# Soil Water
# MEASUREMENT

## Author Details

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Soil is vital for production of most of our food and it also plays a crucial role in shaping our environment. Rising global population and the attendant demand for more food is putting unprecedented pressure on soil resources, whilst this same pressure, often coupled with poor management, leads to loss of soil through wind and water erosion, and areas of land becoming less fertile and even sterile through salinisation, loss of organic matter and pollution. Soil water plays an important role in all of these. Measurement of soil water and its interaction with vegetation and the weather is, therefore, important for improving agricultural productivity and the environment through work in hydrology, pollution, water resources, geotechnics, civil engineering, hazardous and other waste disposal.

## KEY CONCEPTS OF SOIL WATER

### Three key concepts underlie the behaviour of soil water:

#### Water Content
The most fundamental property of water in soil is the amount stored. Most often, we need to know the volume of water held in a defined volume of space, normally termed the volumetric water content.

#### Soil Water Potential
Ultimately, water is held in soil by the attractive forces between soil particles and the water molecules. In simple granular soils, capillarity is the dominant phenomenon. However, in many clay-dominated soils and at low water contents in other soils, more explicit descriptions of surface interactions are required. In swelling and shrinking soils, water can intercalate clay particles, temporarily forming part of the clay structure. In all cases, however, the lower the water content, the tighter the water is bound into the soil. This has two main consequences. Firstly, as soil dries, it becomes increasingly difficult for water to be removed from the soil. Secondly, water will tend to move from places which are wet to those where it is drier. This is usually quantified by defining a soil water potential as the amount of work required to place an infinitesimal amount of free water in the soil at a given location. Since work is usually needed to remove water from the soil, this quantity is normally negative. The concept of water potential also allows the effects of gravity and osmotic forces to be incorporated into the same formulation. As in conventional mechanics and electrical problems, the force moving water can be defined by the gradient of the potential.

There is a characteristic relationship between water content and water potential for each soil and, often, for each location in the soil. This is rarely unique, since the relationship is hysteretic.

#### Hydraulic Conductivity
To quantify the movement of water through soil, a relationship is needed between the potential gradient and the water flux induced. A proportionality constant relating the two has been found to describe the process well:

$$v = - K \, d\phi/dz$$

where $v$ is the soil water flux, $K$ is the hydraulic conductivity, $\phi$ is the soil water potential and $z$ is the directional co-ordinate (often vertically downwards). This equation is known as Darcy's Law. In unsaturated conditions, $K$ is found to fall very rapidly with soil water content (or potential).

#### Measurement Techniques
Space does not permit a discussion of all types of instrument used in soil water investigations. The rest of this article will, therefore, confine itself to describing the two most common methods for measurement of soil water content *in situ*.

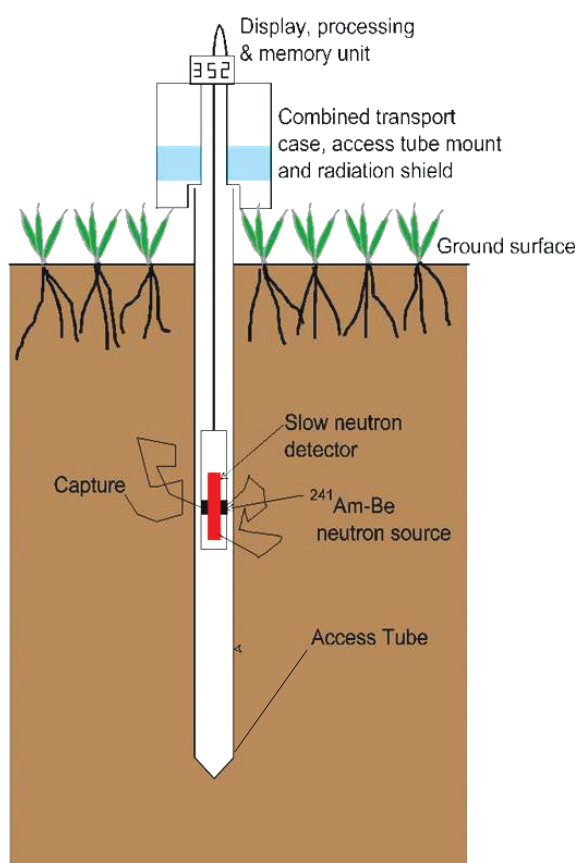Depending on the objective, one may need to know the amount of water stored in a relatively large volume, such as the



*Figure 1.  Arrangement of neutron source and detector in IH II neutron probe, with illustrative neutron paths*

total depth of water from the surface to some defined depth, such as the bottom of the root zone. Alternatively, knowledge of the distribution of water with depth may be needed.

The definition of soil water content requires some care. Water can be held in soil by a variety of physico-chemical mechanisms, which hold it in various degrees of tightness. There is no clear dividing line between water which is chemically bound within the soil particles and that which may be removed by plants or evaporated. For most purposes, a definition of soil water as that removed when the soil is left in an oven maintained at 105° C (Gardner *et al*., 2001) is quite adequate.

This does not, however, provide a practical basis for a routine measurement technique. The taking and drying of samples from field soils is laborious, destructive and very difficult to obtain accurate results with. Variability of soil water content, over even small areas, means that the number of samples required to obtain a modest precision in the mean value is prohibitively large. Where changes in water content are needed, the problem becomes even more severe, since repeated measurements cannot be made at the same place. For these reasons, non-destructive methods are needed, capable of making measurements at the same point easily and repeatedly with a minimum of disturbance to the site. Two major classes of

measurement technique are in common use. These are neutron moderation and a family of methods relying on measuring the dielectric constant of soil.

#### Neutron Moderation
Dating from the late 1940s, this method has been well established for at least 40 years (Bell, 1987). It relies on the fact that hydrogen nuclei are much more efficient at moderating neutrons than the nuclei of most other soil constituents. Except for soils with very high amounts of organic matter, such as peat,
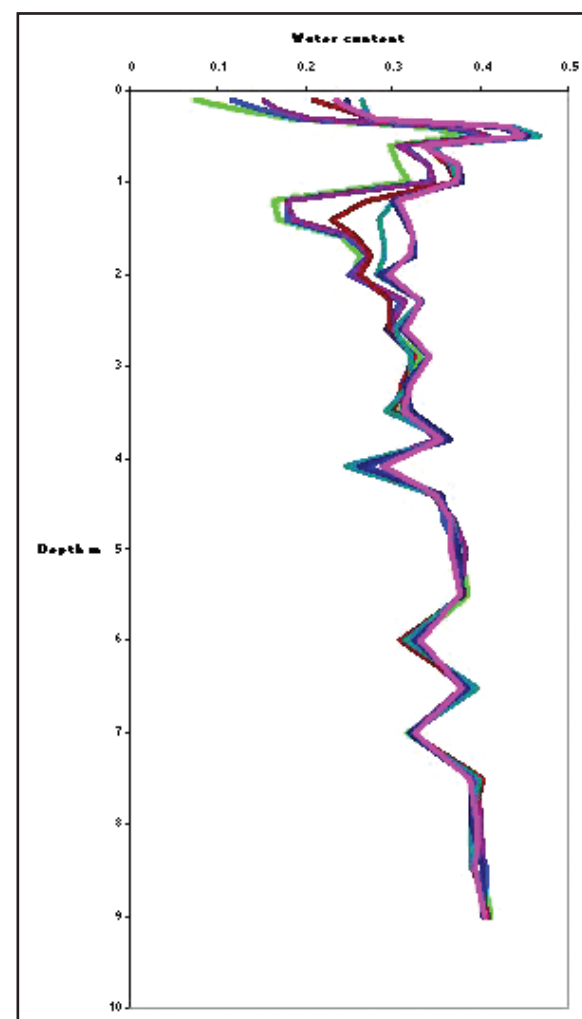


*Neutron probe readings of soil water content to 9 m depth beneath woodland in Berkshire between 21 October 2003 and 5 February 2004. Note that changes of water content occur to at least 4 m depth*

almost all of the hydrogen in a soil is in the water. Even where this is not the case, changes in hydrogen content are normally associated exclusively with changes in water content. Hence a method sensitive principally to hydrogen content is an excellent means of measuring soil water.

The apparatus is usually called a neutron probe and can be

made easily portable. It is normally constructed as shown in Figure 1, where a fast neutron source is mounted close to a detector of slow neutrons. Ideally, the two are coincident, but for practical reasons the source is an annulus around the detector, or a small capsule mounted alongside or at the end of the detector. The neutron source is, in all modern probes, a mixture of $^{241}$Am and $^9$Be. This yields neutrons with energy in the range predominantly 2 – 8 MeV.

The fast neutrons are slowed principally by elastic collisions with nuclei of soil constituents (mainly Si, Al, Fe, O) and water (H, O). Energy transfer is maximised when the two particles are of equal mass (i.e. a neutron and hydrogen nucleus). Hence the number of slow neutrons near the source is very sensitive, in fact almost proportional to, the hydrogen density and therefore the water content.

The slow neutrons are counted by a detector which is a proportional counter filled with $^{10}$BF$_3$ or $^3$He, or a scintillation detector using $^6$Li doped glass. These all absorb slow neutrons and produce a measurable pulse for each event.

Both the slope and the (quite small) intercept of the relationship between neutron count rate and soil water content reflect the effect of elastic scattering and capture by nuclei of soil constituents and are, therefore, dependent on the chemical composition of the soil and its dry bulk density (the mass of dry soil in a unit volume of space). Calibration of the probe for different soils is, therefore, necessary.

Sources in the range of 0.4 – 2 GBq are suitable for field use, allowing measurements with a precision of the order of 0.1% volumetric water content to be made with an integrating time of 1 minute or less. A source of this strength presents a small radiological hazard, which requires appropriate precautions to bring it within acceptable safety levels.

Measurements are normally made by lowering the probe down an "access tube", a close-fitting tube of aluminium, brass, steel or plastic of diameter about 50 mm. The measurement represents an average water content of an approximately spherical volume of soil with a radius of the order of 150 mm. Installation of the access tube must be performed with care so as to leave no gap between it and the soil. Should this occur, the calibration relationship between count rate and soil water content is unreliable. Additionally, if a gap extends to the surface, this would provide a route for rainwater to run down, thus making measurements from the access tube unrepresentative.

In many agronomic applications, readings deeper than 1 m below ground level are not required; other applications often need information from deeper in the profile. Use of a light drilling rig allows tubes to be emplaced to at least 10 m depth, whilst measurements to much deeper depths and over horizontal distances up to 600 m beneath landfill have been reported (Kramer *et al*., 1995). Although attempts have been made to automate measurements, several factors including cost, the size of equipment and radiological safety regulations mean that the device is employed almost exclusively for manual measurement. It is very widely used because of its ability to make measurements to considerable depth with minimal disturbance to the environment it measures. Because it has been so long established, it has become a *de facto* standard, with other, newer methods enjoying less confidence.

The method has a number of uses outside the soil and unsaturated deposit area. Monitoring has been conducted beneath and within landfill, in sewage treatment beds, to detect biofilm build up, and to measure density and thickness of ice layers in snowpacks (Morris and Cooper, 2003).

## Dielectric methods

Neutron moderation exploits the large contrast in the neutron moderating power of hydrogen compared with most other constituents of soil. Another property of water, which contrasts sharply with that of other soil constituents, is permittivity. This fact is used in a wide range of devices.

Water has a remarkably constant relative permittivity (dielectric constant), $\varepsilon_r$, of about 80 over a wide range of frequency from about 1 kHz to about 3 GHz, whilst that of most other soil constituents is less than about 6. The permittivity of soil is, therefore, very sensitive to water content. The permittivity affects a number of electromagnetic properties of the medium, which have been used as the basis for water content measurement.

## Time Domain Reflectometry

The speed at which an electromagnetic wave is propagated, $v$, is given by:

$$v = c / \sqrt{\varepsilon_r}$$

where $c$ is the speed of light *in vacuo*. By measuring the travel time of an electromagnetic pulse through the medium, a measure of its relative permittivity, and, hence, water content, can be determined. The most common arrangement is for two (or more) parallel rods to be inserted into the soil 10 – 50 mm apart. A step voltage with a rise time of less than 300 ps, having frequency components predominantly in the several hundred MHz range, is applied and the time taken for the pulse to travel down the rods, reflect from the end and return to its origin is timed. If more than two rods are used, these are usually configured as one central
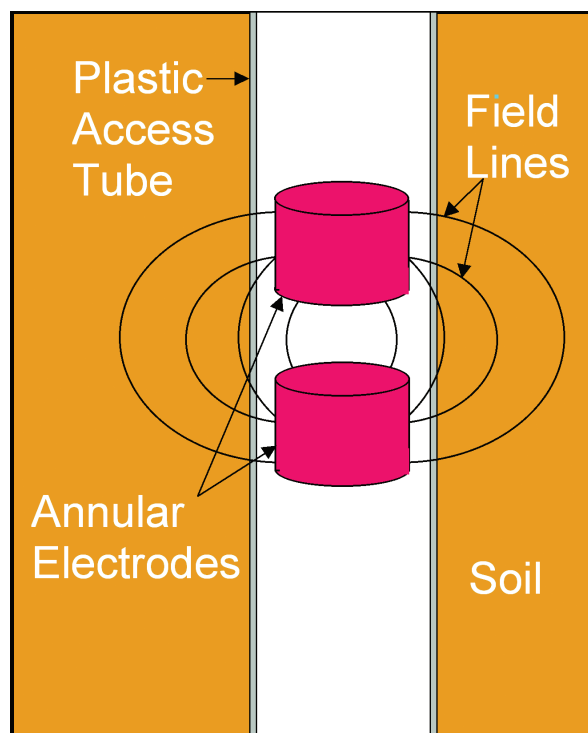


*Figure 2. Penetration of electric field lines into soil from annular electrodes in an access tube*

rod with the others connected together in a coaxial arrangement. This technique for measuring water content is known as Time Domain Reflectometry (or TDR).

Typically, the relative permittivity of wet soil is about 16, so that the speed of propagation of the pulse will be about 0.75 x 10$^8$ m s$^{-1}$. Water content is approximately linear in $\sqrt{\varepsilon_r}$ and thus to the time of travel of the pulse. The method is limited by a number of factors, including attenuation of the signal by electrical conduction in the soil, time resolution of the signal, dispersion of the pulse and partial reflections from inhomogeneities in the soil. If the rods are inserted vertically in the soil, depth resolution is impaired, but total storage of water to the rod depth is measured.

Because of the very fast electronics needed, specialised equipment is essential for TDR. Until recently, standard cable testers, which employ the same technique to locate a break in a cable, were most commonly used. Improvements to the basic methodology of a two-wire waveguide and cable tester have been made steadily. These include the use of three- or more wire guides, various different matching transformers to improve coupling between the waveguide and cable tester, insulated probes and RF diodes (Hook *et al*., 1992) to obtain clearer reflections. Several manufacturers produce dedicated instruments, which are reasonably weatherproof and can be operated in the field automatically. These often incorporate mulitplexers to allow several waveguides to be connected to one electronics box. This is attractive, since waveguides are cheap, whilst the electronics, because of its sophistication,is expensive.

Solutes in the water increase the electrical conductivity of the solution. In most cases, this has an almost negligible effect on the speed of propagation but does attenuate the pulse as it travels down the waveguide and back. By measuring this attenuation, an estimate of soil electrical conductivity and, hence, solute concentration can be made.

Skill is needed to interpret the waveforms which result from TDR measurements, in particular in recognising the reflections characterising the soil entry and (particularly) exit points of the pulse. Automatic software is available for this task, both proprietary (usually built into commercial devices) and freely available. Such software is not, however, foolproof.

## Capacitance Measurements

The capacitance, $C_1$, between a pair of electrodes embedded in a medium of relative permittivity $\varepsilon_r$ is given by the formula:

$$C_1 = \varepsilon_r \, \varepsilon_o \, S$$

where $\varepsilon_o$ is the permittivity of free space and $S$ is a shape factor depending on the geometry of the two electrodes. The capacitor so formed can be incorporated into an oscillator circuit by attaching an inductor in parallel with the capacitor. The oscillation frequency of this circuit is given by:

$$\omega = 2\pi f = \sqrt{LC}$$

where $L$ is the value of the inductance and $C$ is the total capacitance, which includes $C_1$. Thus the frequency of oscillation can be used to derive a value for the capacitance and hence $\varepsilon_r$, although empirical calibration is necessary (Dean, 1994; Robinson *et al*., 1998).

In reality, the electrodes need not be immersed fully in the medium. A successful arrangement has the electrodes as two separate annuli, mounted coaxially one above the other, as shown

in Figure 2. This arrangement can be mounted permanently inside a plastic access tube or incorporated into a portable probe, which can be lowered to a series of depths inside the tube to obtain readings. By this means, data acquisition is much quicker than by a neutron probe, there is no radioactive hazard or heavy shielding and the depth resolution of measurements is much better (Dean *et al*, 1987; Bell *et al*., 1987). Penetration of the field lines into the soil is limited, making the effective volume of soil measured considerably less than by the neutron probe (Dean *et al*., 1987) and hence the measurements are more sensitive to the quality of access tube installation (Bell *et al*., 1987).

A great advantage of the capacitance probe technique is the flexibility possible in electrode arrangements. Provided that electrodes can be designed such that a large proportion of the field lines pass through the soil, then soil water content can be successfully measured.

Operating at a frequency in the region of 100 MHz, the capacitance probe is relatively insensitive to soil electrical conductivity, although incorporation of this into a correction factor improves results (Robinson *et al*., 1999). At lower frequency (say, 20 MHz), the measurement is much more sensitive to electrical conductivity and by switching different inductances into the circuit to vary the frequency, simultaneous estimates of water content and electrical conductivity can be obtained.

## Characteristic Impedance

The characteristic impedance of a transmission line is given by:

$$\sqrt{(L/C)}$$

where L and C are the inductance and capacitance of the line per unit length.

By feeding a fixed frequency wave from an oscillator in the 100 MHz region through a matched transmission line, into a further short length of line, embedded in a dielectric medium (soil), an impedance mismatch occurs, whose magnitude is dependent on the permittivity of the soil. Reflection occurs at the end and a standing wave is set up. Measurement of the voltage at the oscillator end allows the permittivity of the medium to be calculated. The instrument invented by Gaskin & Miller (1996), sold commercially as the Theta Probe, has 70 mm long electrodes forming the second transmission line.

Further development of this instrument into a profiling probe (Delta-T Devices Ltd., Burwell, UK) has abandoned the short transmission line in favour of rings similar to that of a capacitance depth probe. These are mounted on a plastic rod, which is inserted into a plastic access tube in the ground. Water content may be monitored simultaneously and continuously at up to six depths.

## Complex Impedance Bridge

In many ways, the most natural method to use for measurement of dielectric permittivity is to use a complex bridge circuit. Such approaches have been employed, although difficulty has been experienced in designing circuitry suitable for use under field conditions that will work reliably at frequencies in the 100 MHz or higher range.



*Sentek Envirosmart capacitance probe, showing annular electrodes and top of access tube. Picture courtesy of Campbell Scientific Ltd*
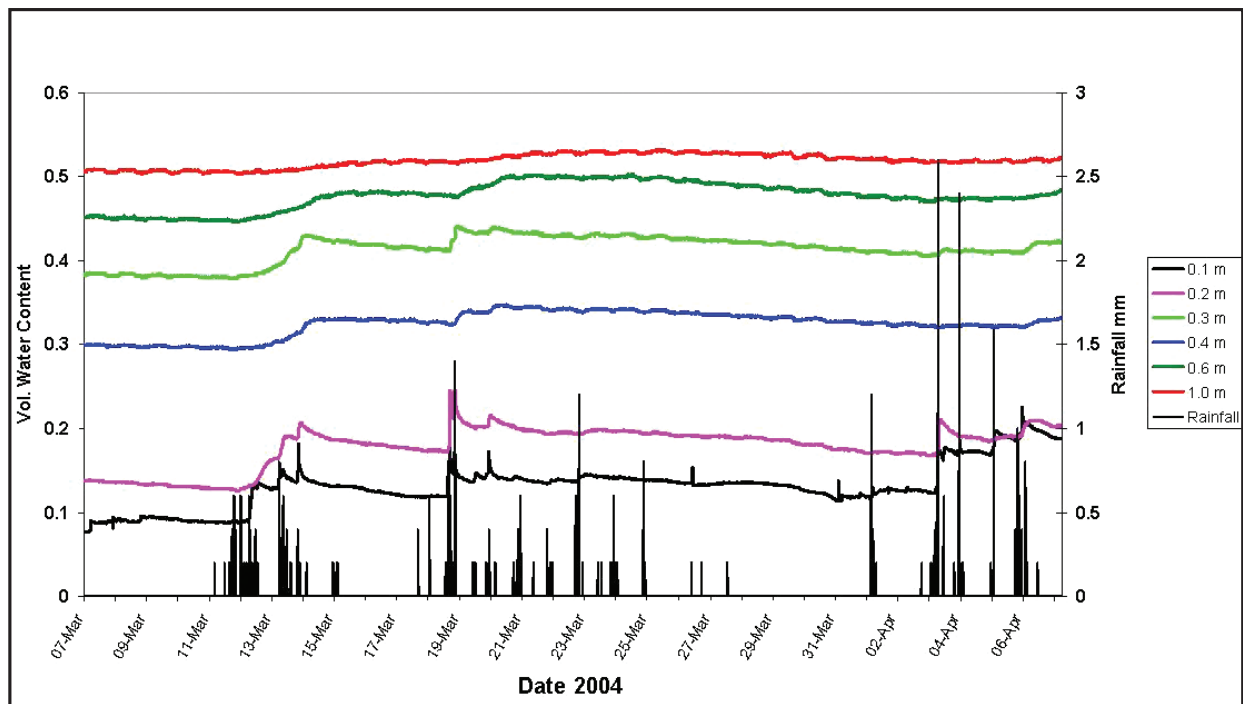
*Water content variations measured every 15 minutes over a one month period in Spring 2004 beneath a grass field at West Ilsley, Berkshire using a Delta-T Devices Profile Probe*

Campbell (1990) reported a complex bridge circuit, which was later adapted for routine field use and exploited commercially. His design operated at a frequency of 50 MHz, which is near the lower end of frequencies needed to avoid problems caused by polarisation of clay colloids.

More recently, Hilhorst *et al.* (1993) designed an ASIC which analyses signals in quadrature to measure the real and imaginary components of the relative permittivity between two small electrodes. The device operates, however, at only 20 MHz, which causes very large relative permittivity values (over 100) to be obtained for some clays.

## Relation between Soil Water Content and Permittivity

All methods based on measurement of dielectric properties depend on there being a reliable relationship between soil water content and the permittivity of the medium. The complexity of soil makes this, at best, a semi-empirical task. A simple model assumes that the relative permittivity of the mixture of soil and water can be represented by:

$$\sqrt{\varepsilon_r} = f_{air}\sqrt{\varepsilon_{air}} + f_{solid}\sqrt{\varepsilon_{solid}} + f_{water}\sqrt{\varepsilon_{water}}$$

where $f_i$ represents the volumetric fraction of constituent $i$ and $\varepsilon_i$ is its relative permittivity.

## Conclusion

Although this short article has highlighted only the measurement of water content of soil, many other aspects need to be measured to obtain a complete description of the state of the soil. These include measurement of water potential, solute concentration, water and solute flux and hydraulic properties of the soil.

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