Agricultural Water Management 212 (2019) 283–294

Contents lists available at ScienceDirect

Agricultural Water Management

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

Smart irrigation forecast using satellite LANDSAT data and meteo-hydrological modeling

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ARTICLE INFO

Keywords:
Irrigation forecast
Satellite land surface temperature
Meteo-hydrological modelling

ABSTRACT

The paper discusses advances in coupling satellite driven soil water balance model and meteorological forecast as support for precision smart irrigation use in a case study of an operative farm in the South of Italy where semi-arid climatic conditions holds. Crop water needs forecast are computed with the intuitive idea of forcing the soil water balance model with the meteorological model outlooks. Discussion on the methodology approach is presented, comparing, for a reanalysis period between June and September 2014, the forecast system outputs with observed soil moisture and crop water needs. Two main issues are here in emphasized: the characteristic of soil moisture water balance model, that due to its state variables may be directly calibrated and validated using satellite or near sensing land surface temperatures; the accuracy of those forecast meteorological variables that are the most important in driving the soil water and energy balance. The soil water balance model performances are then discussed highlighting the importance of using a model which state variable (the pixel surface equilibrium temperature) is the same as the data detected by satellite (Land Surface Temperature), so that it can be used for calibrating and validating soil hydrological parameters. Model outputs are also validated with a comparison of ground latent and sensible heat fluxes from an eddy covariance station and soil moisture data. Problems insight into the meteorological modeling, such as temporal and spatial scale, and their influence on soil moisture forecast are discussed showing on the base of several observation periods the need to increase the meteorological forcings accuracy for this type of applications.

The obtained results show how the proposed methodology of the forecasting system is able to have a high reliability in soil moisture forecast correctly providing irrigation suggestion.

1. Introduction

Increasing problems of water scarcity indicate the need for a more sustainable approach to water resources management especially in agriculture which is the biggest water consumer: in Europe for around 24% of the total water use, which reaches the 80% in the Southern part of Europe (EEA, 2009) and about 50% in Italy (Zucaro, 2014). Hence, there is the need of operational tools for real-time forecast of irrigation water requirements to promote parsimonious irrigation and a more accurate water management in case of actual or forecasted drought periods, that will result in a mitigation of conflicts in water use among farmers, but also among hydroelectric producers, environmental agencies, tourist activities.

Literature provides several studies on the optimization of irrigation water management starting from the FAO Paper 56 based on crop coefficient (Allen et al., 1998), to water balance modeling and genetic algorithms for optimizing off-farm irrigation scheduling (D'Urso and Menenti, 1995; Roerink et al., 1997; Bastiaanssen et al., 2005; Casa et al., 2009; Ceppi et al., 2014). Different irrigation triggering techniques have been developed in literature based on the deficit between potential and actual evapotranspiration or on a soil moisture threshold. The most common approach based on potential ET relies on the methodology proposed by FAO in 1998 (Allen et al., 1998) which uses the Penman-Monteith equation and the crop coefficient (D'Urso and Menenti, 1995). However, Consoli et al. (2014), among others researches, showed that even with a deficit irrigation (e.g. 50% of the potential evapotranspiration), no changes in crop yield are obtained. Allen et al. (1998) suggested that irrigation should be applied when the readily available soil water (RAW) is depleted and irrigate just enough to get back up to field capacity.

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https://doi.org/10.1016/j.agwat.2018.09.005
Received 15 January 2018; Received in revised form 30 August 2018; Accepted 2 September 2018

In the last years, new studies focus on the coupling of meteorological forecasts and hydrological models for irrigation scheduling, such as the EPIC-PHASE model developed by Cabelguenne et al. (1997), the real-time scheduled irrigations approach in UK by Gowing and Ejieji (2001), the Danish warning system eWarning (Jensen and Thysen, 2003), the real-time forecasts for daily evapotranspiration by (Cai et al., 2007), the PREGI (which is an Italian acronym that means "hydro-meteorological forecast for irrigation management") system for irrigation thresholds (Ceppi et al., 2014); the reference evapotranspiration forecast (Pelosi et al., 2016). However, the effect on hydrological soil moisture of meteorological forecasts accuracy for agricultural applications is still an open issue (Venäläinen et al., 2005; Ceppi et al., 2014); while it has been extensively analyzed for flood forecasts (Kitanidis and Bras, 1980; Berthet et al., 2009; Zappa et al., 2011; Pappenberger et al., 2015).

Moreover, thanks to the diffusion of remote sensing data, especially for vegetation monitoring ((Normalized difference vegetation index) NDVI, (Leaf area index) LAI), an increasing number of applications for irrigation management is now available (D'Urso and Menenti, 1995; Bausch, 1995; Roerink et al., 1997; Bastiaanssen et al., 2000; Belmonte et al., 2005; D'Urso et al., 2010; Forrest et al., 2012). However, for real time applications, remote sensing data have some disadvantages due to the fact that are instantaneous in time, sometimes affected by clouds cover in the visible and thermal infrared bands, and also only provide indirect measurement of the variables of interest for water management. So the integration of remote sensing data with distributed hydrological models is needed for operative water management (Su, 2002; Jia et al., 2003; Kustas et al., 2004; Anderson et al., 2012; Corbari et al., 2013).

In the agricultural area, the calibration and validation of distributed hydrological models become more problematic in respect to basin scale studies where parameters calibration relies on the comparison between simulated and observed discharges at the available rivers cross sections (Refsgaard, 1997; Rabuffetti et al., 2008). At local scale, soil water balance models can be calibrated and validated against soil moisture measurements or evapotranspiration data from eddy covariance stations (Corbari et al., 2011; Ingwersen et al., 2011; Cammalleri et al., 2012).

However for large irrigation districts, where ground measurements are not representative and available, some approaches based on multi parameters calibration approach have been developed using remote sensing data recalling the idea of controlling internal model processes and variables can be controlled in each pixel of the domain (e.g. soil moisture (SM), land surface temperature (LST) and evapotranspiration fluxes (ET)) (Franks and Beven, 1999; Crow et al., 2003; Immerzeel and Droogers, 2008; Gutmann and Small, 2010; Corbari and Mancini, 2014; Corbari et al., 2015).

The main objective of this paper is the development of a system for operative irrigation water management based on the coupling of remote sensing data, distributed water-energy hydrological model and meteorological forecasts. Furthermore, two sub-objectives can be identified: i) the energy water balance model calibration using satellite data of land surface temperature, ii) the accuracy of the forecasted meteorological variables and the effects on the hydrological forecast.

Remote sensing data from LANDSAT 8 are used as hydrological model parameters (leaf area index (LAI), fractional vegetation cover (fv), albedo), which are used as inputs to hydrological model, and as model state variable (land surface temperature). The distributed hydrological model, Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation- Energy Water Balance model (FEST-EWB) (Mancini, 1990; Corbari et al., 2011), which is based on the energy and water balance, will be firstly calibrated using LST data from LANDSAT 8. The model will then be applied in real time using meteorological forecasts from WRF (Weather Research and Forecasting–Advanced Research WRF) meteorological model based on 8 ensemble members with 72 h as the forecast horizon provided by Epson Meteo Centre (EMC)) model for soil moisture forecasts.

This approach is experimented in an asparagus field in Southern Italy irrigated with drip irrigation where ground measurements of eddy covariance and soil moisture are collected for model calibration and validation. The period of analysis is from November 2013 to September 2014.

2. Materials and methods

2.1. Hydrological model and the calibration procedure based on LST

FEST-EWB is a distributed hydrological energy water balance model that computes all the main processes of the hydrological cycle in each cell of the domain. A detailed description of the different updates of FEST-EWB model can be found starting from (Mancini, 1990; Corbari et al., 2011, 2013).

FEST-EWB model is based on the system of energy-water balances equations which are written in terms of the LST, so that this model internal variable can be directly compared with remotely sensed LST. The model solves the system between energy and mass balance at the ground surface:

$$\left\{\frac{d\,SM}{dt} = \frac{P + I - R - PE - ET}{dz}\right. \tag{1}$$

$$\left\{R_n - G - H - LE = \frac{dS}{dt}\right. \tag{2}$$

where: SM (-) is the soil water content, P (mm) is the precipitation rate plus the irrigation rate I (mm), R (mm) is the runoff flux, PE (mm) is the drainage flux, ET (mm) is the evapotranspiration, dz (mm) is the soil depth, Rn (Wm^{-2}) is the net radiation, G (Wm^{-2}) is the soil heat flux, H (Wm^{-2}) is the sensible heat flux, LE (Wm^{-2}) is the latent heat flux, dS/dt encloses the energy storage terms, such as the photosynthesis flux and the crop and air enthalpy changes.

In particular ET is linked to the latent heat flux through the latent heat of vaporization (λ) and the water density (ρw):

$$LE = \lambda \rho_w ET \tag{3}$$

The latent heat flux is then computed as:

$$LE = \frac{\rho_a c_p}{\gamma}(e^* - e_a)\left[\frac{f_v}{(r_a + r_c)} + \frac{1 - f_v}{(r_{abs} + r_s)}\right] \tag{4}$$

where ρa is the air density, γ is the psychometric constant (Pa°C^{-1}), f_v is the vegetation fraction and c_p is the specific heat of humid air (MJ kg^{-1} K^{-1}). The saturation vapour pressure (e*) is computed as function of RET while the vapour pressure (e_a) as a function of air temperature. The canopy resistance (r_c) is expressed following (Jarvis, 1976), while the soil resistance (r_s) according to Sun (1982). The aerodynamic resistance (r_a for vegetation and r_{abs} for bare soil) is computed using the model from Thom (1975).

The energy budget equation is then solved explicitly looking for the representative equilibrium temperature (RET) which is the land surface temperature that closes the energy balance of each pixel. In fact, it includes the heterogeneity of pixel surface, the multi-source emissivity of land surface temperature and the link with the aerodynamic resistance in the turbulent fluxes estimate. So following the proposed approach, LST can be seen as a proxy of soil moisture and thus a key variable in the fluxes estimates.

In particular, the innovative proposed calibration method of the soil hydraulic and vegetation parameters is based on the minimization of the differences, pixel by pixel, between the model RET and the remotely observed LST with a trial and error approach (Corbari and Mancini, 2014; Corbari et al., 2015). This new method improves the actual calibration of distributed hydrologic models which is generally performed by comparison between simulated and available observed discharges at limited river cross sections or few local soil moisture measurements.