Feasibility of water desalination for irrigation: the case of the coastal irrigated area of Dyiar-Al-Hujjej, Tunisia

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ABSTRACT

Irrigation in Tunisia is threatened all over the country. The irrigated coastal area of Dyiar-Al-Hujjej has observed a drop in agricultural activity following a seawater intrusion. Thus, yields have become disrupted in direct relation to the quantities of fresh water supplied and transferred over a distance of 100 km. For the sustainability of this area, the feasibility of using desalinated water to stabilize the irrigation water supply was analyzed. When all crop water requirements are to be met with desalinated water, the net income is negative for crops currently grown, except strawberry. All the open-field crops remain unprofitable even in the case of agro-industrial development, except tomatoes. A blending between desalinated seawater and aquifer saltwater also leads to a negative income for the main crops. The introduction of greenhouses to replace the same open-season crops is beneficial when desalinated water is used. The use of desalinated water in irrigation faces the high cost of desalination (0.5 US $/m^3) while the average price of irrigation water in Tunisia is 0.05 US $/m^3. Desalination can be recommended only in the case of crops with low need for water and high added value.

Key words | added value crops, net revenue, rainy season crops, water desalination for irrigation, water scarcity

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HIGHLIGHTS

- The cost of desalination has been decreasing over the years. As a result, desalination has become a viable option for certain strategic uses.
- Today, over 20,000 desalination plants in more than 150 countries supply about 300 million people with freshwater every day.
- The continued decrease in cost and environmental viability of desalination has the potential to significantly expand its use – particularly for agricultural purposes.
- Desalination can be seen as an option in water supply sources, including traditional surface water and groundwater sources as well as wastewater reuse, to meet the growing water demand gap.
- As renewable sources of energy such as wind and solar expand, and as advances in setting up combined stations with renewables energies and desalination make producing water from desalination plants much cheaper, the prospect of producing freshwater become more promising.

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INTRODUCTION

The Mediterranean region is vulnerable to the consequences of climate change. According to the Inter-governmental Panel on Climate Change (Eckstein *et al.* 2019), North Africa is considered a vulnerable area to climate risks worldwide. For Tunisia, by 2050, average temperature could increase between 2 °C and 2.3 °C and precipitation could decrease by 1 to 14%. It becomes strategic for Tunisia to maintain food production for sustainable socio-economic development.

Tunisia is an arid country in two-thirds of its territory. Average annual rainfall is about 200 mm and around 15% of the working population works in agriculture (Chebbi *et al.* 2019). Tunisia suffers from structural droughts; 25% of Tunisian arable lands are saline (Hamrouni & Daghari 2010). The main source of soil degradation is water irrigation and sodium chloride is the most prevalent salt in Tunisian water resources (Slama 2004).

All these constraints have affected the irrigation sector. Indeed, irrigated areas represent only 10% of arable lands. Despite of these constraints, the irrigated sector accounts for over 35% of national agricultural production while the world average is about only 20%. Thereby, the role of irrigation in Tunisian development is certain but the main constraint is the lack of fresh water. Only 30% of mobilized water resources in Tunisia have salinity less than 2.3 dS/m.

For example, in Tunisian oases, the driving force of development for all of southern Tunisia, the average yield of irrigated date palms is 4.6 tonnes/ha. In Egypt, where these oases are also present in the arid zone, 36,000 hectares (El-Juhany 2010) produce 1.47 million tonnes of dates (Zafar 2020). This represents 41 tonnes/ha, or 9 times the yield in Tunisia. The date palm in Egypt is irrigated with water from the Nile.

In Sidi Bouzid governorate, economically based solely on irrigated agricultural activity, the aquifer is overexploited and we must expect that this aquifer will be exhausted within a few years, while many other aquifers with an electrical conductivity (EC) of more than 8 dS/m are available in the area. In this rural region, no other alternative for economic development is possible apart from agriculture.

This is confirmed by the allocated water volume for a Tunisian which does not exceed 500 m^3/capita/year, far below the Food and Agriculture Organization (FAO) standard which is a minimum of 1,000 m^3/capita/year.

Another big problem is dam water transfer in Tunisia. All the coastal areas are supplied by state networks either for irrigation, drinking water, industry or tourism by transferring water from other very distant regions localized in the interior of the country (even over a distance of more than 300 km). All these transfer systems are saturated today and water shortages have multiplied in recent years. After the Arab Spring which started in 2011, the local populations living in the regions where water is produced contest this transfer and they ask that this water be used for local development. These people live with money sent by family members working in other regions or abroad. Protests, brutal breakage of pipes and vandalized drilling have become common in these regions. By contrast, the coastal regions observe a high economic development (rural exodus). The rural population is forced to migrate to these coastal areas in search of employment leaving their families on the spot or living in popular neighborhoods with very high population densities. Also, several aquifers currently used for this transfer are overused. Tunisia no longer has sites where we can build dams with a capacity exceeding 100 million m^3. The regions sheltering these saltwater resources are inhabited by peasants who have no source of living.

The search for sustainable agricultural development for all these regions with the potential for saltwater, drainage water, wastewater, or seawater is essential in Tunisia. Desalination can be an alternative for freshwater production, especially since Tunisia has great potential in desalination. Tunisia has commendable experience in the desalination of seawater and groundwater. Desalination of water started in the 1980s (Elfil 2018) to improve the quality of drinking water in all urban agglomerations in the south and in islands with a daily production of 210,000 m^3 of drinking water produced throughout the country via 16 desalination plants. A further 3 large seawater desalination plants will be added to the existing stations for the citizen of Sousse (50,000 m^3 to 100,000 m^3 per day), Zarat (50,000 m^3 to 100,000 m^3 per day), and Sfax (100,000 m^3 to 200,000 m^3 per day).

Indeed, policymakers in Tunisia are aware of the desalination potential offered by the Mediterranean Sea over 1,300 km of coastal shore.

Desalination plants have enormous potential to provide freshwater for irrigation in Tunisia. Indeed, many studies of water desalination costs appear regularly to promote this option for water supply intended for drinking water or irrigation.

Tunisia has experienced several field studies of desalinated water in irrigation. In the 'fifth season' private project in southern Tunisia, where cherry tomato is grown under greenhouse, desalinated water has been blended with saltwater for more than 20 years. The selling price of cherry tomato is 0.5 US $/kg at least and a great part of the production is intended for export.

According to Mhiri (2014), a 1.2 ha farm occupied with olive trees in southern Tunisia irrigated by reverse osmosis desalinated water using electrical energy saw its gross margin evolving from 57 US $/ha under rainfed conditions to 3,676, 3,869 and 3,819 US $/ha respectively for the years 2011/2012, 2012/2013 and 2013/2014 following a supplementary irrigation with desalinated water.

A reverse osmosis desalination project was realized in the Gounat area in Mahdia governorate in Tunisia to irrigate 3.5 ha (75 greenhouses with vegetable crops) during 2016. The farmer's profit should double at least (Ergaieg *et al.* 2018).

In our study area, a widespread salinization of the groundwater which was the main source of irrigation has been observed following a sea intrusion. The average sodium adsorption ratio (SAR) was $8.6^{0.5}$ (meq L^{-1}) and the average EC was 6.6 dS/m (Mekni 2017). Thus, there was an abandonment of irrigated areas that had become unsuitable for agricultural production-land which was previously considered as the best tomato production area in Tunisia with the main processing factories. Some farms and wells were abandoned because of sea intrusion and general salinization. Following overexploitation, salinity levels of 19 dS/m were measured in some irrigation wells. To save this irrigated area considered vital for Tunisian agriculture, the Tunisian state carried out an expensive transfer (with many pumping plants) of fresh water over a distance exceeding 100 km from another watershed. But in recent years, this operation of transferring fresh water has been disputed by the populations of the area where the transferred water comes from. Furthermore, this transfer is not regular. While during the years 2015 and 2016, the volumes of water transferred were 1,714,603 and 1,714,492 m^3, this volume was only 800,000 m^3 in 2017. During the year 2018, no transfer of water was completed due to the lack of rains, which weakened the agricultural system and limited farmers' choices.

The farmers adopted localized irrigation and blended the transferred fresh water and the aquifer saltwater, which made it possible to partially save this area. All farms very close to the sea were abandoned definitively because the salinity of the aquifer was very high. In addition to this operation of freshwater and saltwater blending, farmers' adaptation to this new situation has been observed by:

- the adoption of crop rotation by the application of successions between irrigated crops, rainfed crops and fallow by all farmers in order to reduce the soil salinity (Bani *et al.* 2020);
- the introduction of new and more profitable crops such as strawberries following this supply of fresh water and the practice of associated crops on the same site (strawberry-pepper combination) (Daghari *et al.* 2020a);
- the adoption of winter and spring crops with the aim of reducing water supply and taking advantage of leaching of salts by the rains.

The objective of this paper is to evaluate the economic feasibility of the use of desalinated seawater to irrigate this area. Several scenarios have been studied: (i) if all the irrigation water comes from a desalination plant, (ii) if the food-industry development of this region is exploited, which will allow an increase in the selling prices of agricultural products and (iii) if a blending between desalinated water and groundwater will be practiced (in reproduction of the current situation) except that the supply of desalinated water will become regular and safe.

MATERIALS AND METHODS

In our work, to consider integrating a desalination plant as a matter of urgency to save an agricultural area threatened by salinity requires various information (Figure 1) concerning

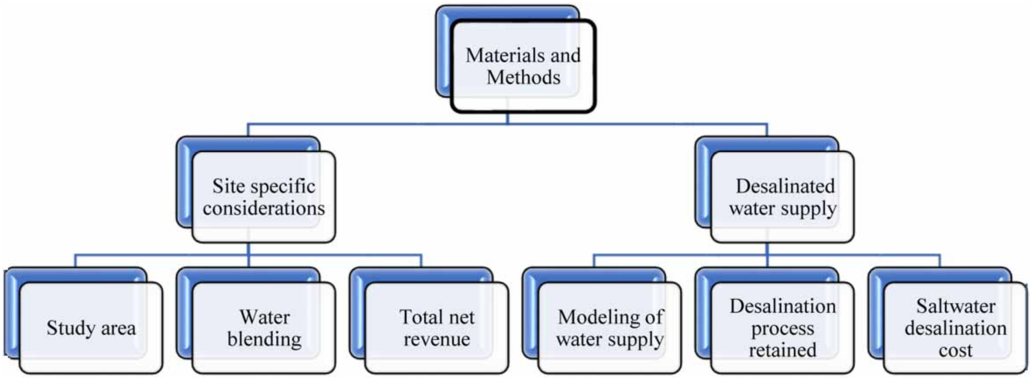

Figure 1 | Flowchart of the methodology.

the specific considerations of the study site and also concerning the water supply of the area.

Site specification considerations

Study area

The irrigated area of Dyiar-Al-Hujjej, in Tunisia, the subject of our study, plays an important role in the production of tomato and pepper. The main tomato and pepper processing factories in the country are located in the peninsula of Cap Bon (Nabeul, Korba, Dyiar-Al-Hujjej, Menzel–Temime, Grombalia). It is also the main productive strawberry-growing area in Tunisia. This area has experienced seawater intrusion and aquifer salinization has been observed. Dyiar-Al-Hujjej has a coastal irrigated area of 800 hectares located inside the Delegation of Korba northwest part of Tunisia (Figure 2) having as latitude and longitude 36,617 N and 10,817 E, respectively. The selected location belongs to the Mediterranean semi-arid floor with warm winter. The average annual rainfall is 441 mm and it is very irregularly distributed with most rains from September until April and no rain during all the period May-August when the main crops (tomato and pepper) are grown, while the evapotranspiration (ETP) is about 1,167 mm (Table 1).

Water blending

The irrigation water is currently managed by a farmers' association called 'Izdihar'. The selling price of one cubic meter of fresh water to farmers is around 0.05 US $; these are only expenses corresponding to the operating costs for the irrigation management. All mobilization costs (dam, pipes, and pumping stations) as well as all major repairs (broken pipes, maintenance of pumping stations) are not taken into account in the calculation of the sale price of irrigation water to farmers. Within this area, the farmers blend fresh water (60%) with salty pumped water (40%) by themselves, with a pumping cost of about 0.02 US $/m^3.

To determine the percentage of desalinated water to be blended with saline water, the principle of mass conservation will be applied.

The system can be written:

$$C_s * V_s + C_d * V_d = C * V \quad (1)$$

$$V_s + V_d = V \quad (2)$$

where:

- C_s: saline aquifer water salinity concentration (ppm)
- C_d: desalinated water salinity concentration (ppm)
- C: blended water salinity concentration (ppm)
- V_s: saline aquifer water volume (m^3)
- V_d: desalinated water volume (m^3)
- V: blended water volume (m^3)

By combining Equations (1) and (2), the ratio x ($=V_d/V_s$) of desalinated water to be blended with saline water is:

$$x = \frac{C_s - C}{C - C_d} \quad (3)$$

Figure 2 | Geographical location of Dyiar-Al-Hujjej (https://www.arcgis.com/index.html).

Table 1 | Average temperatures, wind speed, relative humidity, sunshine duration and evapotranspiration in the Nabeul (chief town governorate) station (1968–2004)

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average maximum temperature (°C)	15.9	16.2	17.8	19.6	22.9	27.5	30.5	31.2	28.4	25	20.6	17.1
Average minimum temperature (°C)	8.9	9	10.5	12.3	15.7	19.4	22	23.2	21.3	18.2	13.7	10.3
Wind speed (m/s)	3.1	3.4	3.6	3.6	3.4	3.4	3.1	3.1	3.3	3.1	3.2	3.1
Relative humidity (%)	75	73	72	72	72	68	67	70	73	75	74	74
Duration of sunshine (hours/day)	4.3	6.2	6.8	8.0	8.4	9.6	10.6	10.0	7.6	6.8	4.6	3.2
ETP (mm)	37	47	70	96	131	163	182	162	115	79	48	37

To calculate relative yield (Y_r), when saline water is used in irrigation, the following equation (Maas & Hoffman 1977; Ayers & Westcot 1985) will be applied:

$$Y_r = 100 - b\,(EC_s - a) \tag{4}$$

where b = the curve slope expressed in percent per dS/m (equal to 9.9, 14 and 12 respectively for tomato, pepper and potato), and a = the salinity threshold expressed in dS/m (equal to 2.5, 1.5 and 1.7 respectively for tomato, pepper and potato) (Maas & Hoffman 1977).

EC_s = the mean electrical conductivity of a saturated paste normally taken from the rootzone, related to the EC of the irrigation water (EC_w) by this equation:

$$EC_s = 1.5 * EC_w \quad (5)$$

Total net revenue

Yield (ton/ha), selling price ($/ton) and production cost ($/ha) are taken according to the Tunisian Ministry of Agriculture database and farmers associations of different irrigated areas in the region and verified by our surveys. In the production cost, the price of water is not included. The selling price of the agricultural products considered is the selling price at the farm level (MAREP 2019a).

In order to determine the total net revenue/year ($ million), the following parameters (Gul *et al.* 2016) must be calculated:

- *Value* of agricultural products ($/ha) = Selling price ($/ton)*Yield (10^3kg/ha) (6)
- *Gross* margin($/ha) = value of agricultural products ($/ha) − production cost($/ha) (7)
- *Net* revenue($/ha) = Gross margin($/ha) − Water cost($/ha) (8)

Desalinated water supply

CROPWAT model

CROPWAT 8.0 for Windows is a free downloadable computer program used to calculate potential evapotranspiration using the Penman-Monteith formula, the crop water requirements and the quantity of water essential for irrigation, taking into account the characteristics of the soil, crops, and data collected on the dominant climate for the crops cultivated in the study (Onyancha *et al.* 2017).

Desalination process retained

Current water desalination technologies are classified into two categories, according to the principle applied (Cabrera-Reina *et al.* 2019): (i) the processes using membranes called reverse osmosis (RO), (ii) thermal processes involving a phase change multi-effect distillation (MED).

RO and MED are technologies whose performance has been proven for water desalination. Indeed, these two processes are the most widespread in the world desalination market.

In our study, the desalination technique chosen is desalination by reverse osmosis which is a process for separating water and dissolved salts using semi-permeable membranes under the action of pressure. As the experience of Tunisia in the use RO goes back several years, this technique is well mastered. Recent studies have shown that it is more profitable to use Photovoltaic (PV) + RO technology which cheaper and cleaner by comparison to thermal desalination technologies. The Emirate of Abu Dhabi paid in excess of US $100 million in 2012 due to its choice of multi-stage flash (MSF) and MED over RO to fuel expenses for seawater desalination (Kaya *et al.* 2019).

The RO process operates at room temperature and does not involve a phase change. The polymer membranes used allow water molecules to pass through and do not allow particles, dissolved salts and organic molecules to pass through (Figure 3).

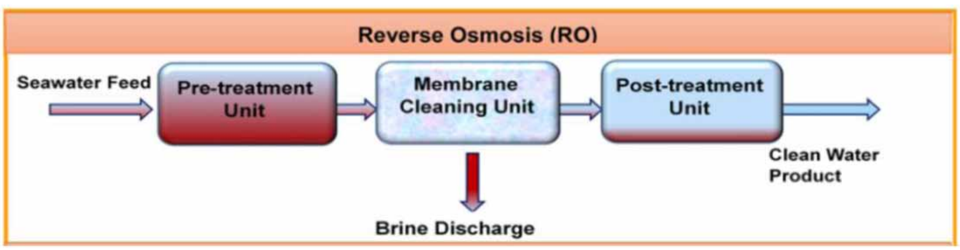

Figure 3 | Schematic diagrams of reverse osmosis desalination technology (Ouda *et al.* 2018).

Saltwater desalination cost

The irrigation water is currently managed by a farmers' association called 'Izdihar' (prosperity). The selling price of one cubic meter of fresh water to farmers is around 0.05 US $ and is an average price for all Tunisian irrigated areas. These are only fees corresponding to the operating expenses. All mobilization costs (dam, pipes) as well as all major repairs (broken pipes, maintenance of pumping stations) are not taken into account in the calculation of the selling price of irrigation water to farmers. The saltwater pumping cost is 0.02 US $/m^3. Within this area, the farmers blend fresh water (60%) with salty pumped water (40%) by themselves in concrete tanks or by injection directly in wells if no tank is available; the quantities of fresh water are insufficient to meet the total water needs of crops throughout the area. The prices of the desalinated water and brackish water were respectively 0.55 and 0.19 US $/m^3 in the Campo de Níjar region (Aznar *et al.* 2017). Other costs must be considered such as those as a result of high boron amounts contained in sea water which can damage crops; its elimination costs at least 0.05–0.07 US $/m^3 for a large system (Hilal *et al.* 2011).

The desalination can be used for water supply and it can improve the food security and the economic prosperity of these peasants. The expansion of irrigation in Tunisia will stabilize yields and develop several other regions with no other economic activity. Kang *et al.* (2015) concluded that it is significant to develop irrigated agriculture to mitigate climate change effects and yield variation. For the whole world, whose population will increase to 10 billion by 2050, the expansion of irrigation is imperative.

In the reverse osmosis solar desalination project in the Gounat area in the Mahdia governorate in Tunisia, the additional energy costs generated by the electromechanical equipment of the desalination plant induces a total cost, including the pumping from drilling and the discharge to the blending tank, of the order of 0.12 US $/m^3 without taking into account the initial investment cost of US $140,000 taxes not included. The salty aquifer water price sold by the state is about 0.05 US $/m^3 in this irrigated area (Dhahbi 2016).

The average solar desalinated water cost covering all expenses was 0.42 US $/m^3 for a small private exploitation using aquifer water in a farm planted with olive trees in southern Tunisia irrigated by reverse osmosis desalinated water (Mhiri 2018). In our case, the use of groundwater is forbidden because the region already suffers from a sea intrusion which should not be accentuated. In a study done for all of south-eastern Spain, the cost of desalinated saltwater varies from 0.55 to 0.74 US $/m^3 (Martínez-Alvarez *et al.* 2017). The barrier for desalinated water use is price (Aznar *et al.* 2017). According to SONEDE (Tunisian National Agency of Potable Water), dealing with the production and supply of drinking water throughout Tunisia and whose experience in reverse osmosis desalination dates back to the 1980s, energy accounts for 40% of the cost of desalination using electrical energy. The average desalination cost of the production of one potable cubic meter is about 0.5 US $/m^3 for large desalination plants; investment cost is about 0.3 US $/m^3 (Kamel 2017). In Tunisia, for all dams, irrigation networks, pumping and desalination plants, the state tries to make stakeholders pay only the operating costs and it fails. A seawater desalination cost equal to 0.5 US $/m^3 will be retained for this study.

RESULTS AND DISCUSSION

Before analyzing the feasibility of seawater desalination's added value in the irrigated area of Dyiar-Al-Hujjej, an assessment of the current situation was carried out.

Current income with aquifer saltwater and surface fresh water blending

The crust has a depth less than 20 cm sometimes, which limits the growing to only vegetable crops. The soil is inherently low in organic matter and high in sand (clay: 10%, silt: 36%, sand: 55%). Manure is always added.

Currently, only surface water is supplied to farmers and blended with salt water from the aquifer. The average well depth is about 20 m measured in 2011 and in 2019.

Irrigation network

Following our field visits, we noted a 100% localized irrigation adoption ratio which was only 5% before the freshwater transfer in 1998. This water transfer operation allowed a resumption of agricultural activity. The network is in good condition with 90% irrigation uniformity (Daghari *et al.* 2020a). The area originally developed was 950 ha (Table 2). Many small owners do not exploit their farms regularly due to their unprofitable income. Some farms with high salinity are left fallow for a whole year while waiting for the salts to be washed off in the rain. The size of the farms is divided into two classes: 0–4 and 4–10 ha each occupying 435 ha with 185 farmers and 365 ha with 60 farmers, respectively. The intensification rate is 136 and 125%, respectively, for small and medium farms. The area actually exploited is around 750 ha. It is an irrigated area equipped with a large number of hydrants, which allows good proximity to farms and easier coordination between farmers. The irrigated area is divided into 29 districts. The number of hydrants is 260 for 621 subscribers. One hydrant serves about 3.5 hectares while the average in Tunisia is 1 hydrant for 5 hectares. The same hydrant is used by a small number of irrigators with an average of 2.4 subscribers per hydrant. Farmers highlight the commendable services of the farmers' association. Irrigated agriculture was the only source of income in this region, and this is an activity passed on from one generation to the next. Water management is on demand and dispatchers ('aiguadiers') are responsible for opening and closing the irrigation valves.

Table 2 | Number of hydrants, of subscribers and surface areas initially equipped in the irrigated area of Dyiar-Al-Hujjej, Tunisia

Irrigation district number	Number of hydrants by district	Number of subscribers by district	Surface area by district (ha)
1	12	32	28.25
2	9	20	34.30
3	8	34	27.45
4	8	19	34.45
5	6	10	27.40
6	9	24	33.10
7	7	17	28.80
8	7	11	30.33
9	6	10	32.50
10	7	12	31.40
11	11	29	32.10
12	12	29	30.70
13	11	40	37.50
14	11	32	31.50
15	7	20	34.60
16	9	32	27.12
17	11	58	33.20
18	6	10	29.40
19	13	27	52.10
20	14	27	42.10
21	4	4	26.00
22	9	16	38.70
23	9	15	34.60
24	9	12	37.30
25	8	15	30.80
26	8	14	32.90
27	8	14	27.00
28	11	25	35.70
29	10	13	29.20
Total	260	621	950.50

Having an irrigation network in good condition is an advantage for our study because for this particular area, we may not include the cost of the irrigation network in the final desalinated cubic meter cost. Even if this irrigation network will be redone in a few years, the desalination operation will be well advanced and the cost of a new network can be borne by the farmers themselves in the event of significant net income.

Current distribution of crops

For the year 2019, the percentage of land use observed is 23, 15, 17 and 16% respectively for the main crops: tomato, potato, pepper and strawberry (Table 3). The effective irrigated area varies from one year to another, according to the surface water volume supplied. At the beginning of the agricultural season (in September), the extension service indicates to farmers the approximate volumes of water available for the different seasons, and with the farmers, plans the areas to be reserved by each crop. The area occupied by tomato in this irrigated area decreased from 450 to 210 ha between 1998 and 2019 while a net spread of strawberry is observed. Strawberry is a crop with high added value and whose growth has become possible thanks to transferred fresh water and it is cultivated during the rainy

Table 3 | Areas occupied by the main crops grown in the irrigated area of Dyiar-Al-Hujjej during the project start-up year (1998), ten years after (2008) and in 2019 (ha)

	Area occupied by different crops (ha)								
	Total surface	Irrigated crops				Rainfed crops			
Year		Tomato	Potato	Pepper	Strawberry	Cereals	Forage	Spices	Various
1998	605	450	40	60	0	30	15	5	5
2008	610	260	99	60	84	40	21	6	40
2019	741	170	113	128	121	90	75	33	11

period, so part of its water needs is met by very good quality rainwater.

Strawberry plants are imported with high prices. Transplanting of strawberry is done in late September, early October, and harvesting is done until late May. Strawberry is grown in association with pepper during two successive years. Strawberry, being very sensitive to salinity, is grown during the rainy season between September and May while pepper, which is less sensitive to salinity, is cultivated during the dry season between May and August. Farmers are very aware of the problem of salinity. In recent years, if heavy rain does not fall during the month of September to leach the soil salts, strawberry and pepper have been removed after one year and the land left fallow or used to cultivate rainfed or another winter crop resistant to salinity. An increasing salinity was observed when strawberry and pepper are grown in association in two consecutive years; measured soil EC was 1.1, 3.3 and 5.52 dS/m on July 2011, August 2012 and August 2013, respectively (Daghari *et al.* 2020a).

Crop rotation is systematic in this area and it is a successful key in the management of soil salinity. Electrical conductivities measured under irrigated tomato and fallow were respectively 5.6 and 1.4 dS/m (Daghari *et al.* 2020a). On the other hand, the areas occupied by rainfed crops have increased from 55 ha in 1998 to 209 ha in 2019. Tunisia is going through a drought cycle and the transferred amounts of water have been very disturbed in recent years. The dam from which freshwater is transferred has observed a very low filling rate in recent years. Note that during December 2019, January 2020 and February 2020, the rains were almost zero while this period is normally rainy. During 2016, fresh water supply was stopped from May because of general drought in Tunisia and only drinking water was satisfied. The arboreal sector received just 1/3 of its needs to preserve trees.

Crop water requirements and the adequacy of supplied water quantities throughout the irrigated perimeter of Dyiar-Al-Hujjej

Crop water requirements were calculated using CROPWAT software for monthly average values of minimum and maximum temperature, relative humidity, wind speed and sunshine duration and solar radiation. The rain considered is the average monthly rain. The crop coefficients are taken according to Allen *et al.* (1998).

Average total water requirements calculated by CROPWAT model for this area are equal to 2,532,021 m^3/year (Table 4) while the transferred fresh water volume is about only 1,660,321 m^3 for the year 2019. The deficit, i.e. 871,700 m^3, is pumped from the saline aquifer. The amounts of water distributed differ from one year to another depending mainly on the availability of surface water. The farmers' association estimate that generally the contribution of groundwater and surface water are 40 and 60%, respectively. The farmers' association provides insufficient fresh water (1.6 dS/m) amounts to be used for irrigation after blending with the aquifer saltwater (6 dS/m). After examination of the archives of the farmers' association, these quantities were 1,569,467 and 1,700,603 m^3, respectively, during the years 1998 and 2008, ten years later. The most important consumptions are recorded during May-June, July and August corresponding to the period of full growth of the main crops (strawberry, tomato and pepper). During the dry period (May, June, July and August), fresh surface water is allocated primarily to drinking water and the irrigated sector is only partially satisfied. For these 4 months, theoretical crop water requirement calculated by

Table 4 | Monthly water amounts supplied and crop water requirements calculated by CROPWAT model in the irrigated area of Dyiar-Al-Hujjej, Tunisia

Months	Measured amounts of water supplied (m^3)	Crop water requirements (m^3)
January	53,320	17,280
February	41,240	26,400
Marsh	131,240	100,940
April	175,303	254,710
May	370,221	560,100
June	357,371	505,100
July	351,444	550,321
August	90,341	471,250
September	30,271	25,381
October	21,730	11,620
November	20,320	5,780
December	17,530	3,320
Total (m^3)	1,660,331	2,532,202

CROPWAT is 2,086,771 m^3 while the amount of surface water supplied is only 1,169,377 m^3 (about 50%). The farmers use aquifer saltwater to irrigate only tomato resistant to salinity but they accept low yields; pepper is not marketable, the pod is small. The reduction in yields as a function of salinity was 50 and 40% respectively for tomato and for pepper for an EC of irrigation water slightly exceeding 4.5 dS/m (CRUESI 1970). The farmers know that the rains in September wash away all the soil salt, especially since it is a light and thin soil. On the other hand, the quantities of surface water distributed to farmers during the months of January and February far exceed theoretical needs. During this rainy period, when transferred fresh water is available, the farmers over-irrigate to leach out the salts. So, when in May, the farmers are repeating tomatoes and peppers, the soil will have low salinity. Thereafter, the salinity will increase because saltwater is blended with fresh water wish is much lower than the crop water requirement.

Gross margin in the current circumstances

In Tunisia, the average yields of tomato and pepper are respectively 70 and 18 t/ha while they are not more than 50 and 12 t/ha in our study area, due to excessive irrigation water salinity according to the questionnaires asked of farmers. When desalinated water is used, Tunisian average yields will be considered (MAREP 2019b). The strawberry grown only in this region during the rainy season has a good yield of about 70 t/ha. Potato is grown during the wet season also when fresh water is available; an average national yield of 22 t/ha will be considered.

Value of agricultural products and gross margin were calculated by using Equations (5) and (6). Except for strawberry, the gross margin calculated is very low and even negative for pepper (Table 5). The farmers cultivate pepper only in association with strawberry. The pepper benefits from the residual fertilizers left by the strawberry but it also benefits from an unsalted soil support since strawberry is irrigated only with fresh water and is grown during the rainy seasons of autumn, winter and spring (about 400 mm of rainfall) detailed in Table 1. When desalinated water is used, benefit is about 15,000 US $/ha for tomato and watermelon grown under greenhouses in Spain (Reca *et al.* 2018).

In other regions of Tunisia when fresh water is used, the tomato yield can reach 100 t/ha and a profit of 4,192 US $/ha can be reached.

Table 5 | Gross margin for current crops grown in the irrigated area of Dyiar-Al-Hujjej, Tunisia

Crops	Crops yield (10^3 kg/ha) (a)	Selling price at farm level (US $/kg) (b)	Value of agricultural product (US $/ha) (c) = (a)*(b)	Production cost (US $/ha) (d)	Gross margin (US $/ha) (e) = (d) − (c)
Open-field pepper in dry season	12	0.108	1,296	1,401	−105
Open-field extra-early potato in wet season	22	0.133	2,926	1,767	1,159
Strawberry in wet season	55	0.300	16,500	6,000	10,500
Open-field tomato in dry season	50	0.06	3,000	1,808	1,192

Based on crops percentage occupation (23, 15, 17 and 16% respectively for tomato, potato, pepper and strawberry) observed in 2019 and as the size of the farms is divided into two classes 0–4 ha and 4–10 ha, the average gross margin is 4,300 US $ and 15,000 US $, respectively, for average farms of 2 and 7 ha for these two classes. These incomes are low especially for the first class which counts 75% of the farmers with average families of 5 to 6 people. Several smallholders have abandoned their land or are renting it out to other farmers and are looking for work elsewhere. Even those who stay on their land practice other activities in parallel which leaves them unavailable entirely for their farm.

During the dry years, when the amounts of water transferred are reduced, the strawberry crop occupies a very small area and even the crops supporting salinity are cultivated in proportions not exceeding 60%, and the farmers see their incomes fall unfortunately. This weakens the system and also explains the non-use of the entire equipped area. If the amount of water transferred is insufficient, priority is given to potable water by the Tunisian government. In our study area, for the dry agricultural season 2016–2017, water transfer for irrigation was stopped because of lack of rain for all the dry season. Only $0.8 \times 10^6\,m^3$ was supplied during 2016/2017 while this amount is about $1.7 \times 10^6\,m^3$ for a normal year. In Tunisia, the state hopes to settle these populations on their farms. It relies heavily on agriculture for the reduction of unemployment especially since agriculture is the main economic sector which can be the engine of development of all regions of Tunisia. Tunisia is very close to Europe in order to be able to export mainly early vegetables. Neighboring countries have demand for these agricultural products. Agriculture is the largest employer in Tunisia (more than 15% of the working population). So, every effort should be made to extend irrigation to other areas even when only salt water is available; can desalination be a solution? Alternative options such as desalination of seawater or wastewater are increasingly appearing as possible solutions in Tunisia to be a source of water for irrigation.

Net revenue in the case when only desalinated water is used for irrigation

As the problem of sea intrusion is observed and aquifer salinity has continued to increase, an analysis of the scenario using only desalinated seawater deserves to be studied. In the Canary Islands Archipelago (Spain), seawater is used for desalination because an over-exploitation of coastal groundwater and a sea intrusion were observed after several years of operation (Monterrey-Viña *et al.* 2020).

The irrigation water amounts will be equal to the crop water requirements during the dry season given the absence of rain, while for the rainy season we will subtract the actual rain (equal to 70% of the average recorded rain). Crop growing during the rainy season is an advantage when desalinated water is used; low amounts of desalinated water will be supplied and therefore at lower cost.

Choice of cropping pattern in the irrigated area

Normally, in a project where desalination is introduced, we must seek maximum profitability and we must exploit the entire area of 800 ha. The double objective is to focus on specialized production with high added value such as strawberry, tomato, potato, pepper.

But depending on many surveys with farmers and extension service, in the case of available desalinated water, they are very clear:

- all non-profitable irrigated crops will be abandoned, such as marrow, cabbage;
- only high value-added crops will be irrigated: pepper, potato, tomato and strawberry;
- it was considered useful that 25% of the total area, i.e. 200 ha, would be kept fallow or used to cultivate rainfed crops (barley, etc.) for the feeding of their animals. These 200 ha will give farmers some flexibility to manage crop rotation for the entire area. If desalinated water is available enough, supplementary irrigation can be done for these rainfed crops.

Fallow and rainfed crops must be kept to manage crop rotation due to its positive effect on crops nutrition, soil biological activity and to encourage the introduction of small breeding. Crop rotation breaks the cycle of harmful organisms affecting crops by restricting pathogens and weeds (Leteinturier *et al.* 2007).

They suggest also, that even if the strawberry is very profitable, it must not exceed 25% of the total area, about 200 ha, for several reasons. The cost of producing strawberries is quite high (6,000 US $/ha) compared to tomatoes (1,808 US $/ha) and other crops grown in the region (detailed in Table 5). The strawberry market is limited compared to tomatoes, peppers and potatoes. The strawberry damages quickly in 2 to 3 days. Also, if desalination is spreading to other regions, several other farmers who belong to other areas in the region will practice strawberries and we can witness a decline in prices unless a strawberry processing industry and an export policy develops.

On the other hand, for tomato, potato and pepper, the Tunisian market is very demanding in these products. Tunisian cuisine uses tomato paste in all meals. Demand for export to neighbouring countries is also high. For the potato, Tunisia imports quantities many times every year. Tomato and potato can be grown on 400 ha. The tomato is currently grown between May and August. This region is home to more than 2/3 of the tomato processing plants in Tunisia. The potato is grown between November and March taking advantage of the fall and winter rains. The cropping intensity is 200% (Table 6).

The strawberry being very sensitive to salinity, must be cultivated following a rainfed crop or fallow (Table 7). Only a single plot of potato-tomato will be occupied by the same crops two successive years. But for these 200 ha, tomato ends in August and potato is planted in November; in addition, it is a rainy period which promotes the leaching of salts.

Given the high prices and high yields obtained with greenhouse crops, the use of greenhouse farming will be analyzed under desalination, especially given that the surrounding areas are known for greenhouse crops. For crops grown in a greenhouse, during the rainy season, the irrigation water requirements are taken equal to the crop water requirements because these crops will not benefit from the rain given the presence of greenhouses and the rain does not reach crops and soils. Crop water requirement under a greenhouse is equal approximately to 70% of crop water requirements in open-field. In recent years, experiments with movable greenhouses allowing the rains to arrive inside the greenhouses are being conducted but they are very limited.

Regarding the selling price, tomatoes and peppers grown in greenhouses on small areas observe a high price compared to their prices when these crops are grown during the dry season as open-field crops in many regions in Tunisia and when abundant production is observed. The transformation of pepper and tomato into concentrate is only done during the abundance of production. During winter, both for pepper and tomato, they are consumed in Tunisian cuisine in fresh form or exported.

The case of potato is different. It is consumed continuously throughout the year. To stabilize prices, the state often uses potato imports throughout the year. The potato is grown in the open-field. We will retain the extra-early crop which grows between December and March when only few areas are favourable for growing this crop in Tunisia and when the rains are present, which reduces the irrigation water amounts. However, seasonal cultivation between March and June requires more irrigation water

Table 6 | Cropping pattern in the irrigated area of Dyiar-Al-Hujjej, Tunisia

Crops	Strawberry-pepper	Tomato-potato	Fallow-rainfed crops
Surface cropped (ha)	200	400	200
Percentage	25%	50%	25%

Table 7 | Crops rotation schedule in the irrigated area of Dyiar-Al-Hujjej, Tunisia

	First year		Second year		Third year		Fourth year	
Area (ha)	September–May	May–August	September–May	May–August	September–May	May–August	September–May	May–August
200	Strawberry	Pepper	Potato	Tomato	Potato	Tomato	Rainfedcrops-fallow	
200	Potato	Tomato	Potato	Tomato	Rainfedcrops-fallow		Strawberry	Pepper
200	Potato	Tomato	Rainfedcrops-fallow		Strawberry	Pepper	Potato	Tomato
200	Rainfedcrops-fallow		Strawberry	Pepper	Potato	Tomato	Potato	Tomato

because the months of May and June are dry in Tunisia. As an example, water requirements of open-field extra-early potato cropped in the wet season and open-field potato grown in the dry season are respectively 1,345 and 4,000 mm.

Strawberry is cultivated only during the rainy season so a good part of the water needs will be satisfied by the rain and the selling price is quite high because it is rare and can only be cultivated in regions where very fresh water is present. More than 95% of the Tunisian strawberry production is grown in the irrigated area of Dyiar-Al-Hujjej and in nearby irrigated areas.

In calculating the final net revenue, two situations will be analyzed for all these crops (i) case when the cost of the irrigation network is not payable by farmers and (ii) case when the cost of the irrigation network is due to farmers.

Case where the cost of the irrigation network is not payable by the farmers

In Tunisia, the irrigation network is carried out by the state and this cost is not charged to farmers. The state does not seek to recover the initial investment and expects social and economic development that will generate wealth and taxes for the state. All major repairs such as broken pipes, breakdowns in pumping stations, and cleaning of the drainage network are always the responsibility of the state. In our irrigated area, the irrigation network already exists and it is in good condition.

For all open-field crops grown in dry season having a high-water demand, where all water needs have to be met by desalinated water, the use of desalination water is not profitable; their net revenues are negative (−2,457, −1567 and −842 US $ respectively for pepper, potato and tomato) (Table 8). The price of desalinated water is a barrier for use (Aznar *et al.* 2017). The use of desalinated water for irrigation is profitable for (i) crops grown during the rainy season (extra-early potato in wet season and strawberry) when a part of its water requirement is satisfied by rain, and (ii) greenhouse crops where both yields and sale prices are higher compared to the same dry season crops and there is a positive income, 7,413 US $/ha and 1,657 U$/ha respectively for tomato and pepper. But when crops are grown under greenhouse, farmers cannot manage really more than 2,000 m^2 (about 4 greenhouses or less by family); it requires a lot of care.

For the strawberry cultivated during the rainy season, the irrigation water amounts supplied are low (3,600 m^3/ha) and the sale price is high, and it presents the highest net income. The strawberry cannot be generalized

Table 8 | Net revenue calculated without taking into account irrigation network cost for different crops in open-field or under greenhouse in Dyiar-Al-Hujjej irrigated area, Tunisia

Crops	Production cost ($ US/ha) (a)	Yield (10^3 kg/ha) (b)	Selling price at farm level ($US/kg) (c)	Value of agricultural products ($US/ha) (d) = (b)*(c)	Gross revenue ($US/ha) (e) = (d) − (a)	Net water requirement (m^3/ha) (f)	Solar desalinated water cost ($ US/ha) (g) = (0.5 USA $)/$m^3$ *(f)	Net revenue ($US/ha) (without taking into account irrigation network cost) (h) = (e)-(g)
Open-field pepper in dry season	1,401	18	0.108	1,944	543	6,000	3,000	–2,457
Pepper under green house in wet season	2,102	27	0.217	5,859	3,757	4,200	2,100	+1,657
Open-field extra-early potato in wet season	1,767	22	0.133	2,926	1,159	1,345	673	+486
Open-field potato in dry season	1,767	22	0.100	2,200	433	4,000	2,000	–1,567
Strawberry in wet season	6,000	55	0.300	16,500	10,500	3,600	1,800	+8,700
Open-field tomato in dry season	1,808	70	0.06	4,200	2,392	6,467	3,234	–842
Tomato under greenhouse in wet season	2,713	105	0.118	12,390	9,677	4,527	2,264	+7,413

everywhere in Tunisia even if fresh water is present for several reasons including its production cost that is very high compared to other crops; this cost is beyond the reach of the majority of Tunisian farmers.

Already and without taking into account other production costs, for open-field pepper, the solar desalination cost (3,000 US $/ha) by itself is higher than the value of agricultural products (1,944 US $/ha). They are almost equal for open-field potato (Table 8). In this calculated net income, the cost of the irrigation network was not covered. But for a complete vision, the feasibility of desalination in the case when the costs of this network will be charged to farmers also deserves to be analyzed.

Cases where the cost of the irrigation network is to be paid by the farmers

Any seasonal crops that are unprofitable when the cost of the irrigation system is not taken into account will be not considered because they will be more unprofitable. Only greenhouse crops (tomato and pepper), extra-early potato and strawberry will be considered.

In Tunisia, the cost of setting up an irrigation network for all the irrigated area is 7,000 US $/ha for a lifespan of approximately 25 years with an interest rate of 5% given the state incentives for agriculture in Tunisia, an additional amount of 948 US $/ha/year should be expected as a minimum.

To calculate the net revenue taking into account all the charges (water cost, production cost, network cost and irrigation equipment), the amount 948 US $ will be deducted from the income obtained without taking into account the irrigation network cost.

Taking into account the cost of the irrigation network, only crops with a significant income either because the rain contributes to their water needs (strawberries) or because they have a high yield and high selling price, have a positive final net income. For tomato and pepper under greenhouses, their selling prices and yields are superior compared to those of open-field seasonal crops (Table 9); selling price can even reach 5 times the price during the dry season. Open-field extra-early potato grown in wet season observes negative net revenue mainly because of low selling price that does not change during all the year in Tunisia.

Table 9 | Net revenue for different crops (irrigation network cost is included) in the Dyiar-Al-Hujjej irrigated area, Tunisia ($ US/ha)

Crops	Net revenue (without taking into account irrigation network cost) (US $/ha) (h)	Net revenue (irrigation network cost is included) ($ US/ha) (e) = (h) − 948
Pepper under greenhouse in wet season	1,657	+709
Open-field extra-early potato in wet season	486	<u>−462</u>
Strawberry in wet season	8,700	+7,752
Tomato under greenhouse in wet season	7,413	+6,465

In southeast Spain, net margin with 1.95 and 3.39 US $/m^3, is obtained under greenhouse for pepper and tomato respectively. Intermediate net margins of 1.34, 0.82, 0.70 and 0.60 US $/m^3 are observed in the case of watermelon, melon, peach and apricot crops respectively (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2016). In our case, net margins are low and they are 0.17 and 1.43 US $/m^3 respectively for pepper and tomato. The selling prices are low in Tunisia. Chaibi & Bourouni (2007), by analyzing the financial balance sheet of a desalination application for the irrigation of greenhouse crops, found that this balance sheet is positive only for crops with high added value (floriculture). In the Sahel region in Tunisia, extra-early pepper and tomato are grown under greenhouse with drinking water with a price of 0.4 US $/m^3. Yields and selling prices are high because of small quantities of tomato and pepper available in the Tunisian market during winter and spring. When desalinated water is blended with aquifer saltwater, profit of the farmers growing greenhouse tomato and pepper has been doubled in the Gounat irrigated area (Ergaieg *et al.* 2018).

Pepper, potato and tomato grown during the summer dry season as open-field crops show a net negative income with current yields and prices if desalinated water is used. For most open-field crops, there would be zero revenue but we can expect an improvement in crop yields when desalinated water with low salinity is supplied. For hydroponic pepper, the yield obtained was 100,000 kg/ha (López-Marín *et al.* 2017) while it is less than 20,000 kg/ha in our area. The banana highest yield observed with fresh water (1.5 dS/m) was obtained in the case of desalinated water (0.3 dS/m) with almost half the amount of water (Silber *et al.* 2015). We must also look simultaneously for other ways such as agro-industry.

Case when an agro-industry and increasing yields are achievable

The agro-transformation concerns only the open-field season tomato and pepper grown between May and August and when an over-production is observed. When these crops are cultivated as early-crops under greenhouses, the quantities produced are low and the selling prices are high. For potato, no agro-industry is available in Tunisia and the selling price is constant during all the year.

In terms of agro-industry, this region has an important advantage: it is the main region of Tunisia where we proceed to the transformation of tomato and pepper into concentrate and harissa and it is the hub of the majority of processing plants. The agro-industry (tomato and pepper concentrate) can also be a way of developing desalinated water. We can expect an increase in the selling price for food processing, by at least 50% more, compared to the selling prices for everyday consumption.

Besides the agro-industry, the use of desalinated water will improve crop yield. In areas where fresh water is used, tomato yields easily exceed 100 tons/ha. An increase in water productivity with desalinated water was observed for all four staple crops; a statistically significant yield increase was observed for sorghum (+10%), (Ghermandi *et al.* 2013). Reduction in yield of 23% and of only 7% were observed respectively when reclaimed water and desalinated water are used to irrigate almond under deficit irrigation by comparison to full irrigation (Vivaldi *et al.* 2019).

For pepper, even for a 50% increase in yields and selling prices, the net revenue is negative (Table 10). This crop is to be excluded from irrigation with desalinated water. On the other hand, for tomatoes, even a 10% increase in selling prices and yields results in almost zero net income. An increase of 25% in both selling prices and yields results in a net income of 1,521 US $/ha. An increase in yield of 25% is possible especially since tomatoes are a well-controlled crop and high yields are achievable. For the 25% increase in prices, negotiations with the state, agro-industrialists and the farmers' association are necessary because the demand for tomatoes is high both for processing and for export. High value-added crops show positive profit justifying the use of desalination for agriculture (Kaner *et al.* 2017).

We can also think of introducing other crops with a high added value such as condiments or medicinal plants which have a high added value but the Tunisian experience in this field remains very limited. Unfortunately for the farmers, the crust is present everywhere in this area even at a depth of 20 cm, preventing any tree cultivation.

In order to reduce the cost of irrigation water, the scenario consisting of a mixture between desalinated water and aquifer saltwater deserves to be studied, especially since the blending of groundwater and fresh surface water is currently practiced. The blending of desalinated water and other types of water is usually done by farmers with the

Table 10 | Net revenue of pepper and tomato (without taking into account irrigation network cost)

Crops	Yield (10^3 kg/ha) (a)	Percentage of yield increase (%) (b)	Increased yield (10^3 kg/ha) (c) = (a) + (a) *(b)	Selling price at farm level (US $/kg) (d)	Value of agricultural products (US $/ha) (e) = (c)*(d)	Production cost (US $/ha) (f)	Gross revenue (US $/ha) (g) = (e) – (f)	Net water requirement by hectare (h)	Desalinated water cost (US $ /ha) (i) = 0.5 ($ US /m^3) *(h)	Net revenue (without taking into account irrigation network cost) ($US/ha) (j) = (g)-(i)
Open-field pepper in dry season	18	50	27	0.162	4,374	1,401	2,973	6,000	3,000	–27
Open-field tomato in dry season	70	50	105	0.09	9,450	1,808	7,642	6,467	3,234	+ 4,408
		25	87.5	0.075	6,563		4,755		3,234	+ 1,521
		10	77	0.066	5,082		3,274		3,234	+ 40

aim to improve the final water quality, according to a farmers survey (Monterrey-Viña *et al.* 2020). The use of waste water for irrigation can led to an accumulation of chloride, sodium, and boron which damage soils, cause phytotoxicity to crops and reduce yields (Maestre-Valero *et al.* 2019). The water blending of different water sources with better quality is recommended for a sustainable irrigation, after Maestre-Valero *et al.* (2019). The research also points out that soil degradation can be reduced and that the qualities of irrigation water can be improved when blending desalinated water with groundwater or wastewater. A similar growth of Buxus and Pistacia was observed when well water and blended water were used for irrigation (Gori *et al.* 2008). In the case of water blending, the interval between the desalinated and saline water intake must be reduced. A complete water blending before irrigation is recommended. The longer the interval between salt water inflow and freshwater inflow, the higher the observed salinity peak (Daghari *et al.* 2020b).

Net revenue when blending of desalinated and saline waters is observed

As this aquifer is quite salty and a marine intrusion is observed, the pumping of water from the aquifer must be very limited. Only the main field crops (peppers, potatoes and tomatoes) grown during the dry season will be taken into account. Also, when a negative net income is observed if only desalinated water is used, it will be taken into account. Analysis will focus on the net income obtained when desalinated and saline water are mixed for these crops. In this case, the desalinated water supply is regular throughout the year, in contrast to the transferred surface water whose supply is very irregular. The average salinity of salt aquifer water and desalinated water is respectively 6 and 0.5 dS/m. The following percentages will be considered:

- 100% desalinated water
- 25% of desalinated water and 75% of saltwater
- 50% of desalinated water and 50% of saltwater
- 75% of desalinated water and 25% of saltwater
- only aquifer saltwater

The cost of pumping groundwater is 0.02 US $/m^3. The total pumping cost is almost 129 US $/ha even if the entire crop water requirement is pumped, negligible compared to water desalination costs. The highest crop water requirement is observed in the case of tomato (Table 8). Average tomato, pepper and potato normal yields are respectively 70 tons/ha, 18 tons/ha and 22 t/ha (average Tunisian yields).

Crops yield will vary with water blended salinities and the accepted yield is the product of average yield and percentage of yield which depends on water salinity and is calculated by using Equations (4) and (5).

Case of open-field tomato

Even if a blending of desalinated water and saltwater is done, the net revenue is again negative whatever the percentage of mixture, due mainly to yield decrease and/or high cost of desalinated water (Table 11). In Tunisia, the cost of irrigation water never exceeds 25% of other production costs in irrigated areas using water from the state network. For private areas using pumped water, this percentage is less than 10%. When blended water is used, the cost of desalinated water reaches 3,234, 2,425 and 1,617 US $/ha representing almost 200, 150 and 100% of the other production costs respectively for desalinated water percentages of 100, 75 and 50% (Table 11). In the case when the percentage of desalinated water is less than 25%, the final salinity is high because the salinity of the aquifer is already high (6 dS/m) and a drop in yield of at least 50% is observed. The value of agriculture production barely covers the other production costs (Table 11). Low or negative incomes of −368, 22 and −172 US $/ha were observed when fresh water, desalted seawater and mixed water, respectively, were used to irrigate mandarins during Oct-2017 to Sept-2018 (Maestre-Valero *et al.* 2020).

In fact, the tomato is currently profitable when fresh surface water and saltwater are blended, thanks to the low selling price of water (0.05 US $/m^3) (Table 5). A study in progress on the water sector in Tunisia (Water 2050) indicates an overall economic cost for surface water of about 0.55 US $/m^3. Irrigation and drinking water are heavily subsidized in Tunisia.

Case of open-field pepper

The net revenue is also negative for pepper even if a blending of desalinated water and saltwater is done (Table 12).

Table 11 | Net income for open-field tomato in the case of blending desalinated water and saltwater in the Dyiar-Al-Hujjej irrigated area, Tunisia (US $/ha)

						Tomato					
Percentage of desalinated water (%) (a)	Percentage of salt-water (%)	Salinity of blended water dS/m	Annual water tomato requirement (m^3/ha) (b)	Desalinated water volume necessary (m^3/ha) (c) = (a)* (b)	Desalinated water cost ($ US/ha) (d) = (c)* 0.5 $ US/ha	Percentage of yield (%) (e)	Expected yield (10^3 kg/ha) (f) = 70 tons/ha * (e)	Selling price ($ US/kg) (g)	Value of agriculture production ($ US/ha) (h) = (f)*(g)	Cost production ($ US/ha) (i)	Net revenue ($ US) (j) = (h) – ((d) + (i))
100	0	0.5	6,467	6,467	3,234	100	70	0.06	4,200	1,808	**– 842**
75	25	1.88		4,850	2,425	97	68		4,080		**– 153**
50	50	3.25		3,234	1,617	76	53		3,180		**– 245**
25	75	4.6		1,617	808	56	39		2,340		**– 276**
0	100	6.0		0	0	35	24		1,440		**– 368**

Table 12 | Net income for open-field pepper in the case of blending desalinated water and saltwater in the Dyiar-Al-Hujjej irrigated area, Tunisia (US $/ha)

						Pepper					
Percentage of desalinated water (%) (a)	Percentage of salt-water (%)	Salinity of blended water dS/m	Annual water pepper requirement (m^3/ha) (b)	Desalinated water volume necessary (m^3/ha) (c) = (a)* (b)	Desalinated water cost ($ US/ha) (d) = (c)* 0.5 $ US/ha	Percentage of yield (%) (e)	Expected yield (10^3 kg/ha) (f) = 18 tons/ha * (e)	Selling price ($ US/kg) (g)	Value of agriculture production ($ US/ha) (h) = (f)*(g)	Cost production ($ US/ha) (i)	Net revenue (j) = (h) – ((d) + (i))
100	0	0.5	6,000	6,000	3,000	100	18	0.108	1,944	1,401	**– 2,457**
75	25	1.88		4,500	2,250	82	15		1,620		**– 2,031**
50	50	3.25		3,000	1,500	53	9		972		**– 1,929**
25	75	4.6		1,500	750	24	4		432		**– 1,719**
0	100	6.0		0	0	0	0		0		**– 1,401**

Blending between desalinated water and saltwater results in catastrophic net negative returns of −2,457, −1,929 and −1,401 US $/ha for the respective percentages of desalinated water of 100, 50 and 0% (Table 12).

Compared to tomatoes, its yield per hectare is much lower. The yield drops by half if the percentage of desalinated water is less than 50%. The value of agriculture production is generally low and it covers production costs only if the percentage of desalinated water is close to 75% or more. For 50%, the value of agriculture production is 972 US $/ha while the production cost is already 1,401 US $/ha without taking into account water costs (750 US $/ha). Pepper is cultivated only in association with strawberry.

Case of dry season open-field potato

For the open-field potato grown during the dry season, net revenue is also negative whatever the percentage of desalinated water used. If the desalinated water percentage is less than 75%, the value of agriculture production does not cover even the production cost, not considering the water cost (Table 13). The desalinated water cost is very high compared to the current network water cost. If only desalinated water is used, the water cost is 2,000 US $/ha while the current cost is only 200 US $/ha (0.05 US $/ha * 4,000 m^3/ha), i.e. 10%.

Full dry season crops for which all of their water needs must be satisfied by irrigation water are to be excluded from this desalinated water use in irrigation; they have net negative income (Table 14). The blending of desalinated and salted water is unprofitable. High cost of desalinated water limits its use in crop irrigation (Martínez-Alvarez *et al.* 2016). The best economic feasibility due to the higher yield in proportion to the increase in the cost of water is observed in the case of treatment using mixed water compared to the two treatments using fresh water or desalinated seawater when young mandarins were irrigated (Maestre-Valero *et al.* 2020). In our case, the only problem posed is the supply of fresh surface water is not regular; it varies from year to year depending on the amount of rainfall.

For agricultural products with current prices considered low in Tunisia, desalination should be excluded. It may be

Table 13 | Net income for open-field potato in the case of blending desalinated water and saltwater in the Dyiar-Al-Hujjej irrigated area, Tunisia (US $/ha)

						Potato					
Percentage of desalinated water (%) (a)	**Percentage of salt-water (%)**	**Salinity of blended water S/m**	**Annual water potato requirement (m^3/ha) (b)**	**Desalinated water volume necessary (m^3/ha) (c) = (a)* (b)**	**Desalinated water cost ($ US/ha) (d) = (c)* 0.5 $ US/ha**	**Percentage of yield (%) (e)**	**Expected yield (10^3 kg/ha) (f) = 22 tons/ha * (e)**	**Selling price ($ US/kg) (g)**	**Value of agriculture production ($ US/ha) (h) = (f)*(g)**	**Cost production ($ US/ha) (i)**	**Net revenue (j) = (h) − ((d) + (i))**
100	0	0.5	4,000	4,000	2,000	100	22	0.1	2,200	1,767	**−1,567**
75	25	1.88		3,000	1,500	87	19		1,900		**−1,367**
50	50	3.25		2,000	1,000	62	14		1,400		**−1,367**
25	75	4.6		1,000	500	38	8		800		**−1,467**
0	100	6.0		0	0	12	3		300		**−1,467**

Table 14 | Negative (–) or positive (+) net revenue observed under different desalinated water supply in irrigation in the Dyiar-Al-Hujjej irrigated area, Tunisia

	Only desalinated water is used			
Crops	**Network irrigation is not due to farmers**	**Network irrigation is due to farmers**	**Agro-industry and yield increase are achievable**	**Desalinated and aquifer water blending**
Open-field pepper in dry season	–	–	–	–
Pepper under green house in wet season	+	+	The selling of fresh pepper is more profitable than agro-industry	already profitable when desalinated water is used
Open-field extra-early potato in wet season	+	–	No agro-industry available	already profitable when network cost is not due to farmers
Open-field potato in dry season	–	–	No agro-industry available	–
Strawberry in wet season	+	+	No agro-industry available	already profitable when desalinated water is used
Open-field Tomato in dry season	–	–	+	–
Tomato under greenhouse in wet season	+	+	The selling of fresh tomato is more profitable than agro-industry	already profitable when desalinated water is used

necessary to apply it to the arboricultural sector, but in the form of supplementary irrigation. The gross margin of olive trees increased from US $ 57/ha in rainfed conditions to US $ 676/ha, US $ 3,869/ha and US $ 3,819/ha respectively for the years 2011/2012, 2012/2013 and 2013/2014 following a supplementary irrigation with desalinated water (Mhiri 2014).

Martínez-Alvarez *et al.* (2019) indicated that compared to other water resources, desalinated water requires high energy needs and associated costs which limit its widespread use for agriculture. In the case of corn and pepper, a negative benefit is observed whatever the salinity of the mixed water and the volume of water supplied. For grapes and dates, if the mixed water irrigation volume is less than 1,000 m^3/ha, negative profits are observed if desalinated water and saltwater are blended (Kaner *et al.* 2017). More energy is required when desalinated water is used in irrigation due to the ionic concentration standards required for agricultural irrigation water. The mean net margin of farmers was about zero when desalinated seawater was used in many regions in South East Spain. The farmers ask to have simultaneously desalinated seawater and other kinds of water with lower prices. A blending can be done leading to an affordable final water price (Kumar *et al.* 2018). In Tunisia, currently, the blending of desalinated water and groundwater is applied to crops with high selling prices such as greenhouse crops, crops intended for export (cherry tomato, condiment plants, etc.). The selling price of one kilogram of cherry tomato is at least three times the cost of 1 m^3 of desalinated water and a water productivity of more than 3 kg/m^3 is reached. Several foreign promoters come to settle in Tunisia and cultivate crops with high added value mixing desalinated water and saltwater.

CONCLUSION

Tunisia has poor quality water resources. With the increase in population and standard of living, use of poor-quality water is very common in Tunisia. Unfortunately, after about twenty years of use of these waters, drops in yields are observed, and a drop in groundwater levels and sea intrusion are recorded. The desalination of water for irrigation which consumes more than 80% of Tunisian water resources is starting to emerge but the cost of desalinated water constitutes the main handicap to its use for irrigation, especially since the selling prices of agricultural products are very low in Tunisia.

The purpose of seawater desalination to save the irrigated area of Dyiar-Al-Hujjej has shown its limits. The use of desalination for irrigation is profitable only for crops with high added value and whose water needs are partially met by rain. Only the strawberry crop whose water needs is partially satisfied by rain and whose net income is high is of interest when desalinated water is used. But this crop cannot be generalized given the limited market.

For the dry season crops (pepper, potato and tomato), constituting the main activity of the irrigated area of Dyiar-Al-Hujjej and where all their water requirements must be met by irrigation water, the desalination application is not recommended. For these crops, even if a mixture of desalinated water and aquifer saltwater is practiced, they remain unprofitable given the drop in yield observed in the case of the water blending.

For greenhouse crops (pepper and tomato), the use of desalinated water is beneficial because of the high selling price given the areas equipped with greenhouses are very low. Irrigation of greenhouse crops with desalinated water is already practiced but in very few regions of Tunisia.

Even in the case of agro-industrial development and higher yields, irrigation with desalinated water is not profitable for open-field crops except for tomatoes.

If water desalination is used for irrigation in the Dyiar-Al-Hujjej region, the recommended development scheme will be: (i) the use of strawberries and greenhouse crops in the wet season; (ii) the use of field irrigated tomatoes with blended water in the dry season. The acceptance of desalinated water by farmers, the effects on soils and on crops must be considered and analyzed in the future if desalinated water is used. Solar and wind power could be alternative sources of energy, especially in this region that is known for its strong wind speeds and high irradiation and costs of desalination will decline over the years.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. FAO, Rome.

Ayers, R. S. & Westcot, D. W. 1985 *Water Quality for Agriculture*. FAO Irrigation and Drainage Paper 29. FAO, Rome.

Aznar, J. A., Belmonte, L. J. & Valera, D. L. 2017 Perceptions and acceptance of desalinated seawater for irrigation: a case study in the Níjar District (Southeast Spain). *Water* **2017** (9), 408.

Bani, A., Daghari, I., Hatira, A., Chaabane, A. & Daghar, H. 2020 Sustainable management of a cropping system under salt stress conditions (Korba, Cap-Bon, Tunisia). *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-020-09767-0.

Cabrera-Reina, A., Miralles-Cuevas, S., Rivas, G. & Sánchez Pérez, J. A. 2019 Environmental assessment of solar photo-Fenton processes in combination with nanofiltration for the removal of micro-contaminants from real wastewaters. *Science of the Total Environment* **648**, 601.

Chebbi, H. E., Pellissier, J. P., Khechimi, W. & Rolland, J. P. 2019 *Rapport de synthèse sur l'agriculture en Tunisie* [Rapport de recherche]. CIHEAM-IAMM. 99 p. ffhal-02137636f.

Chaibi, M. T. & Bourouni, K. 2007 Development of Solar Desalination Systems, Concepts for irrigation in arid areas conditions. In: *Solar Desalination For the 21st Century, Nato Security Science Series – C, Environmental Security* (L. Rizzuti, H. M. Ettouney & A. Cipollina, eds). Springer, pp. 19–32.

CRUESI 1970 *Recherche et formation en matière d'irrigation avec des eaux salées*. Rapport technique, CRUESI, Tunis/UNESCO.

Daghari, I., Bani, A., Bousnina, H. & Chaabane, A. 2020a On-farm water and salt management under a strawberry–pepper combination in the Korba area. *Irrigation and Drainage* **69**, 441–447. https://doi.org/10.1002/ird.2422.

Daghari, I., El Zarroug, M. R., Muanda, C. & Shanak, N. 2020b Best irrigation scheduling way with saline water and desalinated water: field experiments. *LHB* **4**, 72–74.

Dhahbi, G. 2016 *Final Report of the Project Adaptation to Climate Change Through Improved Water Demand Management in Irrigated Agriculture by Introduction of New Technologies and Best Agricultural Practice*. Gneral Directorate of Agricultural Engineering and Water Exploitation, Tunisia, p. 75.

Eckstein, E., Hutfils, M. L. & Winges, M. 2019 *Global climate risk index 2019: Who Suffers Most from Extreme Weather Events? Weather-related Loss Events in 2017 and 1998 to 2017*. Germanwatch, Bonn, Germany.

Elfil, H. 2018 Dessalement des eaux en Tunisie. *Conférence: Centre de Démocratie, de Citoyenneté et de Développement CD^2 Nabeul*. See: https://www.researchgate.net/publication/325742418_Dessalement_des_eaux_en_Tunisie.

El-Juhany, L. 2010 Degradation of date palm trees and date production in Arab countries: causes and potential rehabilitation. *Australian Journal of Basic and Applied Sciences* **4** (8), 3998–4010.

Ergaieg, K., Farhani, N., Ben Nasr, J., Rehaiem, N. & Ghanmi, D. 2018 Irrigation water desalination potential by reverse osmosis: Gounat case study in Tunisia. In: *3rd International Conference on Integrated Environmental Management for Sustainable Development (ICIEM 2018), Research Letter*, 2018.

Ghermandi, A., Messalem, R., Offenbach, R. & Cohen, S. 2013 Solar desalination for sustainable brackish water management in arid land agriculture. *Renewable Agriculture and Food Systems* **29**, 255–264. doi:10.1017/S1742170513000082.

Gori, R., Lubello, C., Ferrini, F., Nicese, F. P. & Coppini, E. 2008 Reuse of industrial wastewater for the irrigation of ornamental plants. *Water Science and Technology* **57** (6), 883–889.

Gul, M., Kart, O., Murside, S. & Bekir, S. 2016 Determining costs and profitability of lavender farms in Isparta Province of Turkey. *Journal of Essential Oil-Bearing Plants* **19**, 686–692.

Hamrouni, H. & Daghari, H. 2010 *Managing Natural Resources Through Implementation of Sustainable Policies*. Qualiwater Project Publications, Tunis.

Hilal, N., Kim, G. J. & Somerfield, C. 2011 Boron removal from saline water: a comprehensive review. *Desalination* **273**, 23–35.

Kamel, F. 2017 La contribution du dessalement dans la mobilisation des ressources en eau en Tunisie. Projet IRESA-GIZ: "Le développement du secteur agricole en Tunisie par les technologies de dessalement de l'eau utilisant les énergies renouvelables". Jeudi 25 mai 2017 Gammart.

Kaner, A., Tripler, E., Hadas, E. & Ben-Gal, A. 2017 Feasibility of desalination as an alternative to irrigation with water high in salts. *Desalination* **416**, 122–128.

Kang, Y., Khan, S. & Ma, X. 2015 Analysing climate change impacts on water productivity of cropping systems in the Murray Darling Basin, Australia. *Irrigation and Drainage* **64**, 443–453. doi:10.1002/ird.1914.

Kaya, A., Evren, T. & Koç, M. 2019 A levelized cost analysis for solar-energy-powered sea water desalination in the Emirate of Abu Dhabi, 2019. *Sustainability* **11** (6), 1691.

Kumar, R., Ahmed, M., Bhadrachari, G. & Thomas, J. P. 2018 Desalination for agriculture: water quality and plant chemistry, technologies and challenges. *Water Supply* **18** (5), 1505–1517.

Leteinturier, B., Tychon, B. & Oger, R. 2007 Agronomic and agro-environnementale diagnosis of cultural successions in Wallonia (Belgique). *BASE [En Ligne]* **11**(1), 27.

López-Marín, J., Gálvez, A., del Amor, F. M., Albacete, A., Fernandez, J. A. & Egea-Gilabert, C. 2017 Selecting vegetative/generative/dwarfing rootstocks for improving fruit yield and quality in water stressed sweet peppers. *Scientia Horticulturae* **214**, 9–17. doi:10.1016/j.scienta.2016.11.012.

Maas, E. V. & Hoffman, G. J. 1977 Crop salt tolerance – current assessment. *Journal of the Irrigation and Drainage Division* **103**, 115–134.

Maestre-Valero, J. F., González-Ortega, M. J., Martínez-Álvarez, V. & Martin-Gorriz, B. 2019 The role of reclaimed water for crop irrigation in southeast Spain. *Water Supply* **19** (5), 1555–1562.

Maestre-Valero, J. F., Martínez-Alvarez, V., Jódar-Conesa, F. J., Acosta, J. A., Martin-Gorriz, B., Robles, J. M., Pérez-Pérez, J. G. & Navarro, J. M. 2020 Short-Term response of young mandarin trees to desalinated seawater irrigation. *Water* **12**, 159.

MAREP 2019a *Comparative study of the production costs of Orange, almond, peach and tomato between producing countries and the analysis of the impact of free trade agreements in the framework of the development of the CAP strategic plan*. Ministry of Agriculture, Hydraulic Resources and Maritime Fisheries (MAREP), Tunis, Tunisia.

MAREP 2019b *The annual book of agricultural statistics 2017*. Ministry of Agriculture, Hydraulic Resources and Maritime Fisheries (MAREP), Tunis, Tunisia.

Martínez-Alvarez, V., Martin-Gorriz, B. & Soto-García, M. 2016 Seawater desalination for crop irrigation – A review of current experiences and revealed key issues. *Desalination* **381**, 58–70.

Martínez-Alvarez, V., González-Ortega, M. J., Martin-Gorriz, B., Soto-García, M. & Maestre-Valero, J. F. 2017 The use of desalinated seawater for crop irrigation in the Segura River Basin (south-eastern Spain). *Desalination* **422**, 153–164.

Martínez-Alvarez, V., Maestre-Valero, J. F., González-Ortega, M. J., Gallego-Elvira, B. & Martin-Gorriz, B. 2019 Characterization of the Agricultural Supply of Desalinated Seawater in Southeastern Spain. *Water* **11**, 1233.

Mekni, A. 2017 *Characterization of the Artificial Recharge of the Korba-El Mida Aquifer by Treated Wastewater: Hydrodynamic, Hydrochemical and Hydrological Modeling Approaches*. PhD thesis, INAT, Tunisia.

Mhiri, A. 2014 *Final Report on Solar Desalination Extension Site in the SASS Bazin in Algeria, Morooco, Libya and Tunisia*. Sahara and Sahel Observatory (OSS), Tunis, Tunisia.

Mhiri, A. 2018 *Tunisian agriculture at a crossroads, what vision for sustainable agriculture(L'agriculture tunisienne à la croisée des chemins, quelle vision pour une agriculture durable)*. Simpact publishers, Tunis, 2018, 280 p.

Ministerio de Agricultura, Alimentación y Medio Ambiente 2016 *Agricultura, alimentación y medio ambiente en españa 2015*. Ministerio de Agricultura, Alimentación y Medio Ambiente, Government of Spain, Madrid.

Monterrey-Viña, A., Musicki-Savic, A., Díaz-Peña, F. J. & Peñate-Suárez, B. 2020 Technical and agronomical assessment of the use of desalinated seawater for coastal irrigation in an insular context. *Water* **12**, 272.

Onyancha, D. M., Gachene, C. K. K. & Kironchi, G. 2017 FAO-CROPWAT model-based estimation of the crop water requirement of major crops in Mwala, Machakos County. *Researchjournali's Journal of Ecology* **4** (2).

Ouda, O., Khalid, M., Ajbar, A., Rehan, M., Shahzad, K., Wazeer, I. & Nizami, A. 2018 Long-term desalinated water demand and investment requirements: a case study of Riyadh. *Journal of Water Reuse and Desalination* **8**, 432–446. doi:10.2166/wrd.2017.107.

Reca, J., Trilo, C., Sanchez, J. A., Martinez, J. & Valera, D. 2018 Optimization model for on-farm irrigation management of Mediterranean greenhouse crops using desalinated water from different sources. *Agricultural Systems* **166**, 173–118.

Silber, A., Israeli, Y., Elingold, I., Levi, M., Levkovitch, I., Russo, D. & Assouline, S. 2015 Irrigation with desalinated water: a step toward increasing water saving and crop yields. *Water Resources Research* **51**, 450–464. doi:10.1002/2014WR016398.

Slama, F. 2004 *Salinity and Crop Production*. Center of Academic Publications, Tunisia, 163 p.

Vivaldi, G. A., Camposeo, S., Lopriore, G., Romero-Trigueros, C. & Salcedo, F. P. 2019 Using saline reclaimed water on almond grown in Mediterranean conditions: deficit irrigation strategies and salinity effects. *Water Supply* **19** (5), 1413–1421.

Zafar, S. 2020 *Biomass Potential of Date Palm Wastes*. Agriculture, Biomass Energy, Middle East, Waste Management, Aligarh.

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