Soil Moisture Measurement Instrumentation

Abstract

A review of some of the techniques available for the determination of soil moisture content as a tension or a volume is offered. The method of determining soil moisture content by the different techniques is described with attention given to the neutron probe (NP), time-domain reflectometry (TDR) and frequency domain (Capacitance) techniques in particular. The choice of instrumentation for soil moisture determination will depend on the consideration of factors such as: physical limitations of different techniques; the level of information required (either an absolute or relative moisture measurement); the amount of data needed to objectively decide upon an irrigation regime (with consideration to spatial and temporal problems); the initial cost of the instrument and sampling; the reliability of the instrument and the collected data; and, the ease of use of the instrument in the field.

Introduction

Moisture content of the soil is a major factor determining plant growth[1], especially in irrigated systems. Currently there are many and varied methods for determining soil water content on a volume basis (θ_v, m^3m^{-3}) or a tension basis (kPa or bar) as described by Gardener[2].

The basic objective of irrigation scheduling is to minimise water stress of the plant, that of over irrigation, and under irrigation. The manager aims to manipulate the biological process of cell elongation and cell reproduction for improved plant yield[3] and maximum use of available effluent.

In optimising plant cell reproduction and growth (cell expansion), the ability to monitor the soil moisture content is the principal facet of developing good water management programs. A tendency to over or under-irrigate results due to the absence of information about the soil moisture status down the soil profile. The result of over irrigation is poor utilisation of natural rainfall because of high surface run off, and production problems associated with excessively wet soil such as waterlogging, leading to recharge of underlying aquifers, leaching of nutrients, increased incidence of plant disease and reduced daily water use. The reduced daily water use of plants increases the area of irrigated land required to dispose of a given volume of water increasing the capital cost of land based waste water disposal systems.

The decline of soil water content will result in a decrease of photosynthesis and cell expansion of the plant. Under-irrigation will result in stress being placed upon the plant root water uptake mechanism to maintain transpiration rates. A subsequent reduction in daily water use and cell production will occur with decreasing soil moisture content. Ludlow *et al.* [3] showed that stem elongation rate declined (in *Cajanus cajan*) at a linear rate after 10% of available water was utilised by the plant until elongation was 40% of the maximum rate as the plants approached wilting point.

To develop an irrigation scheduling program the basic requirement is the ability to regularly obtain objective data. The ability to accurately measure soil water content, plant size and condition is an integral mechanism in the process of developing an irrigation scheduling program that allows a better understanding of plant and soil water relations. From this basis, an understanding of plant agronomy is developed with an appropriate computer interface giving the manager a better working knowledge of what is happening to the applied irrigation and its relation to plant water use and soil moisture status.

Instruments Available for Objective Measurement of Soil Moisture Content

Objective soil moisture measurement can be undertaken with simple tools, such as a shovel, or complex tools that record measurement of soil moisture on a volumetric basis. The method of measurement is simply a device allowing moisture determination in an objective fashion. It is important that measurements are made regularly and recorded systematically to allow improvement in irrigation scheduling and soil/plant management decisions.

There are different methods available for development of an irrigation scheduling program using different tools to collect relevant information and present the data to the irrigation manager.

The Neutron Probe (NP)

An established technique that is used extensively throughout Australia by farmers, consultants and researchers. The technique is based on the measurement of fast moving neutrons (generated from an Americium 241/Beryllium source) that are slowed (thermalised) in the soil by an elastic collision with existing Hydrogen particles in the soil. Hydrogen (H^+) is present in the soil as a constituent of:

1) soil organic matter
2) soil clay minerals
3) water

Water is the only form of H^+ that will change from measurement to measurement. Therefore any change in the counts recorded by the NP is due to a change in the moisture with an increase in counts relating to an increase in moisture content.

In the field aluminium tubes are inserted into the soil and stopped to minimise water entry. Readings are taken at depths down the profile (e.g. 20, 30, 40, 50, 60, 70, 80, 100 and 120 cm) with a sixteen second count. The three aluminium tubes are then averaged to counter the effect of spatial variability reducing the value of the measured moisture content data.

Measurements are taken two to four times a week and information is down-loaded to a personal computer for interpretation. Use of the NP technique for vadose (unsaturated) zone monitoring has been employed to determine contaminate leak detection along specific transport pathways[5], and to monitor land disposal of effluent with the NP technique[6].

Time-Domain Reflectometry (TDR)

Determines the apparent dielectric (Ka) of the soil matrix and this is empirically related to the volumetric soil moisture content[7]. The method is quick, relatively independent of soil type, non destructive, suited for surface and profile measurements, and allows repeatable *in situ* measurement. The TDR is a portable unit that can be carried allowing point soil moisture measurements or linked to a multiplexer to measure an array of buried waveguides[8]. The moisture content determined by the TDR is the average moisture along the length of the waveguides. Therefore, to measure at depth of 20 cm, waveguides are placed in the soil horizontally at that depth. If 30 cm waveguides are placed vertically into the soil, the moisture content determined by the TDR will be the integrated moisture content from the soil surface to a depth of 30 cm.

The technique is based upon cable testing technology, with a broad-band Electromagnetic step pulse generated and propagated along a coaxial cable (Fig. 1.). At the end of the cable stainless steel rods (waveguides) are inserted into the ground. The time of travel of the EM wave is determined by the apparent dielectric (Ka) of the medium (in this case soil). Water with a high dielectric (Ka ≈ 80), compared to soil (Ka ≈ 3 to 5) and air (Ka = 1), dominates the measured Ka. Thus, if the soil is saturated the Ka is high (due to the presence of increased water) and the travel time of the EM wave along the waveguides is long. If the soil is dry the travel time along the waveguides is short and the Ka is therefore low. Eq. 1. shows the relationship of Ka to travel time (Δt).

$$Ka = (c\Delta t/2L)^2 \qquad \text{eq. 1.}$$

Where c is the velocity of light (3×10^8 ms^{-1}) and L is the length of the wave guide (m). Topp *et al.*[7] empirically related Ka to θ_V via third order polynomial and this equation (eq. 2.) is the basis for soil moisture measurements at present.

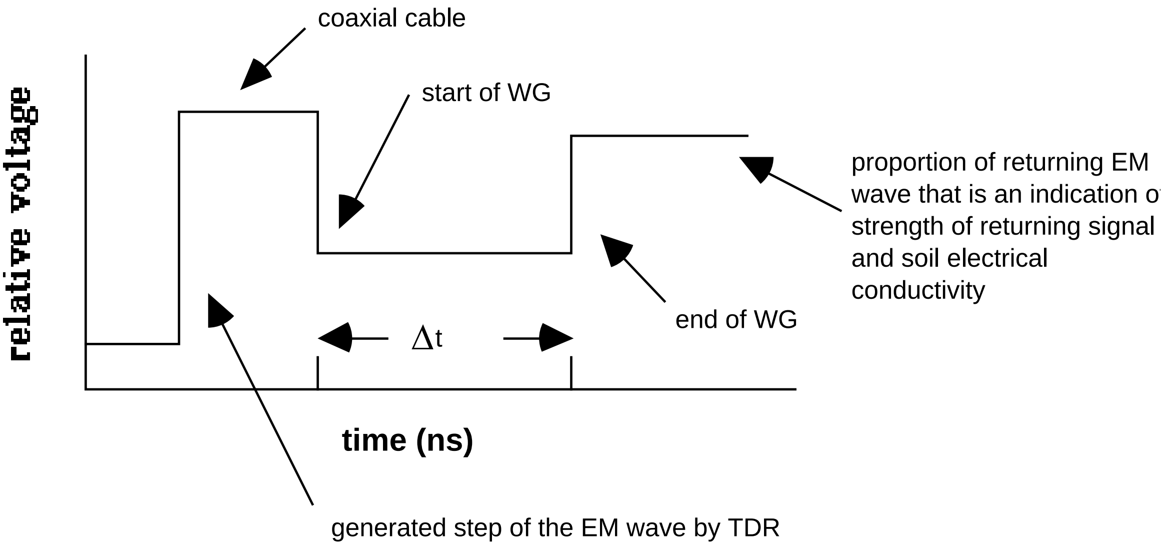

Figure 1. Schematic diagram of an electromagnetic wave generated by a step pulse TDR system as it travels along the coaxial cable and down the waveguides into the soil.

$$\theta_V = -5.3x10^{-2} + 2.92x10^{-2}Ka - 5.5x10^{-4}Ka^2 + 4.3x10^{-6}Ka^3 \qquad \text{eq. 2.}$$

Further calibration is required for soil high in organic matter and other materials such as grain. In the field waveguides (stainless steel) are of two forms being either balanced (two-wire) or unbalanced (three-wire) as shown in Fig. 2. Generally, two wire probes are used for portable measurement and the three wire probes for permanently placed waveguides.

Effective length of waveguides (and therefore the depth of measurement) will be determined by the power of the step pulse generated by the TDR, the soil type (heavy clay attenuates the wave more so than lighter soil types) and the moisture content of the soil. Waveguides of length 2 m have been successfully used to measure moisture content in Australian soil.[9] However, in wet heavy clay soil waveguide length has sometimes been reduced to as little as 30 cm. This current problem is being rectified by increasing the power and stability of the EM wave and by coating waveguides with thin cover of a low dielectric material. This will ensure that a percentage of the wave will travel the length of the waveguides and be reflected allowing determination of Δt. Importantly, the attenuation of the EM wave in conducting soil (soil with a high electrical conductivity) will allow the TDR technique to independently measure moisture content and bulk soil electrical conductivity. This is important for the measurement of solute travel[10,11] (e.g. applied fertiliser).

Research is increasing in developing further applications of TDR such as surface measurements, profile measurements, long range multiplexing of waveguides and solute transport determination. This technique will be more widely used in the future by research and irrigation managers.

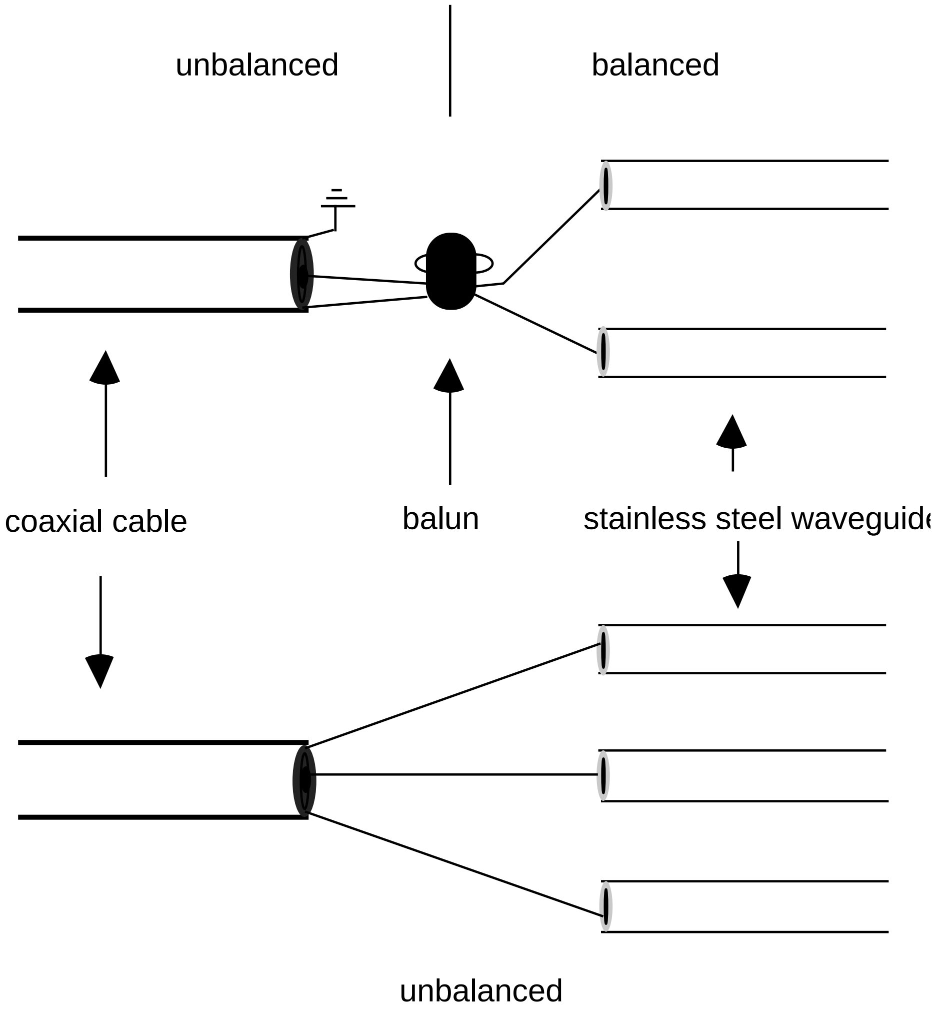

Figure 2. Schematic diagram illustrating the connection of the coaxial cable (unbalanced signal) to the stainless steel waveguides through, a) a balun for the two-wire system, and b) direct to the waveguides in the three-wire system.

Tensiometers

Portable and stationary tensiometers measure the soil moisture content as a tension or pressure ranging from 0 to -100 kPa, (0 to -1 bar). Tensiometers fundamentally act in a similar fashion to a plant root measuring the force that plants have to exert to obtain moisture from the soil. As the soil dries the water is lost from the tensiometer via a ceramic cup. The loss of water creates a vacuum in the tensiometer and is reported as a pressure reading, the drier the soil the higher the pressure reading, (noting -0.1 bar is considered field capacity and -15 bar wilting point).

Tensiometers may be placed permanently in the soil giving an analogue or digital output. Logging of tensiometers is possible via transducers and a communication cable back to a computer or datalogger. Portable tensiometers allow greater freedom of sampling giving relatively quick readings of soil moisture tension. Tensiometers can take time to equilibrate especially in heavier soil types and this should be accounted for in determining an irrigation scheduling regime. Tensiometers must be installed correctly and well maintained to operate accurately and the practical limit for reliable readings generally -800 kPa (-0.8 bar).

Frequency Domain (Capacitance)

The capacitance technique is similar to that of TDR in that the apparent (Ka) dielectric of the soil is measured and empirically related to the moisture content (θ_V). A high frequency transistor oscillator (≈150 Mhz) operates with the soil (dielectric) forming part of an ideal capacitor as shown in eq. 3.

$$C = K\varepsilon_O A/s \qquad \text{eq. 3.}$$

where the dielectric (K) is related to the capacitance (C) via the relationship of the total electrode area (A) and spacing of the electrodes (s), noting that (ε_O) the permittivity of free space is constant.[12]

In a field situation the design of the capacitance probe is not ideal with two annular rings (electrodes) placed in a plastic access tube in the soil. The measured area is now removed from between the electrodes to outside the access tube as shown in Fig. 3. Thus, in a field situation the measured capacitance (C) is determined as:

$$C = gK \qquad \text{eq. 4.}$$

where the C is related to K via a geometrical constant (g).[13] g depends upon electrode spacing, area and orientation of the electrodes in the soil and ε_O.[12]

Measurement is undertaken by either lowering a sensor into the access tube[14] or placing an array of sensors into the access tubes and logging the output frequency. The measured (angular) frequency is related to the soil moisture content via a non-linear calibration. Measurement of absolute moisture content is dependant on soil type and bulk density.

The potential for capacitance based soil moisture determination is good[13]. However, development is required to determine the actual measurement area of the probe and its spatial sensitivity to change in moisture content. Further, the calibration of the technique *in situ* needs to more fully understood to allow universal use and the effect of electrical conductivity, temperature and acid soil on measured frequency has not been fully studied (T.J. Dean, pers comm.).

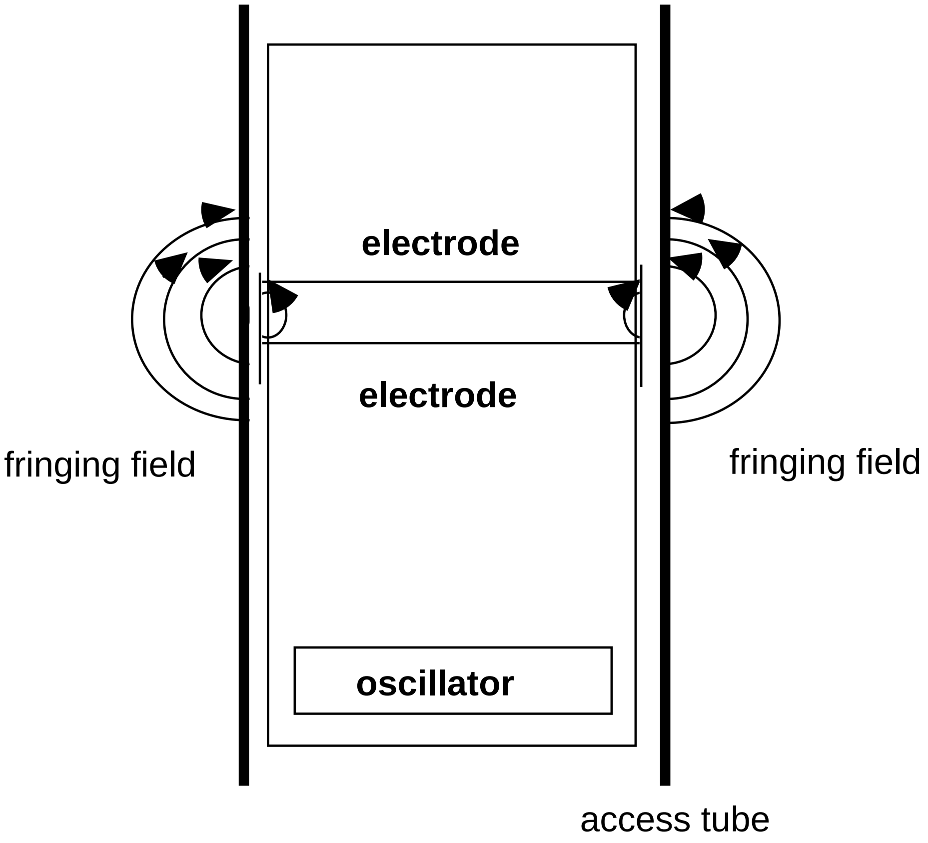

Figure 3. Schematic diagram of capacitance probe in an access tube (after White and Zegelin[12])

Electrical Resistance (Gypsum) Blocks

Electrodes are embedded in a porous (gypsum) block and placed in the soil at different depths in the root zone. The water in the soil will reach an equilibrium with the water in the gypsum block and the electrical resistance is then determined and related to moisture content as a tension (kPa or bars). Gypsum blocks do not measure the moisture content at low potential (from 0 to -100 kPa) well. The operating range is suited from about -100 kPa to -1500 kPa (as the soil dries). Gypsum blocks will dissolve over a period of time (with the rate of dissolution increasing in sodic soil[2]) generally lasting for two to three seasons in good conditions.

Large errors, up to 100%, can occur due to: slow equilibrium of blocks with the actual soil potential; the dependence of resistance on the block temperature; effect of hysteresis on calibration of block (if undertaken to improve accuracy) and actual contact with the soil; and, blocked pores by fine material (e.g. silt or clay particles)[2,12]. Electrical resistance is a useful indicator of the soil moisture content in respect to root conditions such as: plentiful water; good growing conditions; approaching water stress; and water stressed plants.

Conclusions

The need to determine the moisture status of the soil is a critical factor influencing plant production. Correct irrigation scheduling can control the soil moisture status reducing through-drainage and maintaining optimum levels of soil water for maximum plant growth. To implement a reliable and accurate irrigation scheduling regime regular, objective soil moisture readings are essential. There are different tools available for obtaining soil moisture content including NP, TDR, tension and capacitance techniques. The choice of instrumentation will be determined by the form of information required by the operator, the soil type, relative cost, reliability and ease of use in the field.

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