



Variations in groundwater levels and quality due to agricultural over-exploitation in an arid environment: the phreatic aquifer of the Souf oasis (Algerian Sahara)

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Abstract

Groundwater is a major source of supply for domestic and agricultural purposes, especially in arid and semi-arid regions. In this study, we followed the variations in water levels in the Souf oasis in the Algerian Sahara by measuring depths to groundwater across 65 points during the period from 2010 to 2015. Additionally, electrical conductivity (EC) was measured for assessing variations in groundwater salinity in the same groundwater monitoring network over the same time interval. The results from these investigations indicated that there are significant and continuous declines in the groundwater level across all study areas throughout the period of investigation. This is especially the case in the northern part of the study area where the water table declined by up to 18.2 m in Ghamra in 2015. Additionally, this study has indicated that the rate of decline of groundwater levels has increased from 0.29 m/year as an average in 2011 to 2.37 m/year in 2015, where the situation has become alarming. As a consequence of this, the depth to groundwater now exceeds 2 m over more than 77% of the study area, and only about 17% of the study area now has a water table depth that lies within the optimal depth interval for extractive uses (between 1 and 2 m). This decline in groundwater levels has been accompanied by a significant increase in the electrical conductivity values (salinity) of this water, and there is a strong correlation between these variables ($R > 0.99$). This alarming situation has been caused by the continuous over-exploitation and unsustainable management of this limited resource, especially by the agricultural sector. For a long time, this critical situation led to the demise of the agricultural world heritage cultivation system (Ghout) due to the increasing salinity of groundwater. Two solutions are proposed to manage the effects of groundwater depletion in the area: firstly, rationalizing groundwater use through effective groundwater allocation management measures, and secondly by implementing the reuse of treated wastewater as an alternative water source for agricultural use. This latter measure could be in two ways: either by direct use in irrigation to relieve pressure on the phreatic aquifer, or by artificial recharge of the phreatic aquifer.

Keywords Groundwater depletion · Electrical conductivity · Ghout · Agriculture · World heritage · Phreatic aquifer · Souf oasis

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Abbreviations

| | |
|-------|-------------------------------------|
| CI | Intercalary continental aquifer |
| CT | Terminal complex aquifer |
| DAA | Directorate of agricultural affairs |
| DWR | Directorate of water resources |
| FAO | Food and agriculture organization |
| GPS | Globe positioning system |
| NOS | National Office of Sanitation |
| NWSAS | North-Western Sahara aquifer system |
| OSS | Sahara and Sahel observatory |
| PA | Phreatic aquifer |
| TDS | Total dissolved solids |

Introduction

Through human history, all civilizations have developed near readily available water sources (Murad et al. 2007). The practice of agriculture has been the main factor that has helped humans to transition from fishing and foraging to stable lifestyles based on agricultural development (Freeman et al. 2015; Gulyás and Sümegi 2011). In arid and semi-arid regions, groundwater is a major source of supply for domestic and agricultural purposes (Hosseinifard and Mirzaei Aminiyan 2015). Oases are created where the water is near to the surface and readily accessible for various types of use (Burmil 2003). In many arid areas, the cultivation of date palms is the main crop grown (Bouguedoura et al. 2015). This is the case in the Souf oasis where date palm trees are planted in large craters dug by hand, a method of cultivation known as “Ghout” in the local vernacular (Fig. 1) (Acourene et al. 2007). This cultivation method allows water to ascend directly by capillary action from the phreatic aquifer to the date palm roots and allows farmers to avoid the use of more labor-intensive and costly irrigation systems (Cauvet 1914; Despois 1958; Zella and Smadhi 2006).

Ghout is an original and unique irrigation system (Brunhes 1902) that is well adapted to the prevailing harsh conditions in the region (Suchantke 2001). For its historical, economic, and environmental importance, the Ghout cultivation system has been classified by the Food and Agriculture Organization (FAO) as an important Agricultural World Heritage method in the year 2005 (Khezzani et al. 2016).

Because this cultivation system is completely dependent on the position of the water table, it is highly vulnerable to small changes in groundwater levels. Consequently, date palm trees may be threatened either by flooding or by drought depending on the elevation of the water table.

The main objectives of this study are to monitor changes in the phreatic aquifer level in order to determine how the elevation of the water table in the region varies spatially and over time, their environmental impacts (especially on traditional agricultural methods), and the relationship between these fluctuations and various human activities. In addition, this study aimed to determine whether the depth of groundwater in the region continued to be suitable for the use of the Ghout cultivation system.

Description of the study area

Geography of the Souf oasis

Geographically, the study area is located in the south-eastern part of Algeria within El-Oued province, between the latitude 32°30'00" and 34°12'00" N and the longitude 6°15'00" and 7°20'00" E. Souf oasis covers an area of 11,718.4 km², almost 26% of the total surface area of the province. From an administrative point of view, Souf oasis includes 18 of the 30 municipalities within this province (Fig. 2) (Khechana and Derradji 2014). In 2015, the population of this oasis exceeds a half million who mostly live in a group of major cities



Fig. 1 Agriculture under Ghout system. The figure shows a big hole that has been excavated by humans and planted with date palm trees and directly irrigated from phreatic aquifer

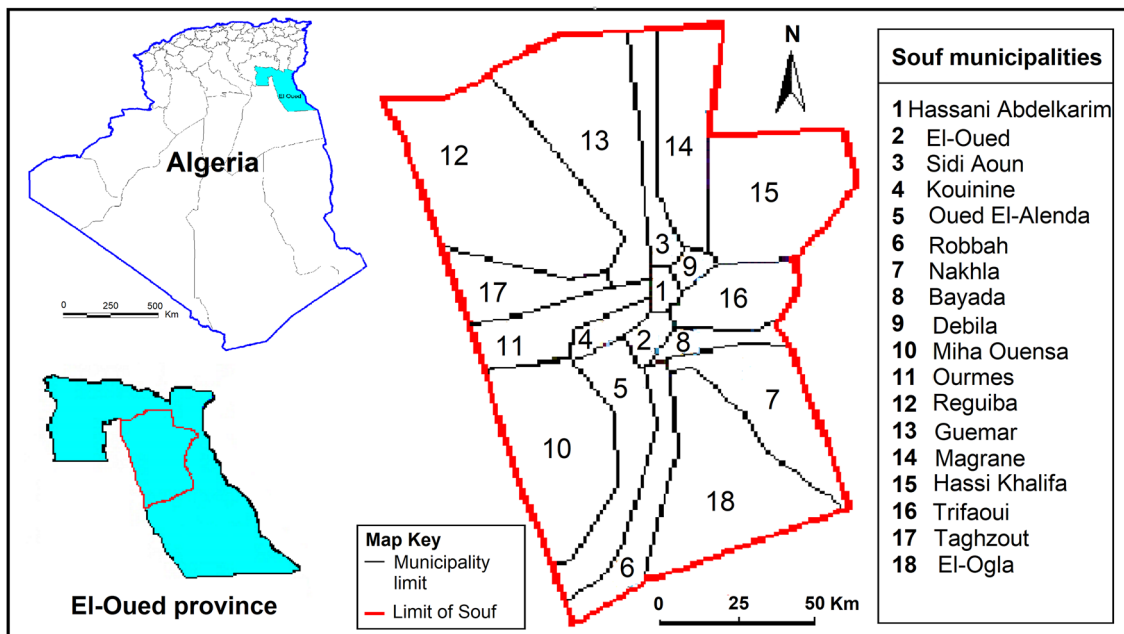


Fig. 2 Study area location

in the region (Khezzani and Bouchemal 2017). Agriculture is the dominant activity, which centered on the cultivation of the date palm trees, but in recent years has expanded to include new other crops such as potatoes, olives, wheat, and various vegetables types. All these types of crops are entirely dependent on groundwater exploitation from the phreatic aquifer that underlies the whole of the region (Khezzani and Bouchemal 2013).

Climate

Similar to other parts of Algerian Sahara, the Souf oasis experiences a Saharan climate (BWh in the Köppen classification system) that is characterized by a hot and dry summer and a mild winter (Dubief 1959). According to statistical series of climatic factors that extend from 1967 to 2015, it is noted that rainfall is very low, oscillatory, and sporadic, with an annual average of 73 mm. Evaporation greatly exceeds rainfall amount with an annual average of about 2200 mm. Consequently, the oasis experiences a permanent water deficit.

The average maximum temperatures in the region range from 19.82 °C in January to 44.41 °C in July, and the average minimum temperatures range from 8.84 °C in January to 29.38 °C in July. The annual mean temperature during the period of record was 26 °C. The insolation lasts almost all year, reaching a maximum in July with 356 h and minimum in January with 241 h. The annual average insolation is about 282 h. Winds are generally low, but in the spring, they become violent and cause sand movements.

Geomorphology of the Souf oasis

The Souf region is located in the northern part of the Great Oriental Erg (Sebaa et al. 2009) that is characterized by sand dunes of continental origin that have formed in the recent Quaternary (Khezzani 2007). The Quaternary formations (sand dunes) are comprised of fine-grained, compact, homogeneous, and uniform sands that cover most of the region, especially in the southern part of the region where dunes may exceed a height of 100 m. Between the sand dunes there appear corridors which form depressed plateaus (called Sahane) which are often fairly extensive, sometimes stony, and are covered by gypsiferous sediments of Quaternary age. In the northernmost part of the region, salty depressions (Sebkha) are found, which occupy the basal part of the immense basin of the lower Sahara.

The average altitude of the Souf region is 80 m, where there is a marked decrease in elevation from south to north to reach an altitude of about 25 m below sea level in the Sebkha area. Also, it should be noted that the altitude decreases from West to East to become negative in Sebkha (Ballais et al. 2002). Similarly, depressions are found in the area forming Ghouts surrounded by a sand mounds give the oasis a particular landscape (Khezzani et al. 2016).

Geology and hydrogeology of the Souf oasis

The study area is located in the northeastern part of the Saharan Mesozoic basin (also known as the Triassic

basin) which is itself located to the northeast of the Saharan platform (Saibi 2014). The area is underlain by sediments that range from the lower Cretaceous to Quaternary in age (Fabre 1976). Paleozoic marine formations rich in water for the base of the sedimentary basin and these sediments are unconformably overlain by a sequence of

sediments that may exceed 2000 meters (Fig. 3) (Nesson 1978).

Although the prevailing climatic conditions, the geology and geomorphology of the region prevent the formation of surface water resources (Dubief 1953), the region is underlain by the largest fresh groundwater resource in North

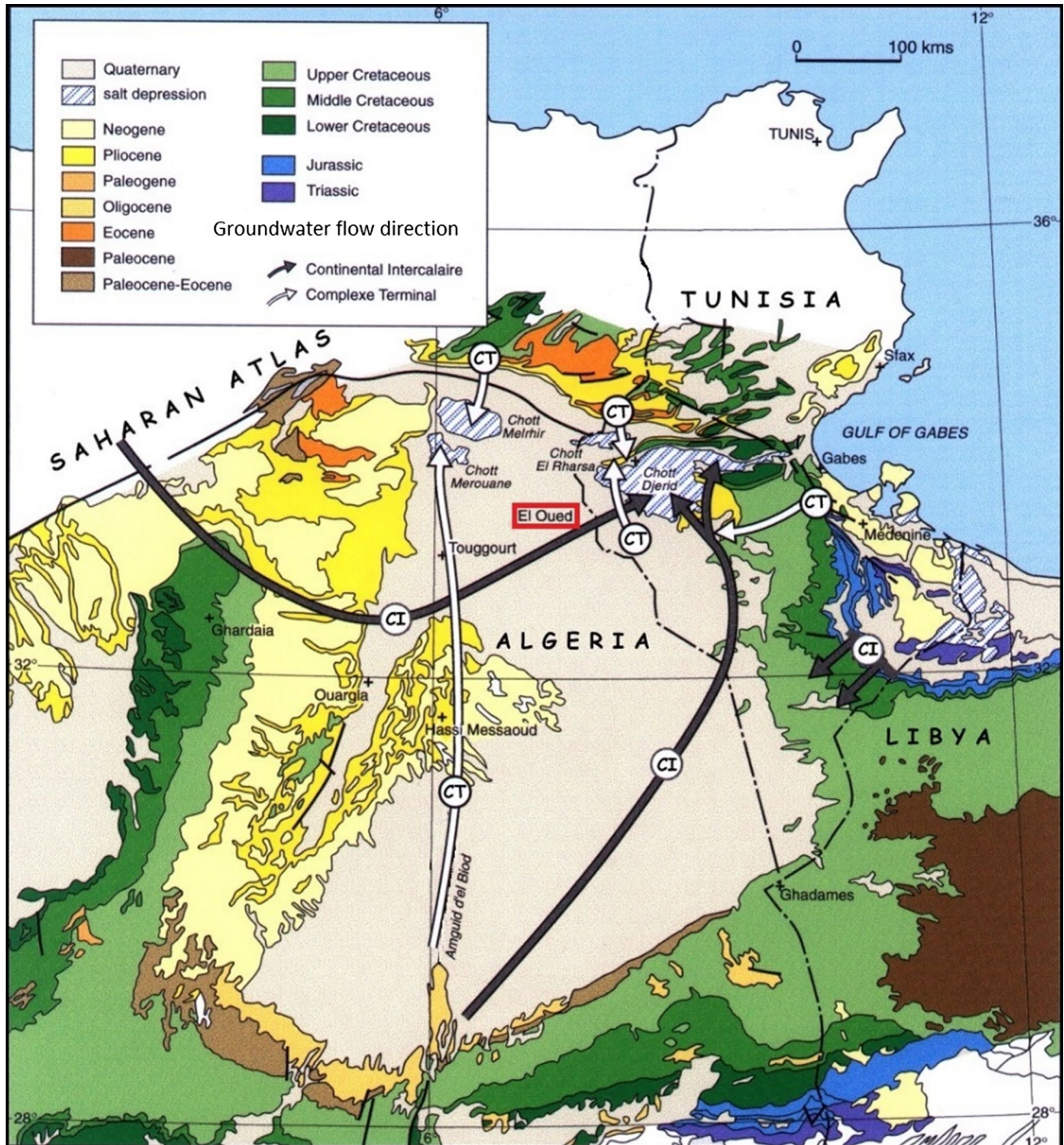


Fig. 3 Location and geological map of the Great Oriental Erg and the study region. The map shows flow direction of the CT and CI aquifers (Guendouz et al. 2003)

Africa which is called the North-Western Sahara Aquifer System (NWSAS) (Khezzani 2007).

In the Souf oasis, groundwater is the only water resource available for all kinds of uses (Chebbah and Allia 2014; Drouiche et al. 2013). From a hydrogeological point of view, groundwater can be found within three main aquifers (Fig. 4) that vary in the depth and in physicochemical characteristics (Khechana et al. 2011; Messekher and Menani 2010; Meziani et al. 2011). These are, in order of increasing depth:

Phreatic aquifer

The uppermost aquifer in the region is the phreatic aquifer (PA). This aquifer has a free water table contained in

fine sands which are locally intercalated with sandy clays and gypsum lenses (Table 1) (Bouselsal and Kherici 2014; Guendouz et al. 2006). The phreatic aquifer has a thickness of about 100 meters with a water table depth between 1 and 40 meters. This aquifer is underlain by an impermeable clay substratum (Ben Hamida 2005). Groundwater from the phreatic aquifer is utilized by thousands of traditionally constructed wells. In 2015, the total number of traditional wells exceeded 35,000 (DRE 2015).

According to Kherici et al. (1996) and Saibi et al. (2016), the mean permeability of the phreatic aquifer is 10^{-4} m/s while horizontal transmissivity and storage coefficient were estimated to be 10^{-2} m²/s and 0.2, respectively. Natural recharge to the phreatic aquifer occurs in two ways: firstly,

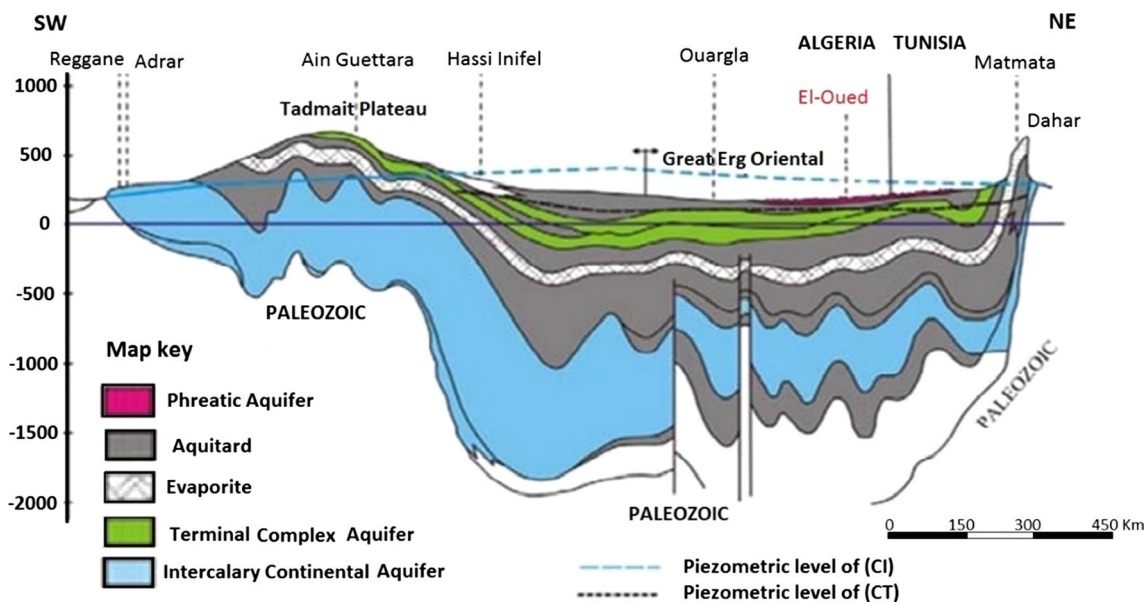


Fig. 4 Hydrogeological section passing through the study area shows position of the three aquifers (Guendouz et al. 2006; Moulla and Guendouz 2003)

Table 1 Local hydrogeology and stratigraphy of the Souf oasis (Ben Hamida and Ben Zeguir 1993)

| Era | Period | Sub period | Epoch | Lithology | Hydrogeology |
|----------|------------|------------|----------------|-------------------------|-----------------------------|
| Cenozoic | Quaternary | | Holocene | Sand | Phreatic aquifer |
| | | | Pleistocene | Clay, evaporite | Impermeable substratum |
| | Tertiary | Neogene | Pliocene | Sand | 1st Sandstone aquifer (CT) |
| | | | Miocene | Gypseous clays | Semi-impermeable substratum |
| | | | Oligocene | Sand, gravel, sandstone | 2nd Sandstone aquifer (CT) |
| | | Paleogene | Eocene | Laguna clay | Impermeable substratum |
| | | | Paleocene | Dolomite, calcareous | Calcareous aquifer (CT) |
| Mesozoic | Cretaceous | Upper | Upper Senonian | | |
| | | | Lower Senonian | Clay, evaporite | Impermeable substratum |
| | | Middle | Cenomanian | Clays, marl | |
| | | | Albian | Sand, sandstone | Albian aquifer (CI) |

by the infiltration of rainfall that falls and runs off on the rock formations of the southern edge of the Great Oriental Erg (Fig. 5); and (Côte 2006; Dubief 1947) secondly, by infrequent torrential local rainfall events, like those that fell on the region in April 1947 and in May 1967 (Najah 1970).

Terminal complex aquifer (CT)

The next deepest aquifer (Table 1) is called the terminal complex (CT). This is a groundwater flow system comprised of several aquifers located in different geological formations (Cornet 1964). The CT aquifer corresponds to continental formations from the upper Cretaceous to the Miocene (Gonçalvès et al. 2013). Its depth varies between 400 and 600 m, and its thickness is typically about 400 m (Ben Hamida 2005). This aquifer contains fossil water which ranges in age from about 20,000–30,000 years (Guendouz et al. 2003; OSS 2003). Until 2015, about 182 deep wells were constructed in this aquifer, with 28 wells being used for irrigation and 154 for urban and drinking purposes.

Intercalary continental aquifer (CI)

The third deepest aquifer is called intercalary Continental (CI) aquifer, which is comprised of continental formations from the middle Jurassic to the lower Cretaceous (Barremian and Albian) (Table 1). The lithology of the aquifer is comprised of sandstones and clayey sandstones (Cornet 1964; Gonçalvès et al. 2013). The CI occurs at a depth of 1800 and 2200 m and has a thickness between 200 and 400 m (Guendouz et al. 2006). This aquifer contains fossil water that ranges in age from 20,000 to 30,000 years (Guendouz and Michelot 2006; OSS 2003). Only four deep wells have been constructed in the CI aquifer in the region and all are used for drinking purposes as groundwater from this depth has a temperature which exceeds 70 °C.

Materials and methods

Statistical data

Information about agricultural land use, the distribution and construction of phreatic and deep wells, irrigation methods, and water resources were provided by the Directorate of Agricultural Affairs (DAA) and the Directorate of Water Resources (DWR) of El-Oued province. Information about the volume of treated wastewater was provided by the National Office of Sanitation (NOS).

Measurement and sampling

Depth to groundwater

This study was based on the measurement of the depth to groundwater from the land surface, where we chose the planting level of date palm trees (floor of the Ghout) as a reference mark ($Z = 0$). To do this, 65 measuring points were selected and distributed over the entire study area. Determining the geographical coordinates of these points was carried out using a Globe Positioning System (GPS). In situations where the water table was below land surface ($Z > 0$), we used traditional wells that were located in the different selected Ghouts as reference points. Measurements of water levels in large-diameter wells (up to 2 m in diameter) were carried out using a water level probe. In situations where the well was equipped with a pump and used for irrigation, the measurement process was carried out before or after the pumping process with sufficient delay to allow the groundwater level to return to its normal status.

In the case when the water level is above land surface ($Z < 0$), we use a graduated stick with centimeter markings to determine the elevation of the water level above the land surface. Water level measurements and sampling were carried out during the period from 2010 to 2015, once each year and in the same month (May) in order to avoid seasonal variations that can occur in the groundwater levels.

Electrical conductivity (EC)

In parallel with measuring the depth to groundwater, the electrical conductivity of groundwater was measured in situ using a conductivity meter.

Determining the optimal water table depth for groundwater uptake by date palms

To determine the optimal depth to groundwater that supports date palm tree without negative effects, we undertook observations of specific vegetative and morphological characteristics which were indicators of hydric stress (to either drought or flood conditions) to the plants.

Data analysis and map production

From the collected measurement data, and using the Surfer 12 program Version 14.3.691 developed by (Golden Software Inc., USA), we have analyzed the data and established six iso-depth contour maps for the water table in the Souf phreatic aquifer for the period from 2010 to 2015.

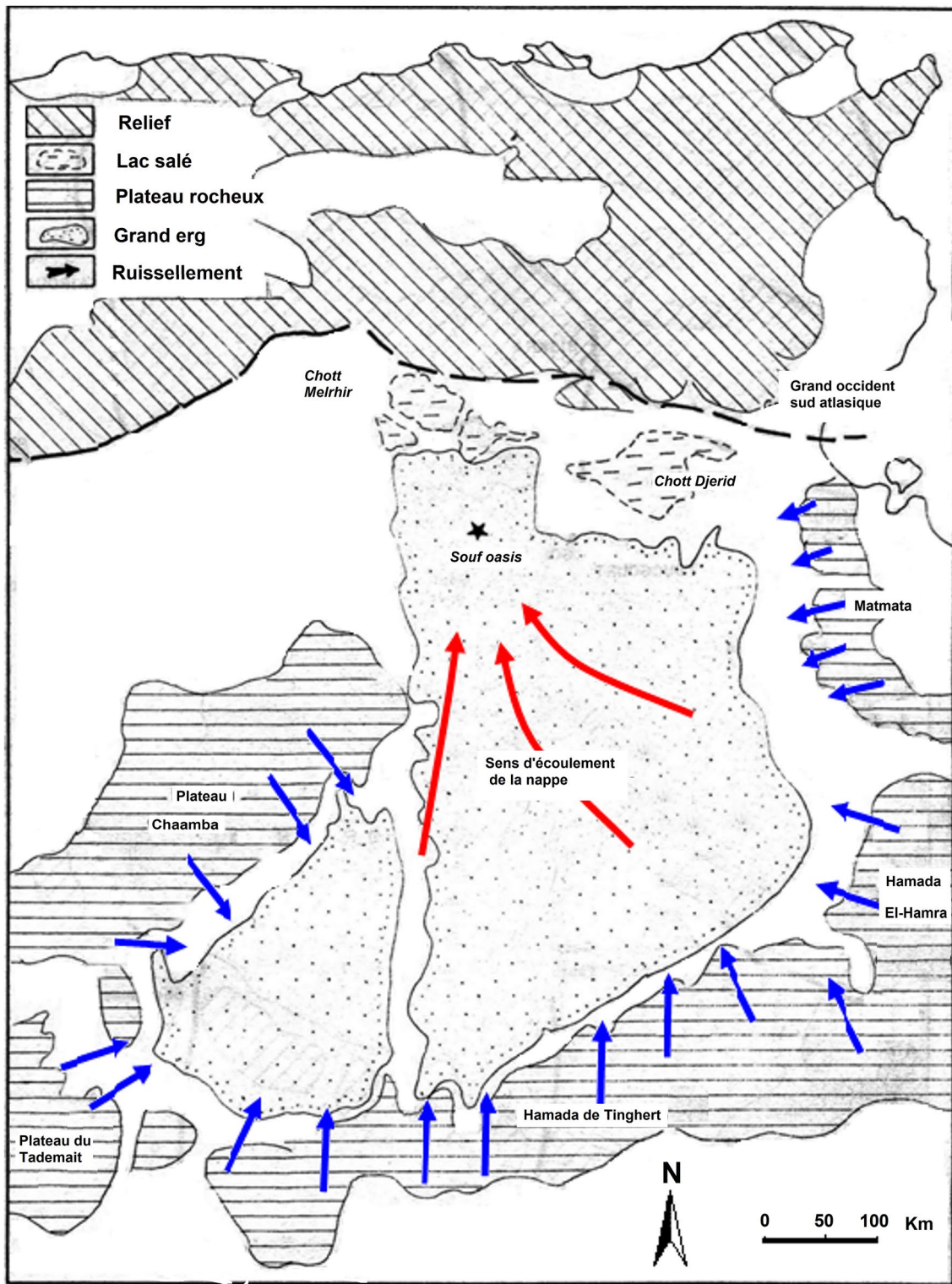


Fig. 5 Natural recharge of the phreatic aquifer from the Great Oriental Erg edges (Côte 2006)

Results and discussion

Optimal water table depth for groundwater uptake by date palms

After the external examination of many date palm trees a number Ghouts across all parts of the oasis, we noted that all Ghouts with healthy palms had an optimal depth to groundwater of between 1 and 2 meters ($1 < Z < 2$). In regions where the depth to groundwater is more than 2 m ($Z > 2$), the date palm trees suffer from hydric stress symptoms due to drought. Finally, when the depth to groundwater is less than 1 m ($Z < 1$), the date palm trees suffer from hydric stress symptoms due to flooding of the roots.

Several previous studies support the obtained results and have indicated that the date palm tree root system absorbs water from different soil levels. For example, the study of Kassem (2007) showed that 97% of the water is absorbed at a depth of 0–180 cm, of which 69.4% is absorbed in the depth interval of 40–140 cm. Additionally, Mumtaz Khan and Prathapar (2012) indicated that 65–80% of water is absorbed by date palms at depth of 1.2 m in the root zone. Munier (1973) observed that roots of date palms extended laterally up to 25 m from individual trees and deeper than 6 m, but 85% of the roots were distributed in the zone of 2 m depth and 2 m laterally from palms.

Depth to groundwater analysis

Historical water level variations in the phreatic aquifer

Previous investigations, such as studies of Aris (1956), Dervieux (1956), Côte (1998), Guendouz et al. (2006), Messekher and Menani (2010), and others, have shown there have been significant water level variations in the phreatic aquifer since at least the latter part of the nineteenth century. These significant historical events provide context to the current study and we can summarize them as follows:

Before the year 1956: a single aquifer for all activities Before 1956, all water needs in the Souf oasis were provided by the phreatic aquifer which was the only known groundwater source at the time (Côte 2006). The first observations about the fluctuations of phreatic aquifer levels were from the late 19th century. Reclus (1886) noted that date palms planted close to water table (Ghout system) could be dehydrated due to declining water levels and that farmers often resorted to uprooting trees and replanting them at a lower elevation in situations where there was a falling water table.

Bataillon (1955) noted that there were significant declines in the elevation of the water table in most of the oasis in 1930 due to the growing demand of shallow groundwater

because of population increases and the increased agricultural demand for water at this time. According to Voisin (2003), the Souf oasis population increased from 21,000 in 1887 to 87,400 inhabitants in 1954. The rate of decline of the elevation of the water table increased during the period 1940–1942 (Bataillon 1955). Consequently, the administrative services of El-Oued decided that the number of date palm trees must not exceed 400,000 for the entire Souf territory (Agier 1949) to limit the decline of the water table. During the period from 1953 to 1956, there was a significant decrease in the groundwater level, which ranged between 50 and 150 cm (Dervieux 1956).

Period from 1956 to 1986: increased groundwater abstraction from deep aquifers In 1956, local authorities resorted to exploiting water from deep aquifers as it was decided that the phreatic aquifer no longer meets groundwater demand in the region. Initially, a deep well was drilled in the terminal complex aquifer (CT) for drinking purposes. This well had a flow rate of about 30 l/s and a depth of 250 m (Côte 1998; Meziani et al. 2012). Later that year, an additional two wells were drilled in this aquifer. At this time, wastewater from a sewage system was discharged to the phreatic aquifer.

After 1986: increased recharge in the phreatic aquifer In 1986, the population of the region had reached more than 224,000 inhabitants. At this time, a deep well was constructed in the intercalary continental aquifer (CI) for potable water supply. This well had a depth of 1850 m and artesian flow rate up to 200 l/s (Côte 1998). Subsequently, additional wells were constructed in both the CI and CT aquifers. The infiltration of this additional pumped groundwater and the operation of the sewage system increased recharge to the phreatic aquifer, and consequently the water table began to rise in the region.

During the study period

Prior to 1930, the depth of the water table was between 1 and 2 m below the surface in all Ghouts within the Souf oasis and was suitable for this form of cultivation. However, during this study we noted that there was a decline in groundwater levels at all measured points (Fig. 6).

Water table status in 2010 Depending on the depth to groundwater and the health of date palms, three patterns of water level variations were observed in the study area in 2010 (Fig. 7). These were: variations in the northern part of the area where the depth to groundwater is more than 2 m and is declining; variations in the southern part of the area where the depth to groundwater is in the optimal range of 1–2 m deep; and central part of the El-Oued municipality

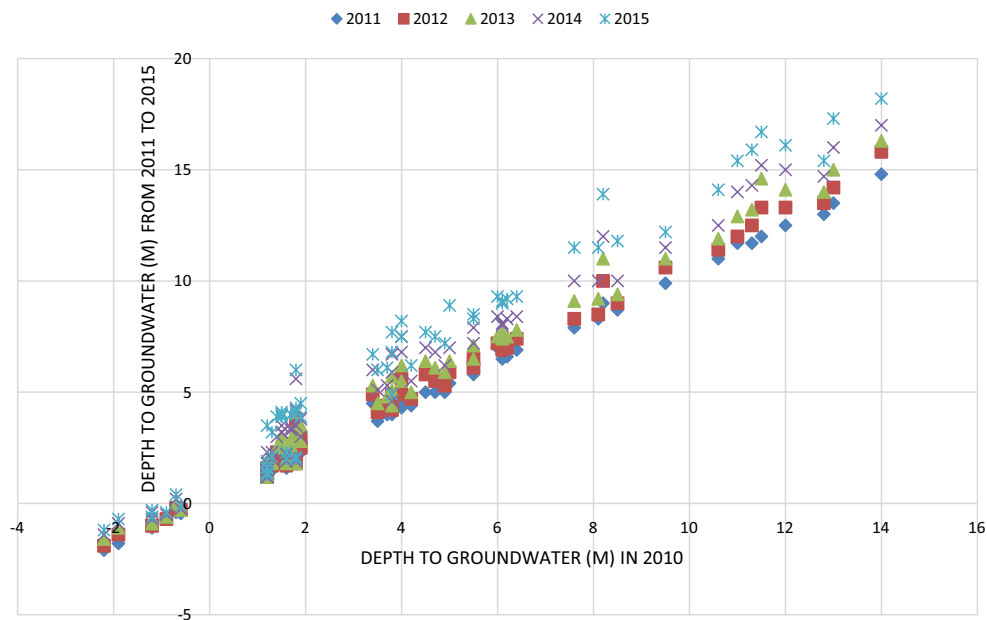


Fig. 6 Evolution of depth to groundwater values compared to the initial status in 2010 through all measured points

and neighboring areas, where the depth to groundwater is less than 1 m deep and is rising. In 2010, the highest water level was -2.2 m in the Chott (El-Oued municipality) and the deepest water level was 14 m in the Ghamra (Guemar municipality). On average, the depth to groundwater fluctuated by about 4.03 m during 2010 (Table 2).

The status from 2011 to 2014 During this period, there was a continuous decline in groundwater levels in all measured points (Fig. 8). The largest depths to groundwater during this period were measured in the northwestern part of the area in Ghamra where values ranged from 14.8 m in 2011, 15.8 m in 2012, 16.3 m in 2013, and 17 m in 2014. The minimum values (height of water) were measured in the central part of El-Oued municipality (Chott) and ranged from -2.1 m in 2011, -1.9 m in 2012, -1.6 m in 2013, and -1.4 m in 2014. Fluctuation rates ranged from 4.32 m in 2011 and 5.68 m in 2014. (Table 2). The difference in the decline rate between the year 2010 and other years is estimated to be 0.29 m in 2011, 0.68 m in 2012, 1.12 m in 2013, and 1.65 m in 2014 (Fig. 10).

Status in 2015 Groundwater levels continued to decline in all parts of Souf oasis (Fig. 9), but at an accelerated rate in the north-western part of the area, reaching a maximum value of 18.2 m in Ghamra (Table 2). In northeast part of the study area, the depth to groundwater reached a maximum value of 15.4 m both in Menanaa and Debila. In the southwestern part of the area, especially in Miha Ouensa and Oued El-Alenda and neighboring areas, the depth to groundwater was between 8.9 and 7.5 m. Date palm trees

located in areas with these water table depths do not directly benefit from groundwater, which has become very distant from the plant roots.

In the central part of the area (El-Oued municipality and neighboring areas), where water levels have historically been rising, we noted that there were significant declines in the depth to groundwater in 2015 but these new levels always remain outside the optimal interval for date palm trees. In 2015, the minimum value was recorded in the Chott with -1.2 m (Table 2), followed by Daouia with -0.6 m and Teksebt with -0.4 m.

Locations where the depth to groundwater was within the optimal interval for growing and developing date palms (between 1 and 2 m) extended to the far south to areas such as Drimini, Bent Lemkhoucher, and Khobna Safra. The fluctuation rate for this year reached a value of 6.39 m, and the difference between the declining rate in the year 2015 and the initial status in 2010 is estimated to be 2.37 m (Fig. 10).

Factors that have contributed to the decline of groundwater levels

The sharp and continuous decline in the groundwater level that noted in all parts of the oasis throughout the study period can be explained by many factors, the most important being the following issues.

The almost complete dependence on the use of water from the phreatic aquifer Of the three aquifers that are

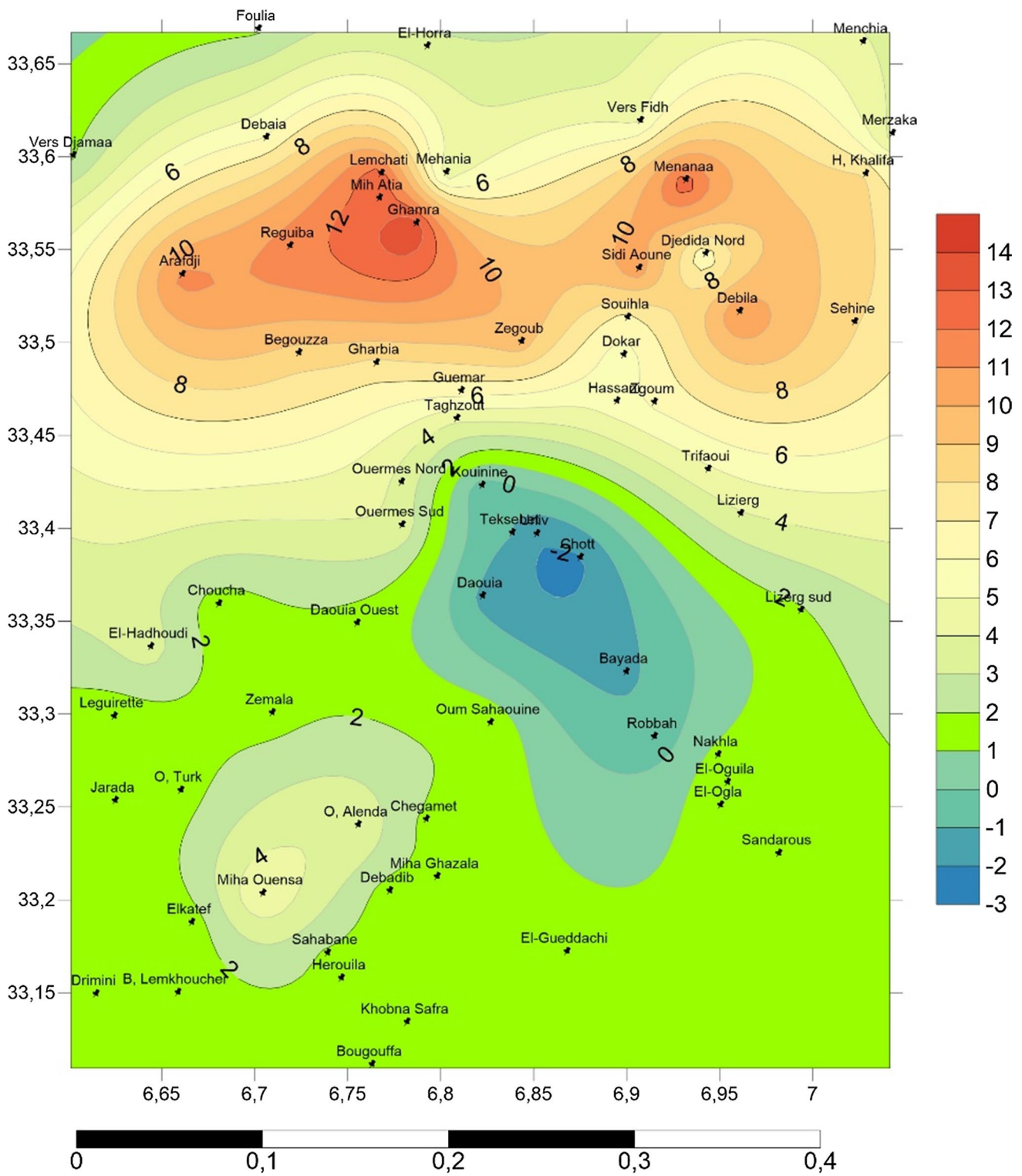


Fig. 7 Depth to groundwater status in 2010 (in meters)

exploited in the Souf oasis, the phreatic aquifer provided the majority of groundwater in 2015, providing about 90.5% (65,429 l/s) of the water needs, followed by CT which meets about 9% (6346 l/s). Only, about 0.5% (347 l/s) of

groundwater is provided by the CI aquifer (Table 3). The dominance of the phreatic aquifer as a source of groundwater is due to its shallow depth and ready accessibility for low cost.

Table 2 Descriptive statistics of depth to groundwater (meter) from 2010 to 2015

| Years | Maximum values | Minimum values | Mean | SD | CV (%) |
|-------|----------------|----------------|------|------|--------|
| 2010 | 14 | - 2.2 | 4.03 | 3.97 | 98.37 |
| 2011 | 14.8 | - 2.1 | 4.33 | 4.10 | 94.79 |
| 2012 | 15.8 | - 1.9 | 4.71 | 4.29 | 90.93 |
| 2013 | 16.3 | - 1.6 | 5.16 | 4.46 | 86.50 |
| 2014 | 17 | - 1.4 | 5.68 | 4.69 | 82.61 |
| 2015 | 18.2 | - 1.2 | 6.40 | 5.10 | 79.73 |

SD standard deviation; CV coefficient of variation

Continuous and rapid development of the agriculture sector in the region In the last 20 years, Souf oasis has experienced an agricultural revolution that has enabled it to greatly increase the quantity and quality of agricultural production (Khezzani and Bouchemal 2013). The Directorate of Agricultural Affairs has indicated that the most important commercial crops in the area are potatoes, olives, cereals, and various vegetables. The area under agricultural production has increased rapidly from at 36,900 ha in 2010 to 51,785 ha in 2013 (Fig. 11). In 2015, the total irrigated area is estimated to have been 72,549 ha. Between 2010 and 2015, the area of irrigated land increased by nearly 200%.

Globally, the agricultural sector consumes about 70% of water resources (Jørgensen 2010; Pimentel et al. 2004), but in arid regions and developing countries, this percentage can be higher (Koundouri and Karousakis 2006). In 2015, the agricultural sector of Souf oasis consumed about 88% (63,453 l/s) of water needs, of which 99% (62,883 l/s) is accessed from the phreatic aquifer (Table 3).

The study of BENDER (1999) shows that the crops water requirements in the Souf oasis and arid regions are higher than in other regions that have more moderate climates. In the case of date palms, the study estimated that the annual needs at 15,726 m³/ha, of which 59% of the water is required in the period from April to September. For other major crops, the water requirements are about 4845 m³/ha for cereals, and 6163 m³/ha for vegetables.

The study of Mumtaz Khan and Prathapar (2012) estimated that the water requirements for date palm trees in the Algerian Sahara reaching a value of 174 m³/tree/year, of which 70.7% is required in the period from April to September. In the same context and in the Souf oasis, Merabet et al. (2007) estimated these water needs at 183 m³/tree/year. All of these values clearly confirm the rise in water demand for agricultural crops production in arid areas, which hastens the depletion of their limited water resources.

Practiced irrigation methods Irrigation methods that are practiced by the farmers are also contributing to the rapid

rate of groundwater decline in the region. This is because despite the emergence of some modern methods in the field of irrigation such as irrigation by sprinkler and drip irrigation systems, the traditional method of flood irrigation is still used today in many farms. This method is simple to undertake, but is not economical in terms of water use (Table 3 and Fig. 11).

Spatial distribution of agricultural wells and land use The sharp decline in the groundwater levels that have been recorded in the northern part of the Souf oasis is due to the heterogeneous distribution of irrigated lands and agricultural wells in this area. For example, Guemar, Reguiba, Magrane, and Hassi Khalifa contain about 88% of the wells and about 85% of the total irrigated land area.

Changes in the method of sewage disposal Historically, untreated sewage was disposed of to ground in the area. Although this water was contaminated, this method of wastewater disposal helped reduce groundwater depletion due to the over-exploitation of the shallow groundwater resource. Starting in 2009, and after, four stations for wastewater treatment were constructed in 12 municipalities (and 58 vertical drainage wells only for El-Oued municipality (Burri and Burri 2004), wastewater inputs to the phreatic aquifer have significantly reduced, after connecting most of the houses to the sewage network and the elimination of most of the wastewater drainage wells. This means that each year, more than 15 million cubic meters of water is no longer discharged to the phreatic aquifer (Fig. 12) (ONA 2015).

The above factors have led to significant changes in the water balance of the phreatic aquifer which has triggered the current decline in groundwater levels in the region. The observed rate of groundwater level decline has varied from 0.29 m/year in 2011 to 2.37 m/year in 2015 (Fig. 10) and has the potential to remove thousands of hectares of land from agricultural production.

Electrical conductivity (EC)

Electrical conductivity is a good parameter for expressing water salinity as this parameter is directly proportional to the total dissolved solids (TDS) content of groundwater (El-Sayed and Salem 2015; Tank and Chandel 2010). The obtained results show that the electrical conductivity values of shallow groundwater from the phreatic aquifer ranged from 2924 to 11,428 µS/cm. These values increase in magnitude from the south to the northern part of the study area. This type of spatial distribution corresponds to the groundwater flow direction in the phreatic aquifer. This view is consistent with that of Guendouz et al. (2006) and Saibi et al. (2009).

The electrical conductivity of groundwater has also increased during the period of the study (Table 4), from a

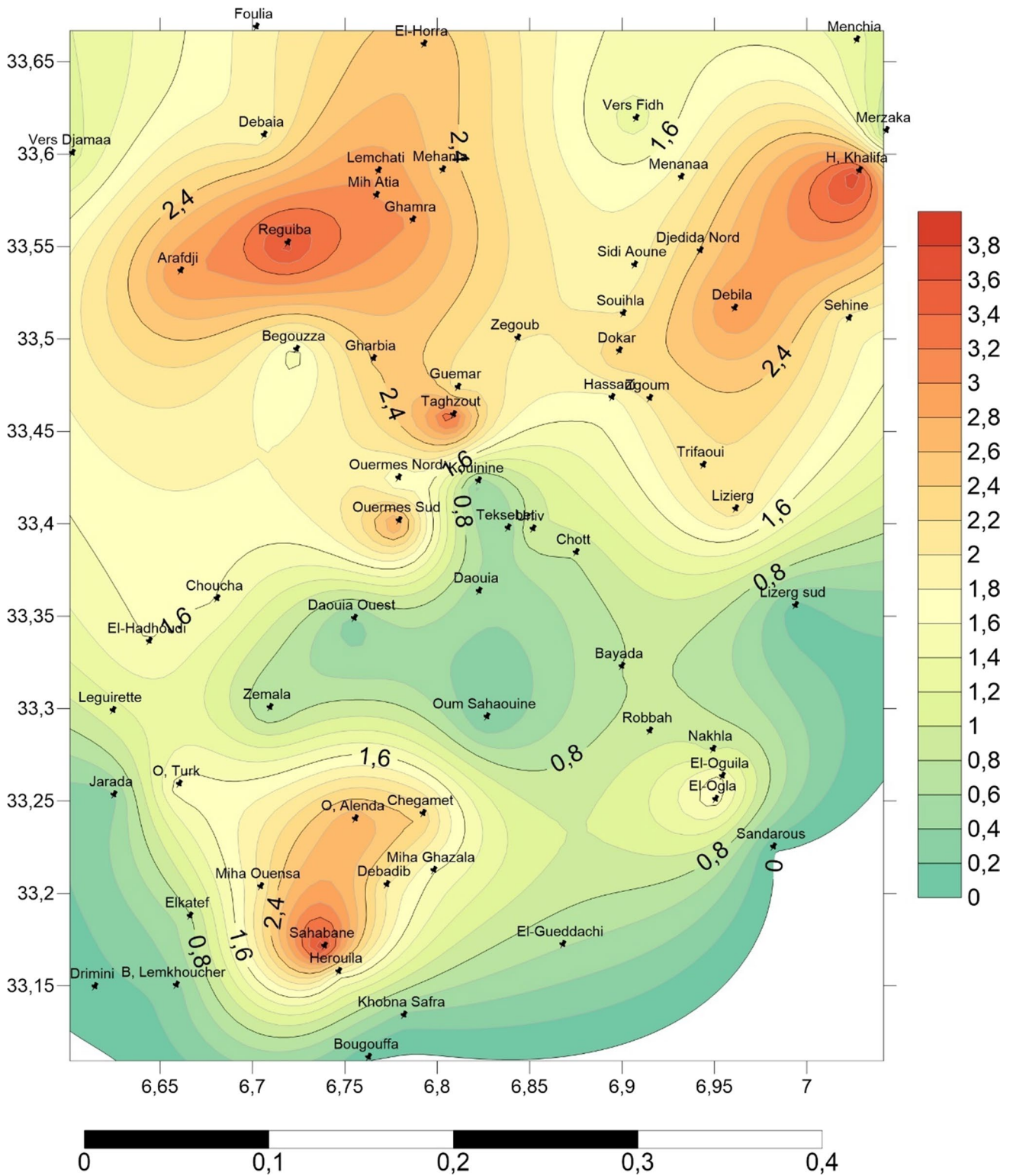


Fig. 8 Changes in decline of groundwater levels between 2010 and 2014 (in meters)

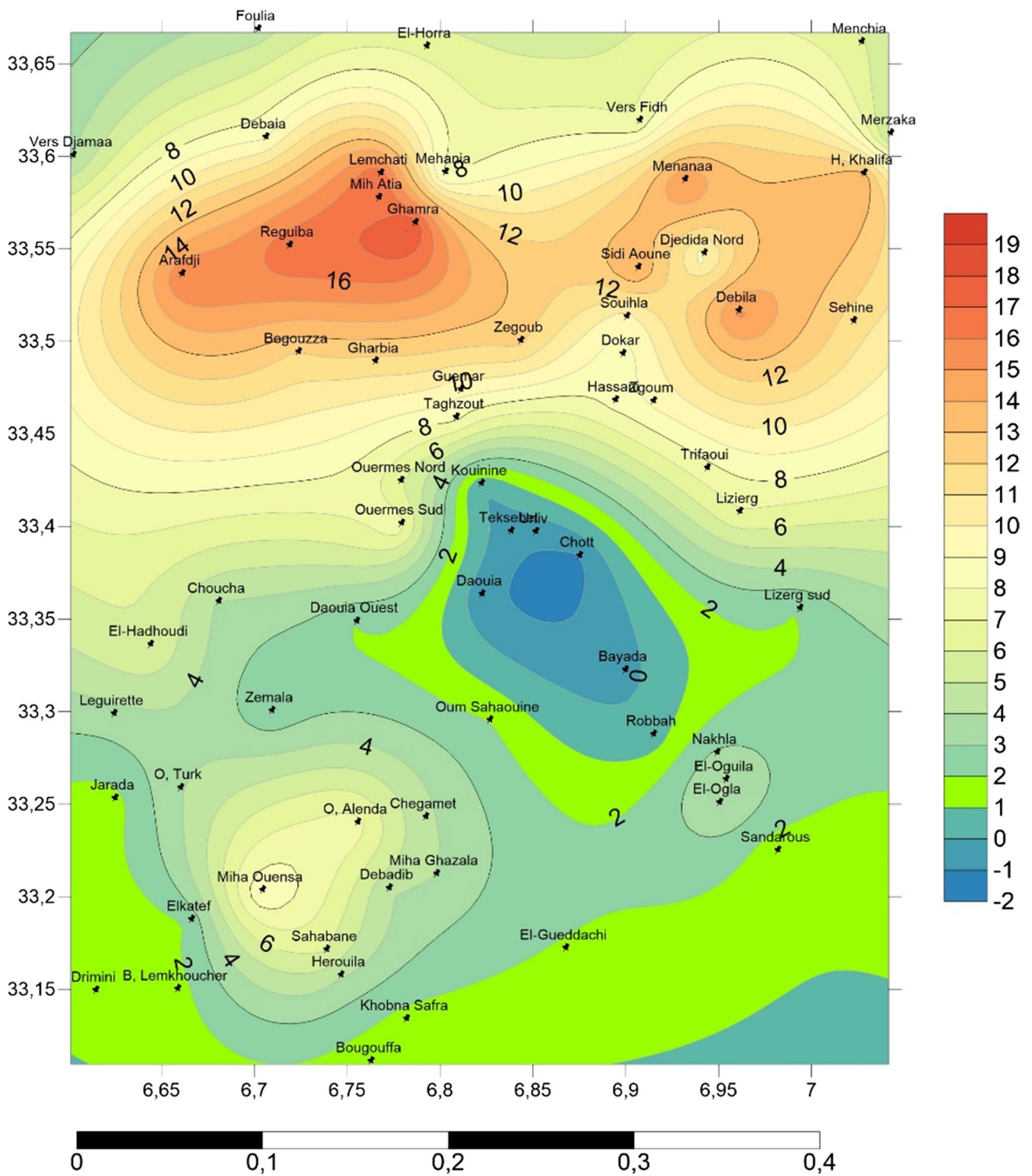


Fig. 9 Depth to groundwater status in 2015 (in meters)

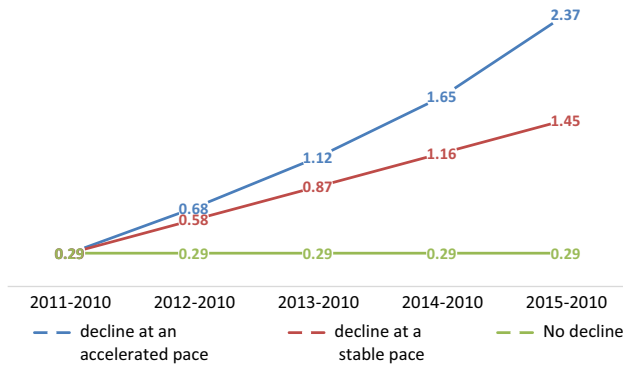


Fig. 10 Rate of depth to groundwater decline values compared to the initial status in 2010 with three scenarios. That is no decline, decline at a stable pace and decline at an accelerated pace

mean value of about 4960 $\mu\text{S}/\text{cm}$ in 2010 to about 6219 $\mu\text{S}/\text{cm}$ in 2015. The increase in the conductivity of groundwater is strongly associated ($R = 0.99$) with the increases in the depth of the water table. Similar results have been obtained in studies of groundwater depletion in arid areas by Al-Naeem (2014) in the Hail region (Saudi Arabia), and by Abliz et al. (2016) in Keriya Oasis (Northwestern China).

Impacts of excess salinity and groundwater decline

Drought and increasing salinity are among the most significant constraints that limit agricultural production throughout the world (Hoffman and Shannon 2007; Sané et al. 2005). In the Souf oasis, changes in the elevation of the water table are causing the demise of Agricultural World Heritage Ghout cultivation system as more than 150,000 palm trees have been killed by drought (Fig. 13b) or by flooding (Fig. 13c) and thousands of additional palms are still threatened in the region. Among the 9792 Ghouts that have been created in the Souf oasis, only about 400 units

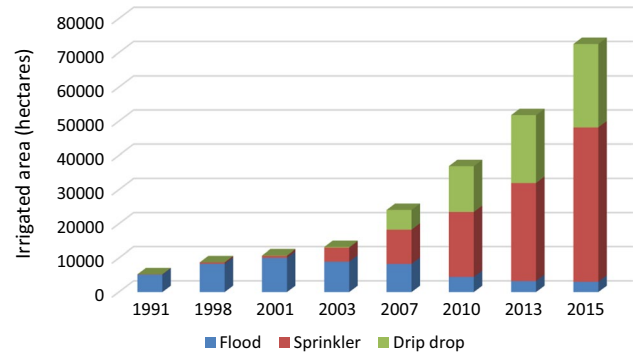


Fig. 11 Evolution of agricultural lands use and practiced irrigation methods (1991–2015)

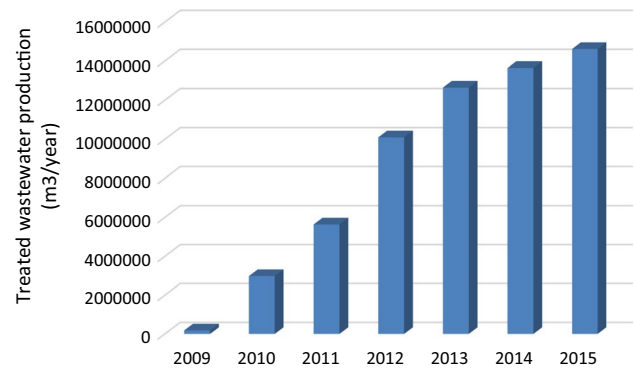


Fig. 12 Evolution of treated wastewater production (2009–2015)

benefits from nature’s gift (i.e., this traditional irrigation method) (Fig. 13a).

Table 5 shows that the area of land where the water table is more than 2 m deep has increased from 42% in 2010 to 78% in 2015. At the same time, the land area in which groundwater is in the optimal depth interval of between 1 and 2 m has become limited and decreased from 47% in 2010 to 17% in 2015. Additionally, the land

Table 3 Evolution of groundwater exploitation according to aquifers and sectors type from 1991 to 2015

| Years | According to aquifer type (l/s) | | | According to sector type (l/s) | | | Total |
|-------|---------------------------------|------|-----|--------------------------------|----------|----------|--------|
| | PA | CT | CI | Irrigation | Drinking | Industry | |
| 1991 | 20659 | 980 | 317 | 21,211 | 735 | 10 | 21,956 |
| 1998 | 30,541 | 1283 | 455 | 31,073 | 1186 | 20 | 32,279 |
| 2001 | 33,187 | 915 | 290 | 33,448 | 917 | 27 | 34,392 |
| 2003 | 36,335 | 1391 | 306 | 36,597 | 1383 | 52 | 38,032 |
| 2005 | 41,112 | 1684 | 321 | 41,352 | 1645 | 120 | 43,117 |
| 2007 | 47,056 | 3131 | 352 | 46,798 | 2917 | 824 | 50,539 |
| 2010 | 51,989 | 4877 | 402 | 51,626 | 4625 | 1017 | 57,268 |
| 2013 | 58,205 | 6040 | 496 | 57,341 | 5737 | 1663 | 64,741 |
| 2015 | 65,429 | 6346 | 347 | 63,453 | 6122 | 2547 | 72,122 |

Table 4 Descriptive statistics of groundwater electrical conductivity (EC) from 2010 to 2015

| Years | Minimum values | Maximum values | Mean | SD | CV (%) |
|-------|----------------|----------------|---------|---------|--------|
| 2010 | 2924 | 9921 | 4961.29 | 1945.91 | 39.22 |
| 2011 | 2998 | 10,256 | 5192.61 | 2024.48 | 38.99 |
| 2012 | 3100 | 10,367 | 5399.57 | 2055.43 | 38.07 |
| 2013 | 3155 | 10,751 | 5649.68 | 2146.46 | 37.99 |
| 2014 | 3100 | 11,287 | 5912.00 | 2272.67 | 38.44 |
| 2015 | 3213 | 11,428 | 6218.89 | 2391.91 | 38.46 |

SD standard deviation; CV coefficient of variation; EC electrical conductivity ($\mu\text{S}/\text{cm}$)

area where the depth to groundwater is less than 1 m has decreased from 10% in 2010 to 6% in 2015, and is likely to disappear altogether within the next 5 years.

The salinity increases associated with the declining water table also threatens agriculture production in the region, especially as the oasis has been producing different kinds of crops such as vegetables and cereals. This salinity can affect plant performance in several ways: through osmotic effects, toxicity, and changes in nutrient interactions (Carillo et al. 2011; Shrivastava and Kumar 2015).

Irrigation by saline water is one of many factors that can lead to soil salinization (Sakadevan and Nguyen 2010). This excess salinity can have negative effects on the biological and physicochemical properties of agricultural soil, which in turn can affect the plants grown in the soil (De Souza Silva and Fay 2012; Yan et al. 2015).

If it is considered that volume of water stored in the phreatic aquifer is limited (Dubost 1986) and that natural recharge rates are very low due to the prevailing climatic conditions (Dubost 1992), it is likely that continued over-exploitation of this resource will lead to ongoing degradation of groundwater quality. This makes the situation alarming in the coming years; therefore, we must work quickly to find solutions and methods able to rectify the problem before it is too late to find solutions to these problems.

Conclusions

Groundwater is one of the most important natural resources, especially in arid and semi-arid regions. In the Souf oasis, the presence of a stable phreatic aquifer is very important element for population and agriculture practices, especially for date palm trees that are cultivated using the Ghout system. Fluctuations of the water table since the 1930s due to changes in land and water management practices have threatened the viability of this World Heritage cultivation



Fig. 13 Status of date palm trees according to depth to groundwater. **a** Date palm trees in Ghout in good status (depth to groundwater between 1 and 2 m). **b** Date palm trees in Ghout degraded by drought (depth to groundwater more than 2 m). **c** Ghout totally degraded by water flooding and occupied by *Phragmites communis* (depth to groundwater less than 1 m)

system. Current groundwater use indicators show that declining water levels and increasing groundwater salinity continue to threaten the viability of irrigated agriculture

Table 5 Evolution of area percentage according to depth to groundwater from 2010 to 2015

| Years | More than 2 m | Between 1 and 2 m | Less than 1 m | Total |
|-------|---------------|-------------------|---------------|-------|
| 2010 | 42.45 | 47.35 | 10.20 | 100 |
| 2011 | 59.59 | 31.43 | 8.98 | 100 |
| 2012 | 63.27 | 28.98 | 7.76 | 100 |
| 2013 | 68.57 | 24.49 | 6.94 | 100 |
| 2014 | 73.06 | 20.41 | 6.53 | 100 |
| 2015 | 77.55 | 16.73 | 5.71 | 100 |
| Mean | 64.08 | 28.23 | 7.69 | 100 |
| SD | 12.41 | 10.80 | 1.66 | |

in the region and management interventions are urgently required to ensure groundwater can be sustainably used in the region.

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Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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