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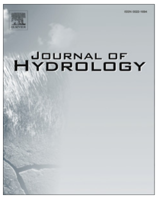

Application of a soil moisture diagnostic equation for estimating root-zone soil moisture in arid and semi-arid regions

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SUMMARY

Knowledge of soil moisture in the root zone is critical for crop growth estimation and irrigation scheduling. In this study, a soil moisture diagnostic equation is applied to estimate soil moisture at depths of 0–100 cm (because the majority of crop roots are in the top 100 cm of soil) at four USDA Soil Climate Analysis Network (SCAN) sites in arid and semi-arid regions: TX2105 in northwest Texas, NM2015 and NM2108 in east New Mexico, and AZ2026 in southeast Arizona. At each site, a dataset of 5–6 years of records of daily soil moisture, daily mean air temperature, precipitation and downward solar radiation is compiled and processed. Both the sinusoidal wave function of day of year (DOY) and a linear function of the potential evapotranspiration (PET) are used to approximate the soil moisture loss coefficient. The first four years of data are used to derive the soil moisture loss function and the empirical parameters in the soil moisture diagnostic equation. The derived loss function and empirical parameters are then applied to estimate soil moisture in the last fifth or sixth year at each site. Root mean square errors (RMSEs) of the estimated volumetric soil moistures in five different soil columns (i.e., 5 cm, 10 cm, 20 or 30 cm, 50 cm, and 100 cm) are less than 3.2 (%V/V), and the accuracy of the estimated soil moistures using the sinusoidal soil moisture loss function is slightly better than the PET-based loss functions. In addition to the three advantages of this soil moisture diagnostic equation, i.e., (1) non-cumulative errors in the estimated soil moisture, (2) no regular recalibration is required to correct the cumulative errors, and (3) no numerical iteration and initial moisture inputs are needed since only precipitation data are required, this study also demonstrates that the soil moisture diagnostic equation not only can be used to estimate surface soil moisture, but also the entire root-zone soil moisture.

1. Introduction

Irrigation is critical for semi-arid and arid agriculture, enabling doubling or quadrupling of crop yields compared to non-irrigated production (Howell, 2001). In the semi-arid and arid regions where groundwater is the primary irrigation source, to meet growing production demands resulting from the expanding food market, both the irrigated agricultural acreage and groundwater demands for irrigation are expected to increase (Colaizzi et al., 2009), with projected increases in groundwater withdrawal as a result. Simultaneously, extremely limited precipitation in arid and semi-arid regions results in a slow recharge to the local groundwater systems. Such conditions are expected to induce a significant decline in groundwater levels and thus threaten the sustainability of agricultural industry in these regions. Therefore, efficient water management technology is critical for sustainable agriculture (Nieswiadomy, 1985; Kim et al., 1989). A relatively accurate irrigation scheduling is vitally important to improve water use efficiency (WUE) (Stanhill, 1986). For example, estimates show that irrigation scheduling could save about 15–35% of the water normally consumed through pumping groundwater for center-pivot (20% for gated-pipe surface) irrigation systems in the Great Plains Region (e.g., Gilley and Supalla, 1983).

Most irrigation scheduling methods can be classified as either soil moisture-based or plant-based (Jones, 2004). Although plant growth directly depends on plant water status and thus a plant-based method could be more accurate than a soil moisture-based method (Jones, 2004), difficulties in measuring plant water stress in an automated fashion make the plant-based irrigation scheduling expensive to implement (Jones, 2004). On the other hand, the plant-based methods mainly time irrigations and do not provide

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information on the amounts of water to apply. Therefore, the soil moisture-based irrigation scheduling methods will continue to be popular and commonly used.

Two types of approaches currently determine the moisture content in soils for the soil moisture-based irrigation scheduling (Jones, 2004): (1) direct soil moisture measurements (e.g., Campbell and Campbell, 1982; Topp and Davis, 1985; Coopersmith et al., 2014; Susha Lekshmi et al., 2014) and (2) soil water balance calculations (e.g., Allen et al., 1998). Direct soil moisture measurement is easy to apply and relatively accurate, but is expensive to implement since soil heterogeneity requires multiple soil moisture sensors to capture the spatial variation of soil moisture (e.g., Pan and Peters-Lidard, 2008). Soil water balance calculations are also easy to apply, but are not as accurate as direct measurement and require a regular recalibration since errors in the estimated soil moisture are cumulative (Jones, 2004), although most models set a soil moisture dynamic range between the field capacity and the permanent wilting point, or between porosity and residual soil moisture content. One possible reason for the cumulative errors in the estimated soil moisture is that the soil moisture dynamics in the vadose zone (i.e., unsaturated soil) is governed by highly non-linear processes and interactions and thus are very complicated (e.g., Bastiaanssen et al., 2007). On the other hand, the uncertainties associated with soil hydraulic properties (e.g., Heathman et al., 2003) and macropores in soils (e.g., Ahuja et al., 1993, 1995) make modeling and prediction of soil moisture even more challenging. Yet, as summarized by Bastiaanssen et al. (2007), over the last 25 years a large number of unsaturated zone models have been developed (e.g., Toksoz and Kirkham, 1971; Neuman et al., 1974; Zaradny and Feddes, 1979; McLin and Gelhar, 1979; Feddes et al., 1988; Workman and Skaggs, 1989; Clemente et al., 1994; Lorre et al., 1994; Faria et al., 1994; Bastiaanssen et al., 1996; Ahuja et al., 1999; Ma et al., 2000; Ines and Droogers, 2001; Gao et al., 2013; Kumar et al., 2013a, 2013b, 2014; and others). Significant progress has been made in the modeling of the relation of soil moisture to irrigation and drainage. However, despite such promising progress, the application of these models for irrigation scheduling is almost nonexistent (Bastiaanssen et al., 2007).

Four possible barriers may be hampering the implementation of soil moisture modeling in operationalizing soil moisture-based irrigation scheduling: (1) soil moisture modeling is complex and time consuming; (2) soil moisture modeling requires regular recalibration to avoid cumulative errors resulting from the differential between simulated and actual soil moisture measurements (e.g., Jones, 2004); (3) uncertainties in soil hydraulic properties and macrospores in soils are not accounted for; and (4) to our knowledge, while there are some crop growth and water usage models, e.g., Hybrid-Maize (http://www.hybridmaize.unl.edu) and SoySim (http://soysim.unl.edu), these models are mainly used for research and are difficult to utilize for farmers, because to run these tools, farmers need first to collect weather data. Therefore these tools have no real-time or online functionality. This paper aims to develop a simple and robust approach for estimating root zone soil moisture using a soil moisture diagnostic equation (Pan et al., 2003; Pan, 2012), and the estimated soil moisture can be used for scheduling irrigation in the future. Our research on the soil moisture-based irrigation scheduling has two phases. The first phase focuses on developing, applying, and validating the soil moisture diagnostic equation approach to estimating the root-zone soil moisture on non-irrigated and natural steppe/desert land in arid and semi-arid regions, which is presented in this paper. In the second phase, a follow-up study will focus on estimating the root-zone soil moisture in irrigated cropland in arid and semi-arid regions.

Pan et al. (2003) derived and validated a daily surface soil moisture diagnostic equation based on a linear stochastic differential equation suggested by Entekhabi and Rodriguez-Iturbe (1994). The estimated soil moisture is a function of the time-weighted summation of the ratio of the historical rainfall rate to the soil moisture loss coefficient (Pan et al., 2003). Using observations from three field campaigns in grassland and agricultural regions, i.e., Monsoon'90 (Schmugge et al., 1994), Washita'92 (Jackson and Le Vine, 1996), and SGP'97 (Jackson et al., 1999), Pan et al. (2003) illustrated that the soil moisture diagnostic equation could estimate the top 5 cm soil moisture with an accuracy comparable to that of remotely sensed soil moisture. Pan (2012) applied the soil moisture diagnostic equation to four Soil Climate Analysis Network (SCAN) sites managed by Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) (Schaefer et al., 2007) and used a sinusoidal wave function of the Day of Year (DOY) to represent the soil moisture loss coefficient. The observed soil moisture data collected at these four SCAN sites were applied to test the proposed method. Small errors (root mean square error < 5%V/V) and high sample correlation coefficients ($r > 0.89$) between the observed and estimated soil moisture indicated three advantages associated with the approach, i.e., (1) non-cumulative errors in the estimated soil moisture, (2) no regular recalibration is required to correct the cumulative errors, and (3) no numerical iteration and initial moisture inputs are needed (Pan, 2012). Thus, the daily surface soil moisture diagnostic equation approach is more efficient than any other known soil moisture numerical modeling approach.

Although the soil moisture diagnostic equation has three advantages as mentioned above, this equation has only been applied to estimate surface soil moisture (Pan et al., 2003; Pan, 2012). To utilize the soil moisture diagnostic equation to estimate soil moisture for scheduling irrigation, we must estimate soil moisture in the entire root zone rather than the top 5 cm to 10 cm soils, because soil moisture in the root zone is critical for seed germination and crop growth especially during the early stage of the plant growth, and thus root-zone soil moisture is one of key variables for crop growth estimation, irrigation scheduling, and crop yield prediction and modeling. Therefore, the goal of this paper is to demonstrate the ability of the soil moisture diagnostic equation to estimate root zone soil moisture and describe the methodology of applying the soil moisture diagnostic equation to estimate root zone soil moisture. The arrangement of this paper is as follows. Section 2 describes the methodology for the derivation of the daily diagnostic soil moisture equation and the determination of the soil moisture loss function and empirical parameters in the soil moisture diagnostic equation. Section 3 introduces study sites and data. Section 4 presents results and discussion. Section 5 summarizes the findings.

2. Methodology

2.1. Derivation of a soil moisture diagnostic equation

Pan et al. (2003) and Pan (2012) derived a daily soil moisture diagnostic equation based on a linear stochastic differential equation suggested by Entekhabi and Rodriguez-Iturbe (1994). For readers who are not familiar with this equation, here we use the same approach developed in Pan et al. (2003) and Pan (2012) to derive a similar daily diagnostic equation for the root-zone soil moisture based on a simplified soil moisture dynamic equation given in Eq. (1):

$$z\frac{d\theta}{dt} = -\eta\theta + \gamma P \tag{1}$$

where z is the thickness of a soil column (from land surface down to depth z), θ is soil moisture of the soil column, $-\eta\theta$ is the loss of soil moisture, η is the loss coefficient, P is precipitation rate, and γ is the