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Variation in the estimations of ET_o and crop water use due to the sensor accuracy of the meteorological variables

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Abstract. In agricultural ecosystems the use of evapotranspiration (ET) to improve irrigation water management is generally widespread. Commonly, the crop ET (ET_c) is estimated by multiplying the reference crop evapotranspiration (ET_o) by a crop coefficient (K_c). Accurate estimation of ET_o is critical because it is the main factor affecting the calculation of crop water use and water management. The ET_o is generally estimated from recorded meteorological variables at reference weather stations. The main objective of this paper was assessing the effect of the uncertainty due to random noise in the sensors used for measurement of meteorological variables on the estimation of ET_o, crop ET and net irrigation requirements of grain corn and alfalfa in three irrigation districts of the middle Ebro River basin. Five scenarios were simulated, four of them individually considering each recorded meteorological variable (temperature, relative humidity, solar radiation and wind speed) and a fifth scenario combining together the uncertainty of all sensors. The uncertainty in relative humidity for irrigation districts Riegos del Alto Aragón (RAA) and Bardenas (BAR), and temperature for irrigation district Canal de Aragón y Cataluña (CAC), were the two most important factors affecting the estimation of ET_o, corn ET (ET_{c_corn}), alfalfa ET (ET_{c_alf}), net corn irrigation water requirements (IRn_{corn}) and net alfalfa irrigation water requirements (IRn_{alf}). Nevertheless, this effect was never greater than ±0.5 % over annual scale time. The wind speed variable (Scenario 3) was the third variable more influential in the fluctuations (±) of evapotranspiration, followed by solar radiation. Considering the accuracy for all sensors over annual scale time, the variation was about ±1 % of ET_o, ET_{c_corn}, ET_{c_alf}, IRn_{corn}, and IRn_{alf}. The fluctuations of evapotranspiration were higher at shorter time scale. ET_o daily fluctuation remained lower than 5 % during the growing season of corn and alfalfa. This estimation fluctuation in ET_o, ET_{c_corn}, ET_{c_alf} , IRn_{corn}, and IRn_{alf} at daily time scale was within an acceptable range, and it can be considered that the sensor accuracy of the meteorological variables is not significant in the estimation of ET_o.

1 Introduction

Knowledge of evapotranspiration (ET) is paramount within several fields such as hydrology, climate and water management, mainly applied to agriculture. ET is the combination of two separate processes: water losses by direct evaporation from soil or plant leaves or stems, and water evaporated trough the crop transpiration. ET can be directly or indirectly measured by different methods: lysimetry, Bowen ratio–energy balance (BREB), eddy covariance, remote sensing energy balance, and scintillometry, among others (Allen et al., 2011). These methods are very expensive, time consuming, complex, and require work done by highly qualified people to obtain data of good quality. Published uncertainty of these methods is also variable – from 5 to 15 % for lysimetry, up to 15 to 40 % for remote sensing using vegetation indices (Allen et al., 2011). For these reasons ET is estimated in most situations for practical applications. The most widely used approach for estimation of crop ET (ET_c) is that recommended by the Food and Agriculture Organization of the United Nations (FAO), i.e. multiplying the so-called reference evapotranspiration ($\mathrm{ET_o}$) by a crop coefficient (K_c) (Allen et al., 1998):

$$\mathrm{ET_c} = \mathrm{ET_o} \cdot K_\mathrm{c}\,. \tag{1}$$

The $\mathrm{ET_o}$ represents the ET for a reference crop (a cool-grass-like virtual crop, 0.12 m tall, bulk canopy resistance equal to $70\,\mathrm{s\,m^{-1}}$, actively growing, completely shading the ground and with adequate water supply). The $\mathrm{ET_o}$ is estimated from meteorological variables recorded at reference weather stations. The K_c is a dimensionless coefficient that represents the effect of the crop properties (including management and soil) on the ET process. The K_c is estimated from specific tabulated values adjusted to local climate, soil, growth stage and cropping characteristics (Allen et al., 1998). Both $\mathrm{ET_o}$ and $\mathrm{ET_c}$ are generally expressed in $\mathrm{mm\,d^{-1}}$. Please note that both variables reflect optimal growing conditions; they may not represent actual evapotranspiration rates under stress, or like rain-fed or natural vegetation conditions. The FAO Penman-Monteith method (Allen et al., 1998) has been selected as the method by which the $\mathrm{ET_o}$ can be unambiguously determined, providing consistent values in all regions and climates (Allen et al., 1998). Estimates of $\mathrm{ET_o}$ are no better than the weather data upon which they are based. Assessments of weather data integrity and quality need to be conducted before their use for estimation of $\mathrm{ET_o}$. Corrections of data should be made for poor sensor calibration or effects due to a poorly watered environment (Allen, 1996). Data quality control is a necessary component of any weather station network used for estimating reference evapotranspiration ($\mathrm{ET_o}$) such as CIMIS (California Irrigation Management Information System) in California (CIMIS, 2012) or SIAR (Sistema de Información Agroclimática para el Regadío) in Spain (MAGRAMA, 2012). The absence of a quality control program can result in poor-quality estimated $\mathrm{ET_o}$ data that severely limits its usefulness for irrigation scheduling and another practical applications (Meek and Hatfield, 1994; Allen, 1996; Eching and Moellenberndt, 1998; Eching and Snyder, 2004). The accuracy of estimated $\mathrm{ET_o}$ depends on three factors: (a) errors in the measurement or estimation of the required weather parameters (Llasat and Snyder, 1998), (b) errors in the estimation of input parameters that generally are empirically calculated, such as soil heat flux (G), net radiation (R_n) and actual vapour pressure (e_a), and (c) errors in the empirical coefficients involved in the equations used to estimate parameters as solar radiation (R_s), clear-sky solar radiation (R_so) and net long-wave radiation (R_nl), among others (Liu et al., 2009). Other authors have analysed the sensibility of the daily reference evapotranspiration equation to climate variables in a range of climates. They have derived daily sensibility coefficients for each variable and quantified daily change of $\mathrm{ET_o}$ per unit of change in each independent variable (Porter et al., 2012; Irmak el at., 2006). The ET-based scheduling approach for controlling the supply of water to crop is becoming more widely used worldwide. The aim is to accomplish that the amount of irrigation water applied and stored in the soil root system be the same as the amount of water used by crops ($\mathrm{ET_c}$). Because of the water losses in every irrigation event, regardless of the irrigation system used, the gross crop irrigation requirements must include the efficiency of the irrigation system. In water balance irrigation scheduling, the goal is to estimate soil water depletion using crop evapotranspiration ($\mathrm{ET_c}$) (Moratiel et al., 2012). The uncertainty in the estimation of $\mathrm{ET_o}$ makes part of the uncertainty in the estimation of $\mathrm{ET_c}$ and thus that of the irrigation scheduling. Growers must obtain adequate irrigation performance particularly in water-scarce Mediterranean countries where there is a mandatory need for increasing the water use efficiency.

The objective of this paper was to assess the effect of the uncertainty due to random noise in the sensors used for measurement of meteorological variables on the estimation of $\mathrm{ET_o}$ and the effect of this uncertainty in the estimation of the crop irrigation water requirements of the two most important crops in the Ebro Basin: alfalfa and grain corn.

2 Materials and method

2.1 Study area: Ebro Basin

The Ebro Basin is located in Spain between 4° W and 2° E longitude (from Greenwich Meridian) and 40° N and 43° N latitude (Fig. 1). Its surface area is $85\,362\,\mathrm{km^2}$, located mostly in Spain (98.9 %), but also includes parts of Andorra and France. The predominant climate is Mediterranean continental. The average precipitation in the basin is $622\,\mathrm{mm\,year^{-1}}$, concentrated in autumn and spring, but the average precipitation in irrigated areas is usually between 300 and 500 mm year (Martínez-Cob and García-Vera, 2004). In the central part of the basin, the climate is semi-arid or arid with annual $\mathrm{ET_o}$ in the range of 840–1500 mm, with an average value of 1150 mm (Salvador et al., 2011). The ring of mountains that surround the basin form a depression in the central zone where most of the irrigated area is located. The Ebro Basin originated during the Tertiary. The central sector of the Ebro Tertiary Basin is characterized by Oligo–Miocene sediments deposited in evaporite and carbonate shallow lakes in a continental environment, disconnected from the sea (Gutiérrez Elorza and Gutiérrez Santolalla, 1998). Most of the soils at the irrigated areas are classified as Xerosol Gypsic and Xerosol Calcic, while the soils near the river are classified as Fluvisol Eutric (Salvador et al., 2011). Soils and surface water (91 % of the irrigation water, CHE, 2012) of the middle Ebro River basin may have the potential to contribute to salinity. The Ebro Basin has 783 948 ha of irrigated land. The irrigation systems used in the basin are surface (69 %), sprinkler (19 %) and drip irrigation (12 %) (CHE, 2012). The main field crops cultivated in the basin are alfalfa (*Medicago sativa* L.), 121 499 ha;

grain corn (*Zea mays* L.), 105 694 ha; barley (*Hordeum vulgare* L.), 83 550 ha; wheat (*Triticum aestivum* L.), 69 026 ha; peach trees (*Prunus persica* (L.) Batsch.), 31 089 ha; vineyards (*Vitis vinifera* L.), 30 605 ha; rice (*Oryza sativa* L.), 30 515 ha; pear trees (*Pyrus communis* L.), 23 397 ha; olive trees (*Olea europaea* L.), 19 393 ha; and apple trees (*Malus domestica* Borkh.), 16 179 ha (CHE, 2012). The three main irrigation projects of the middle Ebro River basin (Fig. 1) were selected for this study: Riegos del Alto Aragón (RAA), Canal de Bardenas (BAR) and Canal de Aragón y Cataluña (CAC). The current irrigated area of RAA, BAR and CAC are 125 899, 81 107, and 104 850 ha, respectively (RAA, 2012; BAR, 2012; CAC, 2012).

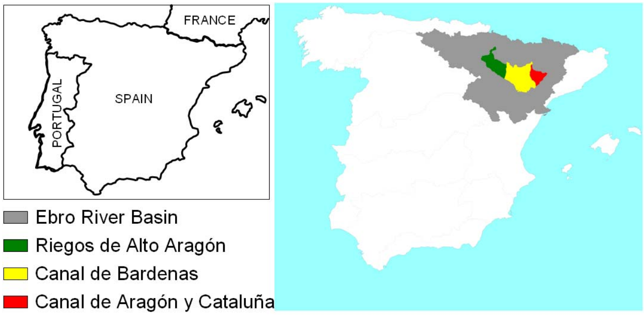

Fig. 1. Location of the Ebro River basin and the irrigation projects studied.

2.2 Climate data and estimation of crop water requirements

The meteorological data required for this study were obtained from the weather stations of Grañén for RAA, Ejea de los Caballeros for BAR and Tamarite de Litera for CAC (Table 1). These stations belong to the SIAR network (in Spanish, Sistema de Información Agroclimática para el Regadío) of Spain. Each station has an automatic data logger (Campbell CR10X) that records, processes and stores the hourly and daily averages of global solar radiation (pyranometer SKYE SP1110), air temperature and relative humidity (Vaisala HMP45C), and wind speed and direction (RM Young 05103 anemometer and wind vane) at 2 m above the ground, as well as the hourly and daily total precipitation (ARG100 rain gauge). Sensors are periodically maintained and calibrated. Daily data from 2004 until 2011 have been downloaded from the web page http://eportal.magrama.gob.es/websiar/SeleccionParametrosMap.aspx?dst=1. These daily data were used to estimate daily ET_o at the three weather stations, using the FAO Penman-Monteith expression (Allen et al., 1998):

$$ET_o = \frac{0.4008\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \qquad (2)$$

where ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the surface (MJ m^{-2} day^{-1}), G is ground heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the saturation vapour pressure curve (kPa °C^{-1}) and γ is psychrometric constant (kPa °C^{-1}). Parameters in Eq. (2) were computed and implemented as described in Allen et al. (1998). The two most cropped species, alfalfa and grain corn, were selected in this study. The monthly values of the corresponding crop coefficients were obtained from Martínez-Cob and García-Vera (2004) (Table 2). These coefficients were locally adjusted values derived from the tabulated values in Allen et al. (1998). The irrigation seasons for both crops were (a) alfalfa: 26 March to 20 September, 26 March to 21 September, and 16 March to 22 September in the RAA, BAR and CAC irrigation districts, respectively; and (b) grain corn: 21 April to 5 October in the RAA and BAR irrigation districts, and 16 April to 30 September in the CAC irrigation district. Equation (1) was subsequently used to get ET_c expressed in mm month^{-1}. The ET_c is also known as the gross crop water requirements. Next, monthly effective precipitation (proportion of rainfall remaining in the soil root system for satisfying the ET_c) was subtracted from monthly ET_c to get the monthly net crop irrigation water requirements (IR_{nn}) (Allen et al., 1998). Monthly effective precipitation was estimated according to Martin and Gilley (1993) as follows:

$$P_e = SF\left(1.25P^{0.824} - 2.93\right)10^{0.000955ET_c}, \qquad (3)$$

where P_e is average monthly effective precipitation (mm month^{-1}), SF is soil water store factor (dimensionless), P is monthly mean precipitation (mm month^{-1}), and ET_c is average monthly crop evapotranspiration (mm month^{-1}). The soil water store factor depends on usable soil water storage (D) and this term is generally calculated as 40 % to 60 % of the available soil water capacity in the crop root zone, depending on the irrigation management practices used (Martin and Gilley, 1993). The term D depends on crop and soil characteristics, and therefore the cases that could be considered for this study would be very high. Thus, we have considered $D = 75$ mm leading to SF = 1 according to Martin and Gilley (1993).

2.3 Uncertainty estimation

The random noise of the sensors under normal operating conditions is considered as a source of uncertainty. The experimental characterization performed by the manufacturers (Campbell Scientific, 2012; R.M. Young Company, 2012) shows that this random error (white noise) is described by a normal distribution. Under this assumption the error does not depend on time and is not correlated between different sensors. In Table 3 the accuracy of the measuring instruments is shown. The calculation of ET_o using Eq. (2) requires, in addition to precise measurements, daily averages of wind speed

Table 1. Location of the weather stations used. Annual ET_o is the long-term average for the period analysed (2004–2011).

Station Name	Irrigation District	Latitude	Longitude*	Elevation (m)	Annual ET_o (mm)
Grañén	Riegos del Alto Aragón (RAA)	41°56′ N	0°21′ W	312	1205
Ejea de los Caballeros	Canal de Bardenas (BAR)	42°05′ N	1°11′ W	317	1264
Tamarite de Litera	Canal de Aragón y Cataluña (CAC)	41°46′ N	0°22′ E	221	1079

* W or E from Greenwich Meridian.

Table 2. Monthly values of K_c for grain corn and alfalfa at three study irrigation districts: Riegos del Alto Aragón (RAA), Canal de Bardenas (BAR) and Canal de Aragón y Cataluña (CAC). From Martínez-Cob and García Vera (2004).

Month	RAA		BAR		CAC	
	Grain Corn	Alfalfa	Grain Corn	Alfalfa	Grain Corn	Alfalfa
March	0.30		0.37			0.49
April	0.28	0.90	0.31	0.92	0.30	1.11
May	0.28	1.01	0.31	1.01	0.31	0.96
June	0.63	0.95	0.65	0.95	0.74	0.93
July	1.17	0.92	1.17	0.92	1.19	0.92
August	1.20	0.92	1.22	0.92	1.18	0.92
September	0.73	1.16	0.78	1.16	0.66	1.18
October	0.39		0.39			

and solar radiation. We calculated the uncertainty associated to these averages, assuming that measurements were taken every 10 s (MAGRAMA, 2012):

$$\sigma_{\mathrm{avg}} = \frac{\sigma_{\mathrm{var}}}{\sqrt{8640}}, \tag{4}$$

where σ_{var} represents the uncertainty of the precise measurements, and σ_{avg} is the error of the daily average. The individual effect of each of the variables involved in the calculation of ET_o was first estimated by propagating their uncertainty numerically. This group of values of the variable considered were supposed to meet a normal distribution that complies with its average value observed and known uncertainty ($\overline{\mathrm{var}}$ and σ_{var}). This procedure results in a group of values of ET_o on which we calculate their average value and standard deviation, obtaining the uncertainty that was looked for. This method could be used to process arbitrary error models, but presents high computational costs as it requires a high number of random input values and ET_o calculations. For this reason, and considering the Gaussian nature of the white noise, this process was simplified analysing only three initial values:

$$\mathrm{var}_1 = \overline{\mathrm{var}} - \sigma_{\mathrm{var}}\,,$$

$$\mathrm{var}_2 = \overline{\mathrm{var}}\,,$$

$$\mathrm{var}_3 = \overline{\mathrm{var}} + \sigma_{\mathrm{var}}\,.$$

These values were introduced in Eq. (2) together with the rest of values observed (Moratiel et al., 2010), obtaining three values of ET_o on which we calculated their standard deviation.

Trials have been carried out, comparing the main method of uncertainty propagation (using 300 initial values) with the simplified calculation, and obtaining similar results of average values and standard deviation with differences lower than 0.01 %. Extreme conditions, as low temperatures or faulty power supply, may introduce additional errors in the measurements. These errors are described by non-Gaussian models of uncertainty under which this simplified calculation is not valid. The group effect of the uncertainty of different variables in the calculation of ET_o was calculated using the method proposed by Ku (1966):

$$\sigma_{\mathrm{ET_o}} = \sqrt{\left(\frac{\partial \mathrm{ET_o}}{\partial \mathrm{var}_1}\right)^2 \sigma^2_{\mathrm{var1}} + \left(\frac{\partial \mathrm{ET_o}}{\partial \mathrm{var}_2}\right)^2 \sigma^2_{\mathrm{var2}} + \ldots} \tag{5}$$

The partial derivatives have been numerically estimated by (Eq. 6):

$$\frac{\partial \mathrm{ET_o}}{\partial \mathrm{var}_1} = \frac{\mathrm{ET_o}\,(\mathrm{var}_1 + \sigma_{\mathrm{var1}}) - \mathrm{ET_o}\,(\mathrm{var}_1 - \sigma_{\mathrm{var1}})}{2\sigma_{\mathrm{var1}}}\,. \tag{6}$$

Once we know the uncertainty of ET_o, we propagated this error to the calculation of ET_c and IR_n as follows:

$$\sigma_{\mathrm{ET_c}} = K_c \sigma_{\mathrm{ET_o}} \tag{7}$$

$$\sigma_{\mathrm{IR_n}} = K_c \sigma_{\mathrm{ET_o}} - P_e\,. \tag{8}$$

Table 3. Scenarios considered in this study representing uncertainties in the meteorological variables and the estimation of ETo. Accuracy according to Campbell scientific (2012) and R.M. Young Company (2012).

Scenario	Description	Measuring Instrument	Accuracy*	Measurement Range	Company
1	Variation in ET_o due to accuracy of temperature	HMP45C Temperature and and Relative Humidity Probe. Sensor: Platinum Resistance Temperature Detector (1000 PRT, IEC 751 1/3 class B)	If $T_M \geq 20\,°C$ Error = $\pm(0.05 \cdot T_M + 0.1)$ If $T_M < 20\,°C$ Error = $\pm(-0.05 \cdot T_M + 0.3)$	$-40 - 60\,°C$	Campbell Scientific, Inc
2	Variation in ET_o due to accuracy of relative humidity	HMP45C Temperature and Relative Humidity HMP45C Temperature and Relative Humidity Probe. Sensor: HUMICAP® 180	If RH > 90 % Error = $\pm(3 + 0.05 \cdot T_M)$ If RH ≤ 90 % Error = $\pm(2 + 0.05 \cdot T_M)$	0 – 100 %	Campbell Scientific, Inc
3	Variation in ET_o due to accuracy of wind speed	Wind Monitor Model 05103	Error $= U \pm 0.3$	1–100 ms^{-1}	R.M. Young Company
4	Variation in ET_o due to accuracy of solar radiation	SP Pyranometer Sensor	Error $= \pm 0.05 \cdot R_s$	0–1370 Wm^{-2}	Campbell Scientific, Inc
5	Variation in ET_o due to accuracy of temperature, relative humidity, wind speed and solar radiation	All	Sum of errors	–	–

* T_M, RH, U and R_s are the recorded temperature, relative humidity, wind speed and solar radiation, respectively.

The daily data of ET_o, ET_c, and IR_n have been totalized considering monthly and annual values. The uncertainty of these accumulated values is calculated as follows:

$$\sigma_{Sum\_} = \sqrt{\sum_i (\sigma)_i^2}\ ; \tag{9}$$

from this expression we can observe that the relative importance of the error decreases with the square root of the number of terms considered (days).

In this paper, five scenarios have been considered (Table 3), studying the individual and group effect of the principal variables involved:

1. Scenario 1 – uncertainty in the estimation of ET_o as a consequence of accuracy of maximum and minimum temperature.
2. Scenario 2 – uncertainty in the estimation of ET_o as a consequence of accuracy of maximum and minimum relative humidity.
3. Scenario 3 – uncertainty in the estimation of ET_o as a consequence of accuracy of wind speed.
4. Scenario 4 – uncertainty in the estimation of ET_o as a consequence of accuracy of solar radiation.
5. Scenario 5 – uncertainty in the estimation of ET_o as a consequence of accuracy of all sensors considered together (Scenarios 1–4).

3 Results and discussion

The three weather stations, Grañén, Ejea and Tamarite, showed similar long-term monthly averages of air temperature and solar radiation for the period 2004–2011 (Fig. 2). Long-term averages of air relative humidity in Ejea were lower than those recorded in the other two locations. Finally, the major differences were found for wind speed: Ejea showed a long-term annual average of 2.7 ms^{-1}, while that for Tamarite was 1.2 ms^{-1}, and that for Grañén was between these two values. The long-term annual precipitation was similar: 373, 328, and 315 mm for Ejea, Grañén and Tamarite, respectively. The long-term annual estimated ET_o for the period studied was 1264, 1205, and 1079 mm for Ejea, Grañén and Tamarite, respectively (Fig. 3, Table 4). The higher wind speed and the lower air relative humidity

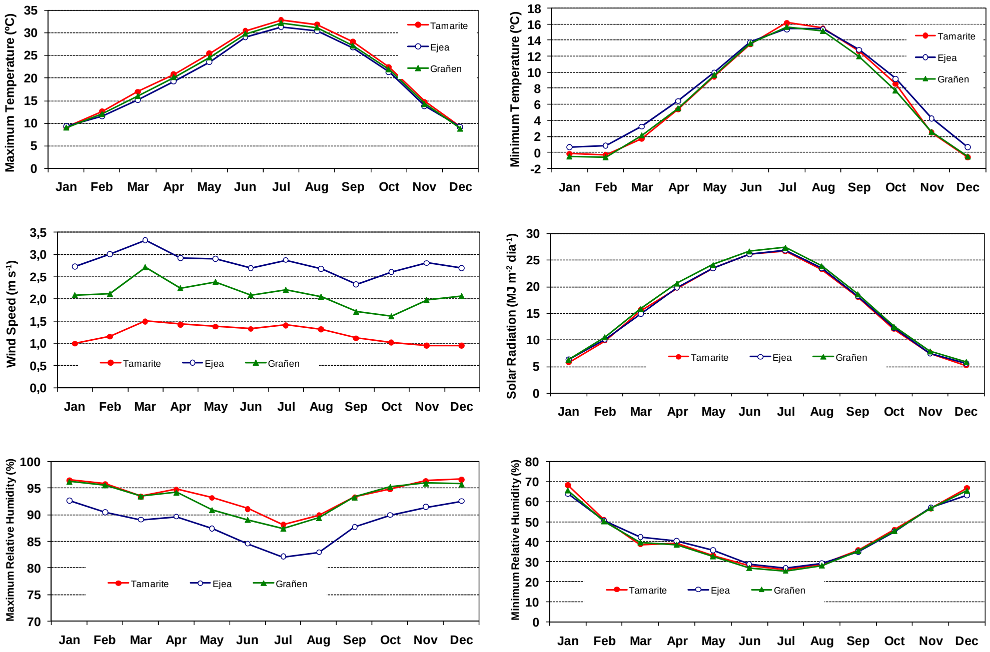

Fig. 2. Long-term monthly meteorological conditions during the period analysed (2004–2011) in the irrigation districts of Riegos del Alto Aragón (weather station, Grañén), Canal de Bardenas (weather station, Ejea) and Canal de Aragón y Cataluña (weather station, Tamarite).

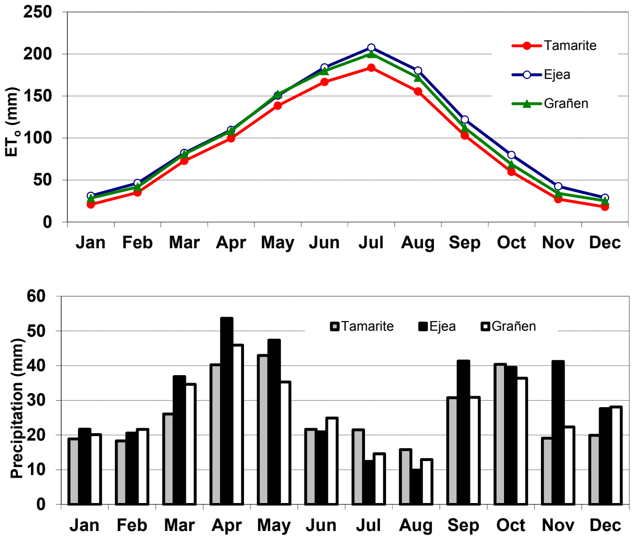

Fig. 3. Long-term monthly averages of ET_o (mm) and precipitation (mm) during the period analysed (2004–2011) in the irrigation districts of Riegos del Alto Aragón (weather station, Grañén), Canal de Bardenas (weather station, Ejea) and Canal de Aragón y Cataluña (weather station, Tamarite).

explained the higher ET_o values for Ejea. In accordance with this, the low wind speed values recorded at Tamarite led to the lower values of ET_o.

The long-term average values of ET_c for grain corn (ET_{c_corn}) and alfalfa (ET_{c_alf}) showed a similar seasonal trend than that of ET_o. Subsequently, the ET_c values for Ejea were the highest and those for Tamarite were the lowest. Seasonal ET values for grain corn were lower than those for alfalfa. Seasonal ET_{c_corn} was 740, 693, and 650 mm for Ejea, Grañén and Tamarite, respectively. These values agree with those from Martinez-Cob (2008) who reported seasonal ET_{c_corn} to be around 700 mm for the middle Ebro River basin. ET_{c_alf} was 884, 856 and 768 mm for Ejea, Grañén and Tamarite, respectively (Table 5).

The seasonal ET_o variations (± mm), according to different scenarios (Table 3), were higher than those for ET_{c_corn} or ET_{c_alf} due to the longer season length considered for ET_o (Table 4), although in relative terms (%) of the ET_o, variations were lower than ET_{c_corn} or ET_{c_alf}. Regarding the Scenarios 1–4, Tables 4–5 show that the variations in ET_o, ET_{c_corn} and ET_{c_alf} due to accuracy of relative humidity sensor (Scenario 2) were higher than those due to the other variables (temperature, wind speed and solar radiation) in RAA and BAR irrigation districts. However, for CAC irrigation district, the variations ET_o, ET_{c_corn} and ET_{c_alf} due to the air temperature variable were higher than those due to the air relative humidity, due to the higher values of this variable recorded in the corresponding weather station. After air relative humidity and temperature, the wind speed was the most influential variable for all the weather stations. The solar radiation was the variable with the least influence for all irrigation districts, except ET_o in RAA. For these Scenarios (1–4) these variations never exceeded 0.26 %.

With regards to Scenario 5 (where we have considered together all errors, Table 3), the error in ET_o was about ±10 mm with a confidence interval of 95 % (±0.85 %) for the three irrigation districts. The errors associated to the

Table 4. Values of average annual ET_o (mm) during the period 2004–2011 with their associated error value ($\pm 2\sigma$) according to different scenarios (Table 3). Irrigation districts of Riegos del Alto Aragón (RAA, Grañén weather station), Canal de Bardenas (BAR, Ejea weather station) and Canal de Aragón y Cataluña (CAC, Tamarite weather station).

Scenario	RAA ET_o 1205 mm		BAR ET_o 1264 mm		CAC ET_o 1079 mm	
	$\pm 2\sigma$ (mm)	$\pm 2\sigma$ (%)	$\pm 2\sigma$ (mm)	$\pm 2\sigma$ (%)	$\pm 2\sigma$ (mm)	$\pm 2\sigma$ (%)
1	0.92	0.077	1.00	0.079	1.80	0.167
2	2.59	0.215	3.20	0.253	1.60	0.149
3	0.07	0.006	0.06	0.005	0.08	0.007
4	0.08	0.007	0.04	0.003	0.04	0.004
5	9.39	0.779	10.67	0.844	7.55	0.700

Table 5. Values of average annual ET_{c_corn} and ET_{c_alf} (mm) during the period 2004–2011 with their associated error value ($\pm 2\sigma$) according to different scenarios (Table 3). Irrigation districts of Riegos del Alto Aragón (RAA, Grañén weather station), Canal de Bardenas (BAR, Ejea weather station) and Canal de Aragón y Cataluña (CAC, Tamarite weather station).

Scenario	RAA		BAR		CAC	
	ET_{c_corn} 693 mm $\pm 2\sigma$ (%)	ET_{c_alf} 856 mm $\pm 2\sigma$ (%)	ET_{c_corn} 740 mm $\pm 2\sigma$ (%)	ET_{c_alf} 884 mm $\pm 2\sigma$ (%)	ET_{c_corn} 650 mm $\pm 2\sigma$ (%)	ET_{c_alf} 768 mm $\pm 2\sigma$ (%)
1	0.105	0.090	0.109	0.093	0.171	0.174
2	0.267	0.234	0.321	0.280	0.173	0.159
3	0.008	0.007	0.007	0.006	0.010	0.008
4	0.003	0.002	0.004	0.004	0.005	0.005
5	0.888	0.803	0.964	0.873	0.770	0.721

sensors were similar in ET_{c_corn} and ET_{c_alf} – about 1 % (Table 5). The error by considering independent variables (Scenarios 1–4) was always less than 0.3 %. Note that we were only considering the error of the sensors without interference by malfunction of sensors, levelling, or even location or vegetation present, among others. These errors can be considered as extremely low. According to Allen et al. (2011), direct methods for measuring evapotranspiration have typical error between 5 and 15 %.

Table 6 lists the seasonal IR_n values obtained for grain corn and alfalfa and the ± variations for the different Scenarios 1–4. As expected, those variations were similar to those listed in the case of evapotranspiration (Table 5), both in absolute and relative terms. Because the magnitude of IR_n was lower than that of ET_c or ET_o, the ± variations in relative terms were slightly higher.

Table 6 shows values of IR_n of 555, 591, and 527 mm for grain corn of the three irrigation districts, RAA, BAR and CAC, respectively. These values agree with those from Salvador et al. (2011), who reported values of IR_n for grain corn between 438 and 734 mm for Ebro Basin. They also reported values for alfalfa within the range from 474 to 893 mm, the values obtained in this studied are within that range. Note that the errors for all scenarios in net crop irrigation water were less than 1.3 %.

Comparison of these results with those from previous works is not easy. Previous studies focused more in sensibility analyses and did not follow a standard or common procedure for computing sensitivity coefficients for the different meteorological variables (Irmak et al., 2006; Gong et al., 2006; Goyal, 2004). Furthermore, assessing the sensitivity of ET_c to the meteorological conditions is more complicated because it will depend on the crop and its management under specific local conditions. Irmak et al. (2006) studied the sensitivity for daily ET_o in different regions of USA and they observed that the ET_o was most sensitive to vapour pressure deficit (VPD) and, second most sensitive, to wind speed. The sensitivity coefficients and methodology used by Irmak et al. (2006) were different from ours. They used increments or decrements of 0.4 kPa in VPD. However, we used the stated error by manufacturer and thus our maximum possible error in relative humidity was 0.07 kPa, i.e. six times less than the minimum error considered by Irmak et al. (2006). Moreover, these authors simulated changes of climate variables by increasing or decreasing in 1 unit steps and not as increments or decrements of recorded data (Table 3) as we did in this study as a consequence of possible measurements errors. Porter et al. (2012) showed that ET_{alf} and ET_o calculations were most sensible to errors in wind speed and air temperature. The important effect on ET_o of changes of wind speed under

Table 6. Values of average annual net crop irrigation water requirements IRn_{corn} and IRn_{alf} during the period 2004–2011 with their associated error value ($\pm 2\sigma$) according to different scenarios (Table 3). Irrigation districts of Riegos del Alto Aragón (RAA, Grañén weather station), Canal de Bardenas (BAR, Ejea weather station) and Canal de Aragón y Cataluña (CAC, Tamarite weather station).

Scenario	RAA		BAR		CAC	
	IRn_{corn} 555 mm $\pm 2\sigma$ (%)	IRn_{alf} 707 mm $\pm 2\sigma$ (%)	IRn_{corn} 591 mm $\pm 2\sigma$ (%)	IRn_{alf} 721 mm $\pm 2\sigma$ (%)	IRn_{corn} 527 mm $\pm 2\sigma$ (%)	IRn_{alf} 621 mm $\pm 2\sigma$ (%)
1	0.131	0.108	0.136	0.114	0.211	0.215
2	0.333	0.283	0.402	0.343	0.213	0.197
3	0.010	0.008	0.009	0.007	0.012	0.010
4	0.004	0.003	0.005	0.005	0.007	0.006
5	1.107	0.972	1.208	1.070	0.949	0.891

Table 7. Average errors values ET_o ($\pm 2\sigma$, %) for different time scale during the period 2004–2011 for irrigation district of Riegos del Alto Aragón (RAA, Grañén weather station).

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
Month	Daily values	Monthly values	Daily values	Monthly values	Daily values	Monthly values	Daily values	Monthly values	Daily values	Monthly values
Jan	2.082	0.456	7.857	1.756	0.121	0.026	0.279	0.275	8.424	7.598
Feb	1.829	0.392	5.310	1.191	0.123	0.025	0.009	0.002	5.661	5.159
Mar	1.542	0.299	4.427	0.895	0.087	0.018	0.020	0.004	4.727	3.407
Apr	1.242	0.238	3.337	0.670	0.072	0.015	0.030	0.006	3.601	2.569
May	1.161	0.218	3.044	0.600	0.068	0.014	0.031	0.006	3.293	2.077
Jun	1.092	0.206	2.462	0.508	0.079	0.015	0.033	0.006	2.739	1.744
Jul	1.107	0.206	2.411	0.512	0.083	0.016	0.032	0.006	2.711	1.659
Aug	1.138	0.213	2.591	0.551	0.093	0.017	0.031	0.006	2.907	1.825
Sep	1.162	0.226	2.815	0.658	0.119	0.023	0.029	0.006	3.154	2.368
Oct	1.319	0.266	4.229	0.936	0.154	0.031	0.022	0.005	4.517	3.621
Nov	1.791	0.383	7.059	1.608	0.165	0.034	0.006	0.002	7.337	6.398
Dec	2.158	0.479	8.697	1.947	0.155	0.034	0.015	0.006	8.998	8.341
Annual	0.077		0.215		0.006		0.007		0.779	

semi-arid conditions was reported by Moratiel el al. (2011) and Donohue et al. (2010). Variations in daily ET_o of 2–4 % were cited by Llasat and Snyder (1998), considering the effect of 4 % overestimation of the solar radiation (R_s) in the Ebro River basin. Note that Scenarios 3–4, wind speed and solar radiation variables, showed lower variations (±) due to data collection (the sample frequency was 10 s); as the frequency of samples frequency increases, errors decrease. Our study shows not only the sensitivity of each variable over ET_o, but the accuracy of the sensors and its sampling interval. That is, in an area where the wind speed may be variable with a greater sensitivity over ET_o and with no good sensor accuracy, the sensitivity over ET_o can be reduced by a reduction in the sampling interval.

Table 7 shows the variations of error values of ET_o in RAA for different time scales. These errors were smaller as the time scale increased. This behaviour was also noticed for the other irrigation districts. Relative errors in daily ET_o (Scenario 5) can reach values of 9 % for daily time scale during December. Nevertheless, the absolute errors for December were quite low because this month has low ET_o rates.

Table 8 shows the average monthly values of ET_o, ET_c and IR_n to identify possible errors in % (Table 9) in the different stages of crop development. From a point of view of water use in a growing season, error for the accuracy of the sensors are much smaller than those that can be made by direct measurements (Allen et al., 2011; Martínez-Cob, 2008). These error values were very low because we have only studied the error of the sensors without interference by malfunction of sensors, levelling, or even location or vegetation present, among others, and with perfect reference conditions to estimate ET_o.

4 Conclusions

Any uncertainty in the meteorological variables for estimating ET_o have a profound effect on agriculture and especially on water resource planning in semi-arid regions. Commonly, ET_o is estimated by means of meteorological variables such

Table 8. Average monthly values for ET_o, ET_{c_corn}, ET_{c_alf}, IRn_{corn} and IRn_{alf} (mm day^{-1}) during the period 2004–2011 for irrigation district of Riegos del Alto Aragón (RAA, Grañén weather station).

Variable (mm day^{-1})	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_o	0.916	1.493	2.606	3.610	4.905	5.995	6.456	5.546	3.735	2.213	1.191	0.817
ET_{c_corn}				1.011	1.373	3.777	7.554	6.655	2.727	0.863		
ET_{c_alf}			0.782	3.249	4.954	5.695	5.940	5.102	4.333			
IRn_{corn}				0.113	0.643	3.146	7.098	6.281	2.002	0.172		
IRn_{alf}			0.121	2.162	4.022	4.979	5.531	4.766	3.601			

Table 9. Associated error ($\pm 2\sigma$, %) to average monthly values (Table 8) under the five scenarios considered during the period 2004–2011 for irrigation district of Riegos del Alto Aragón (RAA, Grañén weather station).

Scenario	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	ET_o	0.46	0.39	0.30	0.24	0.22	0.21	0.21	0.21	0.23	0.27	0.38	0.48
	ET_{c_corn}				0.24	0.22	0.21	0.21	0.21	0.23	0.27		
	ET_{c_alf}			0.30	0.24	0.22	0.21	0.21	0.21	0.23			
	IRn_{corn}				2.13	0.47	0.25	0.22	0.23	0.31	1.34		
	IRn_{alf}			1.93	0.36	0.27	0.24	0.22	0.23	0.27			
2	ET_o	1.76	1.19	0.89	0.67	0.60	0.51	0.51	0.55	0.66	0.94	1.61	1.95
	ET_{c_corn}				0.67	0.60	0.51	0.51	0.55	0.66	0.94		
	ET_{c_alf}			0.89	0.67	0.60	0.51	0.51	0.55	0.66			
	IRn_{corn}				5.98	1.28	0.61	0.54	0.58	0.90	4.70		
	IRn_{alf}			5.76	1.01	0.74	0.58	0.55	0.59	0.79			
3	ET_o	0.03	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03
	ET_{c_corn}				0.02	0.01	0.02	0.02	0.02	0.02	0.03		
	ET_{c_alf}			0.02	0.02	0.01	0.02	0.02	0.02	0.02			
	IRn_{corn}				0.14	0.03	0.02	0.02	0.02	0.03	0.15		
	IRn_{alf}			0.12	0.02	0.02	0.02	0.02	0.02	0.03			
4	ET_o	0.28	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
	ET_{c_corn}				0.01	0.01	0.01	0.01	0.01	0.01	0.00		
	ET_{c_alf}			0.00	0.01	0.01	0.01	0.01	0.01	0.01			
	IRn_{corn}				0.05	0.01	0.01	0.01	0.01	0.01	0.03		
	IRn_{alf}			0.03	0.01	0.01	0.01	0.01	0.01	0.01			
5	ET_o	7.60	5.16	3.41	2.57	2.08	1.74	1.66	1.82	2.37	3.62	6.40	8.34
	ET_{c_corn}				2.57	2.08	1.74	1.66	1.82	2.37	3.62		
	ET_{c_alf}			3.41	2.57	2.08	1.74	1.66	1.82	2.37			
	IRn_{corn}				22.92	4.44	2.09	1.77	1.93	3.22	18.19		
	IRn_{alf}			21.92	3.86	2.56	1.99	1.78	1.95	2.85			

as temperature, relative humidity, solar radiation and wind speed. Our study shows the effect of the uncertainty due to random noise in the sensors used for measurement of meteorological variables for estimating ET_o, and the effect of this uncertainty in the estimation of the crop irrigation water requirements of alfalfa and grain corn. The behaviour of this uncertainty in the three irrigation districts was very similar. From annual point of view the accuracy of relative humidity variable for RAA and BAR irrigation districts and temperature variable for CAC irrigation district (Scenarios 2 and 1, respectively) were that affecting most to ET_o, ET_{c_corn}, ET_{c_alf}, IRn_{corn}, and IRn_{alf}, although this variation was never greater than ±0.5 %. Note that the accuracy of climatic variables can affect ET_o estimation with different intensity under local conditions and season. Considering the accuracy for all sensors over annual scale time, the variation was about ±1 % of ET_o, ET_{c_corn}, ET_{c_alf}, IRn_{corn}, and IRn_{alf}. The magnitude of these errors (both absolute and relative) decreases with increasing time scale. However, despite errors in meteorological variables, the estimation error in ET_o, ET_{c_corn}, ET_{c_alf}, IRn_{corn}, and IRn_{alf} at a daily time and, of course, monthly and annual scale is within an acceptable range.

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