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ORIGINAL ARTICLE

Assessment of groundwater resources in Siwa Oasis, Western Desert, Egypt

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Abstract One of the major challenges facing Egypt is limited water resources associated with rapid increase in population. In 1960s, Egyptian government started to use groundwater from the Nubian Sandstone Aquifer System (NSAS) in the Western Desert to expand agricultural sector. Siwa Oasis is the focus of this study to assess the efficiency of groundwater use and corresponding impacts from 1980 to 2012. Results show that from 1980 to 1998, withdrawal from poorly designed wells increased rapidly causing an increase in excess water about 336%. The increase of excess water with the usage of poor drainage produced lakes. Remote Sensing showed in 2000, there were 21,348 acres of lakes with an increase of 89% since 1987 due to unmanaged withdrawal. After management intervention, excess water decreased about 94.7% from 1998 to 2012 causing a decrease in lakes area by 24%. Groundwater electrical conductivity (EC) increased from 4.5 to 10.5 ds/m in 1996 and 2013, respectively. Yields of olives and date palms decreased about 46% and 55%, respectively from 2000 to 2011 resulting in net revenue decrease of more than 60%. Results show that salinity has a strong negative correlation with yield and net revenue. Findings showed the importance of developing a meaningful groundwater resources management plan for Siwa region.

1. Introduction

The primary source of water in Egypt is the Nile River which provides 55.5 billion m^3 annually since the agreement between Egypt and Sudan in 1959 [1,2]. This amount represents 94% of all renewable water resources in Egypt [3]. Egypt's climate is arid with an average annual rainfall of 18 mm [1]. Consequently, water resources are limited. Further, Egypt's population has experienced rapid growth; an increase of 66 million to 96 million between 2002 and 2018, respectively [4] with an average increase of 2.7% annually. The rapid increase in population has contributed to water stress by widening the gap between availability and demand. The total renewable water resources per capita decreased to 570 m^3/year/capita in 2018 (https://www.egypttoday.com/Article/2/67788/Egypt-s-per-capita-share-of-pure-water-rises-by accessed in November 2018) from 1000 m^3/year/capita in 1997 [5], indicating serious water scarcity. If this number decreases below 500 m^3/year/-capita, inhabitants can face acute scarcity [6]. In essence, water resources management is important to develop and protect

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these limited water resources especially for sustainable socio-economic development in Egypt [5].

Although the Nile Valley and the Delta region cover about 5.5% of Egypt, this region contains 95% of the population. To satisfy the high food demand, the agricultural sector consumes about 80% of available water [2]. Therefore, the Egyptian government is constantly seeking ways to increase and better manage its water resources. For example, the government is reclaiming the desert using the groundwater to increase agricultural production and attract people from the already over-populated Delta region.

In the early 1960s, the government started to use groundwater from the non-renewable Nubian Sandstone Aquifer System (NSAS) which is a transboundary aquifer occupying Egypt, Libya, Sudan, and Chad as shown in Fig. 1. It is one of the largest aquifers in the world with a total area of 2.2 million km^2 distributed as follows: 828,000 km^2 in Egypt (38%), 760,000 km^2 in Libya (34%), 376,000 km^2 in Sudan (17%), and 235,000 km^2 in Chad (11%) [7–9].

NSAS has two aquifers; the most important is the Nubian Aquifer System (NAS) which is located underneath the Post Nubian Aquifer (PNA) as shown in Fig. 1. Low permeability layers are located between these two aquifers. PNA is an unconfined aquifer located only in the northern region of NSAS and is used by Egypt and Libya. NAS covers the whole area of NSAS and is used by all four countries. Although NAS is unconfined in the south of NSAS, it is confined in the northern region due to the presence of PNA. NSAS contains a large amount of groundwater amounting to about 475,753 km^3 assuming storativity values of the confined and unconfined aquifers to be 10^{-4} and 7×10^{-2}, respectively. However, only a small portion of this volume can actually be developed due to deep depths to groundwater and the corresponding high pumping costs [9,10]. Bakhbakhi [9] calculated the total recoverable groundwater in each country assuming maximum water declines in unconfined and confined aquifers are 100 m and 200 m, respectively. The result found that the total recoverable groundwater in Egypt to be 5,367 km^3 and the extraction at that time was only 0.506 km^3/year, indicating the availability of a large volume of unused water.

NSAS occupies almost all of Egypt. However, the largest volume of available groundwater is within the Western Desert region which covers approximately two-thirds of Egypt [8,1]. The Use of NSAS in the Western Desert region started in 1960 in an effort to increase agricultural productivity. Groundwater withdrawal was initiated at five locations; Kharga, Dakhla, Farafra, Bahariya, and Siwa Oases, as shown in Fig. 2, for both agricultural and domestic uses. In 1990, a new agricultural area was developed using groundwater from East Oweinat [7,8].

Siwa received great attention in previous studies given the abundance of groundwater that can be used for future development. It has salty lakes that had been formed due to the absence of good drainage [11,10]. Abou El-Magd [12] showed that lakes areas are increasing which were; 12,409, 14,702, and 18,414 acres in years 1986, 1992, and 2000 respectively. Abdallah and Khedr [13] used Remote Sensing (RS) and Geographic Information System (GIS) to estimate these areas and found total lakes area decreased to 11,476 in 2010.

Monitoring water and soil salinity is important because plants have difficulty absorbing and extracting water under high soil salinity. Two indicators can be used to evaluate salinity; total dissolved salts (TDS, ppm) and electrical conductivity (EC, ds/m). A conversion factor of 650 is used to transfer salinity units from ppm to ds/m [14]. According to World Health Organization [15] and Egyptian Higher Committee for Water [16], maximum acceptable TDS for drinking water is 1000 ppm (1.54 ds/m) and 1200 ppm (1.85 ds/m), respectively. Acceptable groundwater for irrigation and soil salinity levels are developed by US Salinity Laboratory [17] and given in Table 1.

Aly et al. [18] monitored groundwater quality from PNA by measuring EC of 44 wells in Siwa from 1998 to 2008. The

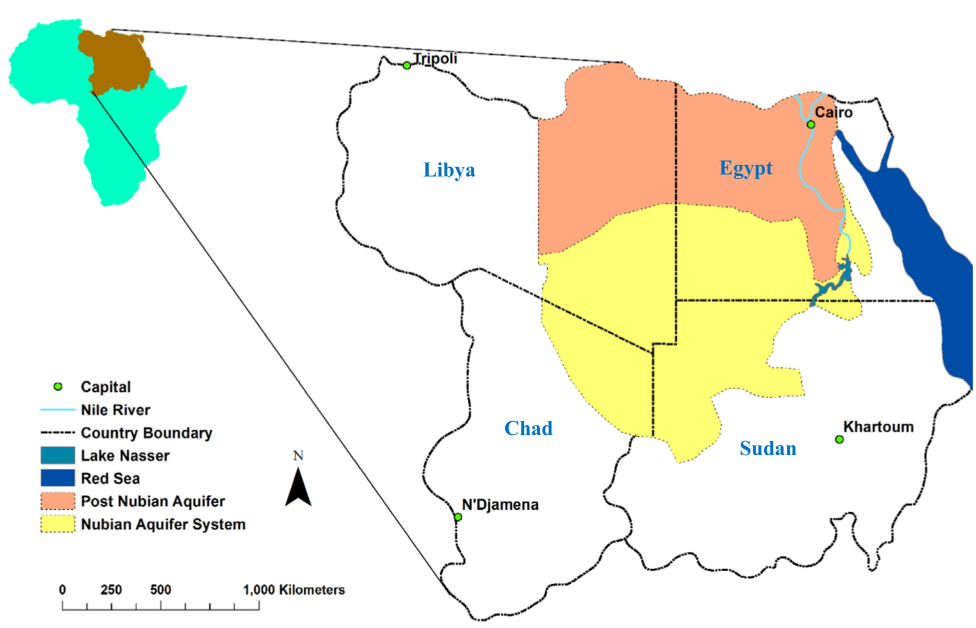

Fig. 1 Distribution of NSAS transboundary aquifer between Egypt, Libya, Sudan, and Chad [8].

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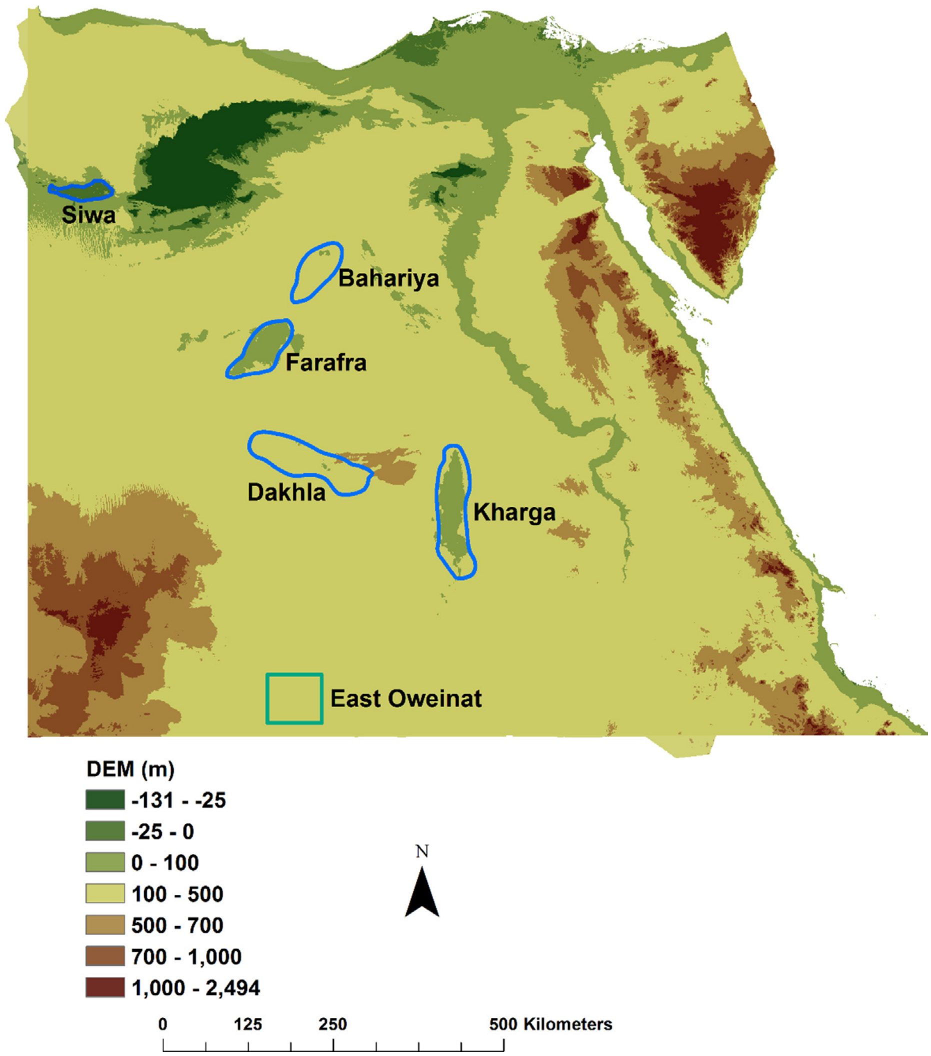

Fig. 2 Locations of groundwater withdrawal in the Western Desert, Egypt [8].

Table 1 Soil and water irrigation classification developed by US Salinity Laboratory [17].

Soil EC (ds/m)	Soil classification	Water EC (ds/m)	Water classification
0–2	Non-saline	0–0.25	Low salinity
2–4	Low salinity	0.25–0.75	Medium salinity
4–8	Mild salinity	0.75–2.25	High salinity
8–16	High salinity	> 2.25	Very high salinity
> 16	Severe salinity		

Table 2 Groundwater salinity in different locations of Siwa [18].

Location	EC (ds/m)	
	1998	**2008**
North and middle of Siwa	3.92	5.2
Western Siwa	4.09	5.6
Maraqi area	6.54	9.51
Zeitoun area	8.1	10.7
Mean	**5.7**	**7.8**

results are shown in Table 2 indicating from 1998 to 2008, groundwater salinity increased in the entire Siwa region from 5.7 to 7.8 ds/m, respectively with highest values in Zeitoun area. Abo El-Fadl et al. [19] collected 24 groundwater samples from different shallow and deep wells in 2014 and showed that total dissolved salts (TDS) from shallow wells range from 1794 to 7473 ppm (2.8 to 11.5 ds/m). The highest values were found in Siwa, Aghurmi, and Zeitoun lakes. TDS from deep wells ranged from 169 to 325 ppm (0.26 to 0.5 ds/m). Aly [20] measured soil salinity in 2011 from 10 different locations in Siwa and the EC values range from 4.7 to 12.3 ds/m with the highest values were found around Aghurmi Lake, and the western region of Siwa Lake.

Although groundwater withdrawal from NSAS comes from six major locations, Siwa is the focus of this study because of its large volume of groundwater available for the future expansion of the agricultural area under proper management. Several studies analyzed groundwater withdrawal in Siwa [8,21] and others monitored the changes in lakes area [12,13]. However, none of the studies focused on the efficiency of groundwater use and the long term management affecting salt lakes formation. Others have monitored groundwater and soil quality [18,19,20,22], but, the effects of salinity on agricultural productivity or income have not been studied as well.

Therefore, the primary purpose of this research is to assess the efficiency of groundwater use from the Nubian aquifer and the corresponding negative impacts on crop yields and income.

2. Study area description

Siwa is a region with a natural depression located in the Matrouh Governorate, northwest of the Western Desert (see Fig. 2). It has an area of 1,200 km^2 (or 285,714 acres) with an elevation ranging from 0 to −25 m above mean sea level. It is located between longitudes 25° 16′ and 26° 7′ E and latitudes 29° 7′ and 29° 21′ N. Climate in this region is arid to semi-arid with monthly average maximum and minimum temperatures of 39.6 °C in August and 7 °C in January, respectively. Monthly average maximum and minimum relative humidity are 60% in December and 29% in May, respectively. Average annual rainfall is 13 mm and evaporation ranges from 5.2 mm/day in December to 17 mm/day in June [10,22].

RS and GIS were used in Siwa to define land uses in 2006. A Landsat Enhanced Thematic Mapper Plus (ETM+) image was downloaded from the United States Geological Survey (USGS), and Supervised Classification was used by GIS. Fig. 3 shows the land use of Siwa which includes six saline lakes; Maraqi, Siwa, Aghurmi, Zeitoun, Tamera, and Massir. Around these lakes, there are wet and dry marshes which cover 40% of Siwa's land area, whereas cultivated areas only cover about 6%.

The region's primary economic activity is agriculture, which in turn depends on NSAS. The two major cash crops are olives and date palms, whereas the other crops are for local consumption. Groundwater is the only source of water in Siwa. PNA has high salinity ranging from less than 4.62 to 10.8 ds/m that can be used for irrigation with restrictions but not for domestic use. However, NAS contains high-quality groundwater with a lower salinity of 0.31–0.62 ds/m that can be used for all purposes [19,21].

2.1. Historical use of the Nubian aquifer

Siwa is a unique oasis given the natural depression and groundwater is under pressure. Groundwater pressure in PNA ranges from 0 to 10 m above mean sea level. However, groundwater pressure in NAS ranges from 80 m in the west of Siwa to 120 m in the east [23,21]. From 1960 to 1980, the only source of water was 200 flowing springs with a total discharge of 65.9 MCM/year which was used to irrigate 2000 acres [7,8,21]. Groundwater from these springs is recharged from PNA. In the period from 1962 to 1977, the water table increased about 1.33 cm/year [24]. Since the discharges from these springs started to decrease in 1981, farmers built about 700 wells (±100 m) which freely discharge from PNA [7]. These hand-dug wells were poorly designed and operated without proper management. When the discharge from a well decreases, farmers tend to build a new well without government approval. In 1990, the total discharge from PNA was 235 MCM from 1350 shallow wells [7,21]. From 1977 to 1990 the water table increased about 4.6 cm/year [24]. In 1991, the government developed five deep wells of ±1000 m depth for drinking purposes with an annual discharge of about 20 MCM using high water quality of NAS. By the end of 1998, there were 1500 shallow wells and the total annual discharge from both aquifers reached 308 MCM [7].

Starting in 1996, Research Institute for Groundwater (RIGW) monitored the wells used for groundwater withdrawal. They found that only 60% of groundwater withdrawal was used for irrigation and the rest found its way through the existing poor drainage system [21]. RIGW later developed new regulations on withdrawal from the Nubian aquifer. More

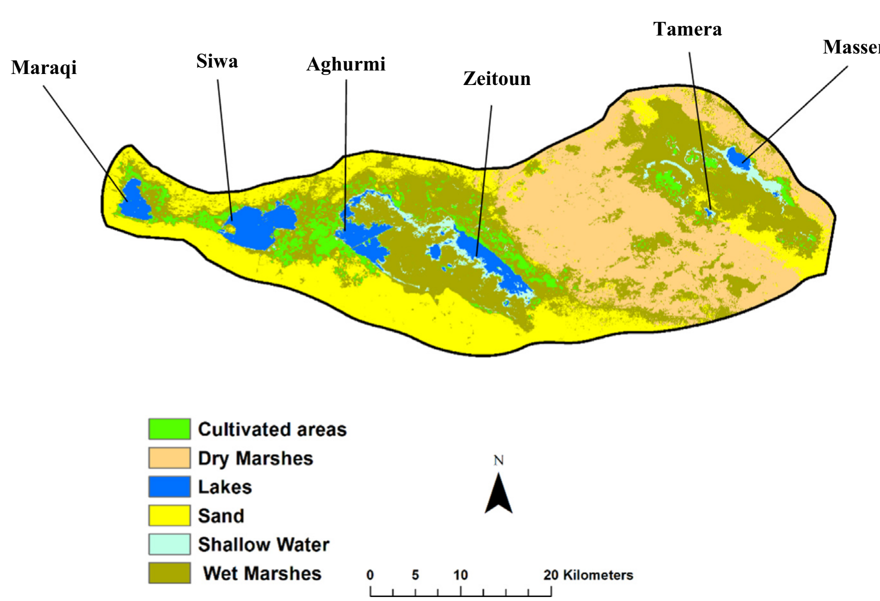

Fig. 3 Land use of Siwa in 2006.

than 300 shallow wells were closed and replaced with 180 legal wells [21]. In 2006, the total annual groundwater withdrawal reached 275 MCM [25] and continued to decrease to 172 MCM in 2012 [26].

3. Methodology

3.1. Water use

The total water use in Siwa was estimated from 1980 to 2012. Total water use is the sum of crop water irrigation, and domestic and industrial water uses. Industrial water demand is insignificant compared to crop water demand [27]. Therefore, it can be ignored and only crop water irrigation and domestic water use are considered.

Evapotranspiration (ET) was calculated to determine crop water demand. The FAO Penman-Monteith method was used to calculate reference evapotranspiration (ET_o) on a monthly basis [28]. The FAO Penman-Monteith equation is given as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_o is monthly reference evapotranspiration (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean monthly air temperature at 2 m height (°C), u_2 is monthly average wind speed at 2 m height (m/sec), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is slope vapor pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$).

$$G_{month,i} = 0.14(T_{month,i} - T_{month,i-1}) \quad (2)$$

where $T_{month,i}$ is mean air temperature of month i (°C), and $T_{month,i-1}$ is mean air temperature of the previous month (°C).

$$R_n = R_{ns} - R_{nl} \quad (3)$$

where R_{ns} is incoming net shortwave radiation (MJ m^{-2} day^{-1}), and R_{nl} is outgoing net longwave radiation (MJ m^{-2} day^{-1}).

$$R_{ns} = (1 - \alpha)R_s \quad (4)$$

where α is albedo (0.23), and R_s is incoming solar radiation (MJ m^{-2} day^{-1}).

$$R_{nl} = \sigma\left[\frac{{T_{max,K}}^4 + {T_{min,K}}^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}}\right) \quad (5)$$

where σ is Stefan-Boltzmann constant (4.903*10^{-9} MJ K^{-4} m^{-2} day^{-1}), $T_{max,K}$ is maximum absolute temperature in K, $T_{min,K}$ is minimum absolute temperature in K, and R_{so} is clear-sky radiation (MJ m^{-2} day^{-1}).

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a \quad (6)$$

where k_{Rs} is adjusted coefficient (0.16 $°C^{-0.5}$ for interior locations), T_{max} is maximum air temperature (°C), T_{min} is minimum air temperature (°C), and R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}).

$$R_{so} = (0.75 + 2 * 10^{-5}z)R_a \quad (7)$$

where z is the elevation above sea level (m).

$$R_a = \frac{24(60)}{\pi}G_{sc}d_r[\omega_s\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \quad (8)$$

where G_{sc} is solar constant (0.0820 MJ m^{-2} min^{-1}), d_r is the inverse relative distance Earth–sun (dimensionless), ω_s is sunset hour angle (rad), φ is the latitude (rad), and δ is the solar declination (rad).

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (9)$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad (10)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (11)$$

where J is the number of the day in the year.

To calculate monthly ET_o, four meteorological data types are required; maximum temperature, minimum temperature, wind speed, and relative humidity. The available monthly data relevant to Siwa from 1980 to 2012 were downloaded from the National Centers for Environmental Prediction (https://globalweather.tamu.edu/).

Crop evapotranspiration ET_c (mm/day) is actual crop water demand and monthly ET_c was calculated as [28]:

$$ET_c = K_c * ET_o \quad (12)$$

where K_c is the crop coefficient (dimensionless).

Crop coefficient values should be used under standard climatic conditions with a minimum relative humidity of 45% and moderate wind speed with an average of 2 m/sec. If the actual climatic conditions differ from standard conditions, then crop factor values should be adjusted as described by [28].

Annual ET_c is computed as:

$$ET_c = \sum(K_c * ET_o) \quad (13)$$

After crop water demand was calculated, crop water irrigation was estimated as follows [29]:

$$IR = \frac{ET_c - R}{(1 - LR) * E} * 4.2 \quad (14)$$

where IR is crop irrigation requirement (m^3/acre/day), R is effective rainfall (mm/day) which is almost negligible in Siwa [22], LR is leaching requirement, E is irrigation efficiency, and 4.2 is a conversion factor from mm/day to m3/acre/day. Furrow irrigation is the domain irrigation system in Siwa [21]. The corresponding efficiency is 65% [30,31]. Elnashar [32] provided values of LR for crops in Egypt under different irrigation water salinity conditions and accumulated salts in soils. Due to the use of high groundwater salinity from PNA, we found that 20% is a good estimate as recommended by Abdrabbo et al. [33].

To estimate the total water use since 1980, data on crop types, areas, and population are needed. Crop areas from the years 2000–2011 are shown in Table 3 [27] where olives, date palms, and alfalfa are occupying the largest areas. The cultivated area was only 2,000 acres in 1980 and thereafter, increased to 10,000, 13,352, and 17,182 acres in 1995, 2000, and 2011, respectively [7,27].

As a consequence of missing data, the following assumptions were made: (a) before 2000, only three crops were cultivated; olives, date palms, and alfalfa with areas distributed at 53%, 37% and 10%, respectively; (b) cultivated areas gradually increased from 1980 to1995 and from 1995 to 2000; and (c) crop area distributions are the same in 2011 and 2012.

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Table 3 Areas of cultivated crops (in acres) in Siwa [27].

Year	Winter Vegetables	Summer Vegetables	Wheat	Barley	Broad Bean	Winter Onion	Alfalfa	Olives	Date Palms	Other	Total
2000	67	59	77	41	6	29	1,450	7,619	5,250	204	14,802
2001	47	93	15	50	6	10	1,450	7,646	5,250	209	14,776
2002	43	47	50	0	6	10	1,300	7,650	5,000	283	14,389
2003	43	72	30	0	5	12	1,300	7,650	5,000	156	14,268
2004	35	61	58	150	5	32	1,300	7,700	5,642	232	15,215
2005	67	62	140	0	5	32	2,000	7,700	5,642	232	15,880
2006	68	87	150	0	6	35	2,848	7,750	5,642	234	16,820
2007	32	110	70	40	0	0	2,830	8,000	5,800	233	17,115
2008	66	238	150	35	0	60	2,850	8,000	5,800	234	17,433
2009	39	90	200	20	0	0	2,850	8,000	5,800	234	17,233
2010	30	91	175	0	0	32	2,800	8,000	5,800	233	17,161
2011	59	79	200	0	0	0	2,800	8,000	5,800	244	17,182

Table 3 provides the guide for assumption (a) to use the same crop pattern for olives, date palms, and alfalfa. Additionally, these three crops have been cultivated over larger areas compared with other crops. Assumption (b), regarding the gradual increase in agricultural areas, was made because groundwater withdrawal has been increasing since 1980. Assumptions (c) was made due to the unknown crops area distributions in 2012. Eq. (14) was used to calculate annual crop water irrigation from 1980 to 2012.

Population in Siwa increased from 7,200 in 1976 [34] to 26,610 in 2009 [27]. In 2016, population reached 32,741 (https://en.wikipedia.org/wiki/Siwa_Oasis accessed in June 2019). Average domestic water use is assumed to be 70 and 100 m^3/capita/year before and after 2000, respectively [1,3]. Therefore, annual domestic water use was calculated from 1980 to 2012.

3.2. Water use efficiency (WUE)

A rapid increase in population with limited water resources increases the risk of water scarcity. Therefore, improving WUE is vital, particularly in arid and semi-arid regions. Unfortunately, WUE has different definitions in literature. For example, Sinclair et al. [35] defined WUE as the ratio between crop yield to crop water use. Ali and Talukder [36] defined WUE as the amount of water used to produce a crop. Meanwhile, FAO [37] has a different definition, where WUE is the ratio between effective water use and actual water withdrawal. Given that the focus of this study is making comparisons between actual withdrawal in Siwa and the estimated water use, the FAO [37] definition was used.

3.3. Lake areas

The changes in the areas of all Siwa lakes were monitored from 1987 to 2010 to study the effect of groundwater management on lakes areas. Due to the lack of field data, RS and GIS are used. There are different indices that extract water bodies using RS such as Normalized Difference Water Index [NDWI; 38], Modified Normalized Difference Water Index [MNDWI; 39], and Automated Water Extraction Index [AWEI; 40]. NDWI was calculated as [38]:

$$\mathrm{NDWI} = \frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}} \tag{15}$$

where Green is a green band and NIR is a near-infrared band which represent bands 2 and 4 respectively, in Landsat Thematic Mapper (TM). Positive values represent water bodies while zero and negative values represent vegetation and soil [38]. Satellite images from Landsat TM are used for years; 1987, 1993, 2000, 2005, and 2010. These images are with spatial resolution 30 m and can be downloaded using USGS Global Visualization Viewer (GLOVIS) (https://glovis.usgs.gov/ accessed in May 2019).

3.4. Groundwater and soil salinity

The changes in groundwater and soil salinity in Siwa were analyzed. As PNA is commonly used for irrigation while it has high groundwater salinity. Groundwater salinity data about PNA are provided by RIGW. In 1996 more than 1200 groundwater samples were collected from different shallow wells to monitor groundwater quality [41]. Again in 2013, RIGW collected groundwater samples from 42 wells [21]. Due to the limited field data available on soil salinity, data and results from Aly [20] are also used.

3.5. Crop yield

World Bank et al. [42] stated that calculating crop yield is one of the essential indicators of agricultural development. Crop yield is the amount of crop production harvested per unit of land area (tons/acre). Since olives and date palms have the largest crop areas in the region while being the cash crops, yields of these crops were calculated from 2000 to 2011. Data on yields of these crops were collected from the Agriculture Directorate of Matrouh [43].

High groundwater and soil salinity may affect crop yield, especially for crops with lower tolerance to salinity. Maas and Hoffman [44], and Ayers and Westcot [45] provided toler-

Table 4 Crop tolerance related to water and soil salinity [45,46].

Crop	EC (ds/m)	Maximum yield	Yield reduction by 10%	Yield reduction by 25%	Yield reduction by 50%	Can't be cultivated
Olives	Water	1.8	2.6	3.7	5.6	11
	Soil	2.7	3.8	5.5	8.4	14
Date Palms	Water	2.7	4.5	7.3	12	21
	Soil	4	6.8	11	18	32

ance values of crops, with regards to water and soil salinity as shown in Table 4. This table is used to study the effect of salinity on crop yields.

3.6. Net revenue

To understand the impact of high salinity on crop yield and therefore on the local economy, it is important to calculate net revenue. Net revenue is calculated as follows:

$$\text{Net revenue} = (\text{Price} * \text{Yield}) - \text{Cost} \quad (16)$$

where units of net revenue and cost are in \$/acre, price in \$/ton, and yield in tons/acre. Through the period from 2000 to 2011, the average price of olives and date palms are \$569 and \$711 per ton, respectively [27] and the average cost per acre for both is \$747 [46] in 2010 dollars. This cost included labor, seeding, irrigation, pesticides, fertilizers, and maintenance.

3.7. Trend and correlation tests

Many statistical tests have been developed to detect the trends of variables over time. Linear regression is a parametric test that assumes a normal distribution of data. However, Mann-Kendall [47,48] and Spearman's Rho [49,50] are non-parametric tests that applicable independent of existing distributions of the variables. In this study, Mann-Kendall and Spearman's Rho are applied to investigate the changes of groundwater salinity, yields of olives and date palms and their revenue over time from 2000 to 2011. The null hypothesis (H_0) is that there is no trend over time, while the alternative hypothesis (H_1) is that there is a positive or negative trend. Correlation tests are used to measure the strength of relation between variables. Results are considered significant when two-sided p-value $<$ 0.025. R software version 3.6.1 has been used for these tests (https://www.r-project.org/).

As groundwater salinity data is few and limited, the observed average salinity in 1996 and 2013 and the data from Aly et al. [18] in 1998 and 2008 are used in this analysis. Accordingly, EC values are assumed gradually increased during each period.

4. Results and discussion

4.1. Water use efficiency

One goal of this work is to calculate water use efficiency in Siwa. Therefore, total water use is estimated, which is the sum of crop water irrigation and domestic water use. Monthly average ET_o in Siwa from 1980 to 2012 was calculated using Eq. (1). The results showed that maximum ET_o is 9.8 mm/day in June and the minimum is 2.7 mm/day in January. Fig. 4 shows a comparison between the calculated monthly average ET_o values and the estimated values by Farrag et al. [51]. The results show that there are slight differences between both results which range from −0.47 to 0.76 mm/day with a

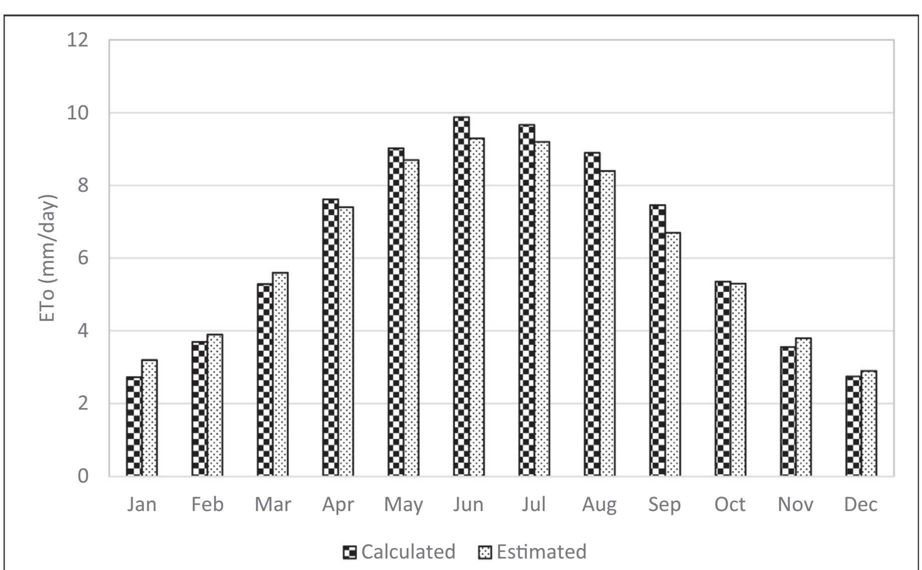

Fig. 4 Comparison between calculated monthly average ET_o from 1980 to 2012 and estimated values by Farrag et al. [51].

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mean value of 0.126 mm/day and standard deviation of 0.4 mm/day.

To calculate crop water demand, crop evapotranspiration was calculated using Eq. (13). Average water demands for cultivated crops were calculated for the period of 2000–2012 and compared with published literature as shown in Table 5. The comparison shows that water demand values are within the acceptable ranges.

Crop water irrigation from Eq. (14) and domestic water use were calculated from 1980 to 2012. A comparison between estimated total water use and actual withdrawal in Siwa is shown in Fig. 5. It is clear that total water use is gradually increasing since 1980 due to the increase in population and cultivated areas. However, actual groundwater withdrawal has been increasing rapidly given the readily available groundwater present under pressure in shallow wells. The difference between actual withdrawal and estimated total water use is excess water and can be defined as wasted water. In the absence of an appropriate groundwater management plan, these excess water amounts were significant until 1998. Table 6 shows the values of excess water and WUE. Excess water volume increased about 336% over 19 years (1980–1998). In this period WUE was low with an average of 35% due to the large volume of groundwater from uncontrolled shallow wells. After the closure of many wells by RIGW, this excess water volume decreased by about 94.7% from 1998 to 2012. The corresponding WUE increased gradually; 61.3%, 71%, and 93.9% in 2006, 2008, and 2012, respectively showing the importance of groundwater management to avoid the depletion of NSAS and to ensure sustainability for future generations.

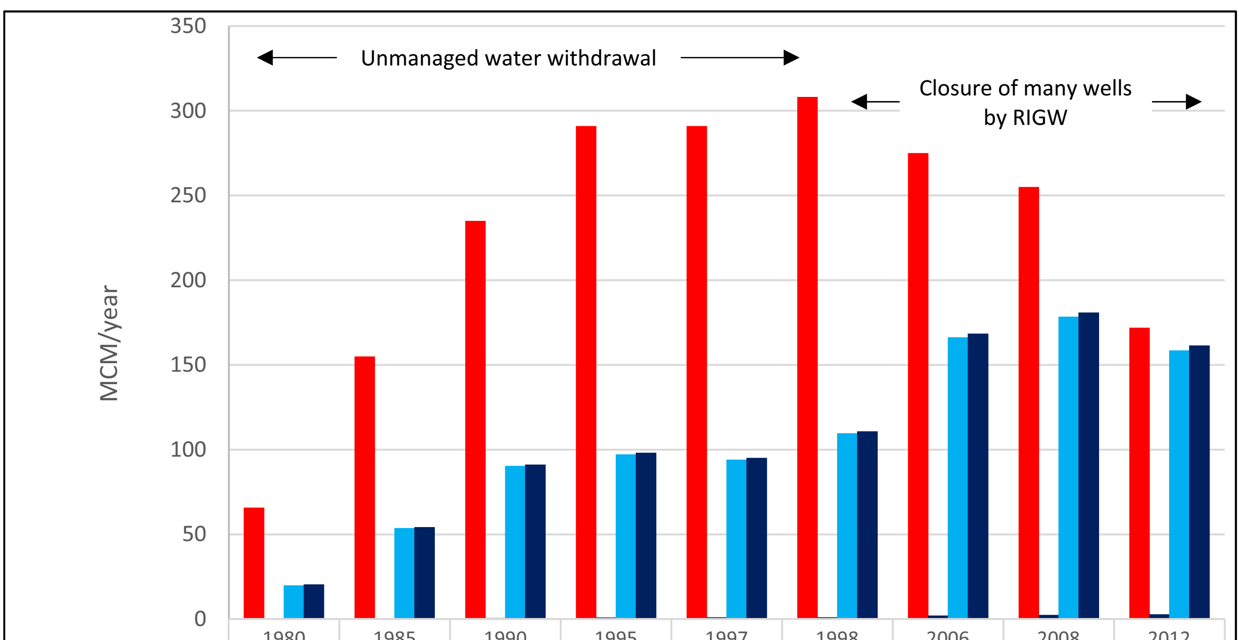
Table 5 Comparison between calculated and estimated crop water demand.

Crop	Calculated crop water demand (2000–2010) (m^3/acre)	Estimated crop water demand (m^3/acre)
Wheat	2,142	1,890–2,730[a]
Barley	1,919	1,890[b]
Broad bean	1,839	1,260–2,100[a]
Onion	1,979	1,470–2,310[a]
Alfalfa	5,443	3,360–6,720[a]
Date palms	5,443	7,000[b]

[a] http://www.fao.org/land–water/databases-and-software/crop-information/en/ accessed in April 2019.
[b] [46].

4.2. Lake areas

NDWI was used to estimate lake areas in Siwa through 1987 to 2010. The results showed that lake area was 11,295 acres in 1987 then continued to increase to 13,096 and 21,348 acres in 1993 and 2000, respectively. Thereafter, this area decreased to 16,852 acres in 2005. In 2010, lake area was 16,144 acres. These findings are similar to the work of Abou El-Magd [12], and Abdallah, and Khedr [13]. In the period from 1987 to 2010, the minimum and maximum areas of lakes were in 1987 and 2000, respectively. Fig. 6 clearly shows that in



	1980	1985	1990	1995	1997	1998	2006	2008	2012
Actual Withdrawal	65.85[1]	155[1]	235[1]	291[1]	291[1]	308.14[1]	275[2]	255[3]	172[4]
Domestic Use	0.5	0.6	0.8	1.0	1.1	1.1	2.1	2.5	2.9
Crop Irrigation	20.0	53.8	90.5	97.3	94.1	109.7	166.3	178.5	158.6
Total Water Use	20.5	54.3	91.2	98.2	95.2	110.9	168.5	181.0	161.5

Fig. 5 Comparison between actual withdrawal and estimated total water use in Siwa. [1][8]. [2][25]. [3][53]. [4][26].

Table 6 Excess water produced and WUE.

Year	1980	1985	1990	1995	1997	1998	2006	2008	2012
Excess water (MCM)	45.3	100.7	143.8	192.8	195.8	197.3	106.5	74	10.5
Water use efficiency %	31	35	39	34	33	36	61	71	94

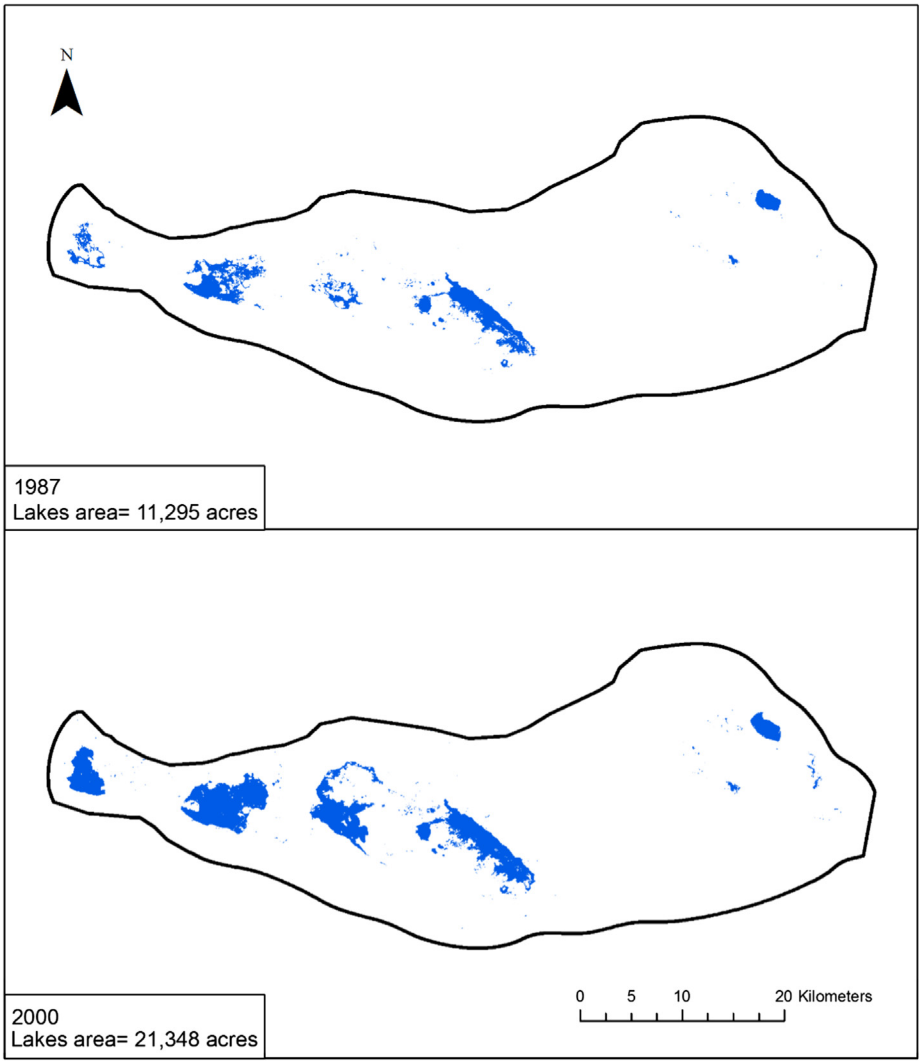


Fig. 6 A comparison of salty lake areas between 1987 and 2000.

2000, there is a significant increase in the areas of lakes; Maraqi, Siwa, and Aghurmi.

Fig. 7 shows the relationship between groundwater withdrawal and lake areas. These results show that from 1980 to 1990, groundwater withdrawal increased about 257%. As a consequence, lake areas covered 11,295 acres in 1987. From 1990 to 1995, groundwater withdrawal continued to increase by about 24%. This continuous withdrawal without proper management increased lakes area by about 89% over fourteen years (1987–2000). After the closure of hand-dug wells, groundwater withdrawal decreased by about 11% (1998–2006). The replacement of old dug-wells with newly designed wells with proper management by the government, decreased groundwater withdrawal by about 33% from 2008 to 2012. As a consequence, lake area decreased by 24% over 10 years (2000–2010).

Comparing these two situations before and after 1998 confirms that there is a direct relationship between groundwater withdrawal and lake areas. As a large volume of unused excess water is accumulated in addition to an existing poor drainage system produced salty lakes causing waterlogging in Siwa. This shows the necessity of proper groundwater management. As good management practices help formulate effective and productive groundwater withdrawal, excess water production is decreased and as a consequence lakes areas have decreased. It is also important to improve the drainage system in Siwa to help reducing lakes areas further.

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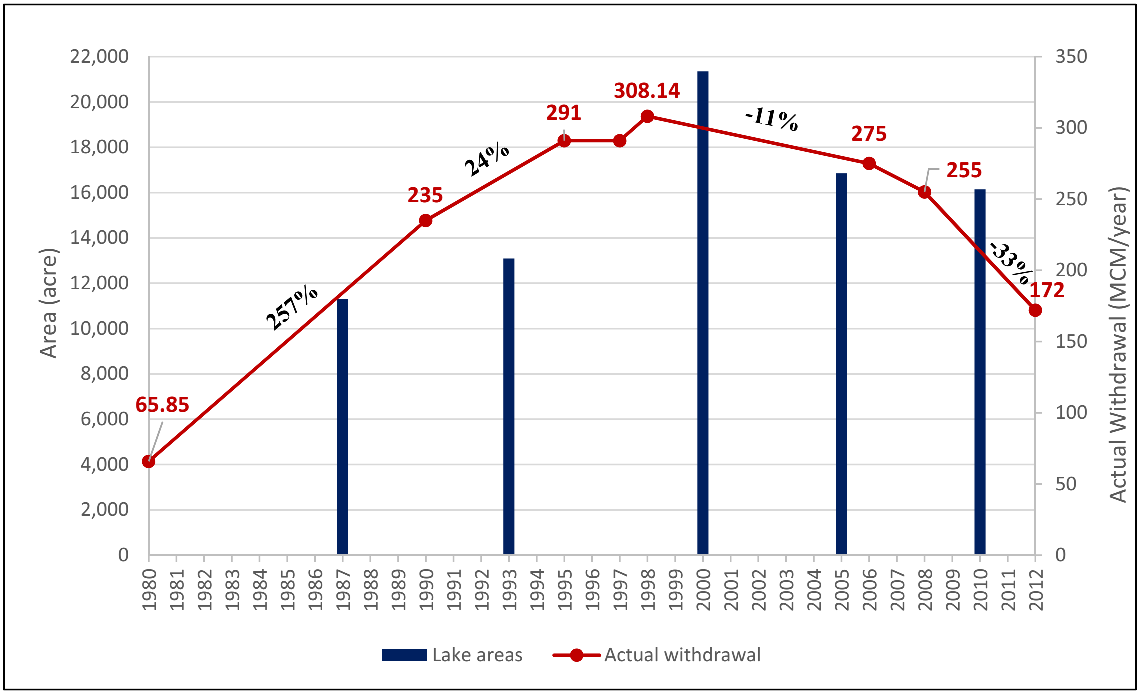

Fig. 7 Relationship between groundwater withdrawal and lake areas (numbers in percentage are the changes in withdrawal through different periods).

4.3. Groundwater and soil salinity

EC data from RIGW is used to analyze the changes in groundwater salinity in 1996 and 2013. The results show that groundwater EC values in Siwa increased from 1996 to 2013 with an average of 4.5 and 10.5 ds/m, respectively. According to US Salinity Laboratory [17] information shown in Table 1, groundwater is classified as *very high salinity* with an increase of 100% to 366% above the acceptable ranges in 1996 and 2013, respectively indicating severe restrictions using water for irrigation. In such instances, more water is required for leaching in addition to the choice of crops that can tolerate high salinity.

Fig. 8 shows a comparison between groundwater salinity distribution in 1996 and 2013 in Siwa using inverse distance weighted interpolation. The results in Table 7 show that the Zeitoun area has the highest EC in 1996. However, in 2013, Aghurmi area and the western part of Siwa lake have the highest EC values. These results are in agreement with the findings of Aly et al. [18] who found that EC values in PNA increased from 1998 to 2008 as listed in Table 2. The increase in groundwater salinity is due to the excess usage of groundwater from PNA for irrigation in addition to the existing of poor drainage in the region.

The results from Aly [20] found that soil EC values of 4.7–12.3 ds/m in 2011. Using the soil classifications of Richards [17] shown in Table 1, mild (4 < EC < 8) to high (8 < EC < 16) soil salinity affects yields of many of crops. This finding is not surprising in existing salty lakes in Siwa given the accumulation of salts on the surface.

4.4. Crop yield and revenue impact

Yields of olives and date palms are calculated from 2000 to 2011. Fig. 9 shows that in 2000, the yield of olives was 4 tons/acre but decreased to 2.2 tons/acre in 2011, amounting to a 46% decrease. The same occurred with date palms, where the yield decreased from 10 tons/acre in 2000 to 4.5 tons/acre in 2011 with 55% decrease. The average yield of olives and date palms from 2000 to 2011 were 2.9 and 8.4 tons/acre, respectively (Fig. 9). The corresponding average values in Egypt were; 3.63 and 14.6 tons/acre, respectively [52]. The comparison showed that in Siwa, there were a decrease of 20% and 42% in yields of olives and date palms, respectively. Therefore, it is important to analyze the factors causing this decrease in yields and the corresponding revenue impacts.

Fig. 10 shows net revenues for olives and date palms from 2000 to 2011. Net revenue for olives changed from $1,564/acre in 2000 to $491/acre in 2011 with a decrease of 68%. Similarly, net revenue for date palms decreased from $6,418/acre in 2000 to $2,426/acre in 2011, with 62% decrease. This decrease in net revenue affects farmer income, and therefore, the local economy. For a region with limited economic activity, this type of decrease in agricultural income can be a devastating for the local population.

4.5. Effect of salinity on crop yield and revenue

Figs. 9 and 10 show that the yields and net revenue of olives and date palms are decreasing with time from 2000 to 2011. However, groundwater EC values are increasing annually throughout this period. Mann-Kendall and Spearman's Rho tests are both applied to investigate the significance of trend for these variables over time. Table 8 shows the results of these two tests where the decrease of yields and net revenue for olives and date palms are significant throughout this period with 95% confidence interval. The increase of groundwater salinity is also significant at 95% level. To detect the correlation between these variables, Kendall and Spearman

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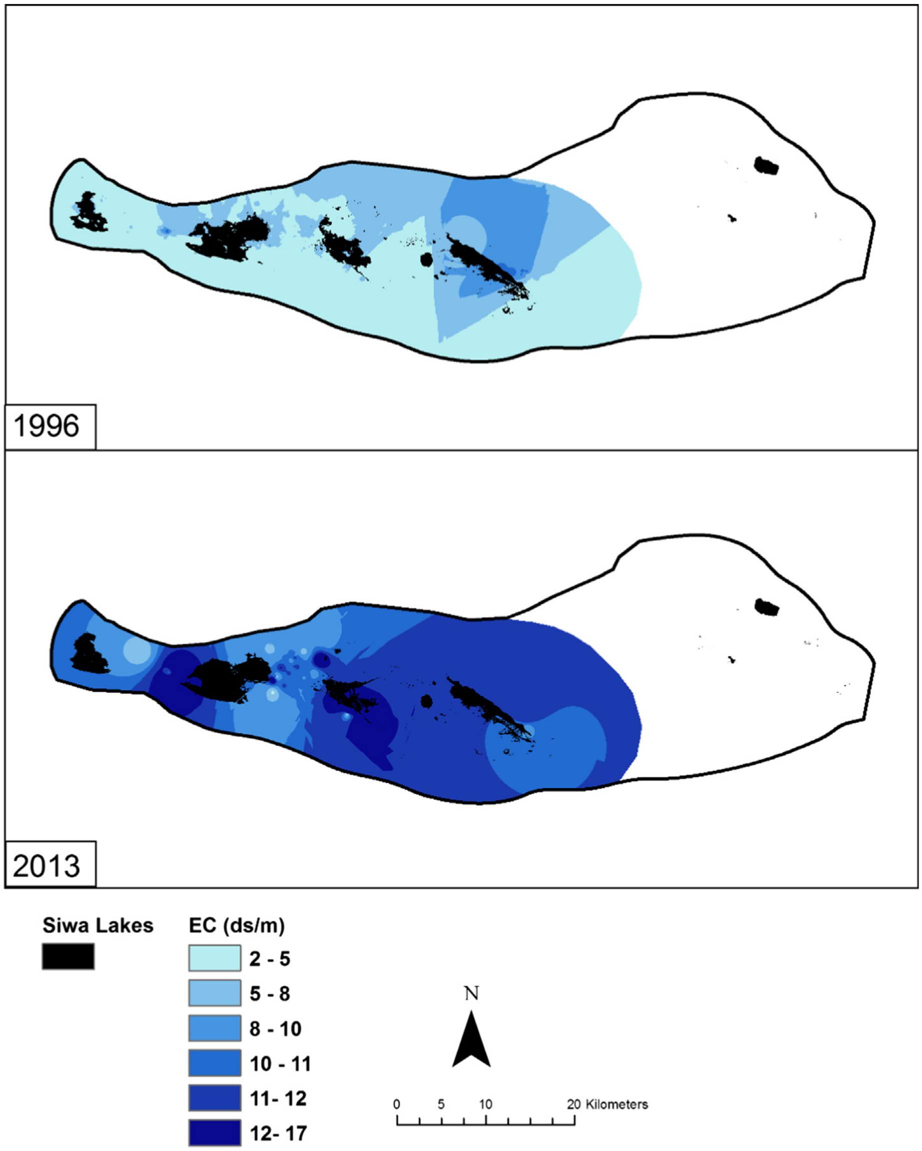

Fig. 8 Comparison between groundwater salinity distribution in 1996 and 2013.

Table 7 Comparison between groundwater salinity in 1996 and 2013.

Location	EC (ds/m)	
	1996	2013
Maraqi area	2–5	8–11
Siwa area	2–8	8–17
Aghurmi area	2–8	12–17
Zeitoun area	5–10	10–12

correlation tests are applied. Figs. 11 and 12 show the correlation coefficients between groundwater salinity and the yields and net revenues of olives and date palms, respectively using both tests. These results show that there is significant negative correlation between groundwater salinity and olives yield as the correlation coefficients are −0.56, −0.74 using Kendall and Spearman, respectively. The same for date palms that yield has a significant negative correlation with groundwater salinity where coefficient values are −0.55, −0.75 using Kendall and Spearman, respectively. Correlation between yield and net revenue for both crops is statistically significant with a coefficient value of 1 which is not surprising as net revenue depend on yield (Eq. (16)). Therefore, the correlation tests show that increase in groundwater salinity decreased yield and net revenue for both crops.

However, correlation does not necessarily produce information on causation. The observed data of groundwater and soil salinity are used to identify the sensitivity of crop yields to salinity in Siwa. According to work of Maas and Hoffman [44], and Ayers and Westcot [45] shown in Table 4, when the average EC values of groundwater are 4.5 and 10.5 ds/m in 1996 and 2013, respectively, then the expected decrease for olives yield range from 36% to 95%, respectively. The same for date palms is 10% to 42% in 1996 and 2013, respectively. Meanwhile, soil EC values ranged from 4.7 to 12.3 ds/m in 2011 that corresponds to a decrease in olives yield in the ranges

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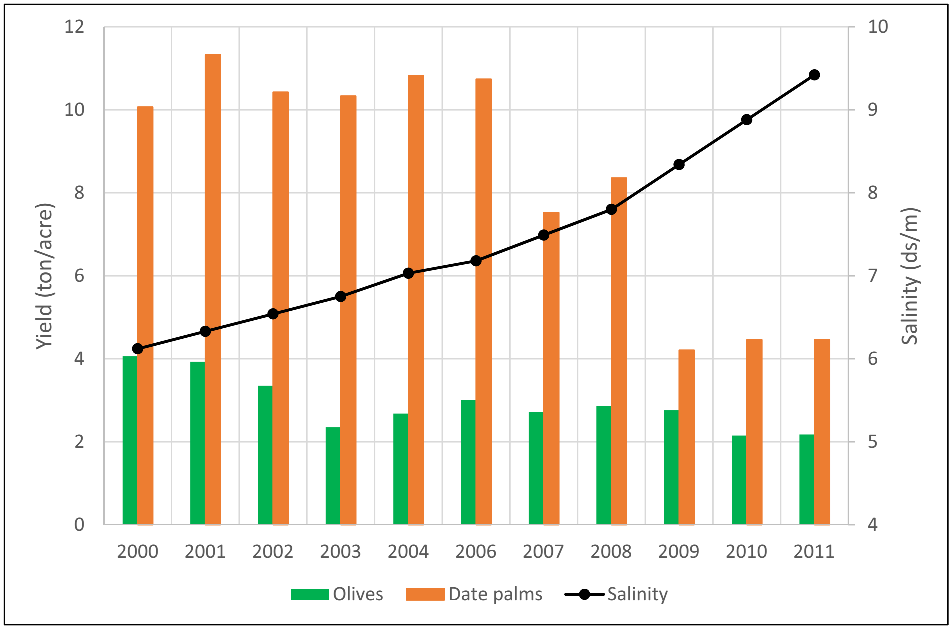

Fig. 9 Groundwater salinity and yields of olives and date palms.

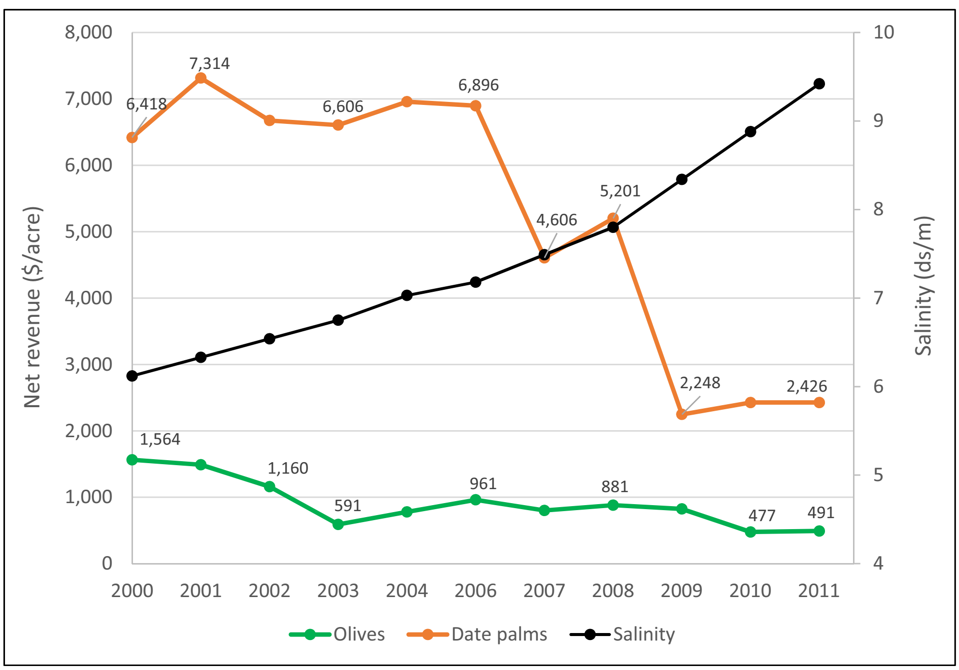

Fig. 10 Groundwater salinity and net revenues of olives and date palms.

Table 8 Mann-Kendall and Spearman's Rho trend results.

Parameter	Mann-Kendall		Spearman	
	τ	2 sided p-value	ρ	2 sided p-value
Olives yield	−0.564	0.019517*	−0.736	0.01338*
Olives revenue	−0.564	0.019517*	−0.736	0.01338*
Date palms yield	−0.55	0.023542*	−0.7517	0.0076*
Date palms revenue	−0.55	0.023542*	−0.7517	0.0076*
Groundwater salinity	1	2.62E-05*	1	< 2.2E-16*

* Statistically significant at $p < 0.025$.

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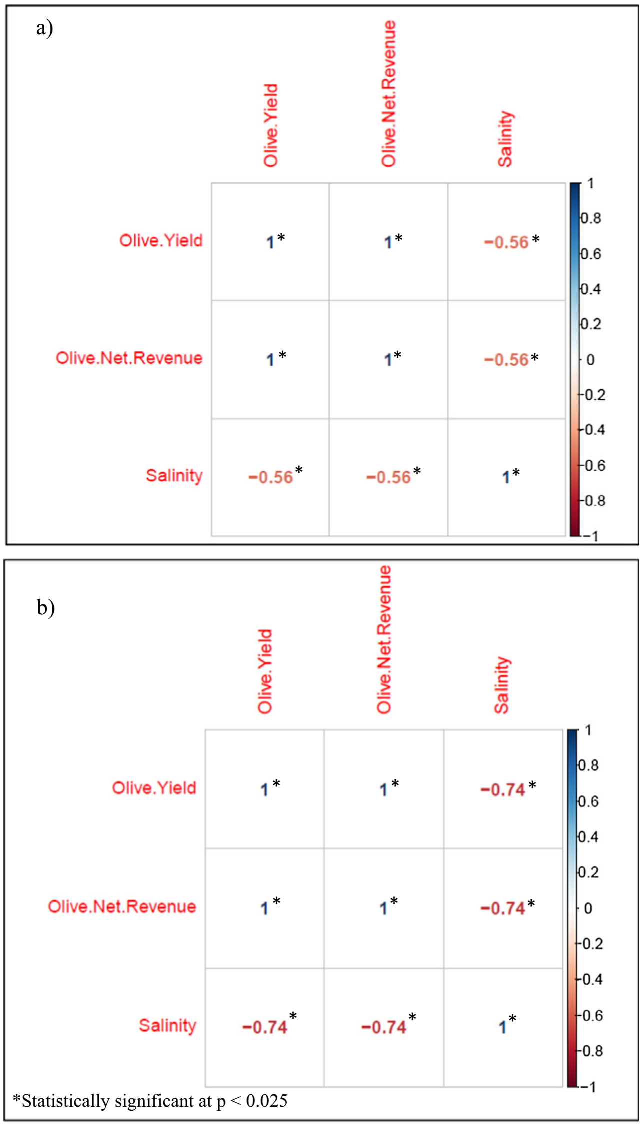

Fig. 11 Correlation coefficients between groundwater salinity and olives using: (a) Kendall test, and (b) Spearman test.

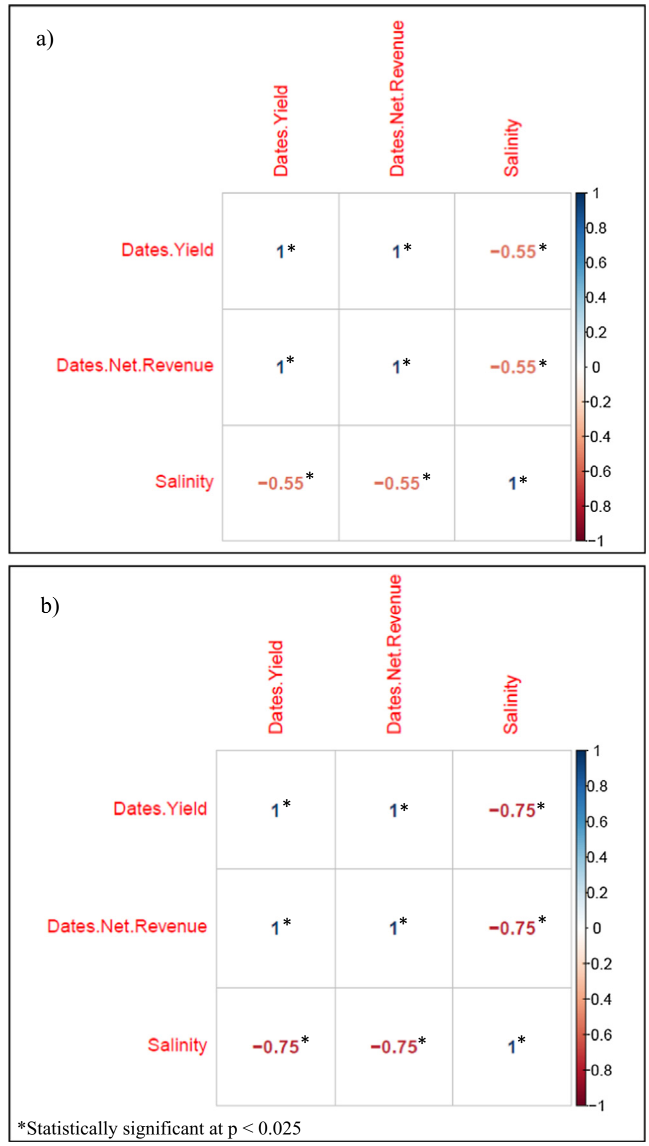

Fig. 12 Correlation coefficients between groundwater salinity and date palms using: (a) Kendall test, and (b) Spearman test.

of 18% to 85% respectively. For date palms, the corresponding decreases are from 2.5% to 30% respectively.

These results confirm that groundwater and soil salinity are the major reasons for crop yield reduction in Siwa which is causing a detrimental impact on rural livelihood, especially in agriculture income indicating salinity management is a priority for this region.

5. Conclusions

The Siwa Oasis was selected for this study to address groundwater development issues and associated impacts in the Western Desert Region of Egypt, given the abundance of groundwater. In this study, the historical water use, groundwater and soil salinity, agricultural crop yield, and agricultural income from the Nubian aquifer in Siwa Oasis were analyzed. Total water use was estimated as the sum of crop water irrigation and domestic water use. Thereafter, estimated water use was compared with actual withdrawal to define the amount of excess water and the corresponding water use efficiency from 1980 to 2012. Normalized Difference Water Index (NDWI) was used to identify the total area of salty lakes in Siwa. The impact of salinity of groundwater and soil on crop yield and the corresponding income were analyzed.

The results show the importance of groundwater management in the Nubian Sandstone Aquifer System. The findings determined that two starkly different situations have taken place in Siwa. Until 1998, total annual groundwater withdrawal was 308 MCM from 1500 shallow hand-dug wells. When this volume is compared with estimated total water use, it was found that a large amount of excess water amounting to 197.3 MCM was produced with only 35% WUE. Due to the increase in excess water since 1960, salty lakes were formed as a result of the existing poor drainage system prevailing in the region. The total area of these lakes reached 21,348 acres in 2000. In 1996, RIGW of Egypt developed policies and

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regulations to limit groundwater withdrawal from the Nubian aquifer. This was an important step and improved the conditions in Siwa by reducing annual groundwater withdrawal to 172 MCM in 2012. Therefore, excess water decreased to 10.5 MCM with an increase of WUE to 94%. As a consequence, the total area of salty lakes decreased to 16,144 acres in 2010.

Average groundwater EC values increased from 4.5 to 10.5 ds/m in 1996 and 2013, respectively. These values exceed the acceptable limit for irrigation water with an increase of 100% to 366%, respectively and classified as very high salinity. Therefore, severe restriction on water use needs to be considered. Soil EC ranged from 4.7 to 12.3 ds/m in 2011 which classified as mild and high salinity. Using PNA as the primary source of irrigation in addition to the existing salty lakes are the major reasons for high groundwater and soil salinity. From 2000 to 2011, the yields of olives and date palms decreased about 46% and 55%, respectively. As a result, net revenues of these crops decreased more than 60%. Mann-Kendall and Spearman trend tests showed that the increase in groundwater salinity and the decrease in crops yield and net revenue over time are significant. The results of this work showed a direct link between the increase in salinity and a corresponding decrease in crop yield affecting income.

In conclusion, the findings of this study clearly show that groundwater management is a critical need in this region, especially to avoid significant depletion of this non-renewable water resource and to ensure the sustainability of this aquifer for future generations. Although recent groundwater management increased WUE and decreased the area of salty lakes, the concerns related to the poor drainage system in addition to high salinity are still present and require immediate attention. It is recommended to use efficient irrigation methods such as drip or sprinkler systems instead of furrow irrigation which is a good solution to decrease water waste. Replacing shallow wells with deep wells given the higher water quality in the deep aquifer with the usage of good drainage systems are important to decrease salinity in Siwa.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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