Effect of irrigation efficiency enhancement on water demand of date palms in a Tunisian oasis under climate change

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ABSTRACT

Consideration of future change in water salinity is important for estimating irrigation demand in salinity-prone arid regions. Further, it is important to evaluate the contribution of irrigation efficiency enhancement to climate change resilience. Based on field measurements in 2019, a simulation approach from 2019 to 2050 was carried out in this study to investigate the impact of climate change and its consequences (i.e., change in water salinity) on the future gross irrigation demand of date palms and possible applied dose of water in a Tunisian oasis considering different irrigation efficiency enhancements. The estimation was done under very high (RCP 8.5), medium (RCP 6.0), and low (RCP 4.5) emission scenarios using the CROPWAT model. Results first showed an increase in gross irrigation requirement under inefficient surface irrigation (37% efficiency) from 3,340 mm year\(^{-1}\) in 2019 to 3,588–3,642 mm year\(^{-1}\) in 2050 for different climate change scenarios. This significant increase is mainly attributed to a significant change in climate variables and a high increase in water salinity. Second, considerable water savings (up to 1,980 mm) can be achieved if surface irrigation efficiency increases from the current value of 37–70%. Finally, much water can be saved only by reducing the overdose amount of water.

Key words | climate change, irrigation demand, irrigation efficiency, water salinity

HIGHLIGHTS

- Takes into consideration future change in applied water salinity and potential contribution of irrigation efficiency enhancement to climate change resilience.
- Investigates the effect of three climate change scenarios (RCP 8.5: very high emission scenario, RCP 6.0: medium emission scenario and RCP 4.5: lowest emission scenario) and its consequences (i.e. change in water salinity) on future gross irrigation demand (GIR) of date palms.

INTRODUCTION

Annual evapotranspiration (ET) greatly exceeds the annual rainfall (R), and the R/ET ratio is less than 0.65 in dry regions (Huang et al. 2017). During recent decades, the rapid growth of population (≈ 2.1 billion people, growth rate ≈ 18% over 2008–2018; IPCC 2019) coupled with on-going socio-economic development has led to increased dependence on irrigated agriculture and agricultural intensification to satisfy growing food demand. Consequently, a significant pressure on water resources has become evident over recent years, especially in water-stressed arid regions (Xie et al. 2019). Because of
increasing air temperature and changing drought and rainfall patterns, climate change is intensifying this pressure and presents foreseeable water governance challenges (Al-Faraj et al. 2016). As reported in FAO (2007), due to the potential climate change, about 51% of the people in arid countries will be living in high water-stressed areas by 2050.

Irrigated agriculture and agricultural intensification can affect the quantity and quality of water resources (Foley et al. 2011). The qualitative degradation includes groundwater pollution (e.g., nitrate pollution), river water eutrophication, salt intrusion in coastal aquifers, etc. (Xie et al. 2019). The quantitative degradation refers mainly to the continuous decrease in fresh water resource availability (Dahal et al. 2016). As revealed by several studies (e.g., Zubari 2002; Pfister et al. 2011; Núñez et al. 2013), inefficient irrigation water use, inappropriate selection of crop type, and improper soil management in agricultural fields are causing a continuous decline in the quality of water resources. Accordingly, due to the above critical effects, enhancement of irrigation efficiency in arid regions may lead to a more sustainable use of water resources (Al-Faraj et al. 2015).

Much research has shown that water losses from irrigated fields (e.g., conveyance loss, distribution loss, evaporation, seepage, percolation, and run-off) can contribute to an important increase in water demand (e.g., Nikkami 2009; Ali & Klein 2014; Nassah et al. 2018). For example, Nassah et al. (2018) concluded that a water loss of 37% from deep percolation contributed to increasing the irrigation demand of citrus crops by more than 11%. Accordingly, the reduction of water losses is likely to decrease irrigation water demand, such as by enhancement of irrigation efficiency (i.e., optimal crop productivity with less irrigation water), improvement of the knowledge-based irrigation demand management, and development of proper irrigation management practices (irrigation method, timing, water quantity, and irrigation duration). As reported by IPCC (2019), such improved practices will need to be supported in many arid regions due to their outdated irrigation networks that cause inefficient irrigation water management, largely because farmers lack the necessary information and skills and the absence of water conservation irrigation technologies.

Based on climate data projections and their inclusion in crop water use simulation models (e.g., CROPWAT), it was recently noted that many studies have been conducted to evaluate the effects of climate change on irrigation water demand (e.g., Khattak et al. 2017; Zhang et al. 2019). However, as suggested by IPCC (2019), under expected high risks of climate change (such as drought and rainfall decrease), continued research is needed to identify the implications of irrigation efficiency enhancement on agricultural water demand, and to improve on water resources management in arid regions. Also, irrigation water salinity plays a key role in improving the knowledge-based irrigation demand management (Haj-Amor et al. 2020). Accordingly, future changes in irrigation water salinity as caused by pumping groundwater of increasing salinity must be considered as well, to evaluate its effect on agricultural water demand (Letey et al. 2011).

In the Tunisian oases, date palm (Phoenix dactylifera) is an important horticultural crop and is at the heart of oasis cultivation systems. For those oases, it is expected that date palm water demand will increase over the next few decades due to rising temperatures and evaporative demand (Haj-Amor et al. 2020). Climate change may increase this water demand because of a projected decrease in effective rainfall and an increase in crop ET. Therefore, the effects of climate change and its consequences (i.e., irrigation water salinity) on irrigation water demand should be quantified to improve on irrigation efficiency, water conservation, and for long-term water resources development and planning. In this context, the objectives of this research were (1) to estimate the irrigation water demand of date palms during 2019–2050 in Metouia Oasis (i.e., one of the important oases in Tunisia) utilizing downscaled climate scenarios, (2) to identify the implications of different levels of irrigation water salinity on water demand, and (3) to assess implications of different levels of irrigation efficiency on irrigation water demand. The 2019–2050 period was selected so that necessary information is becoming available toward the implementation of irrigation water management options in the Tunisian oases for the next decades. The study also provides recommendations to enhance water availability for irrigation under climate change.

**METHODS AND TECHNIQUES**

**Study area**

This research work was based on 310 ha of date palm fields located in the Tunisian coastal oasis called Metouia Oasis.
(Figure 1). The oasis area is divided into 155 equally sized plots of farmland. Each plot is rectangular in shape, typically 100 m long and 50 m wide. The date palm (*Phoenix dactylifera*) is the main crop cultivated and plays a key role in agricultural production, as in several Mediterranean countries. Even though the date palms are adapted to the harsh climate of the oasis (i.e., average yearly temperature $\approx 25.2^\circ C$, average yearly rainfall $\approx 162.2 \text{ mm year}^{-1}$), enormous amounts of water (1,900–2,500 mm year$^{-1}$) are required to produce commercial yields (Haj-Amor *et al.* 2018). Irrigation is ensured from a coastal Quaternary aquifer (Haj-Amor *et al.* 2018). Basin irrigation is the main irrigation method. Sand and loamy sand are the textural classes of the cultivated soil. The agricultural fields were equipped with subsurface drainage systems to reduce the contribution of perched saline groundwater to soil salinization.

**METHODOLOGY**

The methodology involves nine successive steps (Figure 2) as follows:

**Step 1: data collection during field visit**

A pre-investigation was conducted in Metouia Oasis during December 2018 to collect required field data. The location was identified by a handheld GPS (Oregon 700) and found 33°58'N and 10°00'E latitude and longitude, respectively. The total and irrigated areas were 310 and 270 ha as obtained from the Agriculture Development Office (ADO), Metouia, Tunisia. The irrigation aquifer was a Quaternary aquifer. The electrical conductivity of irrigation water was measured by a portable electrical conductivity meter (Aquaprobe AP-7000 device, Aquaread Instruments...
Company, UK) and found to be 4.2 dS m$^{-1}$. The main cultivating crop was date palm (*Phoenix dactylifera*), and the plant density was 100 plants ha$^{-1}$.

### Step 2: collection of climate data

The daily climate data including rainfall, temperature, wind speed, relative humidity (RH), and solar radiation were obtained from the Tunisia Meteorological Department. These data are summarized in Table 1. The 2019 climatic data were used for estimating the current irrigation demand in Metouia Oasis (details in step 4), whereas the data of the 1964–2013 period were mainly used as a reference period for validating future climate projections (details in step 5).

### Step 3: assessment of the current irrigation efficiency

The irrigation efficiency was determined in 2019 for one research plot after each irrigation event. In the Metouia Oasis region, irrigation water is conveyed from the well to the irrigated plots through a distribution network of concrete canals. Because water conveyance losses from the well to the plot were low, the irrigation efficiency ($E_a$ in %) was calculated by the ratio of the volume of irrigation water stored in the root zone ($V_s$ in mm) and the total volume of irrigation water delivered to the plot ($V_i$ in mm) (Burt et al. 1997):

$$E_a = \frac{V_s}{V_i} \times 100$$  \hspace{1cm} (1)

$V_i$ was calculated by dividing the volume of applied water to the area of the plot. The volume of applied water was calculated by multiplying the actual flow rate ($Q_a$; m$^3$ min$^{-1}$) by the duration of flow ($t$; min). $Q_a$ was determined by a magnetic flowmeter with high accuracy. Due to the high soil salinity levels in Metouia Oasis (Haj-Amor et al. 2016), $V_s$ was measured based on the time-domain reflectometry (TDR) technique. For this purpose, a disposable TDR probe, model 6005CL2, Trase, Soil Moisture Corporation Company, was used (Cichota et al. 2008) to measure $V_s$ after 24 h for each irrigation event. Calculations of $E_a$ are illustrated in Table 2.

### Step 4: estimation of the current irrigation demand

In this step, the 2019 gross irrigation requirement (GIR) of the date palms for the Metouia Oasis was calculated. This calculation was performed by FAO developed CROPWAT 8.0 software (Smith 1992). The FAO Penman–Monteith
(FAO-PM) equation is a basic equation for computing irrigation requirement with CROPWAT 8.0 software. This equation is defined as follows (Allen et al. 1998):

$$\text{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$$  \hspace{1cm} (2)$$

where $\text{ET}_0$ is the reference evapotranspiration (mm day$^{-1}$); $\Delta$ is the saturated vapor pressure slope (kPa °C$^{-1}$); $G$ is the heat flux density of soil (MJ m$^{-2}$ day$^{-1}$); $R_n$ is the net radiation (MJ m$^{-2}$ day$^{-1}$); $T$ is the mean temperature (°C); $u_2$ is the average daily wind speed (m s$^{-1}$); $e_s$ is the saturation vapor pressure (kPa); $e_a$ is the actual vapor pressure (kPa); $(e_s - e_a)$ is the deficit of vapor pressure (kPa); and $\gamma$ is a psychrometric constant (kPa °C$^{-1}$). GIR was calculated based on the following four successive steps: (1) calculation of reference ET ($\text{ET}_0$) based on climatic data; (2) calculation of actual ET ($\text{ET}_a$), based on crop coefficient values for date palm and $\text{ET}_0$; (3) calculation of net irrigation requirement (NIR) based on soil–water balance, and (4) calculation of GIR based on determined irrigation efficiency. Details of these calculations are presented in Figure 3. Soil data (i.e., field capacity, wilting point, and infiltration rate) are required for calculating NIR. Accordingly, these data were measured according to standard methods. Field capacity was determined in the laboratory based on the soil water retention curve method, whereas the wilting point was estimated with a pedotransfer function based on soil texture, organic matter content, and bulk density (Saxton & Rawls 2006). The infiltration rate was experimentally measured by a double ring infiltrometer following the D3385-03 standard test method (ASTM 2003). Field capacity and wilting point for sandy soil of the study plot were 0.19 and 0.033 cm$^3$ cm$^{-3}$, respectively, whereas steady infiltration rate was 3.4 cm h$^{-1}$.

### Table 1: Average monthly climate data in Metouia Oasis over 2019

| Month  | Air temperature (°C) | Solar radiation (MJ m$^{-2}$ day$^{-1}$) | RH (%) | Wind speed (m s$^{-1}$) | Rainfall amount (mm) |
|--------|----------------------|----------------------------------------|--------|-------------------------|----------------------|
| January| 13.5                 | 10.2                                   | 55.6   | 2.3                     | 17.9                 |
| February| 16.1                | 13.4                                   | 51.5   | 2.1                     | 17.8                 |
| March  | 20.3                 | 18.8                                   | 43.1   | 3.7                     | 15.9                 |
| April  | 24.5                 | 23.4                                   | 42.2   | 3.3                     | 13.9                 |
| May    | 27.3                 | 24.5                                   | 37.3   | 3.6                     | 11.9                 |
| June   | 32.8                 | 26.4                                   | 30.4   | 3.2                     | 10.9                 |
| July   | 35.5                 | 26.3                                   | 30.3   | 3.1                     | 10.8                 |
| August | 35.9                 | 27.6                                   | 33.2   | 3.1                     | 10.3                 |
| September| 31.6                | 15.5                                   | 41.9   | 3.1                     | 10.1                 |
| October| 26.9                 | 13.2                                   | 45.2   | 3.1                     | 10.9                 |
| November| 21.5                | 11.2                                   | 53.4   | 2.2                     | 12.7                 |
| December| 16.4                | 10.3                                   | 61.2   | 2.1                     | 19.5                 |
| Average| 25.2                 | 18.4                                   | 43.7   | 2.9                     | 162.2                |

### Table 2: An example showing irrigation efficiency ($E_a$) determination (data for the first irrigation event occurred in Metouia Oasis over 2019)

| Data                              | Value |
|-----------------------------------|-------|
| Irrigated area $A$ (ha)           | 1     |
| Irrigation duration $D$ (min)      | 662   |
| Flow rate $Q_a$ (m$^3$ min$^{-1}$) | 4.2   |
| Total volume of water delivered to the plot $V_t = (Q_a \times D)/A$ (mm) | 278.04 |
| Volume of water stored in the root zone $V_s$ (mm) | 110.71 |
| Irrigation efficiency $E_a = V_t/V_s$ (%) | 39.8  |
Step 5: projection of the future climate variables

The climate data (i.e., temperature, rainfall, wind speed, RH, and solar radiation) over 2019–2050 were obtained through climate projection using the HadCM3 model and the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012). The performance of 37 global climate models (GCMs) of CMIP5 (e.g., GISS-E2-R-CC, HadCM3, INMCM4, HadGEM2-ES, NorESM1-ME, and NorESM1-M) were evaluated to identify the optimal model which can provide the best climate data modeling. The performances of these models in simulating climatic data (e.g., temperature and rainfall) for the 1964–2013 reference period were assessed against measurements. Using various statistical indicators (e.g., relative root mean square error and Kling–Gupta efficiency), results showed that HadCM3 was the desired optimal model to be applied for the climatic forecasting. Three
Representative Concentration Pathways (RCPs) for greenhouse gases were considered: RCP 8.5 (very high emission scenario), RCP 6.0 (medium emission scenario), and RCP 4.5 (lowest emission scenario). An RCP is a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC). The RCPs focus on the trajectory of greenhouse gas concentrations over time to reach a particular radiative forcing at 2100. RCP 4.5 is a scenario that stabilizes radiative forcing at 4.5 W m\(^{-2}\) in the year 2100 without ever exceeding that value. RCP 8.5 is a scenario representing the highest levels of radiative forcing (up to 8.5 W m\(^{-2}\)) and changes in greenhouse gas concentrations (N1370 ppm CO\(_2\) equivalent). RCP 6.0 is a scenario that stabilizes radiative forcing at 6.0 W m\(^{-2}\) in the year 2100 (Meinshausen et al. 2011). The projected climate data were validated based on the comparison between the future climate data (2019–2050) and past observed data (1964–2013 period), available in Haj-Amor et al. (2020).

Because the spatial resolution of HadCM3 output (3.75° × 2.5°) is large relative to the investigated area, the climate change scenarios were downscaled at the investigated area scale by the statistical downscaling tool (SDSM). The SDSM was used to develop each future climate scenario (i.e., RCP 8.5, RCP 6.0, and RC P4.5), including data for temperature, wind speed, solar radiation, and rainfall (daily data). These downscaled data were bias-corrected by comparing the past model data with historical observed data (1964–2013 period). The RH was not available from the HadCM3. Therefore, RH was calculated by the ratio of actual water vapor pressure (\(e_a\)) and saturation vapor pressure (\(e_s\)) (Eccel 2012). The data of saturated vapor pressure slope (\(\Delta\)), heat flux density of soil (\(G\)), net radiation (\(R_n\)), saturation vapor pressure (\(e_s\)), actual vapor pressure (\(e_a\)), and psychrometric constant (\(\gamma\)) that could not be provided by GCMs are determined empirically from the temperature, the altitude above sea level, and the latitude of the investigated area following the details reported in Zhang et al. (2019).

**Step 6: estimation of the future irrigation demand with current irrigation efficiency**

In this step, under the current irrigation efficiency (i.e., average yearly value for the year 2019, \(E_a \approx 37\%\)), the GIR was calculated by considering the potential change in irrigation water electrical conductivity (EC\(_{iw}\)) from 2019 to 2050 (data shown in Figure 4), to account for changes in leaching requirements (data shown in Figure 5). The potential change in EC\(_{iw}\) was simulated based on sea level rise (i.e., as a consequence of climate change), causing seawater intrusion and changes in aquifer recharge. Solute transport simulation using the calibrated and validated saturated–unsaturated transport (SUTRA) model was employed to compute EC\(_{iw}\) change from 2019 to 2050 under various climate change scenarios (RCP 4.5, RCP 6.0, and RCP 8.5). All the details about this simulation (i.e., SUTRA model description, simulation domain, equations, required data, boundary conditions, calibration, validation, and simulation results) were reported in Haj-Amor et al. (2020). Here, the objective is to evaluate the effect of changes in EC\(_{iw}\) on future GIR.

![Figure 4](http://iwaponline.com/jwcc/article-pdf/12/5/1437/923494/jwc0121437.pdf)
Step 7: analysis of trends of changes in water loss and overdose amount

Water loss was defined as the difference between gross (GIR) and net irrigation requirement (NIR), i.e., GIR - NIR. Moreover, we define overdose as the amount of water applied in addition to gross irrigation demand to meet actual dose (AD) applied by the local farmers, i.e., AD - GIR. AD depends on farmers’ field practices. Also, future irrigation water efficiency was estimated considering the same annual average AD - NIR in relation to NIR as present, i.e., (AD - NIR)/NIR*100. This efficiency value was 191.2% using 2019 field data. In this step, the trends of changes in water loss and overdose amount during 2019–2050 were estimated following the Sen’s slope estimation. The non-parametric Sen’s slope estimation (Sen 1968) is simply given by the median slope, and this method calculates the slope as a change in measurement per change in time, as defined by

\[
\text{Sen's slope} = \text{Median} \left( \frac{x_j - x_i}{j - i} : i < j \right)
\]

where \(x_i\) and \(x_j\) are time series elements with \(i < j\). Furthermore, the ratio of simulated leaching requirement (LR) and total loss of water (i.e., the difference between applied dose and NIR) was estimated to illustrate the importance of salinity management in relation to irrigation water management.

Step 8: estimation of the future irrigation demand with improved irrigation efficiencies

In this step, GIR was re-estimated by inputting three variations of irrigation efficiency: 50, 60, and 70%. These percentages were adapted from FAO (1997) for efficient surface irrigation. 50 and 60% refer to efficient surface irrigation, whereas 70% refers to very efficient surface irrigation which could be ensured through perfect drainage and irrigation conditions. Here, the objective is to evaluate the effect of surface irrigation efficiency enhancement on future GIR.

Step 9: summarize and analyze water availability for irrigation

In this final step, the possible and effective ways to reduce irrigation water loss and increase irrigation efficiency were identified, using technical reports provided by the ADO, Tunisia.

RESULTS AND DISCUSSION

Current irrigation efficiency

Twelve irrigation events were applied in the investigated irrigated plot of the Metouia Oasis, following one irrigation per month. Accordingly, 12 values of irrigation efficiency (\(E_a\)) were identified. These values are shown in Figure 6. Based
on the identified average yearly value of $E_a$ (37%) and following the classification proposed by Merriam & Keller (1978), the irrigation in Metouia Oasis would be classified as inefficient. In this classification, a 30–45% range refers to inefficient surface irrigation. This low efficiency value reflects the poor irrigation water management practice by the farmers. Several factors could contribute to this inefficient irrigation: (1) hydraulic properties of top-soil (sandy soil with a weak retention and a high hydraulic conductivity estimated to be 123 cm d$^{-1}$); (2) unsuitable soil management (e.g., unsuitable land leveling; unsuitable cow manure application); (3) absence of water saving technologies within the irrigated plots; and (4) the dysfunction of the subsurface drainage system. Similar low irrigation efficiencies were identified in many Tunisian oases such as Lazala Oasis (Haj-Amor et al. 2014) and Douz Oasis (Haj-Amor et al. 2018). Furthermore, weak surface irrigation efficiency is noted in many of the world’s arid regions (e.g., Ali & Klein 2014; Al-Faraj et al. 2016). These numbers show that the farmers who apply surface irrigation should have the required skills for ensuring efficient irrigation management in their plots, especially under some specific conditions (e.g., high levels of soil salinity).

As suggested by FAO (1997), good drainage conditions and proper maintenance of the irrigation system may contribute to a significant increase in the surface irrigation efficiency (up to 70%). In addition to these four factors, based on field measurements, it was observed that during each irrigation event, the applied water dose was much more than the required dose (see data in Figure 7). These overdoses could be the main factor behind the inefficient
irrigation. Indeed, knowing how much water is applied is a fundamental element of suitable irrigation management.

Increased surface irrigation efficiency in Metouia Oasis can be achieved through the formulation of adequate water dose which must be applied by all farmers and the urgent adaptation of some innovative and low cost technologies within the irrigated plots for water saving (e.g., PVC pipes). Also, the irrigation water overdoses can be avoided by adjusting irrigation duration by the farmers and the introduction of adequate incentives that increase the profitability of irrigation water use. Furthermore, the continuous control of the function of the subsurface drainage system is fundamental for achieving this objective (Ritzema et al. 2008). Indeed, controlled drainage allows significant irrigation water saving by providing part of the consumptive use through capillary rise from shallow groundwater. The objective of controlled drainage is to decrease subsurface drainage intensity during specific periods of time by temporarily raising the level of the drain outlet. Capillary rise from the raised water table contributes to supplying water to the root zone. Field investigations in Kebili Oasis (Southern Tunisia) revealed that about 32% of the total water requirement of date palms could be saved through controlled drainage (Haj-Amor et al. 2016).

Current irrigation demand

In 2019, the total irrigation demand of date palms (GIR) in Metouia Oasis was calculated based on the observed climatic variables (data shown in Table 1), measured irrigation water salinity (data shown in Figure 4), and irrigation efficiency (data shown in Figure 6). Annual and monthly values of GIR are presented in Figure 8. From this latter figure, it was observed that the annual GIR was 3,347 mm. Also, the monthly GIR varied from 259 mm in January (coldest month) to 321 mm in August (hottest month). The important difference between these two values (i.e., 259 and 321 mm) demonstrated the contribution of climate conditions to GIR variation. Differences in monthly irrigation demand are common in many date palm-growing countries such as Algeria (Mihoub et al. 2015) and Syria (Brunel et al. 2006). In addition to the climate conditions, the high value of annual GIR (3,347 mm) could also be related to the high LR (=14%), as a consequence of the high salinity of the applied water (data shown in Table 4) and the low value of irrigation efficiency (data shown in Figure 6). However, as mentioned in Figure 8, the big difference between the annual net irrigation demand (1,389 mm) and the annual GIR (3,347 mm) confirmed that irrigation efficiency (hence water losses within the irrigated fields) may have a larger impact (i.e., increasing trend) on the GIR than climate and LR factors. Accordingly, water losses from the irrigated fields (e.g., overdoses, percolation, and run-off) must be reduced in order to decrease the water demand of date palms. For that purpose, farmers must be provided with the water conservation skills, as currently farmers over-irrigate (see data in Figure 8).

Future irrigation demand

Under various climate change scenarios (RCP 8.5, RCP 6.0, and RCP 4.5), Figure 9 shows the variation trends of future
GIR in the study area during 2019–2050. Under these scenarios, a continuous increase in future GIR is predicted from 2019 to 2050. GIR will increase from 3,347 mm year\(^{-1}\) in 2019 to 3,588–3,640 mm year\(^{-1}\) in 2050, depending on the simulated climate change scenario. The data in Figure 9 revealed also that the highest increase in future GIR is noted for the highest greenhouse gas emissions scenario (RCP 8.5), whereas the lowest increase is noted for the lowest scenario (RCP 4.5). This confirms the important contribution of climate change, especially increasing temperature and decreasing rainfall (data shown in Table 5) to the increasing GIR, as commonly observed in many arid countries such as Bangladesh (Acharjee et al. 2017), Zimbabwe (Nkomozepi & Chung 2012), and South Australia (Connor et al. 2009). Also, Haj-Amor et al. (2020) have clearly confirmed that the high increase in water salinity during 2019–2050 (Figure 4) is a contributor to the continuous increase in future GIR as a consequence of increasing LR (data shown in Figure 5).

In many arid zones, a decrease in winter rainfall which may change between −20 and −30% coupled with an increase in air temperature (especially during the summer) would reduce crop yields by 15% and increase demands for irrigation water (IPCC 2019). So, there is an urgent need to develop suitable risk management strategies for fighting the negative effects of climate change on irrigation demand.

### Trends of water loss and overdose with the current level of practice

The difference between the gross irrigation requirement and net irrigation requirement (i.e., GIR–NIR) reflects the amount of water loss which can only be managed by improving the irrigation system efficiency. The difference between applied dose and gross irrigation requirement (i.e., AD–GIR) is an additional loss of water which can easily be managed by measured and controlled application of irrigation of

| Data                              | Abbreviation | Unit      | Value   | Source                                                                 |
|-----------------------------------|--------------|-----------|---------|------------------------------------------------------------------------|
| Irrigation water electrical       | EC\(_{iw}\)  | dS m\(^{-1}\) | 4.2     | Measured with an electrical conductivity meter (Aquaprobe AP-7000 device) |
| conductivity                     |              |           |         |                                                                         |
| Crop salt tolerance threshold     | EC\(_{\bar{e}}\) | dS m\(^{-1}\) | 6.8     | From Allen et al. (1998)                                               |
| Leaching requirement              | LR           | %         | 14      | Calculated\(^a\) (FAO 1997)\(^a\) = EC\(_{iw}\)/(5 EC\(_{\bar{e}}\) – EC\(_{iw}\)) |

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**Figure 9** | Determined (2019) and simulated irrigation demand of date palms (GIR) in Metouia Oasis from 2020 to 2050 under three climate change scenarios (RCP 8.5: very high emission scenario, RCP 6.0: medium emission scenario, and RCP 4.5: lowest emission scenario).
the existing irrigation system (Figure 10). Figure 10 shows a slight decrease (10 mm year\(^{-1}\)) in water loss (i.e., GIR–NIR) during 2019–2050 for the RCP 8.5 scenario. Similar trends were found for RCP 4.5 and RCP 6.0 scenarios. However, the results indicate a considerable increase (44.79 mm year\(^{-1}\)) in overdose, if farmers continue to apply same overdose/NIR ratio as present for the future periods for all scenarios (see Figure 10 for RCP 8.5). Hence, it is extremely important to ensure controlled application of irrigation with proper measurement techniques to reduce the overdose amount. With possible increase in NIR in the future, it is therefore essential to ensure more careful application of

| Year | Temperature (°C) | Rainfall (mm) | Solar radiation (MJ m\(^{-2}\) day\(^{-1}\)) | RH (%) | Wind speed (m s\(^{-1}\)) |
|------|------------------|--------------|--------------------------|--------|-------------------------|
| 2020 | 25.31            | 162          | 18.4                     | 43.5   | 2.91                    |
| 2021 | 25.38            | 161.7        | 18.63                    | 43.87  | 2.915                   |
| 2022 | 25.45            | 161.4        | 18.86                    | 44.24  | 2.92                    |
| 2023 | 25.52            | 161.1        | 19.09                    | 44.61  | 2.925                   |
| 2024 | 25.59            | 160.8        | 19.32                    | 44.98  | 2.93                    |
| 2025 | 25.66            | 160.5        | 19.55                    | 45.35  | 2.935                   |
| 2026 | 25.73            | 160.2        | 19.78                    | 45.72  | 2.94                    |
| 2027 | 25.8             | 159.9        | 20.01                    | 46.09  | 2.945                   |
| 2028 | 25.87            | 159.6        | 20.24                    | 46.36  | 2.95                    |
| 2029 | 25.94            | 159.3        | 20.47                    | 46.83  | 2.955                   |
| 2030 | 26.01            | 159          | 20.71                    | 47.2   | 2.96                    |
| 2031 | 26.08            | 158.7        | 20.93                    | 47.57  | 2.965                   |
| 2032 | 26.15            | 158.4        | 21.16                    | 47.94  | 2.97                    |
| 2033 | 26.22            | 158.1        | 21.39                    | 48.31  | 2.975                   |
| 2034 | 26.29            | 157.8        | 21.62                    | 48.68  | 2.98                    |
| 2035 | 26.36            | 157.5        | 21.85                    | 49.05  | 2.985                   |
| 2036 | 26.45            | 157.2        | 22.08                    | 49.42  | 2.99                    |
| 2037 | 26.57            | 156.9        | 22.31                    | 49.79  | 2.995                   |
| 2038 | 26.65            | 156.6        | 22.54                    | 50.16  | 3.01                    |
| 2039 | 26.73            | 156.3        | 22.77                    | 50.53  | 3.015                   |
| 2040 | 26.81            | 155.9        | 23.11                    | 50.9   | 3.02                    |
| 2041 | 26.89            | 155.7        | 23.23                    | 51.27  | 3.025                   |
| 2042 | 26.97            | 155.5        | 23.46                    | 51.64  | 3.03                    |
| 2043 | 26.99            | 155.1        | 23.69                    | 52.01  | 3.035                   |
| 2044 | 27.07            | 154.8        | 23.92                    | 52.38  | 3.04                    |
| 2045 | 27.15            | 154.5        | 24.15                    | 52.57  | 3.045                   |
| 2046 | 27.23            | 154.2        | 24.38                    | 52.85  | 3.05                    |
| 2047 | 27.31            | 153.9        | 24.61                    | 53.13  | 3.055                   |
| 2048 | 27.39            | 153.6        | 24.84                    | 53.58  | 3.06                    |
| 2049 | 27.47            | 153.3        | 25.07                    | 54.23  | 3.065                   |
| 2050 | 27.55            | 153          | 25.31                    | 54.62  | 3.07                    |

(RCP 8.5: very high emission scenario, RCP 6.0: medium emission scenario, and RCP 4.5: lowest emission scenario.)
water for date palm cultivation in Metouia Oasis. The estimation of the ratio of simulated LR to total water loss (water loss plus overdose amount), i.e., LR/(AD–NIR), showed an annual increase of 0.16% year\(^{-1}\) for the projection period, reflecting the significant increase in LR because of the higher irrigation water salinity. Therefore, in comparison to efficiency enhancement, salinity management is also very important for the proper agricultural water management of the Metouia Oasis and for other coastal agricultural systems that depend on groundwater for irrigation.

Decreasing trends of GIR–NIR indicate more rapid increase in NIR than GIR. This finding signifies that a portion of water loss under the current condition would actually contribute to increased LR, and thus, actual water loss amount may reduce by some amount in the future. This finding can more strongly be observed by increasing trends of LR/(AD–NIR) in Figure 10. While increased
overdose amount (AD–GIR) indicates that improper irrigation application (i.e., over-irrigation) may contribute to further future water shortage.

**Irrigation efficiency enhancement and irrigation demand**

The analysis of enhancing surface irrigation efficiency at various levels (50, 60, and 70%) showed that considerable water saving can be ensured over 2019–2050 under the simulated three climate change scenarios. Figure 11 illustrates only the results of the RCP 6.0 scenario; however, similar results were obtained for the other climate change scenarios (RCP 8.5 and RCP 4.5). The data presented in Figure 11 revealed that the future annual GIR is projected to decrease by about 13% (434–469 mm) with an irrigation efficiency of 50% and by 33% (1,103–1,190 mm) with an irrigation efficiency of 60%. With a higher increase in irrigation efficiency (70%), the future annual GIR may result in a reduction of about 55% (1,841–1,980 mm). This suggests that under climate change, the enhancement of surface irrigation efficiency (from 50 to 70%) is likely to save significant amounts of irrigation water. The obtained results show that some actions toward the enhancing of surface irrigation efficiency, such as adaptation of water saving technologies, coupled with improved farmers’ skills (allowed to manage the soils suitably) are steps in the right direction for decreasing GIR in the Metouia Oasis. In this context, the detailed cost-benefit analysis of each potential measure is needed. The adverse climate change affects GIR considerably, and it should be carefully considered for devising strategic plans by policymakers.

**Effective ways to reduce irrigation water loss and increase irrigation efficiency**

In order to improve the management of irrigation of Tunisian oases, many laboratory and field experiences have been conducted over several years (2006–2016) by the Tunisian Agriculture Ministry and other international research organizations, such as the Irrigation Water Management Institute. The results of these experiences (unpublished technical reports) are available in the ADO, Tunisia. In Table 6, the major ways and techniques that can help us to reduce irrigation water loss and increase irrigation efficiency are illustrated. However, these recommended practices of Table 6 are not yet adopted in the Tunisian oases due to the difficulty of integrating smart irrigation techniques with traditional irrigation networks. Moreover, the amount of investment required is often too high for it to be profitable for small-holder farmers.

**Limitations and scope for future research**

The irrigation demand may vary as a result of land-use change (e.g., an increase in the date palm area) which was...
not considered in this work. Accordingly, in future research works, projections of climate and land-use change in Metouia Oasis could be useful for improving the findings of the current study. Also, there is scope for future research to analyze the balance of water demand and availability. Studies on the technical and economic evaluation of different irrigation management strategies to reduce water loss and improve irrigation efficiency are also required.

**CONCLUSION**

The present study investigated the effect of climate change on future GIR of date palms in a Tunisian oasis and then investigated the effect of irrigation efficiency enhancement on this demand. The poor irrigation efficiency ($E_a = 37\%$) of the Metouia Oasis during 2019 reflects mainly a poor management of irrigation water by the farmers within the irrigated fields. The high GIR value of 3,347 mm is representative of the arid climate of the Metouia Oasis and is a reflection of the high LR (=14\%) because of the high salinity of the applied irrigation water (salinity $\approx$ 4.2 dS m$^{-1}$) and low irrigation efficiency value ($E_a = 37\%$). Accordingly, the results of this study showed that inefficient irrigation in combination with climate change and increasing groundwater salinity may significantly affect water resource availability. Moreover, irrigation overdose by local farmers may hamper water resource conservation. Furthermore, this study revealed that despite increasing water demands by future climatic changes, considerable water savings can be achieved if surface irrigation efficiency increases from a current value of 37 to 70\%. Therefore, the implementation of improved irrigation efficiency, the continuous control of the salinity of applied water, and the controlled application of irrigation water by farmers are required for decreasing GIR and solving the encroaching problem of water scarcity.

**ACKNOWLEDGMENTS**

The authors sincerely thank Prof. Jan W Hopmans (University of California Davis, USA)) for his language assistance.

**DATA AVAILABILITY STATEMENT**

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

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First received 22 April 2020; accepted in revised form 16 July 2020. Available online 21 August 2020