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REVIEW OF TECHNIQUES FOR MEASURING SOIL MOISTURE IN SITU.(U)
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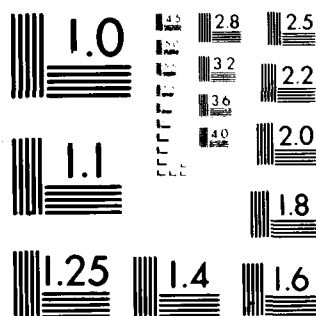
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REVIEW OF TECHNIQUES FOR MEASURING SOIL MOISTURE IN SITU

H.L. McKim, J.E. Walsh and D.N. Arion



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Cover: Tensiometer/transducer system and thermistors interfaced to the GOES data collection system, Sleepers River Research Watershed, Danville, Vermont.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Recently there has been an increased interest in the in-situ measurement of soil moisture content in the areas of hydrology, meteorology, agriculture and environmental studies. Current methods generally have limitations, depending upon the use of the data, that greatly influence acquisition and reliability of the soil moisture determination. This report discusses gravimetric, nuclear, electromagnetic, tensiometric and hygroscopic techniques and the advantages and disadvantages of using the technique. Emphasis is placed on the tensiometric and electromagnetic techniques. These two measurements when coupled together would supply information on the wetting and drying soil moisture characteristic curves and thereby provide a means of tracing moisture movement under field conditions in cold climates.		

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PREFACE

This report was prepared by Dr. H.L. McKim, Research Soil Scientist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, Dr. J.E. Walsh, Associate Professor of Physics, Dartmouth College, and D.N. Arion, formerly a Computer Technician at CRREL. This study was sponsored as part of the U.S. Army Corps of Engineers Civil Works Unit CWIS 31587, *Inventory Techniques for Ground Beneath Snow Cover*.

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REVIEW OF TECHNIQUES FOR MEASURING SOIL MOISTURE IN SITU

H.L. McKim, J.E. Walsh and D.N. Arion

INTRODUCTION

The ability to measure soil moisture in situ is important in all soil science disciplines. It is critical in the planning, design, construction, operation and management of any system where soil is a major component. The problems involved in the measurement of soil moisture are both instrumental and spatial due to the complexity of the soil environment. The major problem seems to be the spatial inhomogeneity of a soil system, both horizontal and vertical.

Many field procedures have been employed to measure soil moisture in situ. This report will review some of these procedures and evaluate advantages, disadvantages and the accuracy of the most commonly used methods. The soil moisture measurement techniques covered in this report are: gravimetric, nuclear, electromagnetic, tensiometric and hygrometric.

The primary problem in measuring soil moisture is determining how many measurements must be made to obtain a representative moisture value and where these measurements should be made. The problem that must be faced no matter which procedure is used is the horizontal and vertical variability of the soil characteristics. Each method has advantages and disadvantages because of the complexity of instrumentation, difficulty in instrument calibration and cost. The selection of a procedure should be based on how the value for soil moisture content is to be used. If very detailed information is needed for research modeling, one may choose a sophisticated measurement technique. But in many engineering, design and operational programs a less detailed procedure can

supply adequate information while costing less and taking less time.

GRAVIMETRIC TECHNIQUES

The oven-drying technique is probably the most widely used of all the gravimetric methods for soil moisture measurement, and it is often used to calibrate other soil moisture procedures. The method consists of oven-drying a soil sample at 105°C until a constant weight is obtained. *Usually this occurs within 12 hours, but with large samples the drying time increases.* The wet weight of the soil sample is taken prior to oven-drying. The amount of water in the sample can be determined and the moisture content calculated and expressed on a percentage basis. If the volumetric water content is required, the gravimetric value is multiplied by the bulk density of the soil:

$$\theta = (W_w/W_d)(\gamma_d/\gamma_w) \times 100 \quad (1)$$

where θ = volumetric water content (%)

W_w = weight of water (g)

W_d = dry weight of soil (g)

γ_d = oven-dry bulk density (g/cm³)

γ_w = density of water (g/cm³)

There are advantages and disadvantages to the oven-drying gravimetric procedure. The advantages are:

1. Samples can be taken with an auger or tube sampler.
2. Sample acquisition is fast and inexpensive.
3. Soil moisture content is easily calculated.

The disadvantages include:

1. It is difficult to obtain representative soil moisture values in an inhomogeneous soil profile.
2. Many samples are required to provide an adequate estimate of soil moisture content.
3. Many samples are required over long periods of time to monitor moisture movement or amount of moisture over time and space. This is very destructive to the site.

Even though gravimetric methods are the most widely used, there are inherent problems in interpreting the data. Hewlett and Douglass (1961) determined the number of sample clusters required at two sites to maintain the estimated standard error of moisture at 1% by volume (a sample cluster contained one soil density and moisture determination). The required number of clusters ranged from 11 to 22 and was dependent on site-specific soil characteristics. A low correlation ($r = -0.40$) between density and moisture percentage resulted from this study. A higher correlation ($r = -0.80$) was obtained when the number of clusters was reduced from 5 to 13. They concluded that the use of gravimetric sampling in evapotranspiration studies at these two sites had doubtful possibilities.

Studies conducted at the Deer Creek Lake, Ohio, land treatment site, where gravimetric moisture determinations were obtained at known time intervals during wastewater application to three 3-acre test sites, showed great variability in the results (Abele et al. 1979). In these studies a 1% error in the measured or computed gravimetric water content resulted in a 1.6% error in computing the volumetric water content. The 1.6% variation corresponds to 49% of the total water applied.

Other gravimetric methods are discussed in National Cooperative Highway Research Program (1973); these include freeze drying, distillation, desiccant weight gain, alcohol burning, alcohol extraction, use of calcium carbide (hydride) or Karl Fisher reagent, and immersion (pyrometer). Of these techniques the calcium carbide method is the most frequently used (Antrim et al. 1970, Blystone et al. 1961).

NUCLEAR TECHNIQUES

Neutron scattering

The neutron scattering method is an indirect way of determining soil moisture content. The method estimates the moisture content of the

soil by measurement of the hydrogen particle density. Initial development of the neutron probe began in 1950 (Belcher et al. 1950, 1952). Gardner and Kirkham (1952) defined the principles on which the method is actually based. In this method, high energy neutrons emitted by a radioactive source are injected into the soil. Collisions with soil components thermalize the injected neutrons. The energy lost in these collisions is much greater when they take place with atoms of low atomic weight than when they occur with heavier atoms. In most soils, hydrogen is the only element of low atomic weight present in large quantities, and hydrogen can decrease the speed of fast neutrons much more effectively than any other element present in the soil. The density of the resultant cloud of slow neutrons is a function of the soil moisture content in the liquid, solid or vapor state. The number of slow neutrons returning to the detector per unit time over a known volume of influence or soil volume is counted and the soil moisture content determined from a standard curve of counts vs volumetric water content.

Two types of probes have been developed. One is a depth probe that is lowered through an access tube to the depth at which the moisture content is desired. The other is a surface probe that gives the moisture content of the top few centimeters of soil.

Several sources of high energy neutrons have been used. The americium-beryllium (Am-Be) source seems to be the one most used (Bell and McCulloch 1966). Van Bavel and Stirk (1967) found that this source eliminated gamma radiation, decreased the probe weight, increased the count rate and possibly increased the depth resolution of the soil moisture measurement.

The strength of the source varies with the type and manufacturer. Van Bavel (1962) found that 1 or 2 millicuries (mc) of a radium-beryllium (Ra-Be) source were adequate. The strength of the source of Am-Be that Van Bavel and Stirk (1967) used was 150 mc. Others (Bell and McCulloch 1966, Long and French 1967) reported use of Am-Be sources of 10, 30, 50 and 300 mc.

If subsurface measurements are required, the neutron probe must be placed in an access tube that may be closed at the bottom. The size and composition of the tube can affect the resultant neutron density (Stolzy and Cahoon 1957). Placement of the tube in the field has been discussed by many authors (Kozachyn and McHenry 1964, Bowman and King 1965, Koshi 1966, Long and

French 1967). The method most used is to drill a slightly undersized hole and tamp the access tube into the drilled hole to ensure a tight fit.

The accuracy of the neutron probe can be found from the deviation calculated from the regression analysis in which neutron counts are converted to volumetric moisture content. Wilson (1971) reported that the calibration depends upon the source strength, the nature of the detector, the geometry of the source and detector in the probe, the materials used to construct the probe, the size and composition of the access tube, and the physical and chemical properties of the soil. In addition, Visvalingam and Tandy (1972) found that vehicle ignition noise greatly influenced the neutron probe readings.

In laboratory calibration the volume of soil used should be large enough to be considered effectively infinite relative to the neutron flux. Manufacturers of probes supply a generalized calibration curve with each unit; however, the probe should be calibrated for each soil type if an accurate moisture content determination is desired. Procedures have been developed for laboratory and field calibration (Douglass 1966, King 1967, Luebs et al. 1968). The moisture content value represents an average over a known volume of soil. Therefore, in laboratory calibration the soil used should be homogeneous in regard to texture, structure, density and moisture content (Belcher et al. 1950, Van Bavel 1971, 1962, Douglass 1966). Field calibration of the neutron probe is reported to be extremely difficult (Stewart and Taylor 1957, Lawless et al. 1963).

No matter what type of calibration is used, all electrical equipment has the potential to drift. Therefore, primary standards should be employed to enable periodic recalibration of the probe. Various recalibration procedures have been reported (Stewart and Taylor 1957, Marais and Smit 1958, 1962, Bowman and King 1965, Churayev and Rode 1966, Holmes 1966, Stone et al. 1966, Bell and Eeles 1967, Long and French 1967, Ursic 1967, Luebs et al. 1968, Olgaard and Haahr 1968).

The sphere of influence of the neutron probe measurement, the volume over which the average moisture content is calculated, depends on the amount of moisture in the soil. Van Bavel et al. (1956) and Glasstone and Edlund (1957) defined the "sphere of influence" as that volume which contains 95% of all the thermal neutrons. This concept has been criticized by Mortier et al.

(1960) and Olgaard (1965). They suggest that the "sphere of importance" is the one which, if all the soil and water outside the sphere were removed, would yield a neutron flux at the source that is 95% of the flux obtained in an infinite medium. The volume of soil over which the measurement is made becomes very important when measuring soil moisture with depth. In many studies however, the diameter of the sphere of importance or influence cannot be easily related to resolution. This is due to the heterogeneity that occurs with soil depth. The vertical resolution is critical to many studies, especially those dealing with soil moisture monitoring over time and space.

The advantages of the neutron probe are:

1. Moisture can be measured regardless of its physical state.
2. Average moisture contents can be determined with depth.
3. The system can be interfaced to accommodate automatic recording.
4. Soil moisture can be monitored on a seasonal basis.
5. Rapid changes in soil moisture can be detected.
6. Readings are directly related to soil moisture.

The disadvantages are:

1. Inadequate depth resolution makes measurement of absolute moisture content impossible (reduces the use of the procedure for determining the exact moisture profile in the study of evaporation, infiltration, percolation and placement of the phreatic water surface).
2. The moisture measurement is dependent on many physical and chemical properties of the soil which are, in themselves, difficult to measure.
3. Care must be taken to minimize health risks.
4. The sphere of influence of the depth probe does not allow for an accurate measurement of soil water at or near the soil surface.

Stone et al. (1966) stated that the accuracy of neutron probe measurements exceeds that of other techniques, but Stewart and Taylor (1957) argued that it is slightly inferior. If the neutron probe is used, the purchaser should look for a portable, durable model with stable electronics and power components that are compatible with available equipment (Bell and McCulloch 1966,

Zuber and Cameron 1966, Bell 1969).

Prudhoe (1970) used the neutron probe to study the water balance of a natural catchment. He found that the use of the neutron scattering moisture meter in conjunction with permanent boreholes proved a convenient and speedy method for obtaining soil moisture at various depths, but that the method of measuring soil moisture at the surface requires improvement. Calibration of the instrument was also a problem because of the large number of samples required. The maintenance and repair costs should be balanced against the advantages of the neutron probe method to determine its use in hydrologic studies.

In a study conducted by Gear et al. (1977), a simple, accurate technique using the neutron probe to initiate an irrigation schedule was developed using a graphic display of the measurements made with the neutron probe. It was found that consistent timing alone could improve water use efficiency by more than 10%. They concluded that a coupling of neutron probe irrigation schedules with system delivery capacity can lead to a coordinated delivery of water to make the most efficient use of both irrigation and drainage systems while improving water use efficiency and reducing farm irrigation cost.

Soil moisture studies conducted at CRREL have shown that the neutron probe can be used to monitor moisture content changes below a depth of 30 cm. Above 30-cm depth the accuracy of the soil moisture value decreased, probably due to the area of influence over which the determination was made. It is difficult if not impossible to calibrate the probe in the field to ensure that the moisture value near the surface is correct.

Gamma ray attenuation

The gamma ray attenuation method is a radioactive technique applicable when a soil moisture content value is required in layers 1-2 cm thick. This method assumes that scattering and absorption of gamma rays are related to the density of matter in their path and that the specific gravity of a soil remains relatively constant. The change in wet density is measured by the gamma transmission technique and the moisture content determined from this change.

Gamma rays may be collimated to a narrow beam, which permits a representative reading to be obtained at any position in the soil. Work by

Gurr (1962), Ferguson and Gardner (1962), Davidson et al. (1963), and Dmitriyev (1966) was instrumental in developing the theoretical basis and procedure for its use.

The basic equipment includes a gamma source surrounded by a collimator, a detector with a collimator, and a scaler. Gurr (1962) used a 25-mc cesium 137 source with a lead collimator, the beam emerging from a circular hole 4.8 mm in diameter. A scintillation counter was used as a detector, shielded by a lead collimator containing a 12.5-mm-diam hole. Mansell et al. (1973) stated that collimated radiation from 300 mc each of ^{241}Am and ^{137}Cs provided a high-intensity beam consisting of 60 and 662 keV photons. Count rates measured by a single detector and a two-channel gamma spectrometer were corrected for coincidence losses due to pulse-resolving time. It was concluded that error in soil water content measurement by the dual energy gamma attenuation method will probably not exceed a standard deviation of 1%.

The gamma attenuation technique has the same advantages of items 2, 3 and 4 listed under neutron meters as well as the following:

1. Data can be obtained over very small horizontal or vertical distances.
2. The measurement is nondestructive.

The disadvantages are:

1. Large variations in bulk density and moisture content can occur in highly stratified soils and lead to a limitation in spatial resolution.
2. Field instrumentation is costly and difficult to use.
3. Extreme care must be taken to ensure that the radioactive source is not a health hazard.

Sloane (1967) and Corey et al. (1971) also used dual energy, collimated beam gamma-rays to make simultaneous measurements of wet bulk density and moisture content in moist soil columns. Others who have investigated the technique include Gardner and Roberts (1967) and Gardner et al. (1972). In their study they used two collimated beams of monoenergetic gamma-rays from ^{241}Am and ^{137}Cs , but moved the soil column from one beam to another. In this study the error in γ_d and θ resulted from 1) randomness of the emission from the sources, 2) random error in attenuation coefficients and soil column thickness measurements, 3) presence of a small higher energy peak in the ^{241}Am spectrum, and 4) counting dead time.

Goit et al. (1976) experimentally showed that the variability due to differences in γ_d and θ of a soil within the beam of a dual-energy system can result in large measurement errors. Nofziger (1978) concluded from his studies that, indeed, large errors in the measurement of γ_d and θ can occur in highly stratified materials when using the dual gamma beam technique. Generally, small errors occur if γ_d and θ change linearly in the collimated beam. Nofziger also confirmed that both the single and dual gamma systems accurately measure the average water content in the collimated beam if the bulk density of the soil is constant. However, the average water content in the beam may not represent the water content at the middle of the collimated beam and in the middle of the present time period. From this study, graphs were prepared to estimate the error due to inhomogeneity of the soil.

A major problem in many areas of cold regions is the inability to measure in-situ water conditions in the freezing, thawing or frozen state. Goit et al. (1976) conducted studies to evaluate attenuation of a dual gamma beam and found that it was a powerful technique for investigating the swelling phenomena associated with freezing soil. They found that errors resulted when attenuation equations developed for homogeneous mixtures were applied to stratified media. Nofziger (1979) determined that the errors in θ and γ_d due to nonuniform soil systems must be considered to establish the overall accuracy of gamma ray measurements.

Since attenuation of gamma rays is independent of the state of the water in the material tested, the measurement of attenuation is unaffected by the transition of liquid water to ice. Therefore, the use of gamma attenuation has an advantage in that measurements of dry bulk density and total water content (including ice) can be made simultaneously.

Nuclear magnetic resonance

Placement of a soil/water mixture in a fixed magnetic field and a varying magnetic field results in an increased absorption of energy at a specific frequency of the varying magnetic field. This is referred to as nuclear magnetic resonance (NMR). The varying nuclear magnetization is converted into a voltage by using either the single coil absorption technique or the quadrature-coil induction technique. Geary (1956) noted that the NMR spectrum is directly related to the water content of the soil. The reliability of the

NMR technique for measuring water in the liquid or solid state under laboratory conditions has been demonstrated by various authors (Ducros and Dupont 1962, Graham et al. 1964, Wu 1964, Hecht et al. 1966, Touillaux et al. 1968, Prebble and Curries 1970, Pearson and Derbyshire 1973). Woessner and Snowden (1969) indicated that pulsed NMR techniques offer a number of advantages over the wide-line NMR absorption procedures. This technique had not been developed previously because of capital costs, but small, relatively inexpensive pulsed NMR systems are now available.

Tice et al. (1978) developed a simple, rapid method for determining the unfrozen water content in frozen soils. The method employs the use of the amplitude of the first NMR pulse. One way to obtain this information is through the PRAXIS Model PR 7103 Pulsed NMR analyzer. The analyzer consists of two parts: 1) a sample probe which contains a permanent magnet (2.51 kilogauss), and 2) a sample coil and a radio frequency (10.72-MHz) pulser.

The console portion of the analyzer contains the electronics required to provide radio frequency pulses, signal detection and signal averaging. The system is tuned to analyze hydrogen (protons) in the sample. The protons accept energy from the radio frequency field when in a strong, fixed magnetic field, and the protons release this energy and return to equilibrium through a series of relaxation processes which can be easily measured. The measured differences in the relaxation processes are related to physical and chemical soil properties associated with the hydrogen in the sample. The analyzer uses the NMR technique to obtain signals from the hydrogen in both the liquid and solid states. Therefore, quantitative information can be obtained without weighing the sample.

Tice et al. (1979) used the instrument to measure unfrozen water in frozen soil. A comparison is made between the first pulse amplitude in the thawed condition and the signal obtained at temperatures below freezing. With this technique the unfrozen water content at various temperatures below freezing can be obtained, and a phase comparison curve can be generated. Tice et al. (1979) were able to complete a phase comparison curve for four soils in about 48 hours. To obtain the same information using isothermal calorimetry techniques would have taken months.

Laboratory studies are continuing at CRREL

using the NMR technique. Currently the system is not well-adapted to field measurement of soil water. In the future the NMR could provide a means of monitoring soil water in the field under freezing, thawing and frozen conditions.

ELECTROMAGNETIC TECHNIQUES

Electromagnetic techniques include all methods which depend upon the effects of moisture on the electrical properties of soil. Excluded but treated elsewhere in this document are those techniques which are essentially electrical methods of estimating proton density, such as nuclear magnetic resonance or gamma ray attenuation. The magnetic permeability of soils is very nearly that of free space and hence the categorization chosen reduces the problem to a discussion of methods of exploiting the moisture dependence of the dielectric properties of soil.

The range of frequencies involved in this analysis is very great and discussion will be facilitated if the spectrum is broken up into the ranges specified in Table 1. The first seven of these categories are given in frequency while the last is more commonly given in wavelength. Before proceeding to the discussion of available techniques in the ranges listed, we will mention some general considerations of the problem.

The dielectric properties of the moist soil may be characterized by a frequency-dependent complex dielectric response function (Bottcher 1952):

$$\epsilon(\omega) = \epsilon_r(\omega) + j\epsilon_i(\omega) \quad (2)$$

where $\epsilon(\omega)$ = dielectric response function

$\epsilon_r(\omega)$ = the real part of ϵ

j = $\sqrt{-1}$

$\epsilon_i(\omega)$ = the imaginary part of ϵ

ω = the angular frequency

The function $\epsilon_r(\omega)$ is approximately constant from $\omega = 0$ out to the neighborhood of the relaxation frequency ω_R of dipoles in the medium. The time ω_R^{-1} is the time constant for the decay of polarization, when the electric field is removed. Beyond ω_R the function ϵ_r decreases until it is equal to the index of refraction squared in the visible region of the spectrum. The real part of the dielectric response function is a measure of the energy stored by the dipoles aligned in an applied electromagnetic field. When the fre-

Table 1. Spectral regions.

Region	Frequency or wavelength range
1	DC to 1kHz
2	1 kHz to 1MHz
3	1 MHz to 100 MHz
4	100 MHz to 1 GHz
5	1 GHz to 30 GHz
6	30 GHz to 300 GHz
7	300 GHz to 3×10^4 GHz (10 μ m)
8	10 μ m to 1 μ m

quency is greater than ω_R the dipoles can no longer follow the field and the ability of the medium to store electric field energy decreases.

The function $\epsilon_i(\omega)$ is a measure of the energy dissipation rate in the medium. Viewed as a function of frequency, and starting from a low value of ω , it rises to a peak at ω_R and thereafter decreases. The behavior described is due to the permanent dipoles in the soil medium. In complicated heterogeneous media there may be more than one relaxation mechanism and more than one absorption peak. Furthermore, at frequencies above ω_R the medium may show further dispersion and absorption regions due to direct molecular excitations. The frequency ω_R will generally lie in the microwave range (18 GHz in water) while the latter molecular excitations will be in the submillimeter or infrared regions of the spectrum (Bottcher 1952, Hasted 1974).

The preceding description applies in a general way to all dispersive media. In soils the value of ϵ_r typically lies within ranges 3 through 5 while the value of ϵ_r for water is about 80. Hence relatively small amounts of free water in a soil will greatly affect its electromagnetic properties. Discussion of the way this is used to monitor soil moisture will be divided according to the basic measurement technique involved. There are three such techniques: 1) use of implanted sensors, 2) monitoring of the radiation emitted by a moist soil (radiometric method), and 3) monitoring of reflected electromagnetic waves (radar method).

A variety of implantable sensors, responsive either to resistivity (ϵ_r), polarization (ϵ_i), or to both have been constructed (DePlater 1955, Gagne and Outwater 1961, Thomas 1963, Wexler 1965, Roth 1966, Silva et al. 1974). Traditionally, and because of engineering limitations, these have been designed for operation in the regions

of the spectrum labeled 1 and 2 in Table 1. Recently, however, due to a steady decrease in the physical size of high quality, high frequency components, implantable sensors in region 3 have become a practical reality (Selig et al. 1975, Layman 1979, Walsh et al. 1979), and implantable sensors in regions 4 and 5 are possible.

The resistivity of soil is sensitive to moisture content and, hence, it can serve as the basis for a sensor. It is possible either to measure the resistivity between electrodes in a soil or to measure the resistivity of a material in equilibrium with the soil. Sensors of either kind can be very compact and an array of them can be connected to standard data collection platforms. The difficulty with resistive sensors is that the absolute value of soil resistivity is dependent on ion concentration as well as on moisture concentration (Bouyoucos and Mick 1948). Therefore, careful calibration is required for this technique. Even with careful calibration, the instrument may require frequent recalibration due to changes in organic or salt concentrations. The calibration problem becomes less severe as the operating frequency is increased, since the relative contribution of ion motion decreases.

Implantable sensors which are sensitive to polarization ϵ_r essentially measure capacitance (DePlater 1955, Gagne and Outwater 1961, Thomas 1963, Selig et al. 1975, Layman 1979, Walsh et al. 1979). This parameter is the electrical quantity which is the most direct indicator of moisture concentration. When the moisture held in the soil can be regarded as free, as it is in most sandy soils, the relationship between ϵ_r and moisture is linear. Furthermore, even in more complicated materials where the water is relatively tightly bound, such as in montmorillonitic clay, it is possible to obtain moisture content data by measuring the capacitance of an implanted sensor. Because of this, a number of capacitive sensors have been constructed. The majority of these sensors have been designed for operation in spectral regions 1 and 2 (see Table 1) although more recently some work has also been done in region 3 (Silva et al. 1974, Selig et al. 1975, Layman 1979, Walsh et al. 1979). The motivation for increasing the operating frequency is again to minimize the contribution of ionic conductivity, since if this is large, it can make accurate measurement of the capacitance difficult. One other promising technique is to work at an intermediate frequency (region 3), and to utilize a bridge technique which allows a determination

of both ϵ_r and ϵ_i . These can be used separately as moisture indicators (Layman 1979, Walsh et al. 1979).

As was the case for resistive sensors, the capacitive sensors can be very compact. They can be implanted at any desired depth and they can be connected to data collection platforms. The present restriction to regions 2 and 3 of Table 1 is dictated on the lower end of the spectrum to escape the large ionic contributions and on the higher end by convenience. If modern microwave solid-state oscillator technology is used, however, there is no reason to assume that implantable sensors could not be made to operate in regions 4 and 5. Such a system might consist of a Gunn diode oscillator and an antenna loaded by the soil. A second antenna could be placed on the surface for data collection purposes.

In addition to the present speculative possibility of implantable sensors operating in the microwave range of the spectrum (region 5 and the lower part of 6) there are two other ways to use microwave radiation in moisture sensing. One, involving a measurement of the brightness temperature of a soil in the microwave range, is a passive radiometric technique (Poe and Edgerton 1971, Eagleman and Lin 1976, Choudhury et al. 1978, Schanda et al. 1978, Schmugge 1978). The other makes use of the reflection of a transmitted signal from the soil surface and is an active radar technique (Battivala and Ulaby 1977). Both are sensitive to moisture in the upper few centimeters of soil and are affected by surface roughness.

In the case of radiometry, knowledge of the effective temperature of the incident radiation, the temperature of the surface, and the reflection and emission coefficients permits a determination of the brightness temperature. Thus, both ϵ_r and ϵ_i affect the brightness temperature. The theoretical dependence on moisture content is very complicated, but a good correlation between soil moisture in the surface layer and microwave brightness temperature has been established in the lower part of region 5. In the upper part of the microwave spectrum the correlation is not as good. As the radiometry method is still in a research phase, the reason for this discrepancy may become clear in the future.

The microwave radar approach utilizes the reflection of an electromagnetic wave from the soil surface to characterize the moisture content. This reflection approach has been studied

extensively by the group at the University of Kansas (Battivala and Ulaby 1977). This is a very complicated problem but the results indicate that the overall scattering coefficient does correlate with soil moisture. There is an apparent variation of reflectance with soil type which may be due to the relatively greater binding for water in a material with a higher clay content. The infrared emission of a moist soil can also be used to measure the relative moisture content. In frequency region 8, corresponding to infrared emission, it is the thermal inertia of the soil water that is used as an indicator. The diurnal variation of the infrared brightness, when all other factors are the same, is less when the soil moisture is increased.

The relative advantages and disadvantages of the implanted sensor techniques are not unexpected. The main advantages are that they are capable in principle of providing absolute values for soil moisture, and they can be implanted at any depth. The latter point means that moisture profile data, which are important in some applications, can be obtained by this method. A wide variety of sensor configurations varying from very small to quite large are possible, and hence there is some control over the sensor volume of influence. The precision of both the resistive and capacitive sensors is high. The first of these is also relatively accurate when adequate control over other parameters is maintained, while the second has a relatively high intrinsic accuracy which is more nearly independent of parameters other than moisture. This follows from the fact that the capacitive sensors are directly responsive to the amount of polarized energy stored in the region of the sensor, and this quantity is normally dominated by the water present.

The moisture sensor must be implanted properly to minimize disturbances to the soil. In addition, there are questions of long-term reliability, maintenance of the calibration, and interface with remote data collection platforms. Nevertheless, it would seem that the overall relative advantages in some applications would warrant serious consideration of the implantable sensors.

The radiometric and active microwave approaches have the advantage that they are both remote sensing techniques. Although they involve expensive instrumentation, very large areas can be covered. The accuracy and precision will probably be less than those of an im-

planted sensor, but results indicate that it is potentially sufficient for some applications. Finally there is the fact that this method is most sensitive to the upper few centimeters of soil, and hence it is probably not the method of choice when moisture profile data are required.

The conclusions about infrared methods are similar to those given for the microwave approach. The main difference is that the infrared technique does not work well in the presence of a crop canopy. This disadvantage for some applications can sometimes be bypassed, however, by making use of the radiation changes related to crop moisture uptake. The radiative methods are sufficiently accurate for survey work. The implantable techniques seem to offer greater accuracy, precision and profile capability with the disadvantage of a somewhat more cumbersome technology.

TENSIOMETRIC TECHNIQUES

The term "tensiometer" was used by Richards and Gardner (1936) to unambiguously refer to the porous cup and vacuum gauge combination for measuring capillary tension, i.e. the energy with which water is held by the soil. Tensiometers were first used to measure soil water tension in unsaturated soils as early as 1922 (Gardner et al. 1922). Richards (1949) and others have made extensive developments and improvements in the tensiometers used in the field and laboratory soil water studies.

The energy term can be expressed as pF, which is defined as the common logarithm of the height of a water column in centimeters equivalent to the soil moisture tension, but is usually expressed as a suction (negative pressure) or a potential (energy per unit mass). Elrick (1967) recognized six components of the total energy of soil water, of which matrix suction is one. He defines matrix suction as the pressure difference across a boundary permeable only to water and solutes which separates bulk water and soil water in hydraulic, chemical and thermal equilibrium. Dissolved salts or chemicals in the soil water contribute to solute suction. Baver et al. (1972) suggested that the term "capillary potential" be used to denote the total potential, which includes not only surface tension force but also the osmotic and adhesion forces.

The most widely known method for measuring the capillary or moisture potential is based upon

the so-called suction force of the soil for water (Baver et al. 1972, Richards 1965). Tensiometers are used to measure suction and consist of a porous ceramic cup filled with a liquid (usually water), connected by a continuous liquid column to a manometer or vacuum gauge. In our recent designs, the liquid is an ethylene glycol-water solution and the measuring gauge a transducer with a millivolt output. The output of the transducer can be interfaced to near real time data acquisition systems. The use of an ethylene glycol-water solution as a replacement for water in the tensiometer allows the use of a tensiometer/transducer system in cold climates (McKim et al. 1976). Since the tensiometer/transducer system has a millivolt output and responds rapidly to changes in soil tension, it is well suited for automatic (including satellite relay) recording systems (Elzeftawy and Mansell 1975, McKim et al. 1975, Gillham et al. 1976).

The essential steps in the technique include de-airing the water or solution in the tensiometer, placing the tensiometer system in the soil, and allowing it to come to equilibrium with the soil water. The ceramic cup is porous to water and solutes but not to air, so that water can flow, and soil water conditions or the change in moisture content can be determined. As the soil water content increases, it is held at a lower tension; when the tensiometer reads zero, the soil is saturated, and there is zero water tension. The highest tension reading that can be obtained with a tensiometer is about 1 bar (1 atmosphere). In most instances, data cannot be obtained beyond 0.8-0.9 bar because the air entry value of the ceramic cup is exceeded. Therefore, the moisture content range over which the tensiometer can be used is limited. Richards (1949) stated that for coarse, sandy soils the tensiometer may cover more than 90% of the available moisture content range. Clay soils pose a different problem. For example, soils containing over about 42% montmorillonite clay can experience a change in tension from 200 to 800 cm water with a 1% change in volumetric water content (Abele et al. 1979).

Many techniques have been used to design a tensiometer system (Cope and Trickett 1965, Ingersoll 1979). In most cases tensiometers are made by gluing a length of rigid plastic tubing to a porous ceramic cup about 20 mm in diameter. A perforation is made in the plastic tube a few centimeters below the top, and the top is covered with a rubber stopper. A vacuum gauge

or manometer can be inserted at the perforation to measure the soil water tension. Cope and Trickett (1965) present information on a tensiometer design that has worked well in their studies. In addition, tensiometers with a Bourdon-type vacuum gauge, reading in centibars to indicate the soil water tension, are commercially available. Richards (1949) and Reeve (1965) have outlined procedures for setting the zero scale for the manometer or Bourdon vacuum gauge.

Many procedures have been used to install conventional tensiometers (Reeve 1965, Richards 1965). Ingersoll (1979) used a technique that required making an oversized hole in the soil to a depth about 8 cm above the point at which the soil moisture content or tension data are required. Another soil probe is then inserted, which produces a hole 8 cm deep and of the same diameter as the ceramic cup. The ceramic cup/plastic tube tensiometer system is inserted firmly into the 8-cm-deep hole, care being taken not to turn the plastic tube and break the ceramic cup. The area around the tube is backfilled with the soil removed from the augered hole and montmorillonite pellets are placed around the tube at the ground surface.

Various types of transducers and many sizes of ceramic cups have been used to design a tensiometer/transducer system that will measure soil water potential which can be converted to soil water content. Studies are in progress at CRREL to evaluate not only the costs of various transducers, but also the size of the ceramic cup and the type of liquid required for laboratory and field tests.

One study recently accomplished was the placement of a tensiometer/transducer and temperature sensor system in the field under the snowpack. The liquid used in the tensiometer was a 50/50 mixture of ethylene glycol and water. The millivolt output of the strain gauge type transducer was passed through an interface, developed at CRREL, to the GOES geostationary satellite. The data were telemetered to a downlink station located at the National Oceanographic and Atmospheric Administration (NOAA) in Suitland, Maryland. It was possible to obtain the data from NOAA on a daily basis via telephone. The tensiometer and temperature data were compiled at six-hour increments so that four data points for each of two sensors, placed at depths of 30 cm and 60 cm, could be obtained. This method of data acquisition could be a powerful tool in management of irrigation

systems, not only for conventional agricultural but also for slow infiltration land treatment systems.

Klute and Peters (1966) have described the use of diaphragm type pressure transducers using strain gauge resistance elements to detect minute deflections under applied pressure. They also developed an operational technique for their use. This tensiometer/transducer system can be installed for field use by utilizing a battery-operated amplifier (and recorder, if necessary) and mercury cells for exciting the bridge circuit in the transducer.

Soil moisture measurement procedures using tensiometer/transducer systems are rapidly becoming the predominant means of monitoring soil tension in the field. Recent studies by Bianchi (1962), Klute and Peters (1962), Watson (1967), Rice (1969), and Anderson and Burt (1977) have shown the advantages of using pressure transducers to produce a fast response, low volume displacement tensiometer system. These types of systems are capable of monitoring soil tension changes that occur in infiltration, irrigation, groundwater recharge and evapotranspiration studies.

Tensiometers have been used for years to measure soil tension, and during recent years advancements in system design and performance have made possible the implementation of soil moisture field monitoring programs. However, care still needs to be taken in monitoring the use of the system. Listed below are some of the advantages of using tensiometers:

1. Systems are easy to design and construct.
2. The cost of a system is relatively low.
3. Information on moisture conditions under saturated and unsaturated conditions in near real time can be obtained.
4. The tensiometer can usually be placed in the soil easily and with minimal disturbance.
5. The system can operate over long time periods if properly maintained.
6. The response time of the tensiometer/transducer system is very rapid.
7. Different types of liquid can be used, e.g. an ethylene glycol solution to obtain data during freezing and thawing conditions.

Disadvantages include the following:

1. The tensiometer can be broken easily during installation.
2. The range of information obtainable is limited to 0-800 cm of water tension.

3. Field installations drift electronically.

The ability to measure soil tension and volumetric water content under field conditions in time and space is necessary for the calculation of soil infiltration rate which is required in the design of land treatment systems (McKim et al. 1975). In addition, these field data can provide required inputs for validation of one- and two-dimensional flow models (Nakano et al. 1978).

Rice (1969) has described two approaches to recording pressure from a number of tensiometers. The first, a hydraulic scanning system, consists of a number of tensiometer cups connected to one transducer through a hydraulic scanning valve. In the second, an electrical scanning system is used (with each tensiometer having its own transducer, usually located near the porous cup), and the signals are electronically scanned. The results from this field study showed that the hydraulic scanning system could be used satisfactorily for 10 months. In the loam soil used in Rice's study, the response time of the electrical scanning-tensiometer system was about two minutes.

Williams (1978) also developed a rapid response automatic tensiometer system that provided on-site recording of soil moisture conditions. He used a 24-way fluid wafer switch to connect 22 tensiometer units sequentially to a pressure transducer. The data were recorded on a chart recorder. The advantage of Williams' system is that it is relatively insensitive to air temperature fluctuation, which Rice (1969) found to be a problem.

Richards et al. (1974) used tensiometers in shallow groundwater studies. They concluded that a tensiometer installed to read the total hydraulic head with a ground surface reference gives water table information roughly comparable to that obtained from water observation wells. The tensiometer reading also allowed determination of equipotential lines above and below the water table.

Tensiometer experiments to evaluate unsteady moisture flow through soils have been performed by many workers (Geisel et al. 1970, Fitzsimmons and Young 1972). Oster et al. (1976) also used tensiometers and salinity measurements in irrigation control. They found that a control system for high frequency irrigation, based on in-situ measurement of soil salinity and water potential, has the capability of controlling irrigation so that a relatively stable and continuous leaching fraction is maintained.

HYGROMETRIC TECHNIQUES

The general nature of the relationship between moisture content in porous materials and the relative humidity (RH) of the immediate atmosphere is reasonably well known (National Cooperative Highway Research Report 138). Therefore, a number of relatively simple apparatus for measurement of RH have been designed. Basically, the sensors can be classified into seven types of hygrometers: electrical resistance, capacitance, piezoelectric sorption, infrared absorption and transmission, dimensionally varying element, dew point, and psychrometric. In evaluating hygrometric methods, the following characteristics are extremely important:

1. Range in soil moisture content,
2. Hysteresis in material tested and sensor calibration,
3. Size of the sensitive element,
4. Kind of water to be measured, and
5. Durability of the sensor.

White hydrocal method

The various types of electrical resistance hygrometers include chemical salts and acids, aluminum oxide, electrolysis, thermal and white hydrocal. Bouyoucos and Cook (1965) considered the white hydrocal hygrometer to be the best one available. The measured resistance of the resistive element is a function of the relative humidity. They state that casting of the stainless steel electrodes in white hydrocal (a form of plaster of Paris) leads to greater accuracy because the cement sets hard, is pure, has a low solubility and contains no added salts.

Capacitance method

Two types of capacitance hygrometers are capacitive transducers and microwave refractometers. A typical capacitive transducer is constructed with a thin plastic film on acetyl resin which is a crystalline form of highly polymerized formaldehyde. The capacitor plates are formed with evaporated gold electrodes that are thin enough to be pervious to water vapor and still be electrically conductive. Webb and Neugebauer (1954) developed a capacitive system using two concentric cylinders for the capacitor plates. Sensors of this type can be used in the range of 10 to 100% RH over a temperature range of 35 to 80°C (Nelson and Anbur 1965). Nelson and Anbur (1965) made improvements in the capacitor method, but the main disadvantage is the rela-

tively small change in capacitance of the sensor related to the change in humidity. Charlson and Buettner (1963, 1964) and Charlson et al. (1966) used a hygroscopic liquid to improve this technique. However, there are still many problems evident in all the capacitance systems.

The piezoelectric sorption, infrared absorption and transmission, and dimensionally varying element hygrometer techniques are all very well documented in National Cooperative Highway Research Program (1973) and will not be discussed further.

Dew or frost point method

The dew or frost point hygrometer technique depends on the measurement of temperatures and is relatively simple and inexpensive. Wexler (1965) showed that modern improvements in the technique, such as using of Peltier devices for cooling and photometric detection of condensation, have added greatly to the cost. Systems have been designed that are very small (Brousaides and Morrissey 1967).

Psychrometric method

Psychrometric instruments form another major hygrometer grouping. The greatest advantage of the psychrometer is its simplicity. If the ambient air has a velocity of more than 3 m/s, two thermometers, one covered with a moist wick, are all that is required. Miniature thermocouple psychrometers are now commonly used for measuring water potential (matrix suction and osmotic suction) in soil systems. Rawlins (1966) has presented the theory of this system. Zollinger et al. (1966), Rawlins and Dalton (1967), and Rawlins et al. (1968) have described the equipment and method to use. The procedure has been used in the laboratory but not in the field. The problems in field use are the necessity of controlling the temperature of the psychrometer chamber, which in some cases must be constant to within 0.001°C, and the time required for the chamber to reach temperature and humidity equilibrium. One method which may be applicable in field use has been described by Rawlins and Dalton (1967). This method is independent of temperature fluctuations of a few degrees Celsius and permits measurement over an entire range of soil suction. However, the precision is only a few tenths of a bar.

Phene et al. (1971, 1973) developed a heat dissipation sensor that was used to measure the soil moisture potential. The accuracy of the matrix

potential sensor proved to be as good as or better than that of the thermocouple psychrometer or salinity measurements. The sensor, which had high sensitivity in the 0 to 2-bar matrix potential range, had an accuracy of ± 0.2 bar. The accuracy decreased progressively to ± 1 bar at a matrix potential of -10 bar.

The primary advantages in using the aforementioned hygrometers are the simplicity of the apparatus and the low cost. The basic disadvantages in using the method include deterioration effects of the soil components on the sensing element and the requirement for special calibration for each material to be tested. The main use for this technology seems to be in applications where RH in the material is directly related to other properties. One example would be drying and shrinkage of cements (National Cooperative Highway Research Program Report 138).

Electrolysis method

Electrolysis systems employ a continuous flow of a gas mixture over a thin layer of partially hydrated phosphorus pentoxide (P_2O_5). The moisture in the gas is absorbed by the P_2O_5 . A sensor can be built with two platinum wires placed helically inside an insulating tube. The tube is then coated with a layer of P_2O_5 (National Cooperative Highway Research Program Report 138). A DC voltage is applied across the two wires, dissociating the water molecules into gaseous hydrogen and oxygen. At equilibrium, the measured current is proportional to the moisture absorbed. The DC voltage must be larger than the polarization voltage (~ 2 V).

Many people have used the electrolysis technique to measure moisture in materials (Fraade 1963, MacCready 1962, Roth 1966, Thacker 1967, Barton and Maffei 1968, Honnell and Hibbitts 1968, Kreider 1968).

The advantages of the electrolysis method are the following:

1. The modular design can permit signal transmission to a remote central location.
2. The sensitivity of the measurement can be up to 1 ppm.
3. The response time for the measurement is relatively short.

The disadvantages include:

1. There is a need for a constant mass flow and constant temperature.
2. There is a possibility of interference from gases that would interact with P_2O_5 .
3. The cost of the system is very high.

Anderson et al. (1976) proposed the use of an electrolysis system to evaluate the occurrence of water on Mars. A Beckman P_2O_5 integrating water detector is being configured for use in the Mars penetrometer soil sampler. Similar in design to the detector discussed above, it consists of two parallel, unconnected electrical conductors bathed in a solution of phosphorus pentoxide-phosphoric acid which functions as an electrolyte. The end of each conductor is connected to a source of EMF sufficient to electrolyze water. The increased current is exactly proportional to the number of dissociated water molecules.

Tests of five P_2O_5 sensors were performed in a simulated Mars environment. The results showed nearly flawless performance of the P_2O_5 hygrometer under Mars-like conditions. This work is continuing at CRREL.

SUMMARY

The measurement of water, wherever it occurs, continues and will continue to be a research area where advances in science and technology will have a great impact. We have covered many of the techniques used to measure soil and planetary water but not all that have been tried. In field use, where low costs must be maintained, the gravimetric method will, at present, give reasonable moisture content values. However, if monitoring of the soil moisture is the important problem, many samples are required using the gravimetric technique, and nuclear, tensiometric, electromagnetic or hygrometric techniques may be more cost-effective.

Capital costs associated with the nuclear methods can be quite large. Of the three nuclear methods discussed in this report only the neutron scattering system is portable and can be used effectively in the field. This technique is nondestructive to the samples, has an accuracy greater than 0.1%, is relatively rapid in obtaining soil moisture data (1 to 5 min per moisture value) and can be set up as an automatic recording system. The major problems are in calibration and resolution, which can limit its use.

Electromagnetic techniques to measure soil water have had limited use because of the inability of the sensors to measure very tightly bound water. This is especially true in high clay content soil/water systems. Recently, a variety of sensors have been configured that work very well under

laboratory conditions.

A number of capacitive sensors have recently been developed and tested at CRREL. Their main advantage is that they are durable, low in cost, measure in all tension ranges, and provide an absolute value for soil moisture. A wide variety of sensor configurations varying from very large to very small are possible and hence there is some control over the area of influence of the sensor. Resistance and capacitance are independently measured and the precision of both is high. The output from the sensor is in millivolts and therefore can be easily interfaced to near real time data acquisition systems.

The tensiometric techniques are primarily used in agriculture, but studies have been accomplished recently using tensiometer/transducer systems for automating irrigation systems, operating land treatment systems, measuring soil tension with depth at specific sites for water routing, and monitoring fluctuations of groundwater. Tensiometers can supply information on tension and soil water close to saturation (tension range from 0-800 cm water), but beyond a tension of 800 cm water the air entry value of the porous ceramic cup is exceeded, air can enter the system, and the water column may separate. A loss of calibration will result. The response time of the tensiometer/transducer system is relatively short, with the lifetime varying from 1 to 12 months.

One important aspect of the tensiometer/transducer system is that it can be used to monitor soil water conditions under the snow. The requirement is that the liquid in the system not freeze when temperatures go below 0°C. The data obtained under winter field conditions can be obtained in near real time using available technology in telemetry systems.

The primary advantage of using hygrometric techniques is that the apparatus for measuring relative humidity is simple and the cost of construction is low. Inherent problems lie in the deleterious effects of the soil components on the sensing element and the site-specific calibration for each material. The accuracy of the hygrometric resistance technique can be very poor because the sensor measures the relationship between the pressure potential in the porous materials and the relative humidity of the immediate atmosphere under equilibrium conditions. In many instances the equilibrium conditions are difficult to achieve.

Many new techniques, including NMR, differential scanning calorimetry, capacitance sensing, use of the P_2O_5 detector and others, may lead the way to new methods for measuring soil moisture. As technology in electronics, computer science, and other related fields advances, the use of this technology in hydrology will greatly improve the ability to measure soil moisture conditions under field conditions. The other problem, relating these values to the spatial distribution of soil water, will continue for many years.

LITERATURE CITED

- Abele, G., H.L. McKim and B.E. Brockett (1979) Mass water balance during spray irrigation with wastewater at Deer Creek Lake land treatment site. CRREL Special Report 79-29.
- Anderson, M.B. and T.P. Burt (1977) Automatic monitoring of soil moisture conditions in a hillslope spur and hollow. *Journal of Hydrology*, vol. 33, p. 27-36.
- Anderson, D.M., J.B. Stephens, F.P. Fanale and A.R. Tice (1976) Mars soil water analyzer: Instrument description and status. *Proceedings, Colloquium on Water in Planetary Regoliths*, p. 149-156.
- Antrim, J.D., F.B. Brown, H.W. Busching, J.A. Chisman, J.H. Moore, J.P. Roston and A.E. Schwartz (1970) Rapid test methods for field control of highway construction. National Cooperative Highway Research Program Report 103.
- Barton, G.B. and H.P. Maffei (1968) Cover gas impurities and their interactions with sodium. Battelle-Northwest, NASA File No. N69-25968.
- Battivala, P. and F.T. Ulaby (1977) Estimation of soil moisture with radar remote sensing. *Proceedings, 11th International Symposium, Remote Sensing of the Environment*, Environmental Research Institute of Michigan, Report 1557.
- Bayer, L.D., W.H. Gardner and W.R. Gardner (1972) *Soil physics*. New York: John Wiley and Sons.
- Belcher, D.J., T.R. Cuykendall and H.S. Sack (1950) The measurement of soil moisture and density by neutron and gamma-ray scattering. Technical Development and Evaluation Center, Technical Development Report No. 127, p. 1-20.
- Belcher, D.J., T.R. Cuykendall and H.S. Sack (1952) Nuclear meters for measuring soil density and moisture in surface layers. Civil Aeronautics Administration Technical Development and Evaluation Center, Technical Development Report No. 161, p. 1-8.
- Bell, J.P. (1969) A new design principle for neutron soil moisture gauges. The "Wallingford" neutron probe. *Soil Science*, vol. 108, p. 164-169.
- Bell, J.P. and C.W.O. Eeles (1967) Neutron random counting error in terms of soil moisture for nonlinear calibration curves. *Soil Science*, vol. 103, p. 1-3.
- Bell, J.P. and J.S.G. McCulloch (1966) Soil moisture estimation by the neutron scattering method in Britain. *Journal of Hydrology*, vol. 4, p. 254-263.

- Bianchi, W.B. (1962) Measuring soil moisture tension changes. *Agricultural Engineering*, vol. 43, p. 398-399.
- Blystone, J.R., A. Pelzner and G.P. Steffens (1961) Moisture content determination by the calcium carbide gas pressure method. *Public Roads Magazine*, vol. 31, p. 177-181.
- Böttcher, C.J.F. (1952) *Theory of electric polarization*. Amsterdam: Elsevier.
- Bouyoucos, G.J. and R.L. Cook (1965) Humidity sensor permanent electric hygrometer for continuous measurement of the relative humidity of the air (1). RILEM/CIB Symposium on Moisture Problems in Building, vol. II, sec. 6.
- Bouyoucos, G.J. and A. Mick (1948) A comparison of electrical resistance units for making continuous measurements of soil moisture under field conditions. *Plant Physiology*, vol. 23, p. 532.
- Bowman, D.H. and K.M. King (1965) Determination of evapotranspiration using the neutron scattering method. *Canadian Journal of Soil Science*, vol. 45, p. 117-126.
- Brousailles, F.J. and J.F. Morrissey (1967) Stratospheric humidity sensing with the alpha radiation hygrometer. Air Force Cambridge Research Laboratories Instrumentation Papers, No. 133.
- Charlson, R.J. and K.J.K. Buettner (1963) The investigation of some techniques for measurement of humidity at high altitudes. *International Symposium on Humidity and Moisture*, Washington, D.C. Report 1, Contract AF 19 (628)-303.
- Charlson, R.J. and K.J.K. Buettner (1964) Liquid film hygrometry. University of Washington Report 2, Contract No. AF 19 (628)-303.
- Charlson, R.J., K.J.K. Buettner and G.A. Maykut (1966) Liquid film hygrometry. University of Washington Final Report, Contract No. AF 19 (628)-303.
- Choudbury, B., T. Schmutge, R.W. Newton and A. Chang (1978) Effect of surface roughness on the microwave emission from soils. NASA Technical Memorandum 79606.
- Churayev, N.V. and L.G. Rode (1966) Measuring the moisture content of organic peat soils by the neutron method. *Pochvovedenie*, vol. 1, p. 96-100.
- Cope, F. and E.S. Trickett (1965) Measuring soil moisture. *Soils and Fertilizers*, vol. 28, p. 201-208.
- Corey, J.C., S.F. Peterson and M.A. Wakat (1971) Measurement of attenuation of ^{137}Cs and ^{241}Am gamma rays for soil density and water content determinations. *Soil Science Society of America Proceedings*, vol. 35, p. 215-219.
- Davidson, J.M., M.W. Biggar and D.R. Nielsen (1963) Gamma radiation attenuation for measuring bulk density and transient water flow in porous media. *Journal of Geophysical Research*, vol. 68, p. 4777-4783.
- DePlater, C.V. (1955) A portable capacitance type soil moisture meter. *Soil Science*, vol. 80, p. 391.
- Dmitriyev, M.T. (1966) Gammascopic measurement of soil moisture. *Pochvovedenie*, vol. 2, p. 208-217.
- Douglass, J.E. (1966) Volumetric calibration of neutron moisture probes. *Soil Science Society of America Proceedings*, vol. 30, p. 541-544.
- Ducros, P. and M. Dupont (1962) A nuclear magnetic resonance study of water in clays in magnetic and electrical resonance and relaxation. C.R.XI Colloque Ampere, Eindhoven.
- Eagleman, J. and W. Lin (1976) Remote sensing of soil moisture by a 21 cm passive radiometer. *Journal of Geophysical Research*, vol. 81, p. 3660.
- Elrick, D.E. (1967) Soil water movement: theory and applications. *Proceedings, First Canadian Conference Micrometeorology*. Part II. Department of Transportation, Canada, p. 477-487.
- Elzeftawy, A. and R.S. Mansell (1975) Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand. *Soil Science Society of America Proceedings*, vol. 39, p. 599-603.
- Ferguson, H. and W.H. Gardner (1962) Water content measurement in soil columns by gamma ray absorption. *Soil Science Society of America Proceedings*, vol. 26, p. 11-18.
- Fitzsimmons, D.W. and N.C. Young (1972) Tensiometer-pressure transducer system for studying unsteady flow through soils. *Transactions of the American Society of Agricultural Engineers*, vol. 15, no. 2.
- Fraade, D.J. (1963) Measuring moisture in gases. *Instruments and Control Systems*, vol. 36, p. 100-105.
- Gagne, G. and J. Outwater (1961) A portable electronic moisture detector for reinforced plastics. University of Vermont Report 3219 (01) (X).
- Gardner, W., O.W. Israelsen, N.E. Edlefsen and H. Conrad (1922) The capillary potential function and its relation to irrigation practice. *Physical Review*, series 2, vol. 20, p. 196.
- Gardner, W. and D. Kirkham (1952) Determination of soil moisture by neutron scattering. *Soil Science*, vol. 73, p. 391-401.
- Gardner, R.P. and K.F. Roberts (1967) Density and moisture content measurement by nuclear methods. National Cooperative Hydrology Research Program Report 43.
- Gardner, W.H., G.S. Campbell and C. Calissendorff (1972) Systematic and random errors in dual gamma energy soil bulk density and water content measurements. *Soil Science Society of America Proceedings*, vol. 36, p. 393-398.
- Gear, R.D., A.S. Dransfield and M.D. Campbell (1977) Irrigation scheduling with neutron probe. *Journal Irrigation Drainage Division*, American Society of Civil Engineers, September, p. 291-298.
- Geary, P.J. (1956) Determination of moisture in solids. Britain Science Instrument Research Association, Research Report M 24, p. 1-52.
- Giesel, W., S. Lorch and M. Renger (1970) Water-flow calculations by means of gamma-absorption and tensiometer field measurements in the unsaturated soil profile. *Proceedings of the Symposium on Isotope Hydrology*, International Engineering Agency.
- Gillham, R.S., A. Klute and D.F. Heerman (1976) Hydraulic properties of a porous-medium—Measurement and empirical representation. *Soil Science Society of America Proceedings*, vol. 40, p. 203-207.
- Glasstone, E. and M.C. Edlund (1957) *The elements of nuclear theory*. New York: Van Nostrand.
- Goit, J.B., P.H. Groenevelt, B.D. Kay and J.G.P. Loch (1976) The applicability of dual gamma scanning to freezing soils and the problem of stratification. *Soil Science of America Proceedings*, vol. 42, p. 858-863.
- Graham, J., G.F. Walker and G.W. West (1964) Nuclear magnetic resonance study of interlayer water in hydrated layer silicates. *Journal of Chemical Physics*, vol. 40, p. 540-550.

- Gurr, C.G. (1962) Use of gamma rays in measuring water content and permeability in unsaturated columns of soil. *Soil Science*, vol. 94, p. 224-229.
- Hasted, T. (1974) *Aqueous dielectrics*. London: Chapman and Hall.
- Hecht, M., M. Dupont and P. Ducros (1966) A study of transport phenomena of water absorbed by certain clay minerals by nuclear magnetic resonance. *Bulletin de la Societe Francaise de Mineralogie et de Cristallographie*, vol. 89, p. 6-13.
- Hewlett, J.D. and J.E. Douglass (1961) A method for calculating error of soil moisture volumes in gravimetric sampling. *Forest Science*, vol. 7, p. 265-272.
- Holmes, J.W. (1966) Influence of bulk density of the soil on neutron moisture meter calibration. *Soil Science*, vol. 102, p. 355-360.
- Honnell, R.E. and I.O. Hibbits (1968) An evaluation of the accuracy of Beckman hygrometers. General Electric Company, Missile and Space Division, Cincinnati, Ohio, PB-18210, GEMP-638.
- Ingersoll, J. (in press) Soil tensiometers for use at temperatures below freezing. CRREL Special Report.
- King, K.M. (1967) Soil moisture-instrumentation, measurement and general principles of network design. In *Soil Moisture, Proceedings of the Hydrology Symposium* No. 6, p. 269-285. Canada Department of Energy, Mines and Resources, Ottawa.
- Klute, A. and D.B. Peters (1966) Hydraulic and pressure head measurements with strain gauge pressure transducers. *Proceedings UNESCO International Hydrological Decade Symposium on Water in the Unsaturated Zone*, Wageningen, The Netherlands, 19-25 June.
- Klute, A. and D.B. Peters (1962) A recording tensiometer with a short response time. *Soil Science Society of America Proceedings*, vol. 26, p. 87-88.
- Koshi, P.R. (1966) Soil-moisture measurement of neutron method in rocky wildland soils. *Soil Science Society of America Proceedings*, vol. 30, p. 282-294.
- Kozachyn, J. and J.R. McHenry (1964) A method for installation of access tubes and the development of field equipment for measuring soil moisture by neutron scattering. *Agronomy Journal*, vol. 56, p. 443-444.
- Kreider, H.B., Jr. (1968) Modified moisture analyzer for solid radioactive materials. Mound Laboratory, AEC Contract AT(33-1)-GEN-53.
- Lawless, G.P., N.A. MacGillivray and P.R. Nixon (1963) Soil moisture interface effects upon readings of neutron moisture probes. *Soil Science Society of America Proceedings*, vol. 27, p. 502.
- Layman, R. (1979) Soil moisture sensor. Dartmouth College Plasma Physics Laboratory, DCPPL-SM3.
- Long, I.F. and B.K. French (1967) Measurement of soil moisture in the field by neutron moderation. *Journal of Soil Science*, vol. 18, p. 149-166.
- Luebs, R.E., M.J. Brown and A.E. Laag (1968) Determining water content of different soils by the neutron method. *Soil Science*, vol. 106, p. 207-212.
- Mansell, R.S., L.C. Hammond, R.M. McCurdy (1973) Coincidence and interference corrections for dual-energy gamma ray measurements of soil density and water content. *Soil Science Society of America Proceedings*, vol. 37, p. 500-504.
- Marais, P.C. and W.B. De V. Smit (1958) Determination of soil moisture with a neutron meter. *Industrial Review of Africa*, p. 78.
- Marais, P.C. and W.B. De V. Smit (1962) Effect of bulk density and of hydrogen in forms other than free water on the calibration curve of the neutron moisture meter. *South African Journal of Agricultural Science*, vol. 5, p. 225-238.
- MacCready, P.B. (1962) A moisture analyzer for martian atmosphere. Final Report, JPL Contract No. 950207, NASA Contract NAS7-100.
- McKim, H.L., R.L. Berg, R.W. McGaw, R.T. Atkins and J. Ingersoll (1976) Development of a remote-reading tensiometer/transducer system for use in subfreezing temperatures. *Proceedings, Second Conference on Soil-Water Problems in Cold Regions* (American Geophysical Union), Edmonton, Alberta, Canada, 1-2 September, p. 31-45.
- McKim, H.L., D.M. Anderson, R.L. Berg and R. Tuinstra (1975) Near real time hydrologic data acquisition utilizing the Landsat system. *Proceedings of the Conference on Soil-Water Problems in Cold Regions* (American Geophysical Union), Calgary, Alberta, Canada, 6-7 May, p. 200-211.
- Mortier, P., M. DeBoodt, W. Donsercoer and L. DeLeenheer (1960) The resolution of the neutron scattering method for soil moisture determination. *Transactions, 7th International Congress of Soil Science*, vol. 1, p. 321-329.
- Nakano, Y., R.A. Khalid and W.H. Patrick, Jr. (1978) Water movement in a land treatment system of wastewater by overland flow. *Proceedings of the International Conference on Developments in Land Methods of Wastewater Treatment and Utilization*, p. 14/1-14/21.
- National Cooperative Highway Research Program Report 138 (1973) *Instrumentation for measurement of moisture. Literature review and recommended research*. Highway Research Board, National Research Council.
- Nelson, D.E. and E.J. Anbur (1965) A relative humidity sensor based on the capacitance variations of a plastics film condenser. In *Humidity and moisture* (A. Wesler and R.E. Ruskin, eds.), Reinhold, p. 597-601.
- Noftziger, D.L. (1978) Errors in gamma-ray measurements of water content and bulk density in nonuniform soils. *Soil Science Society of America Journal*, vol. 42, p. 845-850.
- Olgaard, P.L. (1965) On the theory of the neutronic method for measuring the water content in soil. Risco Report No. 97, Danish Atomic Energy Commission, p. 1-44.
- Olgaard, P.L. and V. Haar (1968) On the sensitivity of subsurface neutron moisture gauges to variations in bulk density. *Soil Science*, vol. 105, p. 62-64.
- Oster, J.D., L.S. Willardson, J. van Schilfgaarde and J.O. Goertzen (1976) Irrigation control using tensiometers and salinity sensors. *Transactions of the American Society of Agricultural Engineers*, vol. 2.
- Pearson, R.T. and L. Derbyshire (1973) NMR studies of water adsorbed on a number of silica surfaces. *Journal of Colloid Interface Science*, vol. 46, p. 232-248.
- Phene, C., G.J. Hoffman and S.L. Rawlins (1971) Measuring soil matric potential in situ by sensing heat dissipation within a porous body. I. Theory and sensor construction. *Soil Science Society of America Proceedings*, vol. 35, p. 27-33.
- Phene, C., G.J. Hoffman and R.S. Austin (1973) Controlling automated irrigation with soil matric potential sensor. *Transactions of the American Society of Agricultural Engineers*, vol. 16, p. 773-776.

- Poe, G.A. and A.T. Edgerton (1971) Determination of soil moisture content with airborne microwave radiometry. Summary Report 4006R-2, Microwave Division, Aerojet General Corporation, El Monte, Cal.
- Prebble, R.E. and J.A. Curries (1970) Soil water measurement by a low-resolution nuclear magnetic resonance technique. *Journal of Soil Science*, vol. 21, p. 273-288.
- Prudhoe, J. (1970) A study of the water balance of a natural catchment using a neutron-scattering moisture meter. Road Research Organization Laboratory Report LR 361.
- Rawlins, S.L. and F.N. Dalton (1967) Theory for thermocouple psychrometers used to measure water potential in soil and plant samples. *Agricultural Meteorology*, vol. 3, p. 293-310.
- Rawlins, S.L. and F.N. Dalton (1967) Psychrometric measurement of soil water potential without precise temperature control. *Soil Science Society of America Proceedings*, vol. 31, p. 297-301.
- Reeve, R.C. (1965) Hydraulic head in methods of soil analysis. *Agronomy*, vol. 9, p. 180-196.
- Rice, R. (1969) A fast-response, field tensiometer system. *Transactions of the American Society of Agricultural Engineers*, vol. 12, p. 48-50.
- Richards, L.A. (1949) Methods of measuring soil moisture tension. *Soil Science*, vol. 68, p. 95-112.
- Richards, S.J. (1965) Soil suction measurements with tensiometers in methods of soil analysis. *Agronomy*, vol. 9, p. 153-163.
- Richards, L.A. and W. Gardner (1936) Tensiometers for measuring the capillary tension of soil water. *Journal of the American Society of Agronomy*, vol. 28, p. 352-358.
- Richards, S.J., L.S. Willardson, S. Davis and J.R. Spencer (1974) Tensiometer use in shallow ground-water studies. *Journal of the Irrigation Drainage Division, American Society of Civil Engineers*, vol. 99, p. 457-464.
- Roth, M. (1966) How to measure moisture in soils. *Chemical Engineering*, p. 83-88.
- Schanda, E., R. Hofer, D. Wyssen, A. Musy, D. Meylan, C. Morzier and W. Good (1978) Soil moisture determination and snow classification with microwave radiometry. *Proceedings, 12th International Symposium on Remote Sensing of Environment*.
- Schmugge, T. (1978) Remote sensing of surface soil moisture. *Journal of Applied Meteorology*, vol. 17, p. 1549.
- Selig, E.T., D.C. Wobschall, S. Mansukhani and A. Motiwala (1975) Capacitance sensor for soil moisture measurement. Transportation Research Board Record 532, p. 64.
- Silva, L.F., F.V. Schultz and J.T. Zalusky (1974) Electrical methods of determining soil moisture content. Laboratory for Applied Remote Sensing Information Note 112174, Purdue University.
- Soane, B.D. (1967) Double energy gamma transmission for moisture and density measurement in soil tillage studies. *International Soil-Water Symposium, Prague, Discussion 197*.
- Stewart, G.L. and S.A. Taylor (1957) Field experiments with the neutron scattering method of measuring soil moisture. *Soil Science*, vol. 83, p. 151-158.
- Stolzy, L.H. and G.A. Cahoon (1957) A field calibrated portable neutron rate meter for measuring soil moisture in citrus orchards. *Soil Science Society of America Proceedings*, vol. 21, p. 571-575.
- Stone, J.F., R.H. Shaw and D. Kirkham (1966) Statistical parameters and reproducibility of the neutron method of measuring soil moisture. *Soil Science Society of America Proceedings*, vol. 24, p. 435-438.
- Thacker, C.C. (1967) Moisture content determination in rigid polyurethane foams. Sandia Corporation Contract AT(29-1)-789.
- Thomas, A. (1963) In situ measurement of moisture in soil and similar substances by fringe capacitance. *Journal of Scientific Instruments*, vol. 43, p. 996.
- Tice, A.R., C.M. Burrous and D.M. Anderson (1978) Determination of unfrozen water in frozen soil by pulsed nuclear magnetic resonance. *Third International Conference on Permafrost*, Edmonton, Alberta, Canada.
- Tice, A.R., C.M. Burrous and D.M. Anderson (1979) Phase composition measurements at very high water contents by the pulsed nuclear magnetic resonance technique. Transportation Research Record No. 675, p. 11-15.
- Touillaux, R., P. Salvador, C. Vandermeersche and J.J. Fripiat (1968) Study of water layers adsorbed on Na- and Ca-montmorillonite by the pulsed nuclear magnetic resonance technique. *Israel Journal of Chemistry*, vol. 6, p. 337-348.
- Ursic, S.J. (1967) Improved standards for neutron soil water meters. *Soil Science*, vol. 104, p. 323-325.
- Van Bavel, C.H.M. (1962) Accuracy and source strength in soil moisture neutron probes. *Soil Science Society of America Proceedings*, vol. 26, p. 405.
- Van Bavel, C.H.M. and G.B. Stirk (1967) Soil water measurement with an Am^{241} -Be neutron source and an application to evaporimetry. *Journal of Hydrology*, vol. 5, p. 40-60.
- Van Bavel, C.H.M., N. Underwood and R.W. Swanson (1956) Soil moisture measurement by neutron moderation. *Soil Science*, vol. 82, p. 29-41.
- Van Bavel, C.H.M. (1961) Calibration and characteristics of two neutron moisture probes. *Soil Science Society of America Proceedings*, vol. 25, p. 329-334.
- Visvalingam, M. and J.D. Tandy (1972) The neutron method for measuring soil moisture content—A review. *Journal of Soil Science*, vol. 243, No. 4, p. 499-511.
- Walsh, J., D. McQueeney, R. Layman and H. McKim (1979) Development of a simplified method for field monitoring of soil moisture. *Proceedings of 2nd Colloquium on Planetary Water and Polar Processes*.
- Watson, K.K. (1967) A recording field tensiometer with rapid response characteristics. *Water Resources Research*, vol. 5, p. 33-39.
- Webb, P. and M.J. Neugebauer (1954) Recording dielectric hygrometer for expired air. *Review of Scientific Instruments*, vol. 25, p. 1212-1217.
- Wexler, A. (1965) *Humidity and moisture*. Vol. 5, p. 1-14, New York: Reinhold.
- Williams, T.H. Lee (1978) An automatic scanning and recording tensiometer system. *Journal of Hydrology*, vol. 39, p. 175-183.
- Wilson, R.G. (1971) Methods of measuring soil moisture. The Secretariat, Canadian National Committee for the International Hydrological Decade, Ottawa, Canada.
- Woessner, D.E. (1974) Proton exchange effects on pulsed NMR signals from preferentially oriented water molecules. *Journal of Magnetic Resonance*, vol. 16, p. 19.
- Woessner, D.E. and B.S. Snowden, Jr. (1969) A study of the

- orientation of adsorbed water molecules on montmorillonite clays by pulsed NMR. *Journal of Colloid and Interface Science*, vol. 30, p. 54-68.
- Wu, T.H. (1964) A nuclear magnetic resonance study of water in clay, *Journal of Geophysical Research*, vol. 69, p. 1083-1091.
- Zollinger, W.D., G.S. Campbell and S.A. Taylor (1966) A comparison of water-potential measurements made using two types of thermocouple psychrometer. *Soil Science*, vol. 102, p. 231-239.
- Zuber, A. and J.F. Cameron (1966) Neutron soil moisture gauges. International Atomic Energy Agency, *Atomic Energy Review*, vol. 4, p. 143-147.

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