Groundwater vulnerability risk assessment in south Darb El Arbaein, south Western Desert

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Abstract

Groundwater resources in the south Darb El Arbaein are currently threatened by agricultural impact and rock water interaction associated with over exploitation. Planning of Nubian sandstone aquifer is required, especially in this new invest area. It is implemented by GIS to establish vulnerability areas and to evaluate protocol plans for hydrogeological parameters and soil. The TDS concentration ranged from 750 to 1350 ppm, confirms the impact of non-point source (agricultural activity). It is because recharging Nile water has TDS concentration of 100–300 ppm. Aquifer vulnerability delineation areas by lithogenic and anthropogenic sources have been recently highlighted for water resources systems planning and management. The correlation among hydrogeological, geological, and hydrogeochemical characteristics was discussed and achieved. Ten stratified beds were matched by GIS with specified average weights to them according to their relative importance for groundwater vulnerability. The chosen layers are TDS, aquitard thickness, water depth, hydraulic conductivity, transmissivity, slope, total hardness (TH), sodium adsorption ratio (SAR), discharge rate (Q), and screen length. The groundwater impact distribution reflect five categories ranged from no to excellent aquifer potential levels. Class I (very low vulnerability) was in the northern part and contains 11.1% (16.02 km²) of the area. While very high vulnerability (class V) was in southeast, east, it represents 10.4% (14.96 km²). The preferred invested area was northeast rather than other areas; otherwise, the groundwater degradation enhanced. The vegetation/ or barren lands were established by band 4/band 3, band 3/band 4 ratios and composite RGB 7, 4, and 1 satellite images.

Keywords Hydrogeology · Groundwater vulnerability · GIS-RS · South Darb El Arbaein · south Western Desert

Introduction

Determining the pollution influences by infiltration into the aquifer represents the vulnerability establishing. It represents the enhancement sources for aquifer contamination and predicts the aquifer management plan (Prasad and Shukla 2014). Margat (1968) firstly determined the aquifer impact by anthropogenic sources. Rapid urbanization, biological, organic–inorganic pollutants, land application, agricultural, and industrial facility impact on groundwater quality and quantity. Therefore, protection strategies should be taken to manage and control the groundwater.

U.S. Environmental Protection Agency (EPA) established DRASTIC techniques in 1987 in order to capture aquifer contamination rate in the USA (Aller et al. 1987). DRASTIC abbreviated as (D): water depth, (R) net recharge, (A) aquifer media, (S) soil media, (T) topography, (I) impact of the vadose zone, and (C) hydraulic conductivity of the aquifer. DRASTIC match previous parameters to evaluate the aquifer contamination rate (Sahu and Nandi 2015) and define aquifer vulnerability (Knox et al. 1993; Kimand and Hamm 1999; Adamat et al. 2003; Hamza et al. 2007; Leone et al. 2009).

In Drastic modeling, GIS (Nasri et al. 2015), remote sensing (Yeh et al. 2006) and statistical techniques (Burkart et al. 1999; Fred et al. 2002), hydrogeochemistry (Mondal et al. 2017), and fuzzy mathematical method (Zhou et al. 2010) were used to investigate aquifer impact. GIS integrate many information layers into a single one with geo-referencing and spatial analysis. The development in Darb-El-Arbaein was determined by GARPAD (General Authority for Rehabilitation Projects and Agricultural Development) in 1997

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(Fig. 1). Darb-El-Arbaein located in between Egypt and Sudan through Kharga Oasis to Assiut. It is the old line for camel walking from Darfur to Assiut. The groundwater is the only water resources for domestic and irrigation uses; therefore, the aquifer potentiality and vulnerability was the point of interest. About 12,000 feddans were reclaimed and used to construct sixteen buildings for worker housing about 400 km from Paris village toward southern border. The bore-hole discharges are in three areas, the northern, the middle, and the southern part of Darb El-Arbaein. The study area (southern part) represent area about 170 km² (Fig. 1). The area of investigation was high aridity (48.6 °C in May and −2 °C in February). The precipitation was lower than 1.1 mm/y with mean of 0.3 mm/month. The evaporation was 172 mm/y.

Geomorphology and geologic setting

Issawi (1971) subdivided the Darb El Arbaein into three zones, the southern Naklai-Sheb peneplain, western Atmur peneplain and plateau. From the geologic point of view, CONOCO map (1989) showed that the exposed rocks ranged from Pre-Cambrian and Quaternary deposits. The stratigraphic setup composed of seven beds, from base to

top, Pre-Cambrian basement, Paleozoic–Mesozoic sandstone, Lower Cretaceous, Upper Cretaceous, Paleocene, Eocene, and Quaternary (Table 1) (CONOCO 1989; Fathy et al. 2001; Korany et al. 2002). The Upper Cretaceous overlain the Pre-Cambrian sediments in southern part of Darb El Arbaein (Table 2). The Darb El Arbaein is related structurally to the Red Sea (EGSMA 1987a, 1987b). The up arching of basement sediments established (Fathy et al. 2002).

Hydrogeology

Eighty wells were drilled in Darb El Arbaein with depths ranging from 130 to 530 m, in 1998 to 2001. The drilling was done in the successive Nubian sandstone (Paleozoic–Upper Cretaceous). Geological sections show the presence of 18 faults (Fig. 2) (Fathy et al. 2002). The amount of feeding for the aquifer in the Western Desert is about 1.5 billion m³ (Ambroggi 1966). The rate of groundwater migration from Libya to Egypt is about 3.782 million m³/y (Ezzat and Abu-Atta 1974). The C₁₄ and H₃ isotope studies showed that the life of groundwater is about 1000 BC or earlier (German Water Group 1977). The Nubian aquifer is fossil water (20,000–40,000 y) (Shata et al. 1962; Shata 1982). The Taref Fm. overlain by Kiseiba Fm. (Table 2),

Fig. 1 Base map of the southern Darb El Arbaein

Table 1 Modified stratigraphic column of Darb El Arbaein (Aggour et al. 2009 and Barseem 2016)

		Age	Rock units
Quaternary		Pleistocene	Lake and playa deposits fluvial and alluvial deposits
Tertiary		Eocene	Thebes Fm
		Paleocene	Gara Fm
			Esna Fm
			Tarawan Fm
Cretaceous	Upper Cretaceous		Kurkur Fm
		Maestrichtian-Paleocene	Dakhla Fm
		Campanian-Maestrichtian	Kiseiba Fm
		Campanian	Duwi Fm
		Turonian-Santonian	Taref Fm
		Cenomanian	Maghrabi Fm
	Lower Cretaceous	Albian	Sabaya Fm
		Aptian	Abu Ballas Fm
		Pre-Aptian	Six Hills Fm
Paleozoic–Mesozoic sandstone layers			
Pre-Cambrian	Pre-Cambrian basement complex (basement)		

Table 2 Stratigraphic setup in southern Darb El Arbaein (GARPAD et al. 2000)

Age		Formation	Member	Thickness, m
Upper Cretaceous	Campanian-Maestrichtian	Kiseiba	El Shab	44–150
			Saghir	
	Turonian-Santonian	Taref		56–80
Pre-Cambrian	Ash basement			Base not reached

both represent the Nubian aquifer. The top part of Kiseiba Fm. act as aquitard. The aquifer thickness increases in the southwestern and northeastern part (Fig. 3a, b). The lithology consists of coarse-grained sandstone at the bottom that finning upward. It conformably overlies the basement. The Taref Formation (168 m thick) consists of medium to very coarse-grained sandstone with claystone intercalations. The Kiseiba Formation covers most of the surface of Bir El-Shab area. The lower portion of this Formation is called Shagir member, while El-Shab member represents its upper portion (Hendriks et al. 1984). The Kiseiba Formation thickness reaches 144 m at type locality. It overlies directly Precambrian basement rocks in Bir Kiseiba area and the Taref Formation in Bir El-Shab area (Ghoubashi 2004). The water depth is generally very shallow before pumping (Fig. 4a), which contributed the increase in TDS concentration by evaporation process. After pumping (Fig. 4b), the water depth is much increased, due to low recharge rate. The maximum water depth difference was in the northeast and southeast (Fig. 5a). The latter areas represent the two recharge zones (Fig. 5b), which contributed to groundwater flow into two piezometric lows. The groundwater flow was in the northwestern and central zones (two piezometric lows)

(Fig. 5b). Hydraulic conductivity and transmissivity increase due to southeastern and southwestern part (9–11 m/d and 1277–1491 m²/d), while hydraulic conductivity decreases in the central—northern part (2.4–6 m/d and 416–749 m²/d and increases again due northwestern part (9–11 m/d), whereas transmissivity declines due the northwestern part (416–749 m²/d) (See Figs. 12b and 13a). The decline in transmissivity was attributed to increase in clay concentration (Fathy et al. 2002). The storage coefficient varied from 2.2×10^{-4} to 3.22×10^{-4} , reflect the confined conditions. The formation loss ranged from 2.36×10^{-3} to 2.51×10^{-3} d/m², while well loss varied from 0.93×10^{-7} to 1.45×10^{-7} d/m⁵ (Fig. 6a, b). The formation loss decreases due southeastern and northwestern part, more or less coincide with the increases in fines in Nubian aquifer that decline the permeability. The well efficiency at discharge of 150 m³/h varied from 84 to 86% (Fig. 7). Generally, the borehole efficiency is excellent (> 71%), which all are satisfactory for the borehole design application. The losses of wells and formation contributed to drawdowns in boreholes. The estimation equation was:

$S_w = BQ + CQ^2$ (Jacob 1946 and Bierschenk 1964)
 S_w (drawdown in borehole, m), Q (abstract rate, m³/d),
 BQ (loss of formation, i.e., drawdown reflect aquifer

Fig. 2 Geological cross section (modified after Abdel El Rahman 2003)

hydraulic conductivity, m), and CQ^2 (loss borehole, i.e., drawdown represent hydraulic resistance of borehole screen/ face, m). The formation loss relies on geological and hydrogeological conditions, whereas borehole

loss based on borehole design and installation such as gravel packing; pipelines screen-casing; screen slotted with respect to slot shape, concentration, number, and size; development; and well depth. If the discharge rate

Fig. 3 Kiseiba (a) and Taref (b) formation thicknesses

increases twice result in decline in borehole efficiency about four times (Jacob 1946).

$$S_w/Q = B + CQ$$

The formation loss coefficient (B) is much higher than well loss coefficient (C) (Fig. 6a, b), reflect a good borehole design and this reflects the excellent well efficiency for all boreholes (> 71%). The hydraulic conductivity is generally not high (< 12 m/d) by the alternation of sandstone, clay,

and shale. The elevation ranged from 132 to 213 m (Fig. 8a, b). The maximum drawdowns was due northeast and south-east, match with maximum formation losses (Fig. 9). The drawdown is mainly attributed to formation loss rather than well loss.

Fig. 4 Water depths before (a) and after (b) pumping

Methodology

Borehole sites (Fig. 1) digitized by ArcGIS 10.3 package. ArcGIS 10.3 spatial analyst has determined spatial distribution layer for each parameter (TDS, aquitard thickness, water depth, hydraulic conductivity, transmissivity, slope, total hardness (TH), sodium adsorption ratio (SAR), discharge rate (Q), and screen thickness). The "Kriging" techniques were used for areal distribution values. Define the most effective parameters to estimate weights in GIS

and multi-criteria decision. Aquifer vulnerability distribution of Nubian sandstone aquifer was constructed. A full flowchart of the techniques was in Fig. 10. The geological, hydrogeological, and hydrogeochemical parameters of the aquifer were collected and distributed by the kriging method. The impact of anthropogenic sources (agriculture), especially in this new investment area, could be evaluated. The hydrogeological and hydrogeochemical interpretation was done by the author. The DRASTIC method was overlay and index category in case of aquifer

Fig. 5 Water depths differences (a) and flow net (b)

grains (USEPA 1993; Aller et al. 1987). The current dissertation represents a new approach to evaluate groundwater vulnerability by preparation of weighted spatial multi-criteria decision. Thematic maps (ten parameters mentioned previously) were prepared using ArcGIS 10.3. Attribute values are assigned for each and every theme according to classification. Thematic maps reclassified and converted to rasters with common weight scale of 1–5. The classes were assigned for theme based on aquifer vulnerability from very high to very low vulnerability

(Table 3). The area and percentage of the parameters for each class is determined in Table 3. The output raster maps were integrated with weighted overlay analysis. The result of overlay analysis (vulnerability map) has been classified into five classes, which ranged from very low to very high aquifer vulnerability. The hydrogeochemical parameters used are total dissolved solids (TDS), total hardness (TH), and sodium adsorption ratio (SAR), while the hydrogeological parameters are aquitard thickness, water depth, hydraulic conductivity, transmissivity, slope,

Fig. 6 Formation (a) and well (b) losses

discharge rate (Q), and screen thickness (L). Spatial investigation produces the hydrogeological and hydrogeochemical parameters distribution rasters. It defines the best and worst place for the existence of groundwater in order to give the correct decision to the officials and to maintain the management and non-pollution of the groundwater and not drain it. The digital elevation model (DEM) and Landsat_5 (path/176 and row/045) were acquired from Image courtesy of the U.S. Geological Survey. LANDSAT_SCENE_ID was "LT51760452000036AAA02". The

image contains seven bands and no cloud cover (0.00). The available imagery corrected for wavelengths, quick atmospheric, UTM projection WSG84, and contrast stretching.

Fig. 7 Well efficiency of the aquifer

Results and discussion

Vulnerability parameters

TDS, aquitard thickness, water depth

Groundwater salinization is a conspicuous aspect of deterioration in groundwater quality, especially in this new invest area. The River Nile recharge the aquifer by original TDS concentration of 100–300 ppm, which degraded by lithogenic and anthropogenic sources. The TDS concentration increased because southeastern part (Fig. 11a) coincides with low thickness of capping shale (aquitard) (Fig. 11b). It is caused partially by anthropogenic infiltration enhanced by low capping thickness. The TDS concentration decreased with groundwater flow (two piezometric lows) (Fig. 5b). Therefore, the hydrogeology (groundwater flow, Fig. 5b) does not consistent with hydrogeochemistry (TDS content, Fig. 11a). It is attributed to upward vertical increase in hydraulic conductivity, which enhance the upward of deep fresh groundwater flow due to northeastern part, in addition to concealed faults, which concentrated in northeastern part. They facilitate the upward and downward flow of deep fresh groundwater and rainfall, respectively. It led to groundwater dilution in the northeastern part. TDS takes five classes 1 (lowest vulnerability) to 5 (highest vulnerability). The low to very TDS vulnerability represents about 33% of the study area, while high to very high vulnerability constitutes 37% of the area under investigation. (Table 3). The soil textures effect on the infiltrated

water (Babikeretal 2005). Less aquitard thickness makes groundwater more vulnerable, while high thickness accompanied by less groundwater vulnerability. The aquitard thickness ranges from low (high vulnerable) to high (low vulnerable) (Fig. 11b). The aquitard thickness low to very low vulnerability includes about 21% of the study area, whereas the high to very high vulnerability represents about 45% of the study area (Table 3). The pollutant dispersion into aquifer depends on water depth (Thirumalaivasan et al. 2003; Brady and Weil 2002). The pollution rate increases in shallower aquifer rather than deeper. The water depth classified into five categories, which ranged from shallow (high pollution rate) to deep (low contamination risk) (Fig. 12a). The water depth high to very high vulnerability showed 34% of the study area, while low to very low vulnerability represents about 40% (Table 3).

Hydraulic conductivity and transmissivity

They increases due southeastern and southwestern part (Figs. 12b and 13a), it is attributed to aquifer thickness increase in these directions. They reflect the contaminants flow into the porous media of the aquifer system. The maximum hydraulic conductivity and transmissivity indicate the highest vulnerability rate. The hydraulic conductivity and transmissivity low to very low vulnerability constitute about 30 and 40% of the study area, respectively (Table 3).

Fig. 8 Elevation (a) and hillshade (b) **Slope, total hardness (TH), sodium adsorption ratio (SAR)**

Earth's surface heights affect the Earth's inclination. The slope rate determines how fast the surface water include dissolved pollutants move. Pollutants in surface water migrate on the earth, leach into groundwater, or settle on the ground. Surface water from agricultural drainage is carried out on different inclinations where the lowest slope is more leaching of pollutants into groundwater (much vulnerable). The slope was estimated from the DEM data and ranged from 0

to 15 degrees (Fig. 13b) with the highest vulnerability grade (5) corresponding to gentle slopes. The total hardness (TH) ranged from 260 to 420 as CaCO_3 with five grades 1 (low TH) to 5 (high TH and max. vulnerability) (Fig. 14a). TH is mainly contributed by both Ca and Mg ions from anthropogenic and lithogenic sources. Total dissolved solids (TDS) and Na + K/Ca + Mg ratio determine the water quality levels (Ayers and Westcot 1985). SAR ranged from 4 (northwest and southwest) to 7.5 (northeast and southeast) (Fig. 14b). It grades into five classes 1 to 5 of maximum SAR and highest

Fig. 9 Drawdown of the aquifer

Fig. 10 Flowchart of model methodology

Table 3 Contribution parameters for aquifer vulnerability distribution

Thematic layer	Map weight (wt.)	Class ranges	Degree	Rank	Capability value (CV.)	Area (km ²)	Area (%)
1– TDS, ppm	20% (0.2)	736–923	Very low	1	0.07	13.59	9.38
		924–1019		2	0.13	34.50	23.81
		1020–1117	Very high	3	0.20	41.41	28.58
		1118–1213		4	0.27	44.59	30.77
		1214–1318		5	0.33	10.81	7.46
2– Aquitard thickness, m	15% (0.15)	30–40.6	Very high	5	0.33	22.79	15.73
		40.7–46.4		4	0.27	42.28	29.18
		46.5–51.1	Very low	3	0.20	48.76	33.65
		51.2–56		2	0.13	21.05	14.53
		56.1–63		1	0.07	10.01	6.91
3– water depth, m	10% (0.1)	12.6–16.9	Very high	5	0.33	18.84	13.01
		17–19.2		4	0.27	30.43	21.00
		19.3–21.9	Very low	3	0.20	37.40	25.81
		22–24.5		2	0.13	28.60	19.74
		24.6–29.5		1	0.07	29.61	20.44
4– Hydraulic conductivity, m/d	10% (0.1)	2.4–6	Very low	1	0.07	5.60	3.87
		6.1–7.1		2	0.13	37.71	26.03
		7.2–8	Very high	3	0.20	32.12	22.17
		8.1–9		4	0.27	52.73	36.40
		9.1–11		5	0.33	16.71	11.53
5– Transmissivity, m ² /d	10% (0.1)	416–749	Very low	1	0.07	24.60	16.98
		750–935		2	0.13	35.17	24.27
		936–1116	Very high	3	0.20	30.85	21.29
		1117–1276		4	0.27	42.92	29.62
		1277–1491		5	0.33	11.37	7.84
6– Slope, degree	10% (0.1)	0–0.7	Very high	5	0.33	0.327	0.22
		0.8–1.7		4	0.27	2.019	1.34
		1.8–3.6	Very low	3	0.20	10.431	6.93
		3.7–7.3		2	0.13	59.867	39.78
		7.4–14.6		1	0.07	77.845	51.73
7– Total hardness (CaCO ₃)	5% (0.05)	260–301	Very low	1	0.07	11.42	10.14
		302–323		2	0.13	33.37	29.62
		324–343	Very high	3	0.20	34.66	30.77
		344–360		4	0.27	33.21	29.48
		361–420		5	0.33	32.23	28.61
8– Sodium adsorption ratio (SAR)	5% (0.05)	4.1–5	Very low	1	0.07	16.58	11.44
		5.1–5.4		2	0.13	39.67	27.38
		5.5–5.8	Very high	3	0.20	37.98	26.21
		5.9–6.4		4	0.27	39.52	27.28
		6.5–7.3		5	0.33	11.13	7.68
9– Pumping rate, m ³ /h	10% (0.1)	60–122	Very low	1	0.07	2.53	1.75
		123–167		2	0.13	4.01	2.76
		168–199	Very high	3	0.20	17.03	11.75
		200–212		4	0.27	33.11	22.84
		213–220		5	0.33	88.28	60.90

Table 3 (continued)

Thematic layer	Map weight (wt.)	Class ranges	Degree	Rank	Capability value (CV.)	Area (km ²)	Area (%)
10– Screen length, m	5% (0.05)	42–71	Very low	1	0.07	4.28	2.95
		72–88		2	0.13	36.59	25.26
		89–100		3	0.20	32.25	22.26
		101–123		4	0.27	70.48	48.64
		124–172	Very high	5	0.33	1.29	0.89

Fig. 11 TDS (a) and aquitard thickness (b) reclassify

Fig. 12 Water depth (a) and hydraulic conductivity (b) reclassify

vulnerability. The slope, TH, and SAR low to very low vulnerability represents about 91, 39, and 38% of the study area, respectively (Table 3), while high to very high vulnerability indicates about 1.5, 58, and 35% of the investigation area, respectively (Table 3).

Discharge rate (Q) and screen thickness

Agricultural drainage depends on the amount of water extracted from the non-renewable aquifer (current case)

in the dry areas, and this increases the salinity of the aquifer. The Q increases due south and east (Fig. 15a) to reach 220 m³/h. The maximum discharge area coincides with the highest potentiometric surface, reflects upward flow of deep fresh groundwater. The screen length ranged from 42 to 172 m (Fig. 15b), with maximum vulnerability in highest lengths. The Q and screen length low to very low vulnerability constitutes 4 and 28%, respectively (Table 3), while high to very high vulnerability indicates about 38 and 49% of the investigation area, respectively (Table 3).

Fig. 13 Transmissivity (a) and slope (b) reclassify

The vulnerability map

The aquifer vulnerability map was extracted from different geological, hydrogeological, and hydrogeochemical thematic maps, and it is very important for aquifer management, recharge, and protection. Each parameter map was given the weights, which is based on the contribution for groundwater pollution (Table 3). These thematic maps were integrated by GIS model to predict the promising map (aquifer vulnerability). The rank of each class was divided by the total

summation values of the layer classes to calculate the capability values (CV.) (Table 3). These capability values (CV.) are multiplied by the respective probability layer weight in each thematic layer to calculate the groundwater vulnerability map (Fig. 12). The latter was mathematically calculated using ARC GIS raster calculator analysis as follows:

$$GWV = \sum Wt. * CV$$

Fig. 14 Total hardness (a) and SAR (b) reclassify

GWV is groundwater vulnerability, Wt is map weight, and CV is capability value.

$GWV = \sum TDS, \text{ aquitard thickness, water depth, hydraulic conductivity, transmissivity, slope, total hardness (TH), sodium adsorption ratio (SAR), discharge rate (Q), and screen thickness.}$

The TDS parameter has the highest contribution in aquifer salinization. The River Nile (TDS < 200 ppm) recharge the groundwater; TDS concentration of the aquifer degraded with time to reach the current contents (Fig. 11a). The

discharge rate influences indirectly the vulnerability evaluation, by overpumping, result in agricultural wastewater leakage and much more rock (soil) water interaction. Five units indicate aquifer vulnerability rate (Fig. 16). Class I (low vulnerability) was in the northwestern part while the high vulnerability (class V) was in the southeast and east (Fig. 16). The output groundwater degradation (vulnerability) map covers area 52.18 km², represents 36.12% for low to very low vulnerability level (Table 4). The moderate, high, and very high vulnerability levels are 18.95, 34.58, and 10.34%,

Fig. 15 Pumping rate (a) and screen length (b) reclassify

respectively (Table 4). The latter sum 64% of investigated area is currently degraded with respect to aquifer quality, which needs new watering techniques. Darb El Arbacin represents a new investment area, which should be free from anthropogenic influences now and in future. The application of certain crops (preferred low water consumption), sowing technology, fertilizers (quality and amount), pesticides, and best geological and hydrogeological conditions (hydrogeologist consultant), is specified to maintain and improve the aquifer and crops products. The high vulnerability level

covers 10.35% of the investigated area, it is distinguished by the highest total dissolved solids (TDS 1214–1318 ppm, Fig. 11a). Although the TDS concentration is less than the irrigation guidelines limits, but the TDS concentration of the original groundwater is less than 200 ppm and turned to the current values by pumping and irrigation system. The aim is to reduce the methods led to increase in groundwater and soil salinity over time and take care of this place so that groundwater irrigation is sustainable and efficient. The preferred invested areas located in the northeast rather

Fig. 16 Groundwater vulnerability map **Table 4** Classes of groundwater vulnerability with area enclosed

Vulnerability class	Area (km ²)	Area (%)
Very low	16.02	11.09
Low	36.16	25.03
Moderate	27.37	18.95
High	49.95	34.58
Very high	14.96	10.35

than other areas; otherwise, the groundwater degradation enhanced.

Remote sensing

Ratio transformation of the satellite images can be used to decline the environmental influences. Ratio gives us most important hydrogeological information such as vegetation covers. They establish irrigated feddans area by aquifer water budget. The groundwater availability in dry areas, like south Darb El Arbaein, was accompanied with vast or little vegetation covers. The dense vegetation covers indicate rainfall and aquifer availability. Band ratios help to distinguish between soils and vegetation.

Band 4/band 3

The band 4/ band 3 ratios of the Landsat_5 discriminate among croplands, water, and vegetation, where band 3 is the red band varied from 0.630 to 0.690 μm -wavelength and band 4 is the near-infrared band. The ratio promotes forests

and barren lands, it is because vegetation or forests reflect higher reflectance in near IR region (0.76–0.90 μm) and strong absorption in red region (0.63–0.69 μm). The ratio determines the vegetation covers distribution (Fig. 17a).

Composite bands 7, 4, and 1

The composites give bright green for vegetation as shown in Fig. 17b, which match with vegetation areas constructed by band 4/band 3 Fig. 17b. Most of the drilled wells coincide with high vegetation covers (Fig. 17b).

Band 3/band 4

The ratio determines barren lands and urban area as shown in Fig. 17c.

Summary and conclusions

The multi-criteria establishment by GIS software was proved to construct aquifer vulnerability map for lithogenic and anthropogenic sources. It helps to manage and protect the Nubian sandstone aquifer. The continuous pumping and low aquifer recharge resulted in dropping in potentiometric surfaces and induced the salts into the Nubian sandstone aquifer systems. The hydraulic conductivity of the aquifer not exceeds 11 m/d, which reflect the fine sediments included within the sandstone. The hydrogeological characteristics of the aquifer are low to moderate, it should be accompanied by good management for pumping or otherwise the aquifer

Fig. 17 Band ratios in southern Darb El Arbaein

will degrade. Therefore, the aquifer vulnerability map was very important for the officials. This dissertation prepares this aquifer vulnerability map to match the hydrogeological and hydrogeochemical parameters. The resulting vulnerability map represents sustainable development for this new investment area. Ten stratified beds inputted into GIS model to construct the aquifer vulnerability model. The constructed map ranged from very low to very high in terms of their vulnerability to groundwater degradation. The low to very low vulnerability levels represent 36.12% (52.18 km² area) of the total study area (144.5 km²), they preferred to be best promising areas. Moderate to very high vulnerability levels contain 63.9% (92.3 km²) of the study area. In spite of the highest TDS concentration is lower than 2000 ppm (irrigation guideline), the groundwater originally was lower than 200 ppm (River Nile) and degraded with time. The continuous increase in TDS concentration and piezometric drop causes soil and groundwater deterioration.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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