



GIS-Based Evaluation of Groundwater Quality and Suitability in Dakhla Oases, Egypt

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Abstract

Groundwater is the main source for agricultural and domestic purposes in the Western Desert of Egypt. Groundwater quality is significantly influenced by the surrounding anthropogenic activities. This paper is one of the attempts to spatially assess groundwater quality and its suitability for drinking and irrigation in Dakhla Oases using Water Quality Index (WQI) and GIS techniques. Calibrated Landsat 8 OLI satellite images were processed to produce Land Use Cover map (LULC) to assess the agricultural and human activities in the study area. Further, eight groundwater quality parameters and WQI were attributed to a GIS layer for 71 investigated wells for mapping purposes using the Inverse Distance Weighting (IDW) method in ArcGIS. LULC map showed that 75% of the study area is a bare land and 25% is urban and agricultural areas. Almost all the studied wells recorded total dissolved solids and sulfate coinciding with the Egyptian permissible limits for drinking purposes. Fe and Mn levels exceeded the allowable limits for drinking in the majority of Dakhla wells. Based on the WQI, 38% and 36.6% of the study area fell within the poor water category according to the Egyptian and WHO standards, respectively. Most of the groundwater wells were of the best quality for irrigation with regard to salinity (less than 2000 mg/L) and the excellent quality in terms of sodium absorption ratio (< 10). It can be concluded that GIS analyses of groundwater quality and suitability can provide one of the necessary inputs for management and planning of Dakhla Oases and other similar regions.

Keywords Dakhla Oasis · Groundwater · Suitability · Water Quality Index (WQI) · GIS

1 Introduction

Over exploitation of water and population growth lead to increasing the fresh water demand. Groundwater, being one of the vital natural resources and at the same time a main constituent of the ecosystem, is facing natural and man-made impacts. Water, as well known, is used for various purposes such as drinking, cultivation, industry, household, recreation, and environmental practices. Groundwater quality utilized for domestic and agricultural purposes can differ

greatly based on the quantity and type of the dissolved solids. One third of the world's population use groundwater for drinking purposes (Nickson et al. 2005). Irrigation requires good water quality to avoid damage of sensitive crops by pollutants such as trace elements, pesticides and salts (Kurdi et al. 2013; Bear 1979).

It is generally assumed that groundwater is safe for utilization because of being below the ground surface and not directly in contact with the external environment (Quist et al. 1988). However, both land use changes and human activities play the key role in groundwater degradation (Narany et al. 2017). In spite of the buffer zone between groundwater and the surface contaminating activities, its quality can be influenced with time due to surface water pollution factors (Yidana and Yidana 2009).

Human activities near to boreholes and shallow hand dug wells may negatively impact the groundwater quality due to poor sanitation, inadequate waste disposal, etc (Carpenter et al. 1998; Jain et al. 2009; Fianko et al. 2010; Salifu et al. 2013). Shallow aquifers are more vulnerable to nitrate contamination compared to deep aquifers due to the

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impact of human activities and hence an increasing nutrient input (Narany et al. 2017). Information on rocks lithology, groundwater storage, and recharge/discharge indications can be interpreted from groundwater quality data (Walton 1970). The main factors that influence the groundwater quality in a specific area are the geological settings and human activities (Subramani et al. 2005; Schiavo et al. 2006; Krishna Kumar et al. 2012; Magesh and Chandrasekar 2013). Groundwater quality can be highly degraded in case of the absence of proper land use and water management (Narany et al. 2017).

In Egypt, rapid population growth, increased urbanization, higher living standards and the agricultural policies are the main factors boosting the increase in water demand. Groundwater is the second resource for irrigation and human usages after the River Nile. Further, it is considered an important source for irrigating some agricultural lands in the Delta region, and inaccessible cultivated lands in the fringes of the River Nile. On the other hand, in many parts of the Nile Delta groundwater is widely used for drinking and other domestic purposes (Fahim et al. 1995).

Urban and agricultural development in the Western Desert of Egypt depends on the available groundwater resources. The Nubian sandstone aquifer system (NSAS) is one of the most important and potable groundwater aquifers in the world. The NSAS extends over wide extension areas in Egypt, Libya, Sudan and Chad. NSAS represents about 850,000 km² in Egypt (670,000 km² in the Western Desert, including the New Valley). The Nubian Sandstone is the main groundwater aquifer in the Dakhla Depression with thickness ranging from 800 m in the south and southwest to 1600 m in the west. Water level in the deep wells reaches about 130 masl as reported in El-Rashda Village (Gad et al. 2011). According to Ball (1927), the flow direction of groundwater in Dakhla Oasis is mainly from southwest to northeast. Gameh et al. (2014) evaluated the groundwater potentiality and suitability for drinking and irrigation in the New Valley where results concluded that soluble iron is the major problem for drinking water and soluble salts in the groundwater were at the safe level for both drinking and irrigation.

Main GIS applications in the studies of groundwater include mapping and suitability analyses, assessing groundwater vulnerability, groundwater flow and assessing groundwater quality integrated with spatial data (Engel and Navulur 1999). In Seoul-Korea, Ahn and Chon (1999) used GIS to analyze groundwater pollution and geographic relations among groundwater characteristics, pollution sources, land uses, topography and geology. Another GIS-based study concluded that groundwater contamination by nitrates is received from dense cultivations which are considered one of the probable sources of groundwater deterioration (Levallois et al. 1998). In Italy, groundwater pollution hazard and water quality maps were produced using GIS analyst tools

(Ducci 1999). Negm and Armanuos (2016) utilized ArcGIS and multivariate statistical analysis in the Western Nile Delta of Egypt to investigate factors controlling groundwater quality and suitability for drinking and irrigation. Additionally, spectral retrieved land use indices integrated with laboratory analyses help to highlight the available resources and the anthropogenic activities. This facilitates the spatial assessment of the probable sources of pollution (Elbeih and El-Zeiny 2018).

Water Quality Index (WQI) technique ranks the combined effects of individual water quality parameters with respect to the overall water quality (Akkaraboyina and Raju 2012). WQI is useful in obtaining water quality information for targeted citizens and decision makers (Ramakrishnaiah et al. 2009). It is a unitless number giving a single value which reduces the number of parameters to represent data in a simplified way (Miller et al. 1986; Poonam et al. 2013). Thus, WQI is an important parameter for groundwater assessment and management (Chauhan et al. 2010). There are four well-known methods used for estimating the WQI; each method has its own parameters as follows:

1. The National Sanitation Foundation Water Quality Index (NSFWQI), developed by (Brown et al. 1972), uses the Delphi method to evaluate water quality of different resources (Tiwari and Mishra 1985). NSFWQI has been used in many developed countries to determine the water quality of rivers (Najah et al. 2009). NSFWQI is based on major water quality parameters such as temperature, dissolved solids, turbidity, dissolved oxygen, acidity, nitrate, and phosphate.
2. The Canadian Council of Ministries of the Environment Water Quality Index (CCMEWQI) (Rocchini and Swain 1995). The index includes three elements: scope: number of variables that do not meet water quality objectives; frequency: number of times these objectives are not met; and amplitude: amount by which the objectives are not met. CCMEWQI produces a number between 0 (worst water quality) and 100 (best water quality) (Canadian Council of Ministers of the Environment (CCME) 2001).
3. Oregon Water Quality Index (OWQI) developed by the Oregon Department of Environment Quality (Dunnette 1979) where the following parameters were covered: temperature, BOD, pH, ammonia, DO, nitrogen, nitrate, total phosphorous, Coliform and total solids. It provides a simple method for expressing the ambient water quality of Oregon's streams for general recreational uses (Cude 2001).
4. Weighted Arithmetic Water Quality Index (WAWQI) classifies the water quality using the degree of clarity based on the most common parameters of water quality (Brown et al. 1972). This method is advantageous over

other methods because multiple water quality parameters are included into a mathematical equation that rates the health of water body through a number called Water Quality Index. In addition, it describes the suitability of surface and groundwater sources for human consumption (Chandra et al. 2017).

The objectives of this research paper are to: first assess and map the groundwater (GW) quality in Dakhla Oasis; second evaluate GW suitability for drinking purposes based on Egyptian and WHO standards; and finally assess GW for agricultural purposes on basis of FAO and international recommendations for irrigation. The aim of the present study was achieved using laboratory measurements of GW samples integrated with geospatial analyses.

2 Materials and Methods

2.1 The Study Area

The investigated area occupies a wide extension of Dakhla Oasis, Western Desert of Egypt (New Valley governorate) that extends for about 65 km from Teneida Village in the East to El-Mawhoub Village in the West (Figs. 1 and 2). The investigated area is located between Latitudes 25°25'45"–25°45'35"N and Longitudes 28°45'40"–29°25'45"E (Fig. 1). The irrigation and cultivation systems in Dakhla Oasis differ from that in the Nile Valley where the NSAS is the main source of fresh groundwater. Population has been concentrated close to the groundwater shallow wells for many decades, and when the wells become abundant, the people move to another area

looking for water supplies. Productive wells are well distributed in Dakhla depression (Gad et al. 2011).

2.2 Satellite Data Acquisition and Processing

Multispectral Landsat OLI image dated 13 August 2014 synchronized with the analyses of groundwater was used. Radiometric corrections were applied on the image for calibration and then processed to produce a number of thematic maps. These maps are land use/cover, Normalized Difference Built-Up Index (NDBI), Normalized Difference Vegetation Index (NDVI), Modified Normalized Difference Water Index (MNDWI), and Normalized Differential Salinity Index (NDSI) to assess the environmental conditions of the study area and highlight the prevailing land uses surrounding the groundwater wells.

2.3 Groundwater Data and GIS Analyses

Analysis of 71 groundwater wells for the year 2014 was obtained from the central laboratory of groundwater (South Western Desert) through a contract project between The National Authority for Remote Sensing and Space Sciences (NARSS) and the New Valley Governorate. Wells' analyses covered the areas from Teneida Village in the East to Balat Village, Ismant, Qalamon, El-Gedida and El-Mawhoub villages in the West as shown in Fig. 2. A GIS thematic layer was generated for the investigated wells then attributed with all the measured chemical analysis. The obtained chemical analyses include pH, total hardness (TH), electric conductivity (EC), total dissolved solids (TDS), sulfate (SO₄), sodium absorption ratio (SAR), manganese (Mn) and iron (Fe).

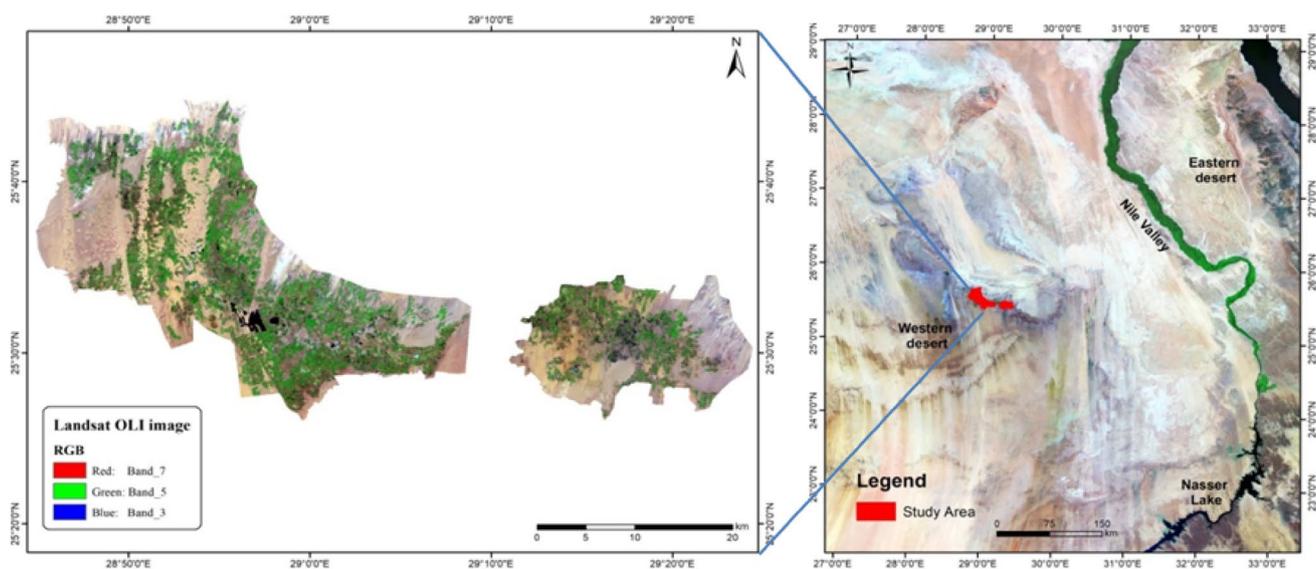


Fig. 1 Location map for the area of study

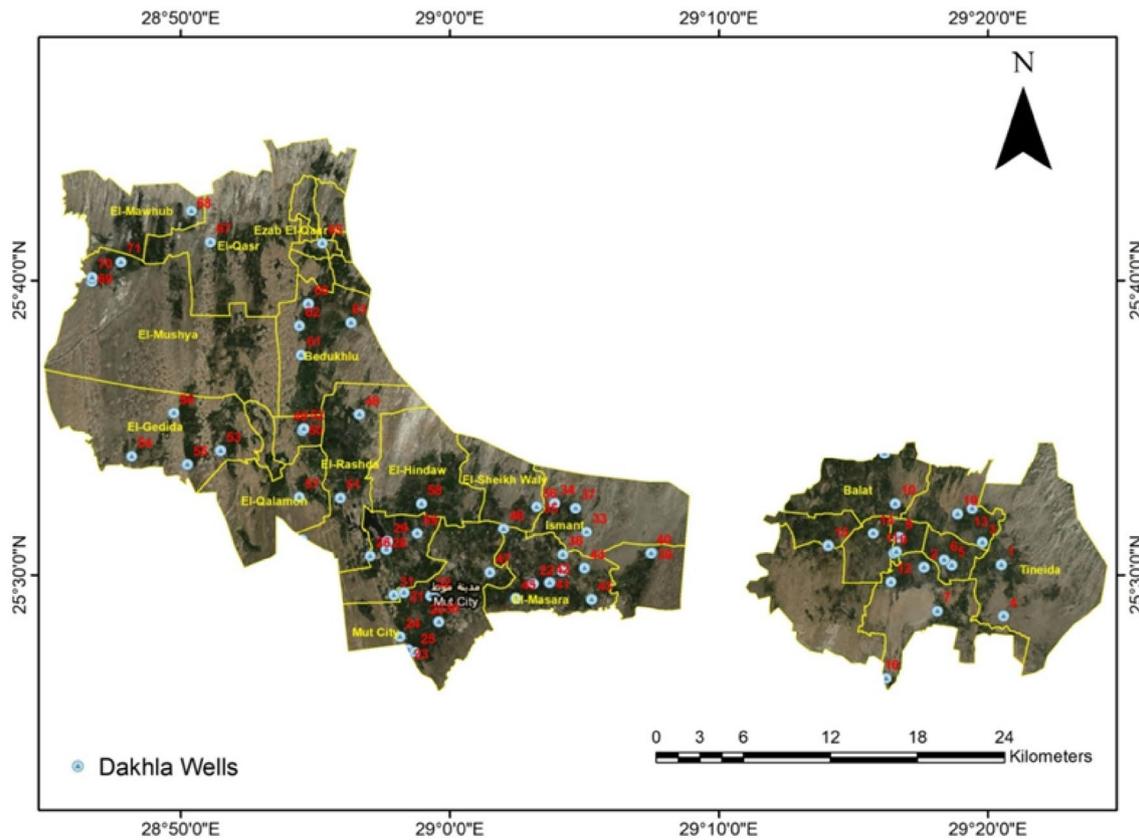


Fig. 2 Investigated wells sites in Dakhla

The geo-statistical analyst wizard, in ArcGIS V.10.1, was used to predict groundwater parameters and WQI in locations surrounding the measured values using the inverse distance weighting (IDW) interpolation method. IDW method was used as it is easier to implement, while kriging method is time consuming and cumbersome. On the other hand, kriging provides a more accurate presentation of the data spatial structure and produces valuable information to estimate error distributions (Franzen and Peck 1995; Weisz et al. 1995). Squared IDW method produced better interpolation results as compared with any other method, including kriging (Weber and Englund 1992). On the other hand, kriging performance can be significantly affected by variability and spatial structure of the data and by the choice of variogram models, search radius, and number of the neighboring points used for estimation (Leenaers et al. 1990). In IDW, interpolation weights are calculated as a function of the observed sampling point and the prediction point (Gunnink and Burrough 1996). This analyst predicts values in unsampled locations based on the measurements at the sampled locations converting the point concentrations into a surface to facilitate the spatial assessment of the obtained results.

2.4 Calculation of Water Quality Index (WQI)

The Weighted Arithmetic Water Quality Index (WAWQI) was used to estimate the water quality index for the chosen parameters using Eq. 1. Table 1 shows the values of maximum allowable limits of the measured parameters, according to Egyptian drinking water standards (E.C.O.P 2005) and WHO (2011). A weight is assigned to each parameter based on its relative significance for drinking purposes. A highest weight of 5 is assigned to the TDS and EC, weight 4 to pH and TH, weight 3 to SO_4 and weight 2 is assigned to Mn and Fe. The rating scale of the WAWQI was categorized into five classes where excellent class is less than 50, good ranges from 50 to 100, poor from 100 to 200, very poor from 200 to 300, and unsuitable for drinking purposes > 300. The following equations are used to determine the WAWQI (Brown et al. 1972):

$$WQI = \sum Qi * Wi \quad (1)$$

where Q_i is the i th quality rate and is calculated from Eq. (2), W_i is the i th relative weight of the water parameter, calculated using Eq. 3.

$$Qi = (Ci/Si) * 100 \quad (2)$$

where C_i is the i th concentration of the water parameter and S_i is the drinking water quality threshold limits identified in the WHO and Egyptian guidelines.

$$Wi = \frac{wi}{\sum_{i=0}^n wi} \quad (3)$$

where wi is the weight of the i th parameter and n is the number of wi of evaluated chemical parameters.

2.5 Groundwater Suitability for Irrigation

Groundwater suitability for irrigation basically depends on the influence of water mineral components on plant and soil. In case of inadequate quality of irrigation water, irrigation of food and crops could represent a possible risk. In the study area, eight parameters were considered for assessing water quality for irrigation, and their threshold limits were obtained from the corresponding references (Table 2): TDS and EC (Wilcox 1955), SAR (US Salinity Lab 1954), pH, Mn and Fe (Ayers and Westcot 1985), SO_4 (FAO 1980), TH (Sawyer and McCarthy 1967).

3 Results and Discussion

3.1 Land Use/Cover Map

In the present study area, LULC and spectral indices were used to assess land uses (Figs. 3 and 4). Mapping various land uses is essential for identifying the impacts of land use on groundwater quality. One of the probable impacts is the change of water quality in relation with land uses (Vinten and Dunn 2001).

Previous studies showed that Dakhla Oasis has undergone major land cover changes (increases in urban areas and cultivated lands) due to land reclamation projects and population

growth (Kato et al., 2014). Therefore, it was necessary to study the current land use in the area to identify the most probable anthropogenic sources of pollution and the spatial distribution of multiple land uses. LULC map showed that 75% of the study area is a bare land, attaining an area of 640,930 km². The salinity index (NDSI) indicates high levels within the desert lands (>0.3) associated with the high reflectance of sand particles where no wells existed in this area. The urban index (NDBI) does not differentiate urban areas from the bare land where both recorded high values (>0.3). Alternatively, the classified map was successful to identify the urban areas where some are scattered in the form

Table 2 Suitability threshold limits of groundwater for irrigation

Parameter	Category	Threshold
TDS ^(a)	Best quality water	200–500
	Water involving a hazard	1000–2000
	Water can be used for irrigation only with leaching and perfect drainage	3000–7000
EC ^(a)	Low Salinity water	100–250
	Medium salinity water	250–750
	High salinity water	750–2250
	Very high salinity water	> 2250
SAR ^(b)	Excellent	2–10
	Good	10–18
	Doubtful	18–26
	Unsuitable	> 26
pH ^(c)	Suitable	6.5–8.4
Mn ^(c)	Unsuitable	> 0.2
Fe ^(c)	Unsuitable	> 5.0
SO_4^{2-} ^(d)	Unsuitable	> 980
TH ^(e)	Soft	< 75
	Moderately hard	75–150
	Hard	150–300
	Very hard	> 300

^aWilcox (1955), ^bUS Salinity Lab Staff (1954), ^cAyers RS, Westcot DW (1985), ^dFAO (1980), ^eSawyer and McCarthy (1967)

Table 1 Maximum allowable limits of water quality for drinking according to Egyptian and WHO standards

Parameter	Egypt maximum allowable limit ^(a and b)	WHO maximum allowable limit ^(c)	Weight (wi)	Relative Weight (Wi)
TDS (mg/l)	1200	1000	5	0.2
EC (µs/cm)	–	1500	5	0.2
pH	6.5–9.2	6.5–8.5	4	0.16
TH	500	500	4	0.16
Mn (mg/l)	0.1	0.1	2	0.08
Fe (mg/l)	0.3	0.3	2	0.08
SO_4 (mg/l)	400	400	3	0.12
			$\sum wi = 25$	$\sum Wi = 1$

^aE.C.O.P. (2005), ^bWHO (2006), ^cWHO (2011)

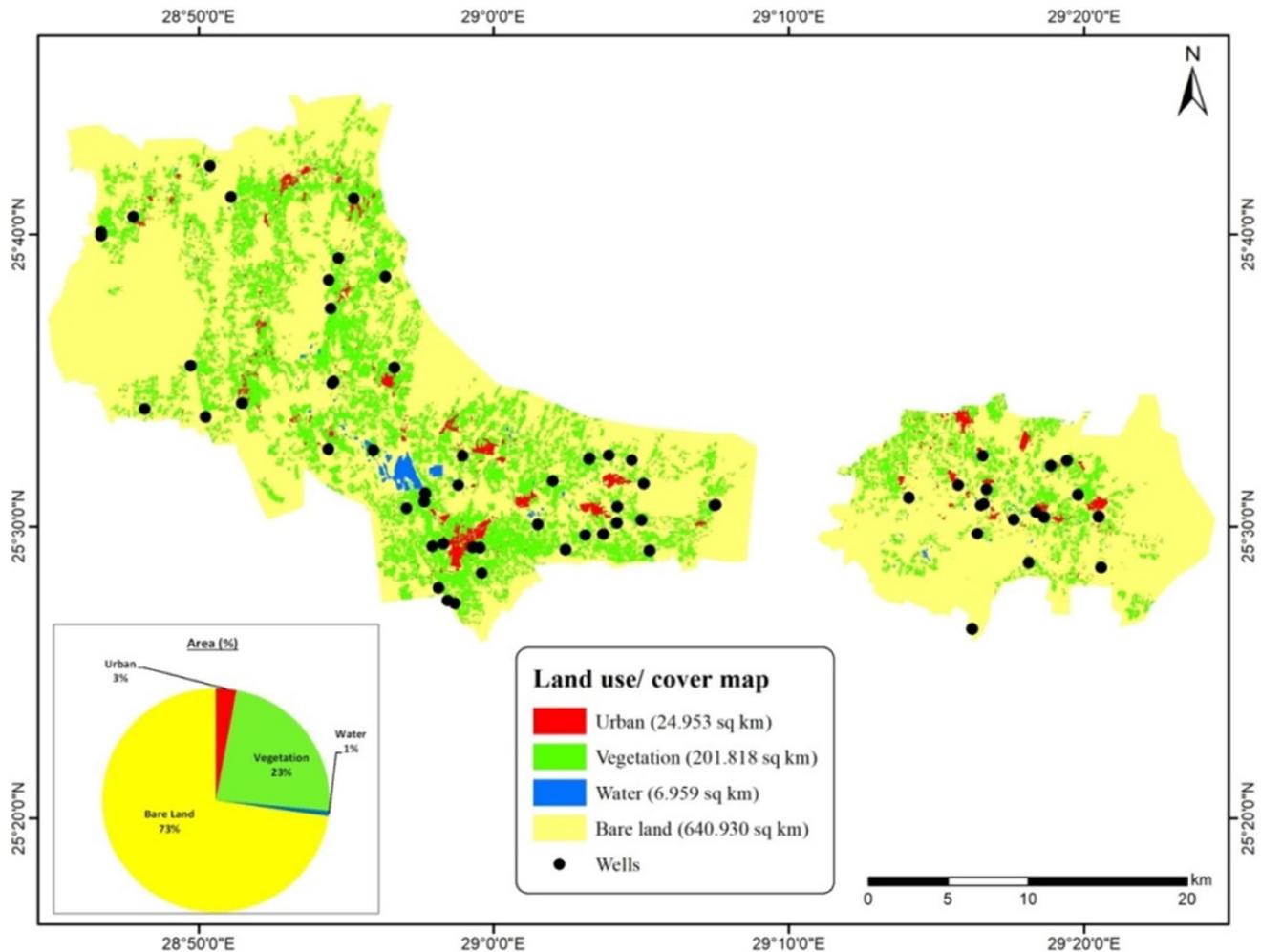


Fig. 3 Land use/cover map of the study area

of “patches” in the study area, occupying the least area in the LULC map (6.959 km²). The second dominant class in the LULC map was the agricultural area (201,818 km², 23%). Vegetation in the study area showed a small fluctuation in its density as shown in the NDVI map. Water bodies are restricted to a small Mut pond attaining an area of 6959 km² (2%) as shown in LULC and MNDWI maps. The most possible wells to be affected, with regard to water quality, by the interrupting land uses are those in the vicinity to the urban and agricultural activities. However, the natural factors have also a considerable impact on the groundwater quality in the Dakhla Oasis as the water source is the NSAS which is saturated with water originating from equatorial rainfall (Abu Al Izz 1971).

3.2 Assessing Water Quality

Table 3 summarizes the statistics of the studied groundwater quality parameters and percentage of the total wells

that exceeds the Egyptian standards. To utilize and protect groundwater resources, it is necessary to recognize the hydro-chemical groundwater parameters such as pH, EC, TDS, SAR, TH, major anions, and major cations concentrations (Guendouz et al. 2003; Edmunds et al. 2006; Prasanna et al. 2010).

A great fluctuation is observed in most of the studied characteristics (i.e., pH, TH, EC, TDS, sulfate, Fe, Mn and SAR) as shown in Fig. 5. This fluctuation is not only associated with the lithology of the study area and the time water is in contact with the rock material, but also reflects the received inputs from rainfall, soil and other polluting sources (e.g., mining, salt water intrusion, industrial, agricultural and domestic wastewater (Babiker et al. 2007).

The pH values of the groundwater dominating in the study range from 4.0 to 7.70 with a mean of 6.51 which means that the water is mainly acidic. A great variation is observed in the dissolved solids and the associated salts in water: TH, EC, TDS and SO₄ recording 41.53–828.85,

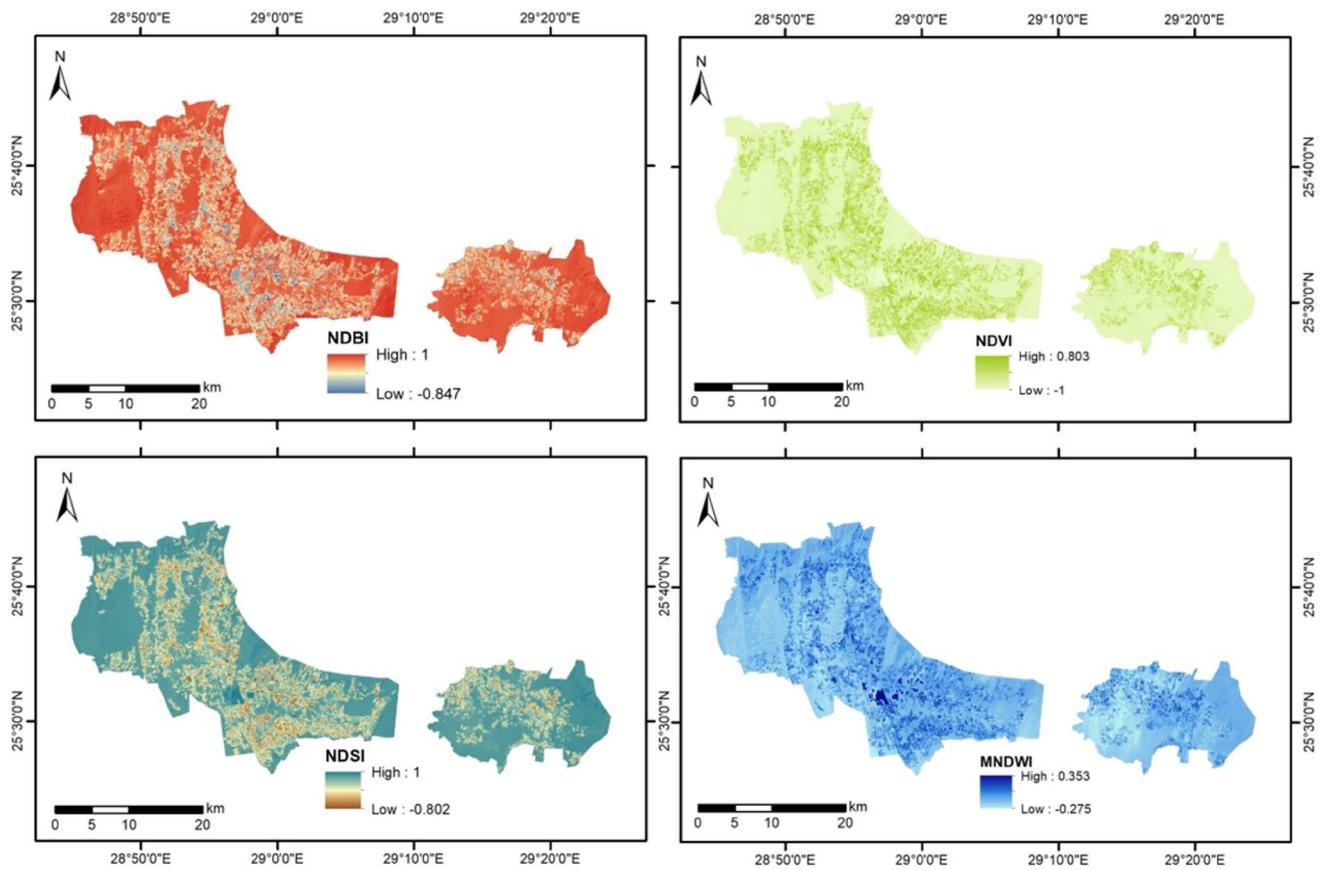


Fig. 4 Spectral land use indices for the study area

Table 3 Summary of the chemical characteristics for the 71 water samples according to the Egyptian standards

Title	Water samples characteristics						% Maximum permissible for drinking (Egypt)	% Not allowable for drinking (Egypt)
	Min/well No	District	Max./well No.	District	Average	Standard deviation		
Variation map of TDS (ppm)	100/32	Ismant	1855/42	Maasara	236.493	266.17	98.59%	1.41%
Variation map of EC (µs/cm)	166.7/32	Ismant	3092/42	Maasara	394.174	443.68	–	–
Variation map of pH	4/42	Maasara	7.7/5	Teneida	6.536	0.66	64.78%	35.21%
Variation map of Fe (ppm)	0.2/17	Balat	44/41	Maasara	4.245	5.91	1.41%	98.59%
Variation map of SO ₄ (ppm)	3/31	Mut	375/42	Maasara	41.646	63.32	100%	0%
Variation map of TH	41.53/28	Mut	828.85/42	Maasara	105.339	118.94	97.18	2.82
Variation map of Mn (ppm)	0/42	Maasara	6/40	Maasara	0.409	0.78	35.21%	64.78%
Variation map of SAR	0.37/52	Rashda	4.68/42	Maasara	1.122	0.82	–	–

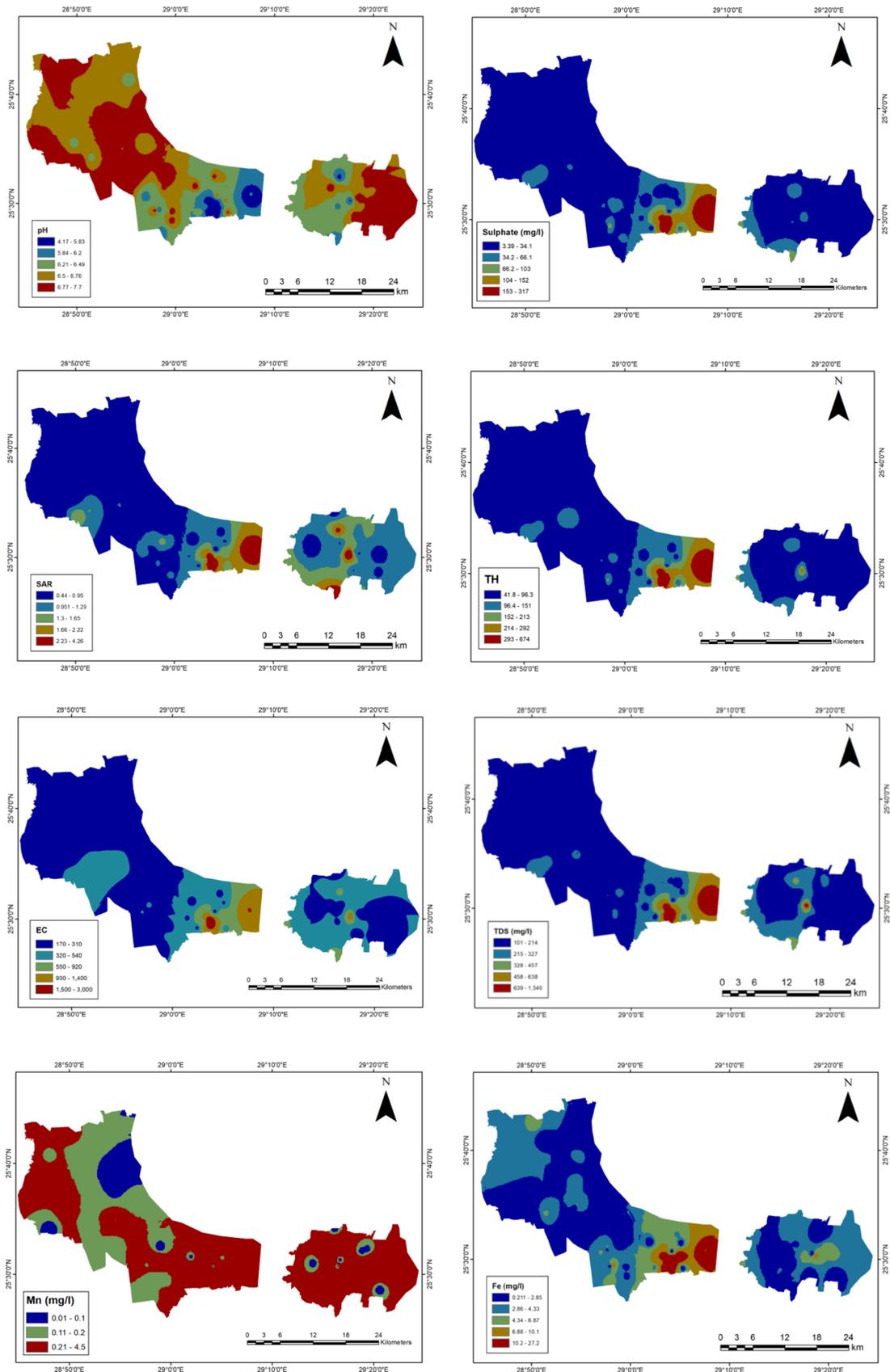


Fig. 5 Spatial distribution of studied groundwater quality characteristics

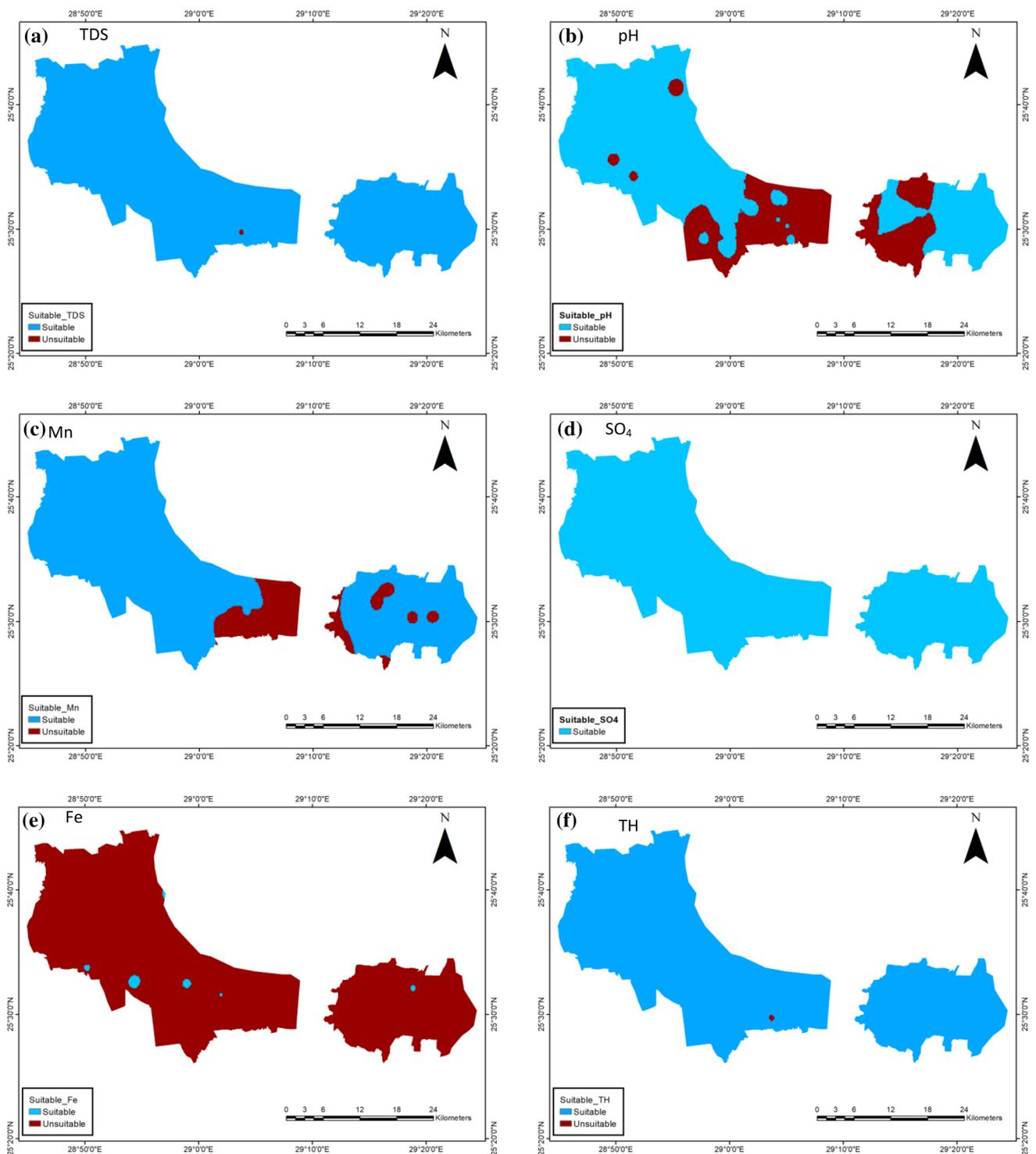


Fig. 6 Spatial variation for suitability of groundwater parameters for drinking purposes based on Egyptian Thresholds limits **a** TDS, **b** pH, **c** Mn, **d** SO₄, **e** Fe, **f** TH

166.7–3092 $\mu\text{s}/\text{cm}$, 100–1855 ppm and 3–375 ppm, respectively (Fig. 5).

The levels of SAR and iron in groundwater showed a fluctuation similar to the dissolved solids fluctuating from

0.37 to 4.68 and from 0.2 to 44 ppm, respectively (Fig. 5). Manganese metal showed a lower fluctuation (0–6 ppm) than iron and a different spatial pattern. Kinds and degrees of groundwater chemical contamination depend tremendously

Fig. 7 Comparing % of the wells suitability for drinking purposes based on WQI

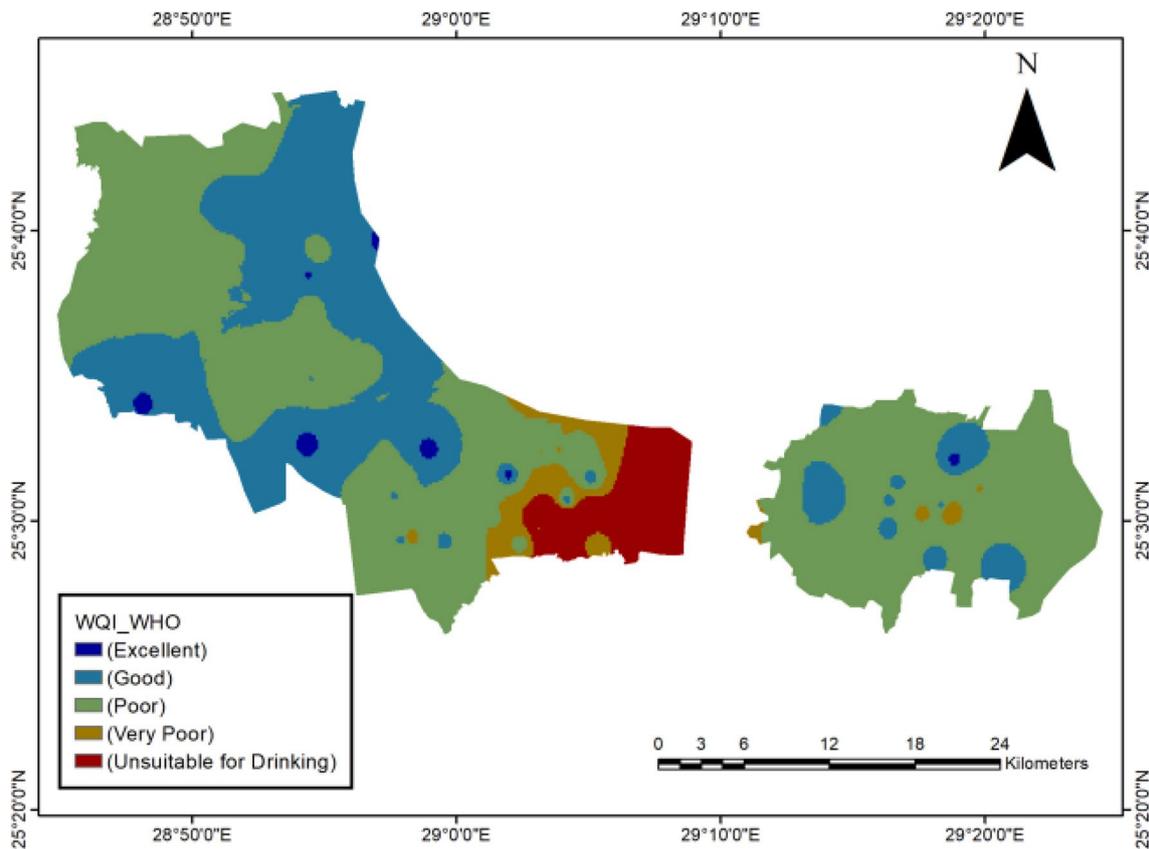
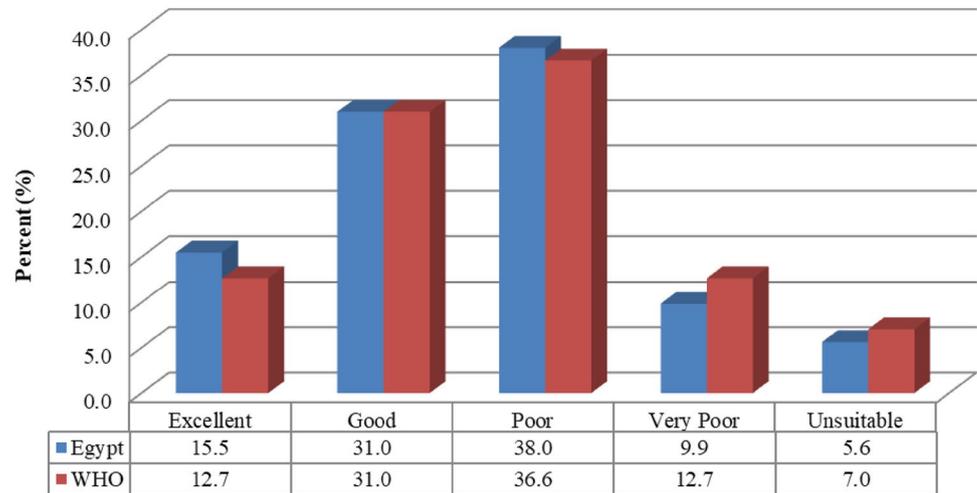


Fig. 8 Spatial distribution of WQI in Dakhla Oasis based on the WHO standards

on the geology and mineral composition of the soil where water flows before reaching the aquifer (Zuane 1990).

The maximum levels of the studied characteristics were recorded in the Maasara district (in the middle of the Dakhla Oasis) except that the highest pH was recorded in Teneida district in the East. Levels of TDS, pH, SO₄ and TH in the

groundwater samples are lower than the maximum Egyptian allowable limits for drinking in the majority of the study area. However, the majority of the studied wells showed the levels of Fe and Mn in groundwater exceeding the allowable limits for drinking: 98.59% and 64.78%, respectively.

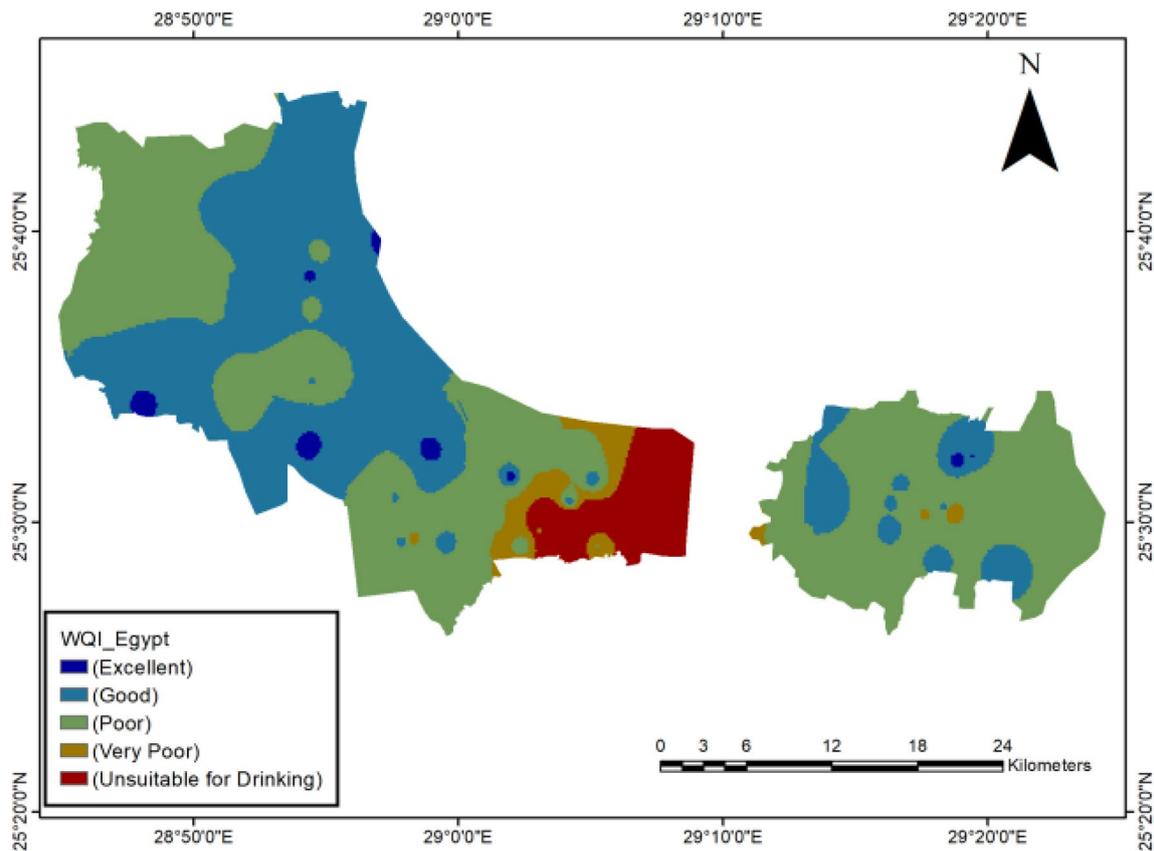


Fig. 9 Spatial distribution of WQI in Dakhla Oasis based on the Egyptian standards

3.3 WQI and Groundwater Suitability for Drinking Purposes

Six groundwater quality parameters (TDS, pH, Mn, SO_4 , Fe and TH) were used to assess their suitability for drinking purposes according to the Egyptian threshold limits. The spatial distributions of their suitability are presented in Fig. 6. Approximately, 100% of the total wells have TDS and SO_4 values within the permissible limits of the Egyptian standards for drinking. Considering the pH values, 64.78% of the wells are unsuitable for drinking. Approximately, 35.21% of the 71 wells have Mn values within the maximum permissible limits given by the Egyptian standards (Table 3).

Fe is the only parameter that was recorded in about 99% of the total wells exceeding the maximum Egyptian allowable limits. Presence of iron in the groundwater is a direct result of its natural existence in the lithology of the water-bearing formations. As water moves, some iron dissolves and accumulates in aquifers that serve as a groundwater source. In spite of its unrecorded health problems in humans, the presence of Fe in potable water is unpleasant due to some undesirable effects. These effects include: bad odors, rusty taste and color, its feel on skin and hair and corrosion

of pipes and screens lining the wells and damage of water pumps.

Considering the previous water quality characteristics and assessments, the WQI is calculated. This index was used to assess groundwater suitability for drinking purposes taking into consideration the Egyptian and WHO (2011) standards. Results of WQI showed that Dakhla Oasis is divided into five categories of water: excellent, good, poor, very poor and unsuitable. The spatial distribution and percentages of the various WQI categories considering both the Egyptian and WHO (2011) are shown in Figs. 7, 8, and 9.

More than one-third of the study area falls within the poor water category (38% and 36.6%) according to the Egyptian and WHO standards, respectively. The second percent was located in the good groundwater quality recording the same percent for both standards (31%). The class of excellent water quality occupied 15.5% using the Egyptian standards and 12.7% using the WHO standards. This category is located in different districts as prescribed in Table 4. Out of the 71 investigated wells, only 4–5 wells were located in the unsuitable class for drinking. Three of these wells are located in Maasara district in the middle. The variability of

Table 4 Water quality index (WQI) values and suitability of groundwater in Dakhla Oasis for drinking purposes

Well No.	District	Egypt standards		WHO standards	
		WQI	Water type	WQI	Water type
1	Teneida	177.74	Poor	181.66	Poor
2	Teneida	217.88	Very poor	236.64	Very Poor
3	Teneida	199.61	Poor	203.45	Very Poor
4	Teneida	51.84	Excellent	55.61	Excellent
5	Teneida	298.94	Very poor	303.08	Unsuitable
6	Teneida	76.25	Good	80.1	Good
7	Teneida	68.99	Good	72.94	Good
8	Balat	42.81	Excellent	46.51	Excellent
9	Balat	70.3	Good	74.21	Good
10	Balat	184.15	Poor	193.9	Poor
11	Balat	169.09	Poor	174.24	Poor
12	Balat	79.69	Good	84.41	Good
13	Balat	49.32	Excellent	55.87	Good
14	Balat	152.13	Poor	156.96	Poor
15	Balat	60.54	Good	63.9	Good
16	Balat	111.73	Poor	122.69	Poor
17	Balat	113.91	Poor	117.57	Poor
18	Balat	72.88	Good	77.91	Good
19	Balat	30.54	Excellent	36.06	Excellent
20	Mut	82.63	Good	87	Good
21	Mut	247.05	Very poor	255.74	Very poor
22	Mut	286.52	Very poor	296.06	Very poor
23	Mut	146.83	Poor	150.76	Poor
24	Mut	160.05	Poor	164.68	Poor
25	Mut	101.98	Poor	105.23	Poor
26	Mut	147.36	Poor	152.59	Poor
27	Mut	469.82	Unsuitable	482.66	Unsuitable
28	Mut	83.6	Good	86.92	Good
29	Mut	160.79	Poor	166.81	Poor
30	Mut	100.12	Poor	105.89	Poor
31	Mut	77.16	Good	80.6	Good
32	Ismant	97.14	Good	100.34	Poor
33	Ismant	49.11	Excellent	53.88	Good
34	Ismant	195.4	Poor	201.05	Very poor
35	Ismant	132.35	Poor	138.41	Poor
Well No.	District	Egypt standards		WHO standards	
		WQI	Water type	WQI	Water type
36	Ismant	222.13	Very poor	227.9	Very poor
37	Ismant	121.62	Poor	125.22	Poor
38	Maasara	50.64	Good	54.61	Good
39	Maasara	204.94	Very poor	233.1	Very Poor
40	Maasara	966.49	Unsuitable	979.81	Unsuitable
41	Maasara	1270.63	Unsuitable	1291.82	Unsuitable
42	Maasara	129.3	Poor	173.73	Poor
43	Maasara	197.66	Poor	204.57	Very poor
44	Maasara	466.11	Unsuitable	476.94	Unsuitable
45	Maasara	143.25	Poor	147.53	Poor

Table 4 (continued)

Well No.	District	Egypt standards		WHO standards	
		WQI	Water type	WQI	Water type
46	Sheikh wali	33.57	Excellent	37.09	Excellent
47	Sheikh wali	185.71	Poor	190.29	Poor
48	Rashda	98.64	Good	102.5	Poor
49	Rashda	76.45	Good	82.59	Good
50	Rashda	61.95	Good	68.45	Good
51	Rashda	74.54	Good	78.25	Good
52	Rashda	209.36	Very poor	215.09	Very poor
53	Gedida	138.97	Poor	145.24	Poor
54	Gedida	41.43	Excellent	45.36	Excellent
55	Gedida	62	Good	69.31	Good
56	Gedida	96.14	Good	100	Good
57	Qalamon	30.79	Excellent	34.27	Excellent
58	Hindaw	26.79	Excellent	31.13	Excellent
59	Hindaw	89	Good	95.8	Good
60	Hindaw	56.48	Good	60.31	Good
61	Bedkhulu	107.44	Poor	111.08	Poor
62	Bedkhulu	43.43	Excellent	47.19	Excellent
63	Bedkhulu	69.27	Good	74.15	Good
64	Bedkhulu	31.07	Excellent	35.03	Excellent
65	Ezab qasr	72.62	Good	77.14	Good
66	Ezab qasr	114.33	Poor	117.94	Poor
67	Qasr	66.06	Good	69.74	Good
68	Mawhoub	171.84	Poor	175.52	Poor
69	Mawhoub	145.73	Poor	149.38	Poor
70	Mawhoub	155.27	Poor	158.87	Poor
71	Mawhoub	101.24	Poor	104.68	Poor

groundwater quality and the resultant suitability within the same region in Dakhla Oases are due to different factors. Water quality gets modified along its movement through the hydrological cycle and number of processes: evaporation, vegetation uptake, transpiration, cation exchange, dissociation of minerals, leaching of fertilizers, mixing of waters, pollution and biological factors, etc. (Appelo and Postma 2004).

3.4 Suitability of Groundwater for Irrigation

Eight groundwater quality parameters, including TDS, EC, SAR, pH, Mn, Fe, SO₄ and TH, were utilized to evaluate groundwater suitability for agricultural purposes. Figure 10 illustrates the spatial distribution of their suitability for irrigation within the Dakhla Oases. The percentage and number of groundwater wells suitability for agricultural purposes are illustrated in Table 5 according to different references as shown in “Materials and methods”.

Most of the studied wells (91.56%) showed low to medium salinity levels (100–750 µs/cm). The majority of groundwater wells (91.55%) have TDS lower than 2000 mg/l which is suitable for irrigation. Measured values of SAR in Dakhla Oases are less than 10 which are excellent for irrigation. Most of the groundwater wells are located in the category of the best quality with regard to salinity and excellent in terms of SAR. The classified pH map shows that about 61.97% of the study area is suitable and 38.03% is unsuitable for irrigation.

Classification of groundwater wells with respect to sulfate showed that all groundwater wells have SO₄ values less than 980 mg/l which are suitable for irrigation. The majority of the study area wells (57.75% and 29.6%) contained soft and moderately hard groundwater considering the total hardness. For Mn, it can be observed that 46.48% of the studied wells are unsuitable for irrigation (Mn > 0.2 mg/l). For Fe, 21.13% of the wells are classified as unsuitable for irrigation where Fe exceeds 5 mg/l.

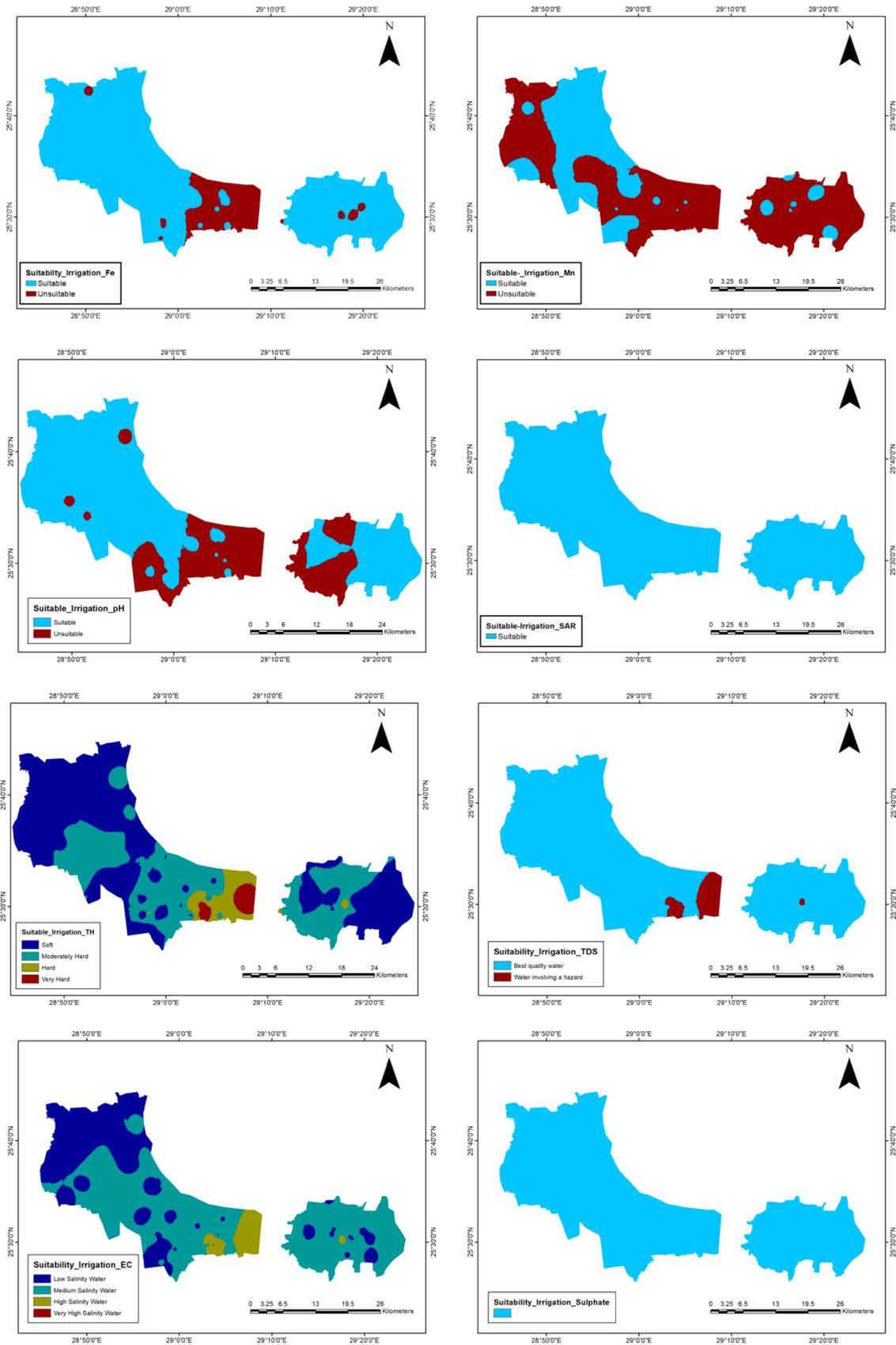


Fig. 10 Spatial distribution of groundwater suitability for irrigation in Dakhla Oases

Table 5 Groundwater wells classification according to its suitability for irrigation purposes

Parameter	Categories	Ranges	No. of wells	Percentage
TDS (mg/l)	Best quality water	< 500	65	91.55
	Water involving a hazard	500–2000	6	8.45
	Water can be used for irrigation only with leaching and perfect drainage	3000–7000	0	0
EC ($\mu\text{s}/\text{cm}$)	Low salinity water	100–250	36	50.71
	Medium salinity water	250–750	29	40.85
	High salinity water	750–2250	5	7.042
	Very high salinity water	> 2250	1	1.41
SAR	Excellent	< 10	71	100
	Good	10–18	0	0
	Doubtful	18–26	0	0
	Unsuitable	> 26	0	0
pH	Suitable	6.5–8.4	44	61.97
	Unsuitable	< 6.5 and > 8.4	27	38.03
Mn (mg/l)	Suitable	< 0.2	38	53.52
	Unsuitable	> 0.2	33	46.48
Fe	Suitable	< 5.0	56	78.87
	Unsuitable	> 5.0	15	21.13
SO ₄ (mg/l)	Suitable	< 980	71	100
	Unsuitable	> 980	0	0
TH	Soft	< 75	41	57.75
	Moderately hard	75–150	21	29.6
	Hard	150–300	6	8.5
	Very hard	> 300	3	4.23

4 Conclusion and Recommendations

Dakhla, as one of the Western Desert oases in Egypt, is one of the pioneering areas with regard to its unique geographic location and groundwater resources. It was necessary to assess and map the available groundwater resources for different purposes in such remote areas to support urbanization and land reclamation projects. In the present study, groundwater quality and suitability for domestic and agricultural purposes were assessed using the spatial analysis of the available wells. WQI showed that about 95% of the studied Dakhla Oases wells are suitable for drinking with different categories (from excellent to very poor) using the Egyptian and WHO standards. Furthermore, considering the international recommendations for irrigation, the majority of the wells characteristics are suitable for irrigation. It can be concluded that the groundwater quality in Dakhla Oasis was not greatly impacted by anthropogenic activities in spite of the wide distribution of urban and agricultural areas. The geospatial analyses of the investigated wells quality and suitability magnified the benefits from results of the present study. Decision making for sustainable governmental projects needs to be informed with the present and future groundwater potentials for

better planning. Geospatial analyses of groundwater quality and suitability for different purposes provide one of the main inputs for management and planning of Dakhla Oases. The spatial assessment of the groundwater resources can explain to which extent the resource is deteriorated and in which areas are more suitable, linking these findings with the current land uses and with the planned strategies for development. Due to the absence of surface water resources and to improve the quality of groundwater in Dakhla wells, the study recommends removal of the iron using the physical treatment method as its levels in the majority of the studied wells exceed 0.3 ppm. Further, the current research highly recommends considering the obtained results for developing the Dakhla Oases and the surrounding areas. Likewise, it is recommended to apply the adopted methodology in similar regions for groundwater suitability studies.

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Compliance with Ethical standards

Conflict of Interest The authors confirm that there is no conflict of interest.

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