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Testing the water balance model criteria using TDR measurements, micrometeorological data and satellite-based information

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ABSTRACT

Aiming at developing real time water balance modelling for irrigation scheduling, this study assesses the accuracy of the soil water balance model CRITERIA, developed by the hydro-meteorological service of the Emilia-Romagna region (Italy). The model consists of (i) an algorithm for coupling the surface flow components (i.e. Richards equation), and (ii) various modules which may be applicable to different topographical and environmental conditions. In this study, CRITERIA was applied to simulate the soil water balance for an orange orchard in semi-arid Mediterranean conditions (Eastern Sicily, insular Italy) during the cropping season 2011.

The model was implemented by varying the evapotranspiration rates (ET) as input; ET fluxes were estimated by using satellite-based approach and the Penman–Monteith expression for reference rates, or were directly measured by the eddy covariance technique and the sap flow heat pulse method for transpiration. Model outputs, in term of soil moisture, were validated with direct measures of volumetric soil water content obtained by time domain reflectrometry (TDR) probes. Results of the study proved the reliability of CRITERIA to reproduce the soil moisture profile at the experimental site. The model performance was significantly high when direct measurements of crop water demand were included as input for model application. The satellite-based approach provided reliable crop evapotranspiration estimates, confirming the utility of the remote sensing techniques as support for water management in agriculture.

1. Introduction

Agriculture is an essential driving force in the management of water use which is currently facing the challenge of supplying the increasing demand for food resulting from current population growth (Martínez-Alvarez et al., 2014). In Europe, 24% of water abstraction is used by agriculture, with huge variations depending on the climatic conditions and the relevance of irrigation practice.

In Southern Europe, often characterized by chronic water scarcity, agriculture is the major user of available resources accounting for 74% of the total water use (Maestre-Valero et al., 2013). The most important countries, in terms of irrigated area, are Spain and Italy, with 4 and 3.1 Mha, which means 31% and 24% of the total European irrigated area, respectively. In countries like Italy agriculture is a very competitive economic activity, but its long-term sustainability is under risk because of the low availability of water resources and the increasing competition with other economic activities (Capra et al., 2013).

Identifying the best management policies in irrigated areas is essential to increase the sustainability of irrigated agriculture (Provenzano et al., 2013). In particular, reliable estimates of soil water content dynamic and crop evapotranspiration rates may help to identifying management strategies under conditions of water scarcity.

Despite the importance of conducting an efficient agriculture water management for optimizing the water source-demand balance, there are still uncertainties in correctly determining the components of the water balance and particularly evapotranspiration (ET). ET is quantitatively the most important component when managing water resources as well as the main driver for the agro-ecosystem productivity (Rana and Katerji, 2000) Without a precise determination of ET it is not possible to (i) improve irrigation effi-

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ciency and (ii) correctly determine the ecosystem water balance required for better prediction of source apportionment of runoff and hence soil erosion, and nutrients leaching to the environment (Donatelli et al., 2003; Marletto et al., 2005; Bittelli et al., 2010). Currently, precise ET measurement is difficult due to the uncertainties in existing methods and in the spatial variability of its magnitude.

Several techniques, such as eddy covariance (EC), Bowen ratio (BR), and weighted lysimeters provide ET measurements, but these are expensive, often limited to small experimental field scales and laborious.

The integration of remotely sensed data into ET models may facilitate the estimation of water consumption in agricultural areas. In particular, the operation of remote sensing-based ET models to hydrology and agriculture has increased in the last few years (Tasumi and Allen, 2007; Minacapilli et al., 2008; González-Dugo et al., 2009; Rallo et al., 2012).

The use of remote sensing to estimate ET_c is presently being developed along reflectance-based crop coefficient and reference ET approach, where the crop coefficient (K_c) is related to vegetation indices (VI_s) derived from canopy reflectance values (Rouse et al., 1974; Huete et al., 1988; Neale et al., 1996; Chavez et al., 2005; Er-Raki et al., 2007, 2013; González-Dugo et al., 2013; Mateos et al., 2013). In particular, in this approach visible and near infrared reflectance measurements are used to compute vegetation indices such as the normalized difference vegetation index (NDVI, Rouse et al., 1974) or the soil adjusted vegetation index (SAVI, Huete, 1988) and these indices can be used to obtain rapid, non-destructive estimates of certain canopy attributes and parameters; one parameter of special interest for water management application is the crop coefficient (K_c) employed the FAO-56 model to derive actual crop ET.

In view of these considerations, and of the importance to provide tools for improving irrigation water management under limited resources availability conditions, this study aims (1) at assessing the performance of the physically based CRITERIA model to simulate the hydrological water balance of agricultural soils and (2) at establishing to what extent evapotranspiration inputs evaluated by techniques characterized by different computational effort, costs and spatial resolution can improve CRITERIA soil water content simulations.

CRITERIA is a mathematical model for the evaluation of cropped soil water balance in a defined territory (Marletto et al., 1993; Marletto and Zinoni, 1996). The model, driven by meteorological, soil and crop data, computes daily soil water balance and auxiliary variables, such as actual evapotranspiration, surface and subsurface runoff and others.

CRITERIA is a scalable model and easily applicable to different approaches. For instance, it is available in 3D version, for detailed water analysis at basin scale, in a one-dimensional approach, for specific agronomical case study, and in a geographic interface (where the domain is subdivided in proper one-dimensional cases), for large scale analysis. It was applied in impact studies as Ensembles project (http://www.ensembles-eu.org/) or the Italian project Agroscenari (http://www.agroscenari.it/). It has been already used in several operational applications on irrigation management such as PTA (Water Protection Plan of Emilia-Romagna region).

Moreover, the model links an empirical approach with few parameters needed to a numeric solution of water fluxes and a detailed description of the rooting system, one of the key factor in a water balance.

CRITERIA, that includes a database with several crops, was already tested in Northern Italy (Emilia-Romagna region) and in USA (Bittelli et al., 2010) but never in typical Mediterranean semi-arid environments where citrus orchards growth and where the assessment of evapotranspiration values is essential to improve the water balance (Licciardello et al., 2011; Cammalleri et al., 2013; Consoli and Vanella, 2014a,b; Cassiani et al., 2015).

In order to verify the performance of CRITERIA, data from an experimental citrus orchard located in Eastern Sicily, insular Italy, were used to test the model. The available ground data set includes meteorological measurements (i.e., hourly shortwave radiation, relative humidity, air temperature, wind speed and direction, and precipitation), micrometeorological mass (H_2O or ET) fluxes from an eddy covariance tower, soil physical properties (i.e., bulk density, texture, soil water retention curves, hydraulic conductivity at saturation), crop transpiration data, soil water content profiles by TDR measurements, agronomic data on the crop main features, supplied irrigation volumes and irrigation timing for the year 2011.

2. Methodology

2.1. The orange orchard test site for CRITERIA application

The test site is a 20-ha orange orchard, planted with 20 year-old trees (*Citrus sinensis*, cv Tarocco Ippolito). The field is located in Lentini (Eastern Sicily, Lat. 37°16′N, Long. 14°53′E) in a Mediterranean semi-arid environment. The planting layout is 4.0 m × 5.5 m and the trees are drip irrigated with 4 in-line drippers per plant, spaced about 1 m, with 16 L h^{-1} of total discharge (4 L h^{-1} per dripper) at a pressure of 100 kPa; the crop is well-watered by irrigation supplied every day from May to October, with irrigation timing of 5 h day^{-1}. Total irrigation, during the monitored season, amounted to 5500 m3 ha−1.

The study area has a mean leaf area index (LAI) of about 4 m^2 m^{-2}, measured by a LAI-2000 digital analyser (LI-COR, Lincoln, Nebraska, USA). The mean PAR (photosynthetic active radiation) light interception is 80% within rows and 50% between rows; the canopy height (h_c) is 3.7 m and the average fraction cover is about 0.70.

The soil characterization was performed via textural and hydraulic laboratory analyses, according to the USDA standards.

In particular, the area, covered by the orange orchard, was divided into regular grids, each having a 18 × 32 m^2 area, where undisturbed soil cores (0.05 m in height and 0.05 m in diameter) were collected at the 0–0.20 m and 0.20–0.40 and 0.40–1.0 m depths for a total 64 soil samples. The undisturbed soil cores were used to determine the soil bulk density, ρ_b (Mg m^{-3}) and the initial water content, θ_i (m^3 m^{-3}), i.e. the θ value at the time of the field campaign. A total of 32 disturbed soil samples were also collected at the 0–0.05 m depth to determine the soil textural characteristics using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium metaphosphate and mechanical agitation (Gee and Bauder, 1986). Three textural fractions according to the USDA standards, i.e., clay (0–2 μm), silt (2–50 μm) and sand (50–2000 μm), were used in the study to characterize the soil (Gee and Bauder, 1986). Most soil textures (i.e., 27 out of 32) were loamy sand and the remaining textures were sandy loam (Aiello et al., 2014).

The undisturbed soil samples were used to determine the soil water retention curve. For each sample, the volumetric soil water content at 11 pressure heads, *h*, was determined by a sandbox (*h* = 0.01, 0.025, 0.1, 0.32, 0.63, 1.0 m) and a pressure plate apparatus (*h* = 3, 10, 30, 60, 150 m). For each sample, the parameters of the van Genuchten (1980, vG) model for the water retention curve with the Burdine (1953) condition were determined (Aiello et al., 2014).

Three soil water content profiles were monitored at the experimental field. Each consists of TDR water content sensors installed horizontally at depths 0.2 (i.e., one probe) and 0.4 (i.e., two probes). TDR measurements were made at 1 h intervals.