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State of the art of measuring soil water content

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Over the last two decades the measurement of soil water content has changed in revolutionary proportions. The major advances in the application of electromagnetic (EM) methods in the collection of water content data have allowed the vadose zone to be included quantitatively in numerous hydrological processes. The basis for these advances in EM methods was the development of improved understanding of microwave interaction in soil as applied to the measurement of water content. The development of digital data handling capabilities that have allowed the collection and analyses of data of radio-frequency ranges above 10 MHz has resulted in a diversification of instruments for measuring soil water content. All EM methods make use of the high relative permittivity (dielectric constant) of the water in soil for estimating the water content. The relative permittivity of water is about 80, whereas the other components in soil, including air, have relative permittivities in the range of one to seven. Hence, these methods are effective for the measurement of water content.

A review of methods for measuring soil water content in the mid-1980s (Gardner, 1986) made only passing reference to time domain reflectometry (TDR) and focused mainly on thermal gravimetric and neutron moderation as the methods available for field investigations. In the most recent update of methods of soil analysis in USA, Topp and Ferré (2002) have included five EM techniques where new developments have occurred. These methods are TDR, capacitance, ground-penetrating radar (GPR), passive microwave and remote active microwave or radar. An EM induction method operating on a different EM basis was also reviewed.

As with all developments, it is well to assess critically the respective capabilities and limitations with a view to improving the choices made for instrumentation. Following a brief review of how each technique operates, I will attempt to identify some of the weaknesses or areas requiring research and development attention.

Most *TDR* instruments operate by launching a fast rise voltage step along the transmission line or probe in the soil. The TDR step pulse travels to the end of the probe and is reflected back to the instrument where it is detected and analysed. The velocity of propagation of the pulse is related to the dielectric permittivity, and thus to water content. Because of the need for probes in the soil, TDR is most often applied within the upper 1 m depth of soil. Numerous variations of probe design have been used to obtain a profile distribution or total root zone water. An advantage of TDR

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is the companion ability to estimate electrical conductivity from the same signal, giving both water content and conductivity on the same sample.

As the name implies, *capacitance devices* determine the apparent capacitance of a probe placed in or near soil. The capacitance changes with water content. Capacitance devices generally use two forms of probe: (1) parallel pronged probes, or (2) parallel pairs of rings along a plastic rod for use in field-installed access pipes. In the latter type the region of measurement lies in the electric field, which fringes out through the access pipes, making sample size and geometry somewhat nebulous. The relatively low cost of capacitive devices enhances their popularity, especially for irrigation management.

GPR, active microwave and passive microwave all make use of unguided EM waves either propagating through soil or being reflected from the soil and the wave received at the detector contains the water content information. Three GPR methods making use of wave propagation are: (1) *Surface launched and subsurface reflections and scattering*, where a GPR transmitter and receiver are placed on the ground surface. As the transmitter and receiver are moved over the ground surface, reflections from interfaces in the soil or scattering from localized objects are recorded. As with TDR, the primary information used for water content estimates is the velocity of the signal. (2) *Borehole transillumination* is a means whereby a transmitter or a receiver, or both, are placed into the ground, usually in access pipe(s), to measure the velocity of the signal between the transmitter and the receiver. (3) For *surface launched direct wave arrivals* the transmitter and receiver are on the ground surface and record air wave and ground wave propagation to estimate the ground wave velocity, and thus water content.

The *air-launched surface reflection method* of GPR places the transmitter and receiver at some distance above the ground using a wheeled vehicle, a low-flying air platform, or a satellite. In these methods, the air–soil reflection coefficient is measured remotely, requiring no physical contact with the ground. The water content information is calculated from the reflection coefficient. The resulting water content measurement is heavily weighted to the near-surface conditions (tens of centimetres deep).

Active microwave remote sensing (radar) is similar in principle to air-launched surface reflection GPR on either airborne or spaceborne platforms operating at an order of magnitude higher frequencies (1 to 10 GHz), which correspond to wavelengths in air of 3 to 30 cm. Plants, plant residue and surface roughness having lengths equivalent to the signal wavelengths cause scattering of the transmitted wave, thus obscuring a pure reflection and a direct interpretation of the soil water content. Hence, empirical calibrations are most often used. Remote radar samples a thin skin of soil (and surface features) of a few centimetres depth by 30 m laterally.

In the *passive microwave method*, the ground surface is the source of the EM signal. This method measures the natural thermal emission of the land surface using very sensitive detectors, 'tuned' to specific frequency bands in the microwave region (0·3 to 30 GHz). As with remote radar the presence of vegetation reduces the sensitivity to soil water content. Depth resolution limits for passive microwaves are similar to active radar, but the lateral resolution is broader, at >50 km from current and future satellites systems.

The *thermogravimetric method* has often been regarded as the only direct measure of water content, as it determines the actual amount of water in a soil sample through evaporative drying of the sample. Because of the site destructive nature of this method and the lack of logging capability for it, the gravimetric method is now largely a reference method and not used extensively in hydrological processes studies.

The *neutron moderation method* is a longstanding, well-established method that operates from 30 cm deep and deeper, depending on the length of cable on the probe and the depth of the access pipe. It is possible to achieve accurate water content profiles to depths not easily attained with most other methods. Owing to regulations concerning the use of radioactive sources, the method is not usable for automatic, unattended measurements and, therefore, is labour intensive.

The advances and improvements that have occurred recently are primarily in the high-frequency EM methods, and these are continuing to evolve rapidly. Currently, we have much improved capability to measure water content in the most hydrologically dynamic soil, near or at the soil surface. Some of the research frontiers exist within the refinements or improvements of performance of the individual methods. For example, the GPR method will be placed on a sounder basis with more information on EM field energy density patterns in the ground wave and the impact of soil variability on the resultant water content data. In TDR there has been commendable effort to characterize the sampling patterns within a variety of probe configurations. In the other EM techniques, much more spatial sample weighting data is required to place the methods on a sounder basis. This is particularly true for capacitance devices.

Improving measurement methods generally, and for water content measurement in particular, the greatest research need was and remains the methodology itself. Having led some of the pioneering effort in TDR methodology, I can attest that on numerous occasions I was told by my employer to quit my TDR work as it was 'not demonstrating promising results'. Later, that outlook changed, but support for pure methodology research in the early stages was limited and the funding atmosphere currently appears even more results-oriented than in the mid-1980s. It is important to recognize and promote the importance of methodology and to build those components within research plans. To appreciate the importance of methodology research for hydrological processes one must realize that almost all of the EM techniques listed above are not operational at this time. TDR and capacitance techniques would generally be considered as operational; the other techniques are showing considerable promise, but they will require major research efforts before major applications in hydrology take place.

There is a need to exploit the complementarity of the various techniques without accentuating the differences. This research area has a high level of risk and difficulty. The difficulty is in designing an appropriate experimental protocol where both techniques in a study are reporting data from the same time and location. The risk arising from this difficulty is that if neither method is operating under optimum conditions then low-quality data result and the complementarity is rated low. An example is TDR and remote radar, where the question is whether TDR can complement radar images to provide time and depth data that augment the intermittent availability of radar images. Current designs of TDR probes do not operate in the 3 cm range alone, as does radar. An effective comparison depends first on redesigning a TDR probe. Most research efforts do not wish to wait for such preliminary preparation. Other examples can be found, but one advantage coming from TDR research is that we can design, within limits, TDR probes to meet specific experimental requirements that exploit the various strengths of other techniques.

The final research area I highlight is the disconnect from the soil–instrument interface to the hydrological process scale of interest. Reference has been made to this as spatial variability or scaling up. The size and shape of the sampled volume of each of the methods are quite different from each other and are different from the size and shape of region of interest in hydrological processes. Coupled to this scale problem is the soil variability, which introduces scales of variability that are often different vertically and horizontally. Considerable advance has been achieved in the statistical tools available to characterize and represent spatially variability. In my opinion, what is needed is research that can amalgamate point measurement data in appropriate ways that respect the variability and the hydrological processes affecting the phenomena as observed at the next broader scale. Variability is too often treated as error and scaling up is plagued by increases in error or uncertainty that are not consistent with the field observations. The variety and scope of soil water measurement techniques and the statistical and computer capabilities make this a potentially useful and rewarding area of research.

How may soil water measurement contribute to this area of research? The variety of sample configurations offered by the various EM techniques can be used to identify operative scales for different processes. TDR has been used to delineate the influence of differing plants, such as maize and orchard trees, on infiltration and water uptake patterns. As GPR methodology research advances and provides improved specification of the region sampled, it will become feasible to map water content patterns where vegetation type is compatible with the particular approach. TDR is and will be used to validate GPR findings, making it natural for these two techniques to be used in complementary ways to define appropriate scales of measurement for calibration and use of hydrological models.

The development of EM methods for water content measurement has, to date, unleashed many possibilities for hydrological research, and the continuing advances offer even more exciting options for improved measurement and monitoring.

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Table 2.1: Measured/observed soil attributes contained in WISE soil database. 8 Table 2.2: National Soil Maps in Sub-Saharan Africa.Â Besides supplying water treatments to plants, soil also supports millions of organisms living in it.Â â–¸â–¸ State of the art on methods and tools for digital soil mapping Digital soil mapping (DSM) is a new technological advancement that seeks to fulfil the increasing worldwide demand in spatial soil data through more rapid and accurate production and delivery of soil information and increased coverage and improved spatial resolution of mapped areas. State of the art equipment (e.g., WP4 Potentiameter) uses chilled mirror dewpoint technique combined with a photoelectric detection system to keep the surface of a mirror at dewpoint temperature. Ambient temperature at the sample surface is measured with an infrared thermometer.Â 22 Parametric SWC Models Measuring a SWC is laborious and time consuming. Usually there are only a few data pairs available from measurements.Â 29 Hysteretic behavior of SWC Soil Water Content and Matric Potential are not uniquely related and depend on the path of saturation or desaturation. SWC can be either obtained by desaturation of an initially saturated sample by applying suction or pressure (DRYING CURVE), or by gradually wetting of an initially oven-dry sample (WETTING CURVE). In recent years several types of sensors and measurement techniques have been developed for measuring the moisture content, water saturation, or the volumetric water content of landfilled wastes. In this work, we review several of the most promising techniques.Â Fiber optic sensors and electrical resistivity tomography hold promise for measuring water distributions in situ, particularly during infiltration events, but have not been tested with independent measurements to quantify their accuracy. Additional work is recommended to advance the development of some of these instruments and to acquire an improved understanding of liquid movement in landfills by application of the most promising techniques in the field.