

Survey of Methods for Soil Moisture Determination

T. J. SCHMUGGE

NASA Goddard Laboratory for Atmospheric Sciences, Goddard Space Flight Center, Greenbelt, Maryland 20771

T. J. JACKSON

*U.S. Department of Agriculture, Science and Education Administration, Agricultural Research, Hydrology Laboratory
Plant Physiology Institute, Beltsville, Maryland 20705*

H. L. MCKIM

*U.S. Army Corps of Engineers, Cold Regions Research Engineering Laboratory
Hanover, New Hampshire 03755*

Increased interest in soil moisture information for applications in such disciplines as hydrology, meteorology, and agriculture has necessitated an overview of both existing and proposed methods for determination of soil moisture. This paper thus discusses methods of in situ soil moisture determination including gravimetric, nuclear, and electromagnetic techniques; soil physics models that track the behavior of water in the soil in response to meteorological inputs (precipitation) and demands (evapotranspiration); and remote sensing approaches that use the solar, thermal infrared, and microwave portions of the electromagnetic spectrum. The abilities of these approaches to satisfy various user needs for soil moisture information vary from application to application. Therefore we have proposed a conceptual scheme for merging these approaches into an integrated system. This system should provide soil moisture information having the potential for meeting the requirements of various applications.

INTRODUCTION

The moisture content in the surface layers of the soil is of great importance to the disciplines of agriculture, hydrology, and meteorology. In the field of agriculture, *Idso et al.* [1975a] described the need for soil moisture information for many diverse applications, including improved yield forecasting and irrigation scheduling. In hydrology, the moisture content of the soil surface layer is important for partitioning rainfall into its runoff and infiltration components; while in meteorology, soil moisture determines the partitioning of net radiation into latent and sensible heat components. Also, recent model studies have indicated the importance of soil moisture to the study of such diverse phenomena as desertification [*Charney, et al.*, 1977; *Idso*, 1977; *Walker and Rowntree*, 1977] and the central Florida sea breeze [*Gannon*, 1979].

The soil layer considered in all of these disciplines is that which can interact with the atmosphere through evapotranspiration (ET), i.e., the soil root zone; and the moisture content of this layer fluctuates in response to precipitation and potential evapotranspiration (PET). The thickness of this layer depends upon the type and stage of the soil's plant cover, but it is typically about 1 or 2 m. Thus we will call the moisture stored in this layer, soil moisture. This moisture is only 0.005% of the total water on the earth's surface [*Nace*, 1964]; but its seasonal variation accounts for a 1.4-cm variation in sea level [*Mather*, 1974].

In this paper we present a survey of the general methods for determining soil moisture. The three general approaches which we will consider are in situ or point measurements, soil water models, and remote sensing. The remote sensing approaches are probably the least familiar to the readers of this journal, and therefore we will give them greater emphasis. It was the development of possible methods for the remote sens-

ing of soil moisture that led to this survey. Several in situ measurement techniques will be described in this paper, gravimetric, nuclear, electromagnetic, tensiometric, and hygrometric.

IN SITU METHODS

Gravimetric Techniques

The oven-drying technique is probably the most widely used of all gravimetric methods for measuring soil moisture and is the standard for the calibration of all other soil moisture determination techniques. This method consists of oven drying a soil sample at 105°C until a constant weight is obtained. Usually, this weight is obtained within 12 hours, but for large samples the drying time increases. The wet weight of the soil sample is taken before oven drying. The amount of water in the sample can be determined and the moisture content calculated and expressed as a percentage of the dry soil weight. If the volumetric water content is required, the gravimetric value is multiplied by the bulk density of the soil:

$$\theta = \frac{W_w Y_d}{W_d Y_w} 100\% \quad (1)$$

where

- θ volumetric water content, %;
- W_w weight of water, g;
- W_d dry weight of soil, g;
- Y_d oven-dry bulk density, g/cm³;
- Y_w density of water, g/cm³.

There are several advantages and disadvantages to the oven-drying gravimetric procedure. Some advantages are (1) samples can be taken with an auger or tube sampler, (2) sample acquisition is inexpensive, and (3) soil moisture content is easily calculated.

Some disadvantages are (1) obtaining representative soil

This paper is not subject to U.S. copyright. Published in 1980 by the American Geophysical Union.

moisture values in a heterogeneous soil profile is difficult and (2) because samples are required over long periods of time to monitor moisture movement or amount over time and space, this method can be very destructive to the site. Additional information on this procedure, as well as most of the others discussed, can be found in the works by *Brakensiek et al.* [1979], *Black* [1965], and *Reynolds* [1970a, b].

Nuclear Techniques

Neutron scattering. The neutron scattering method is an indirect way of determining soil moisture content. This method estimates the moisture content of the soil by measuring the thermal or slow neutron density. Initial development of the neutron probe began in 1950 [*Belcher et al.*, 1950, 1952]. *Gardner and Kirkham* [1952] defined the principles that the method is actually based upon. Neutrons with high energy (a million electron volts or more) are emitted by a radioactive source into the soil and are slowed down by elastic collisions with nuclei of atoms and become thermalized. The average energy loss is much greater than neutrons colliding with atoms of low atomic weight (in soils, this is primarily hydrogen) than from collisions with heavier atoms. As a result, hydrogen can slow 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 are counted, and the soil moisture content is determined from a previously determined calibration curve of counts versus volumetric water content.

Two types of neutron probes have been developed. One is a depth probe that is lowered into the soil 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 widely used [*Bell and McCulloch*, 1966]. Older units used a radium-beryllium (Ra-Be) source. *Van Bavel and Stirk* [1967] found that the Am-Be 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 (mCi) of a Ra-Be source was adequate. The strength of the source of Am-Be that *Van Bavel and Stirk* [1967] used was 150 mCi. Others [*Long and French*, 1967; *Bell and McCulloch*, 1966] reported using Am-Be sources of 10, 30, 50, and 300 mCi.

If subsurface measurements are required, the neutron probe must be placed in an access tube which may be closed at the bottom. The size and composition of the tube can affect the resultant neutron density [*Stolz and Cahoon*, 1957]. The method most used to install the tube in the field is that of drilling a slightly undersized hole and tamping the access tube into the drilled hole to ensure a tight fit.

The accuracy of the neutron probe can be determined from the deviation calculated by regression analysis, where neutron counts are converted to volumetric moisture content [*Visvalingam and Tandy*, 1972]. The calibration depends upon the strength of the source, the nature of the detector, the geometry of the source and detector in the probe [*McCauley and Stone*, 1972], the materials used to construct the probe, the size and composition of the access tube, and the physical and chemical

properties of the soil [*Wilson*, 1971]. *Visvalingam and Tandy* [1972] also found that vehicular ignition noise greatly influenced the neutron probe readings, probably through its influence on the readout electronics, rather than the principle of operation.

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, if an accurate moisture content determination is desired, the probe should be calibrated for each soil type. Procedures have been developed for laboratory and field calibration [*Douglass*, 1966; *King*, 1967; *Luebs et al.*, 1968; *Vachaud et al.*, 1977; *Cohen*, 1964; *Lal*, 1979].

The moisture content value represents an average over a volume of soil. Therefore in laboratory calibration the soil used should be homogeneous in texture, structure, density, and moisture content [*Belcher et al.*, 1950; *Douglass*, 1966; *Van Bavel*, 1961, 1962]. Field calibration of the neutron probe is reportedly extremely difficult [*Lawless et al.*, 1963; *Stewart and Taylor*, 1957; *Rawls and Asmussen*, 1973] but may yield a more representative calibration curve than laboratory methods.

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

The sphere of influence of the neutron probe measurement is the volume over which the average moisture content is calculated and 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 measured is very important when measuring soil moisture with depth. In many studies the diameter of the sphere of influence cannot be easily related to depth resolution because of the heterogeneity with soil depth. The vertical resolution is critical to many studies, especially those dealing with monitoring soil moisture in 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) temporal soil moisture changes can be easily monitored, (5) rapid changes in soil moisture can be detected, (6) readings are directly related to soil moisture, and (7) measurements can be made repeatedly at the same site.

The disadvantages are (1) inadequate depth resolution makes measurement of absolute moisture content difficult and limits its use in studying evaporation, infiltration, percolation, and placement of the phreatic water surface; (2) the moisture measurement depends 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; and (4) the

sphere of influence of the depth probe does not allow 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 standard techniques, but Stewart and Taylor [1957] argued that it is slightly inferior. If the neutron probe is used, the purchaser should look for a stable, portable, durable model with stable electronics and power components, compatible with available equipment [Bell, 1969; Bell and McCulloch, 1966; Zuber and Cameron, 1966].

Gamma ray attenuation. The gamma ray attenuation method is a radioactive technique that can be used to determine soil moisture content within a 1- to 2-cm soil layer. 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 Y_d in (1) remains relatively constant as the wet density changes with moisture content increases or decreases. Changes in wet density are measured by the gamma transmission technique and the moisture content determined from this density change.

Gamma rays may be collimated to a narrow beam, which permits a representative reading to be obtained at any position in the soil. Gurr [1962], Ferguson and Gardner [1962], Davidson *et al.* [1963], and Dmitriyev [1966] were instrumental in developing the theoretical basis and procedures for its use.

Basic equipment includes a gamma ray source surrounded by a collimator, a detector with a collimator, and a scaler. Gurr [1962] used a 25-mCi ^{137}Cs source with a lead collimator. The beam emerged from a circular hole 4.8 mm in diameter. A scintillation counter, used as a detector, was shielded by a lead collimator having a 12.5-mm diameter hole. Mansell *et al.* [1973] stated that collimated radiation from 300 mCi each of ^{241}Am and ^{137}Cs provided a high-intensity beam comprising 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. They 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 ray attenuation technique has the same advantages as 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.

Its disadvantages are

1. Large variations in bulk density and moisture content can occur in highly stratified soils and limit 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.

Soane [1967] and Corey *et al.* [1971] also used dual energy, collimated beam gamma rays to simultaneously measure density and moisture content of soil columns. Others who have investigated the technique include Gardner and Roberts [1967] and Gardner *et al.* [1972]. 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 their study the error in the determination of Y_d and θ of (1) resulted from the randomness of the emission from the sources, random error in attenuation coefficients and soil column thickness measurements, presence of a small higher-energy peak in the ^{241}Am spectrum, and counting dead time.

Goit *et al.* [1976] showed experimentally that the variability

due to differences in Y_d and θ of a soil within the beam of a dual energy system caused large measurement errors. Nofziger [1978] concluded from his studies that, indeed, large error in the measurement of Y_d and θ can occur in highly stratified material when using the dual gamma technique. Generally, small errors occur if Y_d and θ change linearly in the collimated beam. He also confirmed that both the dual gamma and single 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 cold regions is the inability to measure in situ water conditions when the soil is freezing, thawing, or frozen. Goit *et al.* [1976] conducted studies to evaluate attenuation of a dual gamma beam and found this 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 [1978] determined that the errors in θ and Y_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 since measurements of dry bulk density and total water content (including ice), in grams per cubic centimeter can be made simultaneously.

Electromagnetic Techniques

Electromagnetic techniques include those methods which depend upon the effect of moisture on the electrical properties of soil. The magnetic permeability of soils is very nearly that of free space, and hence the electromagnetic approaches exploit the moisture dependence of the soil's dielectric properties.

Dielectric properties of moist soil may be characterized by a frequency dependent complex dielectric response function [Bottcher, 1952]:

$$\xi(\omega) = \xi_r(\omega) + j\xi_i(\omega) \quad (2)$$

where $\xi_r(\omega)$ is the real part of ξ , $\xi_i(\omega)$ is the imaginary part of ξ , j is the square root of -1 , and ω is the (angular) frequency.

The function $\xi_r(\omega)$ is about 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 ξ_r decreases until in the visible region of the spectrum, and it is equal to the index of refraction squared. 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 frequency 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 $\xi_i(\omega)$ is a measure of the energy dissipation rate in the medium. Viewed as a function of frequency, and starting from low ω , it rises to a peak at ω_R and, thereafter, decreases. The behavior described is due to permanent dipoles in the soil medium. In complicated heterogeneous media,

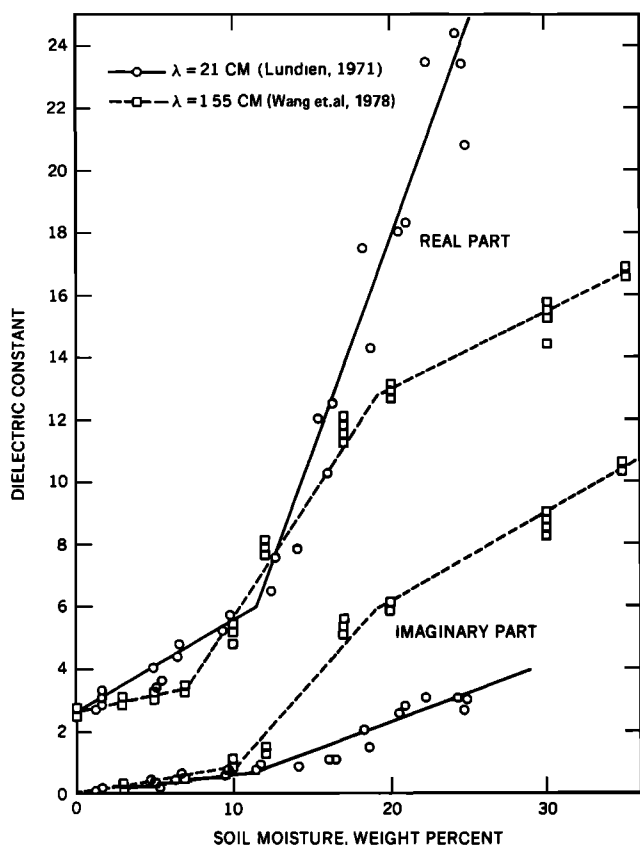


Fig. 1. Real and imaginary parts of the dielectric constant for clay loam soils at wavelengths of 21 cm [Lundien, 1971] and 1.55 cm [Wang et al., 1978].

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 H_2O), whereas the latter molecular excitations will be in the sub-millimeter or infrared regions of the spectrum [Bottcher, 1952; Hasted, 1974]. In soils, ω_R is reduced to around 1 GHz, due to the binding of the water molecules to the soil particles [Hoekstra and Delaney, 1974].

The preceding description generally applies to all dispersive media. In a soil the values of ξ_r are typically between 3 and 5; in water the value is about 80. Hence relatively small amounts of free water in a soil will greatly affect its electromagnetic properties. This dependence is shown in Figure 1, which presents the results of laboratory measurements at wavelengths of 21 and 1.55 cm (frequencies of 1.4 and 19.4 GHz). The wavelength dependence is due to the difference in the dielectric properties of water at these two wavelengths.

At low moisture levels there is a slow increase of ξ with soil moisture, but above a certain point, the slope of the curve sharply increases which is due to the behavior of the water in the soil. When water is first added to a soil, it is tightly bound to the soil particles. In this state the water molecules are not free to become aligned, and the dielectric properties of this water resemble those of ice for which $\xi = 3.5$. As the layer of water around the soil particle becomes larger, the binding to the particle decreases and the water molecules behave as they do in the liquid state; hence the greater slope at the higher soil moisture values. The soil moisture content θ , at this transition

depends on the soil texture, i.e., particle size distribution, θ , is smaller for a sand and larger for a clay and has been found to be linearly dependent on the wilting point for the soil. This effect has been demonstrated in laboratory measurements of the dielectric constant [Lundien, 1971; Newton, 1977].

This dependence of dielectric properties of soil on moisture content can be used for either in situ or remote sensors. In this section, in situ devices, measuring either soil resistivity or capacitance, will be discussed; the remote sensor approaches will be presented later.

A variety of implantable sensors, responsive either to resistivity (ξ_r), polarization (ξ_i), or both, have been constructed [Wexler, 1965; Roth, 1966; Thomas, 1963; Gagne and Outwater, 1961; DePlater, 1955; Silva et al., 1974]. Traditionally, these have been designed for operation at frequencies below 1 MHz. Recently, however, due to a steady decrease in the physical size of high-quality, high-frequency components, implantable sensors have become a practical reality [Selig et al., 1975; Walsh et al., 1979; Layman, 1979; Wobschall, 1978].

The resistivity of soils depends on moisture content and hence 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 depends 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, ξ_r , in essence measure capacitance [Thomas, 1963; Gagne and Outwater, 1961; DePlater, 1955; Selig et al., 1975; Walsh et al., 1979; Layman, 1979]. This parameter is the electrical quantity that most directly indicates moisture concentration. When the moisture held in the soil can be regarded as free, i.e., above transition θ_c , the relationship between ξ_r and moisture is linear. Furthermore, even in more complicated materials, such as a montmorillonitic clay, where the water is relatively tightly bound, it is possible to determine moisture content by measuring the capacitance of an implanted sensor. Because of this, several capacitive sensors have been constructed. Most of these have been designed for operation below 1 MHz, although more recently some work has also been done up to 100 MHz [Wobschall, 1978; Walsh et al., 1979; Layman, 1979; Silva et al., 1974]. The motivation for increasing the operation frequency is again to minimize the contribution of ionic conductivity, which if large, can make accurate measurement of the capacitance difficult. One other promising technique is to work at 10- to 100-MHz frequency and to use a bridge technique that allows a determination of both ξ_r and ξ_i . These can be used separately as moisture indicators [Walsh et al., 1979; Layman, 1979].

The main advantages of either resistor or capacitor type devices are as follows.

1. With calibration, they are capable, in principle, of providing absolute values for soil moisture.
2. They can be implanted at any depth; thus moisture profile data can be obtained by this method.

3. A wide variety of sensor configurations varying from very small to large are possible, and hence there is some control over the sensor volume of influence.

4. The precision of both the resistive and capacitive sensors is high. Resistive sensors are also relatively accurate when other parameters are adequately controlled, and the capacitive sensors have relatively high intrinsic accuracy that is more nearly independent of parameters other than moisture. This follows logically, in that the capacitive sensors are directly responsive to the amount of polarized energy stored in the region of the sensor, a quantity dominated by the water present.

The disadvantages are as follows.

1. The moisture sensor must be implanted properly to minimize disturbances to the soil.

2. There are questions of long-term reliability and maintenance of the calibration, especially if the ionic concentration in the soil water changes.

3. Cost of readout devices and interfaces with remote collection platforms is high.

Overall, it would seem that the relative advantages in some applications would warrant serious consideration of the implantable sensors.

Tensiometric Techniques

The term 'tensiometer' was used by *Richards and Gardner* [1936] as an unambiguous reference to the porous cup and vacuum gage combination for measuring capillary tension or the energy with which water is held by the soil. However, tensiometers were 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 field and laboratory soil water studies.

The energy term can be expressed as pF , which is defined as the common log of the height of a water column in centimeters equivalent to the soil moisture tension, or it can be 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 matric suction is one. Matric suction is 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 using the term 'capillary potential' to denote the total potential, which includes not only surface tension forces 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 the suction and consist of a liquid-filled (usually water), porous ceramic cup connected by a continuous liquid column to a manometer or vacuum gage. In some designs the liquid is an ethylene glycol-water solution and the measuring gage a transducer with electrical output. The transducer output can be interfaced to near real time data acquisition systems. 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 areas [*McKim et al.*, 1976]. Since the tensiometer/transducer system has a millivolt output and responds rapidly to changes in soil moisture ten-

sion, it is well suited for automatic (including satellite relay) recording systems [*McKim et al.*, 1975; *Elzeftawy and Mansell*, 1975; *Gillham et al.*, 1976].

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 solute but not to air, so that water can flow and soil water conditions or 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 water tension is zero. The highest tension (or suction) reading that can be obtained with a tensiometer is about 1 bar (1 atm). In most instances, data cannot be obtained beyond 0.8–0.9 bar because the air entry value of the ceramic cup is exceeded. This means that the moisture content range over which the tensiometer can be used is limited. *Richards* [1949] stated that for coarse, sandy soils the range of the tensiometer may cover more than 90% of the available moisture content range. Clay soils pose a different problem. For example, in soils containing over 42% montmorillonite clay, the tension can change from 200 to 800 cm H_2O with a 1% change in volumetric water content [*Abele et al.*, 1979].

Soil moisture measurement procedures using tensiometer/transducer systems are ways to monitor moisture tension gradients in the field. Studies by *Bianchi* [1962], *Klute and Peters* [1962], *Watson* [1967], *Rice* [1969], *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 moisture tension changes that occur rapidly in infiltration, irrigation, groundwater recharge, and evapotranspiration. These gradient data must be used in flux equations with previously determined conductivity values to calculate water movement.

Tensiometers have been used for years to measure soil moisture tension. During recent years, advancements in system design and performance have made possible the implementation of soil moisture field monitoring programs. However, care is still needed in assessing the use of the system. Listed below are some of the advantages and disadvantages of using tensiometers.

Advantages.

1. Systems are easy to design and construct.
2. Systems cost relatively little.
3. Information can be obtained on moisture distributions under saturated and unsaturated conditions in near real time.
4. Tensiometers can usually be placed in soil easily and usually with minimal disturbance.
5. Systems can operate over long time periods if properly maintained.
6. With the tensiometer/transducer system the response time is very rapid.
7. Different types of liquids, like ethylene glycol solution, can be used to obtain data during freezing and thawing conditions. When the soils are frozen, the tension of the unfrozen water is greater than 800 cm and the system fails.
8. Systems can be used with positive or negative reading tensiometers to read both water table elevation and soil moisture tension, depending on soil water status.

Disadvantages.

1. Tensiometers provide direct measurements of soil water suction but only indirect measurement of soil moisture con-

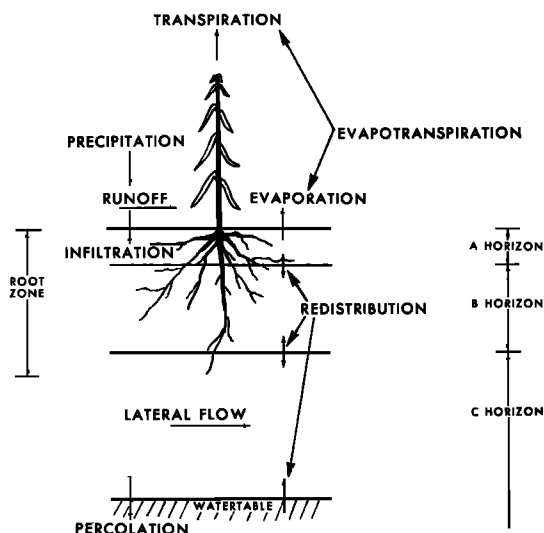


Fig. 2. Schematic diagram of soil-plant-atmosphere-water (SPAW) system.

tent. This translation requires knowledge of the moisture characteristics for the soil.

2. Tensiometers can be broken easily during installation.
3. Results can be determined only within the 0- to 800-cm water tension range.
4. Field installations using pressure transducers drift electronically.

Hygrometric Techniques

The relationship between moisture content in porous materials and the relative humidity (RH) of the immediate atmosphere is reasonably well known. Therefore several relatively simple sensors for measuring RH have been designed. Basically, these 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.

Electrical resistance hygrometers utilize chemical salts and acids, aluminum oxide, electrolysis, thermal, and white hydrocol to measure RH. The measured resistance of the resistive element is a function of the RH. *Bouyoucos and Cook* [1965] considered the white hydrocol hygrometer as the best available. They stated that casting the stainless steel electrodes in white hydrocol (a form of plaster of Paris) causes greater accuracy because the cement sets hard, is pure, has a low solubility and contains no added salts.

Phene et al. [1971, 1973] developed a heat dissipation sensor that was used to measure the matric potential. The accuracy of this sensor proved to be as good as or better than that of the thermocouple psychrometer or salinity measurements. The sensor, which was highly sensitive 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 matric potential of -10 bar.

The advantages of the hygrometer techniques are (1) simplicity of the apparatus and (2) low cost.

The disadvantages are (1) deterioration of the sensing element through interaction with the soil components and (2) special calibration is required 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, an example would be drying and shrinkage of cements.

SOIL WATER MODELS

Recent developments of soil water models based on column mass balance provide an alternative to directly or indirectly measuring soil moisture in the field. Figure 2 is a schematic diagram of the physical system and the driving forces that must be considered in modeling the system.

Based upon conservation of mass, the soil moisture in the system at any time can be determined using the relationship

$$SM_t = SM_{t-1} + P - R - L - E - T + C - Q \quad (3)$$

where

- SM_t soil moisture volume at time t ;
- SM_{t-1} soil moisture volume at previous time;
- P precipitation;
- R surface runoff;
- L net lateral subsurface outflow;
- E evaporation or condensation;
- T transpiration;
- C capillary rise from lower levels;
- Q percolation.

This generalized model represents only a single column that is horizontally homogeneous at all levels. Actual systems are heterogeneous, and they can be represented by spatial averages or by linked columns that account for the spatial variability.

Published soil moisture models vary in the level of detail they use in representing the physical system and temporal variations of the driving forces. Some of the important differences between models are (1) method used for computing the potential evapotranspiration, (2) method used for computing infiltration and runoff, (3) temporal definition of evaporative demand and precipitation, (4) consideration of saturated and unsaturated levels, (5) number of soil layers used, (6) method used for computing soil evaporation and plant transpiration, and (7) consideration of the thermal properties of the soil system.

Many of the published models that simulate soil moisture were developed for agricultural applications. A very simple model, described by *Holmes and Robertson* [1959], treats the soil as a single homogeneous layer. Potential evapotranspiration is computed empirically, and the actual evaporation is set equal to this as long as moisture is available. All precipitation becomes infiltration and groundwater interactions are ignored. All computations are performed on a daily basis.

Jensen et al. [1971] developed an irrigation scheduling model that takes into account soil moisture. Evapotranspiration is computed on a daily basis using one of several alternative procedures. Actual evapotranspiration is not affected by moisture deficits. Infiltration must be computed externally. Percolation is computed using an empirical relationship. In this model the soil is treated as a single layer.

Holmes and Robertson [1959] presented and described another model, the modulated soil moisture model, which is slightly more sophisticated than those described above. This model uses a two-layer soil system and considers the fact that actual evaporation will generally not equal the potential due to moisture deficits. The two are set equal until the moisture in the upper soil zone is depleted. Thereafter, moisture is extracted from the lower zone at a reduced rate proportional to the moisture level. This model also allows a simple runoff computation.

Baier and Robertson [1966] improved on these models with

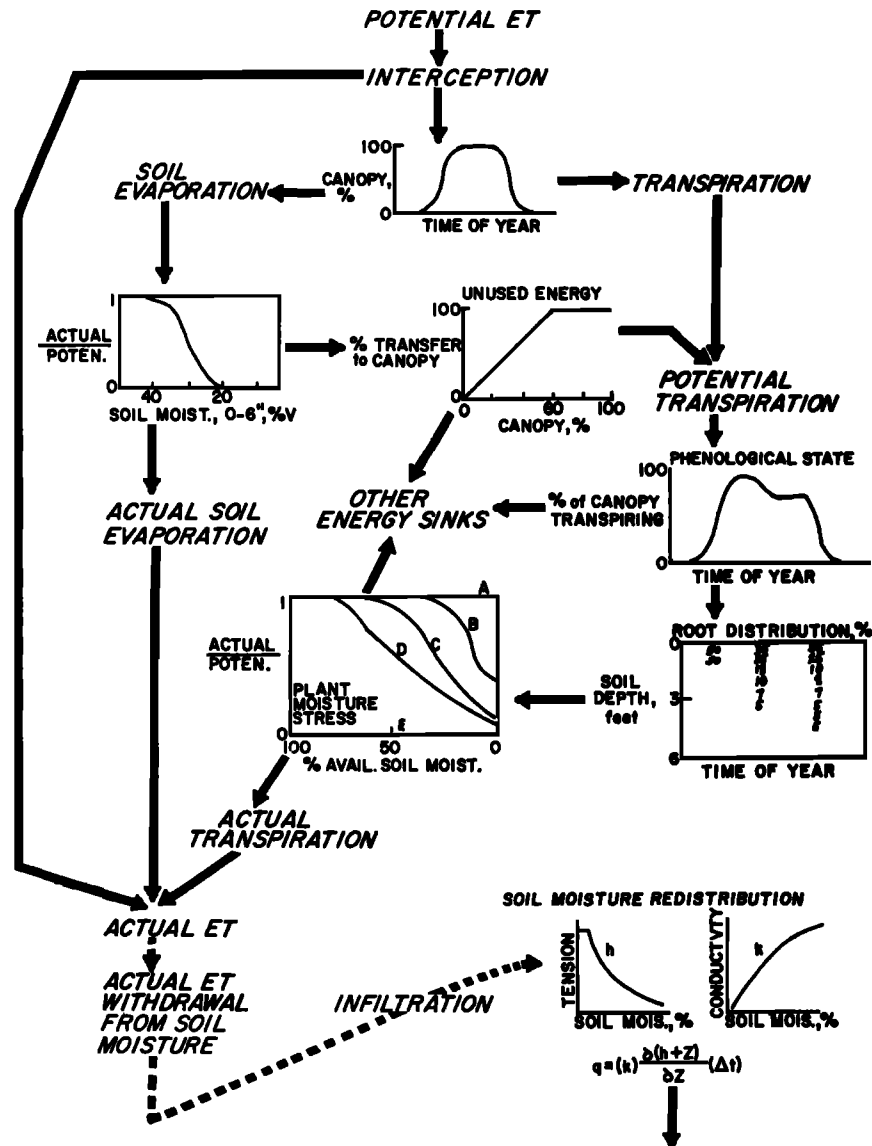


Fig. 3. Flow chart of SPAW model [Saxton et al., 1974].

the versatile soil moisture budget model. In this model the soil is divided into several layers, and the available water capacity of each layer is taken to be the difference between soil's field capacity and wilting point. Evapotranspiration can occur simultaneously from each layer and depends on the soil moisture present and the particular soil and root distribution of the plants involved, which are represented by coefficients. Flow between layers is considered; however, the technique used is empirical, as is the procedure used for computing infiltration.

Saxton et al. [1974] developed a much more comprehensive model that simulates soil-plant-atmosphere-water systems in greater detail than the models described above. A flow chart of the model is shown in Figure 3. As illustrated, this model considers all factors that influence the system. Some processes, like soil moisture redistribution, are modeled using a physics-based approach, whereas others, like plant transpiration, are semi-empirical.

Many other models which resemble those mentioned above have been developed. Additional information can be found in the works by Saxton and McGuinness [1979], Feddes et al. [1978], Hildreth [1978], Singh [1971], Kanemasu et al. [1976],

Stuff and Dale [1978], Shaw [1963], Goldstein et al. [1974], Ritchie [1972], and Youker and Edwards [1969].

All of these models were developed primarily for agricultural applications. Hydrologists have also developed water balance models that include a soil moisture component. State of the art examples of the approaches used in hydrologic modeling can be found in the U.S. Department of Agriculture, Hydrograph Laboratory (USDAHL) model [Holtan et al., 1975] and the National Weather Service River Forecast Model (NWSRFS) [Peck, 1976]. Other models are reviewed by Fleming [1975]. Most of these models can perform a continuous simulation of the volumes and rates of water movement occurring in each component of the watershed.

In the USDAHL model, illustrated in Figure 4, the spatial variability of soils and vegetation is accounted for by using zones within which the hydrologic parameters are averaged. Within each zone the soil is subdivided into several homogeneous layers determined from hydraulic properties. Evapotranspiration is computed daily using an empirical equation which considers the crop and soil characteristics, as well as the current soil moisture. Evapotranspiration is drawn from the

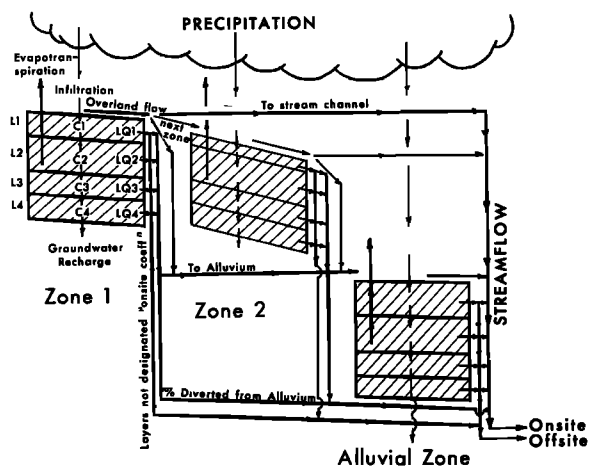


Fig. 4. The USDAHL model [Holtan and Yamanoglu, 1977].

first two layers, which are considered to be the root zone. These computations are performed daily. Infiltration is also based on soil and crop characteristics and the current soil moisture. A 1-hour time step is used for these computations. The procedure used for soil moisture redistribution and percolation only considers gravity flow.

In the NWSRFS Model, illustrated in Figure 5, two zones are used to simulate soil water storage and movement. The upper layer responds quickly to rainfall and controls overland flow. It is usually very shallow. The lower layer is the balance of the soil column extending to the water table. Soil hydraulic properties are averaged within each layer. Moisture is stored as either tension or free water. Infiltration, percolation and soil moisture redistribution involve the free water. They are computed with empirical equations that use as a controlling factor the ratio of the free water present to the field capacity of the layer involved. Evapotranspiration is also computed using an empirical procedure. Actual evapotranspiration is set equal to potential until all moisture in the upper layer is depleted. When this occurs, moisture is extracted from the lower zone using an equation that considers the moisture deficit and the crop characteristics. A 6-hour time step is used for simulation.

Most models mentioned in preceding sections were devel-

oped for practical application to such problems as crop yield estimation, irrigation planning, and runoff forecasting. They were developed to use readily available meteorological data for inputs, and therefore they usually use a 1-day time step. Goldstein *et al.* [1974] pointed out that models which use a 1-day averaging can produce accurate weekly average results; however, the daily results will show some deviation on any given day. Jensen *et al.* [1971] made the same point. They noted that expected daily errors between 10 and 15% should become negligible over 10–20 days.

Some situations, especially research, require information of greater time resolution and accuracy than these models can provide. Several complex models capable of simulating soil-plant-atmosphere-water systems have been proposed. Generally, these models are more physically based than the models described above. Increased detail is usually costly, and these complex models usually have high data and computer requirements, especially if simulation over extended periods is desired.

Much research has been done on the physics of soil water movement and storage under bare soil conditions. These models usually involve solving the equations describing one-dimensional vertical unsaturated flow and horizontal saturated flow. Most of the published models differ on the boundary conditions imposed and the numerical approximations used for solution.

Hillel [1977] described several physically based models designed to simulate soil water conditions under bare soil conditions. All of the models were programed using a versatile simulation language called continuous simulation modeling programs (CSMP) [Speckhart and Green, 1976]. Other examples of this type of model are presented by Hanks *et al.* [1969], Warrick *et al.* [1971], Bresler [1973], Remson *et al.* [1971], and Pikul *et al.* [1974].

Some progress has been made at linking these one-dimensional models to represent spatially varied systems. Figure 6 is a schematic of one such model presented by Hillel [1977]. Others, such as that of Freeze [1978], have extended the solutions to two-dimensional problems.

Including the effects of plants in detailed models greatly increases their complexity. Published models that simulate these effects include those presented by Van Bavel and Ahmed

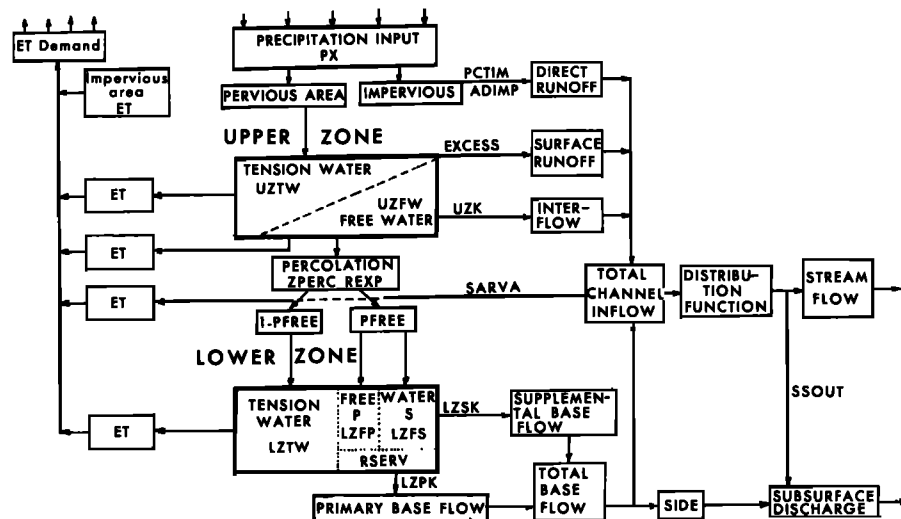


Fig. 5. The NWSRFS model [Peck, 1976].

[1976], *Lemon et al.* [1973], *Makkink and vanHeemst* [1975], *Hanson* [1975], *Slack et al.* [1977], *Feddes et al.* [1976], *Neuman et al.* [1975], and *Nimah and Hanks* [1973].

The reader can gather from the number of references cited in this section that a multitude of models have been developed and documented. A comprehensive description of each, along with their respective advantages and disadvantages, is beyond the scope of this paper. In general, a model that is adaptable to almost every problem can be found in the literature. The principal advantage of models is that they can provide timely soil moisture information without the necessity of field visits. A general disadvantage of models is the error of their estimates.

REMOTE SENSING APPROACHES

The remote sensing of soil moisture depends upon the measurement of electromagnetic energy that has either been reflected or emitted from the soil surface. The variation in intensity of this radiation with soil moisture depends on either the dielectric properties (index of refraction), soil temperature, or a combination of both. The particular property that is important depends on the wavelength region that is being considered as indicated in Table 1.

Reflected solar energy is not a very promising tool in soil moisture determination because the relationship of the soil spectral reflectance to the water content depends on several other variables, like spectral reflectance of the dry soil, surface roughness, geometry of illumination, organic matter, and soil texture [*Jackson et al.*, 1978]. These complicating factors, plus the fact that reflected solar energy responds to only a thin surface layer [*Idso et al.*, 1975b], limit the utility of solar reflectance measurements for soil moisture determination and thus will not be discussed further here.

Water is unique in that it is near the extremes in its thermal and dielectric properties. As a result, the corresponding properties in the soil are highly dependent on its moisture content. These properties are accessible to remote sensing through measurements at the thermal infrared (10 m) and microwave (1–50 cm) wavelengths. The approaches are [*Schmugge*, 1978] as follows:

1. Thermal infrared, consisting of measurement of the diurnal range of surface temperature or measurement of the crop canopy-air temperature differential.
2. Active microwave, consisting of measurement of the radar backscattered coefficient, and passive microwave, consisting of measurement of the microwave emission or brightness temperature.

Thermal Methods

The amplitude of the diurnal range of soil surface temperature is a function of both internal and external factors. The internal factors are thermal conductivity K and heat capacity C , where $P = (KC)^{1/2}$ defines what is known as 'thermal inertia.' The external factors are primarily meteorological: solar radiation, air temperature, relative humidity, cloudiness, and wind. The combined effect of these external factors is that of the driving function for the diurnal variation of surface temperature. Thermal inertia then is an indication of the soil's resistance to this driving force. Since both the heat capacity and thermal conductivity of a soil increase with an increase of soil moisture, the resulting thermal inertia increases.

A complicating factor is the effect of surface evaporation in reducing the net energy input to the soil from the sun. Evapo-

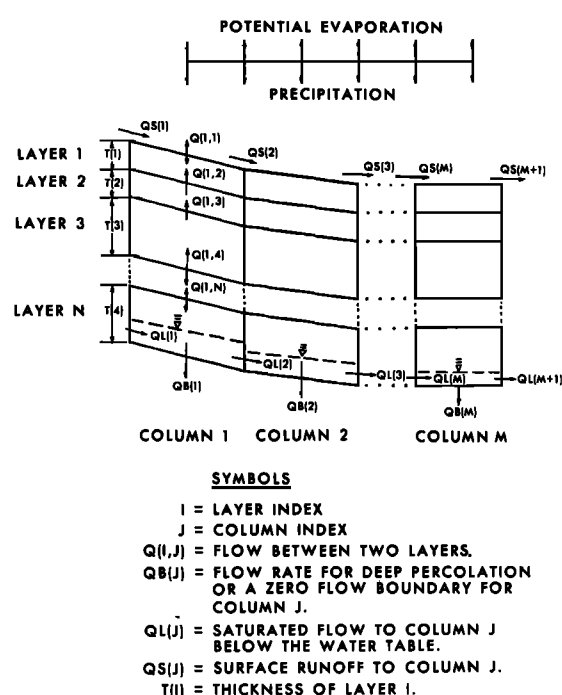


Fig. 6. A distributed soil moisture simulation model.

ration complements the other effects of water in soil by reducing the amplitude of the surface diurnal temperature cycle. As a result, the day-night temperature difference is an indicator of some combination of soil moisture and surface evaporation.

The basic phenomenon has been studied in experiments at the U.S. Water Conservation Laboratory in Phoenix, Arizona, where soil temperatures versus time were measured with a thermocouple, before and after irrigation [*Idso et al.*, 1975c]. They observed a dramatic difference in the maximum temperatures before and after an irrigation. On succeeding days the maximum temperature increased as the field dried out.

Figure 7 is a summary of results from many such experiments. The amplitude of the diurnal range is plotted as function of soil moisture as measured at the surface and in 0- to 1-, 0- to 2-, and 0- to 4-cm layers. Correlation with the soil moisture in the 0- to 2- and 0- to 4-cm layers of the soil is good, and this response is related to the thermal inertia of the soil. Initially, when the surface is moist, the temperatures are more or less controlled by evaporation. Once the surface layer dries below a certain level, the temperature is determined by the thermal inertia of the soil. These results indicated that for this particular soil, the diurnal range of surface temperature is a good measure of the moisture content in the surface (0–4 cm) layer.

These temperature measurements were repeated for different soil types that ranged from sandy or light soils to heavy clay soils; and it was found that for a given set of diurnal meteorological conditions, there can be a wide range of temperature amplitude–water content relationships for these different soils [*Idso et al.*, 1975c]. However, when soil water content was transformed into pressure potential, a single relationship was found to be valid for all of the different soil types investigated. This is the basis for expressing moisture values as a percent of field capacity (FC), where field capacity is the moisture content of the $-1/3$ bar pressure potential.

It should be emphasized that these experiments were all conducted in the field, using thermocouples instead of remote

TABLE 1. Electromagnetic Properties for Soil Moisture Sensing

Wavelength Region	Property Observed
Reflected solar	Soil albedo/index of refraction
Thermal infrared	Surface temperature
Active microwave	Backscatter coefficient/dielectric properties
Passive microwave	Microwave emission/dielectric properties and soil temperature

sensors to acquire surface temperature data. In March 1975 an experiment was performed in which remotely sensed thermal infrared temperatures from an aircraft platform were compared with the in situ thermocouple measurements over a 5-day period. Figure 8 presents the results from both the field experiments (from Figure 7) and the aircraft experiments [Reginato *et al.*, 1976; Schmugge *et al.*, 1978]. The field results are expressed as a percent of field capacity so they can be compared with the aircraft results obtained over a wide range of soil textures. Agreement between the thermocouple measurements and the remotely sensed radiation measurements made from the aircraft was good, indicating that the conclusions based on the thermocouple field measurements would also be valid for radiation temperature observations.

This technique is not applicable to fields with a vegetative canopy. However, the difference between canopy temperature and ambient air temperature has long been known to be an indicator of crop stress [Wiegand and Namken, 1966; Ehler and van Bavel, 1967; Ehler, 1973; Hiler and Clark, 1971; Hiler *et al.*, 1974]. Thus if the canopy temperature is viewed as expressing the soil moisture status, a potential exists for monitoring effective soil moisture over the rooting depth of the particular crop [Idso and Ehler, 1976]. Following this argument, Jackson *et al.* [1977] established that a running sum of daily values called 'stress degree days' (SDD) can potentially be used for irrigation scheduling; and Millard *et al.* [1977, 1978] confirmed the feasibility of this approach for fully grown wheat on the basis of airborne data. Similarly, stress degree days were successfully correlated with the yield of wheat [Idso *et al.*, 1977] and have subsequently been successfully correlated with yields of alfalfa [Reginato *et al.*, 1978]; beans [Walker and Hatfield, 1979]; and barley, soybeans, and sorghum [Idso *et al.*, 1980].

Microwave Methods

As discussed previously, the dielectric properties of a soil are strong functions of its moisture content. Since the dielectric properties of a medium determine the propagation charac-

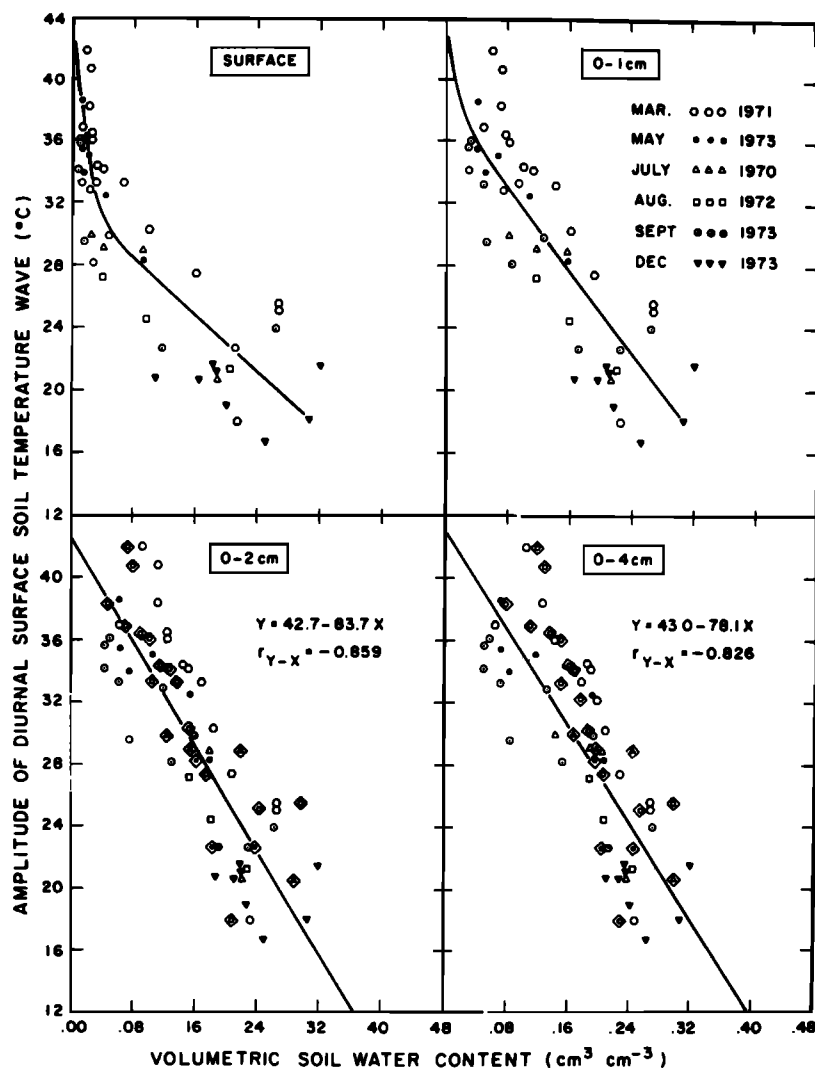


Fig. 7. Summary of results for the diurnal temperature variation versus soil moisture [Idso *et al.*, 1975a].

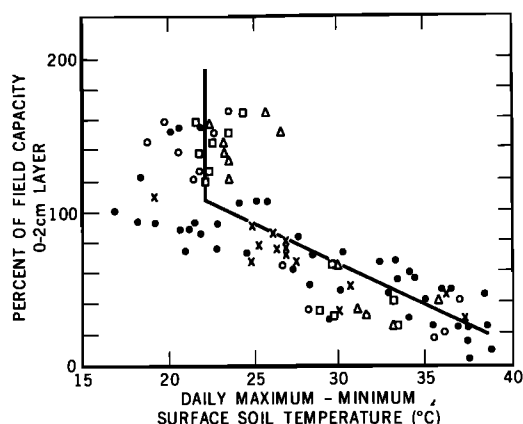


Fig. 8. Plot of T versus soil moisture in the 0- to 2-cm layer. The symbols represent the different types of temperature measurement: solid circle, open box, surface thermocouple; open circle, hand-held radiometer; open triangle, aircraft data over test plot; crosses, aircraft data over the general agricultural fields. Solid circle, open circle, open box, open triangle, from *Reginato et al.* [1976]; crosses from *Schmugge et al.*, [1978].

teristics for electromagnetic waves in the medium, they will affect the emissive and reflective properties at the surface. As a result, the emissive and reflective properties at the soil surface depend on the soil moisture content, which can be measured in the microwave region of the spectrum by radiometric (passive) and radar (active) techniques. This physical relationship between the microwave response and soil moisture, plus the ability of the microwave sensors to penetrate clouds, makes them very attractive for use as soil moisture sensors. In the following sections, results will be presented demonstrating this sensitivity to soil moisture, along with a discussion of some of the noise factors, e.g., vegetation and surface roughness, that affect the relationship between the sensor response and soil moisture.

Passive microwave. A microwave radiometer measures the thermal emission from the surface, and at these wavelengths the intensity of the observed emission is essentially proportional to the product of the temperature and emissivity of the

surface (Rayleigh-Jeans approximation). This product is commonly referred to as brightness temperature. All our results will be expressed as brightness temperatures (T_B). The value of T_B observed by a radiometer at a height above the ground is

$$T_B = \tau(rT_{sky} + (1-r)T_{soil}) + T_{atm} \quad (4)$$

where r is the surface reflectivity and τ the atmospheric transmission. The first term is the reflected sky brightness temperature, which depends on wavelength and atmospheric conditions; the second term is the emission from the soil ($1-r = e$, the emissivity); and the third term is the contribution from the atmosphere between the surface and the receiver. At the longer wavelengths, i.e., those best suited for soil moisture sensing, the atmospheric effects are minimal and will be neglected in this discussion.

Thermal microwave emission from soils is generated within the soil volume. The amount of energy generated at any point within the volume depends on the soil dielectric properties (or soil moisture) and the soil temperature at that point. As energy propagates upward through the soil volume from its point of origin, it is affected by the dielectric (soil moisture) gradients along the path of propagation. In addition, as the energy crosses the surface boundary, it is reduced by the effective transmission coefficient (emissivity), which is determined by the dielectric characteristics of the soil near the surface.

The emission from the soil surface can be expressed as

$$T_B = e \int_{-\infty}^0 T(z)\alpha(z) \exp \left[-\int_z^0 \alpha(z') dz' \right] dz \quad (5)$$

where $T(z)$ is the temperature profile and $\alpha(z)$ is the absorptivity as a function of depth which depends on moisture content. Results from numerical solutions to this equation have been presented by *Njoku and Kong* [1977], *Wilheit* [1978], and *Burke et al.* [1979]. These papers have included results which indicate that the models do a good job of predicting T_B for a smooth surface. One of the most significant results from these models is that the effective sampling depth is of the order of only a few tenths of a wavelength [*Wilheit*, 1978]. Thus for a

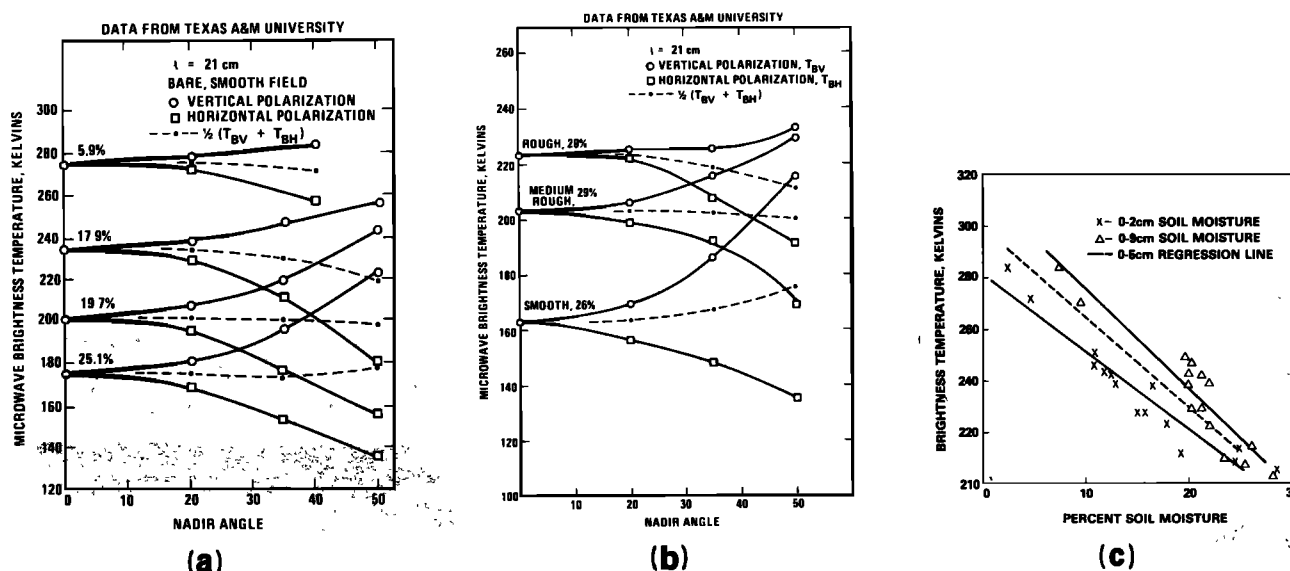


Fig. 9. Results from field measurements performed at Texas A&M University: (a) T_B versus angle for different moisture levels; (b) T_B versus angle for different surface roughness at about the same moisture level; (c) T_B versus soil moisture in different layers for the medium-rough field [*Newton*, 1977].

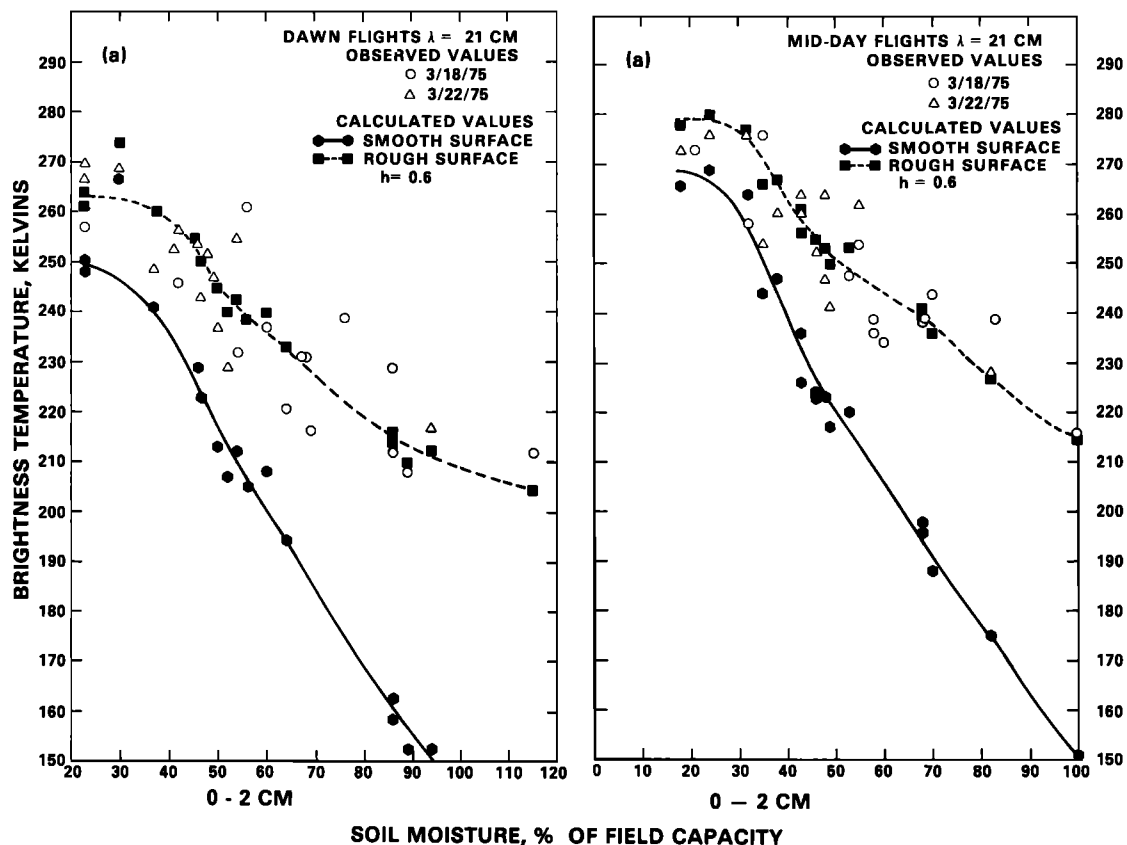


Fig. 10. Aircraft observations of T_B over agricultural fields around Phoenix, Arizona, from March 1975 flights for both early morning and midday flights.

21-cm wavelength radiometer this depth is about 2–5 cm.

The range of dielectric constant presented in Figure 1 produces a change in emissivity from greater than 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck-mounted radiometers in field experiments [Poe et al., 1971; Blinn and Quade, 1972; Schanda et al., 1978; Newton, 1977] and by radiometers in aircraft [Schmugge et al., 1974; Burke et al., 1979; Choudhury et al., 1979] and satellites [Eagleman and Lin, 1976; Schmugge et al., 1977]. In no case were emissivities as low as 0.6 observed for real surfaces. This is primarily due to surface roughness, which generally has the effect of increasing the surface emissivity.

As can be seen in Figure 1, there is a greater range of dielectric constant for soils at the 21-cm than at 1.55-cm wavelength. This fact, combined with a larger soil moisture sampling depth and better ability to penetrate a vegetative canopy, makes the longer wavelength sensors better suited for radiometric soil moisture sensing.

In Figures 9a and 9b the field measurements of Newton [1977] are plotted versus angle of observation for various moisture contents and for three levels of surface roughness. The horizontal polarization is that for which the electric field of the water is parallel to the surface and the vertical polarization is perpendicular to it. These results show the effect of moisture content on the observed values of T_B , as well as the effect of surface roughness, which increases the effective emissivity at all angles and decreases the difference in T_B for the two polarizations at the larger angles.

For the smooth field there is a 100 K change in T_B from wet to dry soils. Clearly, this range is reduced by surface roughness. Roughness decreases the reflectivity of the surface and

thus increases its emissivity. For a dry field the reflectivity is already small (<0.1) so that the resulting increase in emissivity is small. As shown in Figure 10b, surface roughness has a significant effect for wet fields where the reflectivity is larger

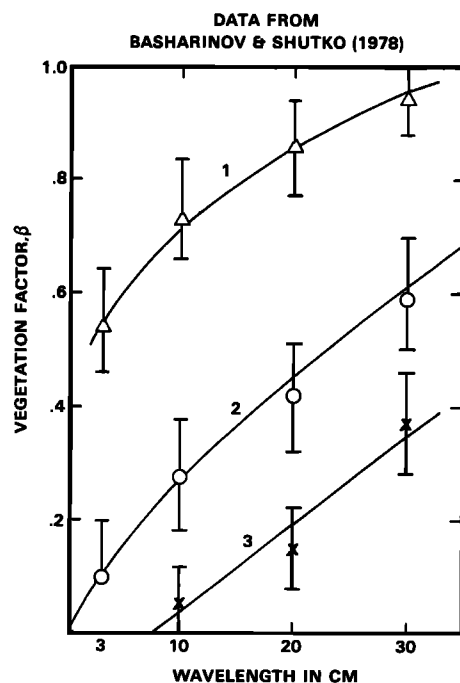


Fig. 11. Effect of vegetation on passive microwave sensing of soil moisture. Three curves are (1) small grains: wheat, barley, rye and grass; (2) broad leaf cultures, like mature corn and cotton; and (3) mixed forest.

(>0.4). Thus the range of T_b for the rough field is reduced to about 60 K. The smooth and rough fields represent the extremes of surface conditions that are likely to be encountered. The smooth field had been dragged, while the rough surface was on a field with a heavy clay soil (clay fraction 60%) that had been deep plowed, which produced large clods. Therefore the medium rough field, with a T_b range of 80 K, is probably more representative of the average surface roughness condition that will be encountered. Another important observation from Figures 9a and 9b is that the average of the vertical and horizontal T_b 's is essentially independent of angle out to 40°. This indicates that the sensitivity of this quantity, $(1/2)(T_{BV} + T_{BH})$, to soil moisture will be independent of angle. This result will be useful if the radiometer is to be scanned to provide an image.

When the brightness temperatures for the medium-rough field are plotted versus soil moisture in the 0- to 2-cm layer, there is an approximate linear decrease of T_b (Figure 9c). As the thickness of the layer increases, both the slope and the intercept of the linear regression also increase. This is because the moisture values for the high T_b cases increase, whereas they remain essentially the same in the low T_b or wet cases. This type of behavior was also seen in the results obtained from aircraft platforms and has led us to conclude that the soil moisture sampling depth is within the 2- to 5-cm range for the 21-cm wavelength. This agrees with the predictions of theoretical models of radiative transfer in soils [Wilheit, 1978; Burke *et al.*, 1979].

Results from a 1975 aircraft experiment over irrigated agricultural fields are presented in Figure 10 [Choudhury *et al.*, 1979]. These results were obtained over fields with a range of soil textures from sandy loam to heavy clays. In the analysis it was observed that the T_b response to soil moisture depended on the soil texture, that is, the slope was greater for sandy soils, which had a narrower range of soil moistures (0–20%) than the clay soils (0–35%). To take this texture dependence into account, the soil moisture values presented in Figure 11 were normalized to the field capacity (FC) value for the particular soil which was estimated from the measured soil textures.

The solid symbols in Figure 10 are calculated values of T_b obtained with Wilheit's [1978] model using the measured moisture and temperature profiles for the fields. The solid line connects the values determined assuming a smooth surface, and the dashed line connects the values adjusted for surface roughness using a one-parameter model. The dashed line fit the observed values quite well. The values of the parameter were selected empirically to give a best fit to the data. Clearly, the same value works well for both the dawn and midday flights. The effects of soil temperature are shown in the T_b differences between the dawn and midday flights.

There is little change in T_b for soil moisture values for the 0- to 2-cm layer out to about 30% of field capacity. When the data were replotted versus the 0- to 5-cm layer, the flat region extended out to about 50% of FC with a steeper slope beyond that value. In Figure 1 the dielectric curve broke at a moisture level of about 10%, which for the soil involved would be 40–50% of FC. Thus these aircraft results supported the conclusion that the sampling depth in the soil is about 2–5 cm.

A vegetative canopy acts as an absorbing layer whose effect will depend on the amount of vegetation and the wavelength of observation. Basharinov and Shutko [1978] and Kirdiashev *et al.* [1979] have reported on observations made in the USSR over the 3- to 30-cm wavelength range for a variety of crops.

Their results are summarized in Figure 11, where the vegetation factor (β) is the effective transmissivity of the vegetation. Thus for small grains the sensitivity is 80–90% of that expected for bare ground at wavelengths greater than 10 cm. Broad leaf cultures, like mature corn or cotton, transmit only 20–30% of the radiation from the soil at wavelengths shorter than 10 cm and about 60% at the 30-cm wavelength. The authors observed a β of 30–40% for a forest at the 30-cm wavelength, although they did not mention the type or height of trees. These results are encouraging for the use of long-wavelength radiometric approaches.

The earth resources experiment package (EREP) on-board Skylab contained a 21-cm radiometer. This sensor was non-scanning; it had a 115-km field of view between half-power points. With this coarse spatial resolution it would be difficult to directly compare sensor response and soil moisture measurements. However, there have been two reports of indirect comparisons. McFarland [1976] showed a strong relationship between the Skylab 21-cm brightness temperatures and the antecedent precipitation index (API) for data obtained during a pass starting over the Texas and Oklahoma panhandles and proceeding southeast toward the Gulf of Mexico.

Eagleman and Lin [1976] carried the analysis of the Skylab data a step further and compared the brightness temperature with estimates of the soil moisture over the radiometer footprint. The soil moisture estimates were based on a combination of actual ground measurements and calculations of the soil moisture using a climatic water balance model. They obtained a correlation of 0.96 with data obtained during five different Skylab passes over Texas, Oklahoma, and Kansas. This result was very good considering the difficulty of obtaining soil moisture information over a footprint of such a size and considering the fact that the brightness temperature was averaged over the wide range of cultural conditions that occurred over the area.

These results from space supported by the more detailed aircraft and ground measurements presented earlier strongly support the possibility of using microwave radiometers for soil moisture sensing. A difficulty with this approach is that the spatial resolution is limited by the size of the antenna that can be flown. For example, at a wavelength of 21 cm, a 10×10 m antenna is required to yield 20-km resolution from a satellite altitude of 800 km. It is possible to make use of the coherent nature of the signal in active microwave systems (synthetic aperture radar, or SAR) to obtain better spatial resolutions, and it is this approach that we discuss next.

Active microwave. The backscattering from an extended target, such as a soil medium, is characterized in terms of the target's scattering coefficient σ_0 . Thus σ_0 represents the link between the target properties and the scatterometer responses. For a given set of sensor parameters (wavelength, polarization, and incidence angle relative to 0°), σ_0 of bare soil is a function of the soil surface roughness and dielectric properties which depends on the moisture content. The variations of σ_0 with soil moisture, surface roughness, incidence angle, and observation frequency have been studied extensively in ground-based experiments conducted by scientists at the University of Kansas [Ulaby, 1974; Ulaby *et al.*, 1974; Batlivala and Ulaby, 1977] using a truck-mounted 1- to 18-GHz (30- to 1.6-cm wavelengths) active microwave system.

To understand the effects of incidence angle and surface roughness, consider the plots of σ_0 versus angle presented in Figure 12 for five fields with essentially the same moisture content but with considerably different surface roughness. At

ACTIVE MICROWAVE DEPENDENCE ON ROUGHNESS

DATA FROM UNIV. OF KANSAS

WET SOILS: 0.34 – 0.4 g/cc IN TOP cm

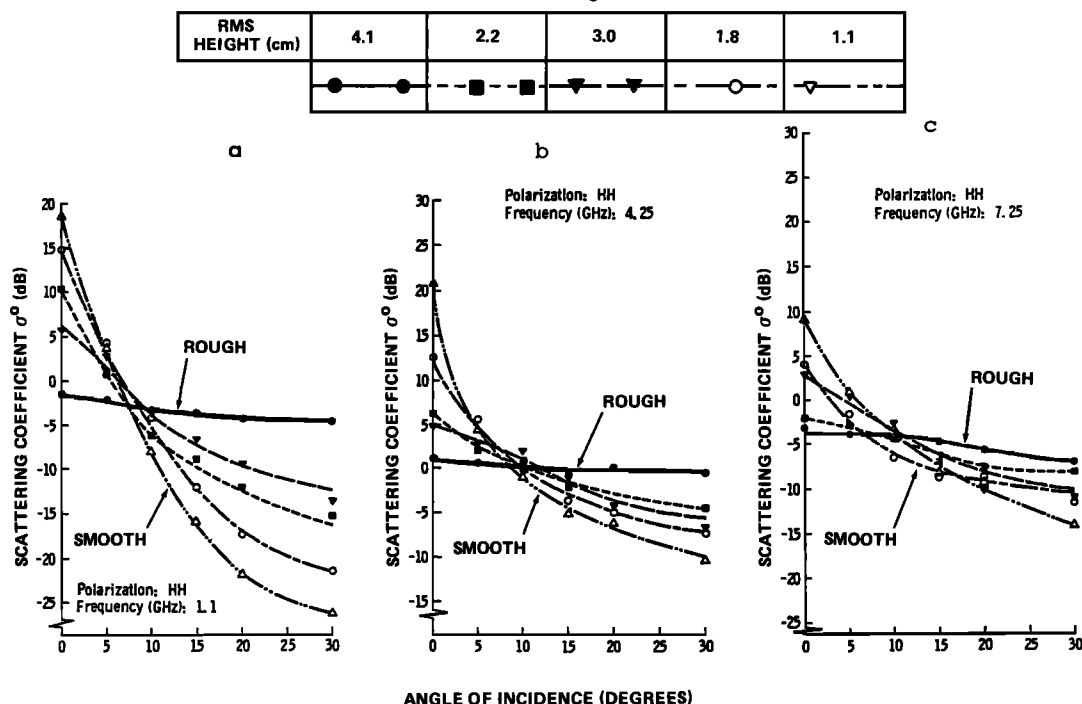


Fig. 12. Angular response of scattering coefficient for the five fields for high levels of moisture content at (a) L band (1.1 GHz); (b) C band (4.25 GHz); and (c) X band (7.25 GHz) for 1975 soil moisture experiment [Batilvala and Ulaby, 1977].

the longest wavelength (1.1 GHz, Figure 12a), σ_0 for the smoother fields is very sensitive to incidence angle near nadir, whereas for the rough field, σ_0 is almost independent of angle. At an angle of about 5°, the effects of roughness are minimized. As the wavelength decreases (Figures 12b and 12c) all the fields appear rougher, especially the smooth field, and as a result the five curves intersect at larger angles. At 4.25 GHz, they intersect at 10°, and it was this combination of angle and frequency that yielded the best sensitivity to soil moisture independent of roughness [Ulaby and Batilvala, 1976; Ulaby et al., 1978].

These experiments were performed in both 1974 and 1975. The first experiment was performed on a field with high clay content (62%), whereas for the second, the clay content was lower. Although both experiments provided the same specifications of the radar parameters for soil moisture sensing, i.e., frequency around 4.75 GHz and a 7°–17° nadir angle, the observed sensitivity of σ_0 to soil moisture in the 0- to 1-cm layer was different for the two experiments (Figure 13b). When the soil moisture content is expressed as a percent of field capacity to account for textural differences, the sensitivities became almost identical (Figure 13a) with a correlation of 0.84. This dependence on the percent of field capacity resembles that observed with the thermal inertia and passive microwave techniques. Similarly, the sampling depth for active microwave sensors also seems to be limited to the surface few centimeters of the soil for the wavelengths considered in the Kansas study [Ulaby et al., 1978].

Although no detailed airborne investigations have yet been reported on the active microwave response to the soil moisture content beneath a vegetation canopy, we observed the difference between dry soil and soil undergoing irrigation in 1971

while conducting radar observations of agricultural fields. During a flight by the NASA aircraft over a test site near Garden City, Kansas, Dickey et al. [1974], using a 13.3-GHz scatterometer, measured several fields, each of which (from aerial photography and field crew's reports) contained sections into which irrigation water was flowing and sections ready for irrigation but not yet wetted. For one of these fields, a corn field, the effect of the irrigation on the radar return seemed to produce a difference of about 7 dB at angles within 40° from nadir between the irrigated and nonirrigated sections. Since all ground conditions, except soil water content, were similar over the entire field, the differences in σ_0 can only be attributed to the effect of moisture.

The presence of a vegetation canopy over the soil surface reduces the sensitivity of the radar backscatter to soil moisture by (1) attenuating the signal as it travels through the canopy down to the soil and back and (2) contributing a backscatter component of its own. Moreover, both factors are, in general, a function of several canopy parameters, including plant shape, height and moisture content, and vegetation density. The effect of the vegetation cover on the radar response to soil moisture is to reduce the sensitivity by about 40% as compared with the response from bare soil when the two responses are compared as a function of percent of FC in the top 5 cm. The response from vegetation-covered soil represents data for several crops, i.e., wheat, corn, soybeans, and milo, covering a wide range of growth conditions [Ulaby et al., 1977].

There are many similarities in the two microwave approaches to soil moisture sensing, e.g., ability to penetrate clouds and moderate amounts of vegetation and the limitation to sampling only the surface 2–5 cm of the soil. The major difference is that of spatial resolution. For passive systems the

ACTIVE MICROWAVE DEPENDENCE ON SOIL MOISTURE

DATA FROM UNIV. OF KANSAS

ANGLE OF INCIDENCE: 10°

RMS HEIGHT VARIATION: 0.9 TO 4.3 cm

HORIZONTAL POLARIZATION

FREQUENCY: 4.25 & 4.75 GHz

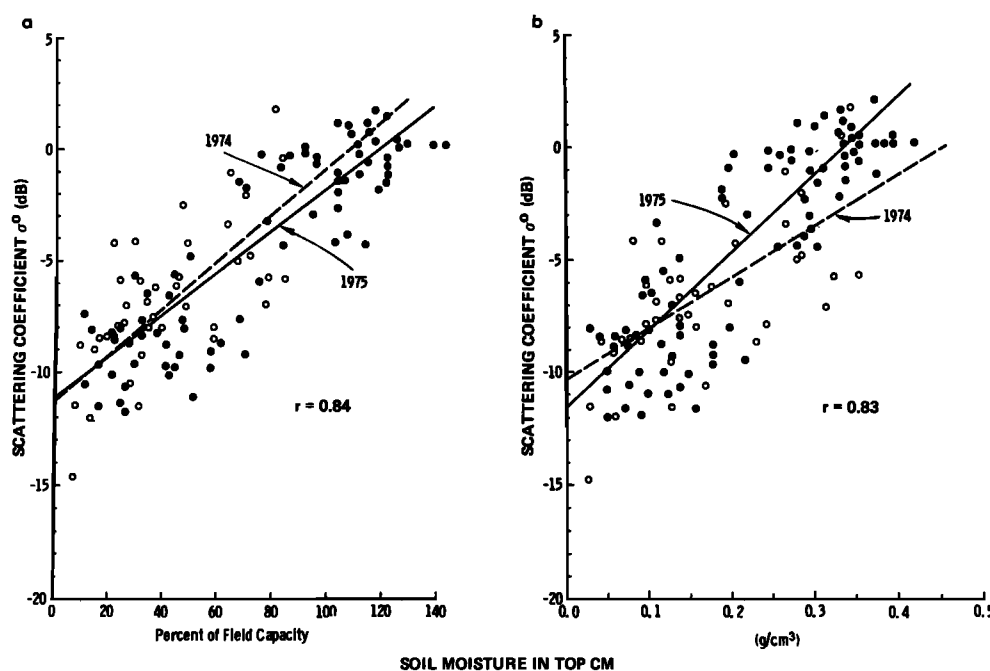


Fig. 13. Backscattering coefficient plotted as a function of soil moisture given (a) in percent of field capacity of top 1 cm and (b) volumetrically in top centimeter. The 1974 and 1975 bare soil experiment data are combined [Battivala and Ulaby, 1977].

resolution is limited by the size of the antenna, and this for practical reasons will be limited to 5–10 km. On the other hand, using the synthetic aperture techniques, spatial resolutions of 100 m or less are possible from space, e.g., 25-m resolution was obtained from the 18-cm wavelength synthetic aperture radar on the Seasat satellite. The problems with the latter approach are the difficulty in getting an absolute calibration for the SAR, the strong sensitivity to surface roughness and look angle, and the large amount of data that would have to be handled in any operational context.

The sensitivity to soil moisture of the three remote sensing approaches discussed here has been demonstrated in field or aircraft experiments and to a certain extent from spacecraft platforms. These experiments have also indicated some of the problems associated with each approach. These problems are summarized in Table 2, which compares the remote sensing approaches. Some of the limitations listed are of a fundamental nature, like cloud cover effects at thermal infrared, whereas others could be reduced or eliminated by more advanced technology, like larger antennas to improve radiometer resolution or the development of SAR calibration techniques. A fundamental limitation applies to all of the approaches: they seem to be sensing the moisture content in a layer only 5–10 cm thick at the surface. This limitation implies that remote sensing approaches will not be able to satisfy those applications which require knowledge of the moisture conditions in the root zone of the soil.

DISCUSSION

Most hydrologic, agricultural, and meteorological applications that could benefit from soil moisture measurements

have three general requirements: frequent observations, an estimate of moisture within the top 1–2 m of the soil, and, generally, a description of moisture variations over large study areas, i.e., a county or state. In preceding sections we have pointed out some of the advantages and disadvantages of the three approaches that can be used to collect soil moisture data. None of the individual techniques completely satisfies the requirements of the applications in a cost effective manner.

In situ methods can accurately estimate soil moisture throughout the profile. However, the information is reliable only at the point of measurement. To achieve a specified level of accuracy in estimating the areal average for most applications, a large number of point samples are required. For example, in a study of a large number of intensively sampled fields (20 or more samples per field), Bell *et al.* [1980] found that for 90% of the cases the standard deviation σ of soil moisture in the surface soil layers was less than 4%. Snedecor and Cochran [1967] presented the following relationship for estimating the required sample size:

$$n = 4 \left(\frac{\sigma}{L} \right)^2 \quad (6)$$

where n is the sample size and L is the desired level of accuracy. Using this equation and specifying $L = 2\%$ and $\sigma = 4\%$ [from Bell *et al.*, 1980], the required number of samples would be 16. Thus if a large number of individual field estimates are required, the costs can become prohibitive. In addition, the current state of the art methods generally require on-site observations, since reliable remote devices have not been developed. Thus a significant commitment of manpower is re-

TABLE 2. Comparison of Remote Sensing Approaches

Approach	Advantage	Limitation	Noise Source
Thermal infrared (10–12 m)	High resolution possible (400 m) Large swath Basic physics well understood	Cloud cover, limits frequency of coverage	Local meteorological condition Partial vegetative cover Surface topography
Passive microwave	Independence of atmosphere Moderate vegetation penetration	Poor spatial resolution (5–10 km at best) Interference from man-made radiation sources, limits operating wavelengths	Surface roughness Vegetative cover Soil temperature
Active microwave	Independence of atmosphere High resolution possible	Limited swath width Calibration of SAR	Surface roughness Surface slope Vegetative cover

quired. Soil water models provide fast answers, as well as predictions, of the soil water regime in a field or over a region. These models require large amounts of meteorological input data that can be difficult and costly to obtain. Model parameters and functions are also difficult to determine. In addition, various sources introduce error into the model predictions that can lead to significant deviations.

Remote sensing methods offer rapid data collection over large areas on a repetitive basis. Several questions still need to be answered concerning the dependence of sensor observations on soil moisture and other parameters, like vegetation. The major problems related to remote sensing seem to be the spatial resolution, depth of penetration, and cost. For the spatial resolution, the passive microwave sensors will measure the areal soil moisture over ground areas about 100 km² in size from satellite altitudes. Presently, we do not know how useful such a measurement would be. The limited depth of penetration of these systems is also a severe drawback. Even if such data were available, how could they be used?

These observations lead us to conclude that a cost effective soil moisture monitoring program must utilize all three of the approaches and not just one. Because each has its advantages and disadvantages, an integrated system should be designed to capitalize on the advantages and minimize the disadvantages. In situ methods, which we consider the most accurate, could be used sparingly in such a system for calibration and verification of models and remote sensing measurements. The other two approaches could be used to interpolate between the point measurements for estimating areal averages. Remotely sensed measurements could provide an estimate of the surface conditions, which could then be extrapolated via a model or used to update a model simulation. These remotely sensed measurements could also be processed rapidly to give us a quick look at the general condition over large areas.

In summary, we reviewed a wide variety of methods for estimating soil moisture in this paper. Each has its own advantages and disadvantages related to large-scale soil moisture monitoring. If a successful monitoring system is to be developed, it must incorporate all of these approaches. A very brief description of such an integrated system was presented; however, considerable research is needed to develop an optimal system.

Acknowledgment. The authors are grateful to the reviewers of this paper for the excellent review they gave and also for suggesting additional references, which we had overlooked. We believe that their efforts have improved the readability of the manuscript considerably.

REFERENCES

- Abele, G., H. L. McKim, and B. Brockett, Mass water balance during spray irrigation with wastewater at Deer Creek Lake land treatment site, *Rep. 79-29*, U.S. Army Corps of Eng., Hanover, N. H., 1979.
- Anderson, M. B., and T. P. Burt, Automatic monitoring of soil moisture conditions in a hillslope spur and hollow, *J. Hydrol.*, **33**, 27–36, 1977.
- Baier, W., and G. W. Robertson, A new versatile soil moisture budget, *Can. Plant Sci.*, **46**, 299–315, 1966.
- Basharinov, A. Ye, and H. M. Shutko, Determination of the moisture content of the earth's cover by superhigh frequency (microwave) radiometric methods: A review, *Radiotek. Electron.*, **23**, 1778–1791, 1978. (*Radio Eng. Electron. Phys.*, Engl. Transl., **23**, 1–12, 1978.)
- Batlivala, P., and F. T. Ulaby, Estimation of soil moisture with radar remote sensing, *Proceedings of the 11th International Symposium*, pp. 1557–1566, Remote Sensing of the Environ. and Environ. Res. Inst. of Mich., Ann Arbor, 1977.
- Baver, L. D., W. H. Gardner, and W. R. Gardner, *Soil Physics*, 498 pp., John Wiley, New York, 1972.
- Belcher, D. J., T. R. Cuykendall, and H. S. Sack, The measurement of soil moisture and density by neutron and gamma-ray scattering, *Tech. Dev. Rep. 127*, pp. 1–20, Civ. Aeron. Admin., Tech. Dev. and Eval. Center, Washington, D. C., 1950.
- Belcher, D. J., T. R. Cuykendall, and H. S. Sack, Nuclear meters for measuring soil density and moisture in thin surface layers, *Tech. Dev. Rep. 161*, pp. 1–8, Civ. Aeron. Admin., Tech. Dev. and Eval. Center, Washington, D. C., 1952.
- Bell, J. P., A new design principle for neutron soil moisture gauges: The 'Wallingford' neutron probe, *Soil Sci.*, **108**, 160–164, 1969.
- Bell, J. P., and C. W. O. Eccles, Neutron random counting error in terms of soil moisture for nonlinear calibration curves, *Soil Sci.*, **103**, 1–3, 1967.
- Bell, J. P., and J. S. G. McCulloch, Soil moisture estimation by the neutron scattering method in Britain, *J. Hydrol.*, **4**, 254–263, 1966.
- Bell, K. R., B. J. Blanchard, T. J. Schmugge, and M. W. Wiczak, Analysis of surface moisture variations within large field sites, *Water Resour. Res.*, **16**, 796, 1980.
- Bianchi, W. B., Measuring soil moisture tension changes, *Agr. Eng.*, **43**, 398–399, 1962.
- Black, C. A. (Ed.-in-Chief), *Methods of Soil Analyses*, part 1, *Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*, American Society of Agronomy, Madison, Wisc., 1965.
- Blinn, J. C., and J. G. Quade, Microwave properties of geological materials: Studies of penetration depth and moisture effects, 4th Annual Earth Resource Program Review, NASA Johnson Space Center, Houston, Tex., Jan. 17–21, 1972. (Available from Nat. Tech. Info. Serv., N72-29327, Springfield, Va.)
- Botcher, C. F., *Electric Polarization*, Elsevier, New York, 1952.
- Bouyoucos, G. J., and R. L. Cook, Humidity sensor permanent electric hygrometer for continuous measurement of the relative humidity of the air, *Soil Sci.*, **106**, 63–67, 1965.
- Bouyoucos, G. J., and A. Mick, A comparison of electrical resistance units for making continuous measurements of soil moisture under field conditions, *Plant Phys.*, **23**, 532, 1948.

- Bowman, D. H., and K. M. King, Determination of evapotranspiration using the neutron scattering method, *Can. Soil Sci.*, 45, 117-126, 1965.
- Brakensiek, D. L., H. B. Osborn, and W. J. Rawls, Field manual for research in agricultural hydrology, *Handbook 224*, U.S. Dep. of Agr., Washington, D. C., 1979.
- Bresler, E., Simultaneous transport of solutes and water under transient unsaturated flow conditions, *Water Resour. Res.*, 9, 975-986, 1973.
- Burke, W. J., T. Schmugge, and J. F. Paris, Comparison of 2.8- and 21-cm microwave radiometer observations over soils with emission model calculations, *J. Geophys. Res.*, 84, 287-294, 1979.
- Charney, J. W., J. Quirk, S. H. Chow, and J. Kornfield, A comparative study of the effects of albedo change on drought in semi arid regions, *Atmos. Sci.*, 34, 1366-1385, 1977.
- Choudhury, B., T. Schmugge, R. W. Newton, and A. Chang, Effect of surface roughness on the microwave emission from soils, *J. Geophys. Res.*, 84, 5699-5706, 1979.
- Churayev, N. V., and L. G. Rode, Measuring the moisture content of organic peat soils by the neutron method, *Pochvovedenie*, 1, 96-100, 1966.
- Cohen, O. P., A procedure for calibrating neutron moisture probes in the field, *Israel J. Agr. Res.*, 14, 169-178, 1964.
- Corey, J. C., S. F. Peterson, and M. A. Wakat, Measurement of attenuation of ^{137}Cs and ^{241}Am gamma rays for soil density and water content determinations, *Soil Sci. Soc. Amer. Proc.*, 35, 215-219, 1971.
- Davidson, J. M., J. W. Biggar, and D. R. Nielsen, Gamma radiation attenuation for measuring bulk density and transient water flow in porous media, *J. Geophys. Res.*, 68, 4477-4783, 1963.
- DePlater, C. V., A portable capacitance type soil moisture meter, *Soil Sci.*, 80, 391, 1955.
- Dickey, F. M., C. King, J. C. Holtzman, and R. K. Moore, Moisture dependency of radar backscatter from irrigated and non-irrigated fields at 400 MHz and 13.3 GHz, *IEEE Trans. Geosci. Elect.*, GE-12, 19-22, 1974.
- Dmitriyev, M. T., Gammascopic measurement of soil moisture, *Pochvovedenie*, 2, 208-217, 1966.
- Douglass, J. E., Volumetric calibration of neutron moisture probes, *Soil Sci. Soc. Amer. Proc.*, 30, 541-544, 1966.
- Eagleman, J., and W. Lin, Remote sensing of soil moisture by a 21-cm passive radiometer, *J. Geophys. Res.*, 81, 3660, 1976.
- Ehrler, W. L., Cotton leaf temperature as related to soil depletion and meteorological factors, *Agron. J.*, 65, 404-409, 1973.
- Ehrler, W. L., and C. H. M. van Bavel, Sorghum foliar responses to changes in soil water content, *Agron. J.*, 59, 243-246, 1967.
- Elrick, D. E., Soil water movement: Theory and applications, Proceedings of the First Canadian Conference on Micrometeorology, Part II, pp. 477-487, Dep. of Trans., Toronto, Ont., Canada, 1967.
- Elzeftawy, A., and R. S. Mansell, Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand, *Proc. Soil Sci. Soc. Amer. Proc.*, 39, 599-603, 1975.
- Feddes, R. A., P. Kowalik, K. Kolnska-Malinka, and H. Zaradny, Simulation of field water uptake by plants using a soil water dependent root extraction function, *J. Hydrol.*, 31, 13-26, 1976.
- Feddes, R. A., P. J. Kowalik, and H. Zaradny, *Simulation of Field Water Use and Crop Yield, Simulation Monogr.*, Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands, 1978.
- Ferguson, H., and W. Gardner, Water content measurement in soil columns by gamma ray absorption, *Soil Sci. Soc. Amer. Proc.*, 26, 11-18, 1962.
- Fleming, G., *Computer Simulation Techniques in Hydrology*, Elsevier, New York, 1975.
- Freeze, R. A., *Mathematical Models of Hillslope Hydrology*, in *Hillslope Hydrology*, edited by N. J. Kirkby, John Wiley, New York, 1978.
- Gagne, G., and J. Outwater, A portable electronic moisture detector for reinforced plastics, *Rep. 3219*, Univ. of Vt., Burlington, 1961.
- Gannon, P. T., Influence of earth surface and cloud properties on the south Florida sea breeze, *Tech. Rep. ERL 402-NHEML2*, Nat. Oceanic and Atmos. Admin., Silver Spring, Md., 1979.
- Gardner, R. P., and K. F. Roberts, Density and moisture content measurement by nuclear methods, *Natl. Coop. Highw. Res. Program Rep.*, 43, 1967.
- Gardner, W., and D. Kirkham, Determination of soil moisture by neutron scattering, *Soil Sci.*, 73, 391-401, 1952.
- Gardner, W., O. W. Israelsen, N. E. Edlefsen, and H. Conrad, The capillary potential function and its relation to irrigation practice, *Phys. Rev., Ser. 2*, 20, 196, 1922.
- Gardner, W., G. S. Campbell, and C. Calissendorff, Systematic and random errors in dual gamma energy soil bulk density and water content measurements, *Soil Sci. Soc. Amer. Proc.*, 36, 393-398, 1972.
- Gillham, R. S., A. Klute, and D. F. Heerman, Hydraulic properties of a porous-medium—Measurement and empirical representation, *Soil Sci. Soc. Amer. Proc.*, 40, 203-207, 1976.
- Glasstone, E., and M. C. Edlund, *The Elements of Nuclear Theory*, D. Van Nostrand, Princeton, N. J., 1957.
- Goit, J. B., P. H. Groenevelt, B. D. Kay, and J. G. P. Loch, The applicability of dual gamma scanning to freezing soils and the problems of stratification, *Soil Sci. Soc. Amer. Proc.*, 42, 858-863, 1976.
- Goldstein, R. A., J. B. Markin, and R. J. Luxmoore, Documentation of PROSPER, A model of atmosphere-soil-plant and water flow, *Rep. EDFB-IBP73-9*, Oak Ridge Nat. Lab., Oak Ridge, Tenn., 1974.
- Gurr, C. G., Use of gamma rays in measuring water content and permeability in unsaturated columns of soil, *Soil Sci.*, 94, 224-229, 1962.
- Hanks, R. J., A. Klute, and E. Bresler, A numeric method for estimating infiltration, redistribution, drainage, and evaporation of water from soil, *Water Resour. Res.*, 5, 1064-1069, 1969.
- Hanson, G. K., A dynamic continuous simulation model of water state and transportation in the soil-plant-atmosphere system, I, The model and its sensitivity, *Acta Agr. Scand.*, 25, 129-149, 1975.
- Hasted, T., *Aqueous Dielectrics*, Chapman Hall, London, 1974.
- Hildreth, W. W., Soil moisture modeling review, *Tech. Memo. N78-23646*, Nat. Tech. Inform. Serv., Springfield, Va., 1978.
- Hiler, E. A., and R. N. Clark, Stress day index to characterize effects of water stress on crop yields, *Trans. Amer. Soc. Agr. Eng.*, 14, 757-761, 1971.
- Hiler, E. A., T. A. Howell, R. B. Lewis, and R. P. Boos, Irrigation timing by the stress day index method, *Trans. Amer. Soc. Agr. Eng.*, 17, 393-398, 1974.
- Hillel, D., *Computer Simulation of Soil-Water Dynamics*, International Development Research Center, Ottawa, Canada, 1977.
- Hoekstra, P., and A. Delany, Dielectric properties of soils at UHF and microwave frequencies, *J. Geophys. Res.*, 79, 1699-1708, 1974.
- Holmes, J. W., Influence of bulk density of the soil on neutron moisture meter calibration, *Soil Sci.*, 102, 355-360, 1966.
- Holmes, R. M., and G. W. Robertson, A modulated soil moisture budget, *Mon. Weather Rev.*, 87, 101-105, 1959.
- Holtan, H. N., and M. Yaramanoglu, A user's manual for the University of Maryland version of the U.S. Department of Agriculture Hydrograph Laboratory model of watershed hydrology, *Rep. MP 918*, Agr. Exp. Sta., Univ. of Md., College Park, 1977.
- Holtan, H. N., G. J. Stiltner, W. H. Henson, and N. C. Lopez, US-DAHL-74 revised model of watershed hydrology, *Tech. Bull. 1518*, Agr. Res. Serv., U.S. Dep. of Agr., Washington, D. C., 1975.
- Idso, S. B., A note on some recently proposed mechanism of genesis of deserts, *Quart. J. Roy. Meteorol. Soc.*, 103, 369-370, 1977.
- Idso, S. B., and W. L. Ehrler, Estimating soil moisture in the root zone of crops: A technique adaptable to remote sensing, *Geophys. Res. Lett.*, 3, 23-25, 1976.
- Idso, S. B., R. D. Jackson, and R. J. Reginato, Detection of soil moisture by remote surveillance, *Amer. Sci.*, 63, 549-557, 1975a.
- Idso, S. B., R. D. Jackson, R. J. Reginato, B. A. Kimball, and F. S. Nakayama, The dependence of bare soil albedo on soil water content, *J. Appl. Meteorol.*, 14, 109-113, 1975b.
- Idso, S. B., T. J. Schmugge, R. D. Jackson, and R. J. Reginato, The utility of surface temperature measurements for the remote sensing of soil water status, *J. Geophys. Res.*, 80, 3044-3049, 1975c.
- Idso, S. B., R. D. Jackson, and R. J. Reginato, Remote-sensing of crop yields, *Science*, 196, 19-25, 1977.
- Idso, S. B., R. J. Reginato, J. L. Hatfield, G. K. Walker, R. D. Jackson, and P. J. Pinter, Jr., A generalization of the stress-degree-day concept of yield prediction to accommodate a diversity of crops, *Agr. Meteorol.*, 21, 205-211, 1980.
- Jackson, R. D., R. J. Reginato, and S. B. Idso, Wheat canopy temperature: A practical tool for evaluating water requirements, *Water Resour. Res.*, 13, 651-656, 1977.
- Jackson, R. D., J. Cihlar, J. E. Estes, J. L. Heilman, A. Kakle, E. T. Kannemasu, J. Millard, J. C. Price, and C. Wiegand, Soil moisture estimation using reflected solar and emitted thermal radiation,

- chap. 4, Soil Moisture Workshop, *NASA Conf. Publ. 2073*, 219 pp., Nat. Oceanic and Atmos. Admin., Greenbelt, Md., 1978.
- Jensen, M. E., J. L. Wright, and B. J. Pratt, Estimating soil moisture depletion from climate, crop, and soil data, *Trans. ASAE*, 14, 954-959, 1971.
- Kanemasu, E. T., L. R. Stone, and W. L. Powers, Evapotranspiration model tested for soybean and sorghum, *Agron. J.*, 68, 569-572, 1976.
- King, K. M., Soil moisture-instrumentation, measurement and general principles of network design, Soil Moisture, Proceedings of Hydrology Symposium 6, *Rep. 269285*, Can. Dep. of Energy, Mines, and Resour., Ottawa, 1967.
- Kirdiashev, K. P., A. A. Chukhlantsev, and A. M. Shutko, Microwave radiation of the earth's surface in the presence of vegetation cover, *Radiotek. Elektron.*, 24, 256-264, 1979. (*NASA Tech. Trans. TM-75469*, 1979.)
- Klute, A., and D. B. Peters, A recording tensiometer with a short response time, *Soil Sci. Soc. Amer. Proc.*, 26, 87-88, 1962.
- Lal, R., Concentration and size of gravel in relation to neutron moisture and density probe calibration, *Soil Sci.*, 127, 41-50, 1979.
- Lawless, G. P., N. A. MacGillivray, and P. R. Nixon, Soil moisture interface effects upon readings of neutron moisture probes, *Soil Sci. Soc. Amer. Proc.*, 27, 502, 1963.
- Layman, R., Soil moisture sensor, *Rep. DCPPL-SM-3*, Plasma Phys. Lab., Dartmouth Coll., Hanover, N. H., 1979.
- Lemon, E. R., D. W. Stewart, R. W. Shawcroft, and S. E. Jensen, Experiments in predicting evapotranspiration by simulation with a soil-plant-atmosphere model (SPAM), in *Field Soil Water Regime*, edited by R. R. Bruce et al., Soil Science Society of America, Madison, Wisc., 1973.
- Long, I. F., and B. K. French, Measurement of soil moisture in the field by neutron moderation, *J. Soil Sci.*, 18, 149-166, 1967.
- Luebs, R. E., M. J. Brown, and A. E. Laag, Determining water content of different soils by the neutron method, *Soil Sci.*, 106, 207-212, 1968.
- Lundien, J. R., Terrain analysis by electromagnetic means, *Tech. Rep. 3-693*, Rep. 5, 85 pp., U.S. Army Waterways Exp. Sta., Vicksburg, Miss., 1971.
- Makkink, G. F., and H. D. J. vanHeemst, *Simulation of the Water Balance of Arable Land Pastures*, Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands, 1975.
- Mansell, R. S., L. C. Hammond, and R. M. McCurdy, Coincidence and interference corrections for dual-energy gamma ray measurements of soil density and water content, *Soil Sci. Soc. Amer. Proc.*, 37, 500-504, 1973.
- Marais, P. C., and W. B. De V. Smit, Determination of soil moisture with a neutron meter, *Ind. Rev. Africa*, p. 78, 1958.
- Marais, P. C., and W. B. De V. Smit, Effect of bulk density and of hydrogen in forms other than free water on the calibration curve of the neutron moisture meter, *S. Afr. J. Agr. Sci.*, 5, 225-238, 1962.
- Mather, J. K., *Climatology Fundamentals and Application*, pp. 151-153, McGraw-Hill, New York, 1974.
- McCauley, G. N., and J. F. Stone, Source-detector geometry effect on neutron probe calibration, *Soil Sci. Soc. Amer. Proc.*, 36, 246-250, 1972.
- McFarland, M. H., The correlation of skylab L-band brightness temperatures with antecedent precipitation, Proceedings of the Conference on Hydrometeorology, pp. 60-65, Amer. Meteorol. Soc., Boston, Mass., 1976.
- McKim, H. L., D. M. Anderson, R. L. Berg, and R. Tuinstra, Near real time hydrologic data acquisition utilizing the Landsat system, Proceedings of the Conference on Soil-Water Problems in Cold Regions, pp. 200-211, AGU, Washington, D. C., 1975.
- McKim, H. L., R. L. Bert, R. W. McGaw, R. T. Atkins, and J. Ingersoll, Development of a remote-reading tensiometer/transducer system for use in subfreezing temperatures, Proceedings of the Second Conference on Soil-Water Problems in Cold Regions, pp. 31-45, Edmonton, Alberta, Canada, 1976.
- Millard, J. P., R. D. Jackson, R. C. Goettelman, R. J. Reginato, S. B. Idso, and R. L. LaPado, Airborne monitoring of crop canopy temperatures for irrigation scheduling and yield predictions, Proceedings of the 11th International Symposium on Remote Sensing of the Environment, pp. 1453-1461, Environ. Res. of Mich., Ann Arbor, 1977.
- Millard, J. P., R. B. Jackson, R. C. Goettelman, R. J. Reginato, and S. B. Idso, Crop water-stress assessment using an airborne thermal scanner, *Photogramm. Eng. Remote Sensing*, 44, 77-85, 1978.
- Mortier, P., M. DeBoodt, W. Donsercoer, and L. DeLeenheer, The resolution of the neutron scattering method for soil moisture determination, *Trans. Int. Congr. Soil Sci. 7th*, 1, 321-329, 1960.
- Nace, R. L., Water of the world, *Nat. History*, 73, 10-19, 1964.
- Neuman, S. P., R. A. Feddes, and E. Bresler, Finite element analysis of two-dimensional flow in soils considering water uptake by roots, I, Theory, *Soil Sci. Soc. Amer. Proc.*, 39, 224-230, 1975.
- Newton, R. W., Microwave remote sensing and its application to soil moisture detection, *Tech. Rep. RSC-81*, 500 pp., Remote Sensing Center, Tex. A&M Univ., College Station, 1977.
- Nimah, M. N., and R. J. Hanks, Model for estimating soil water, plant and atmosphere interrelations, I, Description and sensitivity, *Soil Sci. Soc. Amer. Proc.*, 37, 522-527, 1973.
- Njoku, E. G., and J. A. Kong, Theory for passive microwave remote sensing of near-surface soil moisture, *J. Geophys. Res.*, 82, 3108-3118, 1977.
- Nofziger, D. L., Errors in gamma-ray measurements of water content and bulk density in nonuniform soils, *Soil Sci. Soc. Amer. Proc.*, 42, 845-850, 1978.
- Olgaard, P. L., On the theory of the neutronic method measuring the water content in soil, *Riso Rep. 97*, pp. 1-74, Danish Atomic Energy Commission, Roskilde, Denmark, 1965.
- Olgaard, P. L., and V. Haahr, On the sensitivity of subsurface neutron moisture gauges to variations in bulk density, *Soil Sci.*, 105, 62-64, 1968.
- Peck, E. L., Catchment modeling and initial parameter estimation for the National Weather Service river forecast system, *NOAA Tech. Memo. NWS Hydro-31*, Nat. Weather Serv., Silver Spring, Md., 1976.
- Phene, C., G. J. Hoffman, and S. L. Rawlins, Measuring soil matric potential in situ by sensing heat dissipation within a porous body, I, Theory and sensor construction, *Soil Sci. Soc. Amer. Proc.*, 35, 27-33, 1971.
- Phene, C., G. J. Hoffman, and R. S. Austin, Controlling automated irrigation with soil matric potential sensor, *Trans. ASAE*, 16, 773-776, 1973.
- Pikul, M. F., R. L. Street, and I. Remson, A numerical model based on coupled one-dimensional Richards and Boussinesq equations, *Water Resour. Res.*, 10, 295-302, 1974.
- Poe, G. A., A. Stogryn, and A. T. Edgerton, Determination of soil moisture content using microwave radiometry, *Final Rep. 1684 FR-1*, 169 pp., Aerojet-General Corp., El Monte, Calif., 1971.
- Rawls, W. J., and L. E. Asmussen, Neutron probe field calibration for soils in the Georgia coastal plain, *Soil Sci.*, 110, 262-265, 1973.
- Reginato, R. J., S. B. Idso, J. F. Vedder, R. D. Jackson, M. B. Blanchard, and R. Goettelman, Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements, *J. Geophys. Res.*, 81, 1617-1620, 1976.
- Reginato, R. J., S. B. Idso, and R. D. Jackson, Estimating forage crop production: A technique adaptable to remote sensing, *Remote Sensing Environ.*, 7, 77-80, 1978.
- Remson, I., G. M. Hornberger, and F. J. Molz, *Numerical Methods in Subsurface Hydrology*, John Wiley, New York, 1971.
- Reynolds, S. G., The gravimetric method of soil moisture determination, I, A study of equipment and methodological problems, *J. Hydrol.*, 11, 258-273, 1970a.
- Reynolds, S. G., The gravimetric method of soil moisture determination, III, An examination of factors influencing soil moisture variability, *J. Hydrol.*, 11, 288-300, 1970b.
- Rice, R., A fast-response, field tensiometer system, *Trans. Amer. Soc. Agr. Eng.*, 12, 48-50, 1969.
- Richards, L. A., Methods of measuring soil moisture tension, *Soil Sci.*, 68, 95-112, 1949.
- Richards, L. A., and W. Gardner, Tensiometers for measuring the capillary tension of soil water, *J. Amer. Soc. Agron.*, 28, 352-358, 1936.
- Richards, S. J., Soil suction measurements with tensiometers in methods of soil analysis, *Agronomy*, 9, 153-163, 1965.
- Ritchie, J. T., Model for predicting evaporation from a row crop with incomplete cover, *Water Resour. Res.*, 8, 1204-1213, 1972.
- Roth, M., How to measure moisture in solids, *Chem. Eng.*, 73, 83-88, 1966.
- Saxton, K. E., and J. L. McGuinness, Evapotranspiration, in *Hydrologic Modeling of Small Watersheds*, edited by C. T. Haan et al.,

- American Society of Agricultural Engineers, St. Joseph, Mich., in press, 1979.
- Saxton, K. E., H. P. Johnson, and R. H. Shaw, Modeling evapotranspiration and soil moisture, *Trans. ASAE*, 17, 673-677, 1974.
- Schanda, E., R. Hofer, D. Wyssen, A. Musy, D. Meylan, C. Morzier, and W. Good, Soil moisture determination and snow classification with microwave radiometry, Proceedings of the 12th International Symposium on Remote Sensing of the Environment, Environ. Res. of Mich., Ann Arbor, 1978.
- Schmugge, T. J., Remote sensing of surface soil moisture, *J. Appl. Meteorol.*, 17, 1549, 1978.
- Schmugge, T. J., P. Gloersen, T. Wilheit, and F. Geiger, Remote sensing of soil moisture with microwave radiometers, *J. Geophys. Res.*, 79, 317-323, 1974.
- Schmugge, T. J., J. M. Meneely, A. Rango, and R. Neff, Satellite microwave observations of soil moisture variations, *Water Resour. Bull.*, 13, 265, 1977.
- Schmugge, T. J., B. Blanchard, A. Anderson, and J. Wang, Soil moisture sensing with aircraft observations of the diurnal range of surface temperature, *Water Resour. Bull.*, 14, 169-178, 1978.
- Selig, E. T., D. C. Wobschall, S. Mansukhani, and A. Motiwala, Capacitance sensor for soil moisture measurement, *Record* 532, p. 64, Trans. Res. Board, Washington, D. C., 1975.
- Shaw, R. H., Estimating soil moisture under corn, *Res. Bull.* 520, Iowa State Univ. of Agr. and Home Econ. Exp. Sta., Ames, 1963.
- Silva, L. F., F. V. Schultz, and J. T. Zalusky, Electrical methods of determining soil moisture content, *LARS Inform. Note* 112174, Purdue Univ., Lafayette, Ind., 1974.
- Singh, V. P., Soil moisture models (review), paper presented at the Annual Meeting, Amer. Soc. of Agr. Eng., Pullman, Wash., 1971.
- Slack, D. C., C. T. Haan, and L. G. Wells, Modeling soil water movement into plant roots, *Trans. ASAE*, 20, 919-927, 1977.
- Snedecor, G. W., and W. G. Cochran, *Statistical Methods*, 593 pp., 6th ed., Iowa State University Press, Ames, 1967.
- Soane, B. D., Dual energy gamma ray transmission for coincidence measurements of water content and dry bulk density of soil, *Nature*, 214, 1273-1274, 1967.
- Speckhart, F. H., and W. L. Green, *A Guide to Using CSMP—The Continuous System Modeling Program*, Prentice-Hall, Englewood Cliffs, N. J., 1976.
- Stewart, G. L., and S. A. Taylor, Field experiments with the neutron scattering method of measuring soil moisture, *Soil Sci.*, 83, 151-158, 1957.
- Stolzy, L. H., and G. A. Cahoon, A field calibrated portable neutron rate meter for measuring soil moisture in citrus orchards, *Soil Sci. Soc. Amer. Proc.*, 21, 571-575, 1957.
- Stone, J. F., R. H. Shaw, and D. Kirkham, Statistical parameters and reproducibility of the neutron method of measuring soil moisture, *Soil Sci. Soc. Amer. Proc.*, 24, 435-438, 1966.
- Stuff, R. G., and R. F. Dale, A soil moisture budget model accounting for shallow water table influences, *Soil Sci. Soc. Amer. Proc.*, 42, 637-643, 1978.
- Thomas, A., In situ measurement of moisture in soil and similar substances by fringe capacitance, *J. Sci. Inst.*, 43, 996, 1963.
- Ulaby, F. T., Radar measurement of soil moisture content, *IEEE Trans. Antennas Propagat.*, AP-22, 257-265, 1974.
- Ulaby, F. T., and P. P. Batlivala, Optimum radar parameters for mapping soil moisture, *IEEE Trans. Geosci. Elect.*, GS-14, 81-93, 1976.
- Ulaby, F. T., J. Cihlar, and R. K. Moore, Active microwave measurements of soil water content, *Remote Sensing Environ.*, 3, 185-203, 1974.
- Ulaby, F. T., G. A. Bradley, M. C. Dobson, and J. E. Bare, Analysis of the active microwave response to soil moisture, part II, Vegetation-Covered Ground, *RSL Tech. Rep.* 264-19, Univ. of Kans., Center for Res., Inc., Lawrence, 1977.
- Ulaby, F. T., P. P. Batlivala, and M. C. Dobson, Microwave backscatter dependence on surface roughness, soil moisture and soil texture, I, Bare soil, *IEEE Trans. Geosci. Elect.*, GS-16, 286-295, 1978.
- Ursic, S. J., Improved standards for neutron soil water meters, *Soil Sci.*, 104, 323-325, 1967.
- Vachaud, G., J. M. Royer, and J. D. Cooper, Comparison of methods of calibration of a neutron probe by gravimetry on neutron-capture model, *J. Hydrol.*, 34, 343-356, 1977.
- van Bavel, C. H. M., Calibration and characteristics of two neutron moisture probes, *Soil Sci. Soc. Amer. Proc.*, 25, 329-334, 1961.
- van Bavel, C. H. M., Accuracy and source strength in soil moisture neutron probes, *Soil Sci. Soc. Amer. Proc.*, 26, 405, 1962.
- van Bavel, C. H. M., and J. Ahmed, Dynamic simulation of water depletion in the root zone, *Ecol. Modeling*, 2, 189-212, 1976.
- van Bavel, C. H. M., and G. B. Stirk, Soil water measurement with an Am^{241} -Be neutron source and an application to evapotrimetry, *J. Hydrol.*, 5, 40-60, 1967.
- van Bavel, C. H. M., N. Underwood, and R. W. Swanson, Soil moisture measurement by neutron moderation, *Soil Sci.*, 82, 29-41, 1956.
- Visvalingam, M., and J. D. Tandy, The neutron method for measuring soil moisture content—A review, *J. Soil Sci.*, 243, 499-511, 1972.
- Walker, G. K., and J. L. Hatfield, Test of the stress degree day concept using multiple planting dates of red kidney beans, *Agron. J.*, 71, 967-971, 1979.
- Walker, J., and P. R. Rowntree, The effect of soil moisture on circulation and rainfall in a tropical model, *Quart. J. Roy. Meteorol. Soc.*, 103, 29-46, 1977.
- Walsh, J., D. McQueeney, R. Layman, and H. McKim, Development of a simplified method for field monitoring of soil moisture, Proceedings of 2nd Colloquium on Planetary Water and Polar Processes, U.S. Army Cold Regions Res. and Eng. Lab., Hanover, N. H., 1979.
- Wang, J., T. J. Schmugge, and D. Williams, Dielectric constants of soils at microwave frequencies, II, *Tech. Note* 1238, Nat. Oceanic and Atmos. Admin., Greenbelt, Md., 1978.
- Warrick, A. W., J. W. Biggar, and D. R. Nielsen, Simultaneous solute and water transfer for an unsaturated soil, *Water Resour. Res.*, 7, 1216-1225, 1971.
- Watson, K. K., A recording field tensiometer with rapid response characteristics, *Water Resour. Res.*, 5, 33-39, 1967.
- Wexler, A., *Humidity and Moisture*, vol. 5, pp. 1-14, Reinhold, New York, 1965.
- Wiegand, C. L., and L. N. Namken, Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperatures, *Agron. J.*, 58, 582-586, 1966.
- Wilheit, T. T., Radiative transfer in a plane stratified dielectric, *IEEE Trans. Geosci. Elect.*, GE-16, 138-143, 1978.
- Wilson, R. G., Methods of measuring soil moisture, The Secretariat, Can. Nat. Comm. for the Int. Hydrol. Decade, Ottawa, Canada, 1971.
- Wobschall, D., A frequency shift dielectric soil moisture sensor, *IEEE Trans. Geosci. Elect.*, GE-16, 112-118, 1978.
- Youker, R. E., and W. M. Edwards, Simplified budgeting of plow layer moisture under meadow, *Rep. ARS 41-154*, Agr. Res. Serv., U.S. Dep. of Agr., Washington, D. C., 1969.
- Zuber, A., and J. F. Cameron, Neutron soil moisture gauges, *Atomic Energy Rev.*, 4, 143-147, 1966.

(Received November 21, 1979;
revised March 18, 1980;
accepted April 30, 1980.)