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Original Article

Assessment of groundwater suitability for different activities in Toshka district, south Egypt

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Abstract: Globally, groundwater has globally emerged as a crucial freshwater source for domestic, irrigation, and industrial needs. The evaluation of groundwater quality in the Toshka region is imperative to ensure its suitability for the extensive agricultural and industrial activities underway in this promising, groundwater-dependent development area. This is particularly significant as Egypt increasingly relies on groundwater reserves to address freshwater deficits and to implement mega-development projects in barren lands. In this study, fifty-two samples were collected from the recently drilled wells tapping into the Nubian Sandstone Aquifer (NSA) in the Toshka region. Groundwater quality was assessed through hydrochemical analysis, Piper diagram, and various indicators such as Na%, SAR, RSC, KR, MH and PI. The hydrochemical analysis revealed improved groundwater quality characteristics, attributed to continuous recharge from Lake Nasser. The Piper diagram categorised most of the water samples as "secondary salinity" water type. Almost all wells proved suitable for irrigation with only two wells unsuitable based on MH values and six wells based on KR values. Considering Total Hardness (TH) values, all samples were classified as "Soft", indicating their suitability for domestic and industrial purposes. Water Quality Index (WQI) results concluded that all samples met WHO and FAO guidelines for drinking and irrigation, respectively. Spatial distribution maps, constructed using GIS, facilitate the interpretation of the results. Regular monitoring of quality parameters is essential to detect any deviation from permissible limits.

Keywords: Nubian Sandstone Aquifer; Water Quality Assessment; Hydro-chemical Analysis; Irrigation Quality Indicators; Domestic Use; Water Quality Index

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Introduction

Tapping into fossil groundwater aquifers has become a prevalent adaptive governance strategy for addressing water scarcity, notably in the Middle East and North Africa (MENA) countries. In Egypt, a recent mega groundwater-dependent development project has been proposed within a national framework, aiming to bridge the impending food gap. The Egyptian government has set ambitious plans to reclaim vast stretches of barren land in the Western Desert, seeking to alleviate the overpopulation along the Nile River (Shalby et al. 2023). The success of development in the Western Desert in Egypt hinges largely on the Nubian Sandstone Aquifer (NSA) (Aly et al. 2019). A critical concern regarding the sustainability of these ongoing projects is the NSA's capacity to meet the substantial groundwater withdrawals (Aly et al. 2023). Additionally, groundwater suitability poses a primary constraint on the expansion of development activities.

Hydrogeochemical investigations into groundwater chemistry contribute to the development of

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knowledge about hydro-chemical systems. This, in turn, can help with the efficient use and sustainable management of groundwater resources by identifying relationships among various hydrogeological parameters (Awad et al. 2022). Hydrochemical analysis plays a pivotal role in assessing groundwater suitability for desired purposes (Mohamed et al. 2022). Moreover, this analysis is instrumental in understanding alterations in water quality resulting from rock–water interaction or any form of anthropogenic influence (El-Rawy and Ismail, 2019). The hydrochemical analysis not only addresses the deviation between parameter concentration and its permissible limits, but also guides their specific use (Elsayed et al. 2021). For drinking and domestic purposes, standard limits are given by the World Health Organization (WHO), while for irrigation purposes, the assessment procedure aligns with the Food and Agriculture Organization (FAO) guidelines. Water chemistry can undergo changes due to both natural and anthropogenic influences, complicating its comprehension through simple techniques (Shalby et al. 2020; Aly et al. 2023). Multivariate statistical methods are therefore applied to decipher significant data. Additionally, conventional graphical representation of the water chemistry, such as the Piper (trilinear) diagram, are utilized to screen the groundwater hydrogeochemical facies characteristics (Zhao et al. 2021).

Cultivation requires an adequate water supply of usable quality to prevent sensitive crops from being damaged by pollutants such as trace elements, pesticides, and salts. To assess groundwater quality for irrigation, various indices, including sodium adsorption ratio (SAR), percentage of sodium (Na%), residual sodium carbonate (RSC), permeability index (PI), magnesium hazard (MH), Kelley ratio (KR), electrical conductivity (EC), salinity hazard, total hardness (TH), corrosivity ratio (CR) and total dissolved solids (TDS) are estimated (Anonna et al. 2022). SAR measrues the excessive sodium (Na^+) content relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}), which reduces soil permeability and thus inhibits the supply of water needed for the crops (Alshehri et al. 2023). Kumari and Rai (2020) evaluated groundwater quality for irrigation purposes in India, estimating various indices such as EC, SAR, RSC, SP, KR, MH, and PI. According to SAR, RSC and PI, all water samples were rated as excellent and safe water quality, while SP, KR and MH values implied that some samples were unsuitable and unsafe for irrigation. Ahmed et al. (2021) used irrigation water indices (e.g., EC, SAR, TDS, TH, RBC, KI, SSP, and MH) to identify favourable wells in the southwestern coastal plain of Bangladesh for irrigation. Alshehri et al. (2023) used several indices to assess the groundwater suitability in Saudi Arabia for irrigation purposes. The results revealed that the majority of the water samples are suitable for irrigation.

The Water Quality Index (WQI) is a highly valuable and efficient technique for providing an overall description of the water quality status (Naik et al. 2022). It consolidates various water parameters into a single expression to assess the overall quality of water for certain uses (Akter et al. 2016; Rabeiy, 2018). Consequently, the WQI is commonly employed to evaluate the suitability of water for drinking and other purposes (Naik et al. 2022). A WQI has been developed for qualitative zoning of suitable locations for drinking water wells (Adimalla and Qian, 2019; Khan and Qureshi 2018). In this context, the Geographic Information System (GIS) proves to be an effective tool for spatially mapping groundwater quality data and conducting suitability analyses (Soleimani et al. 2018; Megahed and Farrag, 2019; Tarawneh et al. 2019). The spatial analysis extension of GIS enables the interpolation of observed groundwater quality parameters to create a concentration map of water quality parameters for the entire area. Armanuos et al. (2016) utilized GIS along with multivariate statistical analysis to investigate groundwater suitability for drinking and irrigation in the Western Nile Delta of Egypt. El-Zeiny and Elbeih (2019) estimated the WQI to evaluate groundwater quality in Dakhla Oasis, Egypt, for drinking purposes according to Egyptian and WHO standards. The results indicated that approximately 38% of the wells fall within the poor water category. Ram et al. (2021) developed a GIS-based WQI to assess groundwater suitability in the Mahoba district of India for human consumption. The results confirmed that groundwater is generally safe and potable, except for a few localized pockets. Hagage et al. (2022) interpolated the WQI for the Akhmim district in Egypt, revealing a significant diversity in groundwater viability for drinking and exposure to degradation.

In southern Egypt, the Toshka region stands out as a promising development area where extensive human activities are initiated depending on the NSA's potential. Through a numerical model, Aly et al. (2023) determined a safe pumping rate in accordance with the sustainable criteria. The primary objective of this study is to assess the groundwater suitability for the proposed activities. Given its proximity to Lake Nasser, the debate on surface and groundwater interactions and their impact on groundwater quality is noteworthy. It is imperative to generate a spatial variation map of water quality parameters to zone favorable plots for each proposed activity. This generated water quality map will assist decision-makers in planning procedures for ongoing activities in the region.

1 Study area

The Toshka region is part of the government-advocated rural development reclamation project in Egypt. Covering an area of approximately 25,000 feddans (around 10,000 hectares), the Toshka development area is situated in the southeastern portion of the Western Desert, between latitudes 22° 30′ N and 23° 30′ N and longitudes 31° 00′ E and 32° 00′ E (Fig. 1). It is bounded by the High Dam Lake (Lake Nasser) to the east. The study area is characterized by an extremely arid climate in summer and a relatively short-day rainless winter.

The water-bearing formations in the study area consist of two main aquifers, namely Nile valley aquifer and the NSA, which are considered hydraulically connected, as illustrated in Fig. 2. Groundwater flows from Lake Nasser to the aquifer (Aly et al. 2019). The NSA serves as the primary groundwater resource for the ongoing developments in the southern portion of the Western Desert, Egypt. In contrast, Fig. 3 provides a sample of a groundwater well lithological description in the study area, indicating that the depth to groundwater is approximately 150 m from the ground surface.

2 Samples collection and analysis

Fifty-two groundwater samples were collected from the productive wells located in the Toshka development area, as depicted in Fig. 1, during the summer of 2021. The Groundwater Sector of the Ministry of Water Resources and Irrigation (MWRI) facilitated access to the pumping wells and administered the sampling procedures. The groundwater samples were collected in pre-washed polypropylene sampling bottles. Groundwater was collected after pumping the wells for about 10 min, with the bottles rinsed twice with the water to be sampled. Each sample underwent analysis for eleven parameters at the central laboratory of the Desert Research Center (DRC) (https://drc.gov.eg/en/central-lab/). The in-situ measurements of electrical conductivity (EC), total dissolved solids (TDS) and potential of hydrogen (pH) were compared with laboratory measurements, showing no significant difference. Major cations, including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), were measured, while major anions comprised carbonate (CO_3^{2-}), bicarbonates (HCO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-). Charge Balance Errors (CBE) were calculated using the formula proposed by Hasan and Rai (2023) and were found to be within the permissible limit of ±10% (Tarawneh et al. 2019).

$$CBE = \left[\left(\sum Z_{mc} - \sum Z_{ma}\right) \Big/ \left(\sum Z_{mc} + \sum Z_{mc}\right)\right] \quad (1)$$

Where: Z is the ionic valence, mc is the molarity of cations, and ma is the molarity of anion

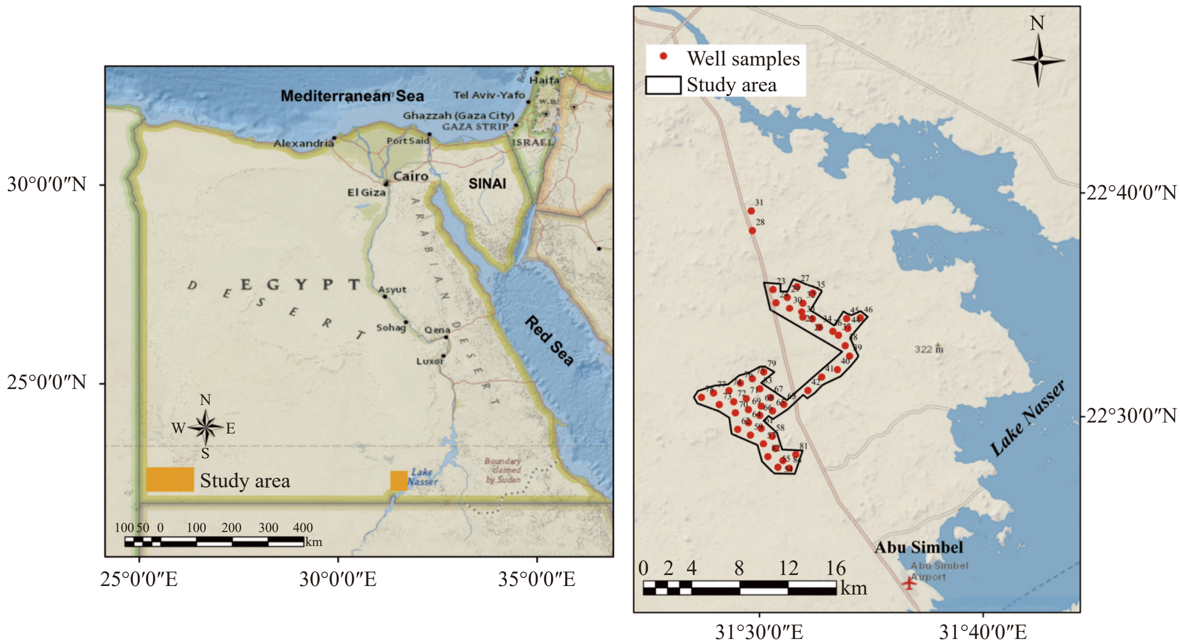

Fig. 1 Study area's map showing wells location where samples are collected

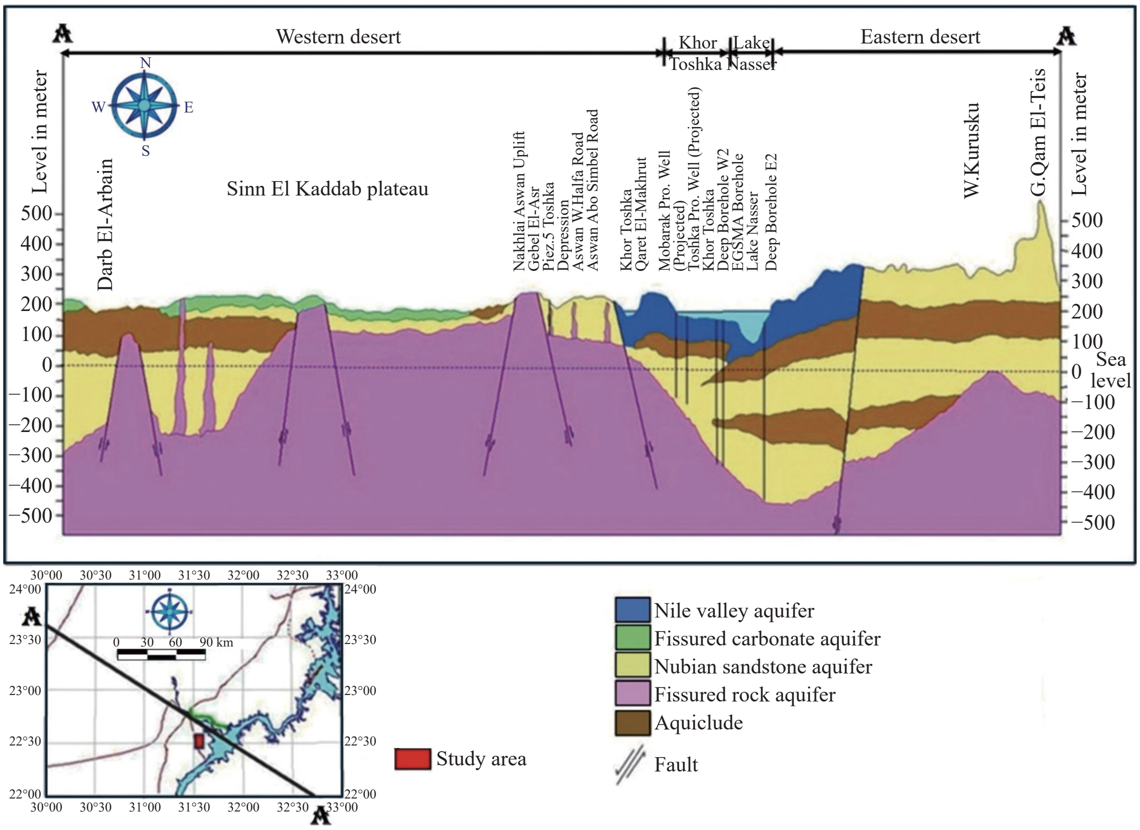

Fig. 2 Hydrological cross-sections of the NSA within the Toshka region

species.

Descriptive statistics, including minimum, maximum, average, and standard deviation, for the physicochemical parameters in groundwater samples from the Toshka area were calculated using Microsoft, while the correlation matrix between water quality parameters was generated using SPSS version 26.0.

2.1 Water origin and type

Three ratios were calculated to assess hydro-chemical processes influencing the water quality of the NSA in the Toshka region:

The first is Na^+/Cl^-, indicating groundwater origin. A value greater than one suggests a meteoric origin, While a value less than one indicates a marine origin.

The second ratio, Mg^{2+}/Ca^{2+}, considers salinity measurements. Cation exchange of (Ca^{2+} and Mg^{2+}) with Na^+ occurs as salinity increases. If the (Mg^{2+}/Ca^{2+}) ratio exceeds 0.8 and TDS is over 500 ppm, the groundwater source is likely seawater, brine or evaporites. If the ratio exceeds 0.8 but TDS is less than 100, the groundwater likely originates from rainwater. A ratio lower than 0.8 suggests groundwater sources from rock weathering.

The third ratio is Cl^-/ Sum of Anions (Z^-), indicating groundwater sources.

To understand dominant chemical facies, groundwater classification, and hydro-chemical processes, groundwater data were analyzed using the Piper diagram. Generally, four hydro-chemical water types can be identified based on different cations and anions in a groundwater sample (Ca–Mg–HCO_3, Na–K–HCO_3, Na–K–Cl–SO_4, and Ca–Mg–Cl–SO_4). Water types often indicate the origin of water composition in nature and the phase of its salinity development in various geological areas of the aquifers (Patel et al. 2023).

2.2 Suitability for irrigation purposes

Groundwater suitability for irrigation purposes necessitates the calculation of irrigation quality indices (IQIs), including total hardness (TH) and various irrigation quality parameters such as Percent Sodium (Na%), Sodium adsorption ratio (SAR), Residual sodium carbonate (RSC), Kelley ratio (KR), Magnesium hazard (MH) and Permeability index (PI). SAR is a key indicator of sodicity (alkali) hazard to crops. Elevated concentration of sodium relative to Ca^{2+} and Mg^{2+} reduces soil permeability, hindering water supply to crops and

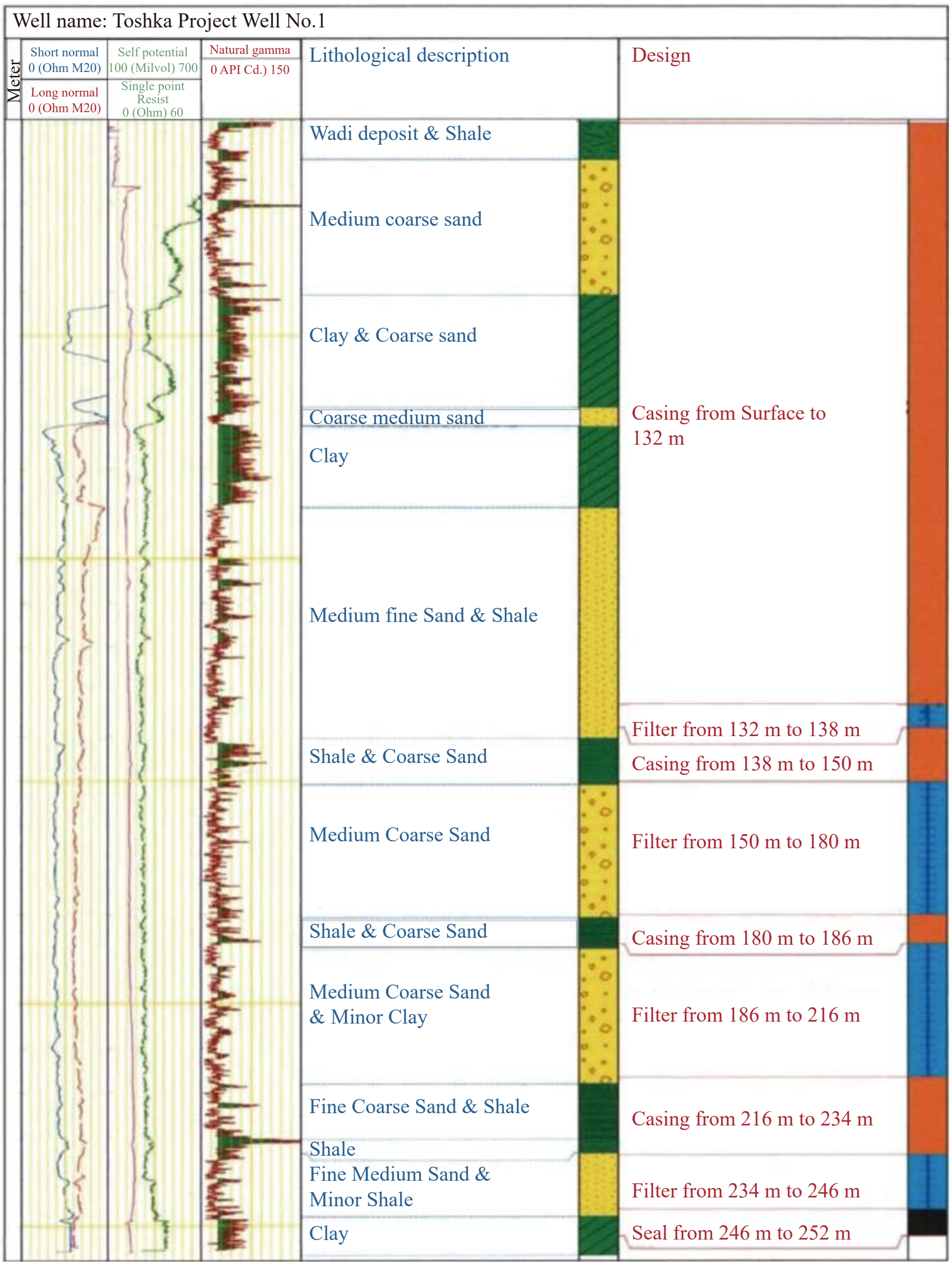

Fig. 3 A sample of a groundwater well lithological description

making cultivation challenging. SAR values for each sample are estimated using Equation (2), while sodium percentage (Na%) is calculated using Equation (3).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (2)$$

$$Na\% = \frac{(Na^{+} + K^{+})}{(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})} \times 100 \quad (3)$$

Excessive bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) in groundwater over alkaline sediments (calcium Ca^{2+} and magnesium Mg^{2+}) also impacts groundwater quality for irrigation purposes. Residual Sodium Carbonate (RSC) is calculated to determine the hazardous influence of CO_3^{2-} and HCO_3^- on water suitability for irrigation purposes. RSC is estimated using Equation (4).

$$RCS = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (4)$$

Permeability index (PI) values indicate the groundwater's suitability for irrigation. Long-term irrigation water use affects soil permeability, influenced by Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- content of the soil. The PI equation developed by evaluates groundwater suitability for irrigation , as shown in Equation (5):

$$\mathrm{PI} = \frac{(\mathrm{Na}^{+} + \sqrt{\mathrm{HCO_3}^{-}})}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+})} \times 100 \tag{5}$$

Generally, Ca^{2+} and Mg^{2+} are present in a state of equilibrium in groundwater. Excess magnesium content makes soil alkaline, reducing crop yield. Szaboles & Darab (1964) proposed the Magnesium Hazard (MH) value for irrigation water, as shown in Equation (6).

$$\mathrm{MH} = \frac{\mathrm{Mg}^{2+}}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})} \times 100 \tag{6}$$

Kelly's Ratio (KR) was introduced to assess groundwater quality for irrigation based on measured sodium relative to calcium and magnesium. Kelly's ratio (KR) can be estimated as in Equation (7).

$$\mathrm{KR} = \frac{\mathrm{Na}^{+}}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})} \tag{7}$$

Total Hardness (TH) is crucial in evaluating groundwater suitability for domestic and industrial purposes (El-Rawy and Ismail, 2019). Although water hardness has no recognized adverse effects, it increases detergent consumption during cleaning, and some evidence suggests a role in heart disease (Benaafi et al. 2022). Using Equation (8), the total hardness (TH) of the groundwater was calculated.

$$\mathrm{TH} = 2.497\ \mathrm{Ca}^{2+} + 4.115\ \mathrm{Mg}^{2+} \tag{8}$$

2.3 Arithmetic water quality index (WQI)

The arithmetic water quality index (WQI) is an indicator for evaluating the groundwater suitability for both drinking and irrigation purposes.

Three stages are involved in computing the WQI. In the initial step, the relative weight (w_i) of each water quality parameter is calculated using Equation (9) (RamyaPriya and Elango, 2017):

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{9}$$

Where: w_i is the weight of each parameter; W_i is the relative weight of each parameter, and n is the number of parameters.

In the second step, the quality rating scale (q_i) for each parameter is computed using Equation (10) (RamyaPriya and Elango 2017):

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{10}$$

Where: q_i is the quality rating scale; C_i is the concentration of each parameter in each water sample (mg/L); S_i is the standard limit for each parameter (mg/L) released by World Health Organization 2011 and FAO standards to assess the suitability of groundwater quality for drinking and irrigation purposes.

In the third step, the Water Quality Index (WQI) was calculated using Equation (11) as follows:

$$WQI = \sum_{i=1}^{n} W_i \times q_i \tag{11}$$

The groundwater is classified into five classes based on WQI values: Excellent, good, poor, very poor and unsuitable. Water is considered excellent when *WQI* values are less than 50; while it is deemed unsuitable for drinking and irrigation when WQI values exceeds 300.

2.3.1 Water quality index (Drinking)

WQI for drinking is calculated in this study using 11 water parameters, including physical parameters (pH, TDS and EC), major cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}), major anions (Cl^{-}, CO_3^{2-}, HCO_3^{-} and SO_4^{2-}). A weight is assigned to each parameter (w_i) according to its relative importance for potable usage and its perceived impact on primary health. Parameters with major effects on drinking water quality, such as TDS and SO_4^{2-}, receive the highest weights (values of 4 and 5). Parameters with lesser influences are given a weight of 1, While weights of 2 and 3 are assigned to other parameters depending on their influence on the water suitability, as detailed in Table 1.

2.4 Water quality index (Irrigation)

The Water Quality Index (WQI) for irrigation was calculated using the weighted arithmetic technique, incorporating eleven parameters. Minimum weights of 1 were assigned to Mg^{2+}, Ca^{2+}, CO_3^{2-}, HCO_3^{-}, while maximum weights of 5 were allocated to SO_4^{2-}, based on their importance for irrigation water quality. Moreover, various weights ranging between 1 and 5 were assigned to other parameters that pose diverse effects on sensitive crops, considering the significance of their impact on irrigation water quality, as detailed in Table 1.

3 Results and discussion

3.1 Hydrochemical characteristics of groundwater

The hydrochemical coefficients were calculated and represented in Table 3.

Analysis of groundwater samples from the Nu-

Table 1 Weight (w_i) and relative weight (W_i) of groundwater parameters used for arithmetic-WQI estimation (Drinking)

Parameter	Standard WHO	Weight (w_i)	Relative weights (W_i)
Na^+	200	3	0.09375
K^+	12	2	0.0625
Mg^{2+}	50	2	0.0625
Ca^{2+}	75	3	0.09375
HCO_3^-	120	2	0.0625
SO_4^{2-}	250	4	0.125
CO_3^{2-}	120	2	0.0625
Cl^-	250	3	0.09375
EC	1000	3	0.09375
TDS	500	5	0.15625
pH	8.5	3	0.09375
	Σ	32	1

Table 2 Weight (w_i) and relative weight (W_i) of groundwater parameters used for arithmetic-WQI estimation (Irrigation)

Parameter	Standard FAO	Weight (w_i)	Relative weights (W_i)
Na^+	919	3	0.1154
K^+	2	2	0.0769
Mg^{2+}	60	1	0.0385
Ca^{2+}	400	1	0.0385
HCO_3^-	610	1	0.0385
SO_4^{2-}	960	5	0.1923
CO_3^{2-}	610	1	0.03846
Cl^-	1063	4	0.1538
EC	2000	2	0.0769
TDS	2000	3	0.1154
pH	8.5	3	0.1154
	Σ	26	1

bian Sandstone Aquifer (NSA) revealed a Na^+/Cl^- ratio less than unity, likely attributed to the dissolution of salts in the aquifer formation. The Mg^{2+}/Ca^{2+} ratio in NSA groundwater, particularly close to Lake Nasser, was found to be lower than unity due to the dissolution of gypsum and anhydrite or ion exchange processes (Ezzeldin et al. 2018; Abd et al. 2023). The chloride/sum anions values in all investigated groundwater samples were less than 0.8, indicating the influence of rock-weathering processes. Continuous recharge from Lake Nasser was identified as having a significant impact on the chemical characteristic of groundwater in NSA, consistent with previous findings (Aly et al. 2019).

Table 3 Hydrochemical coefficients calculated for the 52 water samples

Well	Na^+/ Cl^-	Mg^{2+}/ Ca^{2+}	Cl^-/sum of Anions	Well	Na^+/ Cl^-	Mg^{2+}/ Ca^{2+}	Cl^-/Sum of anions
23	0.62	0.15	0.41	57	0.74	0.31	0.34
24	0.68	0.21	0.34	58	0.69	0.26	0.3
25	0.72	0.44	0.39	59	0.73	0.21	0.32
26	0.79	0.21	0.29	61	0.74	0.27	0.33
27	0.77	0.13	0.38	62	0.68	0.27	0.34
28	0.71	0.57	0.36	63	0.56	0.28	0.38
29	0.73	0.19	0.36	64	0.66	0.27	0.35
30	0.69	0.23	0.32	65	0.63	0.24	0.4
31	0.64	0.34	0.46	66	0.74	0.28	0.31
32	0.7	0.2	0.35	67	0.73	0.15	0.29
33	0.72	0.28	0.32	68	0.68	0.26	0.33
34	0.76	0.15	0.3	69	0.62	0.56	0.31
35	0.81	0.17	0.34	70	0.65	0.36	0.33
36	0.73	0.25	0.31	71	0.58	0.43	0.32
37	0.8	0.16	0.28	72	0.59	0.43	0.34
38	0.79	0.2	0.29	73	0.79	0.42	0.3
39	0.73	0.25	0.3	74	0.69	0.34	0.32
40	0.74	0.33	0.33	75	0.73	0.52	0.29
41	0.89	0.11	0.27	76	0.79	0.52	0.31
42	0.84	0.24	0.27	77	0.77	0.56	0.33
44	0.89	0.14	0.27	78	0.76	1.00	0.28
45	0.86	0.18	0.29	79	0.73	0.26	0.32
46	0.76	0.18	0.33	81	0.79	0.22	0.32
54	0.62	0.82	0.31	82	0.77	0.25	0.32
55	0.7	0.3	0.32	83	0.82	0.25	0.31
56	0.64	0.29	0.37	84	0.78	0.32	0.3

Natural water typically contains cations and anions in chemical equilibrium, with common cations including two "alkaline earths" calcium (Ca^{2+}) and magnesium (Mg^{2+}) and one "Alkali" sodium (Na^+) and common anions including one "weak acid" bicarbonate (HCO_3^-) and two "strong acids" sulphate (SO_4^{2-}) and chloride (Cl^-).

Based on the hydrochemical facies identified using the Piper diagram, as shown in Fig. 4, the majority of the groundwater samples fall into class IV, characterized by a predominance of strong acids (Cl^- , SO_4^{2-}) over weak acids (HCO_3^-,CO_3^{2-}) and earth alkaline element (Ca^{2+}, Mg^{2+}) over alkali element (Na^+, K^+), indicating a hydrochemical facies (Ca^{2+}- Mg^{2+}- Cl^-- SO_4^{2-}).

The remaining groundwater samples fall into class III, representing a primary salinity water type, with a predominance of alkali element (Na^+, K^+) over earth alkaline element (Ca^{2+}, Mg^{2+}) and strong acids (Cl^-, SO_4^{2-}) over weak acids (HCO_3^-, CO_3^{2-}), displaying hydrochemical facies of (Na^+–K^+–Cl^-–SO_4^{2-}).

Table 4 summarizes the analytical results of the major cations and anions data for the 52 groundwater samples, including descriptive statistics such as minimum, maximum, average, and standard deviation. The measurement unit for all groundwater parameters is milligrams per liter (mg/L), except for EC in microsiemens per centimeter (μS/cm) and pH without a unit.

pH is one of the most significant water parameters which measures the degree of alkalinity or acidity of the groundwater (Sinduja et al. 2023). The pH of the collected groundwater samples ranged from 6.6 to 7.9, with an average value of 7.21 and standard deviation of 0.32, indicating a slightly alkaline in nature. All pH values in the Toshka area were within the allowable limits of 6.5–8.5.

EC is a valuable indicator for assessing salinity hazards and the suitability of water for irrigation. In the Toshka area, the EC values of groundwater samples range from 699 μS/cm to 1263 μS/cm, with an average value of 863.32 μS/cm. All the studied groundwater samples exhibited conductivity values within the permissible limits.

TDS of groundwater samples in the study area fall within the range of 458 mg/L to 774 mg/L, with an average value of 569.69 mg/L. Groundwater is categorized as brackish (TDS > 1,000 mg/L) or fresh (TDS < 1,000 mg/L). Consequently, all the groundwater samples in Toshka area belong to the freshwater class. A comparative analysis of TDS values in the 52 collected samples from the study area with values from Lake Nasser reveals an increase in TDS values. This increase may be attributed to the leaching of salts deposited in the soil during the movement of groundwater from Lake Nasser to the NSA. It suggests that the further away from Lake Nasser, the higher the salinity of the groundwater. This observation should be taken into consideration in the selection of future development project planned for the Toshka Region.

The corrosivity ratio **(CR)** is a crucial parameter indicating the safety of groundwater for transport through metallic pipes. Groundwater with CR < 1 is considered safe for transport using any type of pipes, while values greater than 1 suggests a

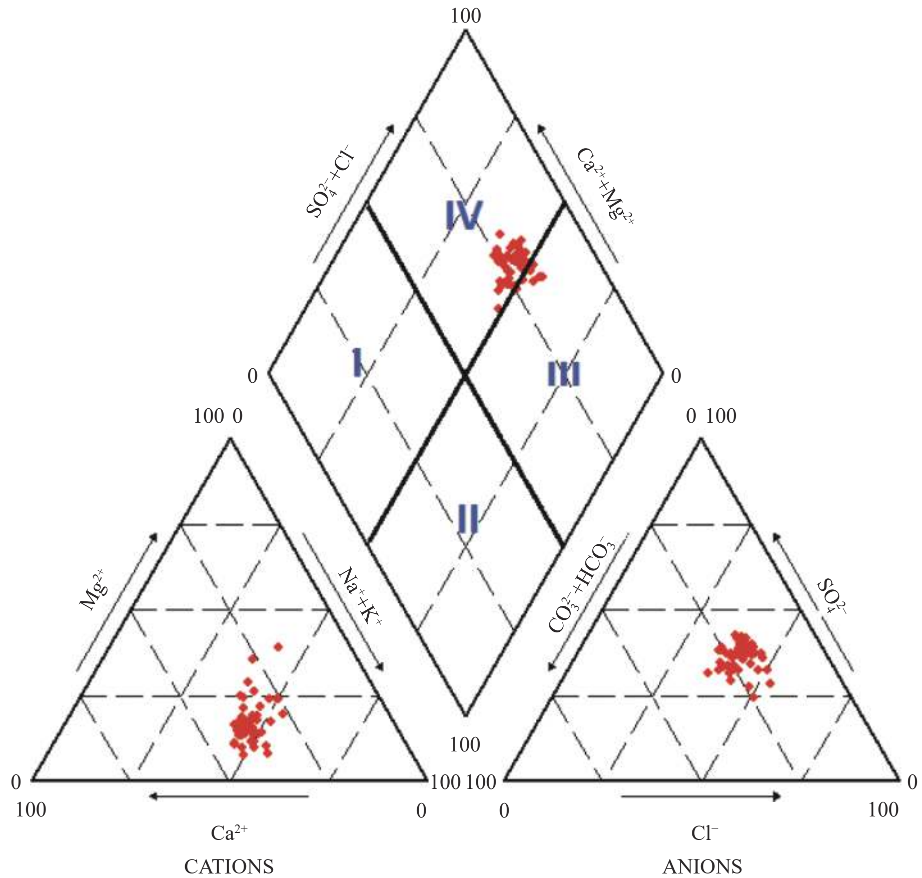

Fig. 4 Groundwater samples Classifications based on Piper Diagram

Table 4 Descriptive statics of groundwater parameters in Toshka area and WHO guidelines

Parameter	Minimum	Maximum	Mean	Standard deviation	WHO allowable limit
PH	6.6	7.9	7.21	0.32	8.5
EC	699	1263	863.32	111.21	1,500
TDS	458	774	569.69	79.65	1,000
Na^+	72	144	95.46	18.39	200
K^+	3.4	7.2	4.50	0.74	12
Ca^{2+}	32	86	64.76	10.93	75
Mg^{2+}	7.9	41.3	18.66	6.90	50
Cl^-	100	224	132.11	25.68	250
SO_4^{2-}	90	210	154.61	25.39	250
HCO_3^-	84	196	116.15	20.78	120
CO_3^{2-}	0	24	1.26	4.48	120

corrosive nature, indicating that water should not to be transported through metal pipes. In this study, all groundwater samples exhibited a corrosive nature based on the CR, emphasizing the need for noncorrosive pipes for groundwater transport.

The concentrations of $\mathbf{Ca^{2+}}$ varied from 32 mg/L to 86 mg/L, with an average value of 64.76 mg/L. While the WHO limit is 75 mg/L, 25% of the groundwater samples exceeded the permissible limit.

The concentration of $\mathbf{HCO_3^-}$ in the study area was found in the range of 84 mg/L to 196 mg/L, with an average value of 116.15 mg/L. Notably, 20 groundwater samples exceeded the the WHO limit (120 mg/L).

The remaining chemical parameters are within the permissible range set by WHO.

3.2 Evaluation of groundwater quality for different purposes

Groundwater suitability for irrigation purposes mainly depends on the mineral constituents impact on both plants and soil. These constitutes can have chemical effects that deactivate plant metabolism and physical effects that reduce soil permeability and lower osmotic pressure in plant cell structure. therefore, prevent water access to branches and leaves, affecting their growth. The presence of salts in water further affect soil structure and permeability. Additionally, aeration affects plant's growth indirectly. Therefore, it is necessary to assess groundwater quality for irrigation purposes.

To evaluate irrigation groundwater quality in the Toshka area, key hydrochemical parameters such as EC, TDS, Sodium Adsorption Ratio (SAR), Percent Sodium (Na%), Residual Sodium Carbonate (RSC), Kelley Ratio (KR), Magnesium Hazard (MH) and Permeability Index (PI) were considere, as presented in Table 5.

EC and TDS:

All groundwater samples in Toshka are considered suitable for irrigation, with 13.5% classified as good and 86.5% as permissible on EC values.

TDS values categorize the groundwater as excellent for irrigation, according to Robinove et al. (1958).

Na%:

Na% in the Toshka area ranges from 38.45% to 53.46%.

Groundwater samples are mostly classified as permissible (98%) for irrigation, with 2% falling into the good category.

MH (Magnesium Hazard):

The irrigation water can be classified based on MH; when MH values < 50, water is considered suitable; and when MH values > 50, water is considered harmful and unsuitable for irrigation uses.

In the study area, 96% of groundwater samples are suitable for irrigation based on MH values, while 4% are considered unsuitable.

KR (Kelley Ratio):

Groundwater with KR < 1 is suitable for irrigation, and it is considered as unsuitable if KR > 1.

88.5% of groundwater samples are suitable for irrigation based on KR values, while 11.5% are considered unsuitable.

RSC (Residual Sodium Carbonate):

Regarding Table 5, it was found that wells have RSC values less than 1.25 are suitable and safe for irrigation and these with values above 2.5 are not suitable (Ramesh and Elango 2012).

All studies groundwater samples showed negative RSC values, indicating a good category and suitable for irrigation.

SAR (Sodium Adsorption Ratio):

The irrigation water is classified based on SAR

Table 5 Classification of groundwater samples of Toshka area for irrigation purposes

Parameters	Range	Classification	No. of samples	Sample%
EC (µS/cm) Todd 1982)	<250	Excellent	/	/
	250–750	Good	7	13.5%
	750–2,250	Permissible	45	86.5%
	2,250–5,000	Doubtful	/	/
	>5,000	Unsuitable	/	/
TDS	<1000	Non saline	52	100%
	1000–3000	Slightly saline	/	/
	3000–10,000	Moderately saline	/	/
	>10000	Very saline	/	/
%Na	0–20	Excellent	/	/
	20–40	Good	1	2%
	40–60	Permissible	51	98%
	60–80	Doubtful	/	/
	<80	Unsuitable	/	/
RSC	>1.25	Good	52	100%
	1.25–2.5	Doubtful	/	/
	<2.5	Unsuitable	/	/
MH	<50%	Suitable	50	96%
	>50%	Unsuitable	2	4%
KR	<1	Suitable	46	88.5%
	>1	Unsuitable	6	11.5%

values into four main classes as shown in Table 6.

SAR values in the study area range between 1.95 and 3.83.

All groundwater samples are located in the low-sodium class (S1), indicating that they are considered excellent (52 wells) and suitable for irrigation purposes.

The spatial distribution of Na%, SAR, RSC, MH, KR and PI are presented in Fig. 5. According to the permeability index values in Doneen's chart (Fig. 6), 96% of the samples fall in class I, indicating good suitability for irrigation purposes, while 4% fall in class II, reflecting moderate suitability for irrigation.

The values of SAR and EC were plotted on the Wilcox diagram (Fig. 7 & Table 7), showing that the majority of samples are in the C3S1 class (low sodium hazard and high salinity hazard). Only a few samples are in the C2S1 class (low sodium hazard and medium salinity hazard). This indicates that all the groundwater samples are suitable for irrigation in almost all soil types under ordinary conditions.

Hardness is an important factor in evaluating groundwater for domestic and industrial purposes. The classification of the groundwater samples in the Toshka area based on hardness following the criteria outlined by is presented in Table 8. The results indicate that all wells in the study area contain soft groundwater. This suggests that the groundwater is suitable for both domestic and industrial purposes.

3.3 WQI results and evaluation

3.3.1 Water Quality Index (Drinking)

The Water Quality Index was calculated to evaluate the groundwater suitability for drinking pur-

Table 6 Classification of irrigation water based on SAR values

Level	(SAR)	Quality	Water class	No. of samples	Sample%
S1	0–10	Low sodium	Excellent	52	100%
S2	10–18	Medium sodium	Good	/	/
S3	18–26	High sodium	Fair	/	/
S4	<26	Very high sodium	Poor	/	/

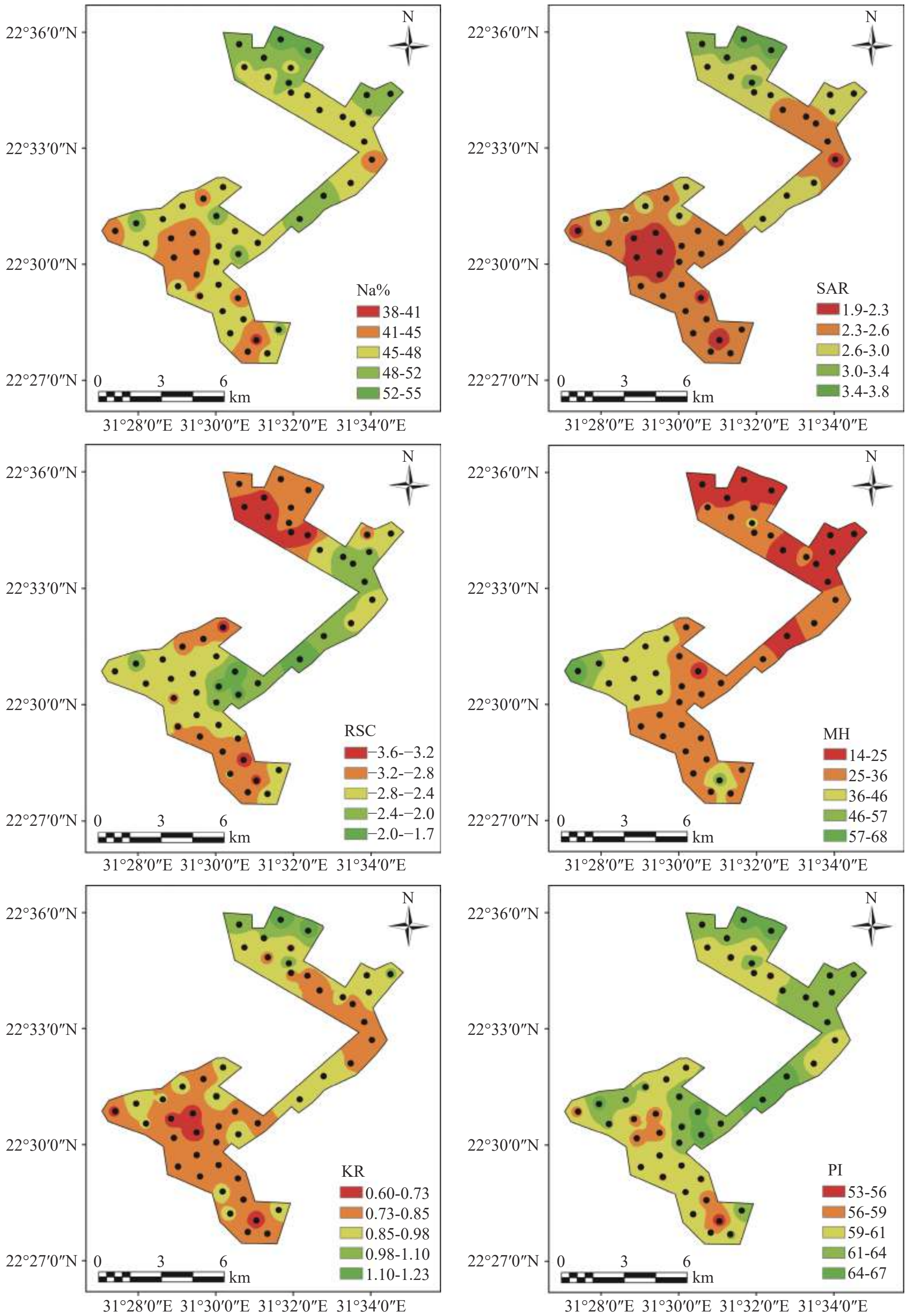

Fig. 5 Spatial distribution of irrigation quality parameters Na%, SAR, RSC, MH, KR and PI

poses. The arithmetic rating method was used, taking into account the weight and relative weight of the specified groundwater parameters, as outlined in Table 1. The calculated WQI values at each sampling site were utilized to assess the groundwater suitability for drinking purposes in the study area. The classification method as presented in Table 9 was employed for interpretation. The results of WQI indicated that all groundwater samples are classified as good for drinking purposes. The spatial distribution of WQI for drinking is presented in Fig. 8.

3.3.2 Water quality index (Irrigation)

Based on calculated WQI for irrigation purposes, all groundwater samples were categorized as "Excellent" for irrigation, as presented in Table 10. The spatial distribution of WQI for irrigation is depicted in Fig. 9.

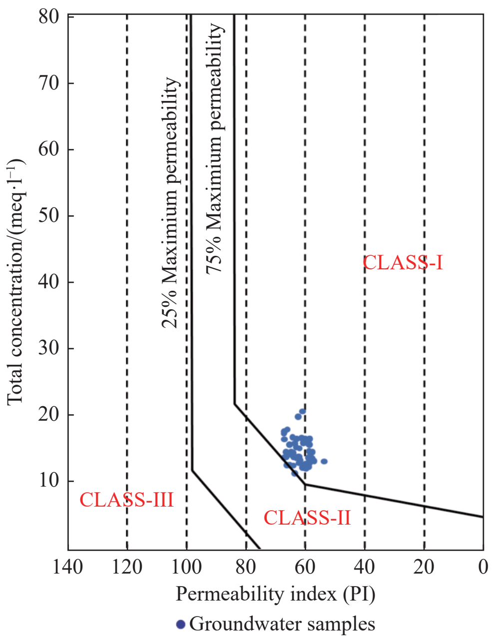

Fig. 6 Doneen's classification for irrigation water based on permeability Index

4 Conclusions

The evaluation of groundwater quality in the Toshka region for domestic, irrigation and industrial purposes revealed several key findings. Each parameter's value was compared to the permissible limits of the WHO and FAO standards to determine whether the suitability for human consumption and irrigation, respectively. The groundwater samples with a pH range of 6.6 to 7.9, were slightly alkaline, falling into the freshwater class (TDS < 1,000 ppm) and indicating suitability for consumption. EC values were within the WHO's permissible limits, affirming water suitability for human consumption. The "Soft" category for hardness suggested groundwater appropriateness for domestic and industrial purposes. However, around 25% and 40% of samples exceeded the WHO limits for calcium and bicarbonate, respectively. Regarding irrigation suitability, most wells were considered suitable for irrigation, except for two samples based on the MH values and six based on

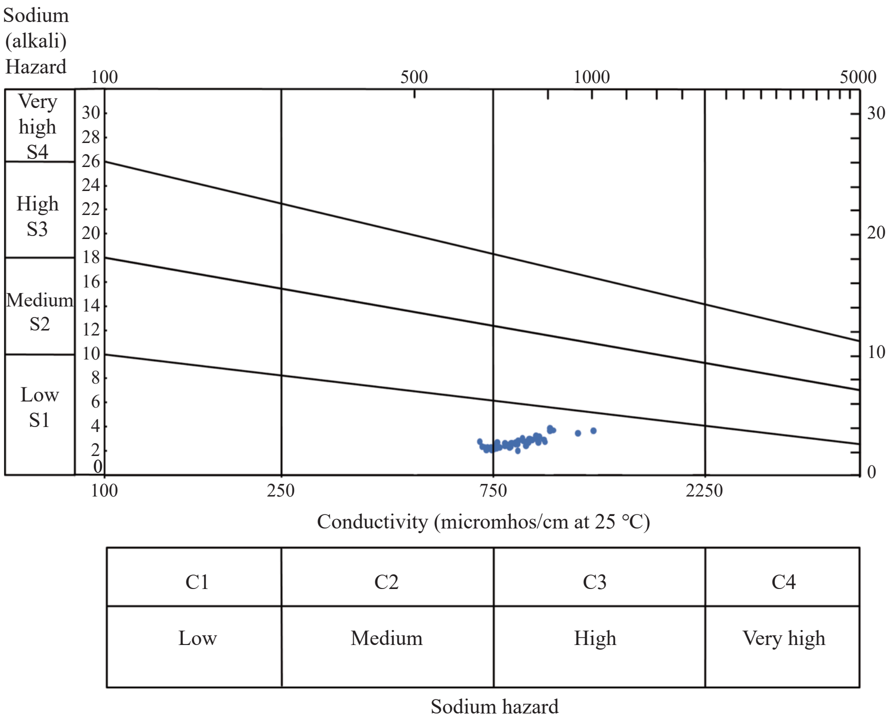

Fig. 7 Wilcox diagram for the groundwater samples in Toshka area

Table 7 Classification of irrigation water based on PI

PI	Water quality	Classification	No. of samples	Sample (%)	PI
>75	Class I	Good	50	96%	>75
75–25	Class II	Moderate	2	4%	75–25
<25	Class III	Poor	/	/	<25

Table 8 Hardness classification of water

TH	Classification	No. of samples	Sample (%)
0–75	Soft	52	100
75–150	Moderately hard	/	/
150–300	Hard	/	/
Over 300	Very hard	/	/

Table 9 Results of WQI for domestic

WQI range	Type of water	No. of samples	Sample (%)
<50	Excellent water	/	/
50–100	Good water	52	100
100–200	Poor water	/	/
200–300	Very poor water	/	/
>300	Unsuitable water	/	/

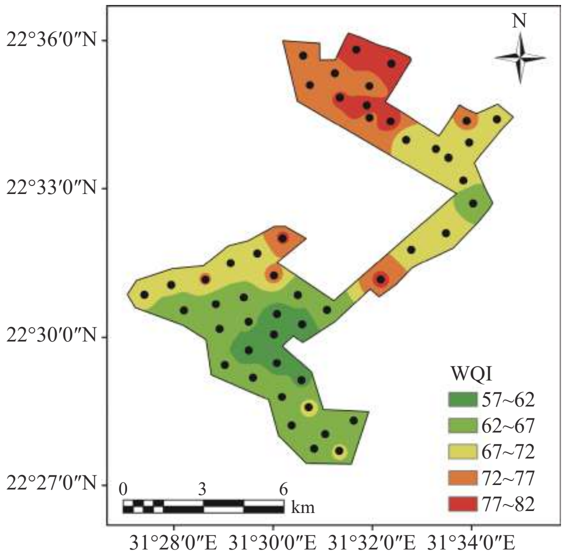

Fig. 8 Spatial distribution of WQI for domestic

Table 10 Results of WQI for Irrigation

WQI range	Type of water	No. of samples	Sample (%)
<50	Excellent water	52	100
50–100	Good water	—	—
100–200	Poor water	—	—
200–300	Very poor water	—	—
>300	Unsuitable water	—	—

KR. The PI values categorize 50 wells as "Good" for irrigation and two as "Moderate". The US Laboratory salinity diagram depicted low sodium and medium salinity hazards, indicating overall suitability for irrigation across various soil types under ordinary conditions. WQI ratings classied all samples as "Good" for domestic and "Excellent" for irrigation. These findings are crucial for stakeholders planning activities in the Toshka region.

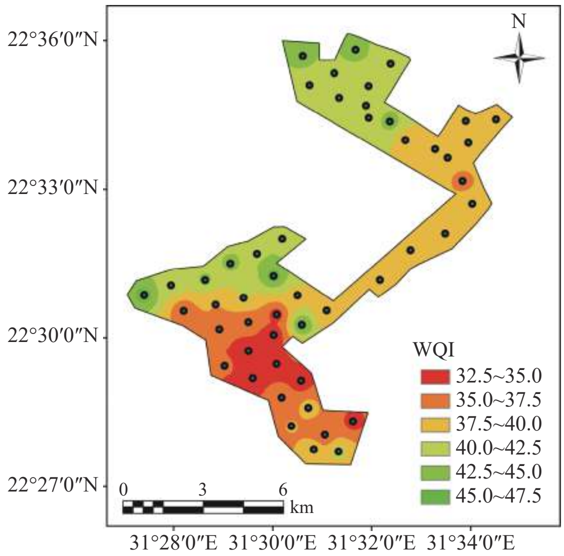

Fig. 9 Spatial distribution of WQI for Irrigation

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