

Article

Combining Hydro-Geochemistry and Environmental Isotope Methods to Evaluate Groundwater Quality and Health Risk (Middle Nile Delta, Egypt)

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Abstract: This study aims to assess the vulnerability of groundwater in the Nile Delta to contamination and evaluate its suitability for drinking and irrigation. A total of 28 groundwater wells (ranging from 23 to 120 m in depth) and two Nile surface water samples were analyzed for total dissolved solids (TDS), heavy metals, groundwater quality index (GWQI), and hazard quotient (HQ). The findings reveal that deep groundwater (60–120 m) displays paleo-water characteristics, with low TDS, total hardness, and minimal heavy metal contamination. In contrast, shallow groundwater (<60 m) is categorized into three groups: paleo-water-like, recent Nile water with elevated TDS and heavy metals, and mixed water. Most groundwater samples (64%) are of the Ca-HCO₃ type, while 28% are Na-HCO₃, and 8% are Na-Cl, the latter associated with sewage infiltration. Most groundwater samples were deemed suitable for irrigation, but drinking water quality varied significantly—4% were classified as “excellent”, 64% as “good”, and 32% as “poor”. HQ analysis identified manganese as a significant health risk, with 56% of shallow groundwater samples exceeding safe levels. These findings highlight the varying groundwater quality in the Nile Delta, emphasizing concerns regarding health risks from heavy metals, particularly manganese, and the need for improved monitoring and management.

Keywords: Nile Delta aquifers; heavy metal pollution; groundwater quality index (GWQI); manganese contamination; paleo-groundwater



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1. Introduction

Groundwater is a vital source of potable water, particularly in arid and semi-arid regions, where it serves as a critical resource for drinking, irrigation, and industrial purposes [1,2]. However, its vulnerability to contamination is increasing due to urbanization, limited recharge from surface water, and various anthropogenic activities. Common sources of groundwater degradation include the leakage of uncontrolled domestic

sewage and sanitation systems [3–6], industrial and mining contamination [7–11], landfill leachates [5,12–15], and contamination from surface water bodies [5,16–20]. Additionally, agricultural practices, such as waterlogging, cause soil salts and agrochemicals to leach into groundwater, especially in flood irrigation systems [7,21–25]. The chemical composition of groundwater significantly affects its usability for drinking. Major ions such as Ca^{2+} , Na^{+} , and K^{+} influence its taste, but heavy metal contamination is one of the most pressing concerns for both environmental and public health [26]. While trace metals such as Fe, Mn, Cu, and Zn are essential nutrients at low concentrations, they can be toxic at high levels, whereas metals like As, Cr, and Pb are toxic even at low concentration [27].

The suitability of groundwater for various purposes (drinking, agriculture, and industrial supply) can be assessed using a variety of geochemical methods. Major ions, as well as stable isotopes of oxygen, hydrogen, and carbon, offer valuable insights into the water's origin, recharge zones, and factors influencing the aquifer system [17,25,28–35]. Other techniques, such as statistical processing and water quality indices, help analyze the interrelationships between water constituents and provide estimates of overall water quality [36–38].

In the Nile Delta, Egypt, groundwater is the primary drinking water source, particularly for rural inhabitants who rely on municipal boreholes or private hand-dug wells. Many households, especially in the Middle Nile Delta, use shallow wells (less than 30 m deep) to extract water for both drinking and irrigation, with the latter consuming substantial amounts of water. Groundwater contamination in the Nile Delta has become a significant issue which is not adequately addressed or controlled [22,25,39–43]. The main sources of contamination in this region are (1) waterlogged soil that affects shallow groundwater quality, (2) inadequate sanitation systems in some villages, and (3) untreated industrial waste discharges into rivers. These contaminants infiltrate the groundwater through downward percolation, affecting both shallow and deeper aquifers. Consequently, assessing groundwater quality and its vulnerability to contamination in this region is essential.

The novelty of this study lies in its comprehensive approach to evaluating the hydrogeochemical characteristics of groundwater in the Middle Nile Delta. By combining traditional hydrogeochemical analyses with advanced stable isotope techniques (oxygen and hydrogen), this study aims to provide a more thorough understanding of groundwater recharge, contamination sources, and health implications. This integrated approach also facilitates the identification of heavy metal contamination, specifically targeting arsenic (As), chromium (Cr), lead (Pb), and manganese (Mn), all of which pose serious environmental and health risks. This study is unique in its investigation of these contaminants in the Middle Nile Delta, an area with limited previous research on this specific issue [44–50].

The problem statement of this study focuses on the contamination of groundwater by heavy metals in the Middle Nile Delta. Arsenic, chromium, lead, and manganese were chosen as target pollutants due to their widespread occurrence in the region and their known health impacts. Arsenic, chromium, and lead are recognized carcinogens, while manganese, although an essential nutrient, can become toxic at higher concentrations.

The methodology used to assess these pollutants includes both hydrogeochemical analyses and stable isotope techniques. Hydrogeochemical analyses provide valuable data on the concentration and distribution of major ions and heavy metals, offering insights into contamination levels and potential sources. However, these analyses are limited in their ability to detect long-term contamination trends or to account for complex interactions between pollutants. Stable isotope techniques, specifically those involving oxygen and hydrogen, provide crucial information on groundwater recharge sources, flow paths, and age, which helps trace how contaminants enter the system. Despite their powerful insights, isotopic methods are more resource-intensive, requiring specialized equipment and ex-

expertise, which can limit their accessibility for routine analysis. Despite these challenges, combining both techniques offers a holistic understanding of groundwater quality in the Nile Delta, providing essential data for improved management strategies.

This study aims to bridge critical gaps in understanding groundwater quality in the Middle Nile Delta by assessing contamination levels and health risks using a combination of geochemical and isotopic methods. The findings will contribute significantly to water resource management, environmental protection, and public health efforts in the region.

Study Area

The Nile Delta covers an area of about 25,000 km² in Northern Egypt and is located ~20 km north of Cairo (Figure 1). The study wells are in the middle part of the Nile Delta between latitudes 30°45' and 30°57' N and longitudes 30°45' and 31°05' E in an area of about 720 km². This area is mainly cultivated and intersected by a web of sealed roads that interconnect between major industrial and commercial centers, e.g., the cities of Tanta and Kafr El Zayat, which are considered the heart of the Nile Delta with many surrounding villages and hamlets.

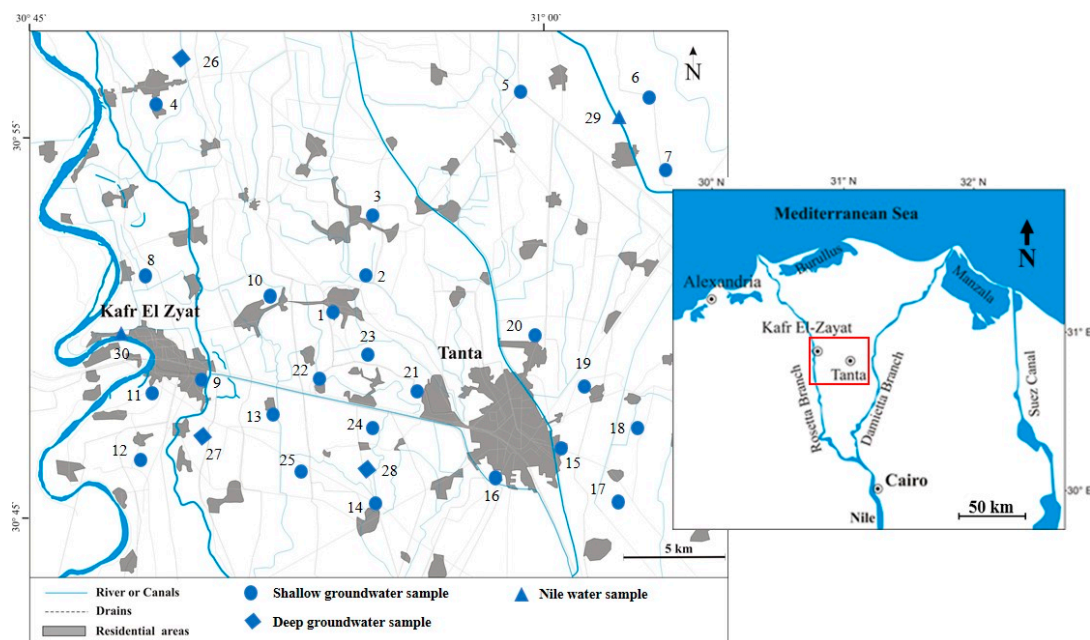


Figure 1. Study area in the Nile River Delta (Egypt) with sampling locations.

From a geological and hydrogeological point of view, the Nile Delta is covered by the soil of the Holocene alluvial plain. The sedimentary sequence of the Nile Delta basin is subdivided into three sedimentary cycles [51] of Miocene, Plio-Pleistocene, and Holocene age. Subsequently, the Plio-Pleistocene and Holocene sequences are subdivided into two rock units, the Bilqas Formation underlain by the Mit Ghamr Formation. These two formations constitute the primary aquifer of the Nile Delta [36,39].

The Bilqas Formation represents an organic-rich agricultural soil plain with predominantly fluvisols that consist of mixed clay and silty clay fluvial sediments deposited by overbank flooding with an approximate accumulation rate of 5 mm per year [52] and a thickness in the study area that ranges from 10 to 23 m [36,53]. The thickness decreases with increasing distance from the main Nile branches and reaches its lowest thickness towards the middle part of the study area. Interbedded within this layer are silt and sand lenses with a thickness between 3 and 5 m.

The underlying Mit Ghamr Formation of Plio-Pleistocene age is the main water-bearing formation in the Middle Nile Delta aquifer [36,39], with thicknesses that range from 500 to 700 m [54]. It is composed of graded sand and gravel with thin interbedded clay layers. These clay layers divide the primary aquifer into several connected and disconnected minor aquifers [55]. The Mit Ghamr Formation is considered a leaky aquifer in the Middle Nile Delta area, which is overlain by and hydraulically connected to the aquitard of the semi-pervious Bilqas Formation [37,56].

The groundwater flows from the southeast to the northwest following the Nile Delta topographic slope, with an average hydraulic gradient of 11 cm/km [57]. Discharge occurs freely northward to the Mediterranean Sea and the Rosetta branch of the Nile River and artificially by municipal and private wells. After the Aswan High Dam construction between 1960 and 1970, the piezometric levels of the aquifer ranged from 2 to 8 m above sea level (m.a.s.l.) and 0.5 to 5.0 from the ground surface [58]. According to Salem [59] and Masoud [60], extensive recharge from unsewered villages and irrigation water combined with the limited permeability of the surface clay layer leads to saturated infiltration conditions and waterlogged soils in large parts of the study area.

2. Materials and Methods

2.1. Field Work and Laboratory Analyses

A 28 groundwater samples were collected from wells with depths ranging between 25 and 120 m. The groundwater sampling protocol involved collecting 28 groundwater samples and two surface water samples using pre-cleaned polyethylene bottles, which were rinsed with sample water before collection. Sub-samples for heavy metal analysis were acidified with nitric acid to pH < 2, while others were kept at 4 °C to preserve their integrity until analysis. Major anions were determined using ion chromatography (Thermo Dionex ICS 2000), Sunnyvale, CA, U.S.A and major cations and trace metals were analyzed by ICP-MS (Thermo iCAP-Q), Bremen, Germany. Calibration was performed using standard solutions, and quality control measures included the use of blanks, duplicates, and certified reference materials to ensure accuracy and precision.

Groundwater samples were selected across different land use types: cultivated, residential, and industrial areas. Additionally, two surface water samples from the Nile River were collected for comparative analysis. The coordinates of the sampling sites were recorded using a portable GPS device (Figure 1). The following physicochemical parameters were measured directly in the field using a multi-parameter portable instrument (YSI model 63): temperature (T), pH, electrical conductivity (EC), and total dissolved solids (TDS), the latter being calculated from EC. The wells were hand-pumped for 10–15 min before sampling to ensure that the measured parameters were stabilized. The total hardness (TH) of the groundwater was calculated according to the formula suggested by Sawyer et al. [61]:

$$\text{TH}(\text{asCaCO}_3)\text{mg/L} = (\text{Ca}^{2+} + \text{Mg}^{2+})\text{meq/L} \times 50 \quad (1)$$

Major anions were analyzed using ion chromatography (Thermo Dionex ICS 2000), while major cations and trace metals were determined by inductively coupled plasma-mass spectrometry (ICP-MS) (Thermo iCAP-Q). For isotopic analysis, the oxygen and hydrogen isotope ratios in the water samples were measured using wavelength-scanned cavity ring-down infrared spectroscopy (CRDS), employing a Picarro L1102-i instrument, which was coupled with a vaporization module. Post-run data corrections were applied according to the methodology described by van Geldern and Barth [62]. Isotopic results are reported

in the conventional delta (δ) notation, calculated with respect to Vienna Standard Mean Ocean Water (V-SMOW) and expressed in per mil (‰):

$$\delta = \left(\frac{R_{sample}}{R_{reference}} - 1 \right) \quad (2)$$

where R represents the $^{18}\text{O}/^{16}\text{O}$ or the $^2\text{H}/^1\text{H}$ stable isotope ratios [63]. The external reproducibility for the isotope measurements was found to be better than 0.1‰ for $\delta^{18}\text{OH}_2\text{O}$ and $\delta^2\text{HH}_2\text{O}$, as determined by control standards.

All chemical analyses were performed at Geozentrum Nordbayern (GZN), Erlangen, Germany.

2.2. Groundwater Quality Assessment

The groundwater quality index (GWQI) was used to assess the suitability of the groundwater for drinking purposes. The GWQI was calculated using the following equation [64]:

$$\text{GWQI} = \sum SI_i = \sum (W_i + q_i) = \sum \left(\left(\frac{w_i}{\sum_{i=1}^n w_i} \right) \times \left(\frac{C_i}{S_i} \times 100 \right) \right) \quad (3)$$

where C_i is the concentration of each parameter, S_i is the limit values concerning WHO standards [26], w_i is the assigned weight according to its relative importance in the overall quality of water for drinking purposes (Table 1), q_i is the water quality rating, W_i is the relative weight, and SI_i is the subindex of i th parameter. In this study, the parameters that have been considered are pH, TDS, Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , SO_4^{2-} , Mn, Fe, Cu, Zn, As, and Pb.

Table 1. Relative weight of chemical parameters in the groundwater quality index (GWQI).
* WHO—World Health Organization [26].

Parameter	WHO * Standards	Weight, w_i	Relative Weight, W_i
pH	7	3	0.06
TDS (mg/L)	500	5	0.11
Na^+ (mg/L)	200	2	0.04
Mg^{2+} (mg/L)	30	3	0.06
Ca^{2+} (mg/L)	75	3	0.06
Cl^- (mg/L)	250	5	0.11
SO_4^{2-} (mg/L)	250	4	0.09
Fe (mg/L)	0.3	4	0.09
Mn (mg/L)	0.4	4	0.09
Cu (mg/L)	2	2	0.04
Zn (mg/L)	5	3	0.06
As (mg/L)	0.01	4	0.09
Pb (mg/L)	0.01	5	0.11
		$\sum w_i = 47$	$\sum W_i = 1.0$

* World Health Organization.

Suitability for irrigation. Assessment of the suitability of groundwater for agricultural irrigation purposes is vital for soil productivity and crop yield [65]. In this study, the sodium percentage (Na%) parameter is applied to assess the suitability of the groundwater for irrigation, which is expressed as follows [56]:

$$\text{Na \%} = \frac{\text{Na}^+ + \text{K}^+}{\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+}} \times 100 \quad (4)$$

2.3. Health Risk Estimation

The human health risk from heavy metals in drinking water was evaluated following established protocols [66–69]. Health risks from ingestion were considered the primary pathway, as inhalation and dermal contact were deemed negligible. The hazard quotient (HQ) for each heavy metal was calculated using the formula from the US EPA model [70–72]:

$$HQ = \frac{ADD}{RfD} \quad (5)$$

with

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (6)$$

where ADD is the average daily dose (mg/kg-day), RfD is the reference dose for different metals, USEPA, 2012 [73], C is the concentration of the heavy metal in groundwater (mg/L), IR is the intake rate (2 L/day), EF is the exposure frequency (365 day/year), ED is the exposure duration (in this study, 60 years), BW is the average body weight (70 kg), and AT is the averaging time for non-carcinogens (21,900 days). An excess risk exists when the HQ is greater than 1.

3. Results

Table 2 lists the physicochemical properties, major and trace element concentrations, and stable isotope values of the analyzed surface and groundwater in the studied area.

3.1. Physicochemical Parameters (pH, Eh, TDS, and TH)

The pH values of the groundwater wells ranged from 7.4 to 8.2 for different groundwater samples. These values were comparable to the Nile River water samples' pH, which was between 8.0 and 8.2. As the WHO prescribes, the allowable pH limit for drinking water is 6.5 to 8.5 [26].

Along with pH, Eh is the other physicochemical parameter affecting elemental mobility. In shallow groundwater wells, Eh values ranged from −14 mV to +23 mV, indicating the water is weakly reducing to weakly oxidizing. The low Eh values may be attributed to the waterlogging problem, where the reduction processes in waterlogged soils result from the anaerobic respiration of soil bacteria [73].

The total dissolved solids (TDS) ranged between 275 and 1274 mg/L, while the deep groundwater wells showed values from 288 to 608 mg/L. The high concentration values were observed in the southeastern and western sections of the study area. In contrast, the Nile River samples had lower TDS values (279 and 394 mg/L). The TDS values of 64% of the shallow groundwater wells were in critical condition according to the US EPA permissible limit (500 mg/L).

The values of total hardness (TH) of groundwater wells ranged from 126 to 496 mg/L CaCO_3 and indicate that the studied groundwater falls into the hard water category (>120 mg/L CaCO_3 ; WHO, 2011). TH was higher in the shallow (average 299 mg/L) than the deep groundwater (average 210 mg/L) and surface Nile water (140 and 177 mg/L). A range of epidemiological evidence has demonstrated the relationship between health risk and long-term consumption of hard water. Its effects on human health include cardiovascular disease, cerebrovascular mortality, central nervous system malformations, childhood atopic dermatitis, digestive health and constipation, bone mineral density, and urolithiasis and kidney stones [74–77].

Table 2. Geochemical and isotopic composition of the groundwater of the area studied.

S. No.	pH	Eh (mV)	EC (μS/cm)	TDS (mg/L)	TH (mg/L CaCO ₃)	K ⁺ (mg/L)	Na ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	HCO ₃ [−] (mg/L)	SO ₄ ^{2−} (mg/L)	Cl [−] (mg/L)	As (μg/L)	Cu (μg/L)	Cr (μg/L)	Fe (μg/L)	Mn (μg/L)	Pb (μg/L)	Sr (μg/L)	Zn (μg/L)	δ ² HH ₂ O (‰)	δ ¹⁸ OH ₂ O (‰)
Shallow Groundwater																						
1	8.1	−14	624	411.5	254.3	4.6	31	70.8	19	273	1.2	73.9	0.5	1.24	0.52	270	670	2.4	490	170	8.61	0.46
2	7.9	3	710	451.2	315.8	3.6	43	82.4	27	273	1.1	136.1	0.5	0.54	1.13	360	690	0.5	690	2200	11.03	0.79
3	7.99	12	823	553	242.2	3.5	36	64.3	20	265	0.6	77.1	0.6	0.5	0.67	600	670	0.6	450	310	10.25	0.65
4	7.98	−5	1572	1002	353.8	5.4	200	96	28	525	88.6	195.0	0.5	0.5	0.82	410	1000	0.5	720	890	16.78	1.68
5	7.86	0	931	595	226.1	3.9	110	57.8	20	331	23.9	124.7	0.5	1.07	0.98	63	770	0.9	689	482	−5.44	−1.39
6	7.8	0	1004	651	262.4	3.5	110	65.8	24	299	43.3	154.8	0.5	0.5	0.96	240	410	0.5	810	260	8.94	0.39
7	7.78	−1	776	500	298.6	3.1	55	75.4	27	397	48.9	34.2	0.5	0.56	0.50	420	530	0.5	750	4600	20.68	2.28
8	7.93	−9	1161	752	339.1	5.0	130	95	25	516	50.7	109.5	0.5	1.3	0.50	19	1700	0.5	750	12.8	21.19	2.3
9	7.92	−7	800	523	311.0	3.9	36	83.7	25	292	0.7	111.1	0.7	0.5	2.18	990	460	0.5	540	520	7.38	0.23
10	8.21	20	961	614	211.7	4.1	140	57	17	479	51.8	54.2	0.5	57.6	0.70	240	530	9.4	440	630	27.61	3.29
11	8.12	−12	928	607	354.4	5.0	47	99.5	26	310	32.8	126	0.5	4.5	0.97	640	530	0.5	710	230	8.94	0.47
12	7.89	−4	1957	1274	442.0	41.0	260	110	41	678	203	209	0.5	2.5	0.50	57.3	1600	0.5	1300	600	19.36	2.2
13	8.11	−13	523	338.6	195.3	3.3	28	53.7	15	232	2.8	48.7	0.5	0.5	0.70	180	410	1.0	360	520	11.08	0.79
14	7.43	23	1057	681.6	466.6	3.8	48	110	47	511	64.9	66.3	0.5	0.9	0.50	100	1700	0.6	640	1600	23.45	2.71
15	7.97	−7	558	356.5	319.6	3.4	52	87.2	25	407	3.6	72.3	1.4	0.5	0.50	290	1300	0.5	690	949	11.51	0.74
16	7.52	15	1198	788.5	367.9	4.5	110	100	29	680	26	21.8	0.5	1.06	0.72	13.4	630.4	1.2	890	280	19.38	2.23
17	7.9	−5	419	274	132.1	2.8	36	36.5	10	169	19	39.9	0.5	0.65	1.55	340	360	0.5	330	150	12.62	0.95
18	7.58	12	1571	1104	496	4.2	180	130	42	342	280	230	0.5	1.07	1.25	450	1500	1.0	940	1400	12.74	1.16
19	7.88	0	571	378	192.4	2.2	53	52.5	15	340	8.4	17.5	0.63	0.91	1.34	150	520	0.7	450	409	10.16	0.65
20	7.97	9	654	424	142.1	2.1	60	35.6	13	245	120	250	0.5	2.17	0.50	16.8	220.3	0.5	380	390	16.36	1.79
21	7.96	−4	656	438.4	243.6	5.7	55	61.6	22	313	73.2	28	0.9	5.76	1.91	1100	1300	2.2	480	840	22.49	2.51
22	8.07	−7	795	518	322.5	4.0	50	86.7	26	454	1.7	46	0.5	0.5	0.50	18.7	970	0.5	590	400	9.6	0.54
23	8.1	−11	721	487	213.5	4.6	90	54.4	19	385	45.1	38.2	0.5	0.87	0.58	510	850	1.9	430	57.8	25.98	3.1
24	8.08	−11	804	531	345.5	4.1	43	95.9	26	448	1.6	55	0.5	0.5	0.50	369.8	1100	0.6	690	160	15.07	1.32
25	7.97	−5	981	641	401.0	4.5	49	110	31	551	0.7	45.6	0.5	0.5	0.50	21.4	1000	0.5	760	150	11.64	0.84
Min	7.43	−14	419	274	132	2.1	28	35.6	10	169.4	0.6	17.5	0.5	0.5	0.5	13.4	220.3	0.5	330	12.8	−5.44	−1.39
Max	8.21	23	1957	1274	496	41	260	130	47	680	280	250	1.4	57.6	2.2	1100	1700	9.4	1300	4600	27.61	3.29
avg.	7.9	−0.4	930	609	299	6.6	86.6	79.1	25	391.3	54.6	97.4	0.6	5.4	0.89	332.6	864	1.4	651	845	14.1	1.2
Deep Groundwater																						
26	7.8	3	936	608	324.8	4.29	53	84.3	28	226	15.0	175	0.5	0.5	0.5	170	790	0.07	730	11	8.74	0.42
27	7.87	0	446	288	147.5	6.22	35	39.4	12	241	0.6	24.7	0.5	5.4	0.67	160	370	0.5	270	5.9	1.4	−0.48
28	8	−8	351	233	126.3	3.25	16	34.4	9.9	163	0.8	22.7	0.5	0.5	0.5	210	340	0.5	240	5.8	8.89	0.49
Min	7.8	−8	351	232	126.2	3.2	16	34.4	9.9	162.6	0.6	22.7	0.5	0.5	0.5	160	340	0.07	240	5.8	1.4	−0.48
Max	8	3	936	608	324.7	6.2	53	84.3	28	240.6	15	175	0.5	5.4	0.67	210	790	0.5	730	11	8.89	0.49
avg.	7.8	−2	604	394	209.9	4.6	34.6	55.36	17.56	206.5	6.4	84.02	0.5	2.46	0.56	182	526	0.32	442	7.9	5.8	0.08
Nile Water																						
29	8.07	5	476	279	139.6	5.4	36	36.3	12	203	27	22.1	0.5	2.07	3.6	440	71.9	0.53	310	8.4	20.3	2.22
30	8.25	−18	658	394	176.6	7.5	56	44.6	16	240	44.7	47	0.6	1.05	0.8	100	98.3	0.50	389	4.8	20.5	2.36

3.2. Major Ions

Chloride concentration varied between 17.5 and 250 mg/L for the shallow groundwater wells, whereas the deeper wells (depth > 60 m) showed higher chloride concentrations (avg. 175 mg/L) compared to wells with depths of 100 m (23 mg/L) and 120 m (25 mg/L). In Nile River water, the average chloride concentration was 34.5 mg/L. Leaching of soil and domestic and municipal effluents are the potential main sources of chloride. For all studied wells, the chloride concentration is below the WHO and Egypt's national permissible limit of 250 mg/L [26].

Chloride and sulfate concentrations ranged widely from 0.6 to 280 mg/L in the shallow groundwater, whereas deeper wells generally displayed lower concentrations (0.6 to 15.0 mg/L).

Except for a single well (no. 18; Figure 1), all studied groundwater possesses SO_4^{2-} content below the permissible limit of 250 mg/L. The surface water of the Rosetta branch of the Nile River had a higher sulfate content (44.5 mg/L) than the Damietta branch (27 mg/L) (Figure 1). This probably reflects the impact of industrial wastewater discharging from the chemical industry factories along the Nile River Rosetta branch.

The HCO_3^- concentration varied between 163 and 680 mg/L in the studied groundwater. The shallow groundwater wells displayed relatively high concentrations (avg. 388 mg/L) compared to the deep wells (avg. 210 mg/L) and Nile water samples (avg. 222 mg/L).

The concentrations of Ca^{2+} , Na^+ , K^+ , and Mg^{2+} were in the range of 38–130, 28–260, 2.1–41, and 27.8–47 mg/L for the water in shallow wells and 34–48, 16–53, 3.2–6.2, and 10–28 mg/L for the water in deep wells, respectively. Except for Na^+ in shallow groundwater wells, the other major cations are within the permissible limits of Egypt's national standards. Concerning Na^+ , two shallow groundwater wells (nos. 4 and 19) have critical values of 200 and 260 mg/L, respectively, which are above the acceptable limit of 200 mg/L. Lower sodium levels in drinking water (30–60 mg/L) are essential for human health, but high levels can cause hypertension [78].

The Piper diagram [79] has been frequently applied to investigate the hydro-chemical facies of groundwater wells, the evolution of phreatic water and understanding the hydro-chemical characteristics, as well as the formation mechanism of groundwater (Lu et al., 2010). The relative abundance of anions and cations is $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$ and $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$, respectively, for most of the studied wells. The Piper diagram (Figure 2) indicates that deep wells and most of the shallow wells (64%) are of the Ca-HCO_3 type, while the other samples (28%) are of the Na-HCO_3 type. Wells nos. 18 and 20 are of the Na-Cl type, which suggests that the shallow groundwater in the western part of the study area might be affected by sewage infiltration. The Na-HCO_3 water type may indicate an ion exchange between sodium-rich soil and the infiltrating surface water with higher calcium and magnesium concentrations [59].

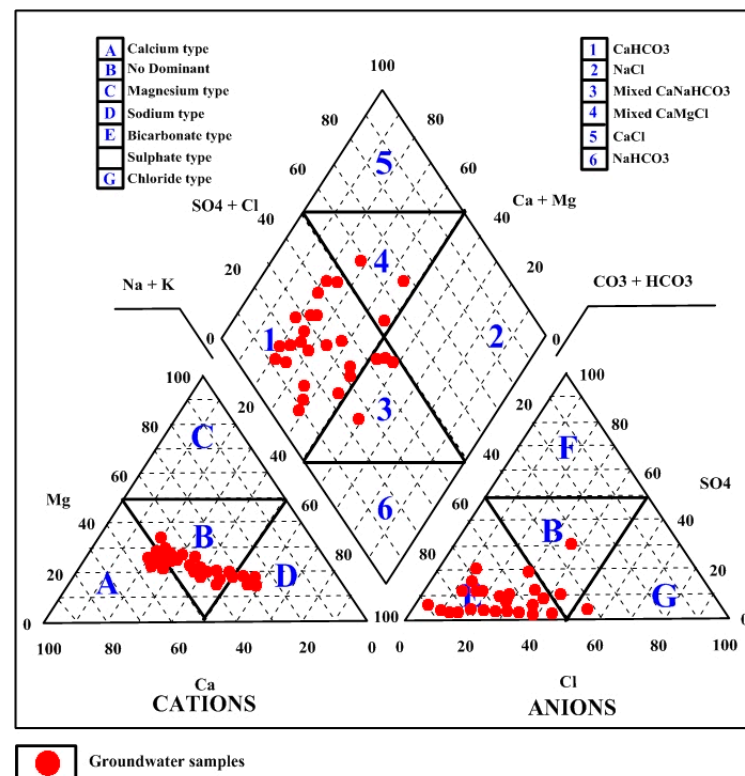


Figure 2. Piper plot of surface water and groundwater samples collected from the central area of the Nile Delta.

3.3. Stable Isotopes

The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the shallow hand-pumped water samples (Figure 3) correlate along a regression line with $\delta^2\text{H} = 6.6 \times \delta^{18}\text{O} + 5.6$. The oxygen and hydrogen isotopes of the water molecule can be used to categorize the sampled water into two main groups representing (1) surface water and (2) deep groundwater endmembers (Figure 3). The surface water was enriched in the heavy isotopes, showing $\delta^2\text{H}$ values of $\sim +20\text{‰}$ and $\delta^{18}\text{O}$ values from $+2.2$ to $+2.5\text{‰}$. In contrast, the deep groundwater samples ranged from $+1.4$ to $+8.9\text{‰}$ for $\delta^2\text{H}$ and between -0.5 and $+0.5\text{‰}$ for $\delta^{18}\text{O}$.

The samples from the deep well plot in the paleo-water field represent the isotopic signature of the Nile River before the completion of the first stage of the Aswan High Dam in 1964 [32,59,80,81]. The broader range of isotope values for the deep wells might indicate that portions of paleo-groundwater, formed under cooler and more humid climatic conditions in the Pleistocene aquifer of the floodplain, are admixed here [82].

The higher isotope values of the shallow groundwater can be attributed to the extensive evaporation processes in Lake Nasser, the Aswan High Dam reservoir, with losses of about 19% of lake water [83], and through the circulation of different irrigation canals [32]. This process enriches the heavy stable isotopes ^2H and ^{18}O in the surface (recent Nile) water [83–85].

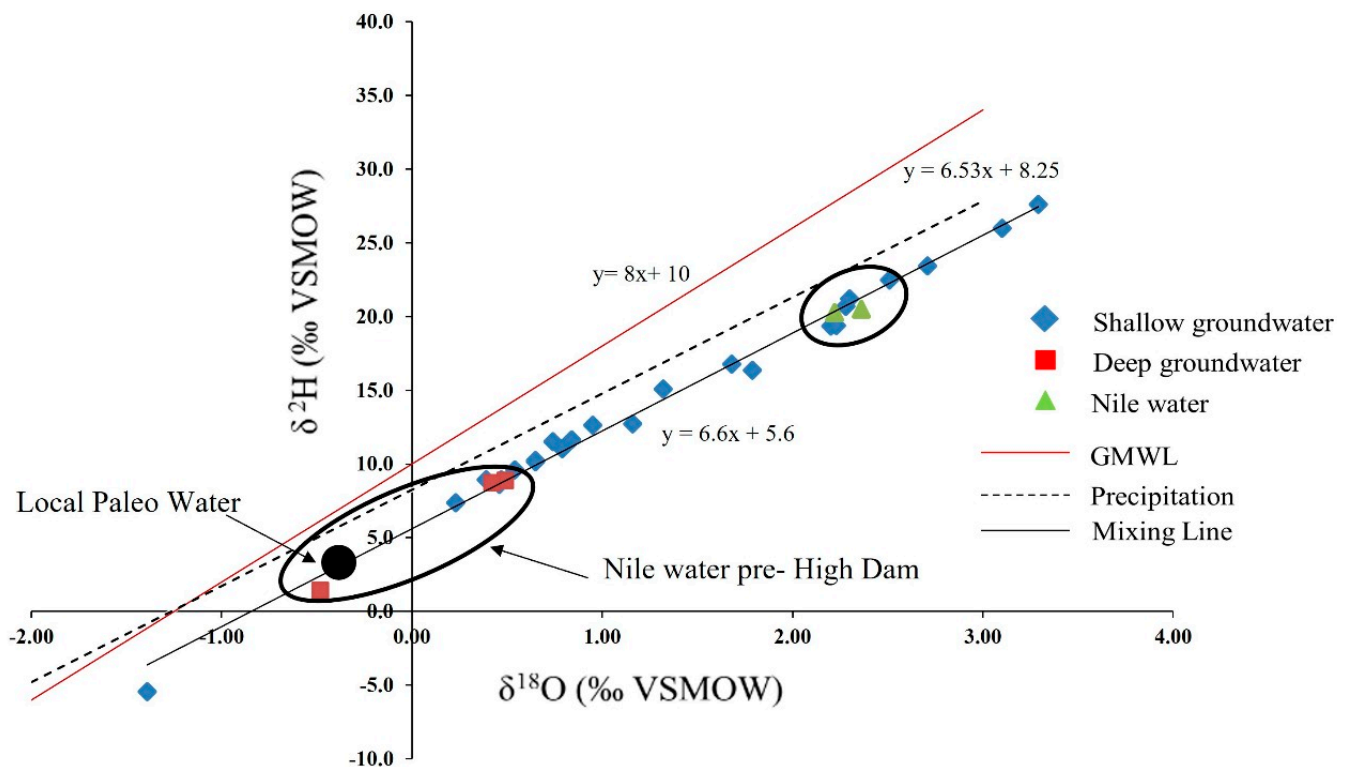


Figure 3. Plot of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for groundwater from the Nile Delta aquifer system with plots of the GMWL according to Rozanski et al. [86] and Nile LPW according to Awad et al. [87].

Figure 3 shows, however, that the shallow groundwater wells can be categorized into three categories: (1) wells with the same isotopic characteristics as deep groundwater (nos. 1, 8, 14, 17, and 36), (2) wells that displayed the same isotopic characteristics as recent Nile water (sample nos. 9, 10, 28, and 34), and (3) mixed water samples that fall along a mixing line between both endmembers. Water samples with isotope values higher than recent Nile water indicate direct recharge from surface irrigation water subject to evaporation before infiltration or from recycling drainage water [29,32,88]. After infiltration, further evaporation of soil water is suspected because of the rising water table during the last few decades, particularly after the completion of the first stage of the Aswan High Dam in 1964.

The spatial distribution pattern of the oxygen and hydrogen isotope ratios (Figure 4) indicates that the recent Nile water is distributed in the study area's western, southern, and eastern parts. On the other hand, the aquifers holding older water are in the northern, central, and southeastern parts, while aquifers with mixed recharged water are located in between. This pattern most probably reflects the spatial distribution of impermeable clay lenses within the Mit Ghamr Fm [36]. The presence or absence of such clay lenses tends to subdivide the main aquifer into sub-restricted or perched aquifers with variable portions of recent Nile water. Samples of paleo-water and recent Nile water are both Ca-HCO_3 type, while most mixed water samples belong to the Na-HCO_3 and Na-Cl water types.

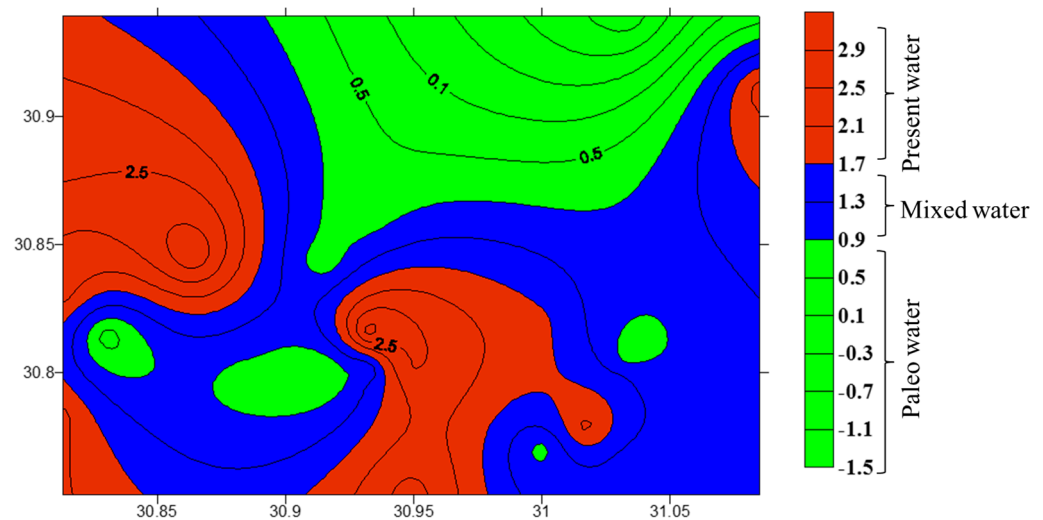


Figure 4. Spatial distribution map of $\delta^{18}\text{O}$ for shallow groundwater from the Nile Delta aquifer system.

3.4. Heavy Metal Contents

The total concentrations of potentially toxic metals in the studied groundwater wells are tabulated in Table 2.

Among the trace elements, Mn and Fe represent critical concentrations compared to the acceptable limits. The manganese concentration in 80% of shallow groundwater samples exceeds the WHO standard limit of 400 $\mu\text{g/L}$ [26]. In shallow groundwater, the Mn concentration ranges from 220 to 1700 $\mu\text{g/L}$, while in deep groundwater, it ranges from 340 to 790 $\mu\text{g/L}$, whereas lower values of 72 to 98 $\mu\text{g/L}$ were measured in Nile River water. The spatial distribution of high Mn concentrations is related to the old and highly populated residential areas in the study area's western and southern parts suffering from waterlogging problems.

Forty-four percent of the shallow groundwater exceeded the permissible limit of 300 $\mu\text{g/L}$. Fe concentrations ranged from 13 to 1100 $\mu\text{g/L}$ in shallow groundwater, 160 to 210 $\mu\text{g/L}$ in deep groundwater, and 100 to 400 $\mu\text{g/L}$ in Nile River water. The spatial distribution of the iron concentration suggests that the pattern is related to the land use type, where the high Fe contents are related to cultivated lands, small unsewered villages, and industrial areas such as Kafr El Zayat city.

The dissimilarity of the spatial distribution of Fe and Mn and the reverse correlation between them (Table 3) indicates the different sources of these elements. Slow groundwater runoff in the poorly drained cultivated lands and waterlogged soil of unsewered villages provides appropriate conditions for the accumulation of soluble Fe and Mn. Reducing Fe and Mn is one of the most critical chemical transformations in waterlogged soils [73]. The uppermost part of cultivated soil is enriched in Fe-organic content compared to urban soil [89]. In addition, industrial activities may contribute in part to the excessive Fe.

On the other hand, the frequently occurring Mn concentration may indicate a pedogenic source rather than anthropogenic. The correlation between Mn and Ca^{2+} , Mg^{2+} , and Sr suggests that Mn is strongly associated with carbonate minerals of the water-bearing layer (Table 3). Under acidic and reducing conditions, the dissolution of Mn-carbonates from poorly drained soils close to water channels and drains can be the primary source of Mn.

Table 3. Correlation matrix of studied physicochemical parameters and major and trace elements of the groundwater in the study area.

	pH	Eh	EC	TDS	TH	K	Na	Ca	Mg	HCO ₃	SO ₄	Cl	Cr	Mn	Fe	Cu	Zn	As	Sr	Pb
pH	1.00																			
Eh	−0.57	1.00																		
EC	−0.37	0.23	1.00																	
TDS	−0.38	0.24	1.00	1.00																
TH	−0.48	0.16	0.77	0.78	1.00															
K	−0.02	−0.08	0.60	0.58	0.33	1.00														
Na	−0.20	0.18	0.89	0.89	0.48	0.63	1.00													
Ca	−0.41	0.09	0.75	0.76	0.99	0.28	0.46	1.00												
Mg	−0.59	0.28	0.77	0.78	0.97	0.38	0.49	0.92	1.00											
HCO ₃	−0.27	0.18	0.72	0.70	0.68	0.45	0.63	0.68	0.65	1.00										
SO ₄	−0.36	0.30	0.70	0.73	0.46	0.48	0.75	0.41	0.52	0.29	1.00									
Cl	−0.18	0.13	0.62	0.62	0.39	0.32	0.57	0.36	0.40	0.07	0.66	1.00								
Cr	0.06	0.06	−0.22	−0.23	−0.27	−0.09	−0.15	−0.28	−0.25	−0.37	0.00	−0.15	1.00							
Mn	−0.34	0.04	0.61	0.62	0.76	0.37	0.49	0.74	0.77	0.62	0.46	0.24	−0.32	1.00						
Fe	0.19	−0.17	−0.15	−0.13	−0.05	−0.14	−0.18	−0.05	−0.06	−0.33	0.00	−0.08	0.52	−0.07	1.00					
Cu	0.31	0.40	0.04	0.03	−0.15	0.00	0.21	−0.15	−0.15	0.14	0.05	−0.11	−0.03	−0.11	0.00	1.00				
Zn	−0.34	0.21	0.12	0.11	0.28	−0.04	0.05	0.23	0.36	0.12	0.21	0.04	−0.09	0.13	0.14	−0.02	1.00			
As	0.06	−0.14	−0.22	−0.21	0.02	−0.07	−0.15	0.03	−0.01	−0.01	−0.12	−0.13	0.09	0.24	0.32	−0.05	0.06	1.00		
Sr	−0.43	0.07	0.86	0.85	0.84	0.58	0.70	0.82	0.82	0.70	0.53	0.52	−0.27	0.62	−0.19	−0.15	0.26	−0.02	1.00	
Pb	0.34	0.33	0.01	0.01	−0.16	−0.05	0.19	−0.15	−0.16	0.15	0.04	−0.18	−0.04	−0.07	0.06	0.95	−0.02	−0.03	−0.18	1.00

3.5. Water Quality Assessment

The calculated GWQI indicated that deep groundwater samples are categorized as “excellent” to “good” quality for drinking water (Table 4). The GWQI values categorized the samples into three categories for shallow groundwater samples, ranging from “excellent” to “poor” water quality. Only 4% of the total wells show “excellent” quality, most of the samples (64%) are categorized as “good” quality, and the rest (32%) exhibit “poor” quality [64]. Spatially, there is no circumscribed distribution of “excellent”- and “good”-quality samples for shallow wells (Figure 5). The eastern and southern parts of the study area, which have waterlogged soils, are in critical condition. Poor-quality water wells roughly correlated with the spatial distribution of high Mn concentration and enriched stable isotope values. However, it is noted that a weak correlation ($r = 0.56$) exists between GWQI values and isotope values. Water samples with higher, evaporative-enriched isotope values display higher levels of substances found in samples with undesirable GWQI values.

Table 4. GWQI classification of the groundwater in the area studied.

S. No	GWQI	Water Type
1	77.2	Good water
2	85.4	Good water
3	82.2	Good water
4	118.9	Poor water
5	83.7	Good water
6	64.1	Good water
7	78.0	Good water
8	147.9	Poor water
9	83.0	Good water
10	169.2	Poor water
11	89.0	Good water
12	162.2	Poor water
13	54.0	Good water
14	155.4	Poor water
15	120.6	Poor water
16	76.1	Good water
17	52.9	Good water
18	165.9	Poor water
19	62.2	Good water
20	48.4	Excellent water
21	154.4	Poor water
22	90.6	Good water
23	94.8	Good water
24	110.0	Poor water
25	96.1	Good water
26	87.1	Good water
27	55.2	Good water
28	44.2	Excellent water

The methods used in Figures 4 and 5 likely involve spatial interpolation techniques such as Kriging or inverse distance weighting (IDW) to visualize the distribution of $\delta^{18}\text{O}$ and groundwater quality index (GWQI) values across the study area. These techniques are commonly used in hydrogeological studies to estimate values at unsampled locations based on nearby measured data points.

For Figure 4, the distribution of $\delta^{18}\text{O}$ values suggests that recent Nile water and older groundwater are separated due to geological barriers, particularly impermeable clay lenses within the Mit Ghamr Formation. The isotope analysis, typically conducted using

mass spectrometry, helps differentiate water sources by identifying evaporation effects and recharge origins [88].

For Figure 5, the groundwater quality index (GWQI) was calculated using a weighted sum of key water quality parameters such as pH, total dissolved solids (TDS), Mn concentration, and major ions. The spatial mapping of GWQI values likely employed geographic information system (GIS) tools to identify areas with poor water quality, which correlated with high Mn concentrations and isotope enrichment.

These findings align with previous hydrogeological studies that emphasize the role of aquifer heterogeneity in water quality variations [89,90].

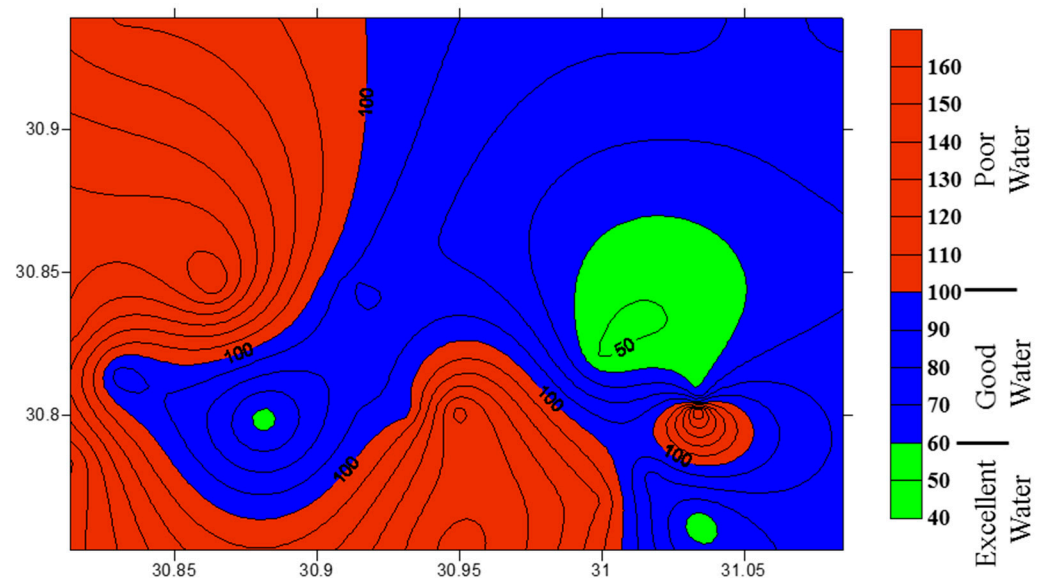


Figure 5. Spatial distribution map of GWQI in the Central Nile Delta groundwater.

3.6. Irrigation Suitability

Wilcox [56] suggested a graphical method based on the sodium percentage parameter (Na%) for irrigation purposes. Sodium percentage values classify the water into five classes: 'excellent' (<20 Na%), 'good' (20–40 Na%), 'permissible' (40–60 Na%), 'doubtful' (60–80 Na%), and 'unsuitable' (>80 Na%). The Wilcox diagram (Figure 6) revealed that 40% of the samples belong to the excellent-to-good class and 50% are good to permissible, while 10% of the groundwater samples are categorized as permissible-to-doubtful irrigation water.

3.7. Health Risk Assessment

The calculated values of health risk are listed in Table 5. HQ values ranked the heavy metals in the order of $Mn > Cr > Zn > As > Fe > Pb > Cu$ based on their detriments. Except for Mn, the HQ values for the evaluated heavy metals were less than one, which indicates little or no risk to residents. On the other hand, Mn shows HQ values indicating an unacceptable non-carcinogenic health risk for 14 wells, representing 56% of the total shallow groundwater wells, mainly located in the southern and western areas of the study region. Manganese is an essential microelement in nutrition, and Mn deficiency (less than 0.1 mg/day) can cause health problems (e.g., weight gain, glucose intolerance, blood clotting, skin problems, lowered cholesterol levels, skeleton disorders, and congenital disabilities). It contributes to maintaining healthy nerves, the immune system, and helps reduce blood sugar regulation symptoms [91].

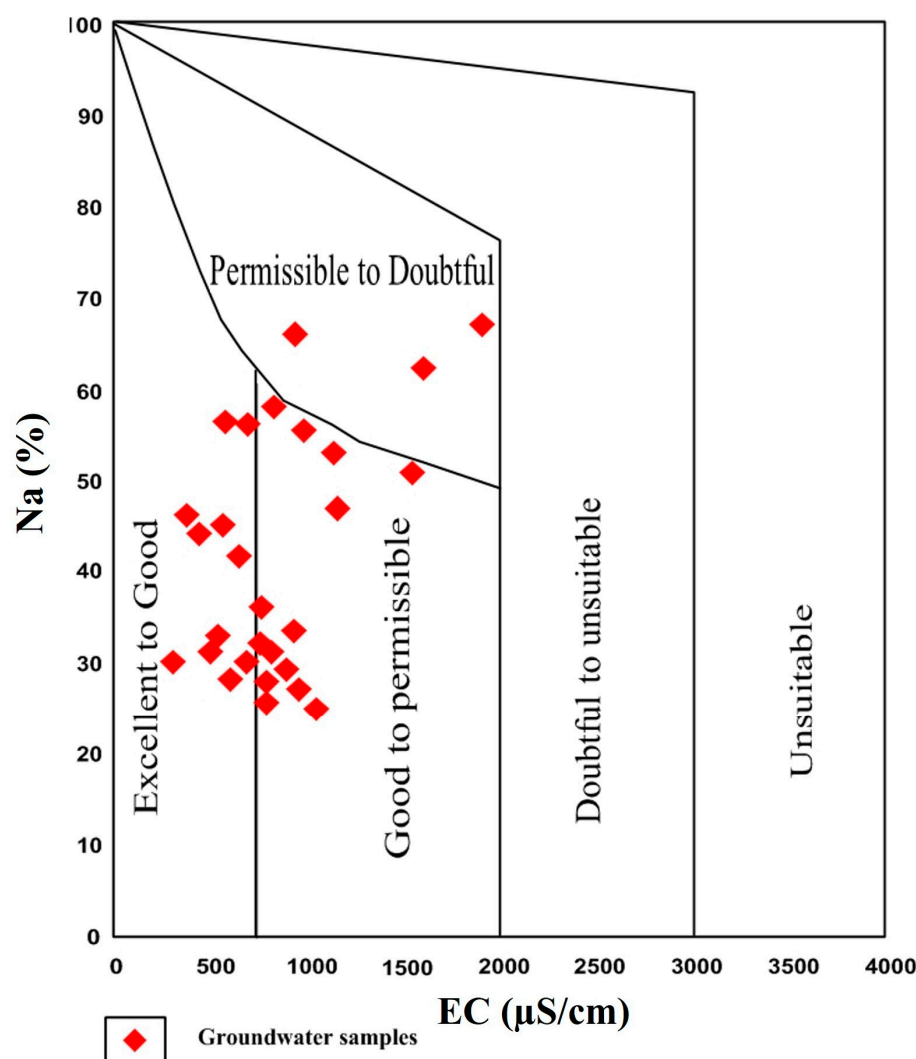


Figure 6. Wilcox's diagram illustrates the suitability of groundwater for irrigation based on electrical conductivity and sodium percentage.

Table 5. Non-cancer health risk (HQ) from heavy metals in the water at each surface and groundwater site (HQ values > 1.0 are shown in bold).

S No.	Mn	Fe	Cu	As	Pb	Cr	Zn
1	9.57×10^{-1}	2.57×10^{-2}	8.91×10^{-4}	4.76×10^{-2}	1.91×10^{-2}	5.00×10^{-2}	1.62×10^{-2}
2	9.86×10^{-1}	3.43×10^{-2}	3.90×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	1.07×10^{-1}	2.10×10^{-1}
3	9.57×10^{-1}	5.72×10^{-2}	3.57×10^{-4}	5.71×10^{-2}	4.45×10^{-3}	6.38×10^{-2}	2.95×10^{-2}
4	1.43	3.90×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	7.82×10^{-2}	8.48×10^{-2}
5	1.10	6.07×10^{-3}	7.67×10^{-4}	4.76×10^{-2}	6.80×10^{-3}	9.36×10^{-2}	4.60×10^{-2}
6	5.86×10^{-1}	2.29×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	9.11×10^{-2}	2.48×10^{-2}
7	7.57×10^{-1}	4.00×10^{-2}	4.00×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	4.38×10^{-1}
8	2.43	1.81×10^{-3}	9.14×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	1.23×10^{-3}
9	6.57×10^{-1}	9.43×10^{-2}	3.57×10^{-4}	6.88×10^{-2}	4.29×10^{-3}	2.08×10^{-1}	4.95×10^{-2}
10	7.57×10^{-1}	2.29×10^{-2}	4.12×10^{-2}	4.76×10^{-2}	7.49×10^{-2}	6.65×10^{-2}	6.00×10^{-2}
11	7.57×10^{-1}	6.10×10^{-2}	3.28×10^{-3}	4.76×10^{-2}	3.97×10^{-3}	9.25×10^{-2}	2.19×10^{-2}
12	2.29	5.46×10^{-3}	1.83×10^{-3}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	5.71×10^{-2}
13	5.86×10^{-1}	1.71×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	8.28×10^{-3}	6.67×10^{-2}	4.95×10^{-2}
14	2.43	9.52×10^{-3}	6.38×10^{-4}	4.76×10^{-2}	5.01×10^{-3}	4.76×10^{-2}	1.52×10^{-1}
15	1.86	2.76×10^{-2}	3.57×10^{-4}	1.37×10^{-1}	3.97×10^{-3}	4.76×10^{-2}	9.04×10^{-2}

Table 5. Cont.

S No.	Mn	Fe	Cu	As	Pb	Cr	Zn
16	9.01×10^{-1}	1.28×10^{-3}	7.63×10^{-4}	4.76×10^{-2}	9.32×10^{-3}	6.88×10^{-2}	2.67×10^{-2}
17	5.14×10^{-1}	3.24×10^{-2}	4.65×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	1.48×10^{-1}	1.43×10^{-2}
18	2.14	4.29×10^{-2}	7.65×10^{-4}	4.99×10^{-2}	7.91×10^{-3}	1.19×10^{-1}	1.33×10^{-1}
19	7.43×10^{-1}	1.43×10^{-2}	6.51×10^{-4}	5.99×10^{-2}	5.86×10^{-3}	1.27×10^{-1}	3.90×10^{-2}
20	3.15×10^{-1}	1.61×10^{-3}	1.56×10^{-3}	5.08×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	3.71×10^{-2}
21	1.86	1.05×10^{-1}	4.12×10^{-3}	9.30×10^{-2}	1.73×10^{-2}	1.82×10^{-1}	8.00×10^{-2}
22	1.39	1.79×10^{-3}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	3.81×10^{-2}
23	1.21	4.86×10^{-2}	6.22×10^{-4}	4.89×10^{-2}	1.49×10^{-2}	5.54×10^{-2}	5.50×10^{-3}
24	1.57	3.52×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	5.03×10^{-3}	4.76×10^{-2}	1.53×10^{-2}
25	1.43	2.04×10^{-3}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	1.43×10^{-2}
Min.	3.15×10^{-1}	1.28×10^{-3}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.76×10^{-2}	1.23×10^{-3}
Max.	2.43	1.05×10^{-1}	4.12×10^{-2}	1.37×10^{-1}	7.49×10^{-2}	2.08×10^{-1}	4.38×10^{-1}
Avg.	1.23	3.17×10^{-2}	3.85×10^{-3}	5.78×10^{-2}	1.15×10^{-2}	8.53×10^{-2}	8.05×10^{-2}
26	1.13	1.62×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	5.64×10^{-4}	5.16×10^{-2}	1.05×10^{-3}
27	5.29×10^{-1}	1.52×10^{-2}	3.91×10^{-3}	4.76×10^{-2}	3.97×10^{-3}	6.45×10^{-2}	5.67×10^{-4}
28	4.86×10^{-1}	2.00×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	3.97×10^{-3}	4.87×10^{-2}	5.55×10^{-4}
Min.	4.86×10^{-1}	1.52×10^{-2}	3.57×10^{-4}	4.76×10^{-2}	5.64×10^{-4}	4.87×10^{-2}	5.55×10^{-4}
Max.	1.13	2.00×10^{-2}	3.91×10^{-3}	4.76×10^{-2}	3.97×10^{-3}	6.45×10^{-2}	1.05×10^{-3}
Avg.	7.51×10^{-1}	1.73×10^{-2}	1.78×10^{-3}	4.76×10^{-2}	2.61×10^{-3}	5.56×10^{-2}	7.54×10^{-4}
RfD							
Mg/kg/day	2.00×10^{-2}	3.00×10^{-1}	4.00×10^{-2}	3.00×10^{-4}	3.60×10^{-3}	3.00×10^{-3}	3.00×10^{-1}

On the other side, it is toxic at higher concentrations ($>300 \mu\text{g/L}$, USEPA [92]), causing Parkinson's disease, hallucinations, forgetfulness, lung embolism and bronchitis, and nerve damage [93], affects fertility in mammals, and is toxic to the embryo and fetus [94]. Manganese neurotoxicity results from an accumulation of metal in brain tissue [95,96].

It is worth mentioning that the intake of Mn by direct water consumption is not the only source of ingestion. Residents could have deleterious health effects from Mn bioaccumulation through the food chain since shallow groundwater is the primary drinking water source for all domestic animals, including cattle, poultry, and other livestock.

The study acknowledges the importance of broadening the scope of health risk assessment beyond manganese (Mn) to encompass other heavy metals. Future research will aim to conduct a more comprehensive evaluation of cumulative exposure and potential synergistic effects among multiple contaminants. Additionally, while the current analysis primarily focuses on direct water consumption as the main exposure pathway, other potential routes such as inhalation of aerosols, dermal absorption, and consumption of contaminated agricultural products will be explored to provide a more holistic understanding of exposure risks.

Moreover, the study recognizes the need for demographic-specific analysis to account for variations in susceptibility among different population groups, including children, pregnant women, and the elderly. Incorporating these factors into future assessments will enhance the accuracy of risk estimations. The temporal aspect of heavy metal concentrations is another area for further investigation. Examining seasonal or temporal variations could provide deeper insights into how exposure levels and associated health risks fluctuate over time.

Lastly, the study highlights the need to propose practical mitigation measures alongside identifying health risks. Future work will focus on recommending strategies to reduce exposure, improve water quality, and safeguard public health, thereby enhancing the study's practical implications. These considerations will be prioritized in subsequent research to address the limitations and strengthen the overall assessment.

4. Discussion

The results of this study on the physicochemical characteristics of groundwater provide valuable insights into the water quality of the region, and a comparison with the existing literature enhances our understanding of regional trends. The pH values of groundwater in this study ranged from 7.4 to 8.2, which is within the acceptable range for drinking water as set by the World Health Organization (WHO), i.e., 6.5–8.5. This slight alkalinity is typical of regions with limestone-dominated geology, where groundwater often interacts with mineral deposits, leading to higher pH values. Similar pH values have been reported in other groundwater studies in the Middle East and North Africa, with pH values ranging from 7.2 to 8.5 in limestone-dominated aquifers [25]. The consistency in pH levels across these studies suggests that the groundwater in the study area remains within a safe range for consumption, with no immediate concerns for acidity or alkalinity that could affect water quality.

The redox potential (Eh) in this study ranged from −14 mV to +23 mV, reflecting a transition from reducing to weakly oxidizing conditions. These values suggest that the shallow groundwater is influenced by organic matter and microbial activity, leading to reducing conditions, while deeper groundwater exhibits weakly oxidizing conditions, indicative of a more stable geochemical environment. Similar findings have been reported in agricultural regions with organic-rich soils, where Eh values range from −50 mV to +50 mV in shallow aquifers, and more oxidizing conditions are found in deeper aquifers [27]. The variation in Eh values highlights the dynamic nature of groundwater systems, where microbial and organic processes in shallow aquifers significantly affect the redox conditions.

The total dissolved solids (TDS) concentrations in shallow groundwater ranged from 500 to 1200 mg/L, while deeper wells had lower concentrations, ranging from 200 to 400 mg/L. These elevated TDS levels in shallow groundwater are typical of regions with high evaporation rates and agricultural activities, where salts from irrigation and evaporation contribute to increased TDS. This observation aligns with other studies from arid regions, such as those in North Africa and the Middle East, where TDS levels in shallow aquifers are often elevated, ranging from 500 to 1500 mg/L, due to similar agricultural practices [29]. In the study area, the highest TDS values were observed in the southeastern and western zones, which are also heavily influenced by surface evaporation and irrigation, consistent with findings from other arid and semi-arid regions.

Water hardness in this study ranged from 126 to 496 mg/L as CaCO_3 , categorizing the water as hard, with higher hardness in shallow wells (299 mg/L) compared to deeper wells (210 mg/L). This is in line with studies conducted in areas with carbonate aquifers, where the dissolution of calcium and magnesium from limestone formations results in elevated hardness levels. For example, a study in Saudi Arabia reported hardness values ranging from 150 to 500 mg/L in carbonate aquifers [31]. The higher hardness in shallow groundwater samples in our study suggests that groundwater chemistry is influenced by the dissolution of minerals from the surrounding limestone geology.

Chloride concentrations were generally higher in deeper groundwater, ranging from 100 to 220 mg/L, compared to 50 to 150 mg/L in shallow wells. This pattern suggests the presence of saline intrusion, which is a common phenomenon in coastal and semi-arid regions. Similar patterns of elevated chloride concentrations in deeper groundwater have been observed in areas like coastal Mediterranean aquifers, where saline water from surrounding sources intrudes into deeper wells, with chloride concentrations often exceeding 200 mg/L [33]. Elevated sulfate concentrations, particularly in shallow groundwater, were observed in the study area, ranging from 40 to 150 mg/L. This is consistent with studies in agricultural and industrial regions, where sulfate contamination from agricultural runoff and industrial effluents is common. In contrast, sulfate concentrations in deeper ground-

water in the study area ranged from 20 to 80 mg/L, indicating less contamination from surface activities.

Stable isotopic analysis revealed that shallow groundwater samples were enriched in heavier isotopes, with $\delta^{18}\text{O}$ values ranging from -3.5‰ to -2.0‰ and $\delta^2\text{H}$ values from -25‰ to -18‰ . These isotopic signatures indicate the influence of evaporation, particularly from Lake Nasser, which is located nearby. This finding is consistent with other studies in arid regions, where evaporation leads to the enrichment of heavier isotopes in shallow groundwater, with $\delta^{18}\text{O}$ values typically ranging from -3‰ to -1‰ in similar settings [35]. In contrast, deeper groundwater samples displayed isotopic signatures consistent with paleo-recharge from wetter climatic periods, with $\delta^{18}\text{O}$ values ranging from -7.0‰ to -5.0‰ , which is typical of recharge that occurred during periods of higher precipitation. This pattern is also seen in other studies of deep aquifers in arid regions, where deep groundwater is recharged during wetter periods that occurred centuries or even millennia ago [36].

Iron and manganese concentrations were elevated in some shallow groundwater samples, particularly in areas with reduced conditions. Iron concentrations ranged from 0.3 to 1.2 mg/L, while manganese concentrations ranged from 0.2 to 0.8 mg/L, exceeding the WHO guidelines for manganese in 80% of shallow wells. These elevated concentrations are typical of groundwater in areas with reducing conditions, where iron and manganese are released from insoluble forms into the dissolved state. Similar findings have been reported in other agricultural regions, where iron and manganese levels are elevated due to reduction processes in shallow aquifers [37]. The elevated manganese concentrations in our study raise concerns about potential health risks, as prolonged exposure to high levels of manganese can lead to neurological disorders, as noted in studies in rural areas with high manganese levels in drinking water [38].

The groundwater quality index (GWQI) classification in this study showed that shallow groundwater was generally classified as “fair” to “poor”, with values ranging from 40 to 60, while deeper groundwater samples were classified as “excellent” to “good”, with values ranging from 75 to 90. These classifications align with findings from other agricultural regions, where shallow aquifers tend to have lower water quality due to contamination from agricultural practices, while deeper groundwater remains of higher quality. For instance, in India, similar GWQI classifications have been reported for shallow and deep groundwater in agricultural zones, with shallow wells classified as “poor” and deep wells as “excellent” due to contamination from agricultural runoff and fertilizers [39].

Consequently, the results of this study provide a detailed comparison of the physicochemical characteristics of groundwater in the region with findings from other studies conducted in similar geological and climatic settings. The study highlights that shallow groundwater in the area is more vulnerable to contamination from anthropogenic activities, with elevated levels of TDS, hardness, and trace metals, particularly iron and manganese, posing potential risks to water quality. In contrast, deeper groundwater remains of higher quality, with less contamination. These findings underscore the importance of ongoing groundwater monitoring and the implementation of sustainable water management practices, especially in agricultural regions, to ensure safe water resources for the future.

5. Conclusions

Groundwater contamination in the Nile Delta region is a highly significant problem that is currently not adequately controlled. The deterioration of the groundwater is attributed to agricultural practices, sanitation systems, and industrial activities. The deep (>60–120 m) groundwater wells are characterized by slightly alkaline (pH = 7.8–8.0), fresh (TDS = 232–608 mg/L), hard water (TH = 126–325 mg/L) that belongs to the Ca-HCO₃

water type. The shallow (<60 m) groundwater wells are slightly alkaline ($\text{pH} = 7.4\text{--}8.2$), mostly (92% of the total samples) fresh water ($\text{TDS} = 274\text{--}1274 \text{ mg/L}$), hard-to-very-hard water ($\text{TH} = 299\text{--}496 \text{ mg/L}$), and the majority (64%) are of the Ca-HCO_3 type, while 28% are of the Na-HCO_3 type and 8% of the Na-Cl water type.

Based on isotope geochemistry, the deep groundwater wells display paleo-water (pre-high-dam-construction), while the shallow groundwater differentiates into paleo-water, recent Nile water (post-high-dam-construction), or mixed between both categories. The presence or absence of clay lenses within the aquifer is the main factor which controls the water type.

Most of the groundwater samples (90%) studied are classified as excellent to good for irrigation purposes, while 10% of the samples are categorized as permissible-to-doubtful irrigation water. Manganese proved to be the most significant element in the Middle Nile Delta groundwater, where its concentration exceeds the permissible limits in up to 95% of the groundwater samples studied. HQ values indicate an unacceptable non-carcinogenic health risk for 56% of the shallow groundwater samples concerning Mn. Detailed studies about the geochemical characteristics of manganese in Nile Delta soil are needed to control the high Mn concentration in underlying groundwater.

This study only provides a thorough description, assessment, and interpretation of inorganic contaminants. However, additional studies are required to assess the organic contaminants in the Nile Delta groundwater. Rural communities that consume shallow groundwater should be warned about the potential adverse effects of such water.

6. Recommendations and Way Forward

Future research should focus on applying advanced isotopic techniques to trace groundwater recharge rates and contamination sources. Long-term monitoring is crucial to detect quality changes and emerging pollutants. Interdisciplinary collaboration among hydrogeologists, geochemists, health experts, and policymakers is essential for effective risk assessment and sustainable management. Additionally, developing accessible databases and cost-effective methods will support broader implementation, especially in resource-limited regions. These efforts will enhance sustainable management of groundwater resources and safeguard public health in arid areas.

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