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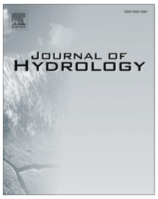

Horizontal monitoring of soil water content using a novel automated and mobile electromagnetic access-tube sensor

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SUMMARY

Advances in sensor technology continue to provide new and significant benefits to agriculture. An innovative approach for observing soil water dynamics in the subsurface is introduced using a mobile electromagnetic sensor prototype traveling through a horizontal PVC access tube. A series of tests for evaluating the prototype were designed and conducted to (i) determine the sensor's area of sensitivity (AOS), (ii) measure varied levels of soil water content along the tube and (iii) track temporal changes in soil water content under; (a) two drippers on a horizontal- and (b) multiple drippers on a sloped-soil surface (i.e., 6° slope). The AOS experiment suggested the sensor's fringing field extends to a radius of 5.5 cm from the pipe wall yielding an AOS of 181.3 cm^2. Measured step-wise changes in soil water content along the tube were highly correlated to those of extracted core samples ($R^2 = 0.99$ and RMSE = 0.012 $cm^3\,cm^{-3}$). The drip emitter tests illustrated spatial hydrodynamics of water infiltration around the access tube. These results illustrate potential applications for this sensing approach, yielding one-dimensional monitoring of soil water along a horizontal line in the root zone or deeper subsurface. Future developments should explore performance in longer and potentially curvilinear pipes for environmental and engineering applications.

1. Introduction

Soil water content is highly variable in time and spatially scale-dependent. Many factors such as soil-structure or -texture, bulk density, tillage method, vegetation distribution, precipitation and irrigation may affect the soil water content distribution from large watershed-scales down to a sensor-based scale of centimeters-to-decimeters (Weiler et al., 1998; Fernández-Gálvez and Simmonds, 2006; Weihermüller et al., 2007). For instance, in a number of studies the large-scale patterns of soil water content reflected the clay content distribution across the fields (Kachanoski et al., 1998; Triantafilis and Lesch, 2005; Mertens et al., 2008; Sun et al., 2011), whereas the small-scale patterns of soil water content distribution were more a function of soil hydraulic properties (Ritsema and Dekker, 1998) or the complex interactions among plant roots and soil-solid, -liquid, and -gas phases (Werban et al., 2008). Weiler et al. (1998) observed that lateral water redistribution changed from the meter-scale to hundreds of meters in scope as a result of topography. Trees can locally alter the soil water redistribution around the basal stem because its crown acts as an umbrella. Meanwhile a tree's large root system can hydraulically redistribute water by extracting deep soil water and transporting it upward to drier surface soils to meet daytime water needs. In general, for comprehensive understanding of vadose zone processes and for optimal water resource management, temporal monitoring of vertical and lateral soil water distribution at different scales is important.

On the technical side, diverse types of dielectric sensors for determining volumetric soil water content (θ_v) have for decades been commercially available and increasingly applied. However, most in situ measurements using electromagnetic sensors only provide point-scale soil water content information on the order of 1 dm^3 (Ferre et al., 1998; Fernández-Gálvez et al., 2006; Robinson et al., 2008). To extend the measurement scale, various dielectric sensing approaches have been applied, including multiplexed TDR probes in a vertical or horizontal array (Casanova

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et al., 2012a,b), wireless sensor network arrays (Cano et al., 2012), parallel ring electrode sensors used in vertical PVC access tubes (Dean et al., 1987), tractor-mounted sensors for on-the-go mapping (Sun et al., 2006), and remote-sensing techniques (Narayan et al., 2006).

Access-tube based sensing of soil moisture profiles was historically quite popular due to the accuracy and utility of the neutron probe (NP). However, with increasing regulations on radioactive source materials, the use of NP-based measurements has dropped significantly. Although the area of sensitivity (AOS) of an access-tube based dielectric sensor remains small ($\approx$dm^3), this sensing approach is viable for local observation of soil water infiltration at the plot scale (Fernández-Gálvez and Simmonds, 2006). Recently, Gravalos et al. (2012) proposed horizontal access tubes for monitoring soil water content using a mobile electromagnetic sensor platform. This integrated system included a commercial soil water content sensor (Diviner 2000) and two driving mechanisms with identical structure. During each measurement cycle conducted in a large tank with a horizontal access-tube, a dc-motor drove the sensor forward while the other motor drove it backward to the starting point upon completion. According to their statements (Gravalos et al., 2012) two technical improvements should be considered in future development. First, the volume of sensitivity of the sensor running through the access tube is an important issue but they did not investigate for this. Second, automatic positioning of the sensor was unsolved. In this study, we presented an alternative prototype, in which both the sensor and the driving mechanism are novel. The horizontal sensing system performance was evaluated in terms of the AOS and the temporal soil water content distribution from paired- and multiple-drip emitters. In addition, the automatic positioning of the sensor was suggested counting the numbers of the pulse generated for driving a stepper motor.

2. Materials and methods

2.1. Prototype description

A schematic of the prototype sensor and transport system are shown in Fig. 1. The sensor was moved through a PVC access tube with an outside diameter of 5 cm (4.8 cm i.d.) and travel length of 4 m. Two cabled pulleys were affixed to and driven by two individual motors, one being a stepper-motor (57BYGH748AA, 24V, 3A, HUISITION Company, China) and the other a dc-motor (12 V, 759 rpm, JGB37-550, ASLONG, China). During a given scanning event, the stepper motor turned counterclockwise to advance the sensor in 5 cm increments along the x-axis shown in Fig. 1. Meanwhile, the dc-motor turned clockwise with some resistance against the drawing force to maintain tension on the nylon string. When the mobile sensor reached a Hall-switch (LJ12A3-4-Z, OMCH Company, China) at the right end of the tube, the dc-motor reversed direction and retracted the nylon string drawing the sensor back to the starting point. The mobile sensor position within the access tube was monitored by tracking the number of stepper motor excitations associated with each 5-cm advance. The sensor scan range was adjustable using either the start or end point programed within the controller. For a sensing speed of 2 cm s^{-1} each measurement cycle required about 200 s to complete. For this experiment 76 total measurements were taken across the access tube's full 3.8 m scan range.

2.2. Sensor principle

Volumetric soil water content (θ_v) can be indirectly determined from soil dielectric permittivity measurements because the relative permittivity of water ($\varepsilon_{\text{water}}/\varepsilon_0 \approx 81$) is much greater than the permittivity of soil minerals ($\varepsilon_{\text{soil}}/\varepsilon_0 \approx 3\text{–}5$) and air ($\varepsilon_{\text{air}}/\varepsilon_0 \approx 1$) (Topp et al., 1980). For capacitance-based measurements, a parallel pair of annular metallic electrodes generate a fringing-field that extends into the soil and 'senses' θ_v based on this dielectric disparity among the soil constituents.

Two capacitance-based measurement methods are commonly used for determining the water content of the soil environment. One method uses the capacitance probe as a resonant circuit component in a radio frequency oscillator (Dean et al., 1987). The resulting oscillating frequency is a function of the soil capacitance, which varies with the soil water content surrounding the probe. The other method measures the impedance of the probe, which is also dependent on dielectric permittivity (Gaskin and Miller, 1996; Sun et al., 2006).

In this study, the impedance method was employed and the measured values were converted into θ_v using a soil-specific calibration. Based on the layout of the electric circuit shown in Fig. 2, the electrical impedance of the probe (Z_p) was determined as

$$Z_p(\varepsilon) = \frac{\overline{U}_b}{\overline{U}_a - \overline{U}_b} Z_o \tag{1}$$

where ε is the relative permittivity of wet soil, Z_o (ohm) is the balance impedance, and $\overline{U}_a$ (V) and $\overline{U}_b$ (V) are the voltage outputs of each wave detector. Since $\varepsilon = \varepsilon_r(f) - j\varepsilon_i(f)$ is a complex variable associated with the measurement frequency (f), many previous studies emphasized that f should be high enough (>30 MHz) in order to ignore the imagery part (ε_i), i.e., to minimize the effect of soil electric conductivity (Thomas, 1966; Paltineanu and Starr, 1997;

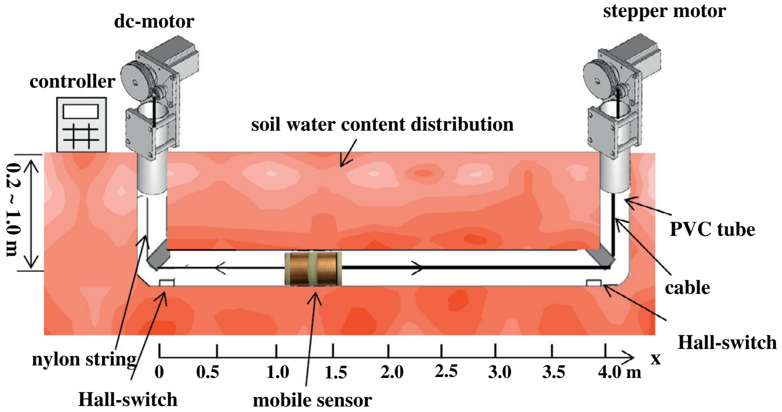

Fig. 1. Schematic illustration of the novel prototype EM sensor moving through a horizontal access tube while measuring soil water content distribution at fixed depth.