



Effects of groundwater over-pumping on the sustainability of the Nubian Sandstone Aquifer in East-Oweinat Area, Egypt

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ABSTRACT

East-Oweinat area relies on groundwater as the main source for agricultural and domestic purposes. As the abstraction continues to increase at an alarming rate, groundwater is constantly being depleted. The present study showed that the water level declines in the last two decades (2000–2018) to reach 2.34 m/year. The resulted thematic maps show that the cultivated areas increased from 4,968 Feddan (1 Feddan = 4200 m²) in year 2000 to 194,549 Feddan in year 2018 where, in the first decade (2000–2009), the total cultivated land was 51,229 Feddan and the groundwater abstraction was 2.5 billion m³ during this period of time, while in the second period (2010–2018), the groundwater abstraction was 12.6 billion m³ and the total cultivated land reached 194,549 Feddan. The groundwater abstraction in the second period (2010–2018) is about five times of the first period (2000–2009). The plant consumption of groundwater in East-Oweinat area for the cultivated area (194,549 Feddan) is 1.89 billion m³/year and the net annual groundwater abstraction from wells is 2.02 billion m³/year. Consequently, the available groundwater in East-Oweinat area can be used for sustain able development for about 174 years under good management of the present situation.

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1. Introduction

East-Oweinat area is one of the most important areas in Egypt for agricultural investments due to its high groundwater potentials and investment facilities provided by the government. Therefore, great comprehensive farms for agriculture production have been well established since the last two decades using groundwater that is the only source of water supply in the study area. The expansion of new cultivated areas and the number of drilled wells are increased year by year.

East-Oweinat area was subjected to many works such as: Nour (1996) stated that the annual rate of groundwater inflow to the East-Oweinat area was estimated to be 120 million m³. Masoud et al. (2013) concluded that the main recharging source of the Nubian sandstone aquifer in East-Oweinat area is the underground inflow reaching the aquifer across the southwestern boundary of the system. El-Alfy (2014) stated that, based on analysis of three different development schemes that were formulated to predict the future response of the aquifer under long-term water stress, a gradual increase in groundwater pumping to 150% of the present levels should be adopted for protection and better management of the aquifer. Ghoubachy and Eissa (2017) concluded that the estimated groundwater quantity of the Nubian sandstone aquifer is 350 billion m³ of fresh water.

The current work aims to study the effects of the groundwater over-pumping on the sustainability of

the Nubian sandstone aquifer in the study area as well as the change detection of the cultivation development through the period (2000–2018). To achieve these objectives the satellite images of the period from 2000–2018 were used to calculate the development of the cultivated areas with time. From the other side, field investigations and measurements of the depth to water and total dissolved solids (TDS) were measured at some representative wells in 2015 and 2018 to find out the changes compared with the previous situation in 2002.

2. Location

East-Oweinat area is located in the southwestern corner of the Western Desert. It is bounded by longitudes 28° 00' 00" E & 29° 18' 56" E and latitudes 22° 7' 39" N & 23° 00' 55" N (Figure 1).

In the study area, climatic conditions had changed over the last 10,000 years from more humid conditions after the last Ice Age to arid conditions during the last 5000 years (Edmunds and Wright 1979; Edmunds 1994; Issar 2003). Under the present climatic conditions, the East-Oweinat area lies within the Great Desert belt in southwest Egypt that is characterised by high temperatures. It is located in a hyper-arid climate zone; where the aridity index is <0.05 (UNEP, 1997). Maximum temperature during

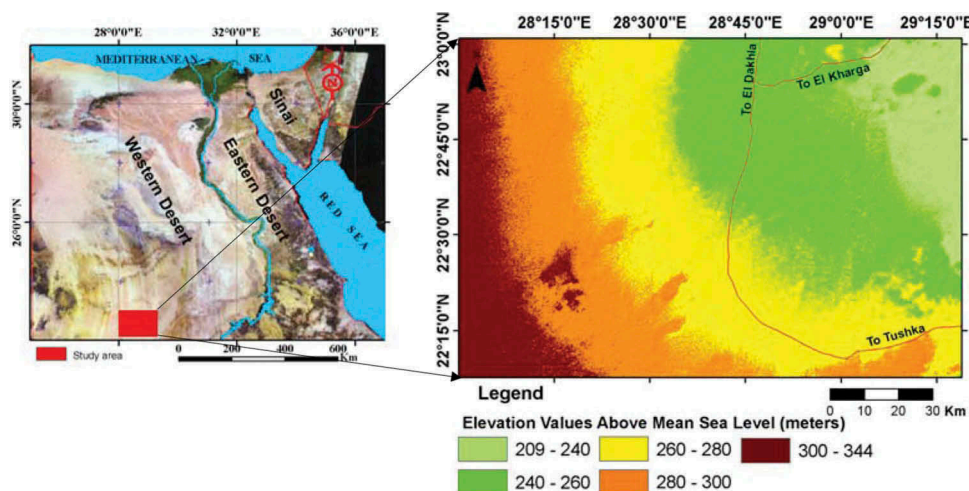


Figure 1. Map showing location and Digital Elevation Model (DEM) of East-Oweinat area.

the summer exceeds 40°C, whereas minimum temperature during the winter may decline close to freezing. Natural evaporation rate ranges between 10 mm/day during January and 31 mm/day during July (Nour 1996).

Based on the Digital Elevation Model (Figure 1) from SRTM data acquired by the National Aeronautics and Space Administration (NASA) and National Imagery and Mapping Agency (NIMA) in February 2000 aboard of the spaceship Endeavour, the ground surface slope in East-Oweinat area is from west to east and from south to north. The ground surface elevations range between 344 m (a.m.s.l) in the southwest and 209 m (a.m.s.l) at the northeast, with the northeasterly surface slope of 0.8 m/km.

3. Geomorphologic, geologic and hydrologic setting

Geomorphologically, in East-Oweinat area, five distinct geomorphic units exist as follows: sand plains, sand dunes, salt marshes, isolated hills (Nubian Sandstone hills) and basement hills (Youssef 1996).

Geologically, the dominance sedimentary succession in East-Oweinat area (Figure 2) is ranging in age from Cretaceous to Quaternary with exposures of igneous and metamorphic rocks belonging to the Precambrian basement rocks (Ghoubachi 2004).

The Upper Jurassic-Lower Cretaceous is represented by the Nubian Sandstone that rests directly on the Precambrian basement rocks and is considered as one rock unit (Six Hills Formation) which occupies the majority of the surface in the study area (El Osta, 2006).

The Nubian Sandstone is unconformably overlain by Quaternary deposits that are composed of aeolian sand dunes and sand sheets, alluvial deposits, playa deposits and inland sabkha (Mansour et al. 1982; Diab 1984; Heintz and Thorweihe 1993; Ebraheem et al. 2003).

From the hydrologic point of view, the Nubian Sandstone is the main exploitable water-bearing formation in the study area and is used for the agricultural and socio-economic development of the whole southern Western Desert of Egypt (CEDARE 2002). Lithological logs of water wells tapping the Nubian aquifer show that the aquifer is composed of intercalations of sandstone, varicoloured and medium to very coarse grained, with interbeds of grey to green, sticky shale. According to Ghoubachi and Eissa (2017), the transmissivity of the Nubian sandstone aquifer in East El-Oweinat area ranges between 1020 m²/day and 3231 m²/day with an average of 2060 m²/day. The transmissivity values indicate that the aquifer is a high potential (>500 m²/day) according to Gheorhge (1978) classification and the estimated groundwater quantity of the aquifer is 350 bcm (billion cubic meters) of fresh water.

4. Materials and methods

To study the negative impact of the over-pumping on the Nubian sandstone aquifer, integrated hydrogeological investigation for the drilled wells (Figure 3) and the satellite digital images are used in this work for East-Oweinat area.

4.1. Hydrogeological data

Investigation of about 1820 wells was considered (Figure 3). Through this investigation, the depth to water and water salinity for most of the drilled wells were measured in 2015 and 2018 to compare these measurements with the available previous data in 2002. The data of 2002, 2015 and 2018 were used to study the change in each of these parameters.

The author collected the data from the reports of the drilled wells by the Drilling Unit in Desert Research Center and the owners of the investigated farms in East-Oweinat area.

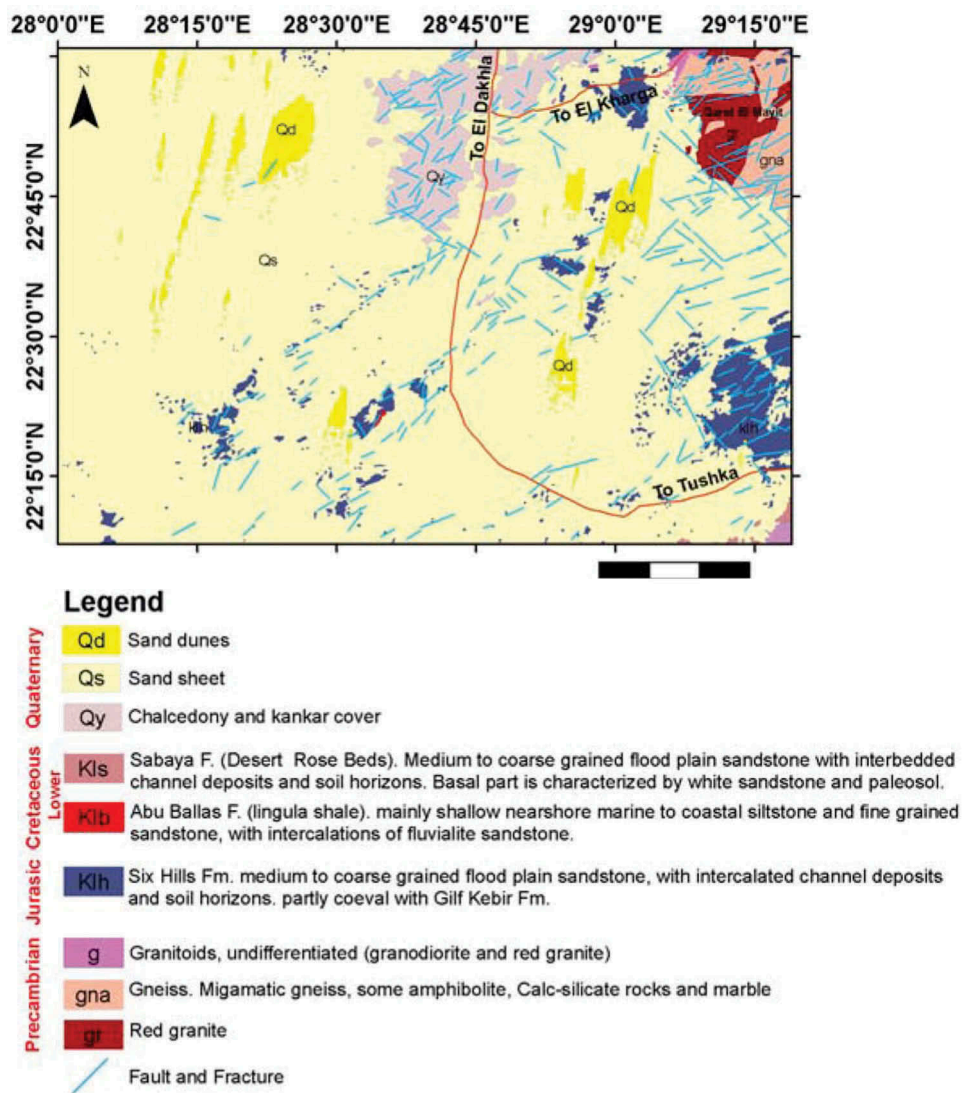


Figure 2. Geological map of East-Oweinat area (Modified after CONOCO, 1987).

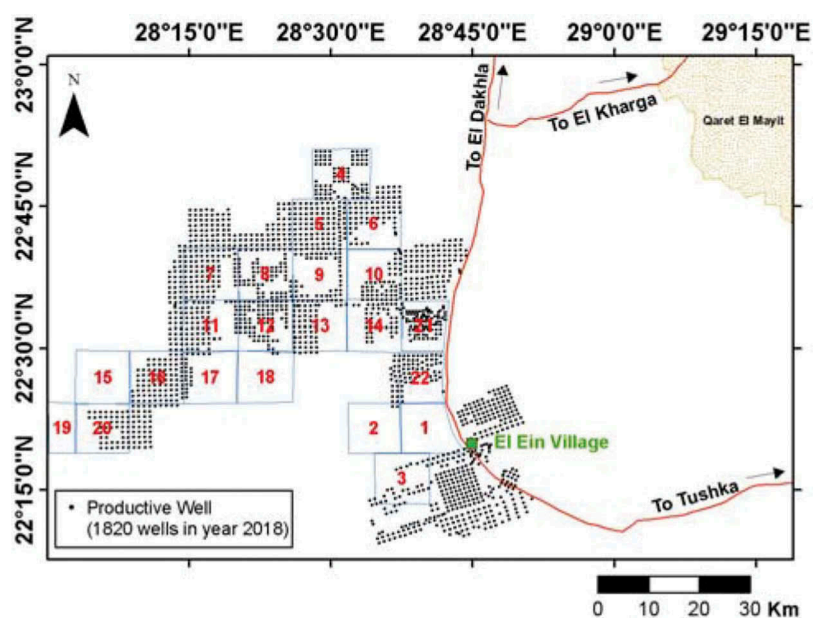


Figure 3. Map showing plots of cultivation and number of drilled wells in East-Oweinat area.

4.2. Remote sensing data

In this study, satellite images were used to monitor the changes in the agricultural activities through the last two decades (2000–2018). They include; Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper plus (ETM+) and landsat-8 Operational Land Imager (OLI) from the United States Geological Survey (USGS) Earth Explorer and Sentinel-2 from the European Environment Agency Copernicus Access Hub. The study area is considered as a part of two scenes path/row: 177/44 and path/row: 177/45.

Processing techniques are applicable for scenes subsets of the different satellite imagery listed by their Granule ID in Table 1 using ArcGIS software, version 10.1.

Over the past few periods, satellite remote sensing has been playing a crucial role in forest monitoring, disaster management and agricultural applications (Hill 2013). A widely used approach in satellite remote sensing is to define various indices to facilitate the classification of diverse land covers or plants (e.g. Normalized Difference Vegetation Index (NDVI). NDVI proposed by Rouse et al. 1973) has the ability to classify land covers in the remote sensing area, as well as vegetation vitality. This index is defined by the

reflectance of visible band (Red) and near infrared band (NIR) according to the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}.$$

5. Results and discussion

The hydrological setting and monitoring the changes of water levels and water salinity of the Nubian sandstone aquifer as well as the agriculture activities and yearly groundwater abstraction will be discussed.

5.1. Areal aquifer distribution

The data of the drilled wells and the Vertical Electrical Soundings that carried by Youssef (1996) were used to construct the maps of the depth to the basement rocks and the level of its top surface with respect to mean sea level as well as the inferred faults that controlled the thickness of the Nubian sandstone aquifer.

The depth to the basement rocks (Figure 4(a)) ranges between 0 m at the northeastern corner of the study area, where it is exposed on the surface at Qaret El-Mayit to 718 m at the western part of the study area. On the

Table 1. Granule ID of satellite images.

Satellite image type	Date of image acquisition	Path/Row	LANDSAT_SCENE_ID
Landsat-5 (TM)	11/01/2000	177/44	LT51770442000011RSA00
		177/45	LT51770452000011RSA00
Landsat-7 (ETM+)	05/01/2001	177/44	LE71770442001005SGS00
		177/45	LE71770452001005SGS00
	13/03/2002	177/44	LE71770442002072SGS00
		177/45	LE71770452002072SGS00
	12/02/2003	177/44	LE71770442003043SGS00
		177/45	LE71770452003043SGS00
	14/01/2004	177/44	LE71770442004014ASN01
		177/45	LE71770452004014ASN01
	05/03/2005	177/44	LE71770442005064ASN00
		177/45	LE71770452005064ASN00
	03/01/2006	177/44	LE71770442006003ASN00
		177/45	LE71770452006003ASN00
	22/01/2007	177/44	LE71770442007022ASN01
		177/45	LE71770452007022ASN02
	25/01/2008	177/44	LE71770442008025ASN01
		177/45	LE71770452008025ASN00
	27/01/2009	177/44	LE71770442009027ASN00
		177/45	LE71770452009027ASN00
	09/01/2010	177/44	LE71770442010094ASN00
		177/45	LE71770452010094ASN00
	01/01/2011	177/44	LE71770442011001ASN00
		177/45	LE71770452011001ASN00
	20/01/2012	177/44	LE71770442012020ASN00
		177/45	LE71770452012020ASN00
Landsat-8 (OLI)	22/05/2013	177/44	LC81770442013142LGN00
		177/45	LC81770452013142LGN00
	13/08/2014	177/44	LC81770442014225LGN00
		177/45	LC81770452014225LGN00
	04/01/2015	177/44	LC81770442015004LGN00
		177/45	LC81770452015004LGN00
	07/01/2016	177/44	LC81770442016007LGN00
		177/45	LC81770452016007LGN00
	09/01/2017	177/44	LC81770442017009LGN00
		177/45	LC81770452017009LGN00
Sentinel-2	02/01/2018	177/44	L1C_T35QPF_A013217_20180102T085330
		177/45	L1C_T35QPE_A013217_20180102T085330

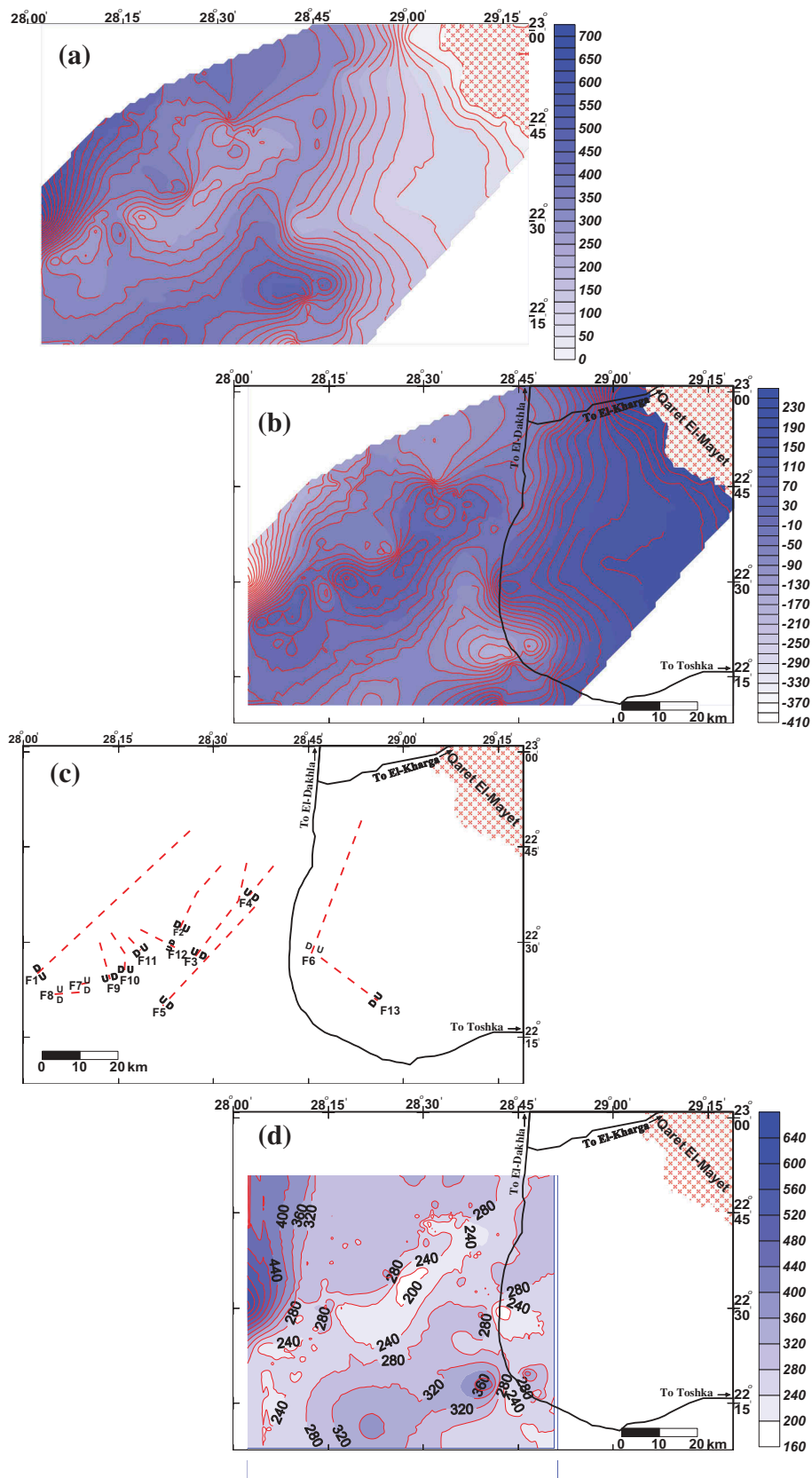


Figure 4. (a): Depth to basement map (meter) from ground surface; (b): Level contour map of basement top surface (meter) with respect to sea level; (c): Detected inferred faults map; (d): Thickness contour map of the Nubian sandstone aquifer.

other hand, the level of the top of basement rocks (Figure 4(b)) shows that this level is 230 m above mean sea level at Qaret El-Mayit in the northeastern corner of the study area and increased southwestward to

reach -408.21 m below mean sea level. From the inferred faults map (Figure 4(c)), it is clear that the study area has been affected by 13 normal faults which have a direct effect on the aquifer thickness and

consequently on its potentials. These faults have NE-SW (F1-F6), NEE-SWW (F7-F8) and NW-SE (F9-F13) directions. Figure 4(a-c) shows that there is a regional uplift of the basement rocks in the central part of East-Oweinat area.

According to the available data of the depth to both water and basement rocks from the ground surface, the thickness of the Nubian sandstone aquifer is calculated (Figure 4(d)). It ranges between 163.4 m at the eastern part and 658.15 m at the western part of the study area. It is clear that the thickness of the aquifer has its lowest values along the uplifted areas of the basement rocks at the central and eastern parts of the study area.

5.2. Hydrogeological cross sections

Three hydrogeological cross sections have been constructed. Two of them (A-A' and B-B') have been constructed in W-E direction and the third one (C-C') has been constructed in SW-NE direction as shown in Figure 5 which shows the following:

- (1) The sedimentary succession consists of the dry zone (sand and sandstone from Quaternary

and Nubian sandstone), saturated Nubian sandstone and the basement rocks.

- (2) The wells along the hydrogeological cross section A-A' (Figure 5(b)) are partially penetrated, where the total depth was reached to 300 m and did not reach the basement rocks. The depth to water ranges between 36.2 m at well No.954 in the west and decreases eastward and reaches 30.82 m at well No.957. The groundwater flow is from the west to the east, ranging between 246.86 m above mean sea level at well No.954 in the west and 241.64 m at well No.957 in the east. The saturated thickness ranges from 232.4 m at well No.909 in the east and increases westward to reach 264.66 m at well No.943.
- (3) The wells along the hydrogeological cross section B-B' (Figure 5(c)) are partially penetrated at the west and fully penetrated at the east and reached the basement rocks. The depth to water ranges from 47.32 m at well No.691 in the west and decreases eastward to reach 15.7 m at well No.174. The groundwater flow is from the west to the east, where the water level

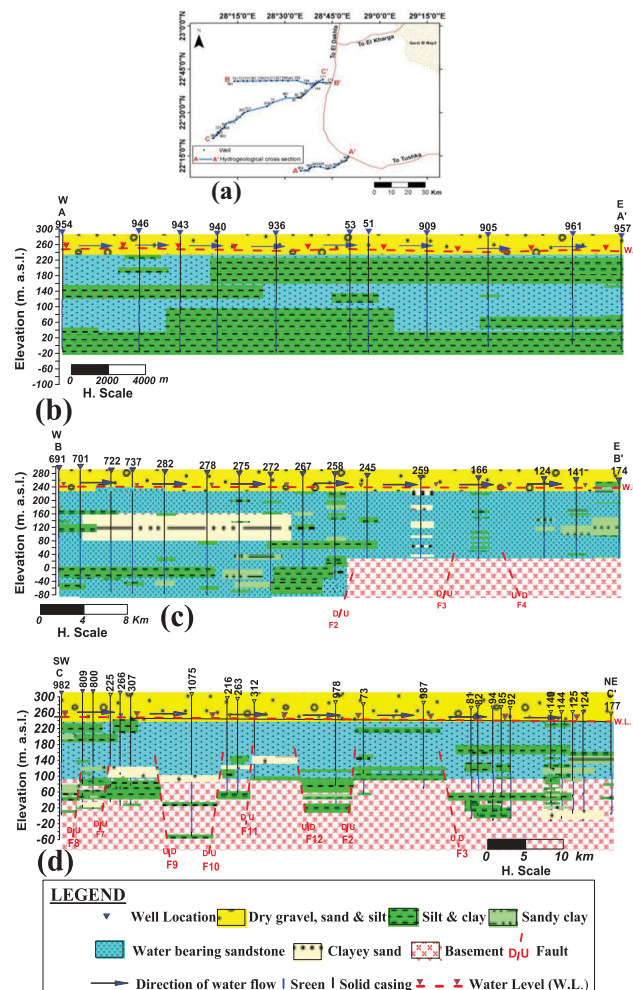


Figure 5. (a): Key map; (b): Hydrogeological cross section A-A'; (c): Hydrogeological cross section B-B'; (d): Hydrogeological cross section C-C'.

ranges between 241.72 m above mean sea level at well No.691 in the west and 237.61 m at well No.174 in the east. The basement rocks were reached at the eastern part, where the depth to its top surface reaches 226 m at well No.166 at the east and increases westward. The saturated thickness ranges between 204.05 m at well No.166 in the east and increases westward to reach more than 300 m.

- (4) The wells along the hydrogeological cross section C-C' (Figure 5(d)) are reached the top surface of the basement rocks. The depth to water ranges between 60 m at well No.982 in the west and decreases eastward to reach 15.1 m at well No. 177. The groundwater flow is from the west to the east ranging between 258.75 m at well No. 809 in the west and decreases eastward to reach 238.1 m at well No.177. The depth to the top surface of the basement rocks ranges between 178 m at well No.312 at the centre and reaches its maximum depth of 300 m at well No.1075. The saturated thickness ranges between 178 m at well No.312 and 300 m at well No.1075.
- (5) Generally, the thickness of the Nubian sandstone aquifer decreases eastward as shown along cross-section B-B' and at the central part as shown along the cross sections C-C'.
- (6) The existing of normal faults have a direct effect on the thickness of the saturated thickness of the Nubian sandstone and forming different structures forms of horsts, grabens and step faults.

5.3. Changes in the water levels

Maps of the water level for years 2002, 2015 and 2018 are constructed (Figure 6(a-c)) to study the changes through the last two decades. These maps show that the regional water flow is from the southwest to the northeast direction. The water levels vary from 229 m to 256 m, 200 m to 254 m and from 198 m to 252 m in years 2002, 2015 and 2018, respectively. The general decrease in the water level contour values with time is an indication of the groundwater depletion with time.

5.4. Changes in the water salinity

The total dissolved solids (TDS) of 61 water samples of some representative wells were measured in the field by the author in 2015 and 2018 using Portable Conductivity Meter to give an idea about the water salinity changes with time. Figure 7 shows that the groundwater salinity of the Nubian sandstone aquifer in East-Oweinat area was 273–860 ppm and 300–917 ppm in 2015 and 2018, respectively that is considered

as fresh water and no critical change in the salinity values.

5.5. Negative impact of over-pumping on the nubian sandstone aquifer

The most important aim of this study is to assess the impact of the increase in the agricultural development in the study area during the last two decades, where the increase of groundwater extraction is very prominent. The negative impact (depletion) on the groundwater resource is also, investigated. Figure 8 shows the flow-chart that illustrates the different steps carried out on the satellite images listed in Table 1 to calculate the agricultural development.

5.5.1. Agricultural development

The resulted thematic maps (Figure 9) show the spatial distribution of the cultivated lands as a specific data for East-Oweinat area in the last two decades (2000–2018). These thematic maps served as a useful tool for the assessment and measurement of the development activities depending on the groundwater of the Nubian sandstone aquifer.

5.5.2. Groundwater abstraction

According to MALR (1997) and MPWWR (1999), the total proposed project area was about 220,000 Feddan (1 Feddan = 4200 m²) in 22 plots at 10,000 Feddan/plot (Figure 3) and the principal goal of this national project was to drill 83 wells within each plot with an average discharge of about 200 m³/h/well and for a pumping period of 12.5 h/day/well.

In the present study, the field observations show different values than that suggested by the Ministry of Agriculture as the followings:

- The plant consumption of water is on the average of 36 m³/Feddan/day and the average irrigation days are 270 day/year. Consequently, the annual plant consumption of water is about 9,720 m³/Feddan/year.
- The average groundwater discharge of each well is 250 m³/h and the average working hours is 18 h. Consequently, the average daily well discharge is 4,500 m³/day.

Table 2 and Figure (10) summarise the number of drilled wells, the reclaimed areas and the groundwater abstraction of each year from 2000 to 2018, and the followings can be concluded:

- The cultivation development is mainly concentrated along and to the west of El Ain – El Dakhla Road, where the thickness of the aquifer is greater than that at the eastern side.

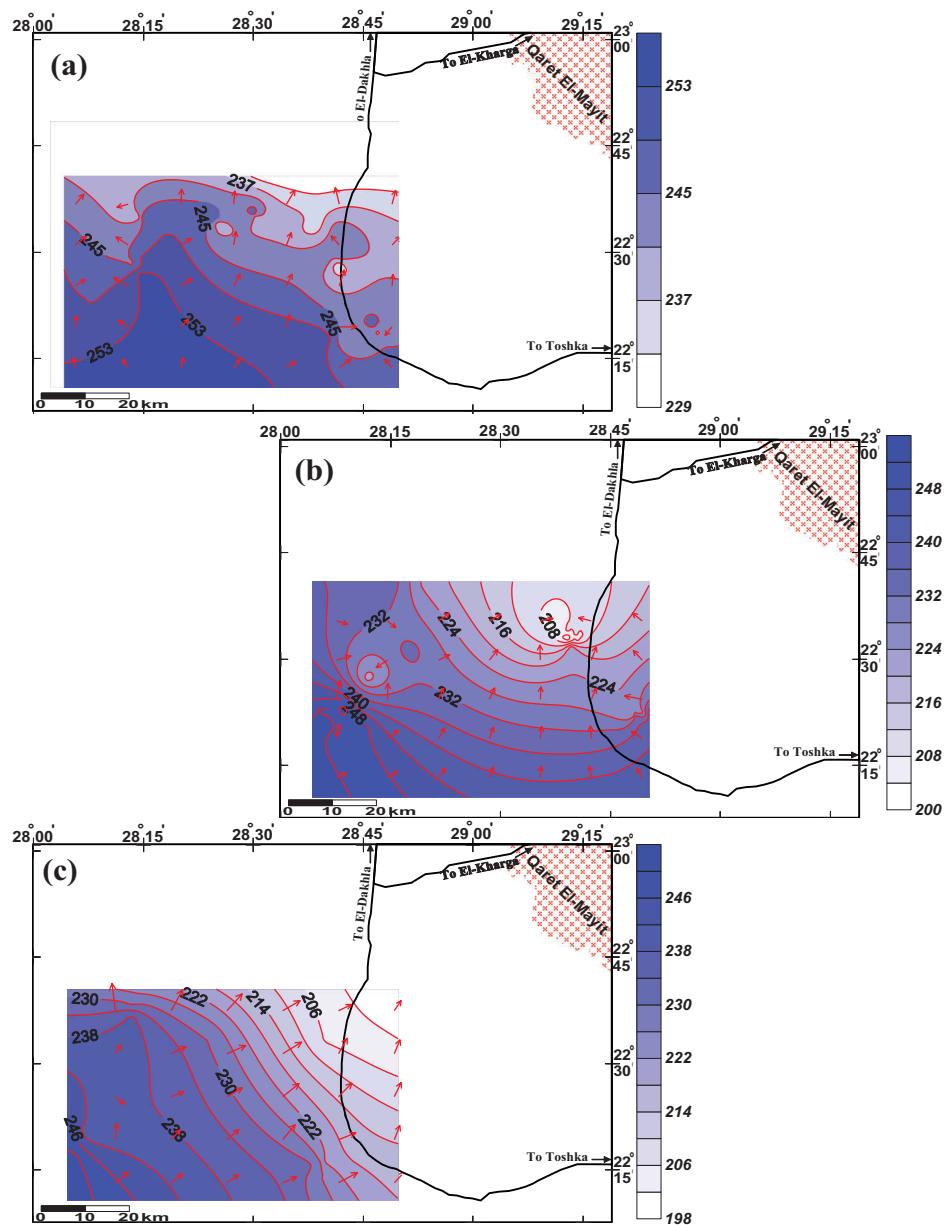


Figure 6. (a): Water level map (2002); (b): Water level map (2015); (c): Water level map (2018).

- The cultivated areas increased from 4,968 Feddan in 2000 to 194,549 Feddan in 2018.
- In the first decade (2000–2009), the number of the productive wells in East-Oweinat area was 492 wells, the total reclaimed area was 51,229 Feddan and the total groundwater abstraction was 2.5 billion m^3 during this period of time.
- In the second period (2010–2018), the number of the productive wells was 1820 wells, the total reclaimed area was 194,549 Feddan and the total groundwater abstraction was 12.6 billion m^3 .
- The groundwater abstraction in the second period (2010–2018) is about five times of the first decade (2000–2009).
- The annual discharged water from wells is greater than that of plant consumption. This is mainly attributed to many factors as; the

losses through evaporation, non-working wells for maintenance and losses through irrigation systems.

5.5.3. Groundwater depletion

To clarify the groundwater depletion with time, a resultant map (Figure 11) is created to show the difference in water level from 2002 to 2018. This will illustrate the depletion as an indication of the over-pumping and increase of cultivation activities. From this map the followings can be concluded:

- The groundwater depletion has its minimum value at the western part (5.6 m) and increases eastward to reach 37.5 m.

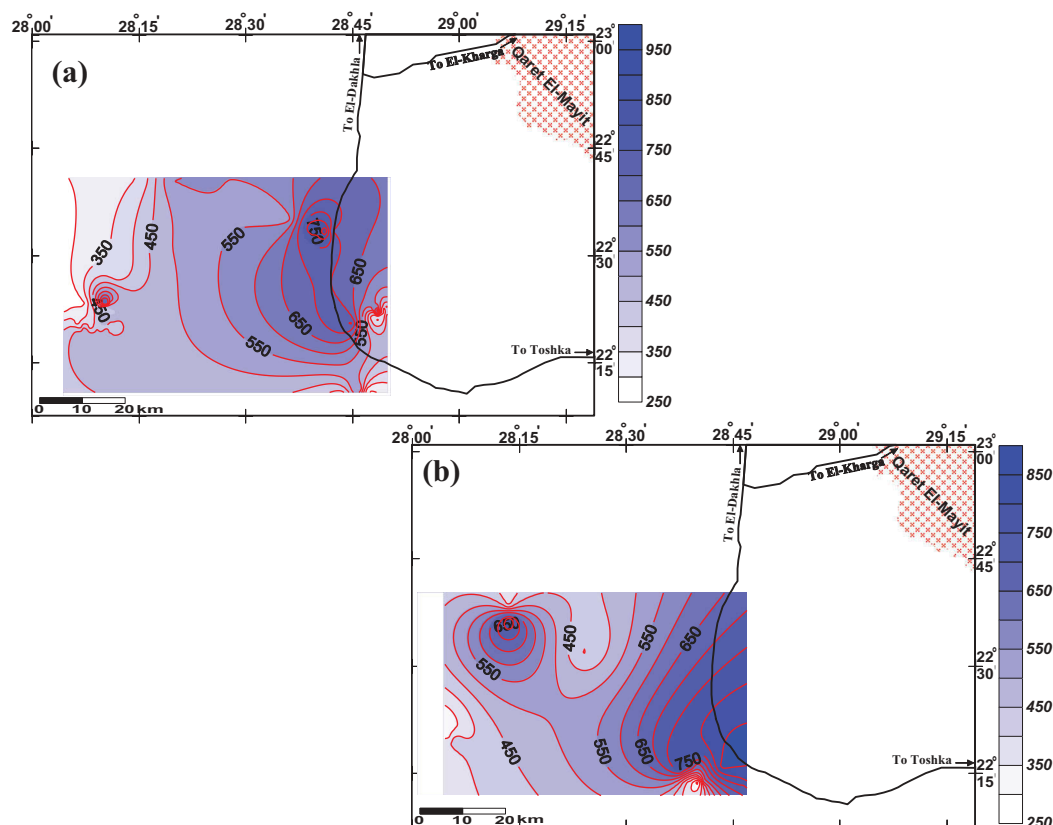


Figure 7. Salinity map of Nubian sandstone aquifer. (a): (2015); (b): (2018).

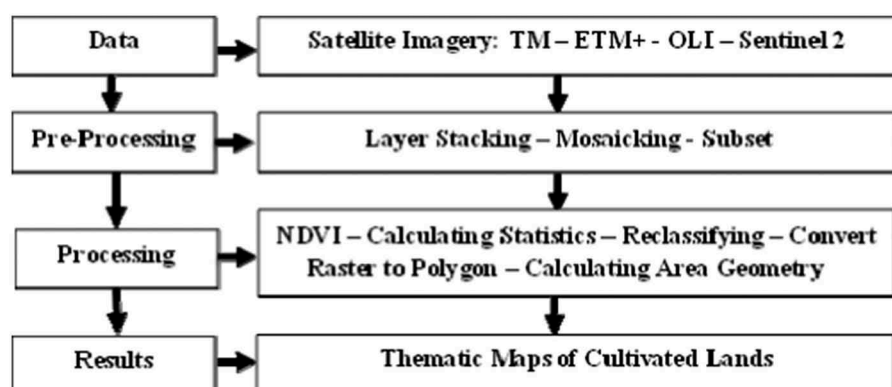


Figure 8. Flow chart of image processing for calculating cultivated lands.

- The depletion of the groundwater level ranges between 0.35 m/year at the western part and increases eastward to reach 2.34 m/year.
- It is clear that the maximum water depletion is attributed to both over-pumping and cultivation activities which started early at the eastern parts of the study area (Figure 9).
- This water depletion (2.34 m/year) is considered as an alarm for the decision makers to overcome this problem through a better management of the groundwater resource to achieve sustainable development in such promised area.

5.5.4. Groundwater storage

Based on the assumptions of this study and the above-mentioned results and discussions, one can state:

- According to Ghoubaichi and Eissa (2017), the estimated groundwater quantity of the aquifer is 350 billion m^3 of fresh water.
- According to Nour (1996), the annual rate of groundwater inflow to the East-Oweinat area was estimated to be 120 million m^3 .
- According to the present work, the plant consumption of groundwater in East-Oweinat area for cultivation (194,549 Feddan) is 1.9 billion m^3 in 2018.

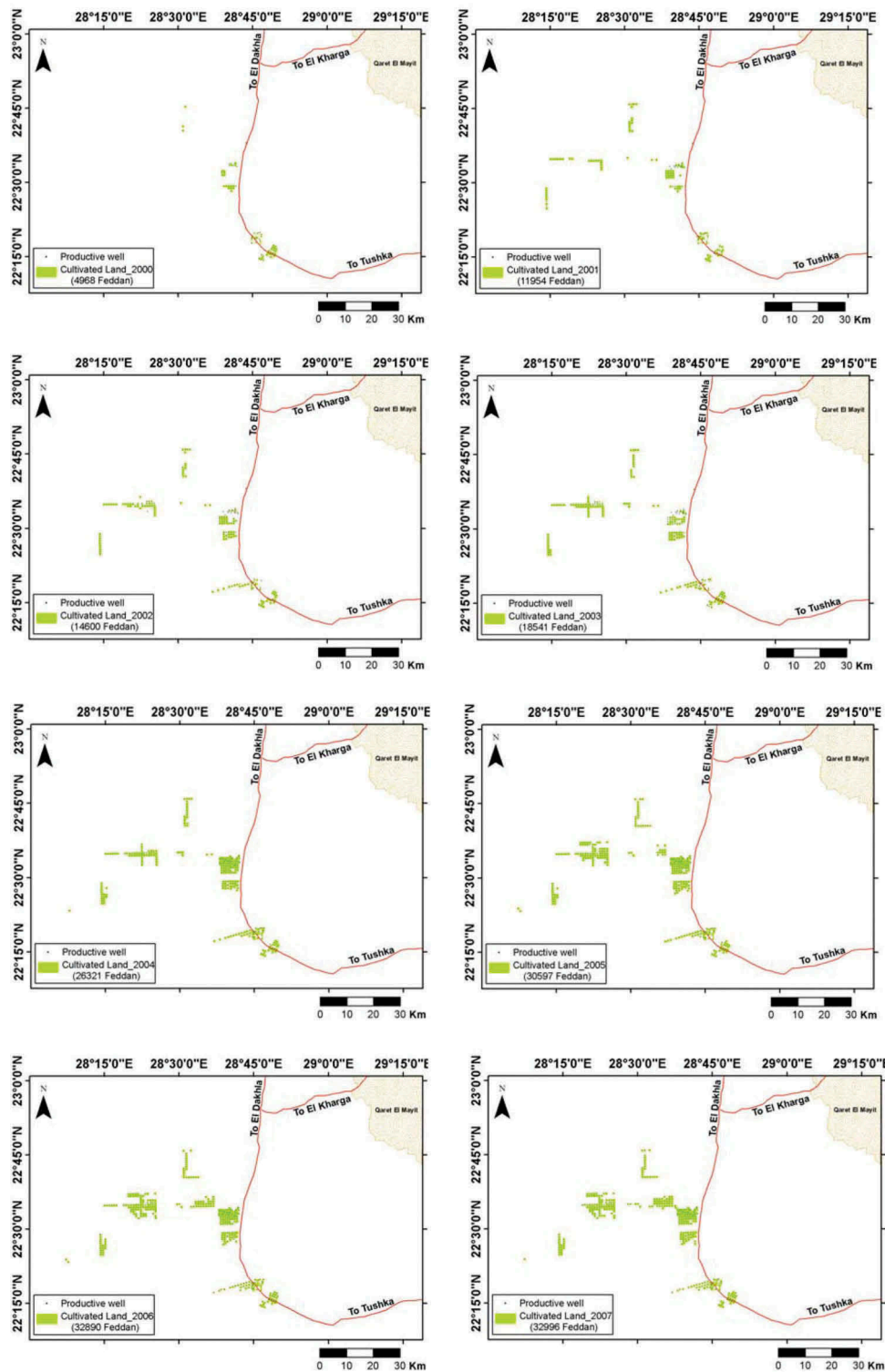


Figure 9. Thematic maps of the cultivated lands for the period 2000–2018 using the satellite images.

- The net annual groundwater abstraction will be estimated through the following simple calculations:

Net annual groundwater abstraction

$$\begin{aligned}
 &= \text{Annual abstraction} - \text{annual recharge} \\
 &= (1.891012 \times 10^9 \text{ m}^3) - (120 \times 10^6 \text{ m}^3) \\
 &= 1.771012 \times 10^9 \text{ m}^3
 \end{aligned}$$

- According to the present annual plant consumption of groundwater, the sustain time of the storage of groundwater will be estimated through the following simple calculations:

$$\begin{aligned}
 \text{Number of years} &= \text{Storage} / \text{net annual abstraction} \\
 &= (350 \times 10^9 \text{ m}^3) / (1.771, 01210^9 \text{ m}^3) \\
 &= 197.63 \text{ year}
 \end{aligned}$$

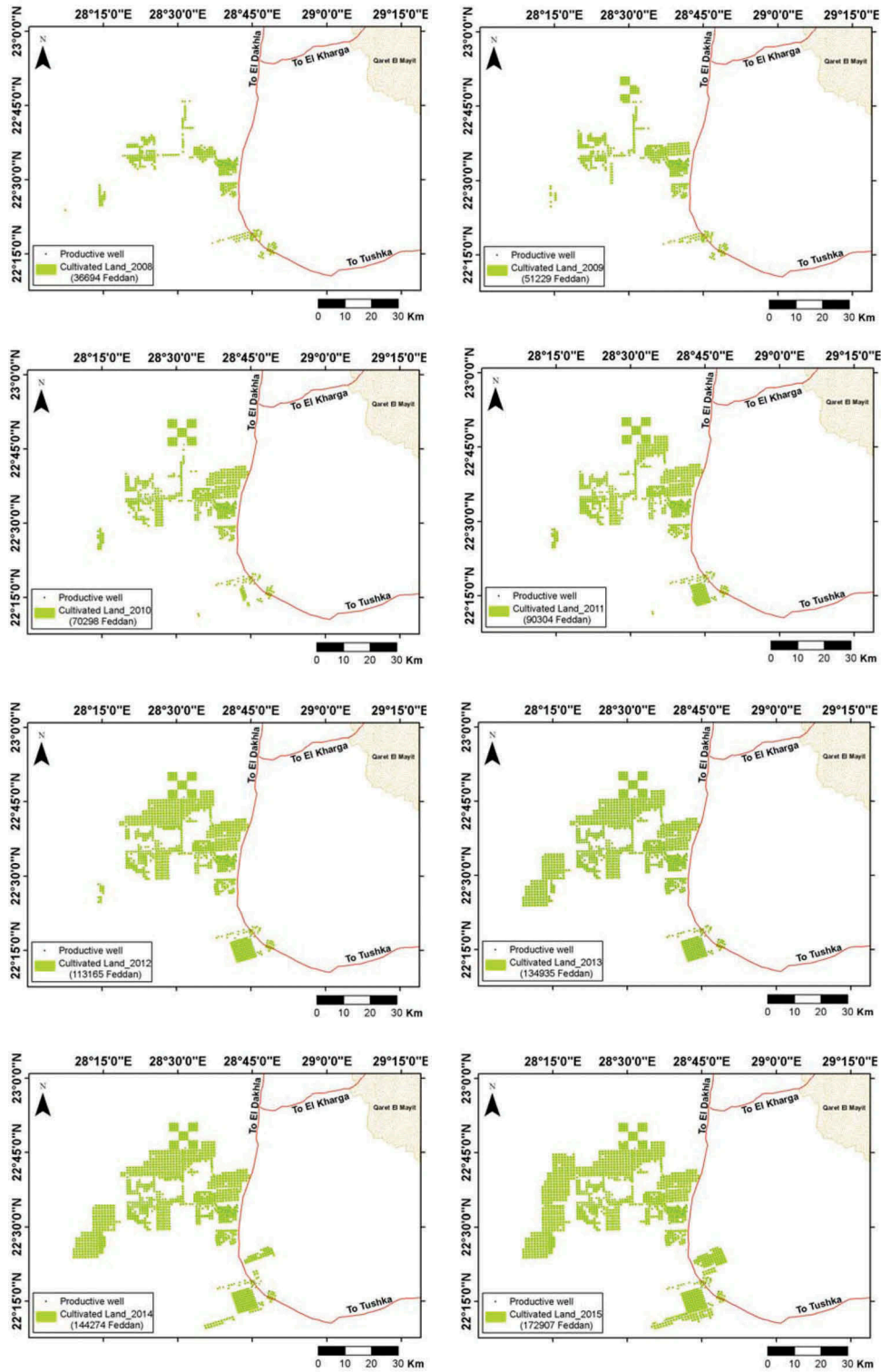


Figure 9. Continued.

- Consequently, the available groundwater in East-Oweinat area can be used for sustainable development for about 198 years under good management of the present situation.
- In case of expansion the cultivated areas from the present status (194,549 Feddan) to the planned area by the Ministry of Agriculture (220,000

Feddan), this will add 25,491 Feddan. This new area will consume about 247.8 million m³/year

- Accordingly, the annual groundwater abstraction will be 2.02 billion m³, and consequently the time of the groundwater storage will be sustained for development of about 173.37 years.

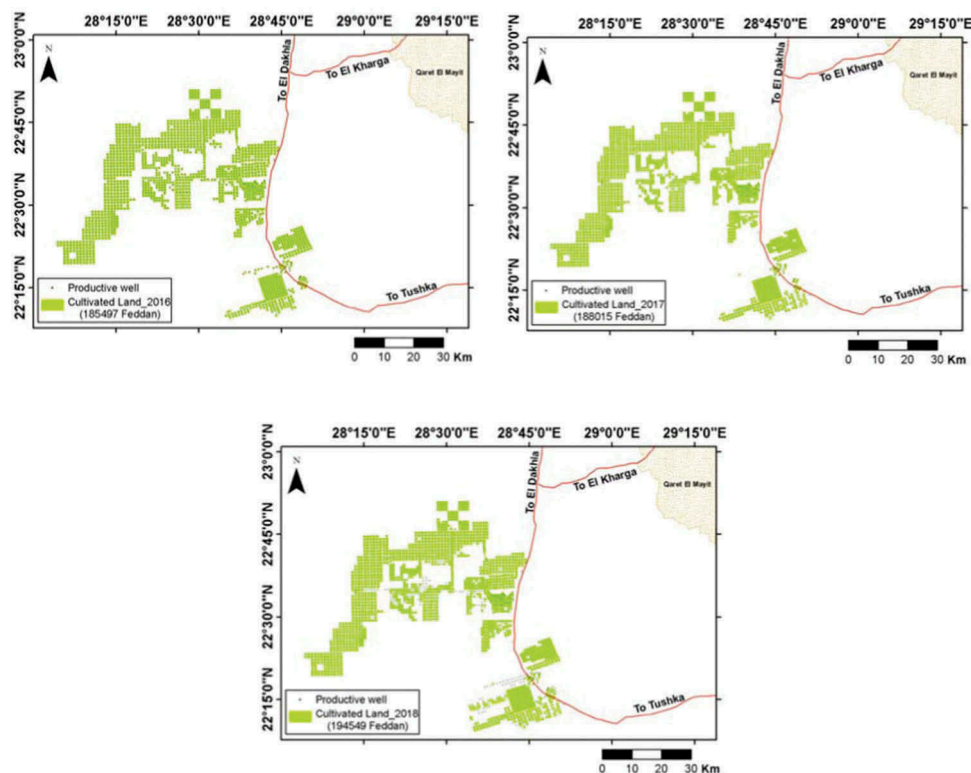


Figure 9. Countinued.

Table 2. Cultivated lands using satellite images, annual groundwater abstraction and number of drilled wells in the period (2000–2018).

Date	Cultivated land (Feddan)	Annual irrigation water (Million m ³)	Number of productive wells	Annual ground-water abstraction (Million m ³)
2000	4968	48.290,520	68	82.62
2001	11,954	116.189,000	125	151.875
2002	14,600	141.916,600	166	201.69
2003	18,541	180.222,500	201	244.215
2004	26,321	255.844,400	250	303.75
2005	30,597	297.407,300	298	362.07
2006	32,890	319.690,300	324	393.66
2007	32,996	320.724,200	326	396.09
2008	36,694	356.663,700	365	443.475
2009	51,229	497.950,500	492	597.78
2010	70,298	683.298,500	680	826.2
2011	90,304	877.751,200	847	1029.105
2012	113,165	1099.968,000	1029	1250.235
2013	134,934	1311.564,000	1205	1464.075
2014	144,274	1402.343,000	1289	1566.135
2015	172,906	1680.652,000	1526	1854.09
2016	185,497	1803.03084	1677	2037.555
2017	188,016	1827.514,000	1700	2065.5
2018	194,549	1891.012000	1820	2211.3

- In case of add new extension of cultivated land, each Feddan will decrease the groundwater storage by about 9,720 m³, yearly.

6. Conclusions and recommendations

This research work is focused on the following main approaches related to the effects of the over-pumping

of the Nubian sandstone aquifer on the sustainable development in East-Oweinat area:

- (1) The basement rocks are exposed on the surface at Qaret El-Mayit at the northeastern part and its depth increases southwestwards to reach 650 m and the general groundwater flow is from the southwest to the northeast.
- (2) The groundwater depletion from 2002 to 2018 has its minimum value at the western part (5.6 m) and increases eastward to reach 37.5 m. The depletion of the water level ranges between 0.35 m/year at the western part and increases eastward to reach 2.34m/year. It is clear that the maximum water depletion is attributed to both over-pumping and cultivation activities which started early at the eastern parts.
- (3) There is no critical change in the groundwater salinity between 2015 and 2018.
- (4) The cultivated areas increased from 4,968 Feddan in 2000 to 194,549 Feddan in 2018.
- (5) Regarding the groundwater abstraction, in the first decade (2000–2009), the number of the productive wells in East-Oweinat area was 492 wells, the total reclaimed area was 51,229 Feddan and the total groundwater abstraction was 2.5 billion m³. In the second period (2010–2018), the number of the productive wells was 1820 wells, the total reclaimed area was 194,549 Feddan and the total groundwater abstraction

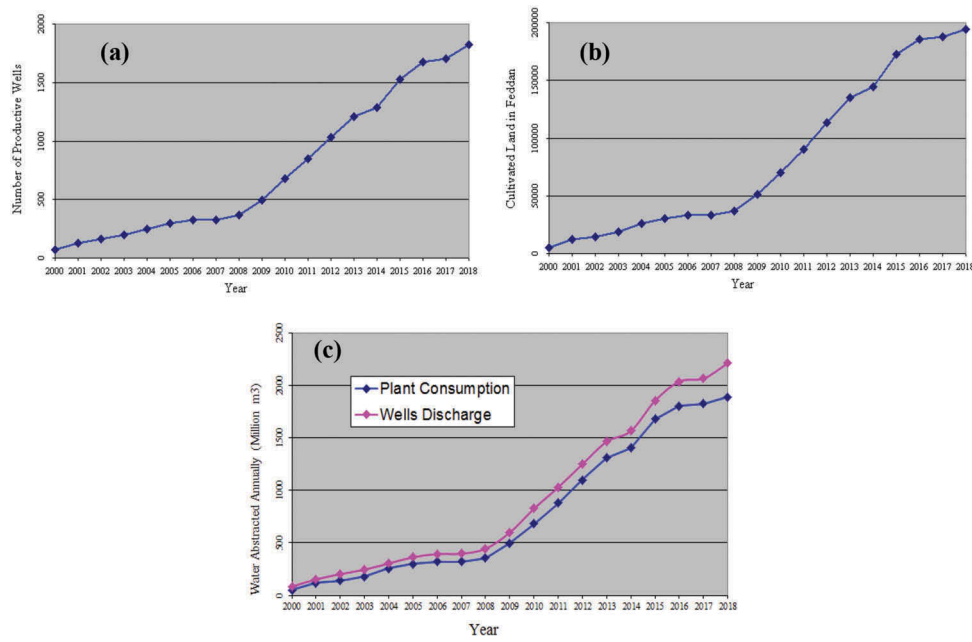


Figure 10. (a): Number of wells, (b): Cultivated lands in Feddan, (c): Water abstracted annually (Million m³).

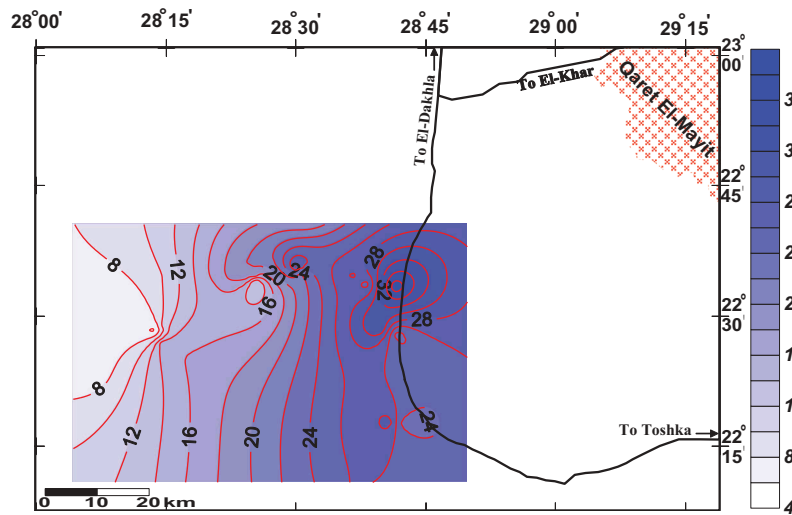


Figure 11. Resultant water level map showing water depletion (2002–2018).

was 12.6 billion m³. The groundwater abstraction in the second period (2010–2018) is about five times of the first decade (2000–2009).

- (6) The annual discharged water from wells is greater than that of plant consumption. This is mainly attributed to many factors as; the losses via evaporation, non-working wells for maintenance and losses through irrigation systems.
- (7) The consumption of groundwater in East-Oweinat area for the present cultivated area (194,549 Feddan) is 1.89×10^9 m³/year.
- (8) The available groundwater in East-Oweinat area can be used for sustainable development for about 174 years under good management of the present situation and the proposed plan (220, 000 Feddan).

From the above-mentioned discussion, the followings can be recommended:

- (1) Generally, the whole area should be subjected to a monitoring network of wells includes both water levels and salinity on a periodical basis.
- (2) The present extraction rate of 1.2 million m³/year for each well in East-Oweinat area is not feasible for the coming 100 years, and will have a negative impact on water levels. So, it is recommended to apply the planned extraction rate of 0.7 million m³/year.
- (3) The coordination between the Ministry of Irrigation & Water Resources and the Ministry of Agriculture and Land Reclamation is very important to make the required management

on the groundwater exploitation in the study area.

- (4) The great farms in the area should change the crop pattern to avoid plants of high consumptive use of water.
- (5) The development activities must be extended in the west direction. This recommendation is, however, emphasised by favourable hydrological properties of the Nubian sandstone aquifer concerning saturated thickness and low values of depletion in this direction. This will keep certain sustainability of the aquifer especially when we know that the eastern part of the study area is heavily pumped, depleted 2.34 m/year and really exhausted.

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