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Effect of Irrigation by Shallow and Deep Nubian Aquifer on Soil Properties and Crop Production in El-Kufra Oasis, Southern Libya

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crop yield, groundwater, irrigation, private farms, soil properties, state farms.

ABSTRACT

El-Kufra oasis lies in southeastern Libya, deep in the Sahara Desert, covering an area of about 3,630 km^2. Rainfall is deficient, and agriculture depends mainly on irrigation from groundwater (The Nubian aquifer). Most El-Kufra farms are private, using flood water irrigation from shallow wells (18–55 m). The Kufra Agricultural Project (state farms) comprises 100 circles, using deep wells (220–352 m). This study aimed to assess the quality of irrigation water from the shallow and deep aquifer in El-Kufra oasis and its effect on the soil properties and crop production (alfalfa and potato). According to the FAO classification system, 97% of the examined deep wells are suitable for irrigation, only 3% were in the slight to moderate restriction category (E.C.> 0.7 dS/m). However, 78% of the shallow wells were in the severe category degree (E.C.> 3 dS/m), and 22% were in the slight to the moderate category of restriction. The water quality is reflected in the soil properties and crop production. The soils of the state farms were in the normal range for pH, E.C., and ESP% values; meanwhile, 10% of the private farms were classified as saline-non alkali soil, and 70% as saline-alkali soils. The salt accumulation in the soil's root zone affects crop production, most obviously in the private farms as they depend on the shallow aquifer with poor water quality and use inappropriate irrigation and cultivation techniques. This study highlighted the urgent need to transfer the agricultural sector in El-Kufra district to depend on the deep aquifer and adjust the agricultural applications and cultivated crops to be more suitable for the desert environment and salty soils.

الري بالمياه الجوفية النوبية الضحلة والعميقة على خصائص التربة وإنتاج المحاصيل في واحة الكفرة ، ليبيا

عياد عبدالكريم بوخريم[1] يونس عبدالمولى محمد الهنداوي[2] . منعم وافي براني سعيد[3]

تقع واحة الكفرة في أقصى جنوب شرق ليبيا، في عمق الصحراء الكبرى. وهي تغطي مساحة تقدر بحوالي 3630 كيلومتر مربع. الأمطار في هذه المنطقة الصحراوية والجافة تعتبر نادرة الحدوث، والزراعة فيها تعتمد بشكل أساسي على المياه الجوفية (الخزان النوبي). معظم المزارع في منطقة الكفرة وما حولها تعتبر مزارع خاصة تستخدم طريقة الغمر في عمليات الري من آبار ضحلة (بعمق 18–55 متر) من الخزان الجوفي العلوي. أما مشروع الكفرة الزراعي (الحكومي) فيتكون من 100 دائرة (قطر كل منها حوالي 1 كيلومتر وتغطي مساحة 78.5 هكتار) ويعتمد على آبار عميقة (بعمق 220–352 متر) من الخزان الجوفي العميق. هذه الدراسة هدفت إلى تقييم جودة مياه الري في كلا الخزانين الجوفيين العلوي والعميق في منطقة الكفرة، وتقييم تأثيرها على خواص التربة وإنتاجية المحاصيل (الصفصفة والبطاطس). طبقا لتقسيم مياه الري لمنظمة الفاو (FAO)، فقد صنفت مواصفات المياه المنتجة من 97% من الآبار العميقة التي تمت دراستها بأنها ملائمة لعمليات الري، وفقط 3% وقعت تحت فئة التحفظ

البسيط إلى المتوسط في الاستعمال للري (E.C.> 0.7 dS/m). وصنفت مياه 78% من الآبار الضحلة حسب تصنيف الفاو في الفئة ذات التحفظ الشديد جدا للاستعمال في الري نتيجة ارتفاع ملوحتها (E.C.> 3 dS/m)، وصنفت 22% من الآبار الضحلة تحت فئة التحفظ البسيط إلى المتوسط في الاستعمال. درجة جودة المياه المستعملة في الري في واحة الكفرة انعكست بشكل مباشر على خصائص التربة وإنتاجية المحاصيل المزروعة. ترب المزارع الحكومية بمشروع الكفرة كانت لها قيم طبيعية لكل من pH، .E.C، و ESP%، في حين صنفت ترب 10% من المزارع الخاصة كترب ملحية غير قلوية، و 70% كترب ملحية قلوية. تركم الأملاح في منطقة نمو الجذور بالتربة يؤثر بشكل كبير على إنتاجية المحاصيل المزروعة، وبشكل أكثر وضوحا في ترب المزارع الخاصة لاعتمادها على مياه الآبار الضحلة مرتفعة الملوحة، وأيضا نظرا لاستخدام طرق ري غير مناسبة. هذه الدراسة سلطت الضوء على ضرورة وأهمية اتخاذ إجراءات عاجلة جدا من أجل نقل قطاع الزراعة في واحة الكفرة للاعتماد على الخزان النوبي الجوفي العميق وعلى تغيير أساليب الزراعة وطرق الري وعلى اختيار المحاصيل الأكثر مناسبة للمناخ الصحراوي الجاف وللترب الملحية القلوية.

INTRODUCTION

In Libya, water demand is rapidly increasing, forcing the intense exploitation of groundwater resources, particularly in the country's south arid areas (Sahara Desert). In El-Kufra oasis and most of the southern parts of Libya, groundwater is the only available water resource, and its development has increased rapidly during the last fifty years. In agricultural production, groundwater usage in southern parts of Libya is an essential and indispensable practice.

According to the figures provided by the Food and Agricultural Organisation (FAO), agriculture is responsible for 69% of the world's water consumption (FAO, 2002). The Libyan context is no exception; on average, the agricultural sector consumes about 83% of the water resources, mainly groundwater. Only about 2% of Libya's land receives enough rainfall to be cultivated without irrigation (Lawgali, 2008). Domestic water use accounts for 14% of the water supplied, and industrial usage makes up the remaining 3% (Laytimi, 2002).

Water quality evaluation for irrigation could be accomplished by considering its parameters and related problems. There are various available guidelines to assess the quality of the water. Richards (1954) stated that when classifying irrigation water, the assumption is that the water will be used under average conditions concerning soil texture, infiltration rate, drainage, the quantity of water used, climate, and salt tolerance of crops.

With the rise of the Libyan population during the last seven decades, the consequent expansion of the agricultural land and increasing the demand for agricultural products, in turn, led to increased use of intensive agriculture and resulted in damage to the soil due to the widespread use of chemical fertilisers and irrigation with saline water on non-saline and saline soils. This is more obvious in the southern oases of the country due to the hot climate, poor sandy soils, and inappropriate cultivation applications, which led to more usage of irrigation water, fertilisers, and pesticides. This has resulted in soil degradation due to the unfavourable alteration of soil properties such as soil texture, bulk density, soil porosity, pH, nutrients availability, salinity, and sodicity (Wang *et al*., 2003; Abedi- Koupai *et al*., 2006). This alteration may limit agriculture's sustainability and decrease land productivity (Gros *et al*., 2006; Bhardwaj *et al*., 2008; Loncnar *et al*., 2010) if not regularly monitored (Henry and Hogg, 2003). This means that irrigation should be managed to minimise adverse effects on soil quality. The efficient management of water is of considerable importance, particularly when it is meant to prevent soil salinisation, losses from deep percolation, soil and water contamination, and over-exploitation of natural water resources.

The effects of irrigation on soil physicochemical properties in arid and semiarid environments were well documented in many parts worldwide; however, the data in the Libyan case is very sparse, particularly in the southern desert areas. Arid and semiarid regions are particularly susceptible to soil degradation and often show low resilience (Bravo-Garza and Bryan, 2005). Therefore, the purpose of the study was to investigate the properties of the shallow and deep Nubian aquifers in El-Kufra oasis, to understand the effect of irrigation water from both aquifers on the soil properties and crop production in private and state farms; alfalfa (*Medicago sativa* L.) and potato (*Solanum tuberosum* L.) are widely cultivated in the oasis, thus were used as a proxy for other cultivated crops.

MATERIALS AND METHODS

The study area (El-Kufra oasis) is located in the southeastern part of Libya, comprising an area of 55 km long from south to north (23º 56'– 24° 27' N) and some 66 km wide from east to west (23º – 23º 39' E), covering an area about 3,630 km^2 lying at approximately 345–418 m above sea level (Fig. 1). The population is estimated to be around 60,000 people (Census 2006).

The area's climate is typical for the Sahara Desert, with an average maximum temperature of 30°C and an average minimum temperature of 15°C. The average annual rainfall is just 3 mm/year, and the average number of rainy days is only two days per year. The average wind speed is 42 km/hour, the average air humidity is 34%, the average length of the day is 13 hours, and the average dew point is 7°C.

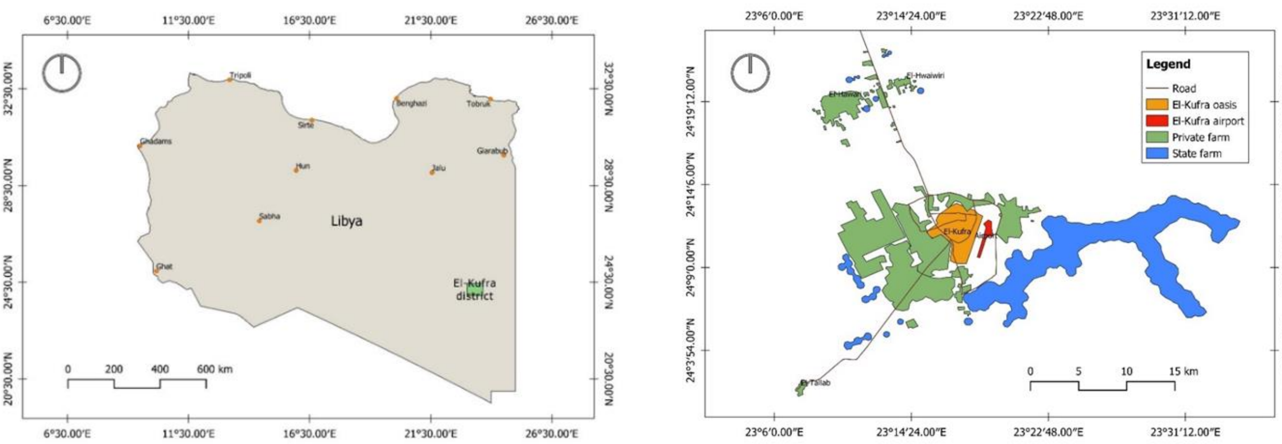

Figure 1. The geographical location of the study area (El-Kufra oasis) shows the oasis surrounded by the private and state farms

El-Kufra Agricultural Project comprises 100 circles (state farms), each approximately 1 kilometer in diameter (78.5 ha), lying mainly to the south of the oasis, depending on deep-water wells (deep aquifer) for irrigation; 36 farms were selected blindly from the list of farms to collect well water samples. The private farms in the study area, which depend on shallow wells (shallow aquifer), were divided into three geographic regions. (1) the central, western, and southwestern area (Al-Jawf including the western Jawf and El-Tawbat, until Talaab), (2) the southern area, (3) El-Hawari, which includes Al- Haweweri, located to the north of the oasis. The average area of private farms is 3.5 ha. A total of 46 water samples were collected from the wells of private farms. The farms to be sampled were selected blindly from an alphabetical list provided by the agriculture office in El-Kufra.

Water samples from the study area were collected in new plastic containers in the morning after a period of irrigation not less than an hour from the operating of the pump. The samples were transported in a cooling box directly to the laboratory. The water samples were collected between the 2nd and the 18th of December 2013.

The soil samples were collected from virgin lands from eight different sampling points, at least 20 m from the edge of any irrigated area and agricultural lands. Another 40 sampling points were chosen blindly; twenty agricultural sampling points were collected from private farms (ten from alfalfa and the other ten from potato fields) and the other twenty from state farms (ten from alfalfa and ten from potato fields). From each sampling point, four different samples from the topsoil layer (0-25 cm) were collected and mixed thoroughly to produce one sample, approximately 500 g. The samples were collected during the winter of 2013.

The plant yield samples were taken from the same area as the soil samples; the method for the selection of sites is based on the type of crop. In this instance, samples were collected in December 2013, the winter season in Libya. The winter crops grown within the study area are alfalfa, potatoes, cereals, forage (cereals and legumes mixed), and vegetables. The plan was to collect ten samples from the alfalfa fields and ten from the potato fields from state and private farms. No potatoes were grown on the state farms in winter 2013, so past seasons data have been used.

The cultivated crop types and yield production over the years were obtained from the records of El-Kufra Agriculture Office. Fresh weight of alfalfa and potato and water and soil analysis was conducted in the laboratories of El-Kufra Agricultural Project following Gregorich & Carter (2007). The saturation water percentage of soil (SW%) was conducted according to Richards (1954) and APHA (1992). The pH was determined using a pH meter (Jenway 3020 pH meter) after standardised with buffer solutions of pH 7.0 and 4.0. The Electrical conductivity (E.C.) was conducted using EC-meter (Wilhelm 8120 EC meter). Sodium and potassium were determined by flame photometry (Corning Model 400). Calcium and magnesium were determined using Perkin Elmer Atomic Absorption Spectrometers (models 1100B and analyst 100). Carbonate and bicarbonate were determined by titration with sulphuric acid. Chloride was determined by titration with silver nitrate. Sulphate was determined by precipitation method using hydrochloric acid and barium chloride. Calcium carbonate was determined using a concentrated hydrochloric acid and a carbonate meter USDA. The cation exchange capacity was determined according to Chapman and Pratt (1961). The mechanical analysis of the soil was determined using different sieve meshes and sieve analysis apparatus. The sodium hazard for irrigated water expressed as sodium adsorption ratio (SAR) was computed from Na^+, Ca^{+2}, and Mg^{+2} results. Exchangeable Sodium Percentage (ESP%) was computed as the percentage of Na^+ to the cation exchange capacity (CEC).

First, the data sets were verified and tabulated in a Microsoft Office Excel spreadsheet (Microsoft

Corporation-2019) and were subject to descriptive analysis and normality distribution tests. As all the data sets have non-normal distribution, the non-parametric tests (Mann-Whitney U and Kruskal-Wallis H) were applied to assess the various treatments' differences. Then the Bivariate correlation (Pearson Coefficient) was applied for all the measured parameters to examine any significant relation. All statistical significances were determined at a significant level ($\alpha \leq 0.05$). The statistical analyses were accomplished using Microsoft Excel (version 2019) and IBM SPSS Statistics software (version 26).

RESULTS

The irrigated water in El-Kufra oasis comes merely from the groundwater (The Nubian aquifer) by using shallow wells in the private farms (the shallow aquifer) and the deep well in the state farms (the deep aquifer). The surveyed wells in the private farms ranged between 18-55 meters deep with a mean of 32 meters (1.404 ± S.E.), while the state farms ranged between 220-352 meters deep with a mean of 257 meters (3.950 ± S.E.). The results showed that the water quality for the deep wells used in the state farm (agriculture project) is much better than the shallow wells used in private farms (Fig. 2), with highly significant differences (p-value = 0.000) in all measured parameters (Table 1). The mean pH value for the shallow was 7.58 and 6.62 for the deep wells. The mean E.C. for the shallow was 4.37 dS/m and 0.26 dS/m for the deep wells. For Ca, it was 9.81 dS/m in shallow and 0.83 dS/m in deep wells. The Mg was 6.37 dS/m for shallow and 0.58 dS/m for deep wells. The Na was 23.28 dS/m for shallow and 1.06 dS/m for deep wells. The SAR was 8.05 for shallow and 1.24 for deep wells. This trend was also applied to the different private farms in the various agricultural areas around El-Kufra oasis (Fig 3).

The soil analysis showed that the soil texture is sandy; the sand fraction values ranged between 85-100%, with a mean of 91.5 %. The silt and clay fraction ranged between 4-10%, with a mean of 7%. The results showed no significant differences in soil texture between state versus private farms and between virgin versus irrigated lands (Table 2).

The SW% values ranged between 10-29%; the mean for virgin lands was 17.8% (0.675 ± S.E.), and for agricultural lands, it was 22.8% (2.320 ± S.E.), with a significant difference between them (p-value = 0.038) (Table 2). For the state farms, the mean SW% was 23.5% (1.793 ± S.E.), and for the private farms was 17% (1.180 ± S.E.), with a significant difference between them as well (p-value = 0.021). The mean pH value illustrated the alkaline reaction of the soil; it ranged between 7.4-9.2; the lowest mean value was in the state farms (7.79 ± 1.793 SE), and the highest mean value was in the private farms (8.99 ± 0.114 SE). There was no significant difference between virgin and irrigated lands, and there was a highly significant difference between the state and private farms (p-value = 0.000). The E.C. values ranged between 1.2-105.9 dS/m, it was higher in virgin lands with a mean of 62 dS/m (8.741 ± S.E.) than in agricultural lands, which had a mean of 3.43 dS/m (1.109 ± S.E.), with a highly significant difference (p-value = 0.000), in the private farms, it was higher (40.8 dS/m ± 14.330 SE) than the state farms (24.7 dS/m ± 9.963 SE), but no significant difference between them was detected (Table 2).

The $CaCO_3$% values were very low ranging between 0.1-2.2% with a mean of 0.45% (0.446 ± SE). The mean value was higher in agricultural (0.54% ± 0.265 SE) than in virgin lands (0.35% ± 0.049 SE), with no significant differences. The private farms showed a higher mean value (0.6% ± 0.249 SE) than the state farms (0.29% ± 0.048 SE), with no significant differences between them as well (Table 2). The virgin lands showed higher mean values for Ca, Mg, Na, K, Cl, and SO_4 than the irrigated lands with high significant differences (p-value = 0.000). The mean values for these ions showed lower values in both the state and private farms, and no significant differences were detected between state versus private farms (Table 2). For crop production, the mean fresh yield for alfalfa was 19.8 t/ha (1.553 ± S.E.); the lowest yield was 9 t/ha, and the highest was 29 t/ha (Fig. 4). For the potato, the mean fresh yield was 31.6 t/ha (2.152 ± S.E.); the lowest yield was 14.7 t/ha, and the highest was 42.2 t/ha. The state farms yield more alfalfa and potato than private farms with a highly significant difference (p-value = 0.000). The yield of alfalfa in private farms showed a declined trend over time (R^2 for linear regression = 0.50) (Fig. 5); meanwhile, the state farms showed an increasing trend (R^2 for linear regression = 0.115) (Fig. 6). The potato yield showed a decreased trend over the years in state farms (R^2 for linear regression = 0.124) (Fig. 7), and no available data about potato yield over the years in private farms.

The Bivariate correlation test showed a highly-significant negative correlation (p-value = 0.000) between alfalfa and potato yield versus soil pH, E.C., Na, and ESP (Table 3). The soil pH showed a highly significant positive correlation versus E.C., Na, and ESP in soil. The soil E.C. showed a highly significant positive correlation versus Na and ESP in soil. The increase of soil pH value affected crop production in two different ways; in private farms, it decreased the production, but in state farms, it increased the production (Fig. 8). The soil E.C. slightly increased the production in the private farms, but its effect was more evident in the state farms. The soil Na had no significant impact on the production of state farms; however, it significantly reduced the production in the private farms. Moreover, the soil ESP had no significant effect on the private farms; meanwhile, it significantly reduced the production in the state farms (Fig. 8).

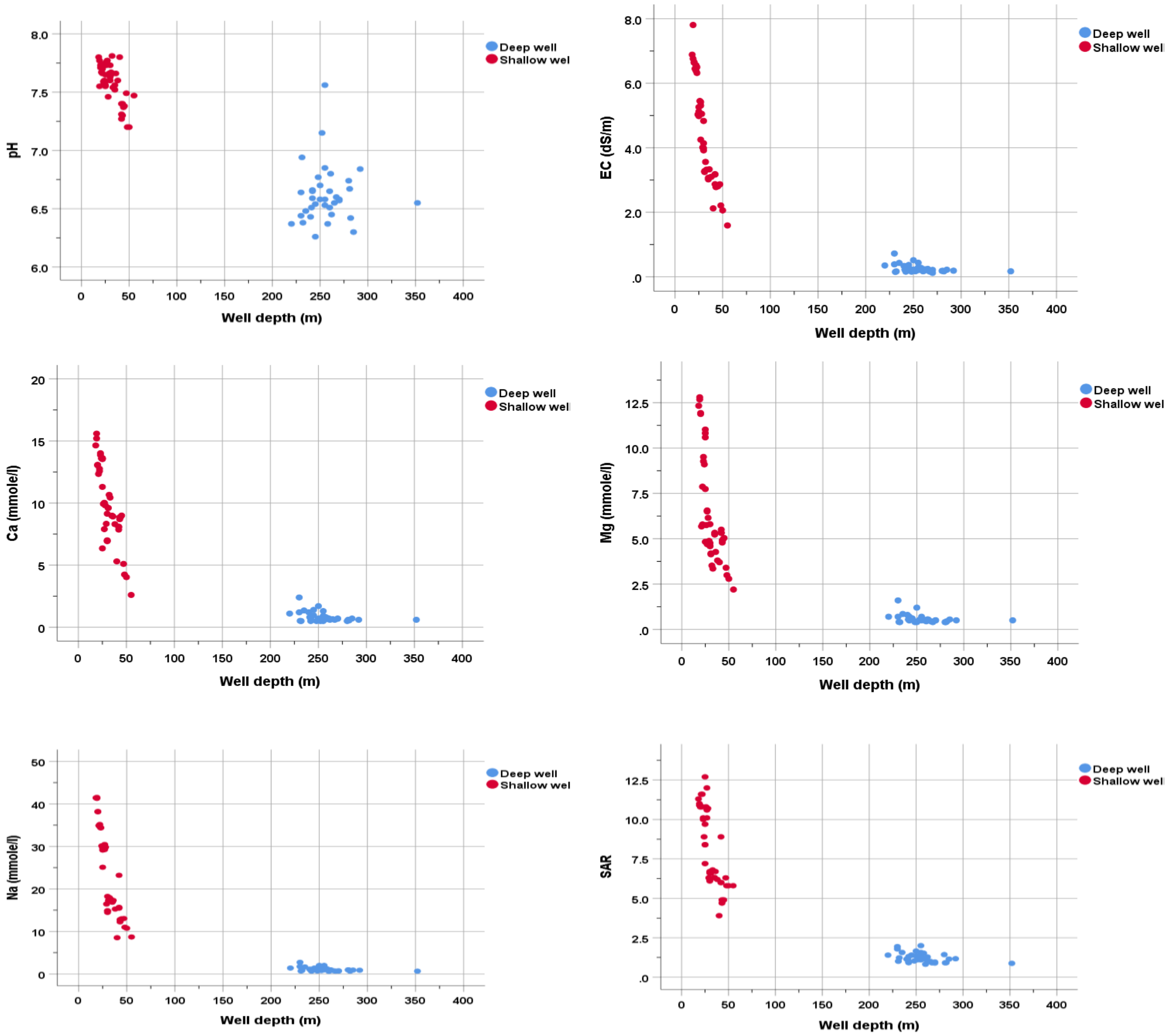

Figure 2. The differences in pH, EC, Ca^{+2}, Mg^{+2}, Na^{+}, and SAR between the shallow and deep aquifer water.

Table 1. Mean and Standard Error values illustrate the water quality for deep (state farms) and shallow aquifer (private farms) used in irrigation in El-Kufra oasis.

Parameter	Mean	Std. Error	Mean	Std. Error	*p*-Value
	Shallow well		Deep well		
pH	7.58	0.024	6.62	0.041	0.000
EC (dS/m)	4.37	0.234	0.26	0.020	0.000
Ca^{+2} (mmol/l)	9.81	0.463	0.83	0.067	0.000
Mg^{+2} (mmol/l)	6.37	0.436	0.58	0.039	0.000
Na^{+} (mmol/l)	23.28	1.481	1.06	0.078	0.000
SAR	8.05	0.360	1.24	0.051	0.000

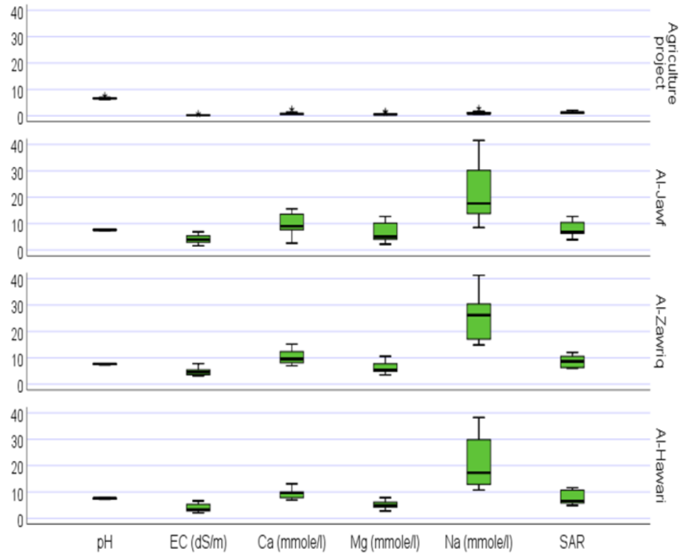

Figure 3. Irrigated water quality for state agricultural project (deep aquifer) and different private agricultural areas (shallow aquifer) in El-Kufra oasis.

Table 2. Mean and Standard Error values illustrate the differences in soil properties between virgin versus agricultural lands and state versus private farms for the different examined parameters.

Parameter	Mean	Std. Error	Mean	Std. Error	*p*-Value
	Virgin land		Agricultural land		
SW (%)	17.75	0.675	22.75	2.320	0.038
pH	8.53	0.212	8.25	0.275	0.279
EC (dS/m)	62.06	8.741	3.43	1.109	0.000
$CaCO_3$ (%)	0.35	0.049	0.54	0.256	0.645
Ca^{+2} (cmol/kg)	2.69	0.386	0.16	0.087	0.000
Mg^{+2} (cmol/ kg)	0.86	0.137	0.07	0.019	0.000
Na^{+} (cmol/ kg)	8.22	1.568	0.40	0.177	0.000
K^{+} (cmol/ kg)	0.42	0.094	0.01	0.003	0.000
HCO_3^{-2} (cmol/l)	0.03	0.003	0.03	0.005	0.161
Cl^{-} (cmol/ kg)	9.98	1.383	0.34	0.168	0.000
SO_4^{-2} (cmol/ kg)	2.35	0.623	0.13	0.051	0.000
Silt and clay fraction (%)	6.3	0.529	6.7	0.519	0.645
Sand fraction (%)	90.9	1.044	92.0	1.68	0.721

Parameter	State farm		Private farm		*p*-value
SW (%)	23.50	1.793	17.00	1.180	0.021
pH	7.79	0.100	8.99	0.114	0.000
EC (dS/m)	24.68	9.963	40.81	14.33	0.161
$CaCO_3$ (%)	0.29	0.048	0.60	0.249	0.442
Ca^{+2} (cmol/kg)	1.41	0.574	1.44	0.536	0.645
Mg^{+2} (cmol/ kg)	0.58	0.210	0.35	0.126	0.574
Na^{+} (cmol/ kg)	2.60	1.154	6.01	2.166	0.130
K^{+} (cmol/ kg)	0.26	0.121	0.17	0.074	0.798
HCO_3^{-2} (cmol/l)	0.03	.004	0.03	0.004	0.574
Cl^{-} (cmol/ kg)	3.83	1.613	6.49	2.338	0.161
SO_4^{-2} (cmol/ kg)	1.26	0.473	1.22	0.721	0.878
Silt and clay fraction (%)	6.01	0.182	7.0	0.676	0.195
Sand fraction (%)	93.2	1.064	89.7	1.407	0.161

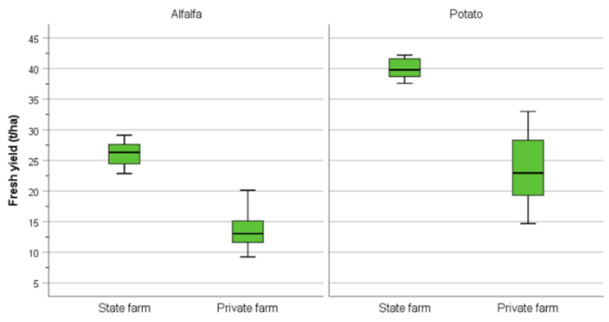

Figure 4. The fresh yield values (t/ha) for alfalfa and potato in state and private farms

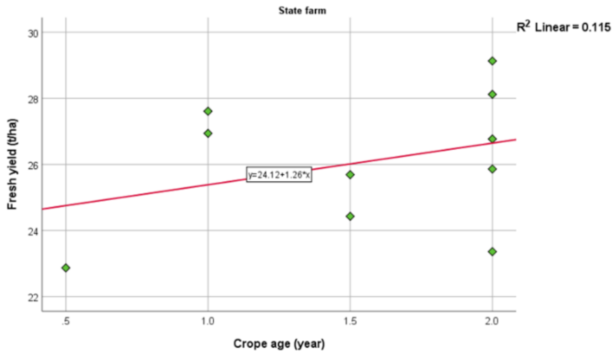

Figure 6. Relationship between fresh yield (t/ha) and crop age (years) showing the increased yield of alfalfa overtime in state farms

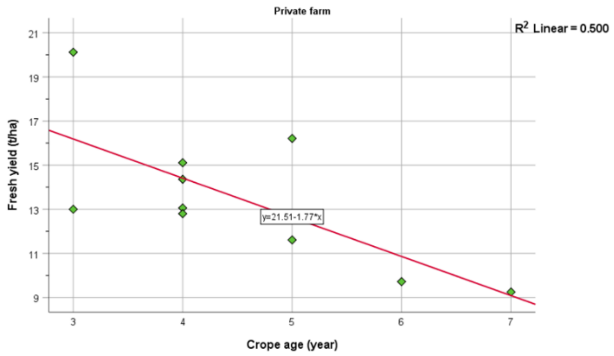

Figure 5. Relationship between fresh yield (t/ha) and crop age (years) showing the declining yield of alfalfa overtime in private farms

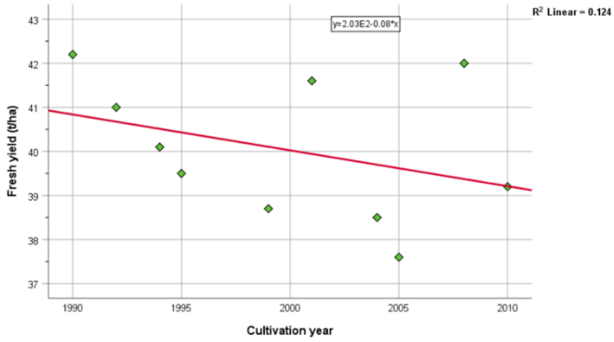

Figure 7. Relationship between fresh yield (t/ha) and crop age (years) showing the declining yield of potato over the years in state farms

Table 3. Pearson correlation between the crop fresh yield and different soil parameters, ** = *p*-value < 0.001

Parameter	Fresh yield (t/ha)	pH	EC (cmol/kg)	Ca^{+2} (cmol/kg)	Mg^{+2} (cmol/kg)	Na^{+} (cmol/kg)	K^{+} (cmol/kg)
pH	-0.665**						
EC (cmol/kg)	-0.615**	0.897**					
Ca^{+2} (cmol/kg)	-0.139	0.122	0.017				
Mg^{+2} (cmol/kg)	0.131	-0.098	-0.181	0.310			
Na^{+} (cmol/kg)	-0.708**	0.837**	0.799**	0.259	0.047		
K^{+} (cmol/kg)	-0.034	-0.213	-0.159	-0.043	0.022	-0.133	
ESP (%)	-0.647**	0.824**	0.872**	-0.119	-0.130	0.890**	-0.125

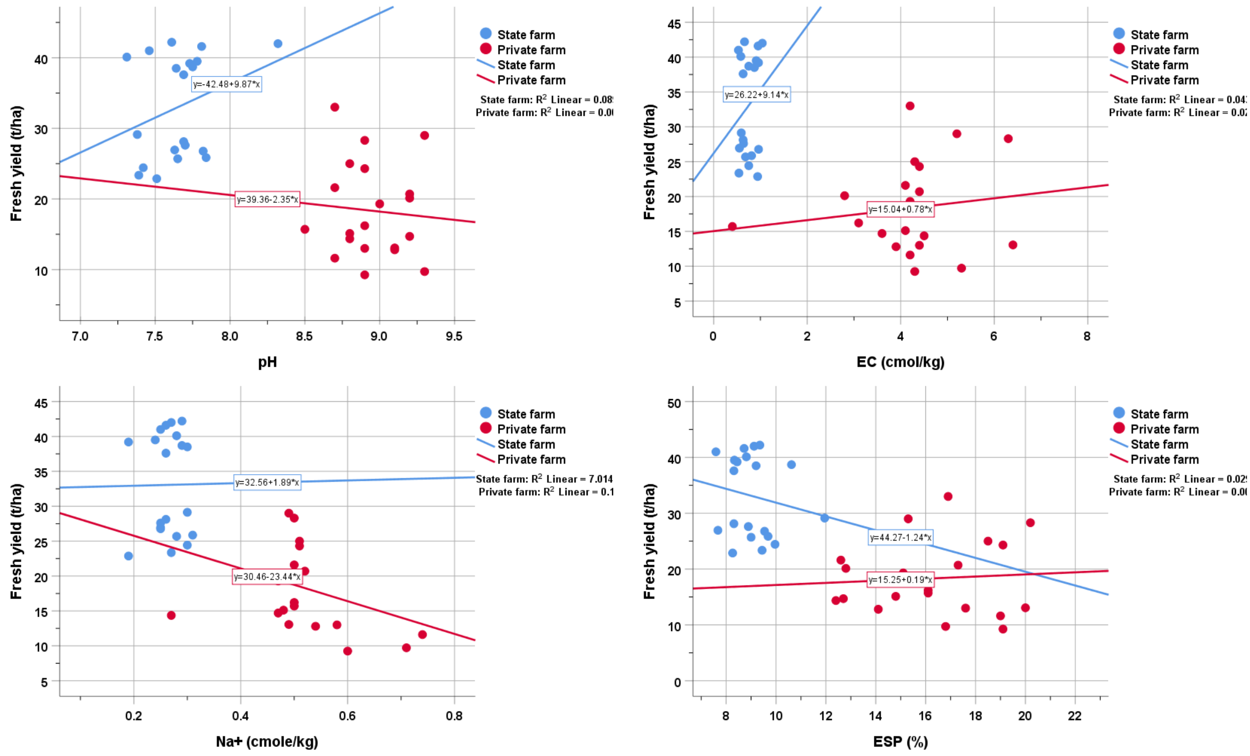

Figure 8. Relationship between fresh yield (t/ha) and soil properties showing the effect of pH, E.C., Na, and ESP of the soil on the crop yield in the study area (state and private farms in El-Kufra oasis).

DISCUSSION

Water quality

The current study illustrated the difference in water quality between the shallow and deep aquifer; the deep showed much better properties than the shallow aquifer. If the water supply depends on ground aquifers (as it is in El-Kufra oasis), the depths of wells are often related to the financial means of the farmers because the digging cost of wells is relatively high. As a result, cultivation will increasingly be forced to use marginal waters such as shallow aquifer or reclaimed effluent to meet its increasing demands, consequently, increasing the risks of soil salinisation and yield reduction. The use of poor water may alter the physical properties of the soil, such as bulk density and soil porosity (Abedi- Koupai *et al.*, 2006; Wang *et al.*, 2003), as well as the incidence of soil water repellence (Wallach *et al.*, 2005; Tarchitzky *et al.*, 2007).

Although the soluble salts within all soils are essential nutrients for plants, the excessive amounts cause soil salinity, inhibiting plant growth (Shrivastava and Kumar, 2015). This is more obvious in arid regions as in the Sahara Desert due to the increased evapotranspiration rate leading to salt accumulation in the topsoil layer. According to Ayers and Westcot (1985), irrigation water might vary significantly in terms of quality, and this depends principally on the nature and amounts of dissolved salts in irrigation water.

The high ion values, particularly for the shallow aquifer in El-Kufra oasis, are reflected as high E.C. and SAR. Sodium was the predominant positive ion in the irrigation water in the study area; this agrees with the previous finding by Ellwood and Hickes (1991). The water of the private farms might represent a real danger for the soil and plant yield if used for irrigation purposes (Yousef, 1985). Observations made during water sample collection from private farms indicated a significant degradation of the soil irrigated by shallow wells, with a white crust of salts (mainly sodium chloride due to the Na^+ and Cl^- ions being predominant among negative and positive ions in the irrigation water) covering the soil. The present study confirmed that sodium was the prevalent ion in irrigation water. Previous studies (e.g., Subba Rao *et al.*, 2002; Qiyan and Baoping, 2002; Kinniburgh and Smedley, 2001; and Zheng *et al.*, 2004) suggested that sodium is considered to be the main factor in determining the suitability of groundwater for irrigation purposes. The amount of sodium is typically expressed in terms of SAR. Following his experimentation, Richards (1954) noticed that the irrigation waters with conductivity values lower than 2.25 dS/cm were used efficiently for a substantial period in arid and semiarid agriculture soils. The deep aquifer values in the study area are less than 1.0 dS/cm; however, some of the shallow aquifer values reached 7.8 dS/cm.

Based on the FAO classification system (Ayers and Westcot, 1985; National Engineering Handbook, part 652, 1997), which depending on three degrees of restriction on use (none, slight to moderate, and severe) concerning potential problems in irrigation water quality due to salinity, infiltration rate, and toxicity of sodium 100% of the examined private wells (shallow aquifer) are not suitable for agricultural irrigation under normal conditions; 78% of the wells were in the severe category degree of restriction, and 22% were in the slight to the moderate category of restriction. 97% of the examined state wells (deep aquifer) are suitable for irrigation, and only 3% were in the slight to the moderate category of restriction.

Soil properties

This study showed that the soils in El-Kufra oasis are sandy and poor in structure and nutrient contents; their water retention capacity is also low. The SW% was higher in the agricultural than the virgin lands due to the accumulation of organic matter and, relatively, improved soil as a result of the management effects (technology management, supply of fertiliser, irrigation methods, and plant protection) over the years; this is more obvious in the state than the private farms.

The results also indicate that calcium was the dominant exchangeable cation in virgin and irrigated soil profiles, while potassium was the lowest. These results are similar to Barber (1995); Robbins and Carter (1983), who pointed out that calcium is the dominant exchangeable cation in many soils in arid and semiarid areas, while potassium is less easily exchanged than other exchangeable cations.

The reaction of the soils is alkaline, which is common in such arid areas; some samples were sodic soils (pH > 9) due to the accumulation of salts, particularly sodium chloride, from the irrigation water. Naturally occurring saline soils are common in arid areas due to evaporation of the soil far surpassing the quantity of water that reaches it. Due to the quality difference of irrigation water and the usage of more advanced agricultural techniques and more effective irrigation systems, the pH and many other soil properties in the state is better than the private farms. In El-Kufra oasis, the high soil alkalinity could be attributed to the high levels of sodium carbonate in the soils. Ardahanlioglu *et al*., (2003) and Khresat and Taimeh (1998) suggested that variations in soil pH may be related to high sodium levels. Ardahanlioglu *et al*. (2003) and Flowers and Flowers (2005) indicated that soils in arid and semiarid regions are often characterised by high salt with high sodium contents. Cardoso *et al*. (2013) revealed that the essential parameter for overall changes in soil chemical properties is pH.

This could be more obvious in the soil salinity, where the virgin were much saline than the agricultural lands; this is most likely due to salt accumulation by evaporation over time in this hot region. The irrigation water, particularly in the state farms, leach part of the soil salt and reduce the salinity. Mostazadeh-Fard *et al*. (2007) suggested that the leaching of the salts of soils depends on the quality and quantity of irrigation water. However, the unsuitable irrigation techniques used in the private farms (flood irrigation) in this hot-desert region cause more accumulation of salt crust on the soil surface. These results are in align with the previous findings in India by Paliwal and Gandhi (1976), who showed that the salinity and SAR of the irrigation water affect some parameters and increase the percentage of sodium exchange in irrigated soils because it contains a high percentage of sodium and other salts. It is also possible that improper management of private farms plays a role, such as fertiliser type, cultivation practices, and irrigation methods.

The salinity is still high in most private farms, and soil degradation and crop reduction are common. These results are consistent with Patel *et al*. (2001), where the soil salinity of private farms ranged from medium to high values. This trend could be attributed to the variability in irrigation water quality and leaching rates or applying fertiliser. According to the standards established by the American Lands Classification (Richards, 1954), the soils of the state farms were in the normal range for pH, E.C., and ESP%; meanwhile, 15% of the private farms were classified as normal soils, 5% classified as non-saline–alkali soils, 10% as saline-non alkali soil, and 70% as saline-alkali soil.

Crop production

Soil salinity represents a real challenge for agricultural productivity (Munns, 2002, 2005; Paranychianakis and Chartzoulakis, 2005). Since 7% of the world's land surface is affected by salinity, it is considered one of the main limiting constraints to agricultural productivity worldwide. Soil salinity, either the result of natural processes or crop irrigation with saline water, generally happens in arid and semiarid areas, impacting plant growth due to water deficit or salt-specific damages. Thus, causing land degradation and reducing food crop production (Tanwir *et al*., 2003; MostafazadehFard, 2007). This effect could be magnified in arid regions due to hot climates, poor irrigation management, and bad water quality (Dregne, 1986 and Ragab, 2010).

Salt accumulation in the root zone of the soil affects plant performance through the development of a water deficit and the disruption of ion homeostasis (Zhu, 2001; Munns, 2002). These stresses change hormonal status and impair basic metabolic processes (Loreto *et al*., 2003). This leads to poor crop growth and low yield. If the salts accumulate in the root zone in high concentration, the crop becomes unable to get enough water from the salty soil solution, and this causes water stress for a substantial period and results in a reduction in plant yield. The lessening in water absorption by plant roots affects the growth of the crop by slowing its rate.

The total yields of potatoes in state farms are similar to that in northern Europe and North America, where the average is more than 40-50 t/ha (FAO, 2011). In Saudi Arabia and Egypt, which have the same arid environment, the averages were 24.8 t/ha and 27 t/ha, respectively (Arab Organisation for Agricultural Development, 2013). However, these values are lower than the yields recorded in the private farms in El-Kufra oasis.

For alfalfa cultivation in Egypt and Saudi Arabia, average production is estimated at 10 t/ha of green (fresh matter) alfalfa per cut in Egypt (Osman and Ibrahim, 1990), while was it 16.3 and 16.6 t/ha in two years in Saudi Arabia (Al-Suhaibani, 2010). These values are similar to that in the private farms in El-Kufra oasis but much lower than the yields recorded in state farms (there would be eight cuts per year in El-Kufra). This could be attributed to the long day length and hot climate of El-Kufra oasis, water abundant, and the tolerance of alfalfa to saline soil.

The production in state farms is significantly higher than the private farms for both; alfalfa and potato. This is most likely attributed to the water quality and soil properties, which are much better in the state farms; also, the cultivation techniques and irrigation ways in the state farm are more suitable for the arid environment prevailing in the study area. This is more obvious when observing the alfalfa yield-change over time; it is increased in the state farms and decreased in the private farms over time due to the accumulation of more salts, and the soils become more saline or saline-alkali, which affect the growth and productivity of crops. There was no available data for potato production in private farms; however, the data on the state farms showed a slight decrease over a long period (about 20 years). This decline could be more attributed to the change in farming activities and market influence rather than the irrigated water quality.

It was evident that the soil pH < 8 did not cause any crop reduction in El-Kufra oasis, meanwhile, the pH > 8.5 significantly decreased the production. The high soil pH indicates infertility because it affects the availability of many micronutrients that substantially decrease (i.e., become less soluble) above a pH value of eight (Saaed, 2018). In contrast, the soil E.C. does not cause crop reduction in state and private farms. In sandy soil, as in the study area, the nutrient contents often are low or near zero; thus, the slight increase in soil salts by irrigation water may increase the crop production to a certain extent, as it provides part of the necessary nutrients.

CONCLUSION

The current study elucidated the water quality differences between the shallow and deep Nubian water aquifer in southeastern Libya. According to the FAO classification criteria, the water quality from the deep aquifer can be used for irrigation purposes without any restrictions regarding the salinity and pH of the irrigation water. The deep aquifer water can be used for most crops in the majority of soils in the study area. Meanwhile, the water from the shallow aquifer has a high pH, E.C., Ca, Mg, Na, and SAR values; thus, it is not suitable for agricultural purposes. Therefore, the private farms, which depend on the shallow aquifer, have saline and saline-alkali soils, and the state farms are non-saline; consequently, the crop production is significantly declining over time in the private farms as the salinity and pH of the soil increase.

The present study illustrated that to put an end to the soil degradation and reduction in crop yield that is taking place in El-Kufra oasis; we have to be very selective in choosing the agricultural lands as many areas in/and around the oasis consisted of salt marshes (Sabkha); also the usage of the shallow aquifer as a source of agricultural water should be banned forever; instead, deeper wells are drilled, to reach the deep aquifer water. Another important implication is to change the irrigation technique used in the private farms (flooding irrigation), which uses more water, thus, more salts accumulated in the top layer of the soil. Sprinkler and drip irrigation could be used as a better alternative. Cultivating crops that tolerate high soil salinity levels may increase the crop productivity in this arid area.

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