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Functional relationship to describe temporal statistics of soil moisture averaged over different depths

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Abstract

Detailed simulation studies, highly resolved in space and time, show that a physical relationship exists among instantaneous soil-moisture values integrated over different soil depths. This dynamic relationship evolves in time as a function of the hydrologic inputs and soil and vegetation characteristics. When depth-averaged soil moisture is sampled at a low temporal frequency, the structure of the relationship breaks down and becomes undetectable. Statistical measures can overcome the limitation of sampling frequency, and predictions of mean and variance for soil moisture can be defined over any soil averaging depth *d*. For a water-limited ecosystem, a detailed simulation model is used to compute the mean and variance of soil moisture for different averaging depths over a number of growing seasons. We present a framework that predicts the mean of soil moisture as a function of averaging depth given soil moisture over a shallow *d* and the average daily rainfall reaching the soil.

Keywords: Soil moisture; Remote sensing; Richards equation; Root-water uptake; Plant model; Modeling

1. Introduction

Soil moisture is the critical variable that dynamically links plants to the overall water balance, thereby influencing feedbacks to the atmosphere [33]. Soil moisture is controlled by complex interactions involving soil, plants, and climate. Plants connect the soil to the atmosphere through their active roots, which provide pathways for water transport from the root zone to the atmosphere [9]. Therefore, knowledge of soil moisture within the root zone, the region where active roots reside in the soil, is essential for estimation of fundamental hydrological and atmospheric processes. Accurate estimation of these processes is important for large-scale climate models as well as for ecohydrological models.

Soil moisture can be estimated by in situ measurements, by remote sensing, or by hydrological modeling. For large-scale applications, in situ methods cannot be used because an in situ measurement network does not exist over large land surface areas and the technique is expensive [16]. Microwave remote sensors have been successful because they are sensitive to soil moisture through the effects of moisture on the dielectric constant and, consequently, the soil's emissivity [30,23]. However, remote sensing has uncertainty that depends on the sensor type (active or passive), vegetation cover, landscape roughness, and soil type. Yet the primary shortcoming of remote sensing is that soil moisture is inferred only for the top few centimeters of the soil column e.g., [8,22]. Consequently, remote sensing must be used in conjunction with some other information to estimate soil-moisture values over the entire root zone.

Hydrological models often have uncertain predictions that result from model assumptions and

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parameterization [16]. Kostov and Jackson [19] suggested that combining remotely sensed data with hydrological models is the most promising approach for soil-moisture estimation. Accordingly, recent research has focused on this combination e.g., [28,6,16, 27,14] with a general strategy of guiding hydrological models with periodic remote sensing of soil moisture. The instantaneous soil-moisture data inferred from remote sensing observations are assimilated into hydrological models with the hope that model biases will be corrected. Fundamental to this strategy is the relationship between the measured instantaneous soil moisture and instantaneous soil moisture at deeper locations.

This paper first investigates the relationship between instantaneous values of soil moisture over different averaging depths, d, using a detailed simulation model with a focus on temporal resolution of measurements. This instantaneous soil-moisture analysis illustrates the difficulties in relating instantaneous soil-moisture values averaged over the top 5 cm to the instantaneous soil-moisture values averaged over the top 30 cm. We then consider an alternative approach to relating instantaneous soil-moisture values over different averaging depths using statistical measures of soil moisture. In particular, we investigate statistical soil-moisture measures as functions of depth, d, focusing on the relationships among the soil-moisture means over different d as well as the variances over different d. Based on this approach, a methodology is presented that enables prediction of the mean of soil moisture as a function of averaging depth, d, as a function of soil and climate parameters.

2. Simulation description

A one-dimensional model, based on the Richards equation, in combination with a model of water uptake by plants and stochastically generated rainfall, is used to simulate soil-moisture dynamics in a water-limited ecosystem, which we take to be a savannah. Assumptions have been made regarding the model's resolution and complexity with some processes simplified. For example, plant growth and nutrient uptake are not modeled, because we assume that these processes are not important to estimate soil moisture for a mature plant in a savanna. We take the output from our highly resolved (in space and time) model to represent actual field conditions.

Data for the model correspond to measurements taken at Nylsvley, South Africa [34]. Since this model only considers the vertical spatial dimension of the soil, an inherent assumption is that only vertical soil-moisture dynamics are important, and, therefore, lateral soil-moisture dynamics do not have to be resolved. The root zone of the vegetation (typically 30–100 cm) is resolved into 1 cm layers. We use highly resolved time discretization, with a maximum time step of approximately 3 min, and finer resolution around storm events. The model represents water uptake by the plant using the so-called 'Type I' model [15,13], in which water uptake is controlled by differences in fluid potential between the soil and the plant [1,38,24,12,13,15,17]. The model may be interpreted as representative of either a single plant or a homogeneous stand of vegetation.

2.1. Infiltration and redistribution

We model vertical infiltration and redistribution, including evapotranspiration, using the one-dimensional Richards' equation with suitable sink terms to account for evapotranspiration. The governing equation has the following form,

$$\frac{\partial(\phi S)}{\partial t} - \frac{\partial}{\partial z}\left(K\frac{\partial \Psi}{\partial z}\right) + \frac{\partial K}{\partial z} = -e' - u' \qquad (1)$$

where S is the relative soil-moisture content or saturation (L^3 water/L^3 voids), ϕ is the porosity (L^3 voids/L^3 soil), K is the unsaturated hydraulic conductivity (L/T), Ψ is the fluid pressure head (L), e' is the rate of evaporation (L^3 evaporated water/L^3 soil/T), u' is the rate of plant uptake (L^3 plant-extracted water/L^3 soil/T), z is the vertical dimension designated to be positive downward (L), and t is time (T) e.g., [3,4,37]. In unsaturated soil, the fluid pressure head, Ψ, is negative and is often referred to as the soil matrix potential. Suction is defined for unsaturated soil as the absolute value of Ψ.

2.2. Rainfall model and boundary conditions

Rainfall input is treated as an external random forcing that is independent of soil moisture. The rainfall input is modeled with the storm occurrence, depth, and duration represented as random variables. Storm occurrence is modeled as a Poisson process with rate λ with a duration and intensity associated with each occurrence. The duration is obtained from a beta distribution. The total storm rainfall depth is taken from an exponential distribution with mean rainfall depth α.

The aboveground portion of plants intercepts a significant amount of rainfall, especially in arid and semi-arid ecosystems where rainfall duration is short and evaporation demand is high e.g., [21,7]. Following the simplified approach of Laio et al. [21], interception is modeled by setting a fixed threshold rainfall depth, Δ. If a simulated storm produces a total storm rainfall depth less than Δ, then no rain reaches the soil due to interception. For storm depths greater than Δ, the depth of rainfall reaching the soil surface is simply the total storm rainfall depth minus Δ. The rate of arrival of storms with rainfall reaching the soil surface, λ', becomes [32,21]