General Comments. A variety of instruments and methods exist for determining soil moisture (Stephens, 1995; Mead, 1998; Orloff et al., 2003). The most direct method, of course, is the gravimetric method whereby the water content of a known volume of soil is measured in the laboratory before and after drying. However determining the porosity of unconsolidated field samples is not trivial, and prone to errors unless strict protocols are followed in the field. In-situ determinations of soil water content are most frequently made with resistance block sensors, tensiometers, lysimeters, psychrometers/hygrometers, heat dissipation sensors, neutron probes, time domain reflectometers (TDR), frequency domain reflectometers (FDR) and capacitance probes. The latter three methods are electromagnetic techniques employing the dielectric properties of water at radio frequencies. Ground penetrating radar (GPR) falls into the latter category as well, and in the last two decades has found increasing applications to hydrological studies, and especially in recent years to those investigations related to agriculture and crop management. In this report we employ GPR to measure antecedent soil moisture and its relation to short term stormflow runoff. This document is an introduction to commonly-used, readily available sensors for monitoring soil moisture, in some cases continuously, in others periodically.

Details on Sensors and Sensor Applications

Resistance Block Sensors. Also known generically as gypsum block or Watermark sensors, soil moisture is determined by measuring the resistance between two electrodes imbedded in the sensor (left panel) using a calibrated portable meter (right panel).
We currently plan to employ Watermark blocks having a range -10 cb to -200 cb. These are ideal for sandy and sandy-loam soil types.

**Capacitance Probes.** The Theta Probe measures soil moisture content using radio frequency capacitance measurements, similar to TDR in that the dielectric properties of the material are used. According to Robinson et al. (1998), capacitance probes are a fast, safe (compared to neutron activation methods) and inexpensive means of measuring the relative permittivity of soils, which can then be used to estimate soil water content. The Theta Probe is close to an industry standard,

![Figure 2. Examples of capacitance probes used for soil moisture studies (Theta Probe ML2).](image)

Capacitance probes can be used in two configurations. In one mode, they can be arranged to continuously monitor a vertical profile of soil moisture at a representative field site. In the second mode, a Theta Probe at the base of the instrument in Figure 3 shown to the right (the Dynamax TH₂O) can be used to horizontally profile soil moisture within 2-3” of the surface during routine resurveys of the field site.

![Figure 3. The Dynamax TH₂O profiling probe will be used to horizontally profile soil moisture during routine periodic checks of each field site.](image)
**Time Domain Reflectometry (TDR).**
This technique (Figure 5) sends an electromagnetic pulse guided along 2 or 3 parallel conducting rods set in the earth (O'Connor and Dowding, 1999). For soil moisture studies, the object is to determine the total time it takes for the impulse to travel from the source, to the reflecting end of the waveguide, back to the source. This travel time is related to the effective velocity of the medium, which in turn depends on the dielectric properties, hence the water content, of the soil using empirical relations (e.g. Topp et al., 1980).

**Tensiometers.** These are water-filled tubes with hollow ceramic tips attached on one end and a vacuum gauge and airtight seal on the other end. The practical operating range for tensiometers is normally from 0 to 75 centibars. The upper limit of 75 cb corresponds to as much as 90% depletion of total available water for the coarse-textured soils, but is only about 30% depletion for silt loam, clay loams, and other fine-textured soils.

**Heat Dissipation Soil Moisture Sensors.** The Campbell Scientific 229-L Water Matric Potential Sensor measures soil water potential over the expanded range from -0.1 to -10 bars (or -10 to -1000 centibars). The sensor consists of a heating element and thermocouple emplaced in
epoxy in a hypodermic needle, which is encased in a porous ceramic matrix. A Current Excitation Module applies a 50 mA current to the 229’s heating element, and the 229 thermocouple measures the temperature rise which varies according to the amount of water in the porous ceramic matrix. While quite accurate, and functional over an impressively wide range of matric potentials, users must individually calibrate each of their 229 sensors for the soil type in which the sensors will reside.

Figure 6. Campbell Scientific heat dissipation probe for wide-range measurements of matric potential. Right panel: Four channel current excitation unit. In addition, a data logger is required.
**Ground Penetrating Radar (GPR: The “Other” Radio Frequency Method).** For some field applications, GPR offers several advantages over other soil sensing methods (James Doolittle, USDA, personal communication, 2002). First, GPR is non-invasive. Second, GPR samples over larger effective volumes than other common techniques, and to greater depths. Finally, GPR is more mobile, and in principle more rapidly deployed.

Figure 7. 200 MHz GPR field system showing transmitter (Tx) and receiver (Rx) deployed to measure soil properties.

Two field procedures by which ground penetrating radar (GPR) can provide subsurface information are illustrated in Figure 8. One procedure (Panel a) uses the direct ground phase; the other (Panel b) uses a reflected phase from an interface in the subsurface. Both methods have been used for agricultural applications (and supported by the USDA). In practice we have found that a combined approach (even allowing for ground refractions) is usually best. For some applications it is important to precise calibrate and compare several of the above
procedures under very tight controls. For example, one might want to employ GPR in conjunction with more traditional techniques described above to determine the soil moisture characteristics under field conditions.

Figure 9 is a simple regression of GPR field velocity against gravimetric soil moisture determined in the lab under various soil conditions. The quality of the correlation coefficient between the two independent data types in Figure 9 underscores the precision of the GPR method to provide “large-volume” estimates (typically 10³ cubic yards) of soil moisture over large volumes of the subsurface.

**Lab Measurements on Field Samples.** For quantitatively interpreting field data, representative soil from each field site should undergo the standard tests summarized in Table 1.

**Table 1. Selected categories of soil properties to measure in the lab*.**

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Hydraulic properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size distribution</td>
<td>Retentivity versus Specific Yield</td>
</tr>
<tr>
<td>Dry density</td>
<td>(short term and long term)</td>
</tr>
<tr>
<td>Porosity</td>
<td>Drainage rate</td>
</tr>
<tr>
<td>Gravimetric soil water content (SWC: θ as Vol/Vol)</td>
<td>Field capacity</td>
</tr>
<tr>
<td></td>
<td>Hydraulic conductivity (saturated)</td>
</tr>
<tr>
<td></td>
<td>Matric potential (ψ)</td>
</tr>
<tr>
<td></td>
<td>Infiltration capacity</td>
</tr>
<tr>
<td></td>
<td>Infiltration rate</td>
</tr>
<tr>
<td></td>
<td>Calibrate ψ(θ) field conditions</td>
</tr>
</tbody>
</table>

*Note: In addition to the measurements of the sample properties, it is recommended to calibrate each field sensor for the particular soil type it will be used to monitor.*

**Summary of Sensor Technology.** Resistance blocks respond over a wider range of operationally-relevant soil moistures (0 to -200 centibars) as compared to tensiometers (0 to -90 centibars), while being more suitable for dry conditions (Hanson, 1999; Lampinen, 2004). Thermal dissipation probes are more expensive and more complicated to use, but have a
significantly broader range of matric potentials (-10 to -1000 centibars), although they need to be calibrated for the specific. The advantage of capacitance probes is that they are relatively accurate in allowing one to directly determine the soil water content over a range of conditions usually appropriate for irrigation monitoring, and, at least for the Theta Probe design, seem to be relatively insensitive to soil salinity effects. A drawback of gypsum blocks is that their response to changes in soil water content tends to lag tensiometers and capacitance probes over the range at which the latter two sensors operate. On the other hand, tensiometers have problems with leaks and desaturation of porous cups in soil that becomes too dry between irrigations. Ley et al. (2002) have concluded, however, that when operated properly, tensiometers are significantly more accurate than resistance block methods. In spite of differing preferences which often depend on local soil conditions, professionals agree that each of these devices has its unique attributes, complementing the others. Several are inexpensive and easy to install and operate.

Example of the Field Deployment of Sensors

As a prototype example of how a systematic monitoring program might be established at a field site, Figure 10 illustrates how soil moisture, complemented by lab gravimetric analyses from cores, and a continuously recording tipping bucket rain gage, could be regularly monitored in the following modes: (a) Continuously logged capacitance probes in vertical arrays of 3 units at each field site; (b) A series of step-and-poke stations along selected profiles at each site using both the 1502a TDR Tektronix cable tester, and the capacitance insertion probe DeltaTheta TH2O; (c) A “nested” set of 3 tensiometers; (d) a nested set of 4 vertical heat dissipation sensors to be hosted by the principal field site (these units are relatively expensive to deploy at all sites); (e) a nested set of 3 to 4 resistance block soil moisture sensors in a vertical array, complemented at each site by 3 additional units horizontally deployed at a uniform depth of 18 inches. The sequence of operations involving the in-situ sensors illustrated in Figure 10 will be interrogated and down-loaded at weekly intervals during the active growing season, with intervals increasing to 2 weeks, then 4 weeks during the dormant season.
Ground Penetrating Radar (GPR) Component. The procedure for GPR-CMP monitoring involves a series of overlapping, variable offset CMP "soundings" (or an equivalent set of “gathers”), using transmitter (Tx) – receiver (Rx) offsets from 1 to 10 m, at step-sizes of 0.2 m or less. In addition, a conventional GPR profile at a fixed Tx-Rx separation of 2 m (also known as a “common offset” GPR measurement) might be acquired during each repeat survey. For planning purposes, the GPR profile might use a step-size of 0.2 m, and a frequency of 200 MHz. Following the initial site characterization, a round of GPR data might be collected monthly on a regular basis, and additionally on an opportunistic or “as-needed” basis, such as before and after significant precipitation "events".
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