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Article

Geomatics-Based Modeling and Hydrochemical Analysis for Groundwater Quality Mapping in the Egyptian Western Desert: A Case Study of El-Dakhla Oasis

Hanaa A. Megahed [1], Hossam M. GabAllah [1], Mohamed A. E. AbdelRahman [2,*], Paola D'Antonio [3], Antonio Scopa [3,*] and Mahmoud H. Darwish [4]

[1] Division of Geological Applications and Mineral Resources, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo 1564, Egypt
[2] Division of Environmental Studies and Land Use, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo 1564, Egypt
[3] Scuola di Scienze Agrarie, Forestali, Alimentari ed Ambientali (SAFE), Università degli Studi della Basilicata, Viale dell'Ateneo Lucano, 10, 85100 Potenza, Italy
[4] Geology Department, Faculty of Science, New Valley University, El Kharga 72511, Egypt
* Correspondence: maekaoud@narss.sci.eg (M.A.E.A.); antonio.scopa@unibas.it (A.S.)

Abstract: Groundwater is the single source of water in El-Dakhla Oasis, western desert, Egypt. The main objective of this study is an assessment of groundwater in the area for agriculture and drinking compared to Egyptian and World Health Organization criteria. Most the contamination of water in the study area comes from human and agricultural activities. Thirty soil profiles were studied in the area and we assessed soil quality. Seventy-four samples were taken from the area's groundwater wells to assess the chemical characteristics of the groundwater. Moreover, the contamination of groundwater by farming and anthropogenic activities was assessed using a land use/land cover (LULC) map. Nine standard water criteria were determined to assess groundwater quality for agriculture. Furthermore, the resulting risk to human health and agricultural crops has been addressed. Therefore, the drinking quality of groundwater samples is graded as low as the hydrochemical study showed high TH, EC, TDS, Ca^{2+}, Mg^{2+}, Mn^{2+}, and Fe^{2+} contents of 40.5%, 2.7%, 1.4%, 3.8%, 1.6%, 86.5%, and 100%, respectively. Human health is risked by drinking this water, which negatively affects hair, skin, and eyes, with greatest exposure to enteric pathogens. Using these criteria, the majority of groundwater samples cause harmful effects on soil types and are toxic to sensitive crops (vegetable crops). In conclusion, the output of this research is a map showing groundwater suitable for consumption and agriculture in El-Dakhla Oasis based on all indices using the Geographic Information Systems (GIS) model. Additionally, there was evidence of a linear relationship between soil quality and irrigation water quality (R^2 = 0.90). This emphasis on tracking changes in soil/water quality was brought on by agricultural practices and environmental variables.

Keywords: El-Dakhla Oasis; water quality spatial model (WPSM); health risk assessment; Geographical Information Systems; Egypt

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Citation: Megahed, H.A.; GabAllah, H.M.; AbdelRahman, M.A.E.; D'Antonio, P.; Scopa, A.; Darwish, M.H. Geomatics-Based Modeling and Hydrochemical Analysis for Groundwater Quality Mapping in the Egyptian Western Desert: A Case Study of El-Dakhla Oasis. *Water* **2022**, *14*, 4018. https://doi.org/10.3390/w14244018

Academic Editors: Zhenhuan Liu, Huabing Huang and Haiyan Yang

Received: 15 November 2022
Accepted: 7 December 2022
Published: 9 December 2022

1. Introduction

The goal of water resource management is not just to meet human demand for water; rather, it is also crucial to take into account water quality as part of the process of developing water resources [1]. The demand for groundwater will rise substantially owing to worldwide climate change, increasing populations, and decreasing precipitation [2], but use will be reduced over time due to pollution [3–5]. Globally, groundwater generates approximately 40% of foodstuffs and 30% of water for consumption [6,7]. Aquifer deposits and water recharge paths have a considerable effect on groundwater quality (physical and chemical characteristics), rendering it unfit for consumption and irrigation [8–12]. In some cases, groundwater is contaminated by heavy minerals as a consequence of human activities such as mineral extraction and manufacturing, decreasing water quality [13–16]. Human activities and geological formations are among the factors affecting groundwater quality [17–20]. Groundwater contamination is caused by rapid development, population increase, urbanization, expanding industrial sectors, heavy fertilizer use in irrigation fields, inadequate sewage systems, urban structures, and human and animal wastes. The most significant point is that nitrate poisoning of groundwater is widespread and has now become a global problem [21–23]. Comparatively, Zhang et al. [21] investigated the origin and distribution of nitrate in several aquifers in the urban region of south China and found that leaks of residential sewage were the primary factor raising the nitrate concentration in groundwater in urban locations. Additionally, the groundwater in south China's development zone is heavily contaminated with nitrates. Zhang et al. [1] reported the discovery of iodide-rich groundwater in the PRD; however, it is still unknown how the groundwater is distributed spatially and where it comes from. The PRD has experienced various degrees of urbanization, but little attention has been paid to how urbanization has affected the distribution of iodide-rich groundwater there.

Recently, there has been considerable interest in the health consequences of groundwater resources [3,24–32]. Using Monte Carlo simulation, we examined the relationship between F and Mn contamination in China's Weining Plain in terms of risk to human health [33]. Other authors showed variations in groundwater quality in China's Guanzhong Plain and alluvial-pluvial fans in North China Plain, and the health risks of drinking nitrate-contaminated groundwater. Additionally, we designed a groundwater quality evaluation methodology that considered pollution loading using the DRATICL model [34]. Other papers verified the bacterial pollution of the Egyptian Nile Valley (Assiut Governorate), and its impact on individual health, showing that it was dangerous to humans, particularly children [4].

The hydrochemical analysis (TDS, major ions, EC, and pH) provides details about the quality of groundwater and its appropriateness for various uses. Numerous Egyptian scholars explored groundwater quality and assessment for a variety of uses in Egypt using hydrochemical analyses [35–42]. The authors observed that the drinking water potential in the northwest was the highest, and the southeast of the Assiut governorate was the lowest [4]. In the same governorate, a model was designed for the movement of groundwater in the Quaternary aquifer based on various environmental circumstances [43], whereas other authors assessed the purity of groundwater for consumption and agriculture, employing the Water Quality Index (WQI) and measuring water quality [44].

Recent studies commonly used the combination of PS methods and statistical methods such as the finite normal-mixture model, the median of the absolute deviations from the median (median ± 2MAD), a box and whisker plot, the 4δ outlier test, as well as Grubbs' test aimed at eliminating the outliers and then the remaining background dataset for natural background level (NBL) assessment [45] such as arsenic (As) and manganese (Mn) in urbanized areas in the Pearl River Delta (PRD) adjacent to the South China Sea [46] and assessment of iron-rich groundwater in the same area in the period 2006–2018 [47].

In contaminated groundwater research, Geographic Information Systems (GIS) implementations include mapping and suitability evaluations, groundwater risk analysis, groundwater movement, and integrated groundwater purity evaluation using spatial data. Ahn and Chon used Geographical Information Systems to examine groundwater contamination and spatial connections between contamination causes, groundwater features, land uses, geography, and geology [48]. Levallois et al. stated that nitrate contamination of groundwater is caused by intensive cultivation practices, which are recognized as among the likely causes of groundwater pollution based on Geographical Information Systems [49]. Negm and Armanuos used statistical analysis and ArcGIS to examine factors that impact the effectiveness, consumability, and agricultural viability of groundwater in the western Nile Delta of Egypt [50]. Elbeih and El-Zeiny used the Water Quality Index (WQI) and Geographical Information Systems (GIS) techniques to analyze groundwater purity, agriculture, and drinkable water compatibility in the El-Dakhla Oasis [51]. The primary objectives of this study are to establish the appropriateness of groundwater for agriculture and consumption uses, as well as to map the quality of groundwater in El-Dakhla Oasis utilizing a Geographical Information Systems and hydrochemical analysis and, finally, to assess potential risks to human health.

The Study Area

El-Dakhla Oasis represents a wide area of Egypt's Western Desert in the New Valley Governorate, which lies between latitudes 25°25′45″ and 25°45′35″ N and longitudes 28°45′40″ and 29°25′45″ E. The studied area extends from Teneida village in the east to El-Mawhoub village in the west, approximately 65 km (Figure 1).

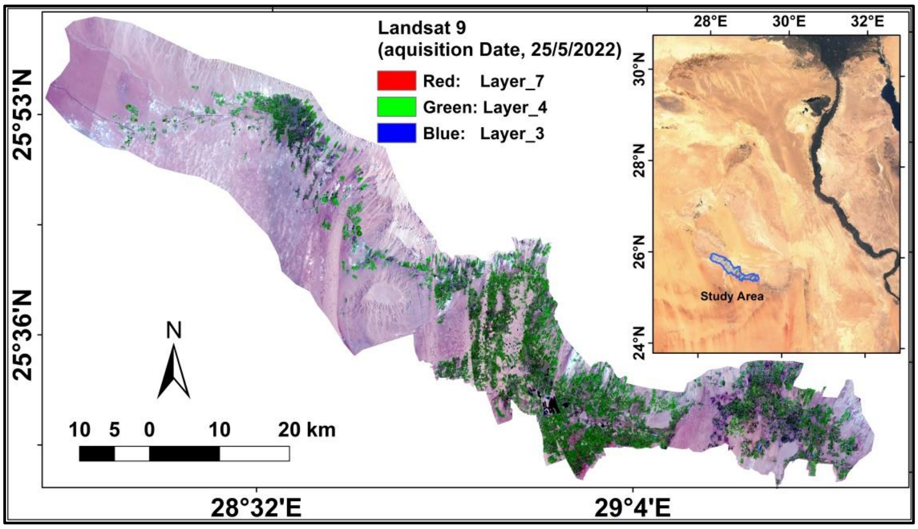


Figure 1. Location map of the study area.

Hydrogeologically, El-Dakhla Oasis has a different irrigation and cultivation system than the Nile Valley and depends on groundwater supply as the single source for water demand for domestic and irrigation purposes. The population has been focused on shallow groundwater wells, where the Nubian Sandstone Aquifer System (NSAS) is regarded as the principal resource of fresh groundwater. Water in this aquifer is ancient and non-renewable. Lying beneath the four northeast African countries of Chad, Egypt, Libya, and Sudan, it covers some two million square kilometers. With growing populations and decreasing water availability from other sources, the aquifer is under mounting pressure. The groundwater recharge in this aquifer depends on the subsurface inflow across the Egyptian/Sudanese borders. Most aquifers are naturally recharged by rainfall or other surface water that infiltrates into the ground. In El-Dakhla Oasis, the Nubian sandstone, with an average thickness of approximately 1500 m, is divided into three main subsurface water-bearing layers with confining layers that are laterally and/or vertically interconnected; and separated by three alternative clay layers [52]. Taref sandstone is represented as the shallow water-bearing formation in the Mut region, the piezometric surface data of the Taref aquifer in the Teneida and Mut areas are 118 m above the mean sea level, On the other hand, due to the water being heavily exploited since the 1960s, a decline in the groundwater level has been recorded [53]. The transmissivity is estimated to be 400 m^2 /day in the east Dakhla depression and increases to approximately 550 m^2/day in the west with increasing sand content; meanwhile, the average hydraulic conductivity of the Taref aquifer reaches 6.76 m/day at a maximum thickness of 110.45 m [54]. The average thickness of the groundwater aquifer in the area becomes thick in general towards the west and south [55]. The other source of water in El-Dakhla Oasis is surface water (wastewater lakes, and canals) results from agricultural drainage operations, to which sewage is sometimes added—this wastewater has very high values of total dissolved solids

(TDS) and sodium adsorption ratio (SAR), which makes this water unfit for any use and leads to long-term soil alkalinity [22].

Geologically, the area under investigation comprises three geological features, including the Upper Cretaceous–Lower Eocene rock units in the area extending between Teneida and Abu Minqar, which is divided into Taref, Quseir Formations of the Nubian Sandstone Group, Duwi, Dakhla, Abu Simbil, Khoman, and Maghrebi formations. The Paleocene rock unit (Tarwan and Garraformations) constitutes the western portion of the depression in the research region, and it is composed of layers of coral limestone with calcite overlaps. Finally, the Quaternary sediments (Pleistocene sediments) are associated with Aeolian, marine, fluvial, and wadies sediments (scale 1:250,000) [56] (Figure 2).

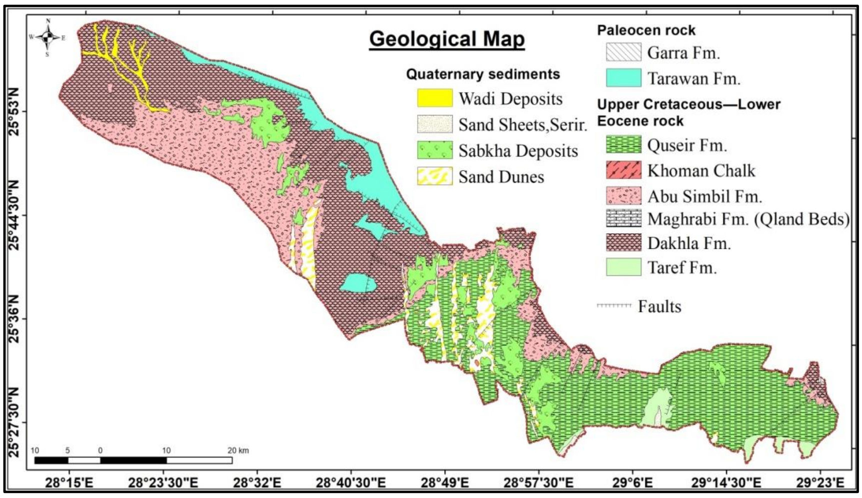


Figure 2. Geological map of the study area (modified by UNESCO, 1997) [56].

2. Materials and Methods

2.1. Data Collection and Processing

To evaluate the ecological circumstances and land usage around the groundwater wells in the research region, we used a multispectral Landsat image (Figure 1 (dated 2022 synchronized with groundwater analyses after radiological and geographical correction. Seventy-four samples of groundwater were gathered randomly from the region under investigation in plastic bottles for chemical and physical analysis. ArcGIS 10.3 was used to generate the research area's site map and sample sites (Figure 3).

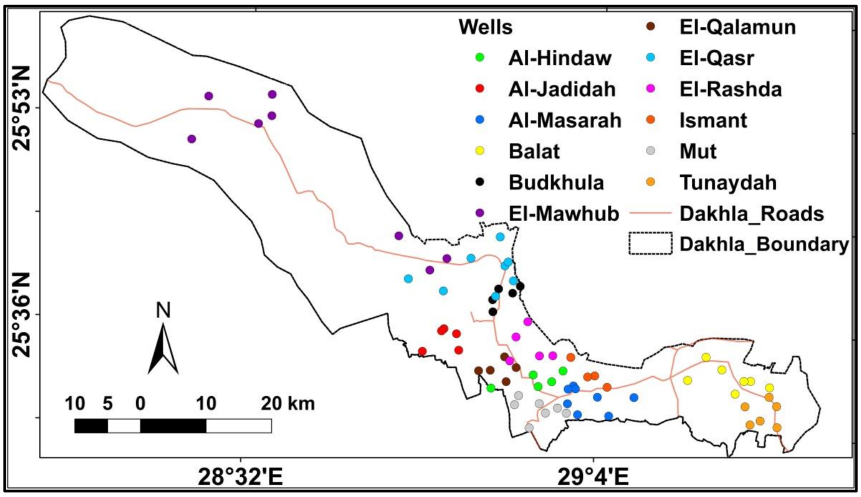


Figure 3. Location map of monitoring points of groundwater samples in the study area.

Multiparameter portable devices were used to test physical parameters, pH, electrical conductivity, and solids dissolved on site after being calibrated with water from the gathered samples. After approximately thirty minutes of pumping the wells, water samples were taken. Before being transported to the laboratory, every sample was vacuum sealed and kept at 4 °C for chemical analysis. The principal anions and cations (K^+, Na^+, Mg^{2+}, Ca^{2+}, $SO_4{}^{2-}$, $HCO_3{}^-$, and Cl^-) were analyzed chemically in line with the requirements of the American Public Health Association (APHA) [57]. Potassium, calcium, sodium, and magnesium were evaluated employing atomic absorption spectrometry (AAnova 350 Analytic Jena GmbH, Thuringia, Germany). The collected data were re-arranged to allow analysis, interpretation, and producing different comparative maps using a geostatistical analysis tool for groundwater quality indices using Geographical Information Systems (ArcMap 10.5). Indicators of water quality were investigated to determine differences in groundwater purity caused by land-use changes. The quality of the groundwater was measured against many criteria, and the findings were evaluated by comparison to WHO 2017 standards [58], and Egyptian drinking water standards (EHCW) [59]. Moreover, the equations in Table 1 were used to determine irrigation quality indices such as pH, sodium absorption ratio (SAR), electrical conductivity (EC), total dissolved solids (TDS), residual sodium carbonate (RSC), magnesium hazard (MH), soluble sodium percentage (Na%), Kelley's ratio (KR), and total hardness (TH).

Table 1. Groundwater quality indices for irrigation.

Index	Mathematical Equation	References
pH		Ayers RS, Westcot DW [60]
EC		WHO [58]
TDS		Raghunath [61]
SAR	$SAR = Na^+/\sqrt{}(Ca + Mg)/2$ all ions in meq L^{-1}	Wilcox [62]
(Na%)	$Na\% = Na^+ + K^+ \ / \ Ca^{2+} + Mg^{2+} + Na^+ + K^+ \times 100$	Doneen [63]
RSC	$RSC = (HCO_3{}^- + CO_2{}^{3-})\ \_((Ca^{2+} + Mg^{2+})$ all ions in meq L^{-1}	Richard [64]
KR	$KR = Na^+/(Ca^{2+} + Mg^{2+})$ all ions in meq L^{-1}	Kelley [65], and Paliwal [66]
MH	$MAR = Mg^{2+}/Ca^{2+} + Mg^{2+} \times 100$ all ions in meq L^{-1}	Szabolcs and Darab [67], Raghunath [61]
TH	$TH = 2.497\ Ca^{2+} + 4.115\ Mg^{2+}$ ions in meq L^{-1}	Todd [68]

2.2. Soil Analysis

The soil physicochemical properties were determined according the methodologies described by authors as follows: particles size distribution [69,70], saturation percentage (SP) [71], soil reaction (pH) [72], organic matter (OM) [70], $CaCO_3$ content [73], gypsum content [74], soil salinity [75], cation exchange capacity (CEC) [76], and exchangeable sodium percentage (ESP) [71].

The measurement and determination of the limiting factors for describing the soil quality in the study area followed the limiting parameters which were proposed by [77].

3. Results

Through previous studies and chemical analyses examined in the present study, it was found that the parameters (pH, EC, and TDS) do not directly affect human or animal health. However, the high concentrations of these parameters cause a modification of how the water tastes according to the location the water is flowing over (a chalky taste). At the same time, the identified ions (Ca^{2+}, Na^+, Mg^{2+}, K^+, $SO_4{}^{2-}$, $HCO_3{}^-$, and Cl^-) cause water degradation and have a significant direct effect on human health [78–90].

3.1. Hydrochemical Characteristics

Table 2 provides a summary of qualitative data for physicochemical properties, containing the minimum, maximum, and mean values for samples of groundwater. In general, the pH of the groundwater samples was at the acidic to slightly alkaline level, varying from 3 to 7.7, with an average value of 5.4. The range of EC values was 168–867 µs cm^{-1}, with an average of 518 µs cm^{-1}. TDS levels ranged from 101 to 520 mg L^{-1}, with an average of 310.5 mg L^{-1}. In terms of the ionic conductivity of the groundwater samples, the vast majority had significant ionic strength. The ranges of Ca^{2+}, Mg^{2+}, Na^+, and K^+ concentrations were 7.13–40.8 mg L^{-1}, 3.4–20.9, 8–120, and 5–25 mg L^{-1}, respectively, with mean values of 24, 12.15, 64, and 14.5 mg L^{-1}. Dissolved anion concentrations such as HCO_3^-, Cl^- and SO_4^{2-} varied from 15.3 to 91.8 mg L^{-1}, 20.71 to 94.65 mg L^{-1}, and 7.5 to 103.5 mg L^{-1} in mean concentrations of 54, 57.68, and 55.5 mg L^{-1}. $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ are the most dominant main cations in groundwater samples, while $Cl^- > SO_4^{2-} > HCO_3^-$ are the most dominant anions.

Table 2. Physicochemical properties of groundwater dataset: a summary.

Parameter		Minimum	Maximum	Mean
pH		3	7.7	5.4
EC (µs cm^{-1})		168	867	518
TDS	(mg L^{-1})	101	520	310.5
Ca^{2+}		7.13	40.8	24
Mg^{2+}		3.4	20.9	12.15
Na^+		8	120	64
K^+		4	25	14.5
HCO_3^-		15.3	91.8	54
Cl^-		20.71	94.65	57.68
SO_4^{2-}		7.5	103.5	55.5
Fe^{2+}		0.8	9.2	5
Mn^{2+}		0.0	0.8	0.4

3.2. Health Risks of Water Quality Indices

The pH readings for drinking purposes have no direct influence on human health and no provided health-based pH guideline value. Excessive pH levels (higher than 11) cause eye, skin, and mucous membrane diseases and irritations, in addition to gastrointestinal irritation, as well as hair fiber swelling (pH 10–12.5). Furthermore, pH values below four cause redness and irritation of the eyes [81]. As a result, according to Table 3, 4.05% of groundwater samples may cause indirect damage on consumption. EC and TDS are proportional to the groundwater ionic concentrations [82]. TDS and EC have no obvious impact on individual health, similar to pH. Table 3 shows that 97.3% of groundwater samples in the region under investigation are categorized inside the low EC category, according to EC and TDS classifications [83,84]. The high EC category was found in 2.7% of groundwater samples. Table 3 shows that 98.6% of groundwater samples have suitable levels of TDS that ranged from good to desirable for drinking and 1.4% unacceptable. The high TDS values indicate highly mineralized water, which has an unwanted flavor and a diluted hue. Water users may cause threats and disturbance due to moderate EC waters and insufficient and inadequate TDS levels in the groundwater.

Table 3. Physicochemical data of groundwater samples comparing with Egyptian and WHO standards.

Parameter	Range	Water Class	Maximum Acceptable Concentration World Health Organization Standards (WHO 2017) [43]	Egyptian Maximum Permissible Limits (EHCW 2007) [44]	Groundwater Samples %
TDS (mg L^{-1}) Davis and Dewiest (1966) [77]	<500	Desirable for drinking	500	1000	98.6%
	500–1000	Permissible for drinking			1.4%
	>1000	Unfit for drinking			——-
TH Sawyer and McMcartly (1967) [78]	<75	Soft	500	500	59.5%
	75–150	Moderately high			40.5%
	150–300	Hard			——
	>300	Very hard			——
EC (µs cm^{-1})	<500	Suitable	500	-	97.3%
	>500	Unsuitable			2.7%
pH	<6.5	Excellent	6.5–8.5	6.5–8.5	17.6%
	6.5–8.5	Good			82.4%
	>8.5	Unsuitable			——
Ca^{2+}	<75	Suitable	75–200	75–200	96.2%
	>200	Unsuitable			3.8%
Mg^{2+}	<50	Suitable	50–100	50–100	98.4%
	>100	Unsuitable			1.6%
Na^{+} (mg L^{-1})	<200	Suitable	200–600	200–600	100%
	>600	Unsuitable			0.0%
K^{+} (mg L^{-1})	<10	Suitable	10–12	10–12	100%
	>12	Unsuitable			0.0%
HCO_3^{-}	<200	Suitable	200–500	200–500	100%
	>500	Unsuitable			0.0%
Cl^{-}	<250	Suitable	250–500	250–500	100%
	>500	Unsuitable			0.0%
SO_4^{2-} (mg L^{-1})	<400	Suitable	400	400	100%
	>400	Unsuitable			0.0%
Mn^{2+} (mg L^{-1})	<0.1	Suitable	0.1	0.1	13.5%
	>0.1	Unsuitable			86.5%
Fe^{2+} (mg L^{-1})	<0.3	Suitable	0.3	0.3	0.0%
	>0.3	Unsuitable			100%

EC and TDS levels for consumption purposes are frequently hazardous to renal and cardiovascular disease-affected individuals. Furthermore, if poisonous salts and/or ions are present, they might induce constipation or laxative complications, arteriosclerotic heart disease, gallbladder inflammation and gallstones, coronary heart disease, cardiac disease, harm to those with renal disease, cancer, and death [85–87]. Table 3 shows that for Ca^{2+} and Mg^{2+} values, 3.8% and 1.6% of groundwater samples, respectively, may pose a concern to water drinkers. Those susceptible to milk-alkali and hypercalcemia conditions are immediately impacted by high Ca^{2+} consumption. Increased Mg^{2+} intake can induce hypermagnesemia and diarrhea in renal disease patients [88]. Meyers found that high levels of soluble Ca^{2+} and Mg^{2+}, as well as TH values, raised the likelihood of ischemic cardiovascular illness and acute myocardial infarction [89]. According to Table 3, the Na^{+} and K^{+} levels of groundwater samples match the standards of the WHO and standard Egyptian limits. The high levels of HCO_3^{-} cause health problems as a result of the rise in pH and TDS, and congestive heart failure may result from an excess of Cl^{-} and SO_4^{2-}.

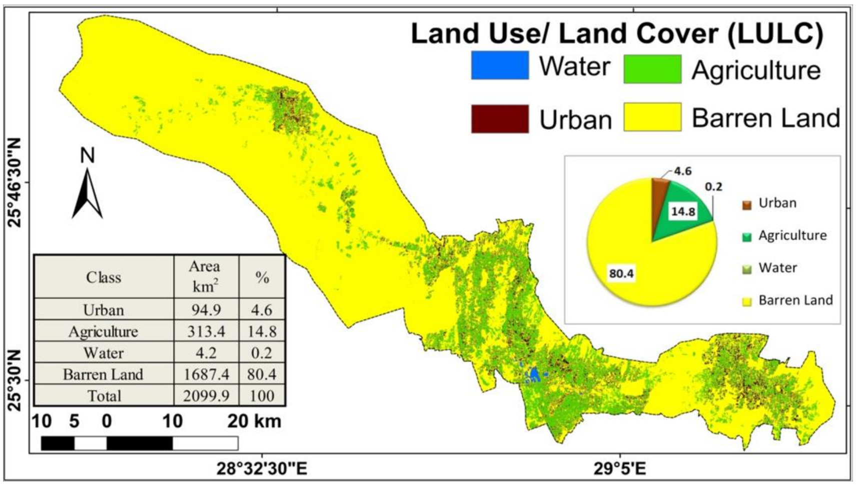
Nevertheless, Table 3 shows that HCO_3^-, Cl^-, and SO_4^{2-} concentrations of groundwater samples match the WHO and Egyptian standards, and do not cause any health problems on drinking. While 96.5% of groundwater samples have Mn^{2+} concentrations over the acceptable limits for consumption, Fe^{2+} concentrations are above the desirable range in all groundwater samples (Table 3). Ingestion of high concentrations of Mn^{2+} and Fe^{2+} in water for consumption has a considerable detrimental influence on human health. Due to their laxative action, there is reduced gastrointestinal food accumulation and a significant rise in stool quantity, leading to a substantial likelihood of dehydration because of diarrhea [90–92].

3.3. Land Use/Land Cover (LULC) Map

Various researchers have examined the effect of change in land use, among the most major human-caused elements affecting the groundwater ecosystem [93–97]. Although the footprint of the land used has increased, its effect on degrading the quality of water has not been widely explored in Egypt. However, this linkage has long been recognized globally. Tang et al. [98] and Bhaduri et al. [99] concluded that the hydrology of the reservoir region is affected by changes in land use. In the recent two decades, land use has changed the spatial pattern in the region under investigation, showing an extension of the agricultural fields.

Due to land reclamation operations and population increase, the study area has witnessed major changes in land cover (agricultural and urban fields). Some spectral land use index maps were created from the satellite image, including the normalized difference built-up index (NDBI), land use/cover, the modified normalized difference water index (MNDWI), the normalized difference vegetation index (NDVI), and the normalized differential salinity index (NDSI), to identify the spatial distribution of multiple land uses and the influence of land use on groundwater purity and detect contamination that is most likely to be caused by humans [100].

According to the LULC map (Figure 4), 80.4% of the study area is barren land, covering 1687.4 km^2. The salinity index (NDSI)) Figure 5a) shows higher levels of salinity in desert lands (>0.3) in which there are no wells. The urban index (NDBI)) Figure 5b) differs between urban areas and barren lands with low values (>0.2). In contrast, the urban areas occupy the smallest area on the LULC map (94.9 km^2). As shown in the NDVI map (Figure 5c), the second class in the LULC map was the vegetation area (313.4 km^2, 14.9%). In LULC and MNDWI maps) Figure 5d), water bodies are limited to a small Mut pond attaining an area of 4.2 km^2 (0.2%). The LULC map (Figure 5) showed that in terms of water quality, the wells closest to agricultural and urban activities are more likely to be damaged. Furthermore, natural causes had a substantial impact on groundwater purity in the studied region.



Class	Area km^2	%
Urban	94.9	4.6
Agriculture	313.4	14.8
Water	4.2	0.2
Barren Land	1687.4	80.4
Total	2099.9	100

Figure 4. Land use/cover map of the area under investigation.

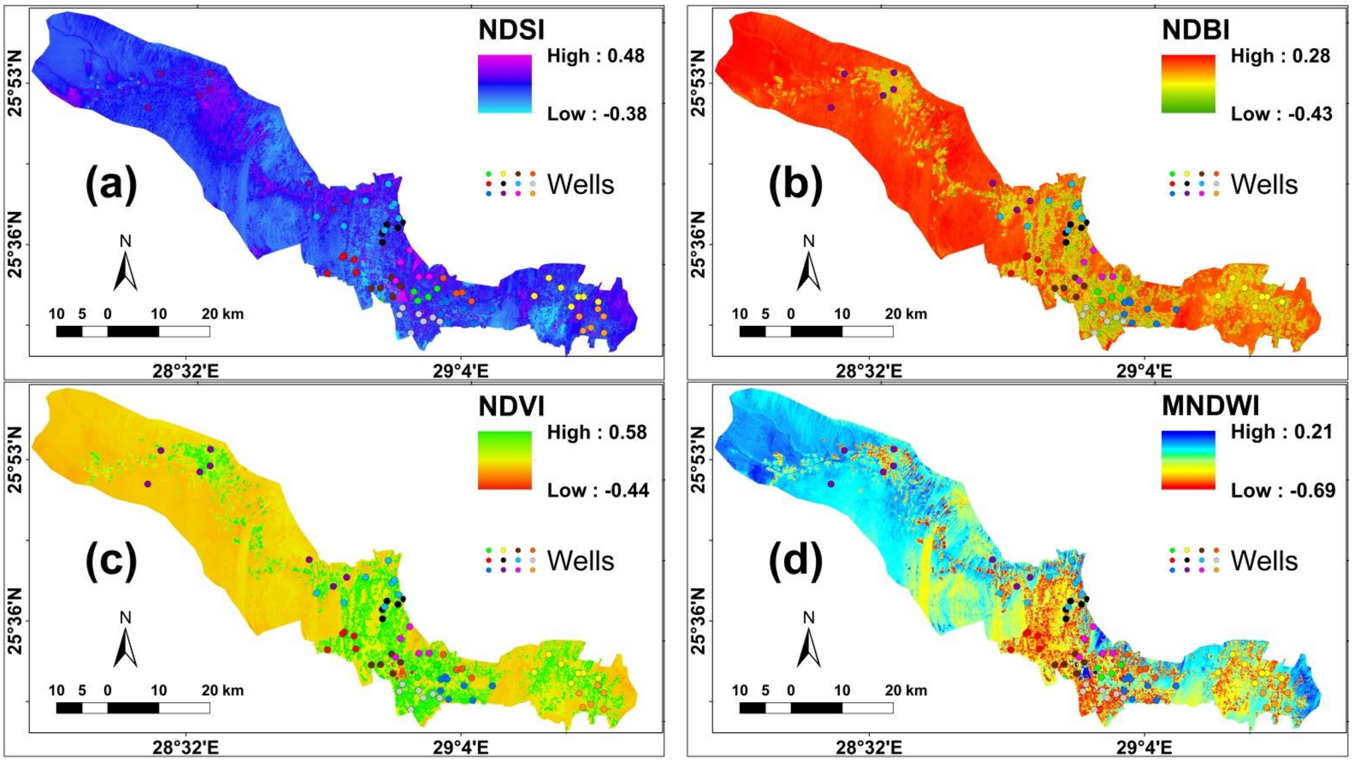


Figure 5. Spectral land use indices for the study area. (**a**); NDSI, (**b**); NDBI, (**c**); NDVI, (**d**); MNDWI.

3.4. Soil Sof El-Dakhla Oasis

In terms of topography, the terrain is morphologically almost flat with a level to nearly level sloping relief, and its geomorphology is classified as a depression inherited from parent materials such as shale, lime stone, and/or sand stone. Drift sand, varnished gravel (stoniness), or both were observed to coat the soil profile surfaces. With permeability varying from extremely slow to very rapid, which is consistent with drainage class, all of the investigated soils are determined to have undergone some degree of erosion. Thus, agricultural production is a common use of the land. The depth of the investigated soil profiles are deep, ranging from 120 to 200 cm. According to the origin of the sediments, such as lacustrine, alluvial, and aeolian sand deposits, the soil texture varies across the full depth of soil profiles and ranges considerably from coarse and moderately coarse to fine. The range of soil textures includes clay, sandy clay loam, extremely gravelly sandy loam, and loam.

The majority of the soil's texture ranged from clay loam to sandy, according to the findings and 1.3 g cm^3, 7.91, 3.73 dS m^{-1}, 49.23%, 8.10%, 24.11 cmol(+) kg^{-1}, and 5.74 were the mean values for bulk density (BD), soil pH, EC, SP, $CaCO_3$, CEC, OM, and sodium adsorption ratio (SAR), respectively. N, P, and K had respective mean levels of 101.24, 33.78, and 122.28 mg kg^{-1}. Fe, Mn, Cu, and Zn had mean values of 24.58, 19.74, 0.45, and 3.21 mg kg^{-1}, respectively. However, they were adversely correlated with pH, EC, and $CaCO_3$. The correlation coefficient of NPK was had a significant positive relationship with clay, OM, and CEC. Clay, pH, OM, CEC, and SAR were inversely correlated with Fe, Mn, and Cu, and positively correlated with EC and $CaCO_3$. Additionally, Zn had a positive correlation with CEC and SAR, and a negative correlation with clay, pH, EC, OM, and $CaCO_3$.

4. Discussion

4.1. Water Quality Assessment

4.1.1. Water Quality Modeling for Drinking

Spatial variation in the appropriateness of groundwater characteristics for consumption according to WHO [58] and Egyptian thresholds [59] are shown in Figure 6 and Table 3. Based on the measured pH values of the groundwater samples and the World Health Organization's guidelines, the bulk of samples fell within the acceptable drinking limit. TDS levels in groundwater samples ranged from 101 to 520 parts per million. TDS levels of less than 1000 ppm were found in 98.6% of groundwater samples, indicating that it is safe to drink, whereas TDS levels of more than 1000 ppm were found in 1.4% of groundwater samples, indicating that it is unsafe to drink. According to the ECW, 500 ppm is the highest allowable level of TH in consumable water. A total of 59.5 % of the samples of groundwater were below the recommended limit, making them safe for consumption.

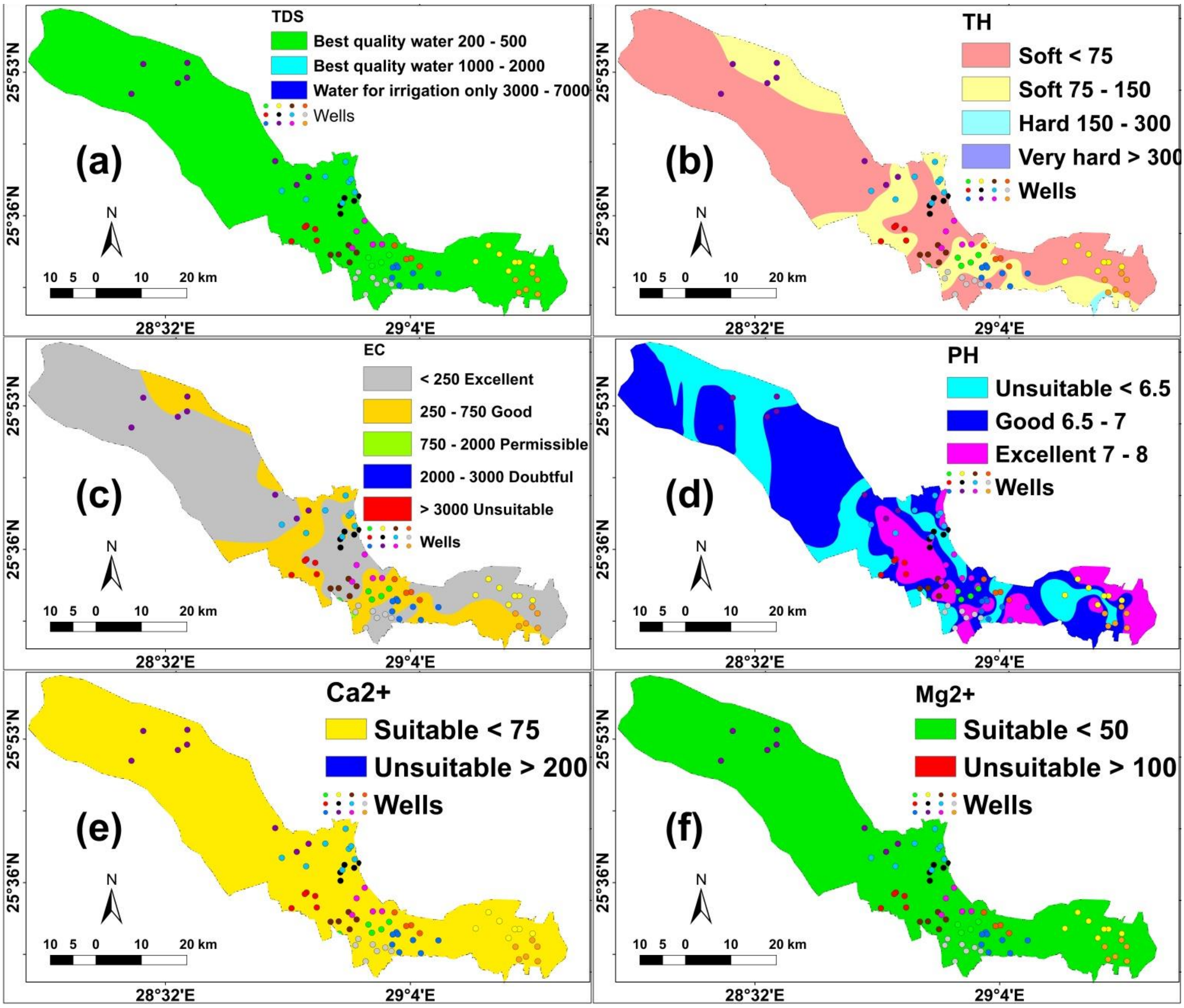


Figure 6. *Cont.*

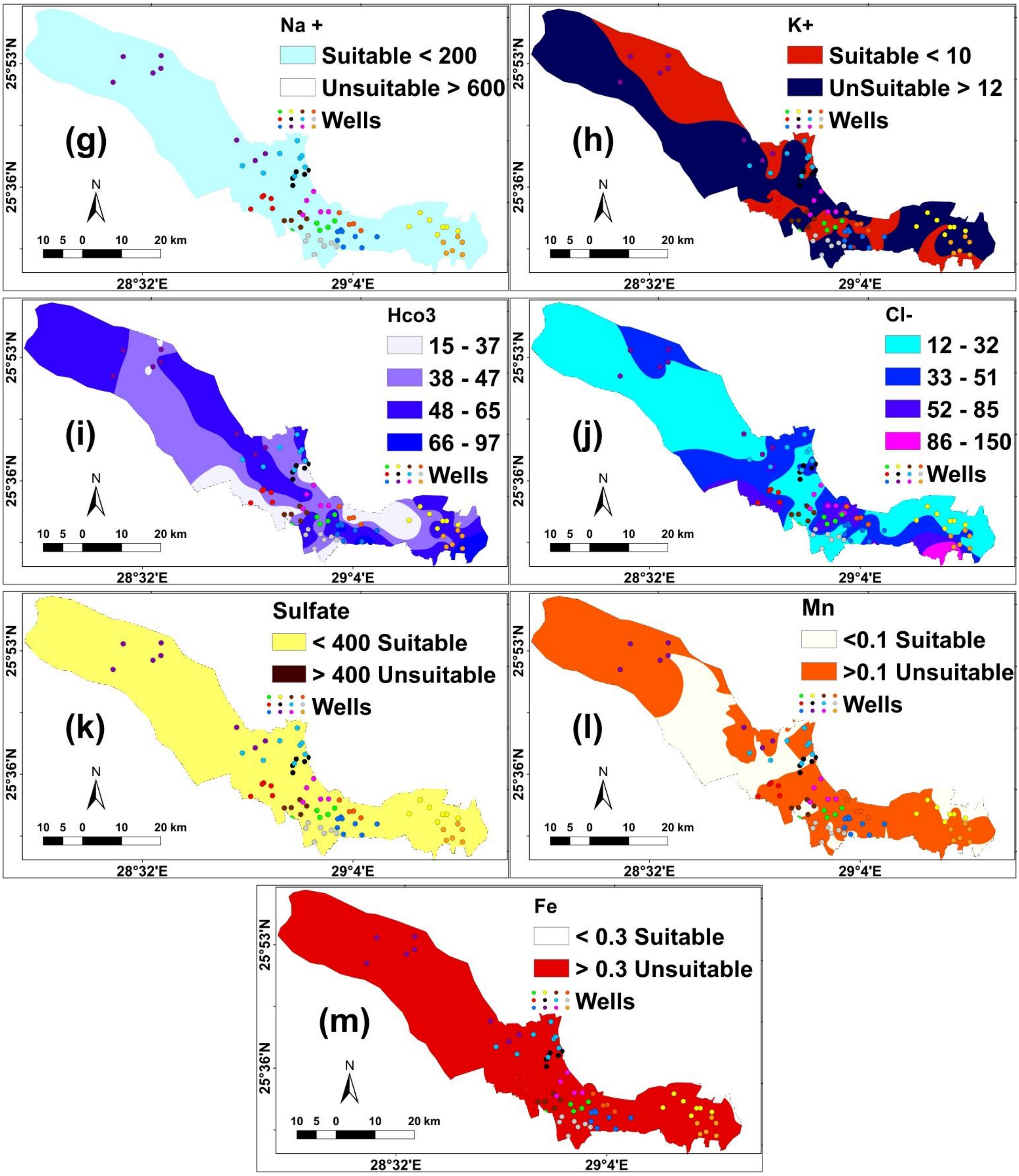


Figure 6. Spatial diversity in the appropriateness of groundwater characteristics for consumption according to WHO and Egyptian thresholds. (**a**); TDS, (**b**); TH, (**c**); EC, (**d**); pH, (**e**); Ca^{2+}, (**f**); Mg^{2+}, (**g**); Na+, (**h**); K^{+}, (**i**); HCO_3^{-}, (**j**); Cl^{-}, (**k**); SO_4^{2-}, (**l**); Mn^{2+}, and (**m**); Fe^{2+}.

To produce the map of groundwater compatibility for drinking in the studied region, we created a water quality spatial model (WQSM) (Figure 7). Each parameter is given a weight depending on its relative value for drinking purposes order, as shown in Table 4.

Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are given a weight of 5; HCO_3^{-}, Cl^{-} and SO_4^{2-} are given a weight of 4; Mn^{2+} and Fe^{2+} are given a weight of 3; TDS, EC, pH, and TH are given a weight of 2; and land use parameters are given 1. The model scale is divided into two categories: excellent and poor (Figure 8). Inspection of the groundwater quality map for drinking uses (Figure 8) indicated that in most of the oasis, the underground aquifer is of superior purity. At the same time, groundwater with reduced quality is focused in the northwestern part of El-Dakhla Oasis, where the water must be treated to be suitable for drinking.

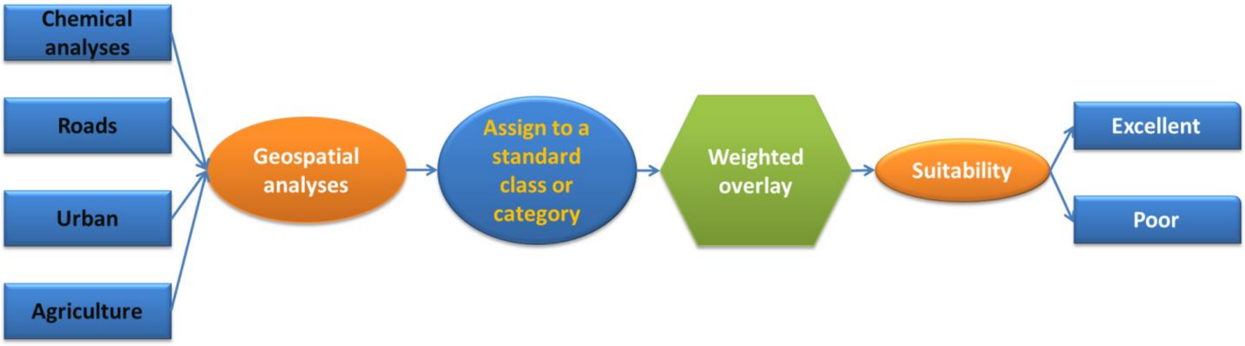


Figure 7. Flow chart of a water quality spatial model for drinking purposes.

Table 4. The rating scores and relative weights of the factors and sub-criteria used for the drinking assessment.

Factor	**Weight**	**Sub-Criteria**	**Rating**	**Weight (Rank—Layer No.) +1**	**Normalized Weight = Weight/Sum * 100**
Land use	0.29	Agriculture	1	17	7
		Urban	1	17	8
		Water	1	17	7
		Roads	1	17	7
Groundwater quality indices for drinking	0.26	TDS	2	16	6.5
		EC	2	16	6.5
		pH	2	16	6.5
		TH	2	16	6.5
	0.12	Mn^{2+}	3	15	6
		Fe^{2+}	3	15	6
	0.15	HCO_3^{-}	4	14	5
		Cl^{-}	4	14	5
		SO_4^{2-}	4	14	5
	0.18	Ca^{+2}	5	13	4.5
		Mg^{+2}	5	13	4.5
		Na^{+}	5	13	4.5
		K^{+}	5	13	4.5
Sum	1			256	100

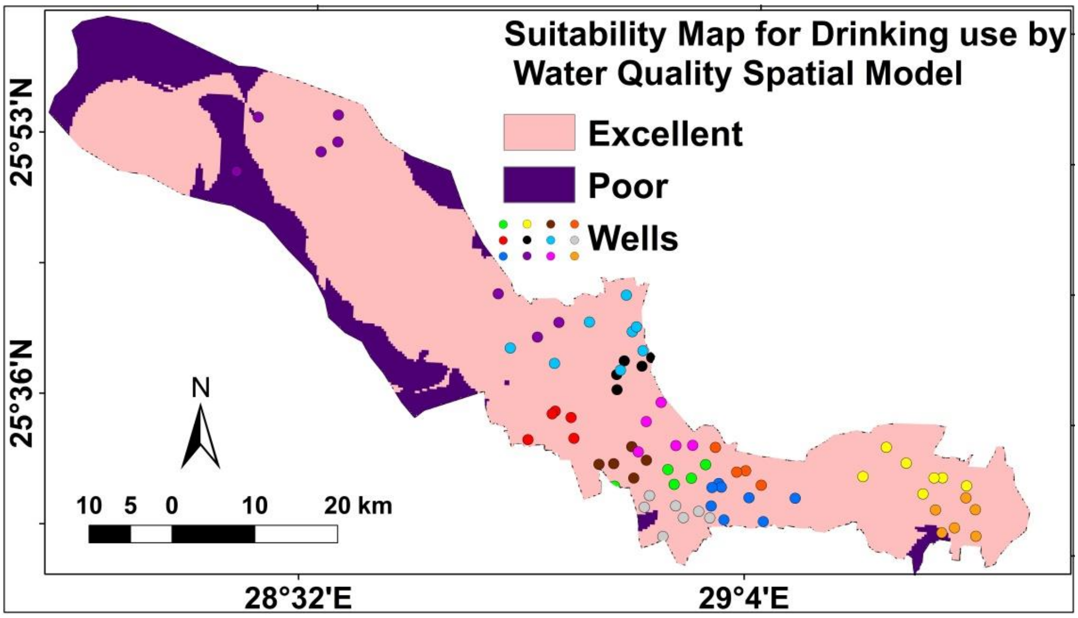


Figure 8. Suitability map for drinking use by a water quality spatial model.

4.1.2. Soil Quality

While NPK had a negative correlation with pH, EC, and $CaCO_3$, NPK had a positive and significant correlation with clay, OM, and CEC. Since the proportion of clay in the soil is known to enhance the amount of nutrients in the soil, this is clear. While clay, pH, OM, CEC, and SAR were inversely correlated with Fe, Mn, and Cu, they were positively correlated with EC and $CaCO_3$. Additionally, SAR had a positive correlation with N, P, and Zn but a negative correlation with K, Fe, Mn, and Cu. In addition, Zn had a positive correlation with CEC and SAR but a negative correlation with clay, pH, EC, OM, and $CaCO_3$. In general, the strong positive correlations may be taken to imply that soil properties are influenced by comparable climatic and biotic factors that are likely to affect the accumulation of nutrients in the soil, while the weak correlations suggest that the soil properties are not influenced by comparable climatic and biotic factors.

Due to the dynamic interactions between environmental elements such as the climate, parent material, terrain, land cover, and land usage as well as the quality of irrigation water, soil physical and chemical qualities vary.

According to the soil quality grades (Figure 9), the soil quality was divided into five groups. The predominant grade (representing 70% of the region) was high quality (Q1 and Q2). Soil quality grades have a strong association with water quality ratings (r = 0.96). This showed that any of the soil and water parameters may be used to gauge the study area’s irrigation water and soil quality. These results on soil quality are in line with other studies [101,102]. Overall, all of the indicators for irrigation water quality had essentially identical patterns of soil quality spatial distribution, which is in line with the results of the studies [16,103]. Additionally, this demonstrated that soil type (sand fraction) has an impact on both good soil quality, which is found in the southeastern part, and most of the center of the study area, as well as poor soil quality, which is found in the northwestern part and some parts of the center. Additionally, due to being categorized as low or very low quality, the remaining 30% had high to severe limits, needing proper management techniques.

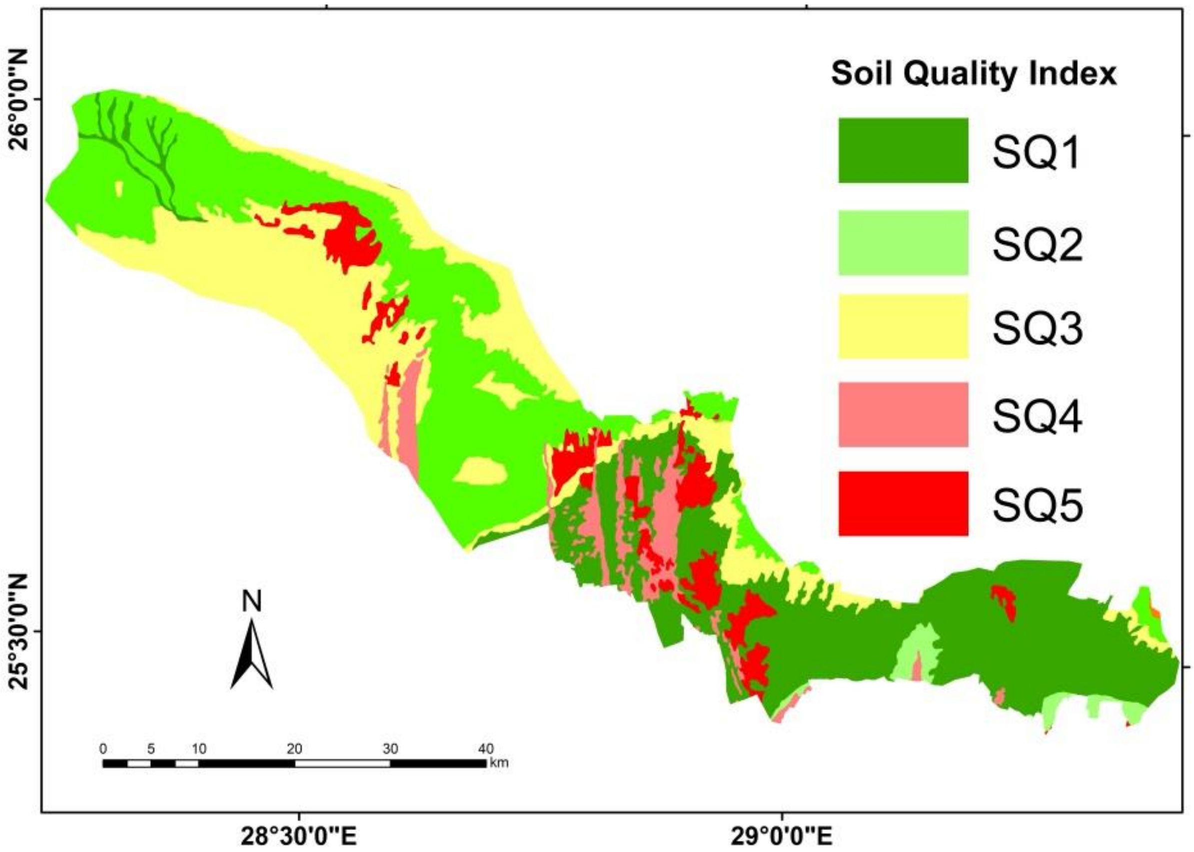


Figure 9. Soil quality categories of the study area.

4.1.3. Water Quality Modeling for Irrigation

The proportion and quantity of groundwater wells appropriate for farming use, depending on the aforementioned factors, are shown in Table 5. All groundwater wells in the study area (100%) have TDS of less than 2000 mg L^{-1}, making them appropriate for irrigation for all types of soil and crops. Measured SAR and RSC values make them suitable for irrigation as well. TH, KR, MH, pH, and Na% values showed that approximately 59.5%, 98.6%, 46%, 44.6%, and 43.2%, respectively, of the study area, are suitable, and 40.5%, 1.4%, 54%, 17.6%, and 56.8%, respectively, are unsuitable for irrigation and cause harmful effects on different soil types and toxic to some types of crops. Figure 10 depicts the regional distribution of their irrigated agriculture suitability inside the El-Dakhla Oasis.

Ten water quality specifications for watering (pH, EC, TDS, SAR, Na%, RSC, KR, MH, TH, and land use parameters) were utilized to evaluate and map the farming appropriateness of groundwater by a water quality spatial model (WQSM) (Figure 11). Each parameter is assigned a weight in light of its relative relevance for farming (Na% is given a weight of 5, KR and MH are given a weight of 4, RSC and SAR are given a weight of 3, pH, TDS, EC, and TH are given a weight of 2, and land use parameters are given a weight of 1 (Table 6). The last irrigation-suitable groundwater map for the research region (Figure 12) shows that it is divided into three categories: excellent and good for irrigation of all types of crops and soils in most areas of the oasis, and poor for irrigation in very small areas in the north part of the oasis and it can be used to irrigate certain types of crops.

Table 5. Physicochemical data of irrigation groundwater samples based on various parameters.

Parameter	Water Class	Threshold	No. of Samples	Groundwater Samples %
SAR (epm)	Low sodic hazard	0–10	74	100%
	Medium sodic hazard	10–18	———	———
	High sodic hazard	18–26	———	———
	Very high sodic hazard	>26	———	———
RSC (epm)	Good	<1.25	74	100%
	Doubtful	1.25–2.5	———	———
	Unsuitable	>2.5	———	———
TH	Soft	<75	44	59.5%
	Moderately hard	75–150	30	40.5%
	Hard	150–300	———	———
	Very hard	>300	———	———
KR (epm)	Good quality water	<1	73	98.6%
	Unsuitable water	>1	1	1.4%
MH (epm)	Suitable	<50	34	46%
	Unsuitable	>50	40	54%
TDS (mg/L)	Best quality water	200–500	74	100%
	Water involving a hazard	1000–2000	———	———
	Water can be used for irrigation only with leaching and perfect drainage	3000–7000	———	———
EC	Excellent	<250	50	67.6%
	Good	250–750	22	29.7%
	Permissible	750–2000	2	2.7%
	Doubtful	2000–3000	———	———
	Unsuitable	>3000	———	———
pH	Excellent	7–8	33	44.6%
	Good	6.5–7	28	37.8%
	Unsuitable	<6.5	13	17.6%
Na% (epm)	Excellent	<20	52	70.3%
	Good	20–40	20	27%
	Permissible	40–60	———	———
	Doubtful	60–80%	1	1.4%
	Unsuitable	>80%	1	1.4%

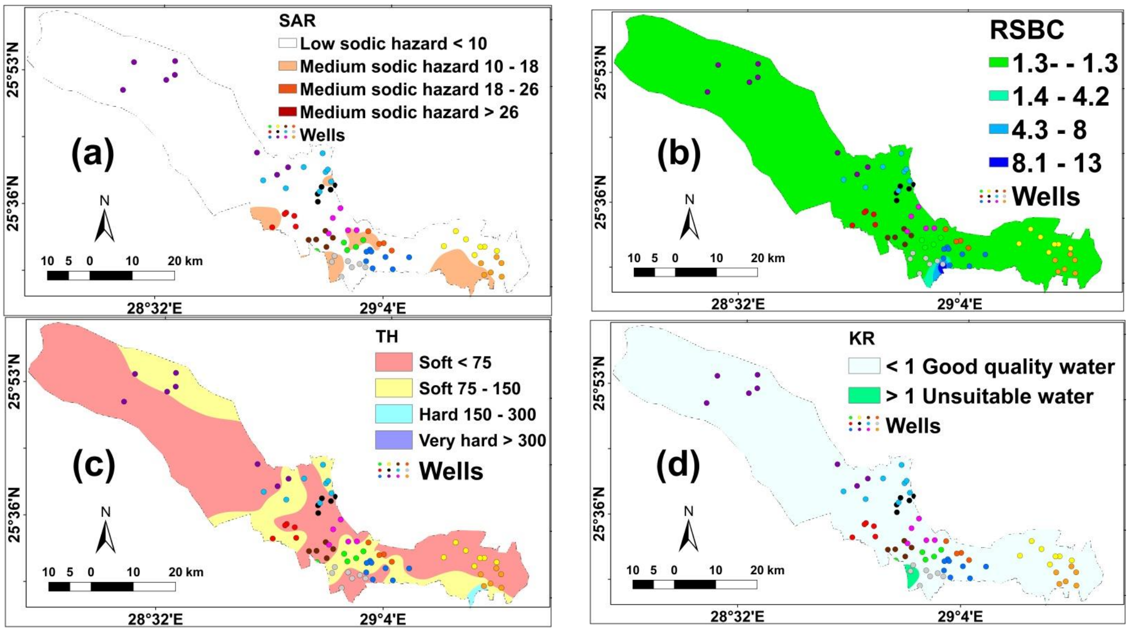


Figure 10. *Cont.*

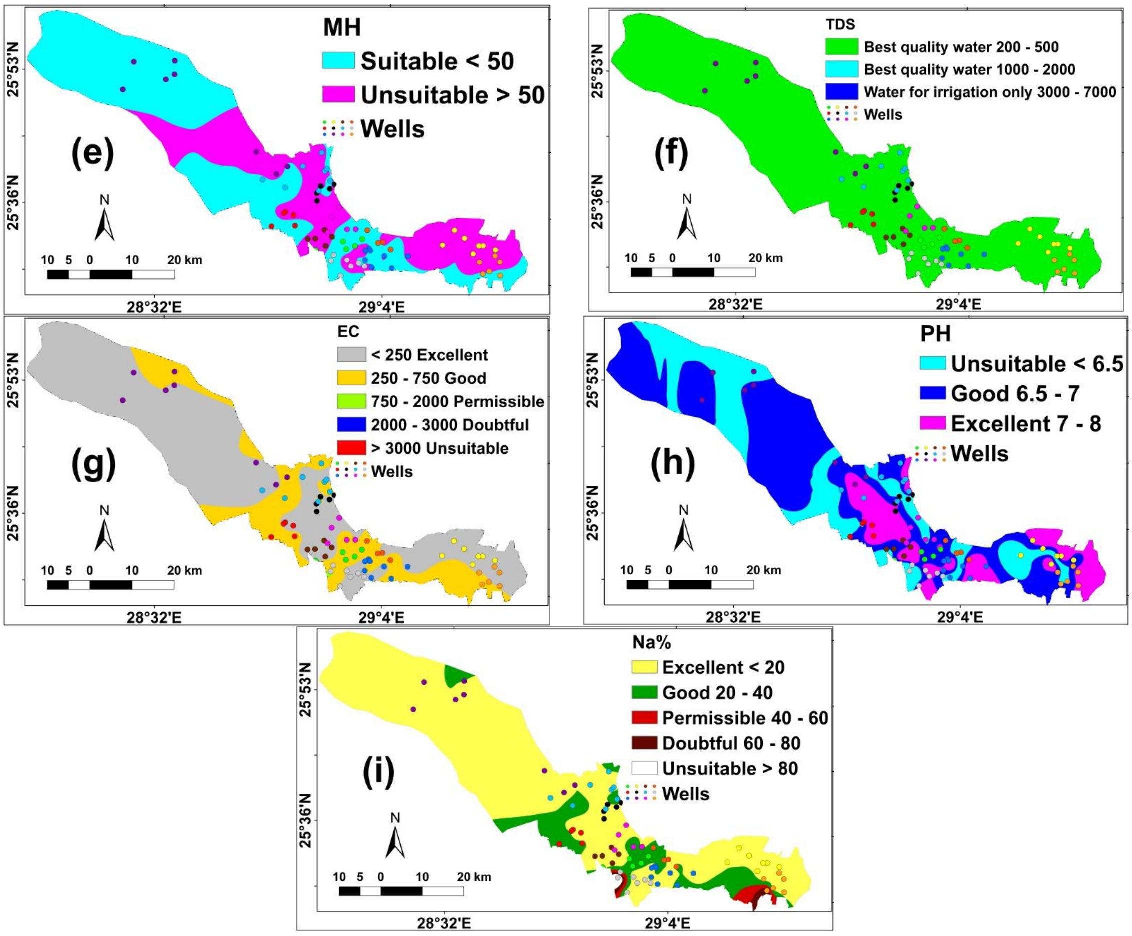


Figure 10. Spatial distribution of groundwater suitability for irrigation. (**a**); SAR, (**b**); RSC, (**c**); TH, (**d**); KR, (**e**); MH, (**f**); TDS, (**g**); EC, (**h**); pH, and (**i**); Na%.

Table 6. The rating scores and relative weights of the factors and sub-criteria used for irrigation assessment.

Factor	Weight	Sub-Criteria	Rating	Weight (Rank—Layer No.) +1	Normalized Weight = Weight/Sum * 100
Land Use	0.37	Agriculture	1	13	10
		Urban	1	13	9
		Water	1	13	9
		Roads	1	13	9
Groundwater quality indices for irrigation	0.32	TDS	2	12	8
		EC	2	12	8
		pH	2	12	8
		TH	2	12	8
	0.14	RSC	3	11	7
		SAR	3	11	7
	0.12	KR	4	10	6
		MH	4	10	6
	0.05	Na%	5	9	5
Sum	1			151	100

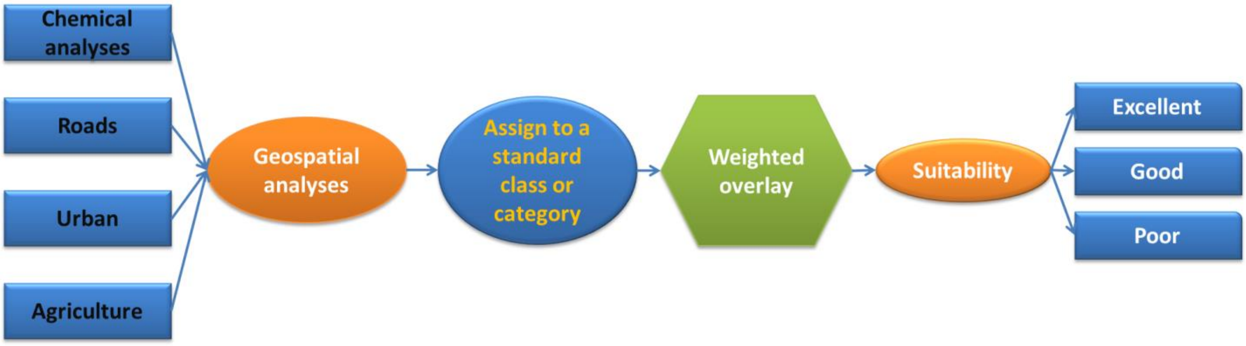


Figure 11. Flow chart of a water quality spatial model for irrigation purposes.

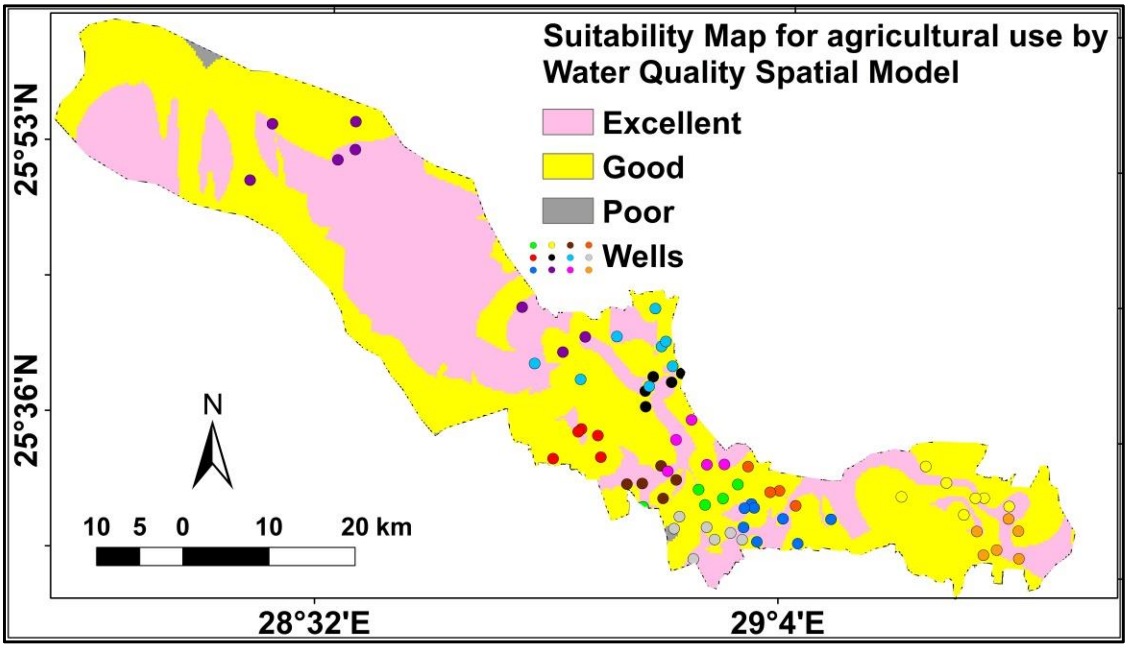


Figure 12. Suitability map for agricultural use by a water quality spatial model.

5. Conclusions and Recommendations

EL-Dakhla Oasis in Egypt is a Western Desert oasis and a pioneering region because of its unique geographical position and groundwater supply. Groundwater is a crucial resource of drinkable water and agriculture in the studied region. From the LULC map, we can observe that agricultural activities in EL-Dakhla Oasis have a significant influence on groundwater quality. At the same time, anthropogenic activities had little impact despite the extensive spread of urban and agricultural areas. As a result, it was necessary to analyze and map the existing groundwater resources to assist urbanization and land reclamation activities. Based on TDS, SAR, and RSC the hydrochemical analysis found that groundwater samples are acceptable for irrigation. Furthermore, most water samples are appropriate for irrigation based on TH, KR, MH, pH, and Na%. According to the drinking water standards, 40.5, 2.7, 1.4, 3.8, 1.6, 86.5, and 100% of groundwater samples had concentrations higher than the desired drinking water quality levels for TH, EC, TDS, Ca^{2+}, Mg^{2+}, Mn^{2+}, and Fe^{2+}, respectively. As a result, it is suggested to treat water to reduce health concerns. The water quality spatial model (WQSM) of groundwater resources in the study area revealed to what extent the resource has deteriorated and which areas are more suited, tying these findings to current land uses and future development strategies. Due to iron levels in all of the wells analyzed surpassing 0.3 ppm, this study recommends adopting a physical treatment approach to remove iron. Furthermore, the current study strongly suggests that the findings be taken into account when developing EL-Dakhla Oasis and nearby areas. Additionally, it is advised that the adopted methodology be used for groundwater suitability evaluations in similar localities.

The soil sample demonstrates the low levels of N, P, and K as well as the comparatively high alkaline nature. For most soils, the EC values fell within a moderate range. In the majority of the sample soils, the excess of micronutrients is within a medium range. Therefore, it is advised to apply more fertilizer and manure to the soil in areas where it is N, P, and K deficient in order to enhance its physical and chemical qualities, make it ideal for plantations, and promote plant development and yield production. For sustainable land use planning, the employment of appropriate agricultural management techniques, and the formation of new communities, particularly in dry terrain to accommodate population increase, a detailed assessment of soil and irrigation water characteristics is necessary. Therefore, the employed quantitative indices might be determined by monitoring temporal changes in both qualities in arid lands in response to management strategies and environmental threats.

Author Contributions: Conceptualization, H.A.M. and M.H.D.; methodology, H.A.M., M.A.E.A., M.H.D., P.D. and A.S.; software, H.A.M., H.M.G., M.A.E.A. and M.H.D.; validation, H.A.M., H.M.G., M.A.E.A., M.H.D., P.D. and A.S.; formal analysis, H.A.M., H.M.G. and M.A.E.A.; investigation, H.A.M., M.A.E.A. and M.H.D.; resources, H.A.M., M.A.E.A. and M.H.D.; data curation, H.A.M., M.A.E.A., M.H.D. and A.S.; writing—original draft preparation, H.A.M., M.H.D. and A.S.; writing—review and editing, H.A.M., M.A.E.A., M.H.D., P.D. and A.S.; visualization, H.A.M., M.A.E.A., M.H.D., P.D. and A.S.; supervision, H.A.M. and M.H.D.; project administration, H.A.M., M.A.E.A., M.H.D. and P.D.; funding acquisition, H.A.M., M.A.E.A., M.H.D., P.D. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This manuscript represents participation between the scientific institutions of two countries (Egypt and Italy) In particular, the authors are grateful for support in carrying out this work from: (1) the National Authority for Remote Sensing and Space Sciences (NARSS), Cairo 11769, Egypt; (2) the National Research Centre, Giza 12622, Egypt; (3) SAFE-Università Degli Studi della Basilicata, and Regione Basilicata; (4) New Valley University, El-Kharga 72511, Egypt.

Conflicts of Interest: The authors would like to hereby certify that no conflict of interest in the data collection, analyses, and interpretation in the writing of the manuscript, and in the decision to publish the results. The authors would like also to declare that the funding of the study has been supported by the authors' institutions.

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