Derived crop coefficients for winter wheat using different reference evpotranspiration estimates methods

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Derived Crop Coefficients for Winter Wheat Using Different Reference Evpotranspiration Estimates Methods

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ABSTRACT

This paper reports the results of using three empirical methods (Makkink, Priestley-Taylor and Hargreaves) for estimating the reference evapotranspiration (ET_0) in the semi-arid region of Tensift Al Haouz, Marrakech (center of Morocco). The Penman-Monteith equation, standardized by the Food and Agriculture Organization (FAO-PM), is used to evaluate the three empirical methods. The obtained ET_0 data were used to estimate crop water requirement (ET) of winter wheat using the crop coefficient (K_c) approach and results were compared with ET measured by the Eddy Covariance technique. The result showed that using the original empirical coefficients a, α and C_m in Hargreaves, Priestley-Taylor and Makkink equations, respectively, the Hargreaves method agreed fairly well with FAO-PM method at the test site. Conversely, the Priestley-Taylor and Makkink methods underestimate the ET by about 20 and 18 %. After adjustment of the original values of two parameters α and C_m coefficients in Priestley-Taylor and Makkink equations, the underestimation of ET was reduced to 9% and 4% for the Priestley Taylor and Makkink methods, respectively, which led to an improvement of 55% and 76% of the obtained values compared with the original values.

Keywords: Crop water requirement, Eddy covariance, Empirical method, Semi-arid Environment.

INTRODUCTION

Accurate estimation of crop water requirements in the arid and semi-arid regions is crucial and important for a sound water-use efficiency. Indeed, semi arid regions are characterized by a water scarcity that is amplified by inefficient irrigation practices. Several research programs have been designed to develop tools to support efficient management of irrigation water in arid and semi-arid zones. SUDMED (Chehbouni *et al.*, 2008) project is among those programs taking place in central of Morocco, Tensift basin (typically semi-arid region), to asses the spatio-temporal variability of water needs and consumption for irrigated crops under shortages.

Crop water requirements vary over the growing cycle, mainly due to variations in crop canopy and climatic conditions, and are governed by crop evapotranspiration (ET). Accurate estimation of crop ET is important for efficient water management. It is generally agreed that the Eddy Covariance (EC) technique is the most accurate means of measuring ET (Ezzahar *et al.*, 2007; Hoedjes *et al.*, 2007), but this method has its shortcomings. The system is expensive, and requires well trained staff to operate and

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maintain it. This leads the scientific community to look for an alternative method to estimate ET.

Due to its simplicity, the FAO-56 methodology (Allen *et al.*, 1998) can be considered as a very attractive method for routine estimates of ET (Er-Raki *et al.*, 2007). This method is based on the calculation of reference evapotranspiration ET_0 and subsequent calculation of crop evapotranspiration as ET=K_c* ET_0, with K_c being the crop coefficient.

Reference evapotranspiration can be estimated by many methods ranging from simple to more complex. Some of these methods are empirically based on solar radiation (Makkink, 1957; Priestley and Taylor, 1972), on temperature (Hargreaves and Samani, 1985), and others are based on the combination of climatic parameters (Penman, 1948; Monteith, 1965; Doorenbos and Pruitt, 1977; Allen *et al.*, 1998, 2006). The FAO Penman–Monteith equation (Allen *et al.*, 1998, 2006) is suggested by the Food and Agriculture Organization of the United Nations (FAO) as the standard method to estimate ET_0, as it gives more accurate ET_0 estimates than other methods (Allen *et al.*, 1998; De Bruin and Stricker, 2000; Hussein and Al-Ghobari, 2000; Kashyap and Panda, 2001). However, this method requires the measurements of several meteorological variables (air temperature, relative humidity, solar radiation and wind speed), which are not always available, especially in developing regions. The lack of meteorological data leads to the adoption of approaches to estimate ET_0 that require less climatic parameters. In this context, Jensen *et al.* (1990) reported a major study where they analyzed the performances of 20 methods for estimating the ET_0 under different climatic conditions. In this study, three empirical equations of ET_0 estimates: Makkink (Mak) and Priestley-Taylor (PT), radiation-based, and Hargreaves (HARG), temperature-based, were applied to estimate ET_0 and the crop water requirement of winter wheat. Because of their empirical natures, these three methods require local calibration and evaluation prior to their applications (Jensen *et al.*, 1997; Xu and Singh, 2002; Er-Raki *et al.*, 2008).

The second term for estimating crop water requirement is the K_c, which depends on the crop and its growing stages. It is worth highlighting that the K_c is affected by all the factors that influence soil water status, for instance, the irrigation method and frequency (Doorenbos and Pruitt, 1977; Wright, 1982, Allen *et al.*, 1998), the weather factors, the soil characteristics, and the agronomic techniques that affect crop growth (Annandale and Stockle, 1994). The K_c values, for many crops under different climatic conditions, have been reported in Doorenbos and Pruitt (1977) and Allen *et al.* (1998). These values are commonly used in regions where the local data are not available. However, it is necessary to develop locally adjusted crop coefficients under different climatic conditions.

In this study, an effort is made to evaluate the local values of K_c for the wheat in the central part of Morocco using the three empirical equations cited above. Wheat is considered as the main cultivated crops in this semi-arid region. The obtained values of Kc were used to examine the daily and seasonal changes in evapotranspiration (ET) for winter wheat.

MATERIALS AND METHODS

Experimental site and plant

The data used in this study were obtained from two experiments conducted in the central Morocco, Haouz plain (31°68'N, 7°38'W, altitude 550m), during the 2002/03 and 2003/04 winter wheat growing-seasons. Wheat was planted on January 14, 2003 during 2002/03 season and on December 19 during 2003/04 growing season. In this section, site description and experimental set-up are summarized; the reader is referred to Er-Raki *et al.* (2007) for a complete description.

An automatic meteorological station, located close to the experimental site, recorded half-hour values of rainfall (FSS500 tipping bucket automatic rain gauge, Campbell Inc., USA), air temperature and relative humidity (HMP45C, Vaisala, Finland), wind speed (A100R anemometer, R.M. Young Company, USA) and incoming global solar radiation (CNR1, Kipp & Zonen, Netherlands). The data of these climatic parameters is presented in Fig.1. As shown in the figure, the solar radiation was clearly affected by cloud cover, especially during 2003/04 (from December to May). It ranged from 4 to 29 MJ/m^2/day with an average of 18 MJ/m^2/day and from 3 to 26 MJ/m^2/day with an average of 15 MJ/m^2/day in 2002/03 and 2003/04 cropping seasons, respectively. Average air relative humidity is partially affected by solar radiation, it was about 58% and 66% for 2002/03 2003/04, respectively. Wind speed remained almost constant during the two growing seasons around 2m.s^{-1}. Instantaneous rise in daily values of wind speed at different times are recorded. The slight difference observed between climates of the two growing seasons leads also to a slight difference in ET_0. The latter, estimated from December to May by the FAO-PM method, was about 570 and 520 mm during 2002/03 and 2003/04 respectively.

Precipitation patterns over the two growing seasons were characterized by low and irregular rainfall events with a total precipitations of 213 mm and 195 mm in 2002/03 and 2003/04, respectively (Figure 1). The irrigations were given by flooding in four times (30 mm each) in 2002/03 and in three times (60 mm each) in 2003/04.

Evapotranspiration

The wheat evapotranspiration ET was measured by the Eddy Covariance system at 2m located at the centre of the field in order to obtain the longest unobstructed wind fetch. This system was consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT) and an open-path infrared gas analyzer (LI7500, Li Cor, Inc., Lincoln, NE). A CR5000 data loggers (Campbell Scientific Ltd) was used for the storage of raw 20 Hz data. The half-hourly fluxes were later calculated off-line using Eddy Covariance processing software 'ECpack', after performing all the required adjustments for planar fit correction, humidity, and oxygen (KH20), frequency response for slow apparatus, and path length integration (Van Dijk *et al.*, 2004). The software is available for download at http://www.met.wau.nl/. As reported by (Duchemin *et al.*, 2006), the approximate fetch (spatial scale) of ET measurement is between 100 m^2 to few ha, depending on wind speed.

One tool to quantify the reliability and accuracy of the Eddy Covariance data is to test for closure of the surface energy balance. By ignoring the term of canopy heat storage and assuming the principle of conservation of energy, the energy balance closure is defined as $R_n - G = H + ET$

Where R_n is the net radiation, G is the soil heat flux and H and ET are, respectively, the sensible and latent heat (or evapotranspiration) fluxes derived from the Eddy Covariance system. By plotting Rn-G against H+ET for the two wheat growing seasons (data not shown here), the linear regression (forced trough the origin) was obtained as follows:

$$H + ET = 0.78 * (R_n - G)$$

with R^2=0.94 and the Root Mean Square Error RMSE= 61 W m^{-2} for the 2002/03, and

$$H + ET = 0.73 * (R_n - G)$$

with R^2=0.91 and RMSE=69 W m^{-2} for the 2003/04 growing season. It is clear that the EC measurements underestimate the available energy during both seasons. However, compared to what has been reported in other experimental studies (the average error in closure ranges from 10% to

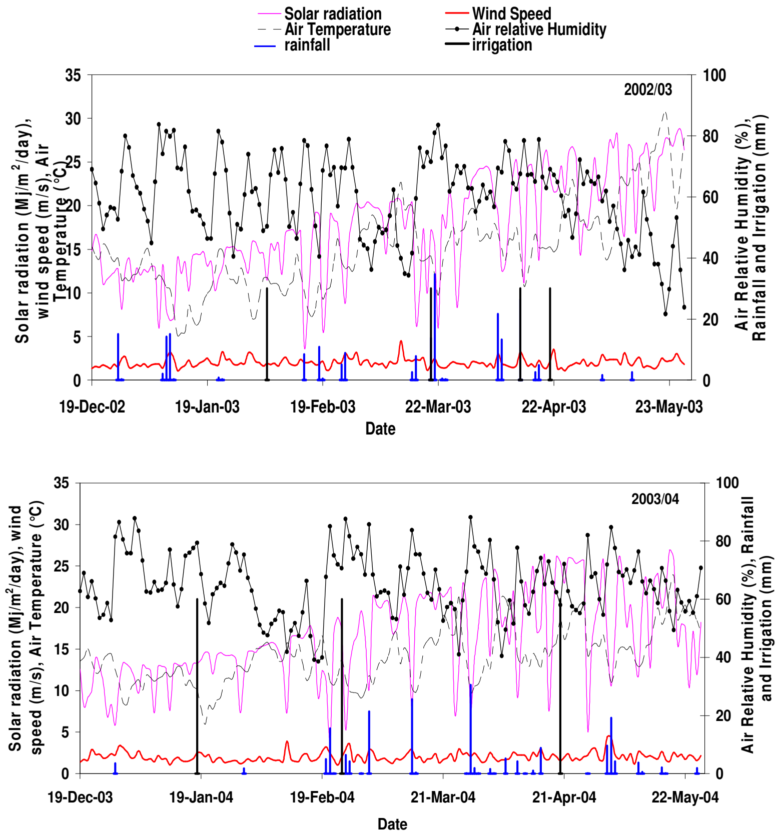

Figure 1. Variation in climate during the experimental periods of December-May over two growing seasons. Precipitation distribution and irrigation events are shown.

30% according to Twine *et al.,* 2000), the energy balance closure obtained here can be considered acceptable. In what follows, the ET at a daily time scale was calculated as the summation of the half hourly values.

Crop coefficient

The measured wheat ET together with reference evapotranspiration (ET_0) were used to calculate the crop coefficients ($K_c = \frac{ET}{ET_0}$). ET_0 was estimated by different methods (Appendix A). The entire growing season of wheat was divided into four growth stages namely: the initial (l_{ini}), the development (l_{dev}), the midseason (l_{mid}) and the late season (l_{late}). The lengths of growth stages were computed according to the FAO-56 method as a fraction of vegetation cover f_c. The initial stage runs from sowing date to when f_c = 0.1, the development stage runs from f_c = 0.1 to full vegetation cover (f_c of 0.9), the mid-season stage runs from the end of the development stage until canopy cover f_c drops back to the same value it had at the end of the development stage and the beginning of the mid-season period (f_c = 0.9). The late season stage runs from end of the mid-season stage until the end of growing season. When f_c does not reach 1, the mid-season stage can be assumed to have started when f_c became equal to 90% of the maximum f_c value reached. Thus three critical K_c values are required to generate the entire K_c curve, namely the K_c during the initial period, K_{cini}, the K_c during the midseason, K_{cmid}, and the K_c at the end of the growth season, K_{cend}. f_c values were derived from the hemispherical canopy photo (Er-Raki *et al.*, 2007) in order to determine the lengths of crop development stages (l_{ini}, l_{dev}, l_{mid}, l_{late}) which are, respectively, 42, 32, 36, and 24 days for 2002/03 and 26, 38, 61 and 36 for 2003/04 growing season.

RESULTS AND DISCUSSIONS

Measured crop evapotranspiration

Figure 2 presents the daily pattern of measured ET for the two wheat growing seasons. ET values ranged between 1.43 and 6.25 and between 0.24 and 3.11 mm per day for 2002/03 and 2003/04, respectively. The magnitude of daily ET was the lowest during the initial stage of growth. It increased continuously up to the mid season stage and decreased during the maturity stage. Instantaneous clear rise in ET values indicate the irrigation or rainfall events (Figure 1). The values of daily ET were lower during the 2003/04 growing season in comparison to those during 2002/03. Indeed, the 2003/04 growing season was characterized by several cloudy days and relatively high air relative humidity (Figure 1). Also, the invading wild oat in wheat growing during 2002/03 season led to higher plant transpiration and the highest crop evapotranspiration (Duchemin *et al.*, 2006).

Estimated crop evapotranspiration

In a previous paper (Er-Raki *et al.*, 2008), the three empirical equations (Appendix A. 2-4) were evaluated and calibrated to estimate ET_0 in comparison to the FAO Penman-Monteith equation under the environmental conditions of the Tensif basin (central of Morocco). Using the original empirical coefficients a, α and C_m in, respectively, HARG, PT and MAK equations, the comparison with the FAO-PM method showed a good agreement for the HARG method and a large deviation for the PT and MAK methods. Therefore, calibration of the two parameters α and C_m in the PT and MAK equations was needed. The same work showed that these two parameters could be adjusted by a linear regression with relative humidity (Er-Raki *et*

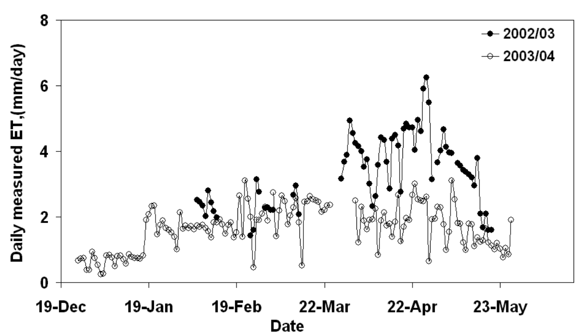

Figure 2. Seasonal changes in daily crop evapotranspiration, measured by Eddy Covariance technique, for both winter wheat seasons 2002/03 and 2003/04 in central Morocco. Some data was missed during the initial stage in 2002/03 growing season and in some other days in the two seasons.

al., 2008). Consequently, using the new locally adjusted coefficients, a good improvement was observed in the estimation of ET_0 i.e. closer to the estimates of the FAO Penman-Monteith equation.

The K_c values suggested by Allen *et al.* (1998) were used to calculate ET using the different ET_0 resulting from the four methods (HARG, PT, MAK and FAO-PM). Cumulative crop water requirements (ET) over 160 days (2003/04 winter wheat season) from three empirical methods (adjusted and unadjusted) were computed and compared with that of FAO-PM (Table 1). The ET estimated by using the HARG method with the original value (0.0023) was very close to that estimated from FAO-PM; the relative difference was less than 1%. On the contrary, the PT and MAK methods with unadjusted parameters α and C_m underestimated the crop water requirement by about 20% and 18% (98 and 85 mm), respectively, in comparison to that estimated by FAO-PM. These values represent about 50% of the amount of water supplied by irrigation (180mm) in the winter wheat season 2002/03. After adjustment of the original value of the two parameters α and C_m, the underestimation of crop water requirement was reduced to 9% and 4% (Table 1) for the PT and MAK methods, respectively, which means an improvement of 55% and 76% of the values obtained with unadjusted values. These results show the importance of adjusting empirical equations, such as the PT and MAK in the present study, which affects crop water requirement.

Crop coefficient

Improvement of the above-mentioned calculation of ET can be achieved through local calibration of K_c. Firstly, a comparison between the measured ET and the estimated one as the product of ET_0 (using different methods cited in the Appendix) and K_c suggested by Allen *et al.* (1998) was reported in Figure 3 for the two growing seasons (2002/03 and 2003/04). According to this figure, the $K_c \times ET_0$ approach underestimates ET at the initial stage of wheat during 2002/03 season in the wetting events (from February 5th through February 12th , 2003) regardless of the method used for calculating ET_0. This is because the single crop coefficient approach was used, which does not estimate correctly the soil evaporation that is very high and the measured ET showed the typical rising pattern (Allen *et al.*, 1998). In 2003/04 growing season, the $K_c \times ET_0$ approach tends to overestimate ET value. This overestimation can be explained by the combination of two factors. First, the use of the original values of K_c established by Allen *et al.* (1998) that are not appropriate for the environmental conditions of the present site. Second, the water stress coefficient that is not taken into account by the approach for estimating ET. By comparing the performances of the three empirical methods for estimating ET, the HARG method is the best one to estimate ET during the two growing seasons. The Root Mean Square Error between the measured and the estimated ET values for this method was the lowest during the two growing seasons in comparison to the other methods. It was about 1.04 and 1.75 mm/day

Table 1. Crop water requirements of winter wheat during 2003/04 calculated as the product of crop coefficient given in Allen *et al.* (1998) and reference evapotranspiration estimated by different methods before and after the adjustment.

	Method			
Crop water requirement(mm)	FAO-PM [a]	HARG [b]	PT [c]	Mak [d]
Unadjusted	481	479	383	396
Adjusted	--	--	438	461

[a] Food and Agriculture Organization, [b] Hargreaves method, [c] Priestley-Taylor method , [d] Makkink method

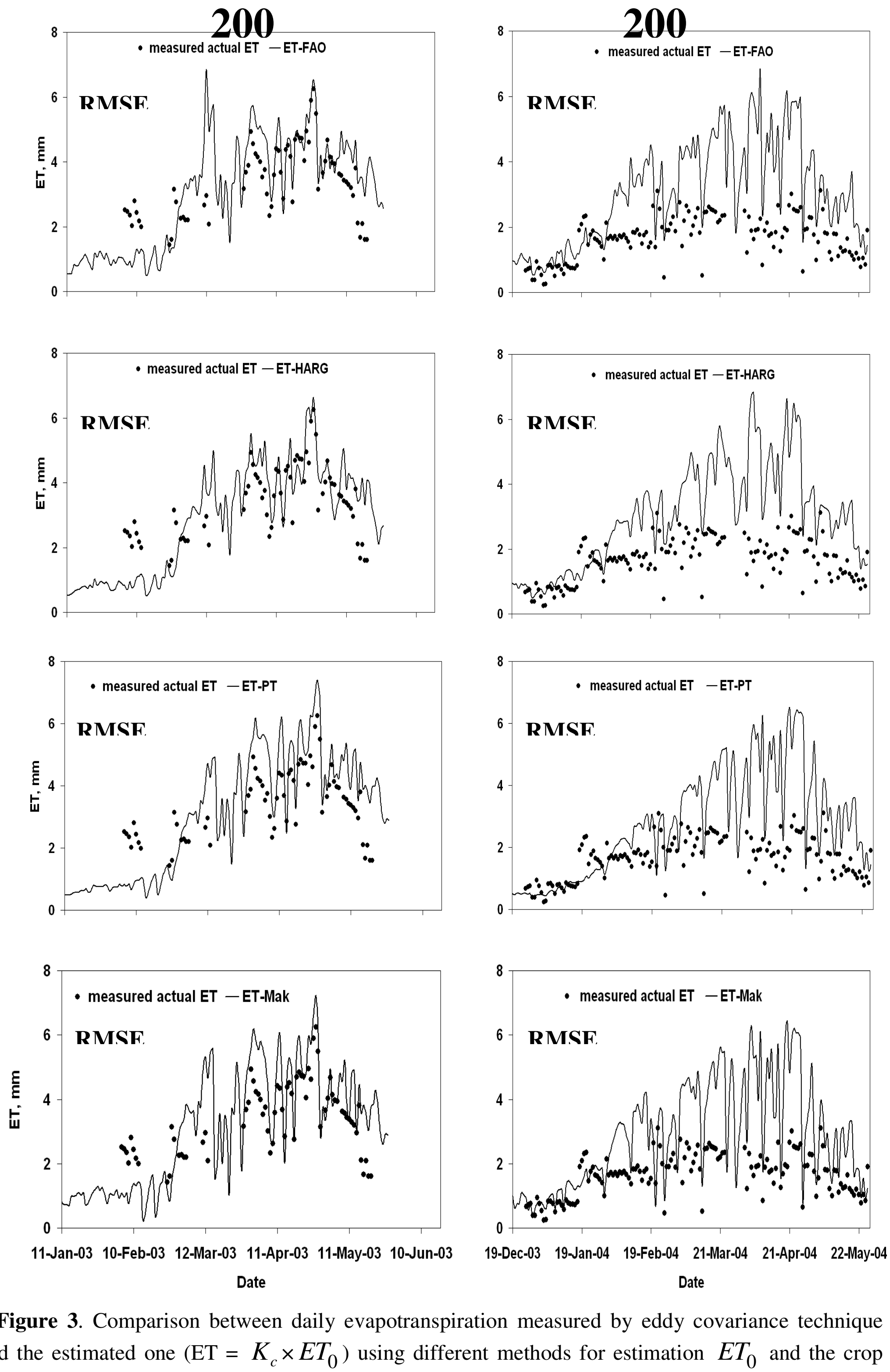

Figure 3. Comparison between daily evapotranspiration measured by eddy covariance technique and the estimated one (ET = $K_c \times ET_0$) using different methods for estimation ET_0 and the crop coefficients proposed by the FAO-56 (Allen *et al.*, 1998) for winter wheat during 2002/03 and 2003/04 growing seasons.

for 2002/03 and 2003/04, respectively.

Although the $K_c \times ET_0$ approach is often preferred for calculating crop water requirements and irrigation scheduling due to its simplicity and, easy applicability for operational purposes, it tends to overestimate ET by about 12%, 7%, 19%, and 16% when using, respectively, FAO-PM, HARG, PT and MAK for estimating ET_0 in 2002/03 season and by, respectively, about 85%, 96%, 83%, and 92% in 2003/04 season.

Therefore, one should be cautious in applying the $K_c \times ET_0$ approach with the crop coefficient values reported in the literature since this may lead to significant uncertainties in estimating water need and consumption and, thus, crop yield. Locally determined K_c values are necessary to estimate the actual ET more accurately.

Figure 4 displays the behaviour of daily K_c for the two growing seasons. These values are calculated as the ratio of daily measured ET and estimated daily ET_0 by the different methods for estimation ET_0. The magnitude of daily K_c for all methods was the lowest during the initial stage. It increased continuously up to the development stage and decreased during the maturity stage. In some days (irrigation events), K_c values are higher than 1.2, reflecting the flooding irrigation technique (soil evaporation). The range of these maximal values for K_c is consistent with other studies. Allen *et al.* (1998) reported the upper limit of the evaporation and transpiration from any cropped surface ranging from 1.05 to 1.3.

Stage wise K_c values for winter wheat, relative to the four methods used for estimation ET_0 and those recommended by Allen *et al.* (1998) in the two growing seasons are presented in Figure 5. Note that for 2002/03 wheat season, there are no values for crop coefficient at the initial stage due to the missing of ET measurements at this stage (Figure 3). In the 2003/04, the K_c values recommended by Allen *et al.* (1998) were found to be higher than those estimated by all the other methods at the initial stage (Figure 5). This can be explained by the low soil evaporation at this stage due to the absence of irrigation and rainfall events (Figure 2). The K_c values at the mid season stage estimated by the four methods in the two wheat seasons were found to be lower than that given by Allen *et al.* (1998), especially during 2003/04 (about 50%). This reduction in K_c value suggests that the wheat crop was not growing in optimal conditions. This is due to stresses induced by shortage of water and nitrogen that affect the growth of wheat (Bandyopadhyay and Mallick, 2003). Another study made by Hadria *et al.* (2007) showed that the grain yield in 2002/03 was about 2 q/ha whereas the optimal yield for the same variety and in the same region was about 6.5 q/ha. At the late season, the K_c values given by Allen *et al.* (1998) were in general closer to the estimated K_c values especially in 2003/04 wheat season. Invasion by a wild oat in wheat growing in 2002/03 season led to a slight overestimation of the crop coefficient compared with that of Allen *et al.* (1998). In comparison to the FAO-PM method, the HARG method gave close K_c values at the three growing stages.

CONCLUSIONS

The following conclusions were drawn from the results of the study:

The measured ET values were found to be between 1.43 and 6.25 mm per day for the sunny season of 2002/03, and it ranged between 0.24 and 3.11 mm per day for the cloudy season of 2003/04.

Comparison with the K_c values recommended by FAO-56 revealed that the K_c values at the mid season stage estimated by the four methods used for estimation ET_0 were found to be less than those given by Allen *et al.* (1998), especially during the cloudy season of 2003/04. This reduction in K_c values suggests that the wheat crop was not growing under optimal growing conditions in terms of water and nutrient. For determination of the actual estimates of ET and an accurate estimate of K_c , attempts should be made to get information about plant water stress.

In the absence of adequate climatic data for FAO-PM method, the Hargreaves method gave the best estimation of the crop coefficient at three growing stages.

Appendix A

Many equations are used to estimate reference evapotranspiration ET_0. They can be divided in two main groups, i) those that are empirical and have limited data requirements, and ii) those that have a sound physical basis and require extensive data. In this study, we chose four methods for estimation ET_0 depending on the available climatic data: The first one is the FAO-Penman Monteith (Allen *et al.*, 1998), which uses several climatic data such as: air temperature and relative humidity, solar radiation, and wind speed (Eq. A.1). The second one is the Priestley Taylor equation (Priestley and Taylor, 1972), which requires net radiation and air temperature data (Eq. A.2). The third one is the Makkink method (Makkink, 1957), which requires solar radiation and air temperature (Eq. A.3). The last method is the Hargreaves equation (Hargreaves and Samani, 1985), which requires only the air temperature (Eq. A. 4). These four methods are expressed as follows:

$$ET_0\_FAOPM = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad \text{(A.1}$$

$$ET_0\_PT = 0.408 \frac{\alpha \, \Delta \, (R_n - G)}{\Delta + \gamma} \quad \text{(A.2}$$

$$ET_0\_Mak = 0.408 \frac{C_m \, \Delta \, R_s}{\Delta + \gamma} - 0.12 \quad \text{(A.3}$$

$$ET_0\_HARG = 0.408 * a \, (T_a + 17.8)(T_{\max} - T_{\min})^{0.5} R_a \quad \text{(A.4}$$

Where ET_0 is expressed in [mm/day]; R_s is the solar radiation [MJ/m^2/day]; R_n and R_a are net radiation and extraterrestrial radiation, respectively, [MJ/m^2/day] computed as described by Allen et al. (1998); G is the soil heat flux density [MJ/m^2 /day], which is assumed to be 0 in daily time step; T_a is the daily air temperature at 2 m height [°C]; u_2 is the wind speed at 2 m height [m/s]; e_s is the saturation vapour pressure [kPa]; e_a is actual vapour pressure; Δ is the slope of the vapour pressure curve [kPa/°C] and γ is the psychrometric constant [kPa/°C]. The value of e_s is computed as: $e_s = \frac{e°(T_{\max}) + e°(T_{\min})}{2}$, where e^0 ( ) is the saturation vapour function and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperatures, respectively. The value 0.408 in Eq 2-4 corresponds to the conversion factor from [MJ/m^2/day] to mm/day. The parameters α, C_m and a in, respectively, equations (A.2), (A.3) and (A.4) are empirical constants. Their original values are 1.26, 0.61 and 0.0023, respectively (Priestley and Taylor, 1972; McAneney and Itier, 1996; Makkink 1957; Allen *et al.*, 1998).

Before applying these three empirical methods, local calibration of the three empirical parameters coefficient in equations (A. 2), (A. 3) is required (Er-Raki *et al.*, 2008). The test of these methods with their original values under the environmental conditions of the Haouz plain, in the central part of Morocco, showed that the HARG method estimated ET_0 correctly, against the FAO-PM equation as a standard method, while the performance of the other two empirical methods was poor, except in humid periods (Er-Raki *et al.*, 2008). The calibration of the two parameters (α and C_m) is needed. These values have been adjusted by a linear regression with relative humidity (Er-Raki *et al.*, 2008).

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استخراج ضرایب گیاهی برای گندم زمستانه با استفاده از روش‌های مختلف برآورد تبخیر و تعرق مرجع

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چکیده

در این مقاله نتایج به کارگیری سه روش تجربی برآورد تبخیر و تعرق مرجع (ماکینک، پرایستلی-تیلور، و هارگریوز) در مناطق نیمه خشک تنسیف الحوض (مرکز مراکش) گزارش شده است. معادله پنمن مانتیث که به وسیله FAO استاندارد شده است برای ارزیابی نتایج سه روش به کار رفته است. داده‌های به دست آمده تبخیر و تعرق مرجع و بر اساس روش ضریب گیاهی برای برآورد نیاز آبی گندم زمستانه به کار رفت و نتایج با مقادیر اندازه گیر شده تبخیر و تعرق با استفاده از روش ادی کوواریانس مورد مقایسه قرار گرفت. بر اساس استفاده از مقادیر اصلی ضرایب ارائه شده در معادلات، در محل اجرای مطالعه روش هارگریوز نسبت به دور روش دیگر (پرایستلی-تیلور و ماکینک) انطباق بهتری با روش پنمن مانتیث فائو نشان داد. درحالی که روش‌های پرستلی تیلور و ماکینک تبخیر و تعرق را به ترتیب به میزان بیست درصد و هیجده درصد کم‌برآورد کرده است. اما پس از تعدیل پارامترهای فرمولهای یاد شده مقادیر کم‌برآورد روش‌ها به نه در صد و چهار درصد تقلیل یافت که نشان می‌دهد بهبود قابل توجهی در برآورد مقادیر اصلی به میزان ۵۵٪ و ۷۶٪ صورت گرفته است.