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Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy

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ABSTRACT

Irrigation planning and scheduling require the availability of modeling tools that are accurate, quick and easy to use. The crop coefficient (K_c)-reference evapotranspiration (ET) method is a traditional method for estimating ET, but has become relatively complicated with the introduction of the dual K_c procedure. The dual crop coefficient approach ($K_{cb}+K_e$) gives a better estimation of daily crop evapotranspiration because it separately considers soil evaporation and crop transpiration. This approach allows one to plan irrigation schedules properly, especially in the case of crops that do not completely cover the soil, where evaporation from the soil surface may be substantial. The SIMDualKc software application was developed with the purpose of simplifying implementation of the computation of the crop coefficient and crop evapotranspiration using the dual crop coefficient approach over a range of cultural practices and to provide ET information for use in irrigation scheduling and hydrologic water balances. The model performs a soil water balance at the field level using a daily time step. It estimates crop transpiration and soil evaporation as well as soil water dynamics to support irrigation scheduling for full and incomplete cover crops. This paper is the first part of a two-part series, where the second part describes model testing and application for various crops, locations and irrigation management issues.

1. Introduction

A variety of irrigation scheduling simulation models have been produced during the past two decades. Generally these models include the computation of crop evapotranspiration (ET_c) and simulation of soil water dynamics. Many models include yield-water functions that estimate yield declines associated with water stress. However, up to present, there have been few irrigation scheduling models that are based on the dual crop coefficient approach and its combination with hydrologic extensions for complete water balances. This paper describes a structured, interactive model having these features that is designed to support general irrigation scheduling needs, including the ability to estimate differences in consumptive requirements among irrigation system types. The model adheres closely to the FAO-56 ET_c methodology and therefore can serve as a convenient and effective means to compare a standardized implementation against other FAO-56 application strategies. The software employs a helpful graphical and menu-driven user-interface to assist a wide range of user backgrounds and skill levels. Some background in ET, irrigation scheduling, water balance and crop coefficient usage is helpful.

Computation of soil water dynamics in modern software is typically based upon the simulation of soil water fluxes, or on the direct calculation of a soil water balance, usually on a daily time step. The first approach is commonly adopted in mechanistic models, usually oriented to the simulation of biomass and yields as influenced by energy, water and nutrient availability. The simulation of evapotranspiration is often performed through parameterizing an evapotranspiration model, or determining the soil evaporation fluxes through the soil upper boundary, and calculating transpiration using a root extraction model. These mechanistic models are highly exigent in terms of data, particularly relative to soil hydraulic properties and crop and nutrients data. They may be used to support irrigation scheduling, but they are generally too complex to apply widely in practice and substantial investment is required for data acquisition and in model parameterization and calibration. Therefore, this class of models is mainly used for modeling crop growth and solutes transport, or for evaluating crop and irrigation management practices. Examples include the models EPIC (Guerra

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et al., 2005), CropSyst (Stöckle et al., 2003), HYDRUS (Mermoud et al., 2005; Simunek et al., 2008), SWAP (Vazifedoust et al., 2008), SWAT (Luo et al., 2008) and AquaCrop (Raes et al., 2009).

In contrast to mechanistic models, soil water balance-based models are generally more directly designed for irrigation scheduling simulation and may be more empirical in nature (Pereira et al., 1992, 1995). They require less soil input data, easier crop parameterization, and may employ a somewhat simpler procedure for estimating ET_c. The yield impacts of water stress are generally considered through empirical means such as the simple and phasic Stewart models (Stewart et al., 1977; Doorenbos and Kassam, 1979), or the phasic Jensen model (1986). The accuracy of these models for irrigation scheduling is high when soil and weather data are of good quality. They are generally very appropriate for irrigation scheduling when they are able to relate water stress to yield declines, e.g., the models ISAREG (Teixeira and Pereira, 1992; Liu et al., 1998), ISM (George et al., 2000), BUDGET (Raes et al., 2006), OSIRI (Chopart et al., 2007) and PILOTE (Khaledian et al., 2009).

1.1. Reasons for employing a dual crop coefficient approach in an irrigation scheduling model

Irrigation scheduling models based upon soil water balance simulation generally estimate crop evapotranspiration (ET_c) using a crop coefficient (K_c) multiplied by the reference evapotranspiration (ET_o). The latter is computed for either grass or alfalfa as reference crops (Allen et al., 1989, 1998, 2007; Pereira et al., 1999). K_c represents an integration of the effects of three primary characteristics that distinguish the crop from the reference: crop height (affecting roughness and thus aerodynamic resistance); crop–soil surface resistance (related to leaf area, fraction of ground covered by vegetation, leaf age and condition, degree of stomatal control, and soil surface wetness); and albedo of the crop–soil surface (influenced by the fraction of ground covered by vegetation and soil surface wetness). Due to the fact that ET_o represents nearly all weather influences on evaporative demand, the crop coefficient varies predominately with the specific crop characteristics and only a little with climate. This fact enables the transfer between locations and climates of standard K_c values and curves. In situations where K_c has not been derived by ET measurement, it can be estimated from the fraction of ground cover or leaf area index (Allen et al., 1998, 2007; Allen and Pereira, 2009). The crop coefficients vary during the growing season as plants develop, since the fraction of ground covered by vegetation changes as plants mature. The K_c also varies according to the wetness of the soil surface, especially when there is little vegetation cover (Allen et al., 2005c): it has a high value when the soil is wet and steadily decreases as the soil dries. The K_c approach has the useful characteristics of being (a) relatively consistent when transferred to new locations of use; (b) self-imposed empirical limits (0 to $K_{c\,max}$); (c) a relatively visual means of definition and construction of seasonal curves that ease the education of and adoption by new users; and (d) relatively easy calibration and specification of parameters as compared to many mechanistic models.

Computing crop evapotranspiration using the time averaged single crop coefficient approach has provided satisfactory results for various time step calculations, including daily ET_c estimation, with appropriate accuracy for many applications. Examples of satisfactory results of the application of this methodology are numerous in the literature as previously cited. However, the single crop coefficient, where transpiration and evaporation are combined, has difficulty in estimating impacts of irrigation or rainfall frequency or irrigation system type on total water consumption. Distinguishing these impacts becomes more and more important as water becomes more scarce.

The adoption of the dual crop coefficient approach has advantages over the single K_c approach, given the essentially separate estimation of crop transpiration and soil water evaporation (Wright, 1982; Allen et al., 1998, 2005b, 2007). However, its application is still somewhat rare. The dual approach is more complicated than the single K_c approach to apply because it requires a daily (or shorter) water balance of the soil evaporation layer in addition to the root zone soil water balance. Thus it requires knowledge on the soil evaporable characteristics, a few parameters describing ground cover, and the energy availability for soil water evaporation as well as knowledge of irrigation events.

1.2. Prior applications of the dual crop coefficient approach

Early applications of the dual K_c methodology as proposed by Allen et al. (1998) include Allen (2000), where applications were made to a range of crops in Turkey in a study comparing several approaches to estimate ET_c, and Liu and Pereira (2000) where applications were made to a crop sequence of winter wheat-summer maize in the North China Plain. That study showed the appropriateness of applying the dual crop coefficient approach and its superiority over the single time averaged crop coefficient in capturing impacts of wetting frequency on total water consumption. The advantages of the dual approach for the winter wheat-summer maize crop sequence have been further confirmed through a number of years of lysimeter data (Liu and Luo, 2010). Other successful applications have been reported by Tolk and Howell (2001) for sorghum, Howell et al. (2004) for cotton, Zhao and Nan (2007) for maize, Bodner et al. (2007) to compare various cover crops, Greenwood et al. (2009) for seven forage systems in Australia, López-Urrea et al. (2009) for onion, and Hay and Irmak (2009) for nongrowing "dormant" periods. Relative to partial cover crops, interesting examples of application are provided by Spohrer et al. (2006) for lychees and Er-Raki et al. (2009) for citrus.

The dual K_c approach has also been used in remote sensing applications for estimating ET_c for various crops, e.g., cotton (Hunsaker et al., 2003), wheat (Hunsaker et al., 2005; Er-Raki et al., 2007), and potato (Jayanthi et al., 2007). Calera et al. (2005) were successful in deriving K_{cb} for various crops from remote sensing that are used to support an irrigation advisory service. Applications at the system level are reported by Allen et al. (2005a), who found the dual K_c approach to produce more accurate results than the single K_c, because separating the K_c into the soil evaporation coefficient (K_e) and the basal crop coefficient (K_{cb}) made it possible to better follow the impacts of wetting of soil by rain and irrigation, as well as the impacts of keeping part of the soil dry, and impacts of using mulches for controlling soil evaporation (E). Other applications adopting the dual K_c for ET estimation at the irrigation system level are reported by Lorite et al. (2004) and Santos et al. (2008).

The review presented above suggests a wide range of applications utilizing the dual crop coefficient approach. However, none of the examples describes the use of an irrigation scheduling water balance model adopting the dual K_c approach. The Irrigation Management-Online software of Abourached et al. (2007) and Hillyer and Sayde (2010) is one of only a few irrigation scheduling programs that employs the dual K_c method. Most of the examples given do illustrate the robustness of the dual approach and the diversity and relative complexity of related applications. These diversities and complexities make it helpful to have a reliable, accurate modeling tool to provide easy adoption of the dual K_c methodology and having a variety of application options.

The SIMDualKc model was developed for the purpose of programming and scheduling irrigations for a variety of vegetation types including partial cover crops such as vegetables and orchard crops, and for use with high frequency irrigation, such as microirrigation. The SIMDualKc approach includes irrigation strategy