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Combining remote sensing and *in situ* soil moisture data for the application and validation of a distributed water balance model (HIDROMORE)

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ABSTRACT

An application of the FAO56 approach to calculate actual evapotranspiration (AET) and soil moisture is reported, implemented by means of the HIDROMORE computerized tool, which performs spatially distributed calculations of hydrological parameters at watershed scale. The paper describes the application and validation of the model over 1 year in an area located in the central sector of the Duero Basin (Spain), where there is a network of 23 stations for continuous measurement of soil moisture (REMEDHUS; Soil Moisture Measurement Stations Network) distributed over an area of around 1300 km^2. The application integrated a series of Landsat 7 ETM+ images of 2002, from which the NDVI series (Normalized Difference Vegetation Index) and the map of land covers/uses were derived. Validation consisted of the use of the REMEDHUS soil moisture series and their comparison with the series resulting from the application. Two simulations were performed, with soil parameters values at the surface (0–5 cm depth) and at the mean of the profile scale (0–100 cm depth). The behaviour of the simulated soil moisture was described by means of its correlation with the measured soil moisture (determination coefficient, R^2 = 0.67 for the surface values and 0.81 for the mean profile values), and the Root Mean Square Error (RMSE), resulting in a range of it for the 23 stations between 0.010 and 0.061 cm^3 cm^{-3}. The application afforded an underestimation of the soil moisture content, which suggests the need for a redefinition of the limits of the plant available water used in the calculation. The results showed that HIDROMORE is an efficient tool for the characterization of hydrological parameters at global scale in the study zone. The combination of the FAO56 methodology and remote sensing techniques was efficient in the spatially distributed simulation of soil moisture.

1. Introduction

Nowadays there is an increasing need to develop and apply remote sensing in distributed hydrological models. Compared with lumped models, distributed hydrological models can account for spatial heterogeneities and they provide detailed descriptions of the hydrological processes in a watershed to satisfy the requirements of hydrological modelling (Abbott and Refsgaard, 1996). They are much more sensitive to problems of extrapolation and calibration than lumped models, but they have the drawback of a crucial demand for spatial datasets and computation resources (Chen et al., 2005). Also, the processes described may be unrealistic at pixel scale (Beven, 1996). In a distributed method, each pixel is a vegetation-soil system, and hence basic model simulations of the physical and biological processes are made at the pixel scale (Chen et al., 2005). When remotely sensed data are used, the image resolution will determine the pixel size, although it is possible to change scale and the minimum spatial unit, depending on the spatial sampling of other data. Using digital processing of images, each pixel provides unique values of spectral indices; these values may in turn be processed to obtain new indices and/or parameters. Another alternative consists of classifying pixels by land uses or types of vegetation and assigning a value of the parameter to each class (Simonneaux et al., 2007; Er-Raki et al., 2010).

Many authors have recognized the need for a precise estimation of soil moisture and evapotranspiration in distributed models, especially in semi-arid zones, where water scarcity in the soil is a limiting factor for crops (Duchemin et al., 2006). Among other remote sensing techniques, vegetation indices and plant cover estimations are widely used (Jiang and Islam, 2001; Nishida et al., 2003; Venturini et al., 2004; Chen et al., 2005; Nagler et al., 2005). Moreover, to quantify water content rates in the soil and AET at field scale, water balance models require specific site inputs such as climate data, plant phenology, and information about agricultural practices (Kendy et al., 2003; Eitzinger et al., 2004; Wegehenkel and Kersebaum, 2005; Zhang and Wegehenkel, 2006).

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The $K_c\mathrm{ET}_0$ (crop coefficient-reference evapotranspiration) method described in FAO56 (Allen et al., 1998) is commonly applied for the estimation of crop water requirements. Recently, important efforts have been made within the remote sensing community to extend the estimation of both terms from plot scale to regional scale (Zhang and Wegehenkel, 2006), linking them to the vegetation indices or to intermediate biophysical parameters such as the leaf area index or the fraction of vegetation cover, f_{vc} (Gonzalez-Piqueras et al., 2003; Nagler et al., 2004; Venturini et al., 2004; Wang et al., 2006; Sobrino et al., 2007; Suzuki et al., 2007; Gonzalez-Dugo and Mateos, 2008).

The relationship between vegetation indices, the crop coefficient curves and the plant cover fractions is already described in Heilman et al. (1982) and Tucker et al. (1981). This idea suggests the use of remote sensing data to evaluate the spatial distribution of evapotranspiration (Moran and Jackson, 1991). The evolution of the basal crop coefficient (K_{cb}) is linearly related to the development of the plant cover (Carlson and Ripley, 1997; Allen et al., 1998; Calera et al., 2001). According to several authors, it may be inferred that the evolution of the NDVI would be similar to that of K_{cb} (Calera and Martín de Santa Olalla, 2005). Different authors, such Bausch and Neale (1987), Neale et al. (1989), Bausch (1995), Gonzalez-Piqueras et al. (2003), Hunsaker et al. (2005), Duchemin et al. (2006), Er-Raki et al. (2007), Jayanthi et al. (2007), Gonzalez-Dugo and Mateos (2008), have reported linear relationships for different crops and study areas with the NDVI. A time series of vegetation index measurements can be correlated with measurements of evapotranspiration to develop a reflectance-based K_{cb}-index curve along the crop cycle. Once calibrated, this curve can provide estimates of AET with a mean absolute percent difference between the estimated and measured daily evapotranspiration varying from 9% to 10% (Hunsaker et al., 2005).

FAO56 proposes the calculation of ET_0 from climatic data and of K_c from tabulated values. The effects of the climate on crop water requirements are represented by ET_0, and the effect of the crop is incorporated in K_c. The dual form of K_c was chosen. This distinguishes evapotranspiration from transpiration by separating the crop coefficient K_c into two parts: soil evaporation (K_e) and crop transpiration (K_{cb}). Water stress conditions were also taken into account.

The aims of the present work were first to check the feasibility of FAO56 methodology in a regionally distributed application and to assess the potential of remotely sensed inputs for the calculation of some of its water balance parameters. A second goal was to assess the use of soil moisture as an alternative for the validation of the results from soil moisture series measured *in situ*.

2. Methods

2.1. The model

HIDROMORE is a distributed hydrologic model based on the water balance equation as is stated on FAO56, and provides daily estimates of deep percolation (DP), water storage ($\Delta\theta$) and evapotranspiration (ET) after calculating effective precipitation (P), surface runoff (RO) and irrigation (I):

$$\mathrm{P} + \mathrm{I} - \mathrm{RO} - \mathrm{ET} - \mathrm{DP} = \pm\Delta\theta \tag{1}$$

$\pm\Delta\theta$ expresses the rate of change in the soil moisture content or water storage (mm) and is a residual of the balance. The soil layer depth is that corresponding to the root length (Z_r), and in the case of no vegetation, the soil layer depth considered is 10–15 cm (Z_e), where evaporation occurs.

HIDROMORE calculates a water balance for each cell individually, considering initial properties and conditions of the soil-vegetation-atmosphere system and their corresponding development with time. For each day and cell HIDROMORE performs the calculation sequence from 1 day to the next. In this application the horizontal movement of water across the surface (runoff) is not considered, and only direct recharge or deep percolation are taken into account. This condition is based on the FAO56 premises and in the present case can be justified for two reasons. Firstly, the precipitation events in the study zone tend to be of moderate intensity. Second, the topographic features and the soil properties make that the infiltration is the predominant process in the area.

In the estimation of the crop coefficient, HIDROMORE applies the dual form. K_{cb} is calculated on the basis of the value of the daily NDVI value, linearly extrapolated from the temporal imagery series (the NDVI–K_{cb} approach), and K_e is calculated from the water balance in Z_e as is suggested by the FAO procedure. Besides, a water stress condition is applied to estimate a coefficient K_s, which allows an AET to be obtained under stress conditions:

$$\mathrm{AET} = \mathrm{ET}_0(K_s K_{cb} + K_e) \tag{2}$$

Choice of a working scale and a spatial sampling of data is a crucial issue owing to the distributed nature of both the input data and the results. HIDROMORE is able to adapt the minimum unit of spatial sampling to the available data. With these data, HIDROMORE has the capacity to detect water stress in the vegetation and can recommend strictly adjusted rates of water supply, with a detailed spatial resolution.

2.2. Integration of data in HIDROMORE

To characterize the evapotranspiration and soil moisture parameters, precipitation and ET_0 (calculated according to Penmann–Monteith equation) were integrated in HIDROMORE from the database of the REMEDHUS stations. The soil database for texture, depth, soil water content at field capacity (θ_{FC}), soil water content at wilting point (θ_{WP}), and soil water at saturation (θ_{sat}) was also integrated. Finally, the map of land covers/uses and the NDVI series were integrated.

The procedure uses a series of intermediate parameters. It obtains those related to the vegetation by means of the NDVI–K_{cb} and NDVI–f_{vc} relationships and by means of the map of land covers/uses (standard tables of root depth and plant height). Parameters concerning the soil water content such as Total Available Water (TAW of the root zone), Readily Available Water (RAW of the root zone), Readily Evaporable Water (REW), Total Evaporable Water (TEW), evaporation, depletion (D_r), stress coefficient, etc. are also extracted.

Root depth is a critical factor for calculating soil water content on the definition of the limits of water storage and availability (e.g., θ_{FC} and θ_{WP}, TAW and RAW). Root depth is established based on the class of land cover resulting from the map, and applying on it the values given in FAO56. For the three classes addressed here, a depth of 1 m was taken for vineyards; 2 m for forests, and a linearly variable depth between 0.1 and 0.9 m for cereals. To account for the effect of root depth, FAO56 uses a fraction of TAW (RAW), water that a crop can extract from the root zone without suffering water stress. RAW is calculated using the depletion factor parameter, p(RAW = pTAW), which represents a reduction in the transpiration demand due to the difficulty of roots for in extracting water as the soil water content decreases. Values for p (0.55, 0.45 and 0.70 for cereals, vineyard and forest, respectively) came from FAO56.

K_{cb} was obtained with the NDVI according to Bausch and Neale (1987) (3). This expression is indicated for NDVI resulting from atmospherically corrected reflectances and here it was adapted for grass reference surface according to the procedure indicated