COMPARING PENMAN-MONTEITH AND PRIESTLEY-TAYLOR APPROACHES AS REFERENCE-EVAPOTRANSPIRATION INPUTS FOR MODELLING MAIZE WATER-USE UNDER MEDITERRANEAN CONDITIONS

Angel Utset[1,2], Imma Farré[3], Antonio Martínez-Cob[4,5], José Cavero[4]

[1] Invited Researcher

Dpto. Genética y Producción Vegetal (EEAD), Lab. Asociado Agronomía y Medio Ambiente (DGA-CSIC), Apdo. 202, 50080 Zaragoza, Spain.

[2] Present position: Agrarian Technological Institute of Castilla y León (ITA), Apdo. 172, 47080 Valladolid, Spain.

[3] Researcher

CSIRO Plant Industry, Private Bag 5, Wembley WA 6913, Australia.

[4] Tenured Scientist

Dpto. Genética y Producción Vegetal (EEAD), Lab. Asociado Agronomía y Medio Ambiente (DGA-CSIC), Apdo. 202, 50080 Zaragoza, Spain.

[5] Corresponding author

E-mail: macoan@eead.csic.es

ABSTRACT

A comparison between experimental and simulated data, considering the Priestley and Taylor (PT) and Penman-Monteith (PM) Reference-Evapotranspiration (ET_0) approaches was carried out. Experimental data, obtained from an irrigation assessment, conducted during the 1995 and 1996 maize growth-seasons at Zaragoza, Spain, was compared to the mechanistic-model SWAP simulation-results, considering each of the ET_0 calculation approaches in the model input. Soil hydraulic properties, meteorological data, seeding and harvest dates, crop water management and other experimental data were used as SWAP input. As corresponding to the windy and dry conditions found in many Mediterranean landplanes, PT ET_0 values were significantly lower than PM ET_0 calculations. Furthermore, simulated actual evapotranspirations considering the PT approach (PT-ET_c) were lower than those found in the simulations that consider the PM approach (PM-ET_c). Correspondingly, simulated drainage flux and soil water contents were higher when the PT ET_0 approach was used. The correlation coefficients between simulated and measured actual maize evapotranspirations and soil water contents were statistically significant, but the same for both ET_0 calculation approaches. Mean and median differences between actual and simulated maize water-use were not statistically different from zero for both considered ET_0 calculation approaches. Experimental data variability was significantly higher than simulated variability. The comparisons among the evaluated irrigation options, made with the experimental water-use data, lead almost to the same conclusions than those achieved from the simulated maize water-use. Considering PM-ET_c rather than PT-ET_c yields no statistical difference in the modeling-based conclusions. According to the obtained results, the PT approach could be used under Mediterranean conditions for comparative assessments aimed to support irrigation decision-making.

Keywords: crop water-use modeling, reference evapotranspiration calculation, Mediterranean conditions, maize irrigation.

INTRODUCTION

Maize is one of the most important crops in the Mediterranean landplanes of Europe. Very cost-effective yields are frequently obtained, due to high radiation rates in the summer, combined with modern management techniques. Since the Mediterranean climate is very dry in the summer, irrigation is an absolute need for obtaining reliable yields. Water availability is a serious limitation for maize production in these zones and hence the focus has been set in optimizing the yield-water relationships, usually through the experimental evaluations of several irrigation options. However, the results of these experiments are constrained to the particular climate conditions and to the zone where the experiments were carried out.

Crop modelling has successfully been used since the last decade as a powerful tool for irrigation and agricultural decision-making (Hoogenboom, 2000). In general, models estimate a daily soil water-balance in order to evaluate the possible crop-growth reduction from its optimal value, due to plant-water deficits (Leenhardt et al., 1995; Ritchie, 1998). The optimum daily growth is generally settled by the evaporation demand of the atmosphere, under the assumption that water and nutrients are adequately provided. Therefore, the reference evapotranspiration (ET_0) is normally needed as model input.

Many approaches have been developed for ET_0 estimations. Among all of them, the physically based Penman-Monteith (PM) approach is presently considered as the state-of-the art in such calculations (Allen et al., 1998; Smith, 2000). According to Allen et al. (1998), the Penman-Monteith reference evapotranspiration can be calculated from:

$$\lambda ET = \frac{\Delta(Rn-G)}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)} + \frac{\rho_a c_p \frac{(e_s-e_a)}{r_a}}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)} \qquad [1.]$$

where λ is the latent heat of vaporization of water, R_n is the net radiation, G is the soil heat flux, (e_s - e_a) is the vapour saturation deficit, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances, respectively.

The practical derivation of equation [1] for a hypothetical grass reference crop requires the values of the following meteorological variables: wind speed at 2 m, maximum and minimum air temperatures, net solar radiation and the actual vapour pressure (Allen et al., 1998). These two last meteorological variables can be estimated from actual duration of bright sunshine and relative humidity, respectively (Allen et al., 1998). The first term in equation [1] has been called the “radiation” term, whereas the second term, called “aerodynamic”, depends directly on vapour deficit (Allen et al., 1998; Mc Aneney and Itier, 1996; Van Dam et al., 1997).

Despite the sounder theoretical background of the combined PM approach, many crop models use empirical approaches to calculate the reference evapotranspiration, due to the frequent unavailability of the meteorological variables needed for PM calculations. Priestley and Taylor, (1972) proposed an empirical equation for calculating the reference evapotranspiration, which can be written as:

$$\lambda ET = \alpha \left[\frac{\Delta (Rn - G)}{\Delta + \gamma} \right] \qquad [2.]$$

where α is an empirical constant with an average value of 1.26 (Priestley and Taylor, 1972; Mc Aneney and Itier, 1996). As can be seen from equation [2], the Priestley and Taylor (PT) approach neglects the influence of vapour deficit on the reference evapotranspiration, relying on the assumption that ET_0 depends only on solar radiation and temperature. The PT data requirement does not include some hardly available meteorological variables as wind speed or relative humidity. Hence this reference evapotranspiration can be computed in places where PM calculations can not be performed due to data lacking.

Since wind speed and actual water vapour pressure are connected to the air temperature also, PT results, although empirically, could be statistically equivalent to PM values by considering a proportionality between evapotranspiration and the available energy. The ET_0 values calculated from the PT approach have been found to be highly correlated to PM calculations (Jamieson, 1982; Pereira and Nova, 1992).

However, despite the success of the PT method, this approach could fail in mimicking PM values under dry conditions or in zones where wind speed is relatively high (Shouse et al., 1980; Jensen et al., 1990; McAneney and Itier, 1996). The Mediterranean landplane is one of these places where PT could underestimate the evapotranspiration rates, compared to PM approach, due to the dryer and windy conditions usually found there. This has been already shown by Martínez-Cob (2002) in a study conducted for Ebro Valley, northern Spain. Martínez-Cob (2002) compared several methods against FAO 56 Penman-Monteith at three different locations (Zaragoza, Ejea and Tamarite) and two time scales, daily and monthly. The PT method clearly underestimated PM ET_0 at the relatively windy locations of Zaragoza and Ejea, while there was not underestimation or overestimation on average at the non-windy location of Tamarite.

Previous sensitivity analysis have shown that the use of PT ET_0 as the model input, rather than the PM method, could lead to notable differences in crop model results, particularly in those cases where PM is significantly underestimated by PT (Dugas and Ainsworth, 1985; Benson et al., 1992). Nevertheless, actual data variability is usually higher than simulated results and many uncontrolled factors can lead to smaller differences between actual and simulated data than those predicted by the theoretical sensitivity analyses. Hence, the correspondence between model outputs and actual data could remain even after model-input changes (Clemente et al., 1994; Utset et al., 2000), although those changes should lead to significant differences, according to the sensitivity analyses. Present paper goal is to assess the differences between actual and simulated maize water-use in a Mediterranean landplane, considering the PT and the PM approaches as the reference evapotranspiration inputs in the model simulations. The reliability of a modeling-based irrigation decision-making, considering both ET_0 calculation approaches, is also evaluated.

MATERIALS AND METHODS

The data used in this study were obtained from experiments conducted in Zaragoza (41º 43’ N, 0º 48’ W, 225 m altitude), Aragón, Northern Spain, during the 1995 and 1996 maize cropping-seasons. The experiment goal was to assess the differences among the evaluated irrigation options, according to the maize actual water-use (Farré, 1998).

The climate in the experimental site was Mediterranean semiarid. Mean annual evapotranspiration is 1150 mm, whereas mean annual precipitation is 350 mm. It yields a precipitation-evapotranspiration ratio of about 0.3, which corresponds to a semiarid climate (FAO, 1977). However, this ratio is close to the arid climate cut-off ratio of 0.2 (FAO, 1977). The mean annual maximum and minimum daily air temperatures are 21 and 8 ºC, respectively, and the annual average wind speed at 2 m height is 2.4 $m.s^{-1}$ (Faci et al., 1994). An automatic meteorological station, located about 2 km from the experimental site, but within the same experimental farm, recorded half-hour and daily values of precipitation, air temperature and relative humidity, wind speed and incoming global solar radiation (Martínez-Cob, 2001).

Maize *cv.* Prisma (FAO 700) was planted on 17 May 1995 and 16 May 1996 Details of the original irrigation experiments were provided by Farré (1998) and Cavero et al. (2000). Nine irrigation treatments were evaluated each year. Irrigation was supplied either to meet the estimated maximum evapotranspiration of the crop (“fully irrigated” treatment, FI) or about one third of this amount (“deficit irrigation” treatment, DI), by skipping some of the irrigation events or applying a lower depth. Between the extreme FI and DI treatments, six different combinations were evaluated, providing from 5 to 7 irrigation supplies at different stages of the maize development. An additional treatment (“half fully irrigated” treatment, HFI), consisting of half of the water used in the FI treatment, was included. Consequently, considering both years, a total number of 18 maize water-management options were evaluated (Table 1). Soil water-content measurements were taken with a neutron probe, approximately every week and for every 0.2 m layer till 1.2 m soil-depth (Cavero et al., 2000). Seasonal crop evapotranspiration (ET_c) in each treatment was estimated through water balance. Soil water content was also determined gravimetrically each 0.2 m (1995) or 0.3 m (1996) layer down to a depth of 1.2 m at two occasions during each-year crop season (Farré, 1998; Cavero et al., 2000).

The mechanistic model SWAP (Van Dam et al., 1997) was used in this study. SWAP follows the same approach than WOFOST, SUCROS, ORYZA and other

Wageningen models for crop-growth simulations (Van Ittersum et al., 2003), but it is particularly addressed to simulate soil-water movement and crop water-use (Van Dam et al., 1997). The Richards equation is solved in SWAP by a numerical scheme (Belmans, 1983), including several practical options for the initial and boundary conditions. Partitioning of evapotranspiration rate into transpiration and evaporation rates is based on crop leaf-area index (Ritchie, 1972; Belmans, 1983).

The actual crop daily evapotranspiration rates are calculated in SWAP by reducing the potential crop evapotranspiration rate (ET_c), according to the simulated root water-uptake and to the maximum soil evaporation flux, which depend on the simulated soil water-contents (Van Dam et al., 1997). SWAP uses the Feddes et al. (1978) root water-uptake function, which has been found suitable for simulating a wide rank of soil-water contents (Leenhardt et al., 1995; Utset et al., 2000). Rainfall interception and soil-evaporation restrictions are also considered in SWAP simulations (Van Dam et al., 1997). Since SWAP follows a physically-based approach, it can account for all the soil water-balance components, including capillary rising (Van Dam et al., 1997). Hence, SWAP water-use and soil water-content simulations can be more sensitive to changes in the reference evapotranspiration inputs, than those models that simulate soil-water movement through the “cascade approach” (Ritchie, 1998), or similar simplifications.

The soil hydraulic properties, required in SWAP inputs, were estimated from the pedotransfer functions proposed by Rawls et al. (1982, 1998). Physical soil data needed for these estimations, i.e. mechanical composition, soil density, and soil organic matter content, were obtained from published data (Farré, 1998; Cavero et al., 2000). Free drainage at the bottom of the 2-m simulated soil layer was considered as the bottom boundary condition, taking into account the soil characteristics of the experimental site (Farré, 1998; Cavero et al., 2000). The gravimetrically-measured soil water contents at each seeding date (Farré, 1998), were considered as the initial conditions for the SWAP simulations. The provided irrigations shown in Table 1, were considered in SWAP simulations as water supplies. The maize crop function included in SWAP (Van Dam et al., 1997) was used for the crop water-uptake calculations.

Daily values of PM and PT reference evapotranspiration were computed through equations [1] and [2], following the parameterization recommended by Allen et al. (1998) and Priestley and Taylor (1972), using the meteorological data recorded at the weather station, i.e. maximum and minimum daily temperatures and solar radiation for PT calculations, as well as relative humidity and wind speed at 2 m height for PM estimates. These ET_0 values were considered as the SWAP top boundary conditions for each simulated day.

SWAP simulations were conducted for all nine irrigation scenarios for both 1995 and 1996 years, using either the PM or the PT method for ET_0 estimations. Paired comparison tests for mean, median and variance were performed between actual ET_c, as measured by the water-balance method and the simulated ET_c considering both the PT and PM approaches for ET_0 calculations. Same test comparison was performed between gravimetrically-measured and simulated SWC considering both ET_0 approaches. Analysis of regression between actual and simulated ET_c and SWC were included.

RESULTS AND DISCUSSION

The annual precipitation recorded in the experimental site, was 188 mm in 1995 and 468 mm in 1996. The precipitation distributions for both crop-seasons (from May to October 1995 and 1996, respectively) are depicted in Fig. 1. The daily means of several other meteorological variables during each crop season were: a) total global solar radiation, 20.4 MJ m^{-2} (1995) and 20.9 MJ m^{-2} (1996); b) wind speeds, 2.0 m s^{-1} (1995) and 2.2 m s^{-1} (1996); c) (¿no será más bien, humedad relativa media?) minimum relative humidity, 65 % (1995) and 68 % (1996). The recorded rainfall in the 1995 maize crop-season was 76 mm, 49% of the historical rainfall mean in those months. However, the precipitation during the 1996 maize crop season was 232 mm, which means 149% of the historical rainfall in Zaragoza from May to October (155 mm). According to these meteorological mean values, the 1995 crop season was dry, whereas that corresponding to 1996 was a wet crop-season. There is a considerable inter-annual variability in rainfall behavior, comparing 1995 and 1996. Farré (1998) found statistical significant differences in maize grain yield between the two years, particularly for those irrigation management options comprising lesser water supplies. The differences were considered to be due to the different rainfall distributions. Nevertheless, despite the different rainfall behavior in 1995 and 1996, radiation and wind speed records were similar in both years and corresponded to the typical climate behavior.

The calculated daily PT and PM ET_0 estimates for both years, 1995 and 1996, are shown in Figure 2. The mean of all PM ET_0 estimates was 2.9 mm day^{-1}; whereas that of PT ET_0 estimates was 2.8 mm day^{-1}. Furthermore, in some instances, the PM values were much higher than the PT ones (Figure 2). Despite the similarity between the two means, the PM and PT ET_0 estimates were significantly different (α = 0.95), according to three conducted paired-comparison tests: t-Student's test of means, sign test of medians and signed rank test of medians. These results agree with those of Martinez Cob (2002) for the same site.

Simulated data analysis

The simulated water-balance results for each crop season and each of the irrigation-management options are shown in Table 2. The shown results comprise the simulated drainage flux at the bottom of the 2-m layer, the simulated crop transpiration and soil evaporation and the simulated total actual evapotranspiration. Simulations indicated no runoff, as it was usually found (Farré, 1998).

As can be seen in Table 2, the average simulated maize evapotranspiration (ET_c), considering PT calculations as ET_0, was 11.7 mm (1995) and 3.9 mm (1996) less than the corresponding ET_c values considering PM calculations as ET_0 in the model input. As expected, the ET differences considering both ET_0 approaches were due mainly to the simulated crop transpiration. The average simulated soil evaporation in the 1995 crop season, considering PM calculations, was only 3 mm higher than that obtained considering PT calculations. Furthermore, the average simulated soil evaporation in 1996, considering the PT approach, was higher than that considering the PM approach.

The differences in the simulated crop ET_c, considering both ET_0 calculation approaches, depended on the irrigation-management option. The highest difference between the simulated ET_c using both ET_0 calculation approaches corresponded to the FI option in 1995 (more than 20 mm). The lowest difference corresponded to the

DI option in 1996. Again, those differences in the predicted ET_c were due to the simulated crop transpiration rather than to the simulated soil evaporation. Besides, the simulated crop transpiration, considering the PM approach, showed higher variability among the irrigation management options than that found by considering the PT approach. This was particularly evident in 1995, the relative dry year, when irrigation was more important for water availability.

The average estimated drainage at the bottom of the 2-m depth soil layer was higher in both years (0.9 mm higher in 1995 and 1 mm higher in 1996) for those simulations that consider the PT calculations as ET_0 than for those which consider PM calculations. Moreover, the estimated bottom fluxes in both years, corresponding to those simulations that consider PT as ET_0 input and the FI irrigation option were 1.9 mm higher than those simulations that consider the PM approach. The same bottom flux differences, but considering the DI irrigation option, were 0.1 and 0.3 mm in 1995 and 1996, respectively.

Since PT values underestimated ET_0 as compared to PM calculations, the simulated water balance predicted higher drainage rates when the PT approach was used for ET_0 calculations. This is particularly evident for the cases of higher water income from rainfall or irrigation. Likewise, total ET_c in both simulations, considering PT and PM, was higher in 1996 than in 1995. As was pointed out above, 1996 was a wet year. Accordingly, the predicted drainage flux and soil evaporation in 1996 were higher than those predicted for the 1995 crop season, for both ET_0 calculation approaches. Although the average crop transpiration corresponding to the PT calculations was higher in 1996 than in 1995, the corresponding crop transpirations considering the PM approach were almost equivalent.

Comparison between simulated and actual data

Table 3 shows the mean and median differences and variance ratio between the measured maize actual-evapotranspiration (A-ET_c) and those simulated actual evapotranspirations considering the PM (PM-ET_c) and the PT (PT-ET_c) approaches for ET_0 calculations. Kolmogorov Goodness-of-fit tests for normality, performed for A-ET_c, PM-ET_c, PT-ET_c, as well as for actual and simulated SWC yield that all these variables can be considered normally distributed at the 95% confidence level.

According to a t-student test, the A-ET$_c$ mean was not statistically different at the 95% confidence level from the PM-ET$_c$ and PT-ET$_c$ means, respectively. The same conclusion was obtained from a signed-rank comparison of medians. Nevertheless, the A-ET$_c$ variances were significantly higher than the simulated actual-evapotranspiration variances, considering both ET$_0$ calculation approaches. Despite that PM-ET$_c$ variability was closer to A-ET$_c$ variability than PT-ET$_c$, both simulated-ET$_c$ variances were statistically different from A-ET$_c$. As pointed out above, experimental data usually involves more variability than simulations, because many uncontrolled factors can be found during experiments and measurements. Hence, from a statistical point of view, PM-ET$_c$ and PT-ET$_c$ showed a similar behavior regarding their average differences with A-ET$_c$, due to A-ET$_c$ variability.

Figure 3 depicts the scatter plots and regressions between PM-ET$_c$ and A-ET$_c$, as well as between PT-ET$_c$ and A-ET$_c$. The regression statistical results are shown in Table 4. The correlation coefficients between measured and simulated actual maize evapotranspiration were 0.96 for both considered ET$_0$ calculation approaches, significant at the 95% confidence level. Furthermore, the PM-ET$_c$ - A-ET$_c$ regression intercept was higher than that obtained for the PT-ET$_c$ - A-ET$_c$ regression. The slope corresponding to the PM-ET$_c$ - A-ET$_c$ regression was also higher than that obtained for the PT-ET$_c$ - A-ET$_c$ regression. The regression lines shown in Fig. 3 were almost parallel, indicating that PM-ET$_c$ was higher than PT-ET$_c$ for the whole rank of actual evapotranspirations considered.

On the other hand, as can be seen in Table 3, mean and medians of simulated SWC as obtained from both ET$_0$ calculation approaches were statistically different from the corresponding measured SWC. Particularly, experimental SWC variability was much higher than the found variability through both simulations. Figure 4 depicts the regression between simulated and measured soil water contents. Accordingly, Table 4 shows the regression statistical results. The correlation coefficients obtained from both ET$_0$ calculation approaches were the same (0.72) and both of them were significant at the 95% confidence level. The regression corresponding to those SWC estimated from considering PM as ET$_0$ (SWC-PM) showed a higher slope and a lower intercept than the regression obtained from those simulations where PT was considered as ET$_0$ (SWC-PT). Differences between SWC-PM and SWC-PT were higher for lower SWC and hence the regression lines diverged as approaching to the ordinate axis. The estimated maize transpiration considering the PT approach were lower than those obtained considering the PM approach, hence SWC-PM were lower than SWC-PT, because the estimated root water-uptake was higher in those cases. This difference, however, was not observed for higher SWC because in these cases, close to soil-water saturation, an important amount of water will drain. As pointed out above, the obtained simulations considering PT for ET_0 calculations predicted higher bottom flux rates than those obtained considering the PM approach. The maximum amount of water retained in the soil pores depend only on the soil hydraulic properties (Van Dam et al., 1997), thus both SWC-PM and SWC-PT simulations agreed predicting the higher SWC.

The goal of the Farré (1998) experiment was to assess the differences between each of the evaluated irrigation options. Therefore, the modeling practical use in this case should be just the same, to point out the statistical significant differences between those irrigation managements. Consequently, Table 5 shows the differences between each of the evaluated irrigation options, according to the actual evapotranspirations measured through the water balance method (A-ET_c) and those simulated actual evapotranspirations, as obtained from both ET_0 calculation approaches (PM-ET_c and PT-ET_c). The Fisher's least significant difference procedure (LSD) was used to indicate the significant differences at the 95% confidence level. The both-years data was considered and only differences respecting to the DI, FI and HFI irrigation options are shown.

According to the experimental data comparison, the maize water-use corresponding to the FI option was equivalent to that obtained by applying the EO1 and EO2 irrigation supplies. The same conclusion can be achieved from the simulation results, considering both ET_0 calculation approaches. Besides, simulations and measured data indicated that the HFI option yielded different maize water uses than the EO2 and the DI options. However, A-ET_c mean for the EO1 option was not different from the HFI option, whereas the corresponding PM-ET_c and PT-ET_c means were statistically different. An identical situation was found for the DI-EO5 comparison, although in the rest of the DI option comparisons the results obtained from measured and simulated actual-evapotranspirations agreed. The differences between means according to A-ET$_c$ values were higher than those differences computed from the simulated data. The simulated ET$_c$ differences according to the evaluated irrigation option, successfully agreed with the experimentally-measured ET$_c$ differences in 19 cases of the 21 shown in Table 5 (90.5%). The ET$_c$ differences estimated from PM-ET$_c$ were closer to A-ET$_c$ differences than those estimated from PT-ET$_c$. However, from a statistical point of view, the simulations obtained from both ET$_0$ calculation approaches gave rise to the same conclusions, while comparing the effects of each irrigation option on maize water-use.

CONCLUSIONS

Considering the PT approach as the reference-evapotranspiration input in a crop model under Mediterranean conditions, lead to lesser simulated actual transpiration and evapotranspiration values than those obtained considering the PM approach. Correspondingly, the simulated drainage flux and soil water contents were higher considering the empirical PT approach as the model ET$_0$ input, than those found considering the combined PM approach. The correlations between simulated and actual data were significant in all the cases, but no disagreements were found according to the ET$_0$ approach followed in simulations. Differences between actual and simulated maize water-use and SWC keep the same statistical significance for both ET$_0$ approaches. Besides, simulations obtained considering both ET$_0$ calculation approaches gave the same successful conclusions, when using the model as a tool for irrigation decision-making support. Hence, despite that the PT approach significantly underestimates the PM physically-based values under Mediterranean conditions; this empirical approach still could be used for modeling-based comparative assessments, if meteorological information is not enough for computing the PM ET$_0$.

REFERENCES

Allen, R., Pereira, L.A., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy. 293 p.

Belmans, C., Wesseling, J., Feddes, R.A. 1983. Simulation function of the water balance of a cropped soil: SWATRE. Journal of Hydrology, 63:271-286.

Benson, V.W., Potter, K.N., Bogusch, H.C., Goss, D., Williams, J.R., 1992. Nitrogen leaching sensitivity to evapotranspiration and soil water storage estimates in EPIC. Journal of Soil and Water Conservation. 47, 334-337.

Cavero, J., Farré, I., Debaeke, P., Faci, J.M., 2000. Simulation of maize yield under water stress with the EPICphase and CROPWAT models. Agronomy Journal. 92, 679-690.

Clemente, R., De Jong, R., Hayhoe, H., Reynolds, W., Hares, M., 1994. Testing and comparison of three unsaturated soil water flow models. Agricultural Water Management. 25, 135-152.

Dugas, W.A., Ainsworth, C.G., 1985. Effect of potential evapotranspiration estimates on crop simulation models. Transactions of the ASAE. 28, 471-475.

Faci, J.M., Martínez-Cob, A., Cabezas, A., 1994. Agroclimatología de los regadíos del Bajo Gállego: doce años de observaciones diarias en Montañana (Zaragoza). Consejería de Agricultura, Ganadería y Montes, Government of Aragón, Zaragoza, Spain. 231 p.

Farré, I. 1998. Maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) response to deficit irrigation: agronomy and modelling. PhD. dissertation. University of Lleida. Lleida, Spain. 150 p.

Feddes, R. A., Kowalik, P., Zaradny, H. 1978. Simulation of field water use and crop yield. PUDOC, Wageningen, Simulation Monographs, 189 pp.

Food and Agriculture Organization (FAO). 1977, Carte mondiale de la désertification a l'échelle de 1:25,000,000, Conférence des Nations Unies sur la désertification, 29 août - 9 septembre, A/CONF. 74/2.

Hoogenboom, G. 2000. Contribution of agrometeorology to the simulation of crop production and its applications. Agriculture and Forest Meteorology. 103, 137-157.

Jamieson, P.D. 1982. Comparison of methods of estimating maximum evaporation from a barley crop. New Zealand Journal of Science. 25, 175-181.

Con formato: Español (España - alfab. internacional)

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evaporation and irrigation water requirements. ASCE manual and Reports on Engineering Practice No. 70. American Society of Civil Engineers, New York, USA. 332 p.

Leenhardt, D., Voltz, M., Rambal, S., 1995. A survey of several agroclimatic soil water balance models with reference to their spatial application. European Journal of Agronomy. 4, 1-14.

Martínez-Cob, A. 2001. Adequacy of Villalobos method to adjust eddy covariance latent heat flux. Irrigation Science. 20, 175-188.

Martínez-Cob, A. 2002. Evaluación de métodos de cálculo de la evapotranspiración de referencia diaria y mensual en Aragón. ITEA. 23, 126-132.

McAneney, K.J., Itier, B., 1996. Operational limits to the Priestley-Taylor formula. Irrigation Science. 17, 37-43.

Pereira, A.R., Nova, N.A.V., 1992. Analysis of the Priestley-Taylor parameter. Agriculture and Forest Meteorology. 61, 1-9.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of the surface heat flux and evapotranspiration using large-scale parameters. Monthly Weather Review. 100, 81-92.

Rawls, D., Gimenez, D., Grossman, R., 1998. Use of soil texture, bulk density and slope of the water retention curve to predict saturated hydraulic conductivity. Transactions of the ASAE. 41, 983-988.

Rawls, W., Brakensiek, D., Saxton, K., 1982. Estimation of soil water properties. Transactions of the ASAE. 25, 51-66.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with an incomplete cover. Water Research. 8, 1204-1212.

Ritchie, J.T. 1998. Soil water balance and plant water stress. In: Understanding options for agricultural production. Tsuji, G. Hoogenboom, G., Thornton, P. (eds.). 41-54. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Shouse, P., Jury, W.A., Stolzy, L.H., 1980. Use of deterministic and empirical models to predict potential evapotranspiration in an advective environment. Agronomy Journal. 72, 994-998.

Smith, M. 2000. The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. Agriculture and Forest Meteorology. 103, 99-108.

Utset, A., Ruiz, M., Garcia, J., Feddes, R.A., 2000. A SWACROP-based potato root water-uptake function as determined under tropical conditions. Potato Research. 43, 19-29.

Van Dam, J.C., Huygen, J., Wesseling, J.G., Feddes, R.A., Kabat, P., van Walsum, P.E.V., Groenendijk, P., van Diepen, C.A., 1997. Theory of SWAP version 2.0. Report 71. Technical Document 45, Wageningen, The Netherlands. 167 p.

Van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J. 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy. 18, 2021-234.

ACKNOWLEDGMENTS

Special thanks are due to Miguel Izquierdo, Jesús Gaudó, Lola Naval and Teresa Molina for the field work.

Table 1. Irrigation water supply at each irrigation event, maize phase and irrigation option(a). DAS, days after seeding. NI, number of irrigations.

	IWS (mm)										
1995	Phase I(b)			Phase II(c)			Phase III(d)			Total IWS	NI
DAS	28	40	51	62	72	84	97	111	125		
FI	79.3	65.2	60.7	60.2	65.0	65.0	60.0	57.4	55.6	568.4	9
EO1	79.3	65.2	60.7	60.2			60.0	57.4	55.6	438.4	7
EO2	79.3	65.2	60.7		52.0		60.0	57.4	55.6	430.2	7
EO3		65.2		60.2	65.0	65.0	60.0	57.4	55.6	428.4	7
EO4	79.3	65.2	60.7		52.0			57.4		314.6	5
EO5		65.2			52.0		60.0	57.4	55.6	290.2	5
EO6		65.2		60.2	65.0	65.0		57.4		312.8	5
DI		65.2			52.0			57.4		174.6	3
HFI	79.3		60.7		65.0		60.0		55.6	320.6	5
1996	Phase I			Phase II			Phase III			Total IWS	NI
DAS	22	43	55	67	81		92	106	120		
FI	63.3	58.4	69.7	70.7	66.0		55.2	59.7	62.4	505.3	8
EO1	63.3	58.4	69.7	70.7	66.0			59.7		387.8	6
EO2	63.3	58.4	69.7		32.0		55.2	59.7	62.4	400.6	7
EO3		58.4		70.7	66.0		55.2	59.7	62.4	372.2	6
EO4	63.3	58.4	69.7		32.0			59.7		283.1	5
EO5		58.4			32.0		55.2	59.7	62.4	267.5	5
EO6		58.4		70.7	66.0			59.7		254.7	4
DI		58.4			32.0			59.7		150.0	3
HFI	63.3		69.7		66.0			59.7		258.7	4

(a) FI, fully irrigated; HFI, half fully irrigated; DI, deficit irrigated; EO1..EO6, evaluated options between FI and DI.

(b) Vegetative phase (first 60 days after seeding)

(c) Flowering phase (from 60 to 90 days after seeding)

(d) Grain filling phase (from 90 to 150 days after seeding)

Table 2. Simulated drainage bottom-flux (BF), crop transpiration (CT), soil evaporation (SE) and actual evapotranspiration (ET) for each irrigation-management option (IMO) and crop season using the SWAP model with two different ET_0 approaches, Penman-Monteith (PM) and Priestley-Taylor (PT).

Year	ET_0	IMO	BF (mm)	CT (mm)	SE (mm)	ET (mm)
1995	PM	FI	42.2	350.7	244.1	594.8
		HFI	22.4	272.9	231.9	504.8
		DI	19.3	179.3	204.5	383.8
		EO1	27.7	327.3	244.1	571.4
		EO3	24.1	328.7	210.4	539.1
		EO4	26.0	270.4	239.6	510.0
		EO5	19.4	248.5	209.0	457.5
		EO6	22.1	295.2	205.9	501.1
		Average	25.4	284.1	223.7	507.8
	PT	FI	44.1	333.3	241.0	574.3
		HFI	22.6	267.9	228.5	496.4
		DI	19.4	178.7	201.9	380.6
		EO1	28.2	314.0	241.0	555.0
		EO3	24.9	313.3	207.7	521.0
		EO4	26.2	267.7	236.5	504.2
		EO5	19.5	238.9	206.4	445.3
		EO6	22.4	288.8	203.2	492.0
		Average	25.9	275.3	220.8	496.1
1996	PM	FI	47.6	337.5	251.8	589.3
		HFI	25.4	290.3	232.0	522.3
		DI	20.8	215.2	216.7	431.9
		EO1	37.3	333.0	250.1	583.1
		EO2	31.0	329.8	251.8	581.6
		EO3	28.5	321.4	218.6	540.0
		EO4	27.8	294.0	250.1	544.1
		EO5	21.9	280.7	218.5	499.2
		EO6	22.6	275.3	222.4	497.7
		Average	29.2	297.5	234.7	532.1
	PT	FI	49.5	330.1	254.8	584.9
		HFI	26.2	285.1	235.0	520.1
		DI	21.2	212.0	218.5	430.5
		EO1	38.9	327.1	253.1	580.2
		EO2	32.1	321.4	254.8	576.2
		EO3	29.3	312.7	220.2	532.9
		EO4	28.7	289.3	253.1	542.4
		EO5	22.4	271.1	220.2	491.3
		EO6	23.3	270.8	224.2	495.0
		Average	30.2	291.1	237.1	528.2

Table 3. Mean (MD) and median (MND) differences and variance ratio (VR) between the experimentally-obtained maize actual-evapotranspiration (ET$_c$) and soil water contents (SWC) and those simulated actual evapotranspirations considering the PM and the PT approaches for ET$_0$ calculations.

Year	Statistics	Experimental-PM	Experimental-PT
ET$_c$	MD	0.6	7.0
	MN	10.4	0.2
	VR	3.01*	3.12*
SWC	MD	0.06*	0.06*
	MN	0.07*	0.07*
	VR	5.30*	5.18*

* Statistically significant at the 95% confidence level.

Table 4. Correlation coefficients (CC), intercepts (INT) and slopes (SLP) of the regression analyses between simulated and measured actual evapotranspiration (ET) and soil water contents (SWC); for each of the evaluated ET_0 calculation approaches.

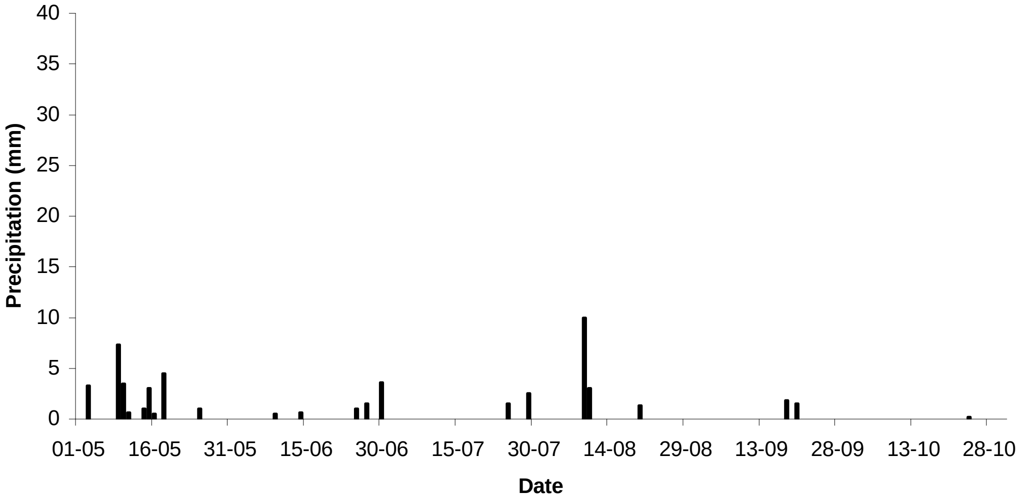
	ET_0 approach	CC	INT	SLP
ET (mm)	PM	0.96^1	235.7^2	0.548^3
	PT	0.96^1	231.6^2	0.541^3
SWC ($cm^3\ cm^{-3}$)	PM	0.72^1	0.522^2	0.036^3
	PT	0.72^1	0.540^2	0.034^3

1. Statistically significant at the 95% confidence level.
2. Statistically different from 0 at the 95% confidence level.
3. Statistically different from 1 at the 95% confidence level.

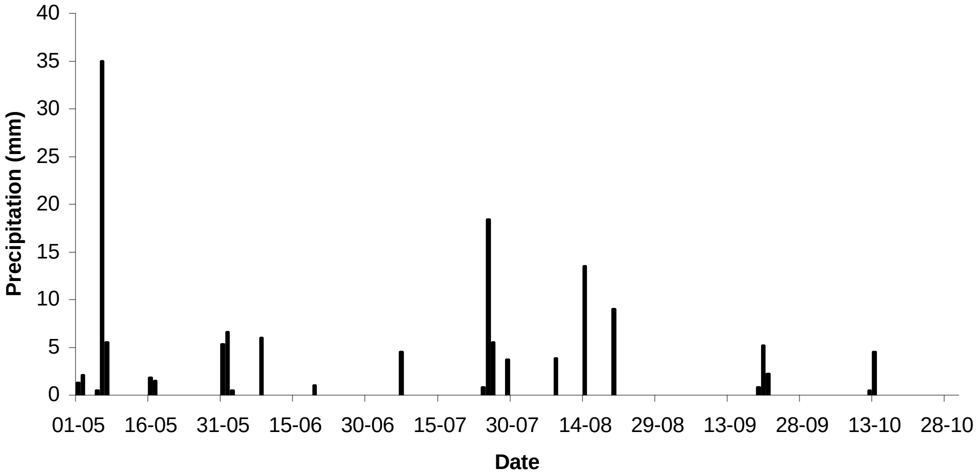
Table 5. Differences between each of the evaluated irrigation management options (IMO) according to the measured actual evapotranspirations (A-ET$_c$) and the simulated actual evapotranspirations, considering the PM (PM-ET$_c$) and the PT (PT-ET$_c$) ET$_0$ calculation approaches.

IMO	A-ET$_c$	PM-ET$_c$	PT-ET$_c$
EO1 - FI	-68.8	-14.8	-12.0
EO2 - FI	-27.3	-10.5	-3.4
EO3 - FI	*-135.0	*-52.5	*-52.6
EO4 - FI	*-122.1	*-65.0	*-56.3
EO5 - FI	*-209.1	*-113.7	*-111.3
EO6 - FI	*-199.3	*-92.6	*-86.1
HFI - FI	*166.5	*78.5	*71.3
DI - FI	*-317.1	*-184.2	*-174.1
EO1 - HFI	97.7	*63.7	*59.3
EO2 - HFI	*139.2	*68.1	*67.9
EO3 - HFI	31.5	26.0	18.7
EO4 - HFI	44.4	13.5	15.1
EO5 - HFI	-42.7	-35.2	-40.0
EO6 - HFI	-32.9	-14.2	-14.8
DI - HFI	*-150.6	*-105.7	*-102.7
DI - EO1	*-248.3	*-169.4	*-162.1
DI - EO2	*-289.8	*-173.7	*-170.7
DI - EO3	*-182.1	*-131.7	*-121.4
DI - EO4	*-195.0	*-119.2	*-117.7
DI - EO5	-108.0	*-70.5	*-62.7
DI - EO6	*-117.8	*-91.5	*-87.9

* Significantly different at the 95% confidence level.



A. 1995



B. 1996

Figure 1. Daily precipitation distribution during the experimental periods of May to October in 1995 and 1996.

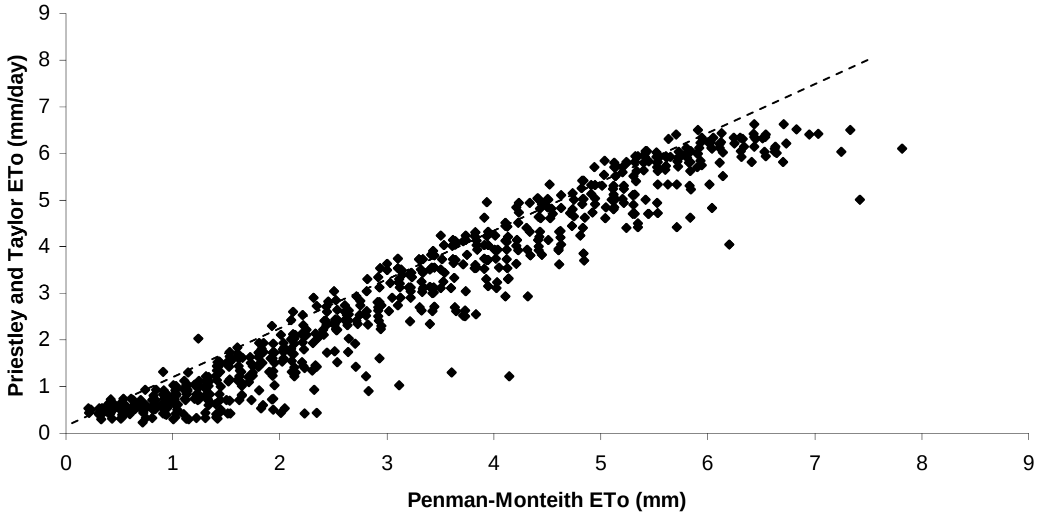


Figure 2. Priestley and Taylor versus Penman-Monteith ET_0 calculations. The dashed line shows the 1:1 relationships.

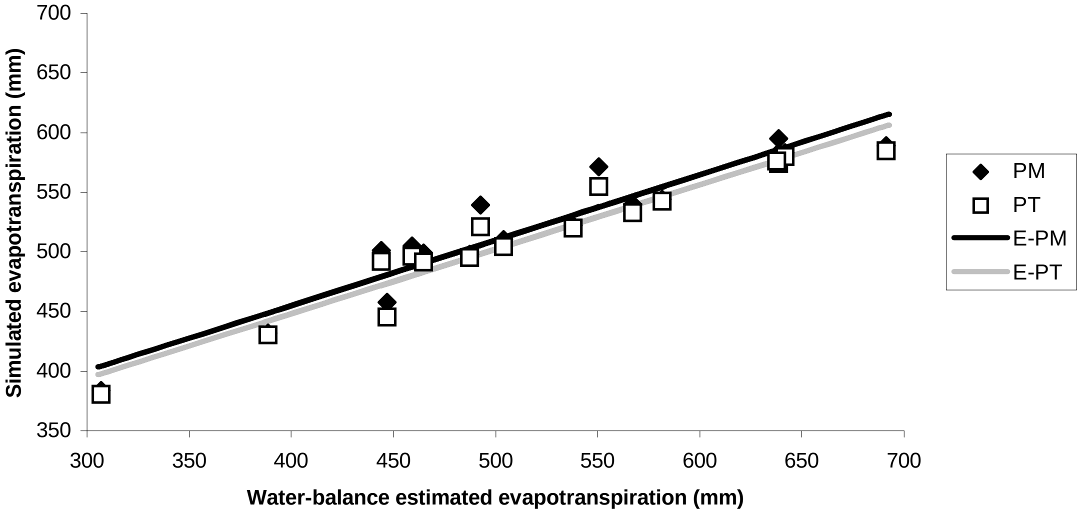


Figure 3. Actual simulated evapotranspirations, as based on Penman-Monteith (PM) and Priestly and Taylor (PT) calculations *vs.* actual measured evapotranspiration, as estimated from the water-balance method. The black (E-PM) and the gray (E-PT) lines show the corresponding regressions.

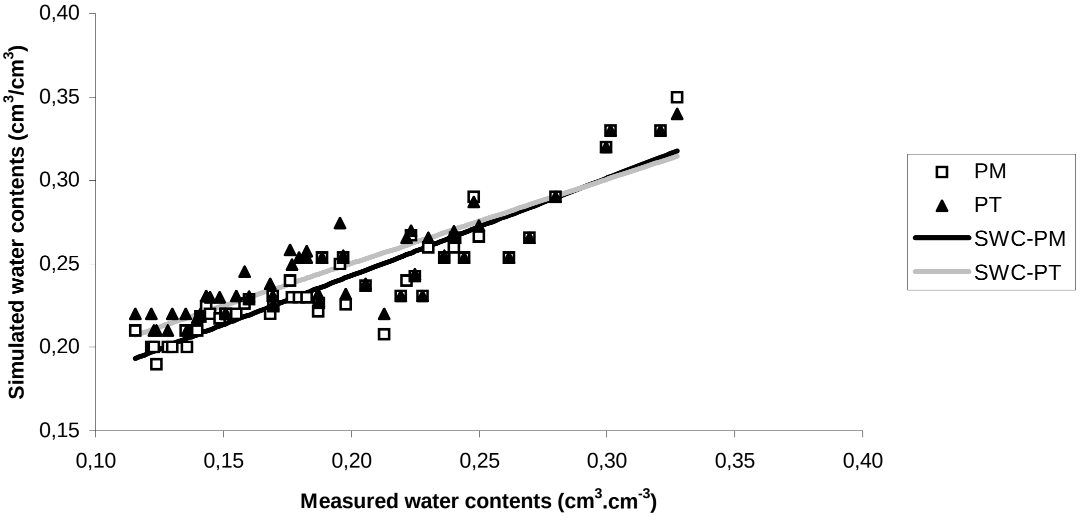


Figure 4. Simulated soil water contents, as based on Penman-Monteith (PM) and Priestly and Taylor (PT) calculations *vs.* actual soil water contents. The black (SWC-PM) and the gray (SWC-PT) lines show the corresponding regressions.