this threshold.

Under each quality index, the scores of indicators were assembled in a single value using the geometric mean algorithm (Eq. 3) as suggested by Kosmas *et al.* (1999) as follows:

$$\text{Index}_x = [S_1 \times S_2 \times S_3 \times S_n]^{(1/n)} \quad \text{Eq. (3)}$$

where x is the index, S is the score of a parameter, and n is the number of selected parameters (5 chemical indicators, 4 physical indicators, and 7 fertility and environmental indicators). Finally, the overall SQI was calculated as follows (Eq. 4):

$$\text{SQI} = [\text{CQI} \times \text{PQI} \times \text{FQI} \times \text{EQI}]^{(1/n)} \quad \text{Eq. (4)}$$

#### The soil quality grades

The SQI was classified into five grades, i.e. very high (I), high (II), moderate (III), low (IV), and very low (V) following the procedure suggested by Nabiollahi *et al.* (2017) and Abuzaid *et al.* (2020). The overall range of the SQIs in the three sites was divided by the number of intervals (5), and the result was then used as the width for each interval. Adding this value to the lowest SQI value, the upper limit of the first interval was reached, and so on, successively, until the upper range of the index was reached.

#### Statistical and spatial analyses

All statistical analyses were performed using SPSS 19.0 software (SPSS Inc., Chicago, IL, USA) and MS Excel. One-way ANOVA followed by Tukey's honest significance difference (HSD) test at 5% probability level ( $p < 0.05$ ) to compare means of soil quality indicators and indices in the three sampling locations. The spatial analysis of SQIs was performed within ArcGIS 10.8 software (ESRI Co, Redlands, USA) using the inverse distance weighting (IDW) interpolation technique. The IDW predicts the value of a continuous soil characteristic at un-sampled location ( $Z_{(x)}$ ) depending on linear combinations of available data as follows:

$$Z_{(x)} = \sum_{i=1}^n W_i Z_i / \sum_{i=1}^n W_i$$

where  $Z_i$  represents a value of measured point,  $n$  is the total number of known points,  $W_i$  is the weight assigned to point  $i$ ,  $d$  is the distance between predicted and measured values, and  $\square$  is an exponent defined by the user.

## Results and discussions

### Water quality for irrigation

Results in Table 2 indicate that water samples collected from different sites were alkaline with pH values higher than 7.0; however, they remained within the normal range for irrigation (6.5 – 8.4) as suggested by FAO guidelines (Ayers and Westcot, 1994). The water salinity was within the acceptable limits for irrigation, since EC and TDS were lower than 3.0 dS  $m^{-1}$  and 2000 mg  $L^{-1}$  (Ayers and Westcot, 1994). The water samples showed a safe level for suspended materials since values of the TSS did not exceed 300 mg  $L^{-1}$  that represents the maximum allowable levels for irrigation as set by FAO guidelines (Pescod, 1992). The SAR values for water samples collected from different sites showed a safe limit for potential

water infiltration problems in soils. This is because water samples contained adequate concentrations of calcium and magnesium ions, thereby governed the SAR was within the permissible limit of 13 (Ayers and Westcot, 1994). Ion concentrations in water samples from the three sites stood below the recommended limits, except  $NH_4^+$  and  $PO_4^{3-}$  in the ADW and SEW that surpassed the safe limits of 5 and 2 mg  $L^{-1}$ , respectively (Ayers and Westcot, 1994). This is probably due to the high discharge of agricultural and/or domestic wastewater (Jahin et al., 2020). The concentrations of PHEs in water samples from the different sites fall within the permissible levels, except Mn in the ADW that was 3.13-folds the acceptable limit of 200  $\mu g L^{-1}$  (Ayers and Westcot, 1994), probably due to chemical fertilizers. The chemical pollutants in water samples from the three sites showed acceptable levels as the concentration of  $BOD_5$  did not exceed the recommended limit of 300 mg  $L^{-1}$  as set by FAO 47 guidelines (Pescod, 1992). Moreover, these organic substances could be considered biodegradable since the  $BOD_5/COD$  ratio fell within the typical range of 0.3 to 0.8 (Abou-Elela, 2019).

TABLE 2. Characteristics of irrigation water used in the studied sites

Parameter	Unit	Fresh water	Drainage water	Sewage effluent	FAO Permissible level
pH	---	7.68 ± 0.06 c	8.13 ± 0.03 a	7.92 ± 0.05 b	6.5 - 8.4
EC	dS $m^{-1}$	0.54 ± 0.07 c	2.89 ± 0.06 a	1.19 ± 0.04 b	< 3
TDS	mg $L^{-1}$	337.67 ± 1.17 c	1702.03 ± 4.74 a	717.67 ± 3.76 b	< 2000
TSS		19.15 ± 2.53 b	64.67 ± 3.62 a	77.69 ± 4.72 a	< 350
SAR	---	1.71 ± 0.05 c	7.41 ± 0.07 a	2.83 ± 0.06 b	< 15
Ca <sup>2+</sup>		44.75 ± 1.05 c	144.49 ± 0.72 a	89.51 ± 1.53 b	< 400
Mg <sup>2+</sup>		10.52 ± 0.24 c	33.26 ± 1.17 a	19.26 ± 1.88 b	< 60
Na <sup>+</sup>		49.15 ± 1.01 c	380.68 ± 1.15 a	112.33 ± 1.21 b	< 620
K <sup>+</sup>		6.91 ± 0.14 c	13.67 ± 0.43 a	12.13 ± 0.12 b	< 78
NH <sub>4</sub> <sup>+</sup>		0.42 ± 0.48 c	36.33 ± 2.33 a	11.67 ± 0.53 b	< 5
Cl <sup>-</sup>	mg $L^{-1}$	43.12 ± 0.33 c	354.11 ± 4.23 a	143.57 ± 1.81 b	< 1065
SO <sub>4</sub> <sup>2-</sup>		54.38 ± 0.97 c	310.12 ± 7.98 a	102.36 ± 1.52 b	< 960
HCO <sub>3</sub> <sup>-</sup>		181.67 ± 2.21 c	605.16 ± 3.73 a	303.61 ± 2.65 b	< 610
NO <sub>2</sub> <sup>-</sup>		0.03 ± 0.04	< 0.02		NM
NO <sub>3</sub> <sup>-</sup>		0.23 ± 0.01 b	5.67 ± 1.94 a	0.31 ± 0.01 b	< 10
PO <sub>4</sub> <sup>3-</sup>		0.06 ± 0.03 c	5.61 ± 0.91 a	3.83 ± 0.62 b	< 2
Cd		< 2	4.17 ± 0.61	< 2	< 10
Cr			< 2	5.33 ± 1.86	< 100
Cu		13.51 ± 2.02 b	36.14 ± 0.58 a	39.51 ± 1.44 a	< 200
Fe		30.31 ± 0.58 b	134.67 ± 7.54 a	149.45 ± 17.11 a	< 5000
Pb	$\mu g L^{-1}$		< 7	11.41 ± 3.14 a	< 5000
Mn		27.51 ± 2.09 c	625.46 ± 6.41 a	97.63 ± 6.62 b	< 200
Ni		6.53 ± 0.29 c	10.33 ± 0.67 b	16.51 ± 1.11 a	< 200
Zn		26.56 ± 1.43 a	29.14 ± 3.61 a	35.33 ± 5.67 a	< 5000
COD		7.01 ± 3.05 b	159.67 ± 14.03 ab	234.33 ± 27.14 a	NM
BOD <sub>5</sub>	mg $L^{-1}$	4.05 ± 1.78 b	97.67 ± 9.12 ab	136.33 ± 30.14 a	< 300

Results are mean ± standard error of ten samples

Means with different letters indicate significant difference at 0.05 probability level

EC, electrical conductivity; TDS, total dissolved solids; TSS, total suspended solids; SAR, sodium adsorption ratio; COD chemical oxygen demand; BOD<sub>5</sub>, biological oxygen demand at 5 days;

*General soil characteristics*

Descriptive statics of main soil properties from different sites are presented in Table 3. On average, the soils showed pH values in the neutral range (6.6 – 7.3) and low SOM content (< 20 g kg<sup>-1</sup>). The EC values indicated non-saline soils in the control and the SEW-irrigated soils, while slightly saline soils in the ADW-irrigated site (Soil Science Division Staff, 2017). All soils showed a moderate CEC, high WHC, moderate BD, and low HC (Hazelton and Murphy, 2016). The nutrient status indicated a high mineral N content (> 120 mg kg<sup>-1</sup> soil) in all soils (Abuzaid et al., 2020). According to Soltanpour (1991), all soils showed a very high available P content. The control and the SEW-irrigated soils showed a very high available K, while the ADW-irrigated soils showed a high

content. Levels of available Fe and Zn were low in the control and the ADW-irrigated soils, while medium in the SEW-irrigated soils. Available Mn and Cu showed medium contents in the control soils, but high contents in the ADW- and SEW-irrigated soils. All soils showed total Cr contents lower than the average natural content (ANC) in the earth's crust (100 mg kg<sup>-1</sup>), while the contents of Co, Cu, Ni, and Zn surpassed that levels, i.e. 10, 55, 20 and 70 mg kg<sup>-1</sup>, respectively (Kabata-Pendias, 2011). The concentrations of Cd were below the detection in the control and the SEW-irrigated soils, while about 14-fold increase than the ANC in the ADW-irrigated soils. The Pb content in the control and the ADW-irrigated soils were below the detection limits, while about 9-fold that of the ANC in the SEW-irrigated soils.

**TABLE 3. Descriptive statics of soil properties in the studied sites**

Property	Unit	NFW-irrigated soils		ADW-irrigated soils		SEW-irrigated soils	
		Range	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE
Chemical							
pH	---	7.01 - 7.27	7.08 ± 0.03 b	7.05 - 7.38	7.22 ± 0.04 a	6.88 - 7.19	7.10 ± 0.03 b
EC	dS m <sup>-1</sup>	0.62 - 3.73	1.26 ± 0.31 a	1.14 - 5.97	2.44 ± 0.55 a	0.87 - 3.33	1.41 ± 0.23 a
OM	g kg <sup>-1</sup>	9.31 - 18.71	14.77 ± 1.03 a	8.71 - 28.12	16.83 ± 2.61 a	9.31 - 32.13	17.95 ± 2.29 a
CEC	cmolc kg <sup>-1</sup>	7.25 - 37.18	15.24 ± 2.99 a	13.08 - 28.88	19.18 ± 2.05 a	8.52 - 22.59	13.47 ± 1.35 a
ESP	---	2.81 - 8.98	5.44 ± 0.49 b	6.23 - 14.51	10.98 ± 0.82 a	8.38 - 14.76	9.72 ± 0.61 a
Physical							
Sand		49.35 - 47.90	62.98 ± 3.08 a	35.21 - 53.42	42.95 ± 2.81 b	42.15 - 70.80	55.03 ± 2.86 a
Silt	%	6.91 - 32.47	19.09 ± 2.48 c	30.82 - 52.06	40.74 ± 2.63 a	17.88 - 37.45	29.12 ± 2.15 b
Clay		8.53 - 43.74	17.93 ± 3.52 a	11.11 - 24.55	16.31 ± 1.75 a	10.02 - 26.58	15.85 ± 1.58 a
WHC		16.91 - 33.62	22.41 ± 1.55 a	22.11 - 28.31	25.06 ± 0.78 a	18.82 - 28.25	22.83 ± 0.85 a
BD	Mg m <sup>-3</sup>	1.31 - 1.62	1.49 ± 0.03 a	1.36 - 1.52	1.45 ± 0.02 a	1.37 - 1.55	1.48 ± 0.02 a
HC	cm hr <sup>-1</sup>	12.81 - 3.36	1.64 ± 0.37 a	0.55 - 2.32	1.48 ± 0.23 a	0.43 - 2.65	1.49 ± 0.25 a
Available nutrients							
N		212.11 - 378.01	276.51 ± 17.19 a	210.13 - 329.11	260.75 ± 16.40 ab	175.21 - 252.31	211.41 ± 8.21 b
P		3.21 - 18.81	8.08 ± 1.50 b	1.42 - 10.63	5.98 ± 1.22 b	4.21 - 42.23	19.72 ± 2.46 a
K		202.21 - 503.14	315.12 ± 27.31 a	75.16 - 200.15	144.38 ± 12.15 b	100.41 - 500.17	242.52 ± 25.65 ab
Fe	mg kg <sup>-1</sup>	0.10 - 1.61	0.59 ± 0.17 b	1.15 - 2.25	1.59 ± 0.14 ab	0.59 - 7.22	3.27 ± 0.74 a
Mn		0.16 - 0.81	0.38 ± 0.16 b	0.71 - 3.60	1.53 ± 0.35 a	0.32 - 3.24	1.51 ± 0.31 a
Zn		0.02 - 0.13	0.05 ± 0.01 c	0.17 - 0.44	0.27 ± 0.03 b	0.31 - 2.72	1.06 ± 0.24 a
Cu		0.11 - 0.45	0.31 ± 0.03 b	0.67 - 1.54	0.98 ± 0.11 a	0.35 - 2.74	1.48 ± 0.26 a
Total forms of potentially harmful elements (PHEs)							
Cd		< 0.002		0.41 - 3.50	1.41 ± 0.38	< 0.002	
Cr		51.11 - 74.15	61.65 ± 1.89 a	46.51 - 110.31	59.44 ± 6.33 a	49.50 - 79.52	62.25 ± 2.78 a
Co		17.51 - 31.41	22.95 ± 1.19 a	9.50 - 25.51	15.63 ± 1.64 b	12.52 - 21.61	15.35 ± 0.95 b
Cu	mg kg <sup>-1</sup>	70.52 - 182.14	103.31 ± 11.11 a	57.51 - 82.46	71.06 ± 2.81 a	63.14 - 564.53	140.82 ± 26.54 a
Pb				< 0.007		55.53 - 193.57	135.31 ± 9.25
Ni		25.51 - 40.61	30.55 ± 1.34 a	15.42 - 30.51	21.81 ± 1.77 b	20.51 - 35.74	26.45 ± 1.61 ab
Zn		55.31 - 108.54	73.05 ± 4.76 a	48.34 - 222.47	79.51 ± 10.91 a	61.63 - 148.64	87.55 ± 5.97 a

Means with different letters indicate significant difference ( $p < 0.05$ )

EC, electrical conductivity; OM, organic matter; CEC, cation exchange capacity; ESP exchangeable sodium percentage; WHC, water holding capacity; BD, bulk density; HC; hydraulic conductivity.

### *Effect of irrigation water on soil quality indicators*

#### *Chemical indicators*

In comparison with the freshwater, irrigation using the ADW generated a significant increase ( $p < 0.05$ ) in soil pH of 0.14 unit, while the SEW irrigation resulted in a slight pH rise of 0.02 unit (Table 3). These findings are in line with previous works of Abuzaid (2016), Abuzaid (2018) and Abd-Elwahed (2019). Such pH rises could be attributed to basic cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) added to the soils through irrigation water (Jahany and Rezapour, 2020).

The average EC values indicated slight increases of 94 and 12% in the ADW- and the SEW-irrigated soils, respectively over the control soils. The build-up in soil salinity is due to higher soluble ion concentrations in the marginal waters compared with the freshwater (Table 2). In spite of these increases, EC values stood below the salinity threshold of 4 dS  $\text{m}^{-1}$  (Soil Science Division Staff, 2017), indicating a suitable level for the growth of many crops.

The ESP was significantly affected by marginal water irrigation recording rises of 102% (in the ADW-irrigated soils) and 79% (in the SEW-irrigated soils) over the control soils. Normally, continuous and elevated additions of  $\text{Na}^+$  and  $\text{HCO}_3^-$  through marginal water irrigation coupled with high evapotranspiration rates under arid conditions are likely to enhance precipitation of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  as insoluble carbonates, leaving more  $\text{Na}^+$  in soil solution that in turn over-accumulate on the colloidal soil surfaces and increase the ESP (Abd-Elwahed, 2019). However, the enrichment of ESP in soils remained below the safe limit of 15, which governs good soil functionality.

Continuous irrigation using marginal water manifested a non-significant effect on the SOM content compared with the freshwater irrigation. However, shifting irrigation water source caused SOM increases of 14% (in the ADW-irrigated soils) and 22% (in the SEW-irrigated soil) over the control soils. These findings are in harmony with those obtained by Abuzaid (2018) and (Abd-Elwahed, 2019) who reported increasing trends of SOM following sewage effluent irrigation. These increases were probably due to the higher content of biodegradable organic substances (as displayed by  $\text{BOD}_5/\text{COD}$  ratio) in the two marginal water sources in comparison with the freshwater (Abbas et al., 2020).

The CEC was not significantly affected by marginal water irrigation; however, a 26% increase in the CEC occurred in the ADW-irrigated soils, while a 12% decrease was found in the SEW-irrigated soils compared with the control soils. Soil exchangeable capacity is closely related to the combination of SOM and particle size distribution of the soil (Hazelton and Murphy, 2016). However, due to low SOM content in arid soils, the fine-earth fractions (sand, silt, and clay) have a major contribution to cation retention on soils.

#### *Physical indicators*

The particle size distribution indicated significant variations in sand and silt fractions among the studied soils, while the soils showed slight differences in the clay content. These findings are in contrast with those obtained by Elcosy et al. (2020) who stated that irrigation using raw sewage effluent for more than 80 years resulted in increasing clay and silt contents in El-Gabal El-Asfar soils. In the current work, the little changes in soil texture might be a result of the period of wastewater irrigation being not enough for particle accumulations on one hand and the relatively low load of suspended particles in the partially treated effluents on the other hand. Therefore, variations in the fine-earth could be attributed mainly to depositional regimes and weathering processes rather than anthropic factors.

Non-significant variations related to WHC, BD and HC were observed among the studied soils. This is because clay and SOM contents in soils are the primary factors controlling soil physical properties (Abuzaid and Bassouny, 2018b) which did not change after marginal water irrigation. These results affirm the findings of Abuzaid (2018) who reported slight increases in WHC and BD of the Nile Delta alluvial soils subjected to prolonged irrigation with sewage effluent. Slight improvements in soil physical quality were noted with increases of 12 and 2% in WHC, while decreases of 3 and 1% in BD and 10 and 9% of HC occurred in the ADW- and SEW-irrigated soils, respectively. The increase in WHC were closely associated with the concurrent increases in the CEC of the ADW-irrigated soils and the SOM content in the SEW-irrigated soils (Hazelton and Murphy, 2016). The decreases in both BD and HC were related mainly to the corresponding augments in the SOM that can block the macro-pores and improve aggregation, thereby decreasing BD and HC (Bassouny and Abuzaid, 2017).

*Fertility indicators*

The available N showed a slight decrease of 6% in the ADW-irrigated soils, but a significant decrease of 24 in the SEW-irrigated soils compared with the control soils. Similarly, the available K showed a marked decrease of 54% but a slight decrease of 23% in the ADW- and SEW-irrigated soils compared with the control soils, respectively. For available P, there was a slight decrease of 26% in the ADW-irrigated soils, but a significant increase of 144% in the SEW-irrigated soils compared with the control soils. Clearly, the accumulation trends of N, P and K were far away from their corresponding concentrations in irrigation water, probably due competitive interaction in soils. Both  $\text{NH}_4^+$  and  $\text{K}^+$  have a similar ionic radius, thereby increasing the competitive mode in the presence of one another. Therefore, increased concentrations of  $\text{NH}_4^+$  and  $\text{K}^+$  in irrigation water may inhibit their adsorption on soil colloids (Buragohain et al., 2019). The remarkable increase in the available P content after sewage irrigation is in agreement with the conclusions of Abuzaid (2018), Abd-Elwahed (2019) and Jahany and Rezapour (2020). Such increase might be a result of increased SOM content coupled with neutral pH level, which in turn enhances the decomposition of organic substances and increases P availability in soils (Hazelton and Murphy, 2016).

The soil content of available micro-nutrients indicated a slight Fe increase in the ADW-irrigated soils, but a significant increase in the SEW-irrigated, representing 2.69 and 5.54-fold than the control soils, respectively. The Mn contents in soils were significantly affected by irrigation water showing a rise of 4.03-folds (in the ADW-irrigated soils) and 3.97-folds over the control soils. The Cu contents showed a rise of 3.16 and 4.77-folds over the control soils, respectively. The Zn content demonstrated a profound effect of marginal water irrigation, where significant increases of about 5 and 2 folds over the control soils were observed. The increases in the available micro-nutrient contents could be directly caused by their high concentrations in the applied marginal waters (Table 2).

*Environmental indicators*

Marginal water irrigation did not induce a significant effect on the total contents of PHEs in soils, except Cd in the ADW-irrigated soils and Pb in the SEW-irrigated soils (Table 3). Abuzaid and Bassouny (2018a) reported that prolonged

irrigation using sewage effluent derived from Al-Qalubiyah main drain resulted in considerable increases in the soil contents of Cr, Co, Cu, Ni, Pb, and Zn compared with the freshwater irrigation. Aging is likely to be the key factor for controlling metal accumulation in wastewater-irrigated soils (Abbas and Bassouny, 2018). In the current work, the period of wastewater application was not enough to render a marked increase in the total metal content. Yosry and El Abas (2004) reported considerable increases of Cr, Cu, Pb, and Zn in the soils of a sewage-irrigated area in El-Gabal El-As far over the none sewage-irrigated soils after 85 years of sewage application.

Although Cr was not detected in the freshwater and ADW, total Cr content was rather similar in all soils. Similarly, the total Co contents in all soils exceeded the ANC in the earth's crust; however, the metal was not detected in irrigation water sources. Cr, Co, and Ni are common in ultramafic rocks (serpentine), which dominate the Nile Delta alluvial sediments (Abuzaid and Jahin, 2019). Total Co showed significant decreases of 1.47 and 1.50-folds in the ADW- and the SEW-irrigated soils compared with the control soils, respectively. In contrast to Ni concentration in irrigation waters, total Ni showed a significant 1.40-fold decrease and a slight 1.16-fold decrease in the ADW- and the SEW-irrigated soils compared with the control soils, respectively. These findings clarify that the accumulations of Cr, Co, and Ni in the studied soils were mainly governed by lithological factors rather than human intervention (Abuzaid and Jahin, 2019 and Abuzaid & Bassouny, 2020). The Cu content in the ADW-irrigated soils showed a slight 1.45-fold decrease compared with the control soils that interfered with the contents in irrigation water. This might be a result of lower clay content in the ADW-irrigated soils than the control soils (Oorts, 2013). On the other hand, the SEW-irrigated soils showed a slight 1.36-fold increase in total Cu content over the control soils. This could be attributed mainly to higher Cu content in the sewage effluent (Table 2). The total Zn contents in soils coincided with the corresponding concentrations in irrigation water, indicating slight increases of 1.09 and 1.20-folds in the ADW- and SEW-irrigated soils over the control soils, respectively.

*Soil quality indices**Chemical quality index (CQI)*

As shown in Fig. 4, the soil chemical quality was adversely affected by marginal water

irrigation. However, these effects were not significant. On average, results in Fig. 5 reveal slight decreases in the CQI represented 23 and 9% in the ADW- and the SEW-irrigated soils compared with the control soils, respectively.

Degradation in the soil chemical quality was mainly due to high soluble ions provided by marginal waters that increased the EC, pH, and ESP, which are the most susceptible indicators for possible changes due to wastewater irrigation in arid and semi-arid regions (Elgallal et al., 2016).

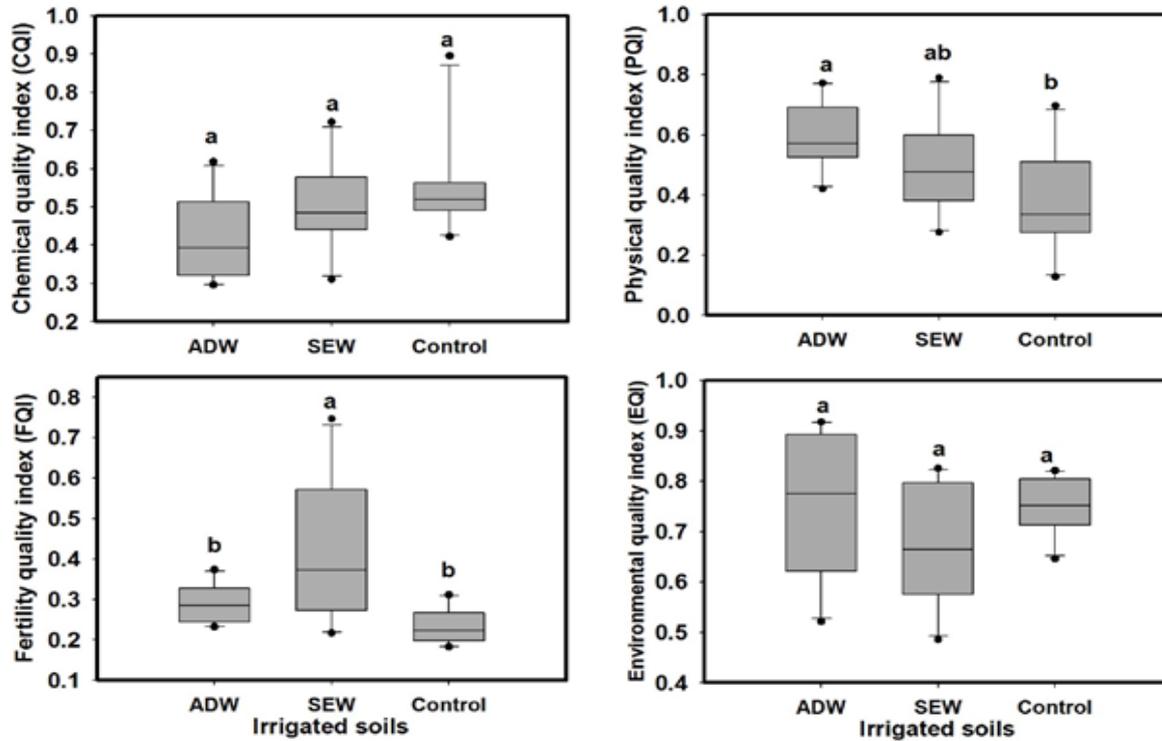


Fig. 4. Chemical, physical, fertility and quality indices of the studied soils

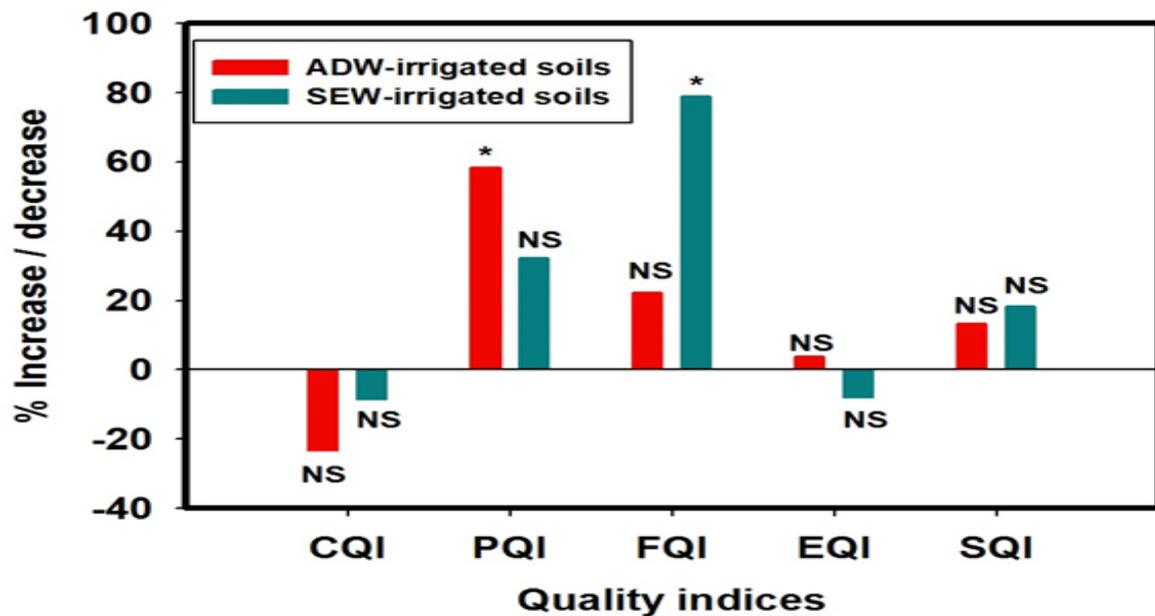


Fig. 5. Changes (%) in quality indices of the studied soils following marginal quality water irrigation (NS; change is not significant compared with control; \* change is significant at  $p < 0.05$ )

#### *Physical quality index (PQI)*

In contrast to the chemical quality, the physical soil quality showed an increasing trend in two marginal water-irrigated soils over the control soils (Fig. 4). Compared with the control soils, the ADW-irrigated soils showed a significant 55% increase in the PQI, while the SEW-irrigated showed a slight increase of 32% (Fig. 5). In fact, changes in the physical soil conditions were related mainly to the particle size distribution, an inherent soil property, rather than the slight increases in the SOM following marginal water irrigation. This is because increases in the fine soil fractions and concurrent modifications in the soil texture require a long period of wastewater irrigation. Elcosy et al. (2020) reported the progressive increases in silt and clay contents and associated decreases in BD and HC of El-Gabal El-Asfar soils after a period of sewage effluent application of 80 years.

#### *Fertility quality index (FQI)*

The fertility status showed an increasing trend after 25 years of irrigation using the marginal quality waters compared with the freshwater irrigation (Fig. 4). The FQI of the ADW-irrigated soils showed a slight 22% over the control soils, while the corresponding increase in the SEW-irrigated soils was significant and represented 75% (Fig. 5). Improving the fertility quality of soils was mainly due to increasing the availability of micronutrients (Fe, Mn, Zn, and Cu) and P (in the SEW-irrigated soils), which were supplied by marginal water. Such results demonstrate that wastewater irrigation can improve the fertility status in arid soils as delineated by previous studies in Egypt (Abuzaid 2018; Abd-Elwahed, 2019) and other parts of the world (Elgallal et al., 2016).

#### *Environmental quality index (EQI)*

Unlike other quality indices, the soil environmental quality showed two different patterns of modification under long-term marginal water irrigation (Fig. 4). In comparison with the control soils, the EQI manifested a slight increase of 4% in the ADW-irrigated soils, while a slight decrease of 8% in the SEW-irrigated soils (Fig. 5). Such slight changes are due to rather similar total soil content of PHEs resulted from several factors, including 1) similar soil parent materials, which is a driving force for their accumulation in soils, 2) proper irrigation water quality with metal content below the safe limits, and 3) the irrigation history, which is not enough to cause considerable changes in total soil content of PHEs.

#### *Soil quality index (SQI)*

The spatial distribution of the SQIs of the studied soils is shown in Fig. 6. Results indicate

that the ranges of SQI were 0.32 (very low) to 0.51 (high) in the control soils, 0.38 (low) to 0.58 (very high) in the ADW-irrigated soils, and 0.36 (low) to 0.62 (very high) in SEW-irrigation soils, respectively. These ranges manifest the improvements in the overall soil functionality following the marginal water irrigation. The average values of SQI were 0.42, 0.48, and 0.51, which indicate low, moderate, and high quality grades for the control, ADW-, and SEW-irrigated soils, respectively. This indicates slight increases in the SQI representing 14% (in the ADW-irrigated soils) and 21% (in the SEW-irrigated soils) over the control soils (Fig. 5). These findings are far from those reported by (Abd-Elwahed, 2019) who found that wastewater irrigation in Bahr Elbaqar area, eastern the Nile Delta for up to 42 years downgraded the soil quality by 1.4 to 1.8% compared with the freshwater-irrigated soils. However, in a semi-arid environment in Iran, Jahany and Rezapour (2020), reported increases up to 6 to 16% in soil quality following ten-years application of wastewater. The effects of wastewater on soil depend mainly on the interaction between wastewater quality and soil properties on one hand and the cropping system and the history of use on the other hand (Abbas Bassouny, 2018 and Elcosy et al., 2020)

Irrigation using two marginal water sources, i.e. ADW and SEW for 25 years resulted in changes in alluvial soil properties compared with freshwater irrigation. However, most of these changes were non-significant. The remarkable effect of the marginal water irrigation was manifested through negative changes in the soil pH, EC, and ESP, thereby declining the CQI, and positive changes in fertility status through improving the availability of P (in the SEW-irrigated soils) and micro-nutrients (Fe, Mn, Zn, and Cu), and thus increasing the FQI. On the other hand, particle size distribution rather than irrigation water contributed mainly to positive changes in the PQI. Chiefly, the soil parent materials governed the total soil contents of Cr, Co, and Ni, while the marginal water enriched the soils with Cd, Cu, Pb, and Zn. The EQI showed a positive change in the ADW-irrigated soils, while a negative change in the SEW-irrigated soils. Overall, the marginal water exhibited high potentiality for contributing sustainable agricultural production in the studied area showing increases of 14 and 21 in the SQI for the ADW- and SEW-irrigated soils over the control soils, respectively. Achieving environmental safety, periodic monitoring of temporal changes in irrigation water, and soil quality in the studied area are recommended. Furthermore, effective remediation techniques along with management programs should be considered.

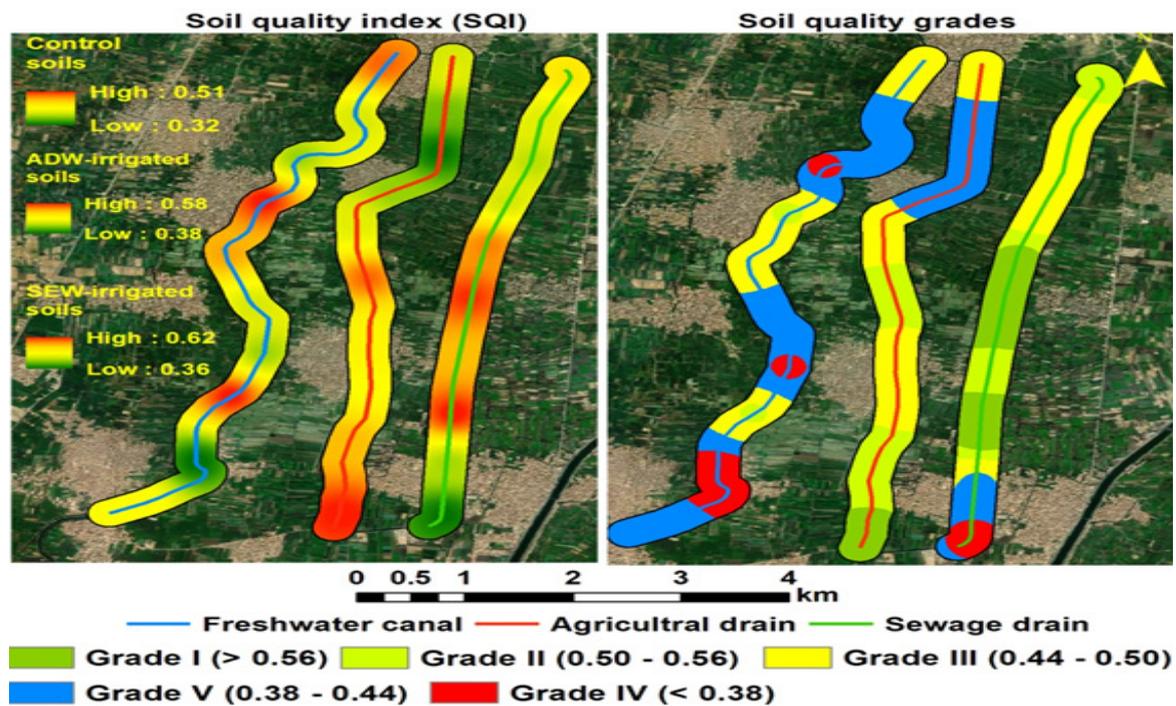


Fig. 6. Spatial distribution of soil quality indices and grades in the studied area

### Conclusion

Irrigation using two marginal water sources (i.e., ADW and SEW) for 25 years resulted in changes in alluvial soil properties compared with freshwater irrigation. However, most of these changes were non-significant. The remarkable effect of the marginal water irrigation was manifested through negative changes in the soil pH, EC, and ESP, thereby declining the CQI, and positive changes in fertility status through improving the availability of P (in the SEW-irrigated soils) and micro-nutrients (Fe, Mn, Zn, and Cu), and thus increasing the FQI. On the other hand, particle size distribution rather than irrigation water contributed mainly to positive changes in the PQI. Chiefly, the soil parent materials governed the total soil contents of Cr, Co, and Ni, while the marginal water enriched the soils with Cd, Cu, Pb, and Zn. The EQI showed a positive change in the ADW-irrigated soils, while a negative change in the SEW-irrigated soils. Overall, the marginal water exhibited high potentiality for contributing sustainable agricultural production in the studied area showing increases of 14 and 21 in the SQI for the ADW- and SEW-irrigated soils over the control soils, respectively. Achieving environmental

safety, periodic monitoring of temporal changes in irrigation water, and soil quality in the studied area are recommended. Furthermore, effective remediation techniques along with management programs should be considered.

### Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

### Consent for publication

All authors declare their consent for publication.

### Contribution of authors

This study was designed and implemented by all the authors, where all contributed to writing the manuscript, interpreting information presented and have read and agreed to the final version of the manuscript.

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### Conflicts of Interest

The authors declare no conflict of interest.

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## التغيرات في جودة التربة الرسوبية تحت الري طويل الأمد بمصدرين للمياه الهامشية في بيئة قاحلة

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يهدف هذا البحث إلى دراسة تغيرات مؤشرات الجودة الكيميائية، الفيزيائية، الخصوبية، والبيئية لبعض الأراضي الرسوبية جنوب شرق دلتا النيل - مصر بعد الري لمدة ٢٥ عام بإستخدام مياه هامشية الصلاحية. ولتحقيق ذلك تم جمع ٣٠ عينة تربة من ٣ مواقع (١٠ عينات من كل موقع) الأول يروي بمياه الصرف الزراعي، الثاني يروي بمياه الصرف الصحي، والثالث يروي بمياه النيل العذبة (للمقارنة). أوضحت النتائج أن الري بالمياه الهامشية أدى إلى حدوث تغيرات في خواص التربة ومن ثم التأثير على دلائل الجودة المختلفة. ظهرت التأثيرات السلبية على دليل الجودة الكيميائية من خلال زيادة قيم الأس الهيدروجيني والتوصيل الكهربائي ونسبة الصوديوم المتبادل في التربة. في حين ظهرت التأثيرات الإيجابية على دليل الجودة الخصوبية من خلال زيادة محتوى التربة الميسر من المغذيات خصوصا □ الأراضي المروية بمياه الصرف الصحي. كما ظهرت تغيرات إيجابية لدليل جودة التربة الفيزيائية الري، ولكن ناجمة عن مادة أصل التربة. أدى الري بالمياه الهامشية إلى زيادة محتوى التربة الكلي من عناصر النحاس، الرصاص، والزنك. على الرغم من ذلك أظهر دليل جودة التربة البيئية تغيرا □ إيجابيا □ في الأراضي المروية بمياه الصرف الزراعي، بينما تغيرا □ سلبيا □ في تلك المروية بمياه الصرف الصحي. أظهرت النتائج زيادة دليل جودة التربة النهائي بمقدار ١٤ و ٢١٪ للأراضي المروية بمياه الصرف الزراعي ومياه الصرف الصحي مقارنة بالري بالمياه العذبة على التوالي.