Agricultural Water Management 131 (2014) 135–145

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

An innovative remote sensing based reference evapotranspiration method to support irrigation water management under semi-arid conditions

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ARTICLE INFO

Article history:
Received 4 March 2013
Accepted 19 September 2013
Available online 19 October 2013

Keywords:
Reference evapotranspiration
Remote sensing
Meteosat Second Generation
Penman–Monteith FAO56
Irrigation water requirements
AquaCrop

ABSTRACT

Reference evapotranspiration (ET_o) is an essential component of irrigation water management due to it being a basic input for estimating crop water requirements. Multiple approaches have been identified for ET_o assessment but most of them are based on daily meteorological data provided by weather station networks that provide an accurate meteorological characterization. A new alternative approach called MA + LSE based on the Makkink-Advection (MAK-Adv) equation in combination with remotely sensed solar radiation and a numerical weather forecast of near surface air temperature has provided good estimates of ET_o under different weather conditions in a semi-arid region located in Southern Spain, without requiring local meteorological data.

In order to evaluate the utility of the MA + LSE approach for irrigation water management, some well-known methods for ET_o assessment and the MA + LSE approach were considered for the development of irrigation schedules in ten irrigation schemes located in a semi-arid region in Southern Spain. The impact of the approach considered for ET_o assessment on irrigation scheduling and on simulated yield for a maize crop was determined. Thus, MA + LSE and Hargreaves methods generated similar irrigation schedules and estimated yield to those determined by using ET_o from the Penman–Monteith (PM-FAO56) approach. Thus, average seasonal irrigation volume estimated by MA + LSE was underestimated by around 2.6%, causing a yield reduction of 2.2% compared with the irrigation scheduling based on PM-FAO56. These results confirm the applicability of the MA + LSE approach, especially in areas where meteorological data are missing or inaccurate, obtaining a similar performance for irrigation water management to that of other approaches with high data requirements such as PM-FAO56.

1. Introduction

In arid and semi-arid Mediterranean environments a very significant percentage of the available water resources is consumed by irrigated agriculture. Thus, in Spain, about 83% of the water resources is devoted to irrigation, and the rest to other uses (CAP, 2011). However, this distribution of the available resources could vary significantly in the next decades due to an increase in the water requirements of other sectors such as the environment, and a foreseen reduction in rainfall from climate change effects in Southern Europe (Christensen and Christensen, 2007). In this context of maximum competitiveness for water resources, a correct irrigation management is essential to ensure the sustainability of the Mediterranean irrigated areas.

Reference evapotranspiration (ET_o) is one of the key inputs for determining proper irrigation water management. The concept of reference evapotranspiration was introduced to estimate crop water requirements combined with tabulated crop coefficients (Allen et al., 1998). The methodology, described in Allen et al. (1998), based on a version of the Penman–Monteith equation, is considered to be the standard procedure for ET_o assessment and it obtains a satisfactory performance under advective conditions (Berengena and Gavilán, 2005), but with a high level of data requirements, complicating its application in areas with unavailable, missing or inaccurate meteorological data. For these reasons, ET_o estimation has long been a critical issue that has concerned researchers, technicians, and qualified farmers, so alternative methodologies requiring lower cost observations have been developed in the past.

The Penman–Monteith equation (Allen et al., 1998) has been widely used and has been demonstrated as producing the most

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http://dx.doi.org/10.1016/j.agwat.2013.09.017

accurate estimations when compared with lysimeter measurements in Mediterranean environments (Berengena and Gavilán, 2005; López-Urrea et al., 2006). However, the need for gathering a relatively large number of variables (e.g., relative humidity of the air, solar radiation or wind speed) under reference conditions, which are generally difficult to measure with any accuracy, limits the widespread use of this equation (Pereira and Pruitt, 2004). It has often been substituted by approaches with lower input requirements such as Hargreaves, Makkink or Priestley–Taylor equations (Gavilán et al., 2006; De Bruin et al., 2010; Espadafor et al., 2011). However, the use of simpler approaches for ET_o assessment with a lower level of data requirements could affect correct irrigation water management, obtaining irrigation schedules of a poorer quality with a negative impact on water savings and yield.

The contribution of remote sensing techniques to the improvement of water management at a basin scale has increased significantly in the last few years. Remote sensing tools allow the obtainment of accurate information of surface and atmospheric conditions for vast areas. The most advanced approaches have been focused on the determination of crop evapotranspiration (ET_c) using energy balance models (Bastiaanssen et al., 1998; Allen et al., 2007a,b; Ghilain et al., 2011, 2012). These approaches have provided relevant information on crop water requirements, enabling the improvement of agricultural water management (Santos et al., 2008, 2010), the monitoring of drought (Sun et al., 2011), and the analysis of the spatial and temporal variability of the vegetation (Stisen et al., 2008a; Ghilain et al., 2012). Studies for estimating ET_o have been less numerous, although, recently, De Bruin et al. (2010) and Cruz-Blanco et al. (2014) have demonstrated that geostationary satellite data can be used to determine accurate ET_o values for vast areas.

Methodologies considering remote sensing and forecast tools for ET_o assessment have been used with success in different semi-arid environments (De Bruin et al., 2010; Ghilain et al., 2011; Cristobal and Anderson, 2012; Cruz-Blanco et al., 2014), but the determination of the impact of these methodologies on irrigation water management, particularly under semi-arid conditions, is still required. Therefore, the main objective of the current study was to evaluate the impact of these new approaches for ET_o assessment on the generation of irrigation schedules, a key component for a sound irrigation water management. For this task, maize, a relevant crop in the irrigated areas in Andalusia, Southern Spain, has been considered. The study covers the period 2007–2009 and includes ten irrigation schemes located throughout Southern Spain (Fig. 1) in order to consider their impact under different weather conditions.

2. Material and methods

2.1. EUMETSAT LSA SAF and ECMWF products

The EUMETSAT Satellite Applications Facility for Land Surface Analysis (LSA SAF) is part of the SAF network, a set of specialized development and processing centers serving the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) (Trigo et al., 2011). The main objective of LSA SAF is the development of remote sensing applications relevant to land surface processes and biosphere applications, such as the case of daily solar radiation at the surface. Within the LSA SAF, this component corresponds to the so-called daily down-welling surface shortwave radiation flux (DIDSSF), determined from the accumulation of 30-min observations provided by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer, on board Meteosat Second Generation (MSG; Schmetz et al., 2002). DIDSSF refers to the daily accumulation of 30-min radiative energy flux in the wavelength interval 0.3 μm–4 μm (Geiger et al., 2008; Trigo et al., 2011). EUMETSAT LSA SAF has an internal quality control for each datum provided (Trigo et al., 2011). In the case of DIDSSF, the quality indicator includes the number of missing slots within the corresponding 24 h period. These data are available in near-real-time (http://landsaf.meteo.pt) at the MSG pixel resolution (3 km at nadir; Trigo et al., 2011), covering an area encompassing Africa, most of Europe and part of South America.

Air temperature at 2 m (T_{2m}) was obtained from the operational forecasts provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The initial 3-hourly T_{2m} forecasts at a resolution of about 25 km were linearly interpolated in time to hourly ones, and bi-linearly interpolated in space to the SEVIRI/MSG resolution. The T_{2m} values underwent a further adjustment to correct differences between ECMWF model surface orography and the finer scale SEVIRI pixel altitude, using a constant slope rate of 0.0067 °C m^{-1} (De Bruin et al., 2010). A detailed full-description of ECMWF data is available in Persson (2011).

2.2. Selected irrigation schemes and meteorological data

Ten irrigation schemes were considered in this study to quantify the impact of different approaches for ET_o assessment on irrigation scheduling. These irrigation schemes are located in the main maize areas in Andalusia, Southern Spain (Fig. 1), and showed significantly different climate conditions (average rainfall ranged between 437 and 641 mm year^{-1} and average temperature between 14.5 and 18.5 °C).

Daily meteorological data obtained from ten weather stations located close to the selected irrigation schemes were used in the study (Fig. 1). These stations are included in the Agroclimatic Information Network of Andalusia (RIA), which is currently composed of 100 automatic weather stations. This network was deployed to provide coverage to most of the irrigated areas with the aim of supplying ET_o values and other meteorological data to improve irrigation water management (Gavilán et al., 2006). These stations are controlled by a CR10X datalogger (Campbell Scientific Inc., Logan, UT, USA) and are equipped with sensors to measure air temperature and relative humidity (HMP45C probe, Vaisala, Helsinki, Finland), solar radiation (pyranometer CM6B, Kipp&Zonen, Delft, Holland), wind speed and direction (wind monitor RM Young 05103, Traverse City, MI, USA) and rainfall (tipping bucket rain gauge ARG 100). Air temperature and relative humidity are measured at 1.5 m and wind speed at 2 m above soil surface. The values collected from each station are checked for validity according to Meek and Hatfield (1994) and Shafer et al. (2000). Daily average values are recorded for each meteorological variable and can be obtained from the Website at www.juntadeandalucia.es/agriculturaypesca/ifapa/ria.

Except Cordoba station (COR_CO) which is placed on a grass reference surface (Berengena and Gavilán, 2005), the rest of the weather stations are located on bare soil, not fulfilling the surface reference requirements determined by Allen (1996) and Allen et al. (1998). However, previous studies have demonstrated the data accuracy although measurements were carried out under non-optimal reference conditions (Cruz-Blanco et al., 2014). In the analyzed period (2006–2009) seasonal rainfall (measured from September to October) varied from 437 mm for Laguna Fuente Piedra irrigation scheme (YEG_MA weather station) to 641 mm for Bajo Guadalete irrigation scheme (JER_CA weather station). Range of ET_o variation measured by the RIA was smaller, varying from 1270 mm year^{-1} for Vegas Bajas irrigation scheme (MAR_JA weather station) to 1419 mm for Viar irrigation scheme (GUI_SE weather station). This characterization depicts the great variability of the analyzed stations, allowing the carrying out of a complete evaluation of different approaches for ET_o assessment for irrigation