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Soil moisture at local scale: Measurements and simulations

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SUMMARY

Soil moisture refers to the water present in the uppermost part of a field soil and is a state variable controlling a wide array of ecological, hydrological, geotechnical, and meteorological processes. The literature on soil moisture is very extensive and is developing so rapidly that it might be considered ambitious to seek to present the state of the art concerning research into this key variable. Even when covering investigations about only one aspect of the problem, there is a risk of some inevitable omission. A specific feature of the present essay, which may make this overview if not comprehensive at least of particular interest, is that the reader is guided through the various traditional and more up-to-date methods by the central thread of techniques developed to measure soil moisture interwoven with applications of modeling tools that exploit the observed datasets.

This paper restricts its analysis to the evolution of soil moisture at the local (spatial) scale. Though a somewhat loosely defined term, it is linked here to a characteristic length of the soil volume investigated by the soil moisture sensing probe. After presenting the most common concepts and definitions about the amount of water stored in a certain volume of soil close to the land surface, this paper proceeds to review ground-based methods for monitoring soil moisture and evaluates modeling tools for the analysis of the gathered information in various applications. Concluding remarks address questions of monitoring and modeling of soil moisture at scales larger than the local scale with the related issue of data aggregation. An extensive, but not exhaustive, list of references is provided, enabling the reader to gain further insights into this subject.

1. Introduction

In general, soil moisture refers to the water present in the uppermost part of a field soil and is a state variable controlling a wide array of ecological, hydrological, geotechnical, and meteorological processes. Soil moisture also regulates the partitioning of the incoming solar energy at the land surface into the outgoing sensible, latent, and surface heat fluxes, mainly through the processes of soil evaporation and plant transpiration.

However, soil moisture does not have a single shared meaning among researchers belonging to different disciplines (Seneviratne et al., 2010). For example, agronomists and climatologists may prefer to look at soil moisture as the water-holding capacity of a land area, eco-hydrologists speculate more on the amount of water present in the rooting zone of a vegetated soil profile, whereas vadose zone modelers are mostly interested in water movement and solute transport issues, and often prefer to view soil moisture in terms of total potential energy gradients. In an attempt to clarify and reconcile some different positions and perceptions that can be found in the literature on this topic, water held in the soil should be conveniently characterized in a unified way in terms of water energy status. Specifically, this status should be identified by the magnitude of the energy of water (the volumetric soil water content, θ) present in the soil volume at a certain energy level (the soil water potential, ψ). When addressing the issues of soil moisture dynamics, in principle one might refer to either θ or ψ, since a relationship exists between these two variables. For the definition and measuring methods of soil water potential the reader is directed to the many treatises and textbooks available in the literature (e.g., Young, 2002; Durner and Or, 2005). Instead, this review paper will address in greater depth the monitoring and modeling of soil water content as it is customarily accepted that soil moisture is the volume of water contained in a certain volume of soil in the field.

A more focused definition of soil moisture and its measuring techniques at a certain scale is imperative to avoid being swamped by documents of various types, with the risk of not being able to extract the information useful for the specific problem in hand.

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This can also help to categorize and contextualize a large variety of studies that deal with land-surface models and data assimilation, with the subgrid space–time variability of soil moisture and its impacts on runoff generation, groundwater recharge, and solute transport, as well as with detailed soil profile measurements carried out to evaluate root-water-uptake models.

The U.S. National Research Council has advocated the need for accurate global measurement of soil moisture (Wei, 1995). In the past, there were only a few locations where soil moisture was measured routinely and, moreover, with the major target of tackling only some very specific problems. Recently, valuable initiatives are being established to meet the above-mentioned need. It is worth mentioning the CRITICAL ZONE (U.S. NSF, 2006; Lin, 2010) and the TERENO (Zacharias et al., 2011) experimental observatories in which the "*Critical Zone*, CZ" unifying concept (U.S. NRC, 2001) is exploited to initiate comprehensive and far-reaching studies on soil moisture dynamics. All these efforts have also been fruitfully developed into a few journals' special sections (van der Kruk et al., 2010; Lin et al., 2011; Fares et al., 2013).

The present contribution deals with the soil moisture status that can be retrieved at a prefixed, albeit sometimes loosely defined, domain of interest: the local scale. It is worth clarifying the general concept of scale, with specific reference to the terms "local scale" that will be used in the subsequent sections. Reference will be mostly made here to the spatial scale, although the time scale will also be addressed when needed. Following the framework proposed by Blöschl and Sivapalan (1995) and also referred to by McBratney (1998) and Neuman and Di Federico (2003), scale is schematically considered as a characteristic dimension made up by the triplet of "support", "spacing", and "extent". This scale triplet may refer to either the measuring or modeling issues, and can be applied to both the spatial and temporal dimensions. To make this concept clearer, if we consider the spatial scale of soil moisture observations, "support" (or, grain) is the volume in which the average value of soil moisture is obtained, "spacing" is the distance between the sensors (being also related to the sampling concept), and "extent" represents the entire domain over which the measurements are carried out (see Fig. 1).

When dealing with measuring issues, the term "scale" is very often identified with its "support" component, which in the sensors' jargon is often associated to the concept of spatial resolution of the sensing probe and linked to the technology employed. A modeler, instead, uses the word "scale" more commonly with reference to the "extent" of the spatial grid where the simulated outputs are computed. Even if it would be highly desirable to have the measuring scale commensurate with the modeling scale (i.e., the scale at which the simulation results are obtained or of interest), unfortunately a mismatch in scale between observations and simulations often occurs (Topp, 2003; Teuling et al., 2006, among many others). A mismatch may occur also between the previous two types of scales and the scales of the spatial and temporal evolution of the phenomenon under study. One should look at the scale, in general, and at the local scale, in particular, much more in terms of an order of magnitude. At the local scale in space, the "support" of soil moisture measurements should be linked mostly to a characteristic length of the soil volume investigated by the sensor probe, usually ranging from about 0.10 m to 0.50 m, whereas from the modeling point of view the support is that of a vertical soil profile or a plot, thus ranging from about 1 m up to 10 m. In summary, I conveniently assume herein the local scale to exhibit a characteristic (average) spatial length of 10^0 m.

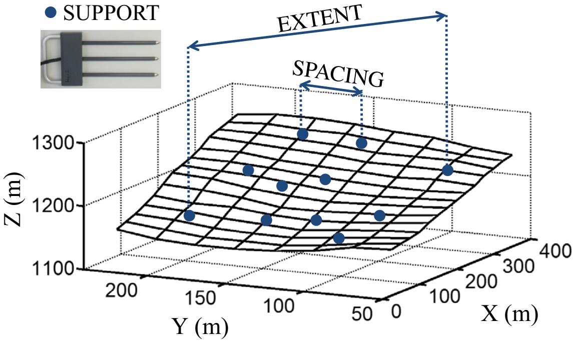

Fig. 1. Schematic representation of the scale triplet of "support", "spacing", and "extent" relating to the space dimension.

In the last decade, huge efforts have been made to establish a more unified view of monitoring and modeling issues, so as to minimize at least the mismatch between the scale of the field measurements and the scale of the model predictions (Romano et al., 2012). Therefore, a specific feature of the present essay, which may make this overview if not comprehensive at least of particular interest, is that the reader is guided through the various traditional and more up-to-date methods by the central thread of techniques developed to measure soil moisture interwoven with applications of modeling tools that exploit the observed datasets. The paper is organized in three main sections followed by the conclusions. After having introduced the common definitions used in the literature, a first section presents the main concepts underlying the determination of moisture flow close to the land surface (uppermost part of soil). Then a section overviews ground-based methods for monitoring soil moisture with emphasis on the local scale of interest. A subsequent section discusses some applications of modeling tools developed to analyze the soil moisture information available. The paper concludes by addressing questions of soil moisture monitoring and modeling at scales larger than the local one, including data aggregation issues.

1.1. Definitions

Soil water content is generally defined as the ratio of the mass of soil water, M_w, to the mass of dried soil, M_s, or as the volume of soil water, V_w, per unit total volume of soil, V_T. In both cases, however, the computation of the soil water content value depends on the definition of the dry soil condition. As the interest of practical applications relies largely upon the determination of the magnitude of relative changes in soil water contents at a certain location, by tradition the dry soil condition refers to the standard condition obtained in the laboratory by extracting water from the soil sample placed in an oven at a temperature of approximately 100–110 degrees Celsius (°C), until variations in the sample weight are no longer noticed. Although the choice of this range of temperatures is indeed somewhat arbitrary, keeping the soil sample in the oven for an adequate duration and at the average temperature value of 105 °C, guarantees evaporation of the "free" water from the soil (Romano, 1999). Moreover, this standard condition can be easily attained using a commercial oven.

This stated, soil water content on a volumetric basis, θ, is defined by the dimensionless ratio:

$$\theta = \frac{V_w}{V_T} \qquad (1)$$

i.e., the ratio of the soil water volume, V_w (with dimensions of L^3 and units of m^3), to the total soil volume, V_T (again with dimensions of L^3 and units of m^3). The latter is the sum of the volume of solid particles (V_s), the volume of soil water (V_w), and the volume of soil air (V_a). Especially when subjecting a soil sample to chemical analyses, one prefers to express the soil water content on a mass basis as follows: