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Assessment of different methods for simulating actual evapotranspiration in a semi-arid environment

Valutazione di diversi metodi per simulare l'evapotraspirazione reale in un ambiente semi arido

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Abstract. Field experiment was carried out to examine the effects of full and deficit irrigation treatments on yield and irrigation water productivity of potato crop conducted under semi-arid conditions of Tunisia. In addition, the accuracy of different models for computing daily ET_0 have been assessed against the standardized FAO 56-Penman Monteith estimations. An application of the FAO-56 dual approach to calculate actual evapotranspiration (ETa) is reported, implemented by means of the FAO-56 model. The obtained daily values of ET_0, were used as input in the FAO-56 model, in order to assess their impact on simulated actual evapotranspiration of potato crop. The obtained results indicate that potato yield decrease significantly with decreasing irrigation amount. However, no significant difference was obtained in term of WP_{irrig}. Comparison between the different ET_0 methods against the FAO-56 PM, revealed that the Makkink and Priestley-Taylor models might be considered as efficient alternatives for estimating ET_0. Furthermore, the simulated actual evapotranspiration are compared with their corresponding obtained by the water balance method. The statistical results of comparison highlighted that the best performances are accorded to the FAO-56 PM. More detailed analysis, evidenced also that the Hargreaves-Samani, Pristley-Taylor and Makkink approaches can be used as valid alternatives for estimating ETa.

Keywords. Reference evapotranspiration, FAO-56 model, deficit irrigation, irrigation water productivity, potato.

Abstract. L'esperimento è stato condotto per esaminare gli effetti sia di trattamenti di piena irrigazione che di irrigazione di soccorso sulla resa delle patate e la produttività di queste legata all'acqua di irrigazione in un ambiente semi arido in Tunisia. In aggiunta, è stata sperimentata l'accuratezza di diversi modelli per calcolare l'ET_0 giornaliera in confronto con le stime standardizzate della FAO 56-Penman Monteith. Nello studio è riportato l'uso del doppio sistema FAO 56 per calcolare l'evapotraspirazione potenziale (ETa). I dati giornalieri di ET_0 ottenuti sono stati usati come input nel modello FAO 56, per valutare la loro influenza sull'evapotraspirazione reale simulata sulle patate. I risultati ottenuti indicano che la resa delle patate diminuisce significativamente con la diminuzione dell'irrigazione. Comunque, non è stata osservata differenza significativa in termini di WP_{irrig}. Un confronto tra i diversi metodi ET_0 con il FAO 56 PM, ha rivelato che i modelli Makking e Priestley – Taylor potrebbero essere considerati delle alternative efficienti per stimare l'ET_0. Inoltre, le-evapotraspirazioni reali simulate sono state confrontate con le loro corrispondenti ottenute dal metodo del bilancio idrico. I risultati del confronto hanno evidenziato che le migliori performance si sono verificate nel metodo FAO-56 PM. Analisi aggiuntive più dettagliate, hanno anche evidenziato che gli approcci Hargreaves-Samani, Pristley-Taylor e Makkink possono essere usati come valide alternative.

Parole chiave. Evapotraspirazione di riferimento, modello FAO-56, irrigazione di soccorso, produttività legata all'acqua di irrigazione, patata.

1. INTRODUCTION

In the Mediterranean regions, characterized by arid and semi-arid climate, water availability is being severely scare (Rinaldi *et al.*, 2011; Provenzano *et al.*, 2013) as consequence of climate change (Rijsberman, 2006) and the increasing competition between municipal, industrial and environmental water users (McCann *et al.*, 2007; Yavuz *et al.*, 2015). In these regions, irrigation consumes more than 85% of the total available water (Er-Raki *et al.*, 2008). In particular, in Tunisia, irrigation water availability is characterized by frequent cutting events which results in social conflict over irrigated area. Therefore, to ensure the sustainability and integrity of the water resources, a substantial improvement in agriculture water use efficiency is required (Shahnazari *et al.*, 2007; Katerji *et al.*, 2013). In this context, irrigation scheduling techniques as full and deficit irrigation applied through regulated drip irrigation systems were widely used (Nagaz *et al.*, 2016). Moreover, Actual evapotranspiration reflects the crop water requirement as it is reflecting water losses from plant transpiration and soil evaporation (Alberto *et al.*, 2014). Thus, accurate estimation of actual evapotranspiration is a key factor for a sustainable water resource management and an effective irrigation scheduling (Rana and Katerji, 2000; Liu and Luo, 2010; Qiu *et al.*, 2015; Odi-Lara *et al.*, 2016).

A wide range of methods (direct and indirect) have been adopted to quantify actual crop evapotranspiration (Djaman *et al.*, 2016). Among the direct methods, it has been reported the weighting lysimeters (Kahyap and Panda, 2003; Xu and Chen, 2005; Liu and Luo, 2010; Schrader *et al.*, 2013) and the Eddy Covariance technique (Er-Raki *et al.*, 2008; Sun *et al.*, 2008; Alberto *et al.*, 2014; Zitouna-Chebbi *et al.*, 2018). Regarding indirect methods, different approaches were described in literature such as the Sap flow measurement method (Wilson *et al.*, 2001; Charfi Masmoudi *et al.*, 2011; Rallo *et al.*, 2014; Qiu *et al.*, 2015) and remote sensing data (Er-Raki *et al.*, 2008; Sánchez *et al.*, 2010; Maeda *et al.*, 2011). However, costs of the above mentioned methods remain quite high and demanding in terms of skilled user and the availability of the instruments are limited especially in the developing countries as Tunisia. Hence, the water balance model can be considered practical for an indirect method of actual evapotranspiration estimation (Katerji *et al.*, 2013; Qiu *et al.*, 2015; Tari, 2016; Tong *et al.*, 2016) since it doesn't require costly equipment and well trained personal.

Although the advanced techniques and methods that have been carried out for crop evapotranspiration determination, the Food and Agriculture Organization (FAO)-crop coefficient approach still to be the most common and simpler method (Allen *et al.*, 2005; Charfi Masmoudi *et al.*, 2011; Odi-Lara *et al.*, 2016; Wang *et al.*, 2018). This method consist on multiplying the reference evapotranspiration by a pre-determined crop specific coefficient (Qiu *et al.*, 2015). According to Allen *et al.* (1998), ET0 is defined as "the rate of evapotranspiration from a hypothetical reference crop, characterized by height of 0.12 m, surface resistance of 70 s m^{-1} and albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" and Kc, defined as ETc/ET0. Commonly, the FAO-56 Penman Monteith model has been adopted and recommended as a standard method to estimate ET0 (Allen *et al.*, 1998). However, this method is not always evident to apply since it requires several meteorological data such as air temperature, relative humidity, solar radiation and wind speed at 2 m height, which are often incomplete or not available in most of developing and poor countries (Sahli and Jabloun, 2008; Djaman *et al.*, 2016). Thus, several alternative estimations considering limited weather data sets have been proposed and calibrated under different climate conditions (Tabari, 2009). They can be classified into one of the following four categories (1) temperature-based (e.g., Hargreaves and Samani, 1985); (2) radiation based (e.g., Makkink, 1957); (3) mass-based (e.g., Mahring, 1970) or (4) methods combining energy and mass balance (e.g., Penman, 1948).

In addition, simulation models, after calibration and validation related to a specific context, can be a suitable tool for water management and irrigation scheduling. Rallo *et al.* (2010) considered Agro-hydrological models as one of the most efficient models for these purposes. Despite their reliability, physically based and stochastic agro-hydrological models, cannot always be applied because of the high number of input data that require (Rallo *et al.*, 2010; Rallo *et al.*, 2014). Therefore, the simplified agro-hydrological model, such FAO-56 model (Allen *et al.*, 1998), which consider a simple water bucket approach, represent a balance between robustness and simplicity to be useful for irrigation scheduling decisions for a wide range of users background and skills level (McCann *et al.*, 2007). Accurate estimation of the seasonal ET is a basic component for calculating the water use efficiency (Katerji *et al.*, 2013). Thus, if a model is conceived to be used for irrigation water scheduling, it is necessary to verify, under water stress conditions, that the daily ET is also correctly simulated by the model during the crop cycle (Stewart *et al.*, 1977).

The main objectives of this research were firstly to investigate the effect of two irrigation levels on yield and irrigation water productivity of potato crop conducted under semi-arid conditions of Tunisia. Secondly to assess, in the same climatic context, the performance of different simpler daily reference evapotranspiration methods by comparing their values against those obtained by the standardized FAO-56 Penman Monteith model using different statistical parameters. Finally, to study the impact of different ET_0 methods, forced as input in the calibrated FAO-56 model on actual evapotranspiration of potato crop conducted under full and deficit irrigation treatments.

2. MATERIAL AND METHODS

2.1 Description of the experimental site and irrigation treatments

Field experiments were conducted at the experimental field of the High Agronomic Institute of Chott Mariem, Sousse, Tunisia (Long. 10.5632° N; Lat. 35.9191° N, Altitude 19 m above sea level). As evidenced by the data registered by the Regional Research center on Horticulture and Organic Agriculture weather station from 1983 to 2014 nearby the experimental site, climate is semi-arid with mild rainy winters and dry hot summers. Minimum and maximum monthly air temperature range from 7 to 21°C and from 17 to 32°C, respectively. The average annual rainfall is about 230 mm (Ghazouani *et al.,* 2016) and is almost concentrated in autumn and winter. Annual reference evapotranspiration, estimated using FAO-56 PM method, is about 1200 mm.

The experiments took place from February 25th, 2017 to Juin 4th, 2017 on a drip irrigation system of 572 m^2 cultivated with Potato crop '*Solanum Tubersum* L.', cultivar *Spunta*. Plants were spaced 40 cm along the rows, and 80 cm between the rows. The drippers were inline type and were set 40 cm apart and had a flow rate of 4 l/h at 1.0 atm pressure.

Data related to the soil properties of the experimental site are summarized in Tab. 1. In addition, the vertical soil profile revealed the presence of calcareous layer at about 1 m deep. Daily climate variables relative to minimum and maximum temperature, relative humidity, wind speed and solar radiation in order to estimate daily reference evapotranspiration were collected from a weather station located adjacent to the High Agronomic Institute of Chott Mariem.

Deficit and full irrigation treatments replicated three times (6 sub-plots) were set according to a split plot design with a subplot size of about 63 m^2 (2.4 m×26 m). The experimental plots were irrigated on the same day. For full irrigation treatment, the irrigation amount per time was equal to the actual evapotranspiration of the previous days as estimated using the FAO crop coefficient approach. However, for deficit treatment, 50% of

Tab. 1. Physical characteristics of the experimental field soil.
Tab. 1. Caratteristiche fisiche del suolo del campo sperimentale.

Soil layer (cm)	Texture	Bulk density (g/cm^3)	Field capacity (%)	Permanent wilting point (%)	Hydraulic conductivity (cm/min)
0- 35	Sandy loam	1.56	21.85	8.13	0.256
35-55	Sandy loam	1.68	25.15	9.74	0.213
55-90	Sandy loam	1.61	21.9	10.3	0.209

full irrigation was imposed along the entire crop season. The first period of the growth cycle was characterized by relatively low atmospheric demand associated to small plants with limited roots which result in a little crop evapotranspiration. Thus, during that period, plants were irrigated once time per week, while, thereafter, irrigation frequency was running twice per week. Each plot was connected by the flowmeter to deliver the desired amount of water.

2.2 Determination of actual evapotranspiration

Actual ET was determined through two-fold approaches, involving the measured water balance model and estimated according to the FAO-56 model.

2.2.1 Soil Water balance model

Actual evapotranspiration was indirectly computed using the simplified water balance method from the change in soil water content. During the investigation period, soil water content was measured gravimetrically, at depths of 0 - 0.25 and 0.26 - 0.45 m from the soil surface. For both treatments, soil water content was recorded before plantation, at approximately every 7 days intervals, and at harvesting. Since maximum depth does not exceed 0.35 m and maximum roots density were in the first layer, the change in soil storage was calculated only for the first soil layer. In addition, runoff and capillary rise can be neglected because of the flat ground and the presence of calcareous layer at 1 m deep that prevents the water stored in the deeper soil layer from moving up to the soil surface (Katerji *et al.*, 2013). Deep percolation was assumed to be zero since irrigations were performed through drip irrigation (Tari, 2016), and that precipitation, over the growing season, was characterized by very low rainfall events with a total precipitations of 10 mm. Thus, actual evapotranspiration can be estimated, at weekly time step, with the following equation

$$ET_a = I + P - \Delta S \quad (1)$$

where ETa actual evapotranspiration (mm); I, irrigation (mm); P, precipitation (mm); ΔS, change in soil water storage (mm).

2.2.2 FAO-56 model

The FAO-56 model estimates actual evapotranspiration from the reference evapotranspiration and the basal and evaporation coefficients. For this purpose, daily ET_0 values, computed by different methods, were forced as input in the model in order to evaluate their corresponding effects on actual ET estimated for potato crop.

2.2.2.1. ET_0 models description

FAO-56 Penman Monteith model (FAO 56-PM)

The FAO 56-Penman Monteith equation for the grass reference crop described by Allen *et al.* (1998) can be estimated as:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma\left(\frac{900}{T_{avg} + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where: ET_0: Reference evapotranspiration (mm day^{-1}), R_n: net radiation at the crop surface (MJ m^{-2} day^{-1}, G: soil heat flux density (MJ m^{-2} day^{-1}), T_{avg}: mean daily air temperature at 2 m height (°C), u_2: wind speed at 2 m height (m s^{-1}), e_s: saturation vapour pressure (kPa), e_a: actual vapour pressure (kPa), e_s-e_a: the saturation vapour pressure deficit (kPa), Δ: slope of the vapour pressure curve (kPa°C^{-1}), γ: psychrometric constant (kPa°C^{-1}).

Hargreaves-Samani model (HgS)

When solar radiation, relative humidity, and wind speed variables are missing, Hargreaves and Samani (1985) proposed the following simplified ET_0 model:

$$ET_0 = 0{,}0135\frac{Ra}{\lambda}\left(T_{avg} + 17{,}8\right) K_{rs}\sqrt{\left(T_{max} - T_{min}\right)} \quad (3)$$

where Ra: the extraterrestrial radiation MJ m^{-2} day^{-1}, Tmax, Tmin: maximum and minimum daily air temperatures (°C), Tavg: mean daily air temperature (°C), K_{rs}: radiation adjustment coefficient (°C$^{-0.5}$); λ: latent heat of vaporization (MJ m^{-2} mm^{-1}).

Priestley Taylor model (PT)

Priestley and Taylor (1972) model is a shorten version of the original Penman model. It is defined as:

$$ET_0 = \alpha\frac{\Delta}{(\Delta + \gamma)}\frac{(R_n - G)}{\lambda} \quad (4)$$

α: the Priestley-Taylor parameter is equal to 1.26. However, it can vary from 1.08 to more than 1.6 (Minacapilli *et al.*, 2015).

Turc model (Turc)

Under humid conditions, Turc equation provides the most accurate estimation of ET0 when climatic data are insufficient (Trajkovic and Kolakovic, 2009)

$$ET_0 = 0.31\ C\ (Rs - 2.094)\frac{T_{avg}}{(T_{avg}+15)} \tag{5}$$

where Rs is the daily solar radiation MJ m^{-2} day^{-1}. If average relative humidity is greater than 50%, then

$$C = 1 \tag{5a}$$

If not, then it can be calculated by

$$C = 1 + \frac{50 + RHavg}{70} \tag{5b}$$

Irmak model (IK)

Irmak *et al.* (2003) developed an empirical models using a minimum number of input data. The model showed reasonable results in wet, arid, coastal, and inland sites under humid climates. According to these authors, ET0 can be estimated as:

$$ET_0 = 0.149Rs + 0.079T_{avg} - 0.611 \tag{6}$$

Makkink model (Mak)

The Mak model (Makkink, 1957), was presented in Netherlands as a modification of the Penman model as:

$$ET_0 = 0.61\frac{\Delta}{\Delta+\gamma}\frac{Rs}{\lambda} - 0.12 \tag{7}$$

Hansen model (Hsn)

The Hsn model (Hasen, 1984), was presented as a modification of the Makkink model. It is defined as:

$$ET_0 = 0.7\frac{\Delta}{\Delta+\gamma}\frac{Rs}{\lambda} \tag{8}$$

2.3 Model calibration

The FAO-56 model evaluates actual crop evapotranspiration (ETa) based on the dual crop coefficient method that separates evaporation from transpiration as:

$$ETa = E + T = \left(K_s K_{cb} + K_e\right)ET_0 \tag{9}$$

where ET_0 is the reference evapotranspiration (mm d^{-1}), Kcb is the basal crop coefficient; Ke is the soil evaporation coefficient. Ke is a function of the evaporation reduction coefficient (Kr), the maximum and basal crop coefficient, and the exposed and wetted soil fraction; Ks is dimensionless water stress coefficient, variable between 0 and 1 (Allen *et al.*, 1998).

Firstly, measured data collected during the experiment, related to plant (root depth, plant height), soil (soil fraction cover, initial depletion, available water) and weather data (Midseason average wind speed, Midseason relative humidity) were used as input in the model. The average values of basal crop coefficient were considered as the same values proposed by Allen *et al.* (1998). The readily evaporable water (REW) was considered as the same value referred by Qui *et al.,* (2015). The used value of REW is also inside the range of variability, for Sandy-loam soil, proposed by Allen *et al.* (1998). Thereafter, the FAO-56 model calibration procedure consisted of adjusting two parameters related to soil (depletion coefficient, p; and Effective depth of evaporable layer, Ze). Thus, estimation of the two considered parameters through iterative approximations was carried out and ceased only when the simulated values of potato actual evapotranspiration become similar to measured values. The daily values of ET0 used for the calibration procedure were estimated according the FAO-56 Penman Monteith method. Based on soil water content observations, the initial depletion for root zone was 20% of TAW (Tab. 2).

2.4 Plant measurements

Field observations included root depth, plant height, fraction of soil covered by crop canopy (fc), and leaf area were measured on different plants collected at different crop stages, from randomly chosen locations of each subplot. Every two weeks, after removing the plants from the soil and washing the roots carefully, the root depths were measured directly using a graduated ruler. Measurements of fc were performed every week. The fraction of the ground covered with the leaves was estimated using a 120 cm*80 cm area divided into 96 squares with equal dimensions, held over the central row. The covered fraction, which ranged from 0,01 to 1 (Allen *et al.*, 1998), was calculated as the number of cells at least half-filled of green leaf divided by the total number of cells (96) (Boyed *et al.*, 2002). However, measurement of leaves area was performed every two weeks with help of planimetric instrument. At harvesting, the crop yield was determined by weighting, per treatment and replicate, the total production obtained in 10 plants.

Tab. 2. Values of input variables used for simulations in the FAO-56 model.
Tab. 2. Valori delle variabili di input usate per le simulazioni nel modello FAO – 56.

Parameter	Value	Source
Soil water content at field capacity (m^3m^{-3})	0.22	m
Soil water content at wilting point (m^3m^{-3})	0.08	m
Available water (mm/m)	140	m
Depletion coefficient during initial stage (%)	20	e
Depletion coefficient after initial stage (%)	10	e
Total evaporable water, TEW (mm)	22	e
Readily evaporable water, REW (mm)	8	b[1],b[2]
Effective depth of evaporable layer, Ze (m)	0.12	e,b[1]
Lengh of initial stage (day)	20	e,b[1]
Lengh of development stage (day)	30	e,b[1]
Lengh of midseason stage (day)	35	e,b[1]
Lengh of late stage (day)	30	e,b[1]
Basal crop coefficient at initial season, $K_{cb\ ini}$	0.15	b[1]
Basal crop coefficient at mid-season, $K_{cb\ mid}$	1.10	b[1]
Basal crop coefficient at late season, $K_{cb\ end}$	0.65	b[1]
Maximuim crop height (m)	0.6	m
Minimuim rooting depth (m)	0.07	m
Maximuim rooting depth (m)	0.35	m
Midseason average wind speed (m s^{-1})	1.3	m
Midseason relative humidity (%)	60	m

m: measured data; e: estimated from field data; b; obtained from bibliography; 1: Allen *et al.* (1998), 2: Qui *et al.*, (2015).

2.5 Irrigation Water productivity (WP_{irrig})

The WP_{irrig} is expressed as the ratio of actual harvestable yield (Ya) and irrigation water (I) received from planting to harvest (Leogrande *et al.,* 2016; Nagaz *et al.,* 2016).

$$WP_{irrig}\left(\mathrm{kg\ m^{-3}}\right) = \frac{Y_a}{I} \tag{10}$$

where: Ya actual harvestable yield (Kg ha^{-1}) and I is the irrigation water (m^3 ha^{-1}).

2.6 Statistical analysis

The normality of data (yield, irrigation water productivity) was tested by Shapiro-Wilk test, following which the data was subjected to one-way ANOVA (irrigation level) conducted by MINITAB.14 software. Tukey's test was used for comparing means estimated at $p<0.05$ probability level.

Evaluation of the accuracy and goodness of fit of model predictions were carried out by simple linear regression forced through the origin. Then, the performance of the models was evaluated using different statistical indices: coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Absolut Error (MAE) and Efficiency coefficient (E).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(ET_{ref} - ET_{est}\right)^2}{N}} \tag{11}$$

$$MBE = \frac{\sum_{i=1}^{N}(ET_{ref} - ET_{est})}{N} \tag{12}$$

$$MAE = \frac{\sum_{i=1}^{N}\left|ET_{ref} - ETa_{est}\right|}{N} \tag{13}$$

$$E = 1 - \frac{\sum_{i=1}^{N}\left(ET_{est} - ET_{ref}\right)^2}{\sum_{i=1}^{N}\left(ET_{ref} - \overline{ET_{ref}}\right)^2} \tag{14}$$

RMSE allow to determine the error with the same units of the original variable (Sabziparvar *et al.,* 2016). MAE quantify the average absolute errors between reference and simulated data, whereas, MBE measure the average tendency of over or underestimation. Finally, E, is used to evaluate the predictive power of the model (Autovino *et al.,* 2016).

Values of RMSE and MAE can range from 0 to infinity (Alexandaris *et al.,* 2008). However, the lower the values of RMSE and MAE, the better the agreement.

There is no higher or lower bound of MBE. Values equal to 0 indicate that the model does not deviate from reference data, considered as true values. Positive MBE value indicates a certain underestimation of the considered variables and negative value corresponds to an overestimation (Negm *et al.,* 2017).

E can vary between -∞ and 1. E=1 correspond to perfect fit between model and reference data (Rinaldi *et al.,* 2011). Values between 0 and 1 are generally considered as an acceptable level of performance, and values lower than 0 indicate that the mean reference value predicts better than the model, indicating its unacceptable performance (Maulé *et al.,* 2006; Marti *et al.,* 2015; Autovino *et al.,* 2016).

3. RESULTS

Fig. 1 shows the temporal dynamics of daily average air Temperature, Tavg, vapor pressure deficit, VPD, short radiation, Rs, and precipitation height. Initial analysis of the climatic variables showed that Tavg and VPD follow the same trend over time. During the experimental period, the Rs values increase progressively from 35 to 47 MJ m^{-2} d^{-1}. However, reductions in Rs values were occurred during rainy events and cloudy days.

The total irrigation volumes applied during the potato cropping cycle, final yield and the Irrigation water productivity for both treatments are reported in Tab. 3. Potato yield varied widely with irrigation amount. In fact, higher yield (28.94 t/ha) was observed under full irrigation treatment, while, reducing irrigation volume by around 50%, resulted in a significant yield decrease of about 36%. Regarding irrigation water productivity, no significant difference was observed between both treatments.

Dynamic of daily reference evapotranspiration estimated by different models are depicted in Fig. 2. At the begin of the experiment (begin of Mars), the values of ET_0 were not very high, varying from 2.5 to 5.5 mm d^{-1} respectively for Hargreaves-Samani and Hansen methods. From the second decade of April, an important increase in term of ET_0 were registered with all considered methods. The highest values were attributed to Hansen and Turc approaches. Excluding Hargreaves Samani model, the increase of ET_0 can be explained by

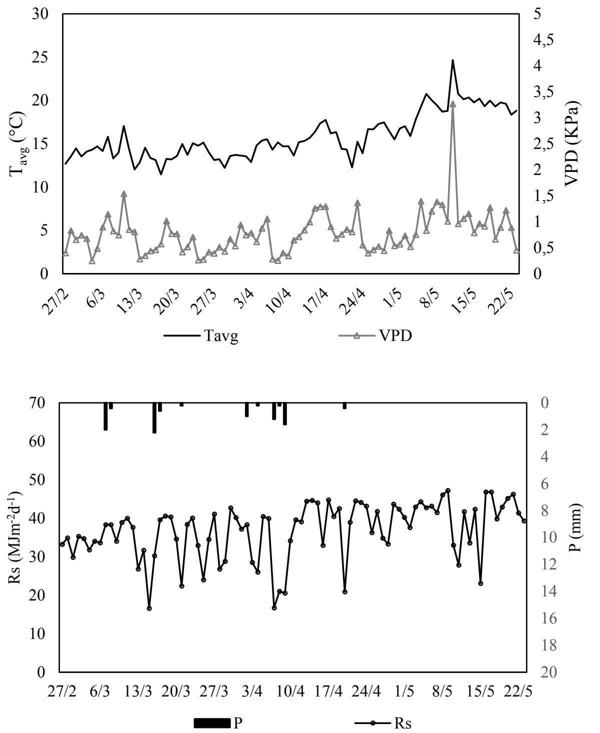

Fig. 1. a) average air Temperature, Tavg (left y-axis), and vapor pressure deficit, VPD (right y-axis); **b**) short radiation, Rs (left y-axis), Precipitation, P (right y-axis).

Fig. 1. a) Temperatura media dell'aria, Tavg (sinistra - asse y), deficit di pressione di vapore, VPD (destra – asse y); b) radiazione a onde corte, Rs (sinistra - asse y), Precipitazioni, P (destra - asse y).

Tab. 3. Potato total irrigations amount, yield and WP_{irrig}.

Tab. 3. Quantità totale di irrigazione, resa e WP_{irrig} nelle patate.

Treatment	Water supply (mm)	Yield (t/ha)	WP_{irrig} (kg/m^3)
Full irrigation	258.9 ± 8.8	28.94 ± 1.78	11.20 ± 1.03
Deficit irrigation	133.15 ± 5.6	18.44 ± 1.83	13.96 ± 1.92
Significance level		**	n.s

**= significant at the p≤ 0.01; n.s.= not significant.

the combining effect of hot temperature and solar radiation during all the investigation period.

Regarding its reliable estimations, the FAO-56 PM results were considered as the benchmark for comparison with the investigated daily ET_0 methods. The statistical results, based on the slope of the regression line, R^2, RMSE and MBE, are summarized in Tab. 4. With reference to the regression equations, the Makkink and Priestly-Taylor methods resulted in a slope values close to the unity (1.14 and 1.18 respectively) showing the best predicted values. Except for Hargreaves-Samani

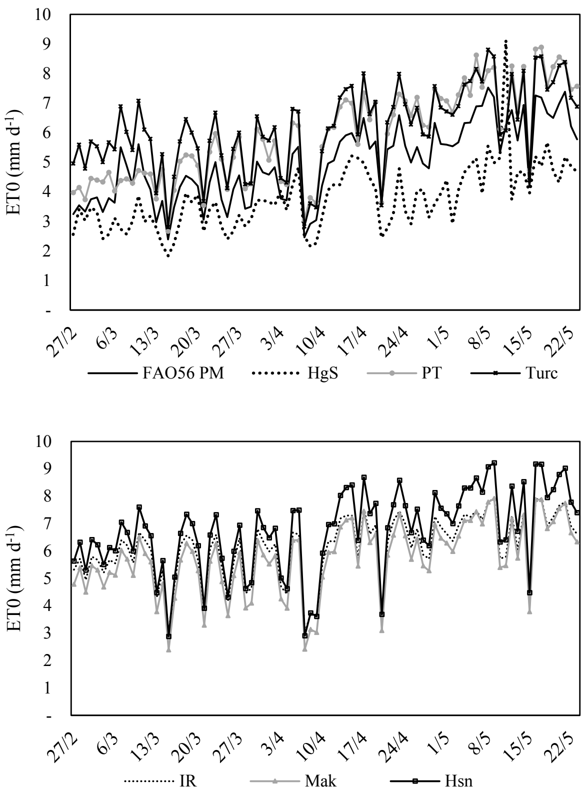

Fig. 2. Temporal patterns of daily reference evapotranspiration estimated by different models.

Fig. 2. Andamenti giornalieri della evapotraspirazione di riferimento stimata da diversi modelli.

Tab. 4. Statistical indicators computed by comparing daily reference evapotranspiration values estimated with the different methods against their corresponding standardized FAO-56 PM values**.**

Tab. 4. Indicatori statistici calcolati confrontando i valori di evapotraspirazione di riferimento giornalieri stimati con i diversi metodi con i corrispondenti valori standardizzati di FAO-56 PM.

Methods	HgS	PT	Turc	IK	Mak	Hsn
Slope (-)	0.75	1.18	1.23	1.20	1.14	1.33
R^2 (-)	0.54	0.89	0.87	0.60	0.80	0.79
RMSE (mm d^{-1})	1.49	1.04	1.27	1.26	0.93	1.86
MBE (mm d^{-1})	1.21	-0.89	-1.19	-1.13	-0.77	-1.76

and Irmak models, the used alternatives are strongly correlated with the FAO-56 PM method with R^2 values higher than 0.79. The RMSE values ranged between 0.93 and 1.86 mm d^{-1} respectively for Makkink and Hansen methods. Statistically, the RMSE associated to Makkink and Priestly-Taylor models were the most satisfactory and equal to 0.93 and 1.04 mm d^{-1}, indicating that these models yielded the lowest mean deviation from ET0 values computed with FAO-56 PM method. On average, all ET_0 methods show negative MBE indicating an overestimation of ET0 values during the springer season. The greatest overestimation (MBE= -1.76 mm d^{-1}) was obtained with Hansen method, giving the worst estimates among all the considered methods. Makkink and Pristley-Taylor models produced the lowest overestimations (MBE= -0.77 and -0.89 mm d^{-1} respectively) showing the best estimates among all the considered methods. However, an unsatisfactory underestimation was obtained for daily ET_0 computed by HgS method with an MBE value equal to 1.21 mm d^{-1}. Considering the statistical results and the linear regressions achieved in this study, it is concluded, in decreasing order, that Makkink, Pristley Taylor, and Turc alternatives are the most promising equations that could be used to estimate ET_0 when climatic data are limited.

The used and calibrated parameters of the FAO-56 model are given in Tab. 2.

The daily values of ET_0 computed by different methods were finally used as input in the calibrated FAO-56 model in order to assess their impact on actual evapotranspiration for a potato crop. The comparisons among actual evapotranspiration values simulated by the FAO-56 model by considering separately each investigated ET_0 method against their corresponding obtained by the simplified water balance model are shown in Fig. 3. As can be noticed from the graphs, the estimated values were in line with the corresponding measurements, with the slope of the regression line forced through the origin varying from 1 to 1.06 respectively for Hansen and Hargreaves-Samani model.

Despite a certain difference between measured and estimated ETa values, the performance of the considered ET_0 methods to estimate actual evapotranspiration were assessed through statistical descriptors (Tab. 5). In fact, all investigated methods are fairly well correlated with the simplified water balance model measurements with an R^2 values greater than 0.7. Except for Hansen model, all methods have a negative mean bias errors indicating that the FAO-56 model tend to overestimate ETa. As can be noticed from Tab. 5, the FAO-56 PM approach shows the best performance with an R^2 and efficiency coefficient (E) values of 0.82 and 0.79 and an RMSE and MAE values of 0.49 and 0.36 mm d^{-1} respectively. However, a further and more detailed analysis evidenced that, Hargreaves-Samani, Priestly-Taylor and Makkink approaches can be used, in such conditions and studies, when climatic data are missing. These methods provide also satisfactory results with an RMSE values varying from 0.55 to 0.61 and MBE values ranging between 0.40 and 0.44 mm d^{-1}.

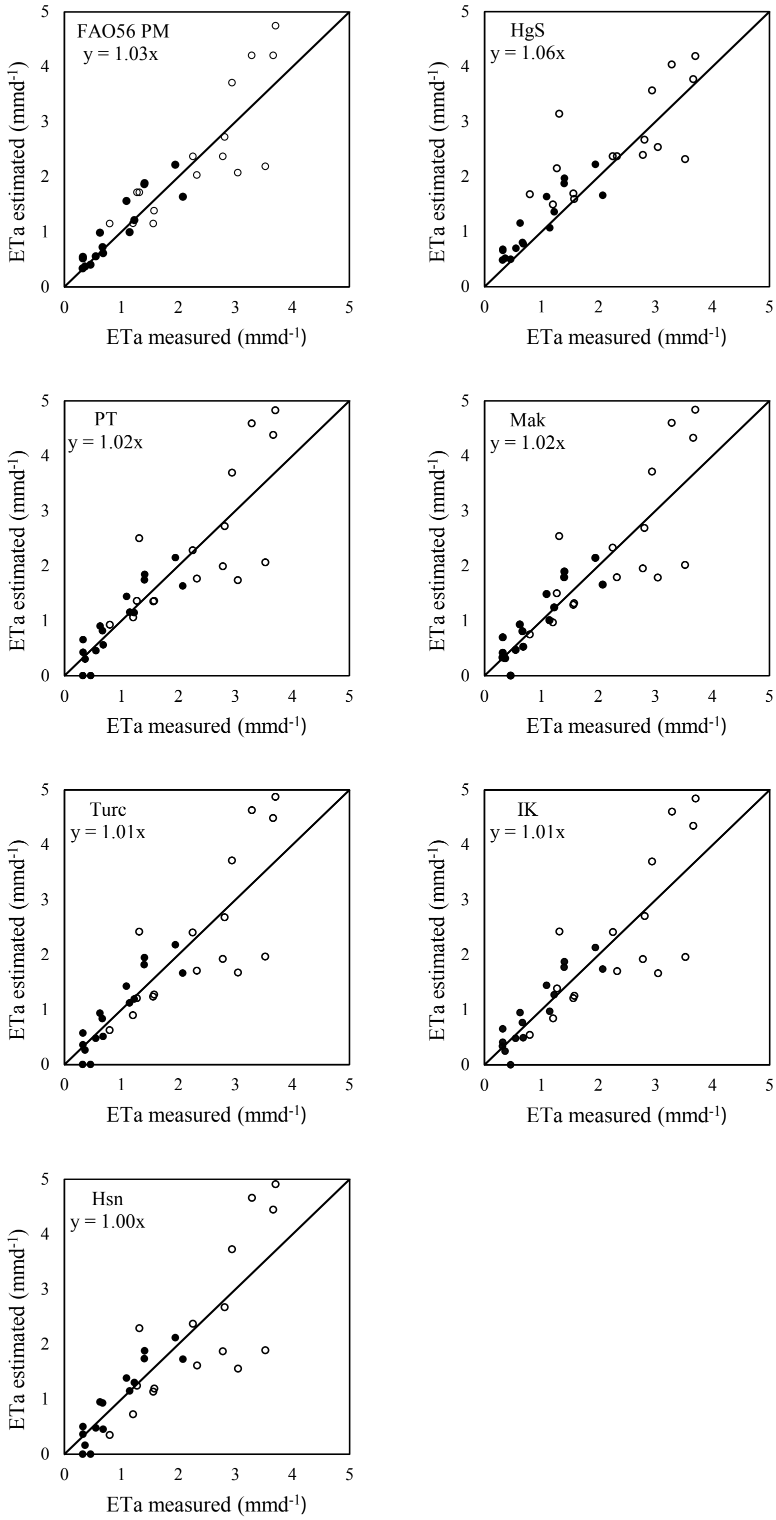

Fig. 3. Scatterplots of comparison between measured and estimated daily actual evapotranspiration under full (open circle) and deficit (filled circle) irrigation treatments.

Fig. 3. Confronto tra l'evapotraspirazione reale giornaliera misurata e quella stimata nei trattamenti di piena irrigazione (tondo aperto) e irrigazione di soccorso (tondo chiuso).

Tab. 5. Statistical indicators computed by comparing daily measured and estimated actual evapotranspiration.
Tab. 5. Indicatori statistici calcolati confrontando l'evapotraspirazione effettiva misurata quotidianamente e stimata.

Method	R^2 (-)	MBE (mm d^{-1})	RMSE (mm d^{-1})	MAE (mm d^{-1})	E (-)
FAO56 PM	0.82	-0.08	0.49	0.36	0.79
HgS	0.73	-0.23	0.55	0.40	0.73
PT	0.76	-0.04	0.60	0.43	0.68
Turc	0.75	-0.01	0.63	0.47	0.65
Ik	0.75	-0.01	0.62	0.46	0.66
Mak	0.75	-0.04	0.61	0.44	0.67
Hsn	0.74	0.03	0.66	0.49	0.62

4. DISCUSSION

A yield reduction of 36%, under deficit irrigation, suggests that potato crop is moderately tolerant to the considered water stress level. As it is known, yield decrease depends on degree, duration and timing of the imposed water stress (Tari, 2016). Therefore, deficit irrigation may be adopted, especially under circumstances of restricted water resources. However, reduction in yield can be avoided by regulating the applied water amount during the most sensitive stage of crop growth to water deficiencies.

Under full irrigation treatment, the obtained water productivity value (11.2 kg/m^3) falls within the range of variability of irrigation water productivity, for potato crop, proposed by Steduto *et al.* (2012). In our case, even it is not statistically different, the higher WP_{irrig} value is associated with the lower yield (18.44 t/ha). Meanwhile, the high WP_{irrig} are of little interest if they are not associated with high or acceptable yield (Ali *et al.*, 2007).

In fact, the FAO-56 PM ET_0 method has been proven to accurately estimate reference evapotranspiration under different climatic conditions (Allen *et al.*, 1998; Er-Raki *et al.*, 2010; Minacapilli *et al.*, 2015). As described by Fisher *et al.*, (2005), the accuracy of FAO-56 PM to estimate ET_0 is related to the fact that this method simulate well the aerodynamic component, while it is not the case for the other models. All the investigated ET_0 alternatives resulted in relatively similar simulations due to the common theoretical basis of their equations. Except for Hargreaves Samani model, all the considered methods required solar radiation data as input to accurately estimate ET0. Thus, they are classified as radiation based methods. Considering the results achieved in this study, it is concluded that, Makkink, Pristley Taylor, and Turc approaches can be used as efficient alternatives to estimate ET_0 while Hargreaves Samani model is not well appropriate in such conditions. The accuracy of both Makkink and Priestley-Taylor methods may be related to the fact that these two methods are established based on a modification of the original Penman equation. These results are consistent with those previously published by Minacapilli *et al.* (2015) who, evaluated in Southern Italy, the performance of seven ET_0 methods against ET_0 measurements acquired with a laser scintillometer. The authors found relatively the same rank of models suitability when the FAO-56 formulations are excluded. In the same context, results obtained by Er-Raki *et al.* (2010), for assessment of ET_0 estimation methods using climatic data generated from ALADIN model, showed that the reliability of Priestley-Taylor and Makkink models is much higher under humid conditions. Therefore, the accuracy of these approaches, in our conditions, may accorded to the closest position of the study area to the sea where relative humidity are relatively high.

The mentioned suggestion is confirmed by the accuracy estimations accorded to Turc approach and the lowest performance achieved by HgS model. In fact, Tabari (2009); Trajkovic and Kolakovic, (2009), found that Turc model is suitable to provide satisfactory estimates of ET_0 in humid conditions. Our findings are in good agreement with those obtained by Kashypa and Panda, (2001), who revealed that Hargreaves model is not to be recommended under sub-humid climatic regions. Moreover, the performances of HgS model achieved in our study, are considered below level when compared with results previously published, in semi-arid conditions, by Jabloun and Sahli, (2008) and Gavilàn *et al.* (2006). The authors found high correlation in the comparison between HgS and FAO-56 PM methods applied in different regions in Tunisia and Southern Spain respectively. It is worth mentioning that their results were also achieved using on ground climatic data. Hence, as recommended by Raziei *et al.* (2013), a local calibration of Hargreaves coefficient (K_{rs}) is required to improve its accuracy. Nevertheless, the suitability of Hargreaves-Samani approach may vary according to the season.

In the previous sections, the suitability of the FAO-56 model to predict actual evapotranspiration was verified according to water balance measurements during the investigation period. However, a little overestimation of ET by about 3.5% was shown with the model results. This mismatch may be the result of measurement errors of rooting depth, Zr, generated by the used method that doesn't reflect the architectural distribution of roots in soil profile. Meanwhile, the bucket models are very sensitive to this parameter (Er-Raki *et al.*, 2008). In fact, higher Zr values causes an increase of TAW within the root zone and consequentially an increments of Ks values (Rallo *et al.*, 2014). Additionally, Er-Raki *et al.* (2008), showed that not only the rooting depth can affect the outputs of FAO-56 model, but also inappropriate depletion factor leads to an overestimation of Ks values.

The results of simulations revealed that the FAO-56 PM method provides the best performance, compared to measured actual evapotranspiration values, followed by Hargreaves-Samani, Priestley Taylor, Makkink and Turc results. These results are relatively consistent with those recently published by Minacapilli *et al.* (2015), who assessed the performance of different ET_0 methods forced as input in the FAO-56 model, on estimating actual evapotranspiration for an olive grove in Southern Italy. They showed that, the considered methodologies provide satisfactory estimated values when compared to FAO56-PM results with according the best performance to Priestly Taylor method so far as daily ET_0 estimation is concerned. Er-Raki *et al.* (2011), evaluated the suitability of four different reference evapotranspiration model to estimate actual evapotranspiration of winter wheat crop, conducted in semi-arid region in Morocco, using the simple Kc approach. The authors found that the Hargreaves-Samani method is the most appropriate model to estimate actual evapotranspiration when compared to results obtained by either FAO-Penman Monteith method or Eddy Covariance measurements. Moreover, the suitability of Priestly-Taylor and Makkink model were proven under different climatic conditions and time scales. In this way, Xu and Chen (2005) assessed the performance of different evapotranspiration models in water balance studies against lysimeter measurement in Germany. They inferred that, for the calculation of actual evapotranspiration at monthly and seasonal scale, the Makkink model perform better than the other methods. However, at yearly scale, the Priestly Taylor can be also used as an efficient alternative with a mean annual error less than 5%. They reported that performances of the investigated methods can be improved by a local calibration of the parameter values used for each model.

Despite its limited accuracy to estimate ET_0, the HgS method provides reliable estimations of actual evapotranspiration when it is used as input in the FAO-56 model. In fact, the obtained results could be due to the over-predictions generated by the FAO-56 model associated to the decrease of the soil water content through the investigated season. Thus a more precise parameterization of the FAO 56 dual approach model in order to improve both the estimation of the evaporation and transpiration rates is recommended.

5. CONCLUSION

Results of this study suggest that deficit irrigation, allows about 50% of water saving, can be considered an appropriate strategy under limited water circumstances. In addition, several reference evapotranspiration models were assessed through comparison with the FAO-56 PM results. This kind of studies is interesting, when climatic data required for computing PM ET0 are lacking. Thus, evaluating the suitability of different simplified methods characterized by limited input data is required. Based on RMSE, MAE, and linear regression analysis, the Makkink, Priestly-Taylor and Turc methods showed the best performances, for this particular study area, so far as daily ET0 estimation is concerned. However, the performances of these methods can be improved by a local coefficients calibration. Furthermore, the FAO-56 model was calibrated and used to simulate actual evapotranspiration of potato crop. The model simulations agreed well with their corresponding measurements based on water balance method.

This paper also evaluates the performance of the different alternatives of estimating ET0, forced as input in the calibrated FAO-56 model, on predicting actual evapotranspiration of potato crop under full and limited water conditions. Exploring the results of the model and the water balance measurements, it can be concluded that the FAO-56 model slightly over-predict actual evapotranspiration. Despite its over-predictions, the highest accuracy of the model is achieved when ET0 values computed by the FAO-56 PM method are forced as input in the model. Although the lowest accuracy of HgS model to estimate ET0, this model provides satisfactory results in term of actual evapotranspiration. Additionally, the performances of Priestly Taylor, Makkink and Turc approaches to estimate reference and actual evapotranspiration have been emphasized. Therefore, it is feasible to affirm that these methods are considered most appropriate for applying in such study area conditions. Nevertheless, in order to obtain more suitable results, an improvement of the FAO-56 model functions is recommended.

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