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Assessing reference evapotranspiration at regional scale based on remote sensing, weather forecast and GIS tools

J.M. Ramírez-Cuesta, M. Cruz-Blanco, C. Santos, I.J. Lorite *

IFAPA-Centro "Alameda del Obispo", Regional Government of Andalusia, Avda. Menéndez Pidal s/n, P.O. Box 3092, 14080 Córdoba, Spain

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ABSTRACT

Reference evapotranspiration (ET_o) is a key component in efficient water management, especially in arid and semi-arid environments. However, accurate ET_o assessment at the regional scale is complicated by the limited number of weather stations and the strict requirements in terms of their location and surrounding physical conditions for the collection of valid weather data. In an attempt to overcome this limitation, new approaches based on the use of remote sensing techniques and weather forecast tools have been proposed.

Use of the Land Surface Analysis Satellite Application Facility (LSA SAF) tool and Geographic Information Systems (GIS) have allowed the design and development of innovative approaches for ET_o assessment, which are especially useful for areas lacking available weather data from weather stations. Thus, by identifying the best-performing interpolation approaches (such as the Thin Plate Splines, TPS) and by developing new approaches (such as the use of data from the most similar weather station, TS, or spatially distributed correction factors, CITS), errors as low as 1.1% were achieved for ET_o assessment. Spatial and temporal analyses reveal that the generated errors were smaller during spring and summer as well as in homogenous topographic areas.

The proposed approaches not only enabled accurate calculations of seasonal and daily ET_o values, but also contributed to the development of a useful methodology for evaluating the optimum number of weather stations to be integrated into a weather station network and the appropriateness of their locations. In addition to ET_o, other variables included in weather forecast datasets (such as temperature or rainfall) could be evaluated using the same innovative methodology proposed in this study.

1. Introduction

Water shortages caused by climate change and by increased competition for water between sectors have led to a growing interest in improving agricultural water management, especially in arid and semiarid regions. Thus, a number of actions such as the promotion of irrigation advisory services for the accurate assessment of irrigation water requirements (Lorite et al., 2012) or the development of deficit irrigation strategies to reduce the volume of water applied without affecting production (Fereres and Soriano, 2007) have gained prominence in Mediterranean agricultural systems.

Estimating crop water demands requires an accurate assessment of the actual evapotranspiration (ET), defined as the sum of soil surface evaporation and crop transpiration, and the reference evapotranspiration (ET_o), defined as the ET from a hypothetical grass reference crop without water stress (Allen et al., 1998). However, lysimetry under reference conditions is the only way to accurately measure these variables (Vaughan et al., 2007). As an alternative, methods based on field measurements of soil water balances (Chávez et al., 2009; De Bruin et al., 2010), energy balances (Todd et al., 2000; Villa-Nova et al., 2007) or micrometeorology techniques (Er-Raki et al., 2009; Chávez et al., 2009) have been developed. Focusing on reference evapotranspiration (ET_o), simpler estimation methods use numerical approaches based on measured weather data; many such equations have been developed (e.g. Penman-Monteith, Makkink or Hargreaves) and some of which require prior local/regional calibration (Gavilán et al., 2006; Cruz-Blanco et al., 2014a). Due to the wide range of available approaches, and in order to standardize ET_o estimation in different climates, Allen et al. (1998) established the Penman-Monteith equation as the reference method for ET_o assessment. This method has been used with very satisfactory results around the world (Berengena and Gavilán, 2005; Temesgen et al., 2005; Allen et al., 2006). However, weather data measurement must comply with

* Corresponding author.
E-mail address: ignacioj.lorite@juntadeandalucia.es (I.J. Lorite).

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strict rules concerning the location and the physical conditions of the field where the weather station is located, which is not an easy task in semi-arid and arid conditions (Temesgen et al., 1999). Unfortunately, these requirements are not always fulfilled in modern weather station networks, thus generating uncertainties and overestimations in ET_o assessment (Cruz-Blanco et al., 2014a). In addition, weather stations provide local measures, and in many cases, these data are representative of only a very limited area, even at times providing non-valid data for fields located near the weather station. Lastly, often there is a limited number of weather stations and vast areas are located far from well-managed weather stations (Voogt, 2006; Collins, 2011).

In order to overcome such limitations, the interpolation of data from weather stations emerges as a promising approach for assessing ET_o (Alves et al., 2013). There are numerous interpolation methods and many have already been applied to the assessment of weather variables with very satisfactory results from around the world (Martínez-Cob, 1996; Nalder and Wein, 1998; Hart et al., 2009; Li and Heap, 2011). The use of interpolation methods has increased as result of the technological advances made in recent decades, mainly related with the development of Geographic Information Systems (GIS) (Irmak et al., 2010). Numerous studies have been conducted to identify the most accurate interpolation methods for climatic variables estimation (Mardikis et al., 2005; Li and Heap, 2008, 2011; Di Piazza et al., 2011; Keblouti et al., 2012). These studies revealed limitations in the validation process due to the low number of checkpoints and highlighted the difficulty in boosting their numbers. Thus, the use of remote sensing techniques to evaluate the quality of the interpolation methods emerges as a promising alternative, although the number of studies taking such an approach is still very limited (Hart et al., 2009; Wentz et al., 2010).

Remote sensing techniques have contributed significantly to the improvement of water management by providing an accurate estimation of crop evapotranspiration (Bastiaanssen et al., 1998; Allen et al., 2007a,b; Santos et al., 2008, 2010), and reference evapotranspiration (De Bruin et al., 2010; Cruz-Blanco et al., 2014a). This study used the geostationary satellite Meteosat Second Generation (MSG), integrated in the Land Surface Analysis Satellite Application Facility (LSA SAF) tool, which provided accurate ET_o values for vast areas (De Bruin et al., 2010, 2012; Cruz-Blanco et al., 2014a). Thus, the LSA SAF estimated spatially distributed ET_o values throughout the Andalusian region (comprising more than 6000 cells), representing the first time that this tool has been used to validate an interpolation approach.

However, the use of LSA SAF data is not limited to validation purposes; it has also helped provide excellent results in studies related to uncertainty in ET_o estimation (Cruz-Blanco et al., 2015) or to irrigation scheduling at the regional scale (Cruz-Blanco et al., 2014b). There is thus a clear benefit to combining weather data from weather station networks with data from LSA SAF and GIS; they are innovative tools that provide support to technicians and farmers attempting to improve water management at field and regional scale (Lorite et al., 2012). In this study, those approaches were developed and evaluated under semi-arid conditions in the Andalusian region (southern Spain).

2. Materials and methods

2.1. Study area description

The study area was the region of Andalusia in southern Spain (Fig. 1), characterized by a Mediterranean climate, with an annual precipitation ranging from 506 to 725 mm, and an average air temperature ranging from 10 °C in winter to 27 °C in summer. The period under study was from 2007 to 2009.

2.2. The Agroclimatic Information Network of Andalusia (RIA)

The Agroclimatic Information Network of Andalusia (RIA) was established with the main objective of improving irrigation water management in southern Spain by providing accurate daily weather data. The network consists of 100 automated weather stations that cover most of the irrigated regions of Andalusia (Gavilán et al., 2006) although in light of the quality analysis performed by Cruz-Blanco et al. (2014a), only 57 of those weather stations were used in this study (Fig. 1). A quality control procedure was applied to the RIA weather data, involving range, step and persistence tests, as well as internal and spatial consistency tests (Meek and Hatfield, 1994; Shafer et al., 2000).

Daily ET_o data were estimated using the Penman-Monteith equation (Allen et al., 1998) for each weather station for 2007, 2008 and 2009. All the weather stations included in the study are located on bare soil (except one located near Cordoba which is installed on near-reference conditions). Under these non-reference conditions, ET_o values calculated by PM-FAO56 could be affected by overestimations, especially in arid and semi-arid conditions (Allen, 1996; Temesgen et al., 1999; Allen et al., 2002; Cruz-Blanco et al., 2014a), which significantly increases the uncertainty in ET_o assessment when using data from weather station networks (Cruz-Blanco et al., 2015).

Weather stations in regions neighbouring Andalusia are managed differently as they form part of weather station networks owned by different institutions, and even from different countries (to the East, Portugal). This implies differences in instrumentation, quality control tests and methodologies for ET_o assessment.

2.3. ET_o calculated from EUMETSAT LSA SAF

The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) created the Land Surface Analysis Satellite Application Facility (LSA SAF) to allow a more effective use of the collected data from the Meteosat Second Generation (MSG) satellite. The LSA SAF tool estimates ET_o from remotely-sensed daily solar radiation data provided by MSG and from the forecasts for air temperature at 2 m provided by the European Centre for Medium-range Weather Forecasts (ECMWF) (Persson, 2013). Thus, the LSA SAF estimated spatially distributed daily ET_o values for the region of Andalusia with pixel sizes ranging from 3.2 km by 4.2 km (13.44 km^2) to 3.2 km by 4.5 km (14.4 km^2) for southern and northern Andalusia, respectively, for 2007, 2008 and 2009.

In order to adjust these ET_o values to the regional conditions of southern Spain, a calibration process was used involving a weighing lysimeter under near-reference weather conditions. This process considered the Makkink equation developed by De Bruin et al. (2012) and is described in Cruz-Blanco et al. (2014a).

Solar radiation (R_s) and near-surface air temperature (T_{2m}) estimated by MSG and ECMWF, respectively, were validated under the semi-arid conditions of southern Spain. The comparison of measured data by the Cordoba station under near-reference conditions with estimations provided by MSG and ECMWF gave root mean square error (RMSE) values of 1.56 MJ m^{-2} d^{-1} and 1.36 °C, R^2 values of 0.97 and slopes of the linear regressions equal to 0.98 and 0.99, for R_s and T_{2m}, respectively (Cruz-Blanco et al., 2014a). Validation results were similar for the 57 weather stations located throughout the Andalusian region (see Section 2.2), with RMSE values of 1.47 MJ m^{-2} d^{-1} and 1.53 °C for R_s and T_{2m}, respectively (Cruz-Blanco et al., 2015). Following these satisfactory validation results for R_s and T_{2m}, validation of reference evapotranspiration (ET_o) estimated by the LSA SAF shows a similarly accurate per-