Day and night time sprinkler irrigated tomato:

Irrigation performance and crop yield

by

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Abstract

The effect of day time *vs.* night time sprinkler irrigation on irrigation performance and tomato crop yield is assessed in this paper for the conditions of Tunisia. Field experiments were performed at the experimental station of Cherfech under two rectangular sprinkler spacings: 24 x 18 m and 18 x 18 m, denoted as plots M_1 and M_2, respectively. Results of performance evaluations indicate a relevant effect of climatic and operation conditions on

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irrigation uniformity and wind drift and evaporation losses (WDEL). Experimental data were used to calibrate and validate a ballistic solid-set sprinkler irrigation simulation model and a soil-water-yield crop model. Based on the analysis of the main meteorological parameters during the irrigation season, the validated models were used to simulate night time irrigation (characterized by moderate wind speed and evaporative demand). Simulation results indicate that night time irrigation greatly improved performance respect to day time operation: WDEL decreased from 24 to 7 %, while CU increased from 50 to 64 % in M_1 and from 71 to 80 % in M_2. Simulated results showed that night time irrigation decreased relative yield losses (from 26 to 16 % in M_1 and from 11 to 3 % in M_2), as well as the spatial variability of crop yield (simulated yield CV in M_2 decreased from 17 to 6 %). Adoption of night irrigation in the study area will finally depend on local socioeconomic and water management constraints.

Keywords: Sprinkler; irrigation; wind; daytime; nighttime; tomato; yield

Nomenclature

α	Angle formed between the drop velocity in the air and the wind speed;
β	Angle formed between the drop velocity in the air and the drop velocity respect to the ground;
C	Drag coefficient;
C’	Modified drag coefficient;
CU	Christiansen uniformity coefficient, %;
CV	Coefficient of variation, %;
D	Drop diameter, mm;
D_{50}	Mean drop diameter, mm;
ET_0	Reference evapotranspiration, mm;
ET_a	Seasonal actual crop evapotranspiration, mm;
ET_c	Crop evapotranspiration, mm;
ET_{max}	Maximum seasonal crop evapotranspiration, mm;
h_d	Water depth discharged by the sprinkler, mm;
h_i	Individual water depth collected at the i^{th} collector, mm;
$\bar{h}$	Average water depth collected at all collectors, mm;
ID	Irrigation duration, h;
k	Number of water depth observations;
K1	Empirical coefficient for the modified drag coefficient;
K2	Empirical coefficient for the modified drag coefficient;
K_c	Crop coefficient;

K_y	Coefficient for water stress effect on crop yield;
L_s	Spacing between laterals, m;
MAD	Management allowable deficit, %;
n	Empirical coefficient for drop diameter distribution;
P_e	Effective precipitation, mm;
Pv	Emitted volume in drops smaller than diameter D, %;
q	Sprinkler discharge, m^3 h^{-1};
R^2	Determination coefficient;
RH	Relative humidity, %;
RMSE	Root mean square error;
S_s	Spacing between sprinklers, m;
T	Air temperature, ºC;
WD	Azimuth wind direction, °;
WDEL	Wind drift and evaporation losses, %;
WS	Wind speed, m s^{-1};
Y_a	Actual yield, t ha^{-1}; and
Y_{max}	Maximum crop yield, t ha^{-1}.

Introduction

Irrigation uniformity and wind drift and evaporation losses (WDEL) are related to crop yield and to the efficient use of agricultural resources. Consequently, engineers and agronomists regard these as important factors to be considered in the selection, design and management of sprinkler irrigation systems (Solomon, 1990). In arid and semi arid regions, water is scarce. Furthermore, competition for water between users, environmental issues and increasing energy costs are the major reasons for improving sprinkler irrigation performance.

Both uniformity and WDEL are affected by meteorological and technical factors such as wind speed, operating pressure, sprinkler characteristics and sprinkler spacing (Keller and Bliesner, 1990). Analyzing the effect of these factors on irrigation uniformity, a set of performance guidelines and recommendations was presented by Tarjuelo et al. (1999) in order to improve design and management of sprinkler irrigation in semi arid areas. Recent progress in ballistic models for sprinkler irrigation (Carrión et al., 2001; Dechmi et al., 2004a) allows simulating irrigation performance under various operation and environmental conditions. Despite the fact that ballistic simulation models require an important effort for calibration and validation, practical applications to sprinkler irrigation management and design have been reported by Playán et al., (2006) and Zapata et al., (2007).

Field experiments and theoretical studies dealing with sprinkler irrigation uniformity and crop yield have been performed by several authors (Stern and Bresler, 1983; Warrick and Gardner, 1983; Lety et al., 1984; Or and Hanks, 1992 and Mateos et al., 1997), indicating a relevant effect of non-uniformity on available soil water and on crop yield. Moreover, using crop production functions, Mantovani et al., (1995) and Li (1998) developed approaches to simulate the effect of sprinkler irrigation uniformity on crop yield.

Simulation results quantified the increase in crop yield with increasing uniformity in different agroecosystems. These results also showed that the optimum irrigation amount depended on agronomic and economic factors.

In this study, sprinkler irrigation experiments were carried out at the Cherferch perimeter, located at the northeast of Tunisia. In Tunisia, sprinkler irrigation systems cover 110,000 ha, representing about 32 % of the total irrigated area. The objectives of this work were: 1) to characterize irrigation uniformity and WDEL under the local, day time, climatic and operation conditions; 2) to calibrate and validate a ballistic sprinkler irrigation simulation model and a soil-water-yield simulation model; and 3) to combine both models in order to explore the impact of night time irrigation on irrigation performance and crop yield. Beyond the regional implications of this work, the presented methodology represents a contribution to the use of irrigation and crop simulation models as tools leading to adequate sprinkler irrigation management.

Materials and Methods

Experimental site

Field experiments were carried out at the Cherfech Experimental Station of the National Research Institute for Rural Engineering, Water and Forests near Ariana, Tunisia (Lat. 37 ° N, Long. 10° E, Alt. 10 m). The climate is Mediterranean semiarid, with yearly average precipitation of 450 mm. According to the USDA classification, soil texture is silty clay loam (34.8 % clay, 57.6 % loam, 7.6 % sand). Bulk density is 1.53 Mg m^{-3}, and the readily available water is 163 mm m^{-1} (water content at field capacity, $\theta_{fc} = 0.42$, water content at wilting point, $\theta_{wp} = 0.26$). Irrigation water is pumped from a reservoir supplied from the Medjerda canal. The average electrical conductivity of the irrigation water is 2.5 dS m^{-1}.

Experimental design

Sprinkler irrigation experiments were performed on a 0.5 ha solid-set field equipped with two sprinkler spacings: square 18 x 18 m and rectangular 24 x 18 m (Fig. 1a). The sprinkler model was RC 11C, manufactured by Rolland Arroseurs (Mognard, France). The sprinkler nozzle (4.5 mm in diameter) was located at an elevation of 1 m over the soil surface. The nozzle operating pressure was kept constant throughout the irrigation season at 300 kPa. Two adjacent experimental plots were defined. The plots were named M_1 and M_2, and were equipped with the abovementioned sprinkler spacings: 24 x 18 m for M_1 and and 18 x 18 m for M_2 (Fig. 1a).

A tomato crop (cv. Rio Grande) was planted in April 26, 2006, at a density of 3 plants m^{-2} (in a square spacing of 0.33 x 1 m). Appropriate fertilizer, herbicide and pesticide applications were performed during the growing season. Crop yield was determined at the end of the season, dividing both plots in arrays of 3 x 3 m parcels (48 in M_1 and 36 in M_2).

Irrigation system evaluation

Sprinkler irrigation evaluations were conducted in plots M_1 and M_2 following the methodology described by Merriam and Keller (1978) and Merriam et al. (1980). A 3 x 3 m square collector network was set up within plots M_1 and M_2, as presented in Figs. 1b and 1c. Collectors were 0.079 m in diameter and 0.24 m high, and were mounted on plastic support tubes so that the top of the collector was located at an elevation of 0.50 m over the soil surface. This collector model resulted very adapted to the experimental requirements, although its diameter was smaller than recommended in international standards (Anonymous 1987, 1990, 1995). Playán et al. (2005) reported the results of an experiment in which similar collectors were compared with collectors as large as 210 mm in diameter. Collector diameter only played a relevant role (errors exceeding 2 %) for wind speeds beyond 4.0 – 4.5 m s^{-1}.

During each evaluation, the wind speed (WS, m s^{-1}), azimuth wind direction (WD, °), air temperature (T, ºC) and relative humidity (RH, %) were recorded with a frequency of 5 min using an automatic meteorological station. The wind measurement instruments (manufactured by Weather Wizard III, Hayward, California, USA) were installed at an elevation of 2 m above the soil surface, and located at a distance of about 100 m from the experimental field.

Following each irrigation, the water collected in both collector sets was recorded and used to determine the Christiansen Uniformity Coefficient (CU) (Christiansen, 1942) using eq. [1]:

$$CU = 100\left(1 - \frac{\sum_{i=1}^{k}\left|h_i - \bar{h}\right|}{k\,\bar{h}}\right) \qquad [1]$$

where h_i is the individual water depth collected at the ith collector (mm), $\bar{h}$ is the average water depth collected at all collectors (mm), and k is the number of observations. Likewise, the Wind Drift and Evaporation Losses (WDEL) were evaluated as:

$$WDEL = 100\,\frac{\left(h_d - \frac{1}{k}\sum_{i=1}^{k} h_i\right)}{h_d} \qquad [2]$$

where h_d is the water depth (mm) discharged by the sprinkler in an irrigation event, determined as:

$$h_d = \frac{1000\ q}{L_s\ S_s}\, ID \qquad [3]$$

where L_s is the spacing between laterals (18 m), S_s is the spacing between sprinklers (18 or 24 m), q is the sprinkler discharge (m^3 h^{-1}) and ID is the irrigation duration (h).

Irrigation scheduling

The irrigation events applied between tomato planting (April 26) and May 24 were performed using a temporary sprinkler system (with a 12 x 12 m spacing) covering the whole experimental field. This narrow sprinkler spacing was used to ensure high uniformity during the initial crop development phase. The water depths resulting from these irrigation events were only used for irrigation scheduling purposes. During the rest of the season the experimental field was setup as described in Figure 1. All irrigation events performed after May 24 were evaluated following the procedures described in the previous section. All experimental irrigation events were performed during the day time.

Locations P_1M_1 (in plot M_1) and P_1M_2 (in plot M_2) (Figs. 1b and 1c) were selected as control points. Irrigation was applied to both plots when the control points reached a management allowable deficit (MAD) of 50 %. Soil water was gravimetrically measured during the season at twelve sites for M_1 and nine sites for M_2 (Figs. 1b and 1c). As selected, these sites represent different situations of water distribution (a quarter of the sprinkler spacing), and were supposed representative of each plot (M_1 and M_2) for irrigation simulation purposes.

Sprinkler irrigation model (Ador Sprinkler)

A ballistic simulation model (Dechmi et al., 2004a) was used to simulate solid-set sprinkler irrigation in the experimental plots. The first step was to model WDEL in the experimental conditions. An empirical approach is commonly used for this purpose, relating observed WDEL to meteorological variables (Playán et al., 2005). For day time irrigation operation, the experimental data set was used to derive empirical WEDL predictive equations based on a multiple linear regression approach using WS and RH as independent variables (Playán et al., 2005). For night time irrigation operation, the following WDEL predictive equation, developed by Playán et al. (2005), was implemented in the model:

$$WDEL = 3.7 + 1.31\,WS^2 \qquad [4]$$

The ballistic model is based on the hypothesis that a sprinkler produces drops of different diameters (Fukui et al., 1980; Carrión et al., 2001; and Montero et al. 2001). For a given pressure, a sprinkler produces a statistical distribution of drop diameters, which can be modelled using the following expression (Li et al., 1994):

$$P_v(D) = 100\left(1 - e^{-0.693\left(\frac{D}{D_{50}}\right)^n}\right) \qquad [5]$$

where P_v is the percentage of emitted volume in drops smaller than diameter D, D_{50} is the mean drop diameter, and n is an empirical coefficient.

The flight of a drop from the sprinkler nozzle to the soil surface is governed by the ballistic equations (Fukui et al., 1980). These equations can be solved numerically to determine the drop velocity vector from the initial condition (at the nozzle) to the landing point (drop elevation is equal to the elevation of the soil, the crop canopy or the collector). During the flight, the drop is subjected to the action of gravity (vertical), to a drag force (same direction as its velocity, opposing to it), and to the wind vector (assumed horizontal). The drag coefficient C was determined in the model as a function of the drop Reynolds number, following Seginer et al. (1991).

Seginer et al. (1991) and Tarjuelo et al. (1994) reported that a model developed following the steps above would not adequately predict the deformation of the circular water application area in the presence of wind. Consequently, they proposed a refined version of the drag coefficient (C'), including empirical parameters K1 and K2:

$$C' = C(1 + K1\sin\beta - K2\cos\alpha) \qquad [6]$$

where α and β are angles related to the drop velocity vector and the wind speed vector (Tarjuelo et al., 1994).

This model formulation requires input data on system geometry, wind speed, nozzle diameter and pressure to simulate the flight of a single drop. In order to simulate a solid-set system, drops of all possible diameters must be simulated at all possible horizontal angles (reproducing sprinkler revolution). Weights need to be assigned to each drop diameter, according to empirical Eq. [5]. Finally, a number of sprinklers in the solid set are to be simulated (typically 16), and the drops landing in different areas of the central sprinkler spacing need to be accounted for in order to estimate irrigation depth and irrigation uniformity.

Model calibration is based on the determination of the four empirical parameters presented in Eqs. [5] and [6]: D_{50}, n, K1 and K2. Calibration proceeds in two steps:

1. A no-wind experiment is used to calibrate D_{50} and n, since K1 and K2 have no effect under these conditions (the water application area is circular). In this experiment the radial water application pattern is determined, and simulations are performed with different values of the empirical parameters to identify the values resulting in: a)

maximum correlation between observed and simulated radial water application; and b) minimum RMSE (Root Mean Square Error) between both variables.

2. A number of experiments under variable wind speed are required to calibrate K1 and K2. For each wind speed, simulations are performed with the calibrated values of D_{50} and n and different values of K1 and K2. The optimum value of these last two parameters results in: a) minimum difference between observed and simulated CU; b) minimum RMSE between observed and simulated irrigation depths; and c) maximum correlation between observed and simulated irrigation depths. This step results in two empirical functions: K1(WS) and K2(WS).

A validation phase completes the process. In this phase, additional experiments are used to establish the predictive capacity of the model.

In previous studies, the Ador Sprinkler model has proven to have a relevant predictive capacity. Dechmi et al. (2004a) reported that following calibration to a particular sprinkler model and operating pressure, the model could explain 87% of the observed variability in CU. When validation focused on the spatial distribution of irrigation water, the calibrated model attained a RMSE of 0.95 mm h^{-1}, which was comparable to the error between two adjacent experimental plots with the same characteristics. In a successive development, Playán et al. (2006) calibrated and validated the model for different sprinkler models and operating pressures, and produced management tables for a variety of sprinkler arrangements and spacings. The model has been recently applied to the environment-sensitive simulation of collective irrigation scheduling in irrigated areas (Zapata el al., 2009).

Soil – water – yield model (ISAREG model)

Assessment of irrigation scheduling was performed using the irrigation scheduling simulation model ISAREG (Teixeira and Pereira, 1992). ISAREG is based on the soil water balance method proposed by Doorenbos and Kassam (1979). The model can be used to determine the adequate dates and volumes of irrigation for a given crop or to evaluate the effect of a selected scheduling on crop yield. As described in Teixeira and Pereira (1992), the ISAREG model requires the following input data:

- Meteorological data: Effective precipitation, Pe (mm) and reference evapotranspiration, ET0 (mm) were determined according to the FAO-Penman-Monteith method (Allen et al., 1998).
- Crop data, including the duration of the different crop stages, crop coefficients K_c, root depth z (m), soil water depletion fractions for no stress and the seasonal response factor K_y predicting yield losses caused by soil water shortages. The yield – water stress function was proposed by Doorenbos and Kassam (1979) :

  $$\left(1-\frac{Y_a}{Y_{\max}}\right)=K_y\left(1-\frac{ET_a}{ET_{\max}}\right) \qquad [7]$$

  where Y_a is the actual yield, Y_{max} is the maximum yield, ET_a is the seasonal crop evapotranspiration, and ET_{max} is the maximum seasonal crop evapotranspiration. Crop data were calculated from field observations using the KCISA program (Rodrigues et al., 2000), following the methodology proposed by FAO (Allen et al., 1998).

Under Tunisian experimental circumstances, ISAREG was validated for yield loss predictions by Teixeira et al. (1995). Zairi et al. (1998) validated the model for sprinkler irrigated winter wheat at the Hendi Zitoun experimental station (Centre of Tunisia). The validation exercise proved that the model had a satisfactory predictive capacity of soil water along the crop season. Rodrigues et al. (2001) used ISAREG to develop strategies for living with drought and water scarcity in semi-arid regions (Siliana, Centre of Tunisia) and sub-humid regions (Vigia, South East of Portugal). These authors proposed irrigation scheduling strategies minimising water demand and producing acceptable impacts on cereals and horticultural crops. Zairi et al. (2003) combined ISAREG with linear programming to identify and evaluate strategies for supplemental irrigation of cereals and deficit irrigation of horticultural field crops in central Tunisia.

In this work, ISAREG was validated using experimental data, and then applied to the simulation of actual ET and crop yield. Measured and simulated irrigation data were used as input to the model.

Results and Discussion

Analysis of the irrigation evaluations: CU and WDEL

Table 1 presents the main characteristics of the irrigation system evaluations performed in the experimental solid set system during the irrigation season. All irrigation events were performed under day time conditions. Except for two irrigation events, the wind speed was higher than 2 m s^{-1}. In 79 % of the irrigation events, the wind speed was in the range of 2 - 4 m s^{-1}. Temperature ranged from 24.2°C to 44.3°C, while relative humidity ranged from 15.0 % to 59.8 %. Table 1 also presents the average meteorological conditions for the night period of the days when daytime irrigations were performed (from 19:00 till 7:00 next day). The Table shows a strong decrease in WS (from 3.0 m s^{-1} to 1.4 m s^{-1} on the average) and a relevant increase in RH (from 41 % to 66 % on the average). Night time conditions are much more suited to sprinkler irrigation than day time conditions.

Using the same experimental working pressure (300 kPa) and wind conditions (simultaneous daytime irrigation), the average CU values were 49 % for M_1 and 71 % for M_2, following the expected trend. According to the classification proposed by Keller and Bliesner (1990) for solid set systems, irrigation uniformity was very low in M_1 and relatively low in M_2. The seasonal CU was determined adding all the seasonally applied water at each collector location. The resulting values were 56 % for M_1 and 80 for M_2. Seasonal uniformity was higher than average uniformity of individual irrigation events (with an increase of 6.9 % for M_1 plot and 9.4 % for M_2 plot). Keller and Bliesner (1990) reported that since the wind speed and direction differ from an irrigation event to another, there is a trend for seasonal uniformity to be higher than average uniformity. Sanden et al (2000) found a general increase of 4 to 8 % in seasonal distribution uniformity over average DUs resulting from multiple evaluations performed in a solid set system.

CU time variability in plot M_1 was large, ranging from 20.9 % to 66.7 %. Very low CU values can be explained by poor sprinkler overlapping caused by inadequate working pressure and/or sprinkler spacing. Montero et al. (2000) reported that the maximum spacing recommended for extensive herbaceous crops is 18 x 18 m. These authors also recommended operating pressures in the range of 250 to 350 kPa. While the experimental pressure was in the adequate range, the sprinkler spacing was too large.

The lowest values of CU in plot M_2 were usually recorded for wind speeds higher than 4 m s^{-1}. The highest CU value (81 %) was recorded under a wind speed of 1.8 m s^{-1}. For the lowest wind speed (1.7 m s^{-1}), the resulting CU was 78 %. The duration of the irrigation events, and the random component of wind speed and direction may explain these differences. For wind speeds ranging between 2 and 3 m s^{-1} (50 % of the irrigation evaluations), the average CU value was 74 %. In the wind speed range of 3 to 4 m s^{-1} (18 % of the irrigation evaluations), the average CU value decreased to 65 %. Under low wind speeds (less than 3 m s^{-1}), uniformity seems to be highly limited by the use of single nozzle. Analysing uniformity in the Loma de Quinto Irrigation District (LQD), Dechmi et al. (2003) found that with relatively low pressure (210 kPa) and double nozzle sprinklers, the 18 m x 18 m spacing resulted in high CU (an average of 87 %) under wind speeds below 3 m s^{-1}.

In both plots, the analysis of wind speed and CU data revealed that uniformity was clearly affected by wind speed. The best regressions between CU and wind speed were obtained by third degree polynomials:

$$\text{Plot } M_1: \; CU = 0.242WS^3 - 2.47WS^2 - 2.08WS + 72.1 \; ; \qquad R^2 = 0.88 \qquad [8]$$

$$\text{Plot } M_2: \; CU = 0.069WS^3 - 0.026WS^2 - 8.97WS + 95.2 \; ; \qquad R^2 = 0.85 \qquad [9]$$

The determination coefficients were significant at the 95 % level. Similar results were reported by Montero et al (2000).

Playán et al. (2006) reported simulation results for two types of two-nozzle sprinklers operating in similar conditions as in plot M_2. The reported values of simulated CU were 92 % for WS = 2 m s^{-1} and 80 % for WS = 4 m s^{-1}. These results are 14 % and 13 % higher than the results obtained in this experiment for the same wind speeds (Eq. [9]), respectively.

WDEL analysis

The average values of WDEL were quite similar in both plots, about 24 % (Table 1). These losses are similar to those reported by Playán et al. (2005). Martinez-Cob et al., (2008) preformed a study based on lysimetric and sap flow measurements, and concluded that in their experimental conditions, 85 % of WDEL are consumptive, i.e., do not contribute to decrease crop water requirements. In the context of water scarcity characterizing Tunisia, it is difficult to accept such consumptive losses.

WDEL variability was higher in M_1 (CV of 31 %) than in M_2 (CV of 25 %). Statistical regressions were performed to model experimental WDEL as a function of environmental variables. The results of fitting a multiple linear regression model on WDEL at M_1 using WS, T and RH as independent variables indicate that WS and T were not statistically significant at the 90% confidence level. RH was the only environmental variable explaining WDEL at M_1 (Eq. [10]). The multiple linear regression model applied to WDEL at M_2, indicated that T was not statistically significant at the 90% confidence level. The model for WDEL at M_2 included WS and RH (Eq. [11]):

Plot M_1 : $WDEL = 43.82 - 0.46\,RH$; $R^2 = 0.32$ [10]

Plot M_2 : $WDEL = 24.91 + 3.70\,WS - 0.28\,RH$; $R^2 = 0.53$ [11]

Calibration and validation of the Ador-Sprinkler model

The results of the first step of the calibration process are presented in Fig. 2. In this figure, the observed radial application pattern in no-wind conditions is presented, along with the simulation results for the optimum combination of the drop diameter parameters: $D_{50} = 1.9$ mm and $n = 2.2$. The correlation coefficient between observed and simulated water application was 0.83, while the RMSE between observations and simulations was 0.79 mm h^{-1}.

The second step of the calibration process (determination of K1 and K2) was performed on irrigations 2 and 18 for M_1 and 2, 11, 14 and 18 for M_2. These six irrigation events covered the range in wind speeds and included data from both sprinkler spacings. Fig. 3 presents the resulting values of K1 and K2, which shows a clear dependence on WS. This dependence was previously reported by Dechmi et al. (2004a) and Playán et al. (2006). On the average of the six calibration cases, simulated CU was 0.86 % higher than measured CU, the correlation coefficient between observed and measured irrigation depths was 0.55, and the RMSE between observed and simulated irrigation depths amounted to 2.08 mm h^{-1}.

The Ador-sprinkler model was validated using the rest of the irrigation evaluations in which all required data was available (Table 1). The comparison between measured and simulated CU is presented in Fig. 4. Different symbols are used in the scatter plot for both sprinkler spacings (M_1 and M_2). The results of the regression analysis confirm that uniformity was adequately predicted by the model ($R^2 = 0.81$), significant at 95 % probability level. The resulting standard error was 4.5 %.

ISAREG model validation

In a first step, ISAREG model validation was performed by comparing the soil water contents observed in the field experimental plots with those simulated by the model

(Fig. 5). For both plots, each observed value of soil water represents the average of measurements performed at the sub-plots. The model appropriately described soil water content ($R^2 = 0.67$, significant at 95 % level) with a standard error of the linear regression model of 0.83 %.

Concerning tomato crop response to applied water, simulations focused on the M_1 plot since it provided larger variability of applied irrigation depths than the M_2 plot. Seasonal crop evapotranspiration for tomato was calculated by performing a water balance at the twelve sub-plots identified in M_1. The crop coefficients (K_c) and the soil water depletion fractions for no stress (p) determined with KCISA are presented in Table 2, as well as the root depth during the crop season. For each sub-plot, ISAREG was run using the corresponding soil characteristics and the measured irrigation depths. The comparison between measured and simulated values of tomato yield is presented in Fig. 6. Results confirm the predictive capability of the model in the local conditions. The resulting value of R^2 (0.81, significant at the 99% level) was higher and more significant than for soil water content.

Meteorological data analysis (day and night conditions)

The irrigation evaluations showed a relevant effect of climatic conditions on uniformity and WDEL. In order to analyse viable management options, the daily climatic data of the experimental season (2006) were analysed, concentrating on day and night values of the main meteorological variables. As in Table 1, the period from 7:00 to 19:00 h was considered as day irrigation timing, and the remaining was considered as night irrigation timing.

Table 3 presents the results of this study. Wind speed and air temperature were reduced by 52 % and 72 % during the night time, respectively. Relative humidity increased by 59 % during the night time period. The moderate values of the meteorological variables during the night time (in Tables 1 and 3) suggest that night time sprinkler irrigation can result in reduced WDEL and increased CU. This justifies the interest of analyzing the opportunity of adopting night sprinkler irrigation to improve irrigation performance and crop yield.

Ador-Sprinkler application to night conditions

The validated Ador-sprinkler model was used to simulate irrigation uniformity under night operation conditions. The data presented in Table 1 for night time meteorology were used as model input, along with the WDEL predictive Equation [3]. During the simulated irrigation season, WDEL fluctuated between 4 % and 20 % in the different irrigation events, with an average of 7 %, much lower than the seasonal average 24 % determined for day time irrigation conditions.

The experimental (day time) and simulated (night time) CU values were plotted against wind speed (Fig. 7). Results illustrate how night time conditions resulted in increased irrigation uniformity in both experimental plots. For the same experimental working pressure (300 kPa) and night wind conditions, the average simulated CU values were 64.4 % for M_1 and 80.2 % for M_2. These results are 14.9 and 9.4 % higher than the respective values for day time operation. For the M_1 plot, irrigation uniformity remains very low because of the inadequate sprinkler spacing. Similar increases in CU owing to night time irrigation operation were reported by Dechmi et al., (2004b) for the conditions of the central Ebro river basin in Spain.

ISAREG model application to day and nigh conditions

The average irrigation depths computed with the ballistic model for day time and night time irrigation operation were used in the ISAREG model to evaluate the water-yield relationship in plots M_1 and M_2. Table 4 presents the crop response to irrigation water application. For both plots, net seasonal irrigation depth for night time irrigations was larger than this for day time irrigation, due to the decrease in WDEL (74 mm in M_1 and 93 mm in M_2). This additional water contributed to reduce irrigation deficit and thus to satisfy crop irrigation requirements. Results show that night time irrigation induced a noteworthy increase in actual ET (59 mm in M_1 and 50 mm in M_2) and a decrease in relative yield loss (9.7 % in M_1 and 8.2 % in M_2). A similar response of tomato to net sprinkler irrigation was reported by Zairi et al., (2003) in similar agrometeorological conditions for Siliana (central Tunisia). These authors indicated that since most tomato ET needs to be supplied by irrigation, any reduction in the applied water will lead to ET and yield decrease. For the M_1 plot, night time irrigation still maintained yield loss at an important value of 16 %. For the M_2 plot, night time sprinkler irrigation resulted in irrelevant simulated yield losses (3 %).

In order to estimate tomato yield variability under night irrigation, the simulated irrigation depths for the M_2 plot (36 parcels of 3 x 3 m) were used in combination with the ISAREG model to estimate the spatial variability in crop yield. Table 5 presents basic statistics for seasonal applied water and simulated yield under day and night time irrigation in M_2. Regardless of day or night irrigation timing, irrigation variability was higher than yield variability. Confirming the results presented in Table 4, the adoption of night irrigation increased net seasonal irrigation depth and crop yield. At the same time, the spatial CVs in irrigation depth and crop yield were severely reduced. Night time irrigation reduced water stress in sub-irrigated areas, thus contributing to high and uniform yield. These results confirm the findings of Dechmi et al. (2004b) for corn in the conditions of Zaragoza (Spain), quantifying the effect in a different agro-ecosystem.

Conclusions

In this paper, field experiments were conducted to analyse the impact of design and operational factors on irrigation uniformity and tomato crop yield. The following conclusions can be drawn from this study:

- For the experimental conditions, irrigation performance and crop yield seem to be limited by inadequate sprinkler spacing in plot M_1 (24 x 18 m). Using a sprinkler equipped with two nozzles could have resulted in better uniformity.
- The high values of WDEL (24 %) highlight a relevant effect of climatic parameters (temperature, relative humidity and wind speed) on the applied water depths during the irrigation season. The hydrological implications of these losses in the dry conditions of Tunisia are very relevant.
- The Ador-sprinkler and ISAREG models were successfully calibrated and validated to the experimental conditions. Their predictive capacity was established trough comparisons with experimental results.
- The night irrigation scenario resulted in a relevant decrease in WDEL (down to less than 7 %) and in an increase in CU (64 and 80 % against average observed CU values of 50 and 71 % for plots M_1 and M_2, respectively).
- For both plots, tomato crop yield simulations indicated that night irrigation reduced water deficit and relative yield losses. The analysis of tomato crop yield response to applied water denoted that plot M_2 (18 x 18 m spacing) reached almost maximum yield night when the irrigation scenario was simulated. A substantial decrease was observed in spatial yield variability in this scenario.

Night sprinkler irrigation stands as an adequate technical choice and a hydrological need in the dry conditions of Tunisia. Although the environmental sustainability of this measure has been demonstrated in this paper through its effect on water conservation, the socioeconomic implications need to be assessed. Increased crop yield needs to overcome the labour or automation costs related to night irrigation operation. The intensification of night water uses will also need to fit in the water management practices of the Medjerda canal.

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Figure 7. Christiansen coefficient of uniformity (CU) vs. wind speed (WS) for the observed day time conditions (solid dots) and for the corresponding simulated night time conditions (white dots). Results are presented for plots M_1 (a) and M_2 (b).

Table 1

Irrig. #	**Date (dd/mm)**	**ID (h)**	**WS (m s^{-1})**		**WD (°)**	**T (°c)**		**RH (%)**		**CU (%)**		**WDEL (%)**	
			Day	**Night**		**Day**	**Night**	**Day**	**Night**	**M_1**	**M_2**	**M_1**	**M_2**
1	29/05	5.8	2.3	1.5	155	36	27	29	50	53	72	32	32
2	02/06	2	6.1	3.5	262	24	19	43	48	21	54	23	29
3	10/06	7	3.6	1.2	109	24	16	47	83	43	59	24	23
4	16/06	7	-		-	36	24	40	67	42	67	21	21
5	22/06	7	3.0	1.4	210	44	27	15	44	47	71	46	34
6	26/06	7	2.5	1.7	71	39	29	39	59	59	77	22	19
7	29/06	6	2.3	2.0	243	34	23	-	-	56	77	20	20
8	03/07	7	2.5	1.8	111	39	29	-	-	63	75	26	24
9	06/07	4	-	-	-	39	28	31	57	50	79	19	18
10	10/07	6	-	-	-	31	25	42	63	34	61	31	27
11	13/07	7	2.6	1.0	135	32	23	45	77	60	75	25	21
12	18/07	7	2.8	1.2	45	31	23	41	69	49	70	30	27
13	21/07	7	2.2	0.7	57	36	24	31	65	57	76	25	22
14	24/07	7	1.7	0.6	129	36	25	37	72	56	78	18	18
15	27/07	7	2.8	0.5	81	33	24	49	76	50	74	23	19
16	31/07	7	3.3	1.5	300	36	28	44	67	43	67	23	27
17	03/08	7	2.1	1.1	105	30	24	53	77	60	77	27	24
18	08/08	5	3.9	2.1	293	33	26	41	60	37	64	23	26
19	12/08	5	1.8	1.2	134	34	25	43	61	67	81	6	13
20	14/08	6	3.1	1.5	39	32	24	41	64	47	69	28	26
21	17/08	6	2.7	1.2	71	35	28	60	79	59	73	15	17
22	21/08	6	4.9	1.7	278	34	26	52	80	38	63	30	37
Average		6.2	3.0	1.4	-	34	25	41	66	49	71	24	24
Maximum		7.0	6.1	3.5	-	44	29	60	83	67	81	46	37
Minimum		2.0	1.7	0.5	-	24	16	15	44	21	54	6	13

Table 2

	Crop development stages			
	Initial	Development	Mid season	Final season
Period (dd/mm)	28/04 – 30/05	30/05 – 04/07	04/07 – 05/08	05/08 – 25/08
Period length (d)	32	35	32	20
K_c	0.83	0.83 – 1.15	1.15	1.15 – 0.68
p	0.45	0.45 – 0.31	0.31	0.45
Rooting depth (m)	0.1 – 0.53	0.53 – 1	1	1

Table 3

Month	Wind speed (m s $^{-1}$)			Air temperature (°C)			Relative humidity (%)		
	Day (m s^{-1})	Night (m s^{-1})	Night/Day (%)	Day (°C)	Night (°C)	Night/Day (%)	Day (%)	Night (%)	Night/Day (%)
May	4.53	2.49	55	25.6	16.9	66	52.4	85.2	163
June	5.22	2.87	55	28.5	19.4	68	43.7	72.3	165
July	4.62	2.02	44	31.1	23.0	74	51.3	82.7	161
August	5.72	3.06	54	29.6	23.0	78	52.8	77.0	146
Average			52			72			159

Table 4

	Net Seasonal Irrigation (mm)	Actual Crop ET (mm)	Relative ET (%)	Relative Yield Loss (%)
Plot M_1				
Day	433	482	75.4	26
Night	507	541	84.7	16
Plot M_2				
Day	549	571	89.4	11
Night	642	621	97.2	3

Table 5

	Net seasonal irrigation (mm)		Yield (t ha^{-1})	
	Day	Night	Day	Night
Average	549	642	49.0	58.6
Maximum	768	762	62.0	61.6
minimum	386	500	35.7	51.3
SD	110	79	8.2	3.2
CV (%)	20	12	17	6

Figure 1

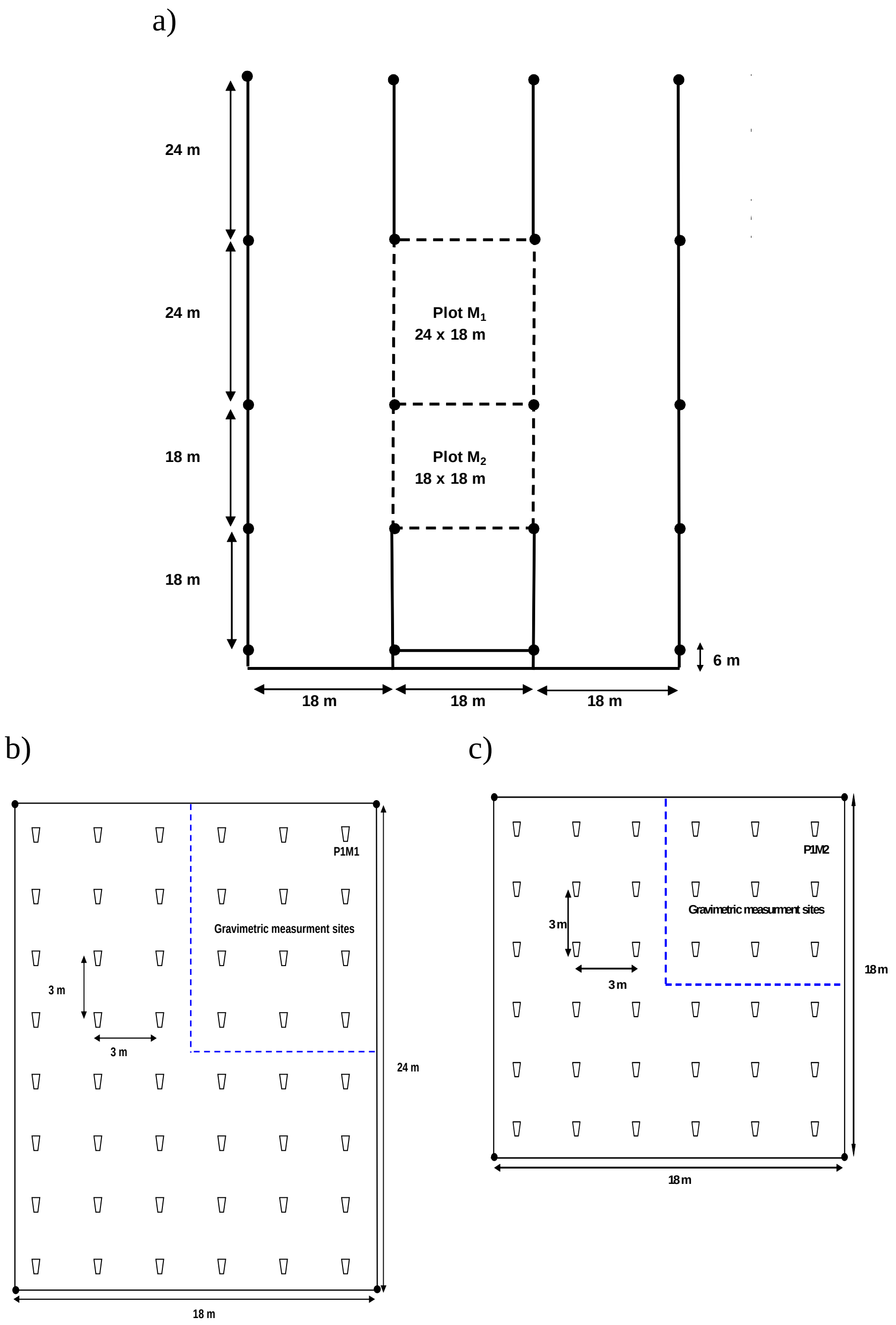

a)
24 m
24 m
18 m
18 m
Plot M_1
24 x 18 m
Plot M_2
18 x 18 m
6 m
18 m
18 m
18 m
b)
P1M1
Gravimetric measurment sites
3 m
3 m
24 m
18 m
c)
P1M2
Gravimetric measurment sites
3 m
3 m
18 m
18 m

Figure 2

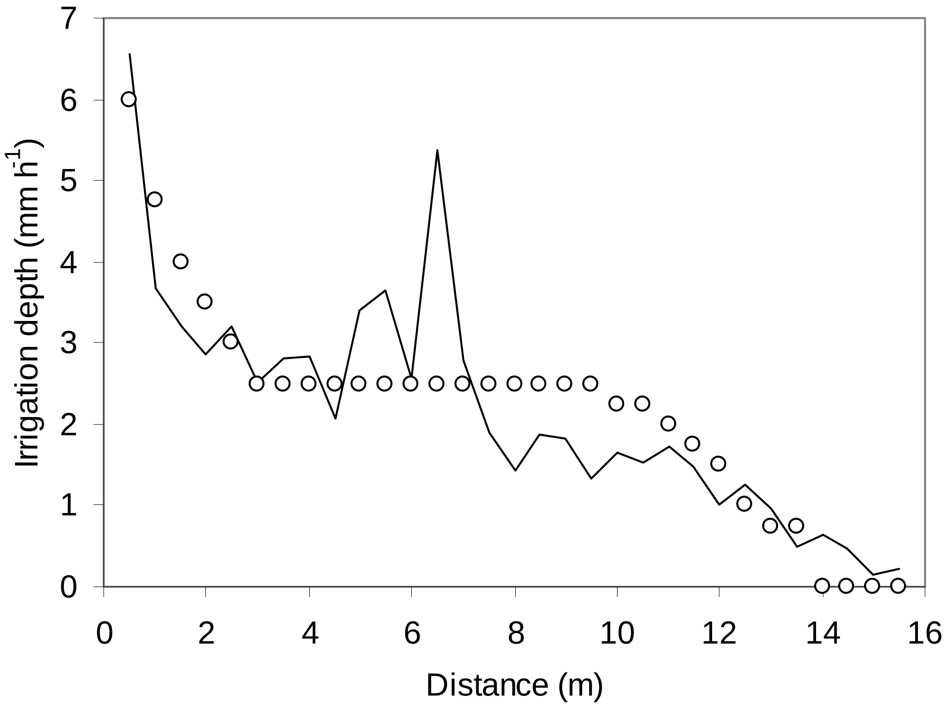


Figure 3

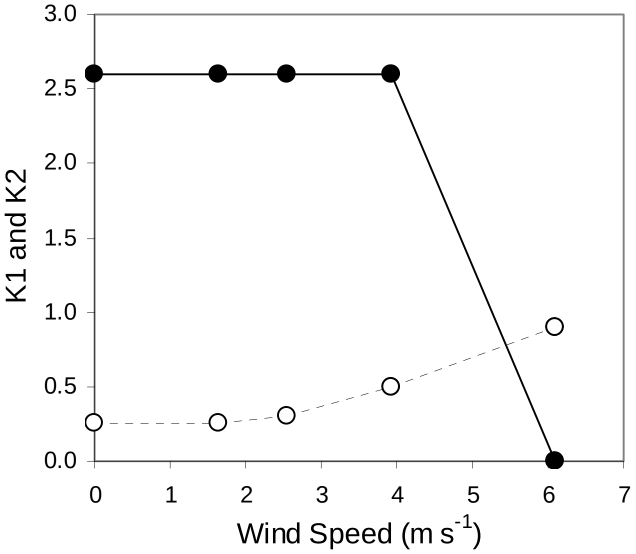


Figure 4

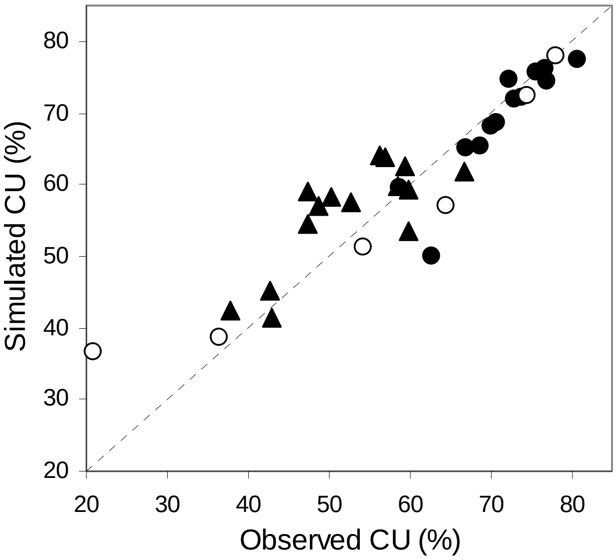


Figure 5

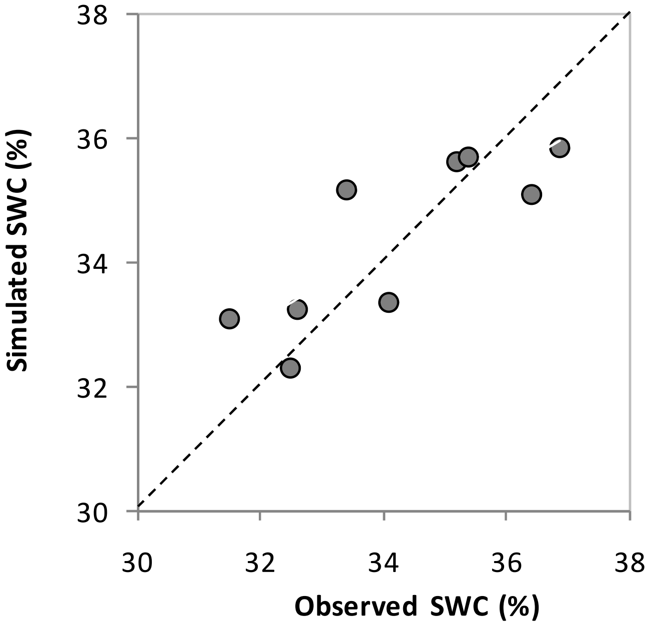


Figure 6

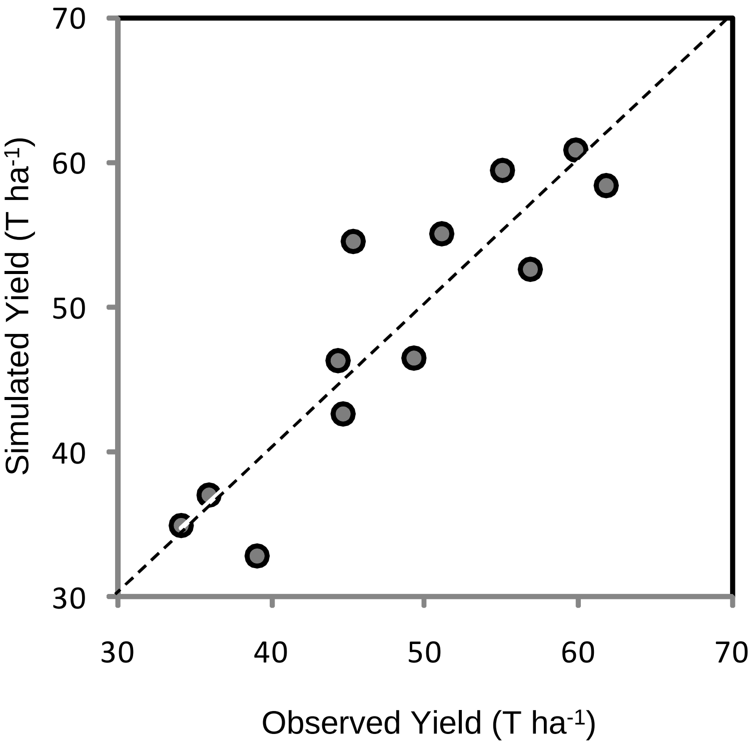
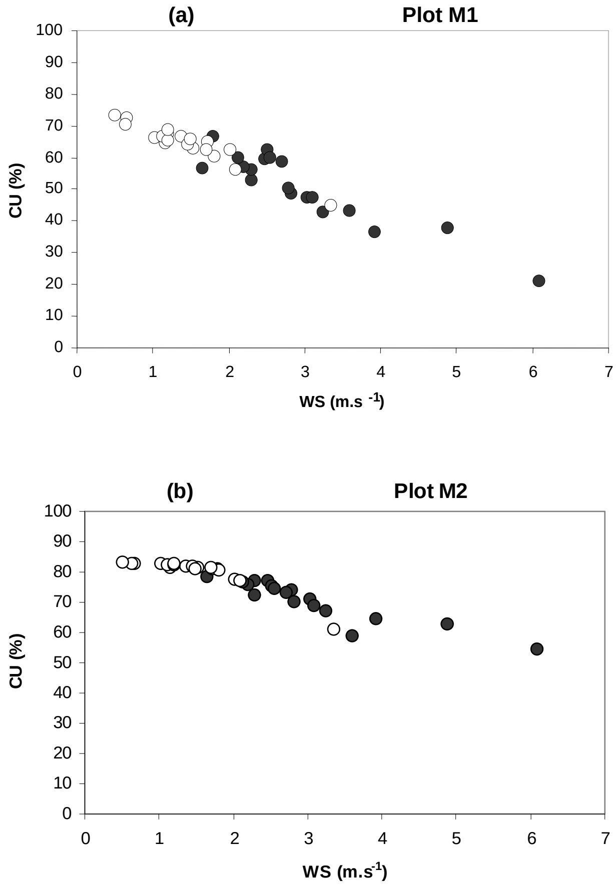

70
60
50
40
30
Simulated Yield (T ha^{-1})
30
40
50
60
70
Observed Yield (T ha^{-1})

Figure 7


(a)
Plot M1
100
90
80
70
60
50
40
30
20
10
0
CU (%)
0
1
2
3
4
5
6
7
WS (m.s -1)
(b)
Plot M2
100
90
80
70
60
50
40
30
20
10
0
CU (%)
0
1
2
3
4
5
6
7
WS (m.s-1)