SOIL WATER MONITORING & MEASUREMENT

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INTRODUCTION

Efficient irrigation requires a systematic water management program. Such a program answers the questions of when to irrigate, how much water to apply during irrigation and how best to apply the water (rate of application, method, etc.). A key component of good on-farm irrigation water management is the routine monitoring and measurement of soil water. Soil water must be maintained between desirable upper and lower limits of availability to the plant. This requires accounting for soil evaporation, crop water use, irrigation, drainage and rainfall. Accurate assessment of the soil water-holding characteristics along with periodic soil water monitoring and measurement are required. Monitoring and measuring soil water available to irrigated crops is part of an integrated management package and helps avoid: 1) the economic losses due to effects of both underirrigation and overirrigation on crop yields and crop quality, and 2) the environmentally costly effects of overirrigation: wasted water and energy, the leaching of nutrients or agricultural chemicals into groundwater supplies and degradation of surface water supplies by sediment-laden irrigation water runoff.

This Extension publication provides information on how to determine soil water content. Soil and crop characteristics which determine the size of the plant available soil water reservoir are discussed. This is followed by a review of several tools and techniques that can be used to monitor or directly measure soil water. Among the most common approaches are:

1) soil feel and appearance

2) gravimetric sampling

3) tensiometers

4) porous blocks

5) neutron scattering

Newer methods which measure the dielectric constant of the soil water medium and then estimate soil water content have recently become commercially available. These methods include time domain reflectometry, frequency domain reflectometry and soil capacitance measurements.

Questions often arise about which technique is best, which is most accurate, how different methods compare under the same situation (irrigation practice, soil type, etc.), what are the relative costs to purchase and operate the different methods, etc. Several tools and techniques available to growers for monitoring and measuring available soil water are evaluated in this publication with these questions in mind.

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SECTION 1

IMPORTANT SOIL AND CROP CHARACTERISTICS IN IRRIGATION MANAGEMENT

Information on soil and crop characteristics is required to determine plant available soil water. Texture, structure, layering, water-holding capacity, and depth are important soil characteristics. Crop rooting pattern, the depth of rooting, density of roots with depth, and crop susceptibility to water stress are important crop characteristics.

Soil Characteristics

Physically, soil is made up of soil particles, air spaces which may be partially or fully filled with water, organic matter, and living organisms. Soils are grouped into **textural classes** depending upon the relative proportion of sand, silt, and clay composing them. Sand, silt, and clay are the basic particle size categories used for determining soil texture. The percentage of each within a given sample of soil can be determined through mechanical analyses which separate the soil particles into the relative size ranges. U.S. Dept. of Agriculture (USDA) textural classes are broken into particle size ranges as follows:

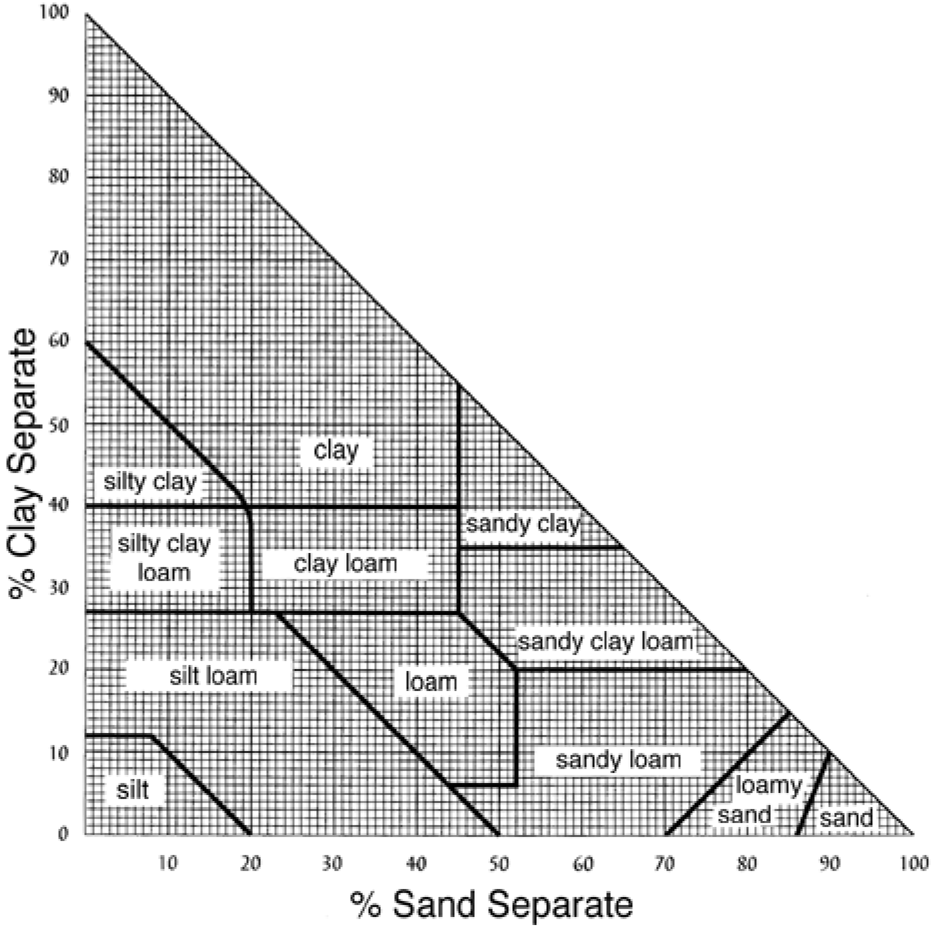
Very coarse sand	1.0 to 2.0 mm
Coarse sand	0.5 to 1.0 mm
Medium sand	0.25 to 0.5 mm
Fine sand	0.1 to 0.25 mm
Very fine sand	0.05 to 0.1 mm
Silt	0.002 to 0.05 mm
Clay	less than 0.002 mm

With the percentages of sand, silt and clay, a textural triangle can then be used to classify the soil in a textural group (see Figure 1). Coarse-textured soils have higher percentages of sand particles, while finer-textured soils have greater amounts of the smaller silt and clay particles.

Soil structure is determined by the arrangement of soil particles relative to each other. Natural and man-made physical and chemical factors affect soil structure over time. Soil structure is important in developing large pores (macropores) that are essential for rapid movement of water and air through soils. One of the most important factors affecting the quantity of water or air a soil can hold is its **void space** or its **porosity**. **Soil compaction** due to land shaping, tillage operations, traffic, etc. reduces porosity by forcing particles closer together. Compaction also collapses macropores and may result in a physical barrier limiting root growth and penetration in the soil. Sandy soils have large pores due to the large individual particle sizes but smaller total porosity overall compared with finer-textured soils. Finer-textured soils have small pore sizes and larger total porosity.

Thus, because of pore size and total porosity differences, coarse-textured soils (like sands) allow water to infiltrate at greater rates but have less space to store water compared with finer-textured soils (loams, silt loams, etc.).

Figure 1. Soil textural triangle. fig 1 pdf



Soil compaction causes the **soil bulk density** to increase with the accompanying decrease in total porosity. Bulk density is the oven dry weight per unit volume of soil (void space included) and is expressed in units of lbs/ft^3 or grams/cm^3. Particle density of a soil is the oven dry weight of soil per unit volume of soil particles only (void space is excluded). An average value of particle density for most mineral soils is 2.65 grams/cm^3. Porosity, bulk density and particle density of a soil are related by the following:

$$\text{Porosity (\%)} = \left(1 - \frac{\text{bulk density}}{\quad}\right) \times 100$$

particle density

Coarse-textured soils have a greater bulk density than finer-textured soils, meaning they weigh more per unit volume than the finer soils. An older concept of finer-textured soils being referred to as heavy soils and coarse-textured soils as light soils does not pertain to bulk density, but rather to the draft requirements of pulling an implement such as a moldboard plow through such soils.

Soil layering occurs naturally as a consequence of the way soils were deposited or formed. Layers resulting from deposition generally vary in texture with depth in the soil profile. Layers may also result from chemical cementing within zones of the soil profile. It may also be caused by land shaping and tillage-induced soil compaction. Changes in texture and porosity in layers of the soil can significantly affect soil water movement, generally causing water to move more slowly (either temporarily or permanently). The net effect is that the apparent water-holding capacity of the soil above such a layer is higher than laboratory analyses would predict. For this reason, water-holding capacity is best determined in the field under normal growing conditions.

The total soil volume available for water storage and for root growth may be effectively reduced by **soil depth**. A shallow soil (e.g., one in which bedrock or hardpan is close to the surface) effectively reduces the available soil water reservoir. A soil with a very compact layer near the surface (possibly due to tillage operations) will have a smaller effective available soil water reservoir compared with a deeper soil.

Laboratory measurements of soil water content held at varying amounts of **soil water tension** can be used to estimate field capacity and permanent wilting point. Soil water tension describes the amount of energy (negative pressure) which must be exerted to extract water from the soil. A **soil water characteristic curve**, a plot of soil water tension with soil water content over the entire range from saturation (zero tension) to very high levels of tension representing very dry soil conditions is constructed and used during this process.

Plant available water holding capacity (available soil water) is defined as the difference between **field capacity** and **permanent wilting point**. Neither of these is a unique function of surface soil properties. Field capacity is especially dependent upon soil profile characteristics as previously discussed, while wilting point is largely dependent on the crop grown.

Field capacity of a soil is the approximate water content at which the internal drainage of water through the soil profile due to gravity becomes negligible, generally within a few hours to a few days after thorough wetting depending upon soil texture, structure and layering (i.e., finer-textured soils take longer to drain).

Field capacity is generally taken as the upper limit of plant available soil water. At water contents greater than field capacity, some plant water uptake occurs; however, it is generally small in proportion to that which occurs near field capacity and below. Water uptake by plant roots can be seriously curtailed by lack of oxygen at soil water contents greater than field capacity, and evaporation from the soil surface may increase.

Permanent wilting point is the approximate soil water content at which a plant cannot exert enough energy to extract sufficient water from the soil to meet its needs. In other words, water is being held by the soil particles with greater tension than the plant can overcome. Adding water usually does not revive the plant, or if it does, the plant is seriously stunted and probably will not produce an economic yield. Permanent wilting point is the lower limit of plant available soil water and depends upon both plant and soil characteristics.

Field capacity is frequently near the soil water content at 0.1 bar of tension for coarser-textured soils (sands, loamy sands) and 0.33 bar of tension for finer-textured soils (loams, silt loams). One bar is equal to one atmosphere of pressure or 14.7 psi. Permanent wilting point is usually taken as the soil water content at 15 bars of tension. Permanent wilting point can vary widely for different crops. There is little error in the total available water when a value of 15 bars of tension is used because the amount of water involved at high soil water tension levels is quite small.

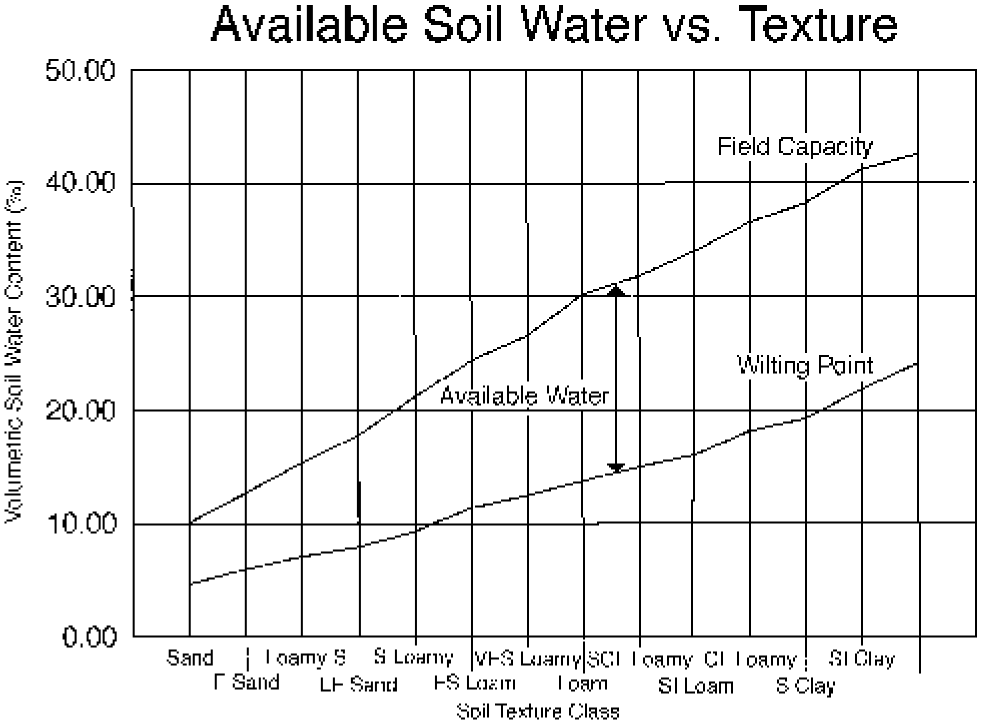
Figure 2 shows how field capacity, wilting point and available water vary with soil texture. Most irrigated soils in the Pacific Northwest have been sampled and mapped by the Soil Conservation Service (SCS), which has information on soil water-holding capacity in county soil surveys and State Irrigation Guides. It is usually expressed as inches of available soil water per foot of soil depth. Estimates of available soil water in inches per foot of soil depth for several generalized soil textures are given in Table 1. Table 1 also gives representative values of total porosity and bulk density for the different textures of surface soil.

Crop Characteristics

Crop rooting depth defines the depth of the soil profile from which the crop can extract soil water. Crop rooting depth varies with crop species, type, and stage of growth. Annual crops planted from seed each year will typically have very shallow root zones (6 inches or less) upon crop emergence. Generally, root zone expansion with depth progresses linearly to maximum rooting depths as the crop develops above-ground vegetative cover to a stage called full effective cover. This occurs approximately when 70% of the ground surface is shaded by the crop canopy. Perennial crops may exhibit similar root zone expansion during the first year of establishment, or the process may take several years, as in the case of tree and vine crops. Once a perennial crop has established its maximum effective rooting depth, that value is used in the determination of available soil water.

Some crops have a greater ability to penetrate the soil with their roots. Thus, soil depth, soil layering, and crop rooting characteristics must be considered in determining the soil volume from which the crop is extracting water and nutrients. In any case, soil water which moves below or is already present below the crop rooting depth is practically unavailable. Some upward movement of water from deeper in the soil profile into the crop root zone may occur in response to tension gradients. This will be particularly true in situations in which water tables are only a few feet deep.

Figure 2. Available soil water vs. soil texture showing estimates of field capacity, permanent wilting point. fig 2 pdf
S-SAND, SI-SILT, CL-CLAY, F-FINE, VF-VERY FINE, L-LOAMY



Crops extract soil water in varying proportions with depth into the root zone. **Crop rooting density with depth** is generally not uniform. The irrigation regime (rate and timing of irrigation applications) under which a crop is produced as well as soil characteristics affects root density and distribution with depth. Studies have shown that under high frequency irrigation, such as with center pivot sprinkle systems, crops expected to have a four foot rooting zone in deep uniform soil were extracting water only to depths of 18 to 24 inches in the profile.

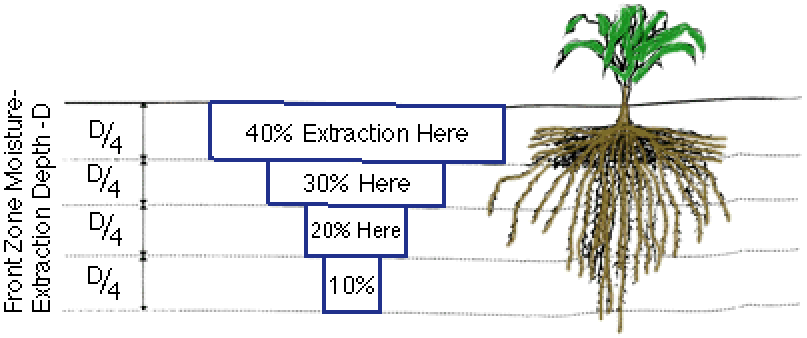
Typically, 70-80% of a crop's water uptake will be from the top half of the rooting depth. Figure 3 shows an idealized plant water extraction pattern. It is important to remember that if soil depth is shallow or if a soil layer impedes root or water penetration, this depth is the effective rooting depth.

Table 1
Representative values of soil bulk density, total porosity, and available soil water for various generalized soil textures.

Soil Texture	Bulk Density (g/cm^3)	Porosity (%)	Available Soil Water (inches/foot of soil depth)	
			Range	Average
Coarse				
Sand	1.65	38	0.5-0.8	0.7
Fine Sand	1.60	40	0.6-1.0	0.8
Loamy Sand	1.60	40	0.7-1.1	0.9
Gravel/Cobble in Coarse Texture	—	—	0.6-0.8	0.7
Moderately Coarse				
Loamy Fine Sand	1.55	42	1.0-1.3	1.2
Sandy Loam	1.50	43	1.2-1.6	1.4
Fine Sandy Loam	1.50	43	1.2-1.7	1.5
Medium				
Gravel/Cobble in Medium Texture	—	—	1.1-1.3	1.2
Very Fine Sandy Loam	1.45	45	1.6-2.2	1.9
Loam	1.40	47	1.6-2.3	2.0
Moderately Fine				
Sandy Clay Loam	1.35	49	1.7-2.4	2.1
Silt Loam	1.35	49	1.8-2.5	2.2
Clay Loam	1.35	49	1.8-2.5	2.2
Fine				
Sandy Clay	1.30	51	1.9-2.5	2.3
Silty Clay	1.25	53	1.9-2.5	2.3
Clay	1.20	55	2.0-2.5	2.3
Peats and Mucks	—	—	2.0-3.0	2.5

Note: Soil profiles with defined layering or abrupt changes in soil texture or bulk density (i.e., due to compaction) will generally have higher apparent water holding capacities than listed above due to the effects of these conditions on water movement in the soil profile.

Figure 3. Idealized soil water extraction pattern of crop.



Available and Usable Soil Water

The total available soil water reservoir is calculated using the simple formula:

$$\mathbf{TAW = (FC\text{-}PWP) \times Y}$$

TAW stands for total available soil water in the root zone in inches, FC is field capacity in inches per foot, PWP is permanent wilting point in inches per foot and Y is effective crop rooting depth or effective soil depth (whichever is shallower) in feet.

Not all of the total available soil water should be allowed to be used before irrigation water is applied. Soil water near the permanent wilting point is not as readily available and many crops will be seriously stressed at these low soil water contents. For this reason, a factor called the management allowable depletion (MAD) (sometimes referred to as maximum allowable depletion) is defined. MAD values are given as a percentage of the total available water which may be safely depleted before moisture stress occurs. Readily available or usable soil water (UW), the amount of soil water which can be safely extracted from the rooting zone between irrigation applications is determined as follows:

$$\mathbf{UW = MAD \times TAW}$$

The value of MAD varies with crop stress tolerance and can even change for a single crop at different stages of growth. For instance, sweet corn can have a range of MAD values from 40-65%. During critical growth stages (tasseling, silk and kernel formation) MAD should be 40%, while at other times of the season MAD may be as high as 65%. This is designed to reduce the chances of water stress occurring during these critical growth stages.

Table 2 gives estimates of maximum and effective rooting zone depths for water management purposes for several crops at maturity (assuming soil depth and/or compaction is non-limiting) and general MAD values. It should be recognized that crop rooting may often be deeper for several of the crops in Table 2, however, only small amounts of water uptake will be extracted from these deeper depths. Rooting depths may be less than indicated if management practices do not encourage root growth throughout the soil profile. Further specific information on reasonable MAD values and rooting depths and patterns can be obtained in Cooperative Extension offices and publications for your area.

Examples

Example 1	Determine the porosities of a sandy soil having a bulk density of 1.65 grams/cm^3 and a silt loam soil having a bulk density of 1.35 grams/cm^3. Assume the particle density of both soils is 2.65 grams/cm^3.
	Sandy soil porosity (%) = (1-1.65/2.65) x 100 = 38%
	Silt loam soil porosity (%) = (1-1.35/2.65) x 100 = 49%
Example 2	Determine the usable water for a crop of potatoes grown on a sandy loam soil assuming the soil is deep and uniform and that the potatoes have reached the maximum rooting depth. From Table 1, a fine sandy loam soil has average available soil water of 1.5 inches per foot of depth. From Table 2, potatoes have an effective rooting depth of 1.5 to 2 feet and a suggested MAD value ranging between 20% and 35%. Assuming a full 2-foot root zone and a MAD value of 20%, the total root zone available water is:
	TAW= (1.5 in/ft) x (2 ft) = 3 inches
The safely usable soil water between irrigations is:	
	UW= (3 in) x (20/100) = 0.60 inch
Example 3	Determine the usable water for a mature apple orchard grown on a silt loam soil assuming the soil is deep and uniform. From Table 1, a silt loam soil has average available soil water of 2.2 inches per foot of depth. From Table 2, apples have an effective rooting

depth of 3.5 to 4 feet and a suggested MAD value ranging between 50% and 65%. Assuming a 3.5-foot root zone and a MAD value of 50%, the total root zone available water is:

TAW = (2.2 in/ft) x (3.5 ft) = 7.7 inches

The safely usable soil water between irrigations is:

UW=(7.7 in) x (50/100) = 3.85 inches

The ability to apply the usable water amount at any given irrigation may be constrained by irrigation system capacity and/or water delivery limitations. In Example 2, the usable water depth of 0.60 inch is easily applied by most types of irrigation systems. However, in Example 3, many systems will not be capable of applying such a large net depth of water without using unacceptable long set times.

The usable water depth (or the net depth applied during an irrigation) is balanced against crop consumptive use rates to determine frequency of irrigation. Historical average crop consumptive use is available in SCS State Irrigation Guides. Real-time or current estimates of crop water use are available from automated weather networks such as the Washington Public Agriculture Weather System in Washington, or the U.S. Bureau of Reclamation AgriMet network which operates weather stations throughout the Pacific Northwest. By knowing the rate at which usable soil water is depleted by the crop, irrigations can be planned and applied when that amount of soil water has been depleted.

Example 4 Using the UW depth calculated in Example 2, if crop water use is averaging 0.30 inch per day, how often is irrigation needed?

Irrigation frequency = UW / Crop water use rate

= 0.60 in /0.30 in/day = 2 days

Table 2
Expected maximum crop rooting depths, effective rooting depths for water management purposes and management allowable depletion (MAD) values for several PNW crops.

Crop	Maximum Root Depth (ft) in Deep, Well-Drained Soil	Effective Root Depth (ft) for Water Management in Deep, Well-Drained Soil	Management Allowable Soil Water Depletion (%)
Alfalfa	6	4	65
Apples (with/without cover crop)	6	3.5-4	50-65
Apricots	6	3.5-4	50-65
Asparagus	6	4	50
Beans, dry	3	2	50
Beans, green	3	2	40-50
Carrots	3	2	40-50
Cherries (with/without cover crop)	6	3.5-4	50-65
Clover/grass hay	2	2	50-65
Corn, grain	4	3	65
Corn, sweet	4	3	40-65
Crucifers	2	2	40-50
Cucumber	4	2	40-50
Grapes (with/without cover crop)	6	3	65
Hop	6	4	65
Mint	3	1.5-2	35
Onions, dry	2	1	40-50
Onions, green	2	1	40-50
Pasture grass	2	1.5-2	50-65
Peaches (with/without cover crop)	6	3.5-4	50-65
Peas	2	1.5	50-65
Pears/plums (with/without cover crop)	6	3.5-4	50-65
Potato	2	1.5-2	20-35
Radish	2	1	40-50
Raspberries	4	3	50
Safflower	6	4	50-65
Sorghum	3	2	65
Soybeans	3	2	65
Spinach	2	1.5	40-50
Spring grain	3	3	50-65
Strawberries	1	1	50-65
Sugar Beets	4	3	50-65
Sunflower	6	4	65

Tomato	4	3	40-50
Turfgrass	2	1.5-2	50
Winter Wheat	3	3	50-65

Notes:

1. Rooting depths must be adjusted according to soil depth or the depth of a restricting soil layer if less than the depths listed.

2. When a range of MAD values is given, do not exceed the larger value. Smaller value of range applies to moisture sensitive growth periods. There may be an advantage to crop yield and quality by using smaller MAD values on fine-textured soils and coarse-textured soils.

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SECTION 2

TOOLS AND TECHNIQUES FOR SOIL WATER MONITORING AND MEASUREMENT

There are several tools and techniques that can be used to monitor or directly measure soil water. Among the most common approaches are:

1) soil feel and appearance

2) gravimetric sampling

3) tensiometers

4) porous blocks

5) neutron probe

Newer methods which measure the dielectric constant of the soil water medium and then estimate soil water content have recently become commercially available. Such methods are known as time domain or frequency domain reflectometry and soil capacitance measurements.

These are all currently used by growers, irrigation scheduling consultants, university research and extension personnel, and others in one form or another. The goal of each monitoring or measurement method should be to determine the soil water available for use by the crop. Typically this will require some calibration of the method or instrument used for the specific soil being sampled.

A routine sampling schedule should be used to obtain the most information from any of these methods. Often the difference in soil water content from one sampling to the next—its relative change, provides more information than its absolute value. Soil water should be measured or monitored at a minimum of two depths in the expected crop root zone. Additionally several locations in a field (a minimum of three for large uniform soil areas) should be measured to obtain a field average. Subareas within fields having different soil characteristics should also be measured.

Soil Feel and Appearance

Soil feel and appearance is easy to implement but requires some skill. The procedure involves the use of a soil auger or core sampler to obtain soil samples at various depths of the rooting zone to assess soil water status. Samples taken are compared to tables and charts which give the characteristics of different soil textures in terms of feel and appearance at different water contents. This requires some judgement, but with enough practice, estimates can usually be obtained within ±10-15% of the true soil water content. In many situations, this may be accurate enough.

Table 3 is one version of the type of chart used to describe soil feel and appearance characteristics versus soil water content. The SCS State Irrigation Guides include similar tables and several excellent photographs of the feel and appearance method on three different soil textures.

A soil probe is recommended rather than a shovel, so that samples can be drawn from deep in the profile without digging a big hole. Augers and core samplers which allow sampling down to 4 feet are available for less than $100. Core sampling on rocky or stony soils can be frustrating, if not impossible.

Table 3
Soil feel and appearance chart for estimating available soil water.

	SOIL TEXTURE			
AVAILABLE WATER	COARSE (SAND, LOAMY SAND)	MODERATELY COARSE (SANDY LOAM, FINE SANDY LOAM)	MEDIUM (LOAM)	FINE (SILT LOAM, CLAY LOAM)

100% (FIELD CAPACITY)	LEAVES WET OUTLINE ON HAND WHEN SQUEEZED. (0.0)	APPEARS VERY DARK, LEAVES WET OUTLINE ON HAND; MAKES A SHORT RIBBON. (0.0)	APPEARS VERY DARK, LEAVES WET OUTLINE ON HAND: WILL RIBBON OUT ABOUT 1". (0.0)	APPEARS VERY DARK, LEAVES SLIGHT MOISTURE ON HAND WHEN SQUEEZED: WILL RIBBON OUT ABOUT 2". (0.0)
70%-80%	APPEARS MOIST: MAKES A WEAK BALL. (0.2-0.3)	DARK: MAKES A HARD BALL. (0.3-0.4)	QUITE DARK: MAKES TIGHT PLASTIC BALL: RIBBONS OUT 1/2". (0.4-0.6)	QUITE DARK RIBBONS AND SLICKS EASILY: MAKES PLASTIC BALL. (0.5-0.7)
60%-65%	APPEARS SLIGHTLY MOIST: FORMS WEAK BRITTLE BALL. (0.4)	FAIRLY DARK: MAKES A GOOD BALL. (0.8)	FAIRLY DARK: FORMS FIRM BALL: BARELY RIBBONS. (0.8)	FAIRLY DARK: FORMS FIRM BALL: RIBBONS 1/4"-1/2". (0.9)
50%	APPEARS DRY: FORMS VERY WEAK BALL OR WILL NOT BALL. (0.5)	SLIGHTLY DARK: FORMS WEAK BALL. (0.8)	FAIRLY DARK: WILL FORM BALL: SLIGHTLY CRUMBLY. (1.0)	BALLS EASILY: SMALL CLODS FLATTEN OUT RATHER THAN CRUMBLE: RIBBONS SLIGHTLY. (1.1-1.2)
35%-40%	DRY: WILL NOT BALL. (0.6-0.7)	LIGHT COLOR: WILL NOT BALL OR FORMS BRITTLE BALLS. (0.9-1.0)	SLIGHTLY DARK: FORMS WEAK BALL: CRUMBLY. (1.2-1.3)	SLIGHTLY DARK, FORMS WEAK BALLS: CLODS CRUMBLE. (1.4-1.5)
LESS THAN 20% (WILTING POINT)	VERY DRY: LOOSE, FLOWS THROUGH FINGERS. (0.8-1.0)	DRY: LOOSE, FLOWS THROUGH FINGERS. (1.3-1.6)	LIGHT COLOR: POWDERY, DRY. (1.6-2.0)	HARD, BAKED, CRACKED, LIGHT COLOR. (1.6-2.3)

NOTE: FIGURES IN PARENTHESES AT END OF EACH ENTRY REPRESENT APPROXIMATE MOISTURE DEFICIT FROM FIELD CAPACITY (INCH/FEET) WHEN SOIL IS UNIFORM WITH DEPTH. BALL IS FORMED BY SQUEEZING SOIL HARD IN FIST. RIBBON IS FORMED BY ROLLING SOIL BETWEEN THUMB AND FOREFINGER.

Soil Sampling

Soil sampling is the only direct method for measuring soil water content. When done carefully with enough samples it is one of the most accurate methods, and is often used for calibration of other techniques. This approach requires careful sample collection and handling to minimize water loss between the time a sample is collected and processed. Replicated samples should be taken to reduce the inherent sampling variability that results from small volumes of soil. Figure 4 is a photo showing soil sampling equipment. Equipment required includes a soil auger or a core sampler (with removable sleeve of known volume to obtain volumetric water content), sample collection cans or other containers, a balance accurate to at least 1 gram and a drying oven.

Soil sampling involves taking soil samples from each of several desired depths in the root zone and temporarily storing them in water vapor-proof containers. The samples are then weighed and the opened containers oven-dried under specified time and temperature conditions (104°C for 24 hours). The dry samples are then re-weighed. Percent soil water content on a dry mass or gravimetric basis, P_w, is determined with the following formula

P_w = [(wet sample weight-dry sample weight) / dry sample weight] x 100

The difference in the wet and dry weights is the weight of water removed by drying. To convert from a gravimetric basis to water content on a volumetric basis, P_v, multiply the gravimetric soil water content by the soil bulk density (BD). Soil bulk density is the weight of a unit volume of oven dry soil and usually is determined in a manner similar to gravimetric sampling by using sample collection devices which will collect a known volume of soil.

BD = weight of oven dry soil / unit volume of dry soil

$P_v = P_w \times BD$

Soil water content on a volumetric percentage basis is a preferable unit for irrigation management. It is easily converted to a depth of soil water per depth of soil. For instance, a volume soil water content of 30% is easily converted to inches of water per foot of soil depth by multiplying by 12 inches/ft and then dividing by 100 to remove the percentage.

P_v = 30% = 30 x 12/100 = 3.6 inches per foot

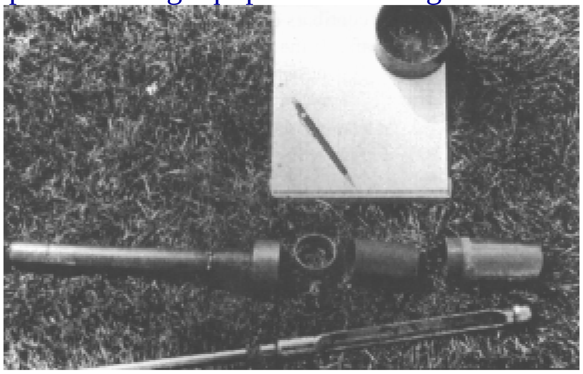
Comparison of the measured volumetric soil water content with field capacity and wilting point of the soil is used to determine the available soil water and the percent of total available soil water. Either of these figures can then be used to determine if irrigation is needed.

Example.

If the above sample having 30% volumetric water content was obtained from a silt loam soil having a field capacity of 4.3 inches per foot and a wilting point of 1.9 inches per foot, then this soil has total available water of (4.3-1.9) = 2.4 inches per foot. At the current total water content of 3.6 inches per foot (30% by volume), the available water above wilting point is (3.6-1.9) = 1.7 inches of water. Or, the soil currently has (1.7/2.4) x 100 = 71% of total available water remaining. If the management-allowable depletion (MAD) for the crop being grown is 50%, then irrigation is not yet needed. However, if the MAD is 30% then irrigation should be scheduled soon, i.e., a MAD value of 30% means irrigation should be applied when the percent of total available water reaches (100-30) = 70%.

Gravimetric sampling is time-consuming and labor-intensive. Results are generally not known for a minimum of 24 hours after sampling. A large number of samples must be taken each time sampling is done to remove the inherent variability of this approach. Samples cannot be taken from exactly the same point on subsequent sampling dates.

Figure 4
Soil sample collecting equipment for the gravimetric method.



Several irrigation scheduling consultants utilize this approach due to its accuracy and low capital (equipment) costs, but it is labor intensive. One of the advantages of gravimetric soil sampling, like the feel and appearance method, is that soil sampling is done at several locations in a field and throughout the soil profile. Information such as soil layering and compaction, changes in soil texture, etc., are often found while other methods may not yield this information. It is necessary to determine soil bulk density for each location when using this method. Otherwise, it is easy to make significant errors in estimation of absolute soil water content.

Tensiometry

Soil water tension, soil water suction, or soil water potential are all terms describing the energy status of soil water. Soil water potential is a measure of the amount of energy with which water is held in the soil. A soil water characteristic or water release curve shows the relation between soil water content and soil water tension.

Tensiometers have been used for many years to measure soil water tension in the field. Tensiometers are water-filled tubes with hollow ceramic tips attached on one end and a vacuum gauge (or mercury manometer) and airtight seal on the other end. The device is installed in the soil with the ceramic tip in good contact with the soil at the desired depth. (See Figure 5 for an example of the typical recommended installation of tensiometers at two depths of the root zone.) The water in the tensiometer eventually comes to pressure equilibrium with the surrounding soil through the ceramic tip. Water is pulled out through the ceramic tip into the soil creating a tension in the closed tube. As the soil is re-wetted, the tension gradient reduces, causing water to flow into the ceramic tip. As the soil goes through wetting and drying cycles, tension readings can be taken.

Most commercially available tensiometers use a vacuum gauge to read the tension created and have a scale from 0 to 100 centibars (one bar or 100 centibars of pressure or tension is equal to 14.7 psi). The practical operating range is from 0 to 75 centibars. If the water column is intact, a zero reading indicates saturated soil conditions. Readings of around 10 centibars (cb) correspond to field capacity for coarse-textured soils, while readings of around 30 cb can approximate field capacity for some finer-textured soils. 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. This limits the practical use of tensiometers to coarse-textured soils or to high frequency irrigation where soil water content is maintained high.

Tensiometer readings may be used as indicators of soil water and the need for irrigation. When instruments installed at shallower depths of the root zone reach a certain reading, they can be used to determine when to start irrigating, based on soil texture and crop type. Similarly, instruments at deeper depths of the root zone may be used to indicate when adequate water has been applied. Generalized soil water release curves such as those shown in Figures 6-11 may be used to translate tensiometer readings into percent of available water, water depletion, etc. They should be used with caution, however, as specific soils will deviate from the generalized relationships shown.

Careful installation and maintenance of tensiometers is required for reliable results. The ceramic tip must be in intimate and complete contact with the soil. This is done by augering a pilot hole out to the proper depth, making a soil water slurry mix with the soil removed and re-introducing this into the hole. Finally the tensiometer tip is pushed into this slurry. Soil is banked up around the tube at the soil surface to prevent water from standing around the tube itself. A few hours to a few days are required for the tensiometer to come to equilibrium with the surrounding soil. The tensiometer should be pumped with a hand vacuum pump to remove air bubbles.

Figure 5

Typical tensiometer bank installation at two depths of the crop root zone.

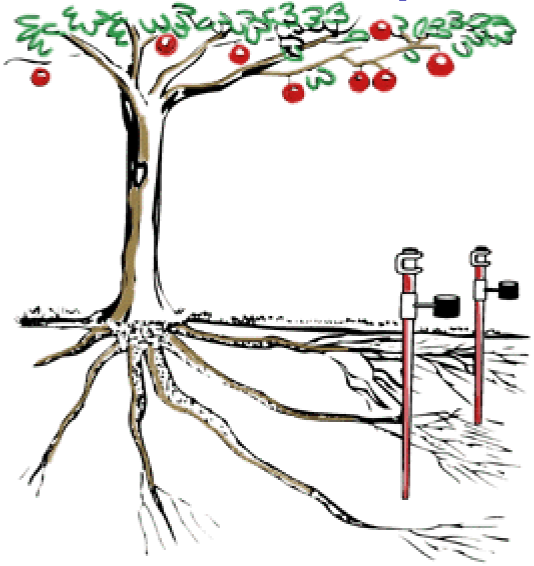


Figure 6 (pdf)

Generalized soil water release curve for sands and loamy sands. From SCS State of Washington Irrigation Guide.

Figure 7 (pdf)

Generalized soil water release curve for sandy loam. From SCS State of Washington Irrigation Guide.

Figure 8 (pdf)

Generalized soil water release curve for loam, silt loam, and silt. From SCS State of Washington Irrigation Guide.

Figure 9 (pdf)

Generalized soil water release curve for clay. From SCS State of Washington Irrigation Guide.

Figure 10 (pdf)

Generalized soil water release curve for sandy clay and silty clay. From SCS State of Washington Irrigation Guide.

Figure 11 (pdf)
Generalized soil water release curve for clay loam, silty clay loam, and sandy clay loam.
From SCS State of Washington Irrigation Guide.

Routine maintenance includes refilling with water and hand pumping. Under extreme drying cycles enough water may actually be lost from the tensiometer that it breaks suction and gives only zero readings. Tensiometers also break suction when improperly installed, when there are air leaks, or there is too much air in the water used to fill the tube. Most tensiometer manufacturers provide maintenance kits which include a hand vacuum pump for checking for leaks, drawing air bubbles out.

Banks or pairs of tensiometers at two lengths should be installed in at least three locations within a field. More may be needed depending upon soil variability. Installation sites should represent the field in terms of water application patterns, soil types, slopes, and exposure.

Tensiometers come in lengths from 6 to 48 inches. Price depends on length, and varies from about $45 to $80. It is generally recommended that tensiometers be installed in pairs, one at one-third and one at two-thirds of the crop rooting depth. They should be installed out of the way of traffic and cultivation. In freezing climates, insulate or remove tensiometers during winter months. It takes only a small frost to knock the vacuum gauges out of calibration.

Porous Blocks

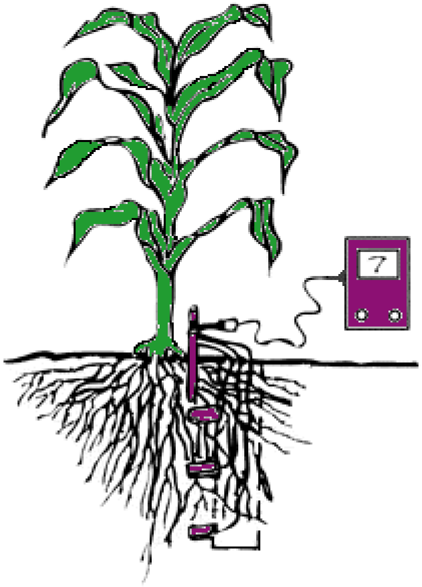
Porous blocks are made of materials such as gypsum, ceramic, nylon, and fiberglass. Similar to tensiometers, the blocks are buried in intimate contact with the soil at some desired depth and allowed to come to water tension equilibrium with the surrounding soil. Once equilibrium is reached, different properties of the block which are affected by its water tension may be measured.

One of the more common types of porous blocks are electrical resistance blocks. Figure 12 shows a typical electrical resistance block installation. Electrodes buried in the block are used to measure the resistance to electrical current flow between them. The resistance is affected by the water content of the block, which is a function of the soil water tension. Higher resistance readings mean lower block water content and thus higher soil water tension. Lower resistance readings indicate higher block water content and lower soil water tension. Individual electrical resistance blocks usually sell for between $5 and $20, depending on materials of construction. Some may last for only a season.

Thermal dissipation blocks are porous ceramic blocks in which a small heater and temperature sensors are embedded. This arrangement allows measurement of the thermal dissipation of the block, or the rate at which heat is conducted away from the heater. This property is directly related to the water content of the block and thus soil water tension.

Thermal dissipation blocks must be individually calibrated. They are considerably more expensive than electrical resistance blocks.

Figure 12
Sketch showing typical electrical resistance block installation.



Electrical resistance blocks are best suited for finer-textured soils. They are generally not sensitive to changes in soil water tension less than 100 centibars. For most coarse-textured soils readings of 100 cb and above are well outside the available soil water range. Newer types of resistance blocks, discussed below, have greater sensitivity to water tension in the 0 to 100 cb range. Tensiometers and electrical resistance blocks are often used together to monitor soil water over a wider range of conditions than either can measure alone. Thermal dissipation blocks are sensitive to soil water content across a wide range.

Meters used to read porous blocks may range in price from $150 to $600. They are portable, may be used to read several blocks and will last for several seasons. Meter readings can be used directly or translated using the manufacturer's charts to soil water tension. Readings do not mean the same across all meters and for all types of blocks. Manufacturers make meters and blocks to be used together. As with a tensiometer, a calibration curve for each specific soil type of soil water content versus soil water tension must be used to obtain soil water content and available soil water (see Figures 6-11 for generalized examples).

Porous blocks require the same careful installation considerations as tensiometers but generally require less maintenance. Gypsum blocks can be prone to breakdown under alkaline soil conditions. High soil salinity (high electrical conductivity of the soil solution) can cause misleading readings.

Gypsum Blocks. One type of electrical resistance block, the gypsum block, has been in use since the 1940s. Blocks are installed in the soil similar to the procedure for tensiometers, ensuring intimate contact with the surrounding soil, and are allowed to come to water tension equilibrium with the surrounding soil. Soil is carefully tamped back into the hole and the wire leads brought to the surface. Readings are taken by attaching an electrical resistance meter to the wire leads. Some meters give readings between 0 and 100, with 0 meaning dry and 100 wet. Manufacturer's charts are required to translate these readings into soil water tension.

Gypsum blocks require little maintenance and can be left in the soil under freezing conditions. Being made of gypsum, the blocks will slowly dissolve, requiring replacement. The rate of dissolution is dependent upon soil pH and soil water conditions. As discussed above, gypsum blocks are best suited for use in finer-textured soils. They are not sensitive to changes in soil water tension from 0 to 100 cb. High soil salinity affects the electrical resistivity of the soil solution, although the gypsum buffers this effect to a certain degree.

Watermark Blocks[2]. The Watermark block, or granular matrix sensor, is a relatively new style of electrical resistance block. The electrodes are embedded in a granular matrix material which approximates compressed fine sand. A gypsum wafer is embedded in the granular matrix near the electrodes. A synthetic porous membrane and a PVC casing with holes drilled in it hold the block together. The granular matrix material enhances the movement of water to and from the surrounding soil, making the block more responsive to soil water tensions in the 0 to 100 cb range. Watermark blocks exhibit good sensitivity to soil water tension over a range from 0 to 200 cb. This makes them more adaptable to a wider range of soil textures and irrigation regimes than gypsum blocks.

Readings are taken by attaching a special electrical resistance meter to the wire leads and setting the estimated soil temperature. The Watermark meter gives readings in centibars of soil water tension similar to the tensiometer. Watermark blocks require little maintenance and can be left in the soil under freezing conditions. The blocks are much more stable and have a longer life than gypsum blocks. Soil salinity affects the electrical resistivity of the soil water solution and may cause erroneous readings. The gypsum wafer in the Watermark blocks offers some buffering of this effect.

Neutron Scattering

Neutron scattering is a time-tested technique for measuring total soil water content by volume. This method estimates the amount of water in a volume of soil by measuring the amount of hydrogen present. A neutron probe consists of a source of fast or high energy neutrons and a detector, both housed in a unit which is lowered into an access tube installed in the soil. The probe is connected by cable to a control unit which remains on the surface. Clips on the cable allow the probe to be set at pre-selected depths in the soil profile. Access tubes should be installed at least to the depth of the expected rooting zone. The control unit includes electronics for time control, a counter, memory, and other electronics for processing readings (see Figure 13).

Fast neutrons, emitted from the source and passing through the access tube into the surrounding soil, gradually lose their energy though collisions with other atomic nuclei. Hydrogen molecules in the soil (mostly in soil water) are particularly effective in slowing the fast neutrons since they are both of near equal mass. The result is a "cloud" of slow or thermalized neutrons some of which diffuse back to the detector. The size and density of the cloud depends mainly upon soil type and soil water content, is spherical in shape, and ranges in size from 6 to 16 inches. Thermalized neutrons which pass through the detector create a small electrical impulse. These electrical pulses are amplified and then counted. The number of slow neutrons counted in a specified interval of time is linearly related to the total volumetric soil water content. A higher count indicates higher soil water content and vice versa.

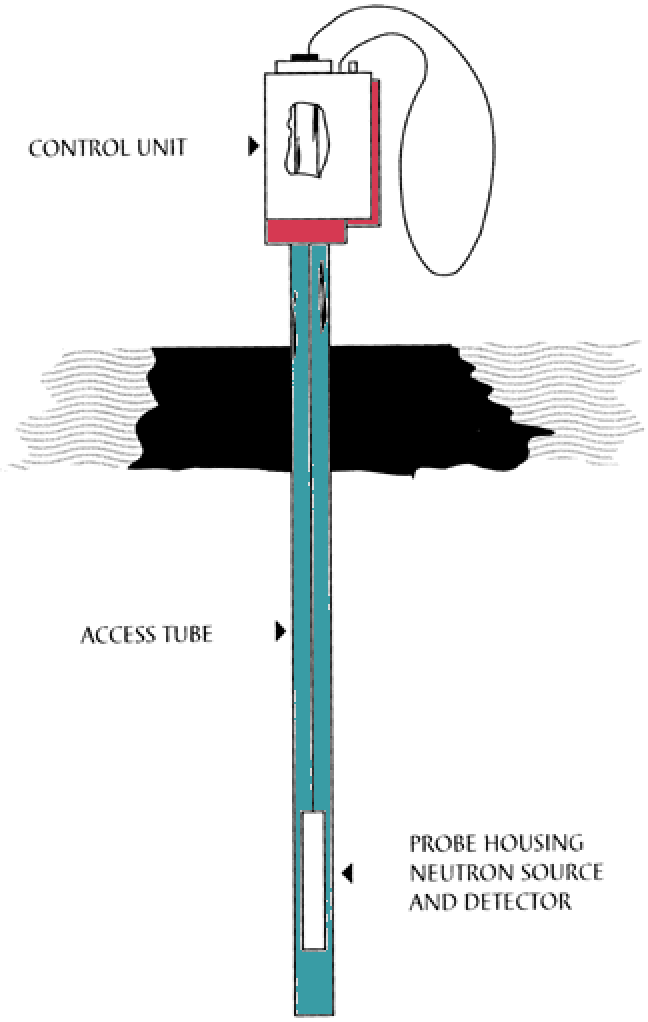
A manufacturer's calibration curve relating the count to soil water content is supplied with the neutron probe. However, a calibration must be developed for the type of access tube used (PVC, aluminum, and steel pipe are most common). Calibrations should be developed for soils high in organic matter and some ions such as boron. If it is desired to translate the total volumetric soil water content reading of the neutron probe into available soil water, then field capacity and wilting point of each soil must be known. Some probes are programmable so several different calibrations can be stored in memory. Also, the desired soil water content units can be changed with the push of a button (inches per foot, percent by volume, pounds per cubic foot, etc.).

The neutron probe allows relatively rapid and repeatable measurements of soil water content to be made at several depths and locations within a field. Being able to repeat measurements at the same location through the growing season minimizes the effects of soil variability on the measurements. Depending on the number of access tube installations per field and number of fields, the time required to take probe readings and analyze the data may become extensive. A minimum of three access tubes per field is recommended. Readings should be taken in 6-inch increments to the bottom of the expected rooting depth.

Neutron probes are considered among the most accurate methods for measuring soil water content when properly calibrated. They are inaccurate, however, when used within the top 6-8 inches of the soil surface, because of the escape of fast neutrons. Surface readings must be carefully calibrated or a different method used.

Due to their high cost, from $3,000 to $4,000 depending upon features, neutron probes are not extensively used by individual farmers. There is also a radiation safety hazard, which requires special licensing, operator training, handling, shipping, and storage procedures. Many larger corporate farms are using this method, as well as a large number of irrigation scheduling consultants.

Figure 13
Sketch of neutron probe and access tube.



Methods Based on Measurement of Dielectric Constant

The dielectric constant of a material is a measure of the capacity (or electrical permittivity) of a nonconducting material to transmit high frequency electromagnetic waves or pulses. The dielectric constant of dry soil varies between 2 and 5, while the dielectric constant of water is 80 at frequencies between 30 MHz and 1 GHz. A large volume of research has shown the measurement of dielectric constant of the soil water media to a be a sensitive measurement of soil water content. Relatively small changes in the quantity of free water in the soil have large effects on the electromagnetic properties of the soil water media.

Two approaches have been developed for measuring the dielectric constant of the soil water media and hence the volumetric water content. These are categorized as either time domain reflectometry or frequency domain reflectometry.

Time Domain Reflectometry (TDR). Currently, TDR technology for soil water content measurement is based upon cable testers, such as the Tektronix 1502B cable tester used by many utilities to test the integrity of buried cables, find breaks, couplings etc. For soil water content measurement, the device propagates a high frequency transverse electromagnetic wave along a cable attached to parallel conducting probes inserted into the soil. The signal is reflected from the end of the waveguide back to the cable tester where it is displayed on an oscilloscope, and where time between sending the pulse and receiving the reflected wave is accurately measured by the cable tester. By knowing the length of the transmission line and waveguide, the propagation velocity of the signal in the soil can be computed The dielectric constant is inversely related to this propagation velocity, i.e., faster propagation velocity indicates a lower dielectric constant and thus a lower soil water content. Or, as soil water content increases, propagation velocity decreases, and dielectric constant increases.

Waveguides inserted into the soil usually consist of a pair of parallel stainless steel rods spaced about 2 inches apart. They may be installed in the soil horizontally, vertically, at a 45° angle, etc. A shielded, parallel transmission line connects the waveguide to the cable tester. The TDR soil water measurement system measures the **average** volumetric soil water percentage along the length of the waveguide. The volume of soil sampled approximates a cylinder surrounding the waveguide with a diameter about 1.5 times the spacing of the parallel rods.

The waveguides may be permanently installed with wire leads brought to the surface, but this requires care to minimize soil disruption. However, this is the only way to obtain TDR measurements at specific multiple soil depths. The installation generally requires the excavation of a pit in the soil, with waveguides inserted into the undisturbed face of one the pit walls. Horizontal insertion yields a depth-specific measurement, while insertion at a 45° angle integrates a larger volume of soil both horizontally and vertically. An alternative to permanent installations are portable hand push waveguide probes, which may be used to measure the top 18 to 24 inches of soil. For either approach, waveguides must be carefully installed in the soil with soil contact along their entire length. Annular air gaps around the rods will affect readings to the low side. The waveguide rods must remain parallel.

Once properly calibrated and installed, the TDR technique is highly accurate. Accurate measurements may be made near the surface, an important advantage compared to techniques such as the neutron probe. Measurements are not affected by soil salinity. Research has shown the dielectric constant to be nearly independent of soil type and bulk density and relatively unaffected by soil salinity. Soil salinity or bulk electrical conductivity affects the degree of attenuation of the electromagnetic pulse in the soil. Research efforts are currently studying this effect so that TDR may be used to measure both soil water content and bulk electrical conductivity.

Figure 14. TDR cable tester, hand held computer, and hand push probes.

Due to the high cost of the cable tester and associated electronics, TDR soil water measurement system costs usually begin in the range of $6,000-$7,000. Individual sets of waveguides cost between $20 and $80 depending on length. TDR instruments are commercially available, however, primary users are university researchers and irrigation consultants. Cable testers currently used for TDR contain many features not used or unnecessary for soil water content measurement. Research efforts have been undertaken to build considerably less expensive TDR units for soil water measurement containing the necessary electric pulse generation and accurate timing electronics. Such devices may make TDR the instrument of the future.

Frequency Domain Reflectometry. Frequency domain reflectometry approaches to measurement of soil water content are also known as radio frequency (RF) capacitance techniques. This technique actually measures soil capacitance. A pair of electrodes is inserted into the soil. The soil acts as the dielectric completing a capacitance circuit, which is part of a feedback loop of a high frequency transistor oscillator. As high frequency radio waves (about 150 Mhz) are pulsed through the capacitance circuitry, a natural resonant frequency is established which is dependent on the soil capacitance. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes. There are currently two commercially available instruments using this technique: the Troxler Sentry 200-AP probe and the Aquaterr probe.

The Troxler Sentry 200-AP probe (Figure 15) uses an access tube similar to the neutron probe approach for measuring volumetric soil water content with depth. The Sentry probe is lowered into the access tube and the natural resonant frequency or frequency shift between the emitted and received frequency is measured by the probe. The access tube used with the Sentry 200-AP must be 2-inch Schedule 40 PVC. This size and wall thickness of pipe ensures very close fit of the Sentry probe inside the access tube, minimizing any annular air gaps which greatly affect the travel of the signal into the soil. Installation of the access tube **requires extreme care to ensure a very tight fit in the augered hole.** Annular air gaps or soil cracks around the outside of the tube result in erroneous low readings.

The manufacturer's calibration of the probe is for sand and yields generally very high volumetric soil water percentages on other soils. Calibration of the probe for soils other than sands is therefore required for use in an irrigation scheduling program. Bulk density differences in soils (i.e., with depth) will also require separate calibrations. The volume of soil measured is not dependent on soil type or water content and approximates a cylinder 4 inches tall with a diameter of about 10 inches assuming there are no air gaps. Properly calibrated and with careful access tube installation, the probe's accuracy can be good. Many of the advantages of the neutron probe system are available with this system including rapid, repeatable measurements at the same locations and depths. The disadvantages of the neutron probe are eliminated—radiation hazard and licensing requirements—while near surface measurements are possible. The cost of the Sentry 200-AP is about $4,000-$4,500.

The Aquaterr probe is an electric capacitance probe and generally works on a similar principle as the Troxler Sentry. The probe is a highly portable hand push probe and allows rapid, easy, but **qualitative** readings of soil water content. Probe use is **difficult** in drier soil, soils with rocks or stones, or hard pans. In these cases, a separate auger is needed to make a pilot hole for the probe.

The probe comes with either an analog, color-coded (for three different soil types: sand, loam and clay) dial gauge, or a digital readout. Both give readings on a scale from 0% to 100%. High readings reflect higher soil water content and vice versa. Probe readings near 100% (blue range) represent saturated conditions. Readings near 85% to 90% (dark green range) are near field capacity. Readings in the 50% to 70% (light green) range indicate adequate soil water. Readings in the 30% to 50% (orange range) represent onset of water stress and readings below 30% (red range) represent conditions approaching wilting point.

The probe operates on a replaceable 9V battery and requires very little maintenance. The volume of soil sampled is quite small and approximates a cylinder 4 inches tall and an inch in diameter. The probe must be calibrated in water (dial the gauge or digital readout to a reading of 100%) before use. This should be done before each field monitored, although the manufacturer suggests it is necessary only once per day. The probe should be dried after water calibration and wiped clean between each insertion into the soil. The Aquaterr probe costs between $400 and $500, depending on length and other features.

Figure 15. The Troxler Sentry 200-AP capacitance probe.

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SECTION 3

FIELD EVALUATION AND COMPARISON OF TECHNIQUES FOR MEASURING SOIL WATER

Methods and Materials

During the summer of 1992, a field study was conducted to evaluate the performance of commercially available soil water monitoring and measurement tools in side-by-side comparisons on different soil types and under different irrigation regimes. Comparisons include the initial capital cost of the equipment, installation requirements, labor requirements, ease of interpretation of measurements, accuracy, operation and maintenance requirements, relative performance on different soils, and other special requirements or precautions. The following methods or devices were evaluated.

1) neutron probe
2) time domain reflectometry (TDR)

3) soil sampling
4) RF capacitance probes
- Troxler Sentry 200-AP
- Aquaterr probe

5) tensiometers
6) electrical resistance blocks
- gypsum blocks
- Watermark blocks

Soil water measurement installations were established in four irrigated locations in south central Washington with four different soil types and irrigation methods. Site details are provided in Table 4.

At each location, instruments were installed so that samples or readings could be taken at depths of 12 and 24 inches. For all methods, three replications of readings or samples were taken at the 12-inch depth. Neutron probe, TDR, and Sentry probe readings were replicated three times at the 24-inch depth. The tensiometers and electrical resistance blocks were replicated only once at the 24-inch depth at each site. Aquaterr probe readings were taken only in the top 12 inches of soil due to difficulty pushing the probe into the ground. Readings or samples were collected on a weekly basis from early June to late September 1992. Soil samples were collected for gravimetric analyses three times during this period.

Irrigation and/or rainfall was measured at each monitoring site using portable raingages. Irrigations were scheduled by the grower/operator at each location, except at WSU-IAREC, where several wetting and drying cycles were implemented to evaluate instrument response.

Table 4
Description of soil water measurement study sites.

Location	**Site Characteristics**	
WSU-IAREC, Prosser, WA:	All instruments installed within a 15' x 15' area	
	Soil type:	Warden very fine sandy loam, uniform with depth, > 5 ft deep
	Crop:	turfgrass
	Irrigation:	surface flooding
Granger, WA:	Instruments installed within dripline on southwest corner of 3 different trees in same tree row. Instrumented trees were in same relative position within sprinkler pattern and about 300 ft apart.	

	Soil type:	Warden silt loam, hardpan at 18-24 inch depth, > 5 ft deep
	Crop:	apples with cover crop
	Irrigation:	solid set undertree impact sprinkler
USDA-ARS Paterson, WA:	Instruments installed in plant row in 25-foot section of same crop row	
	Soil type:	Quincy loamy sand, some pebbles and stones, > 5 ft deep
	Crop:	grain corn
	Irrigation:	linear move sprinkler
Walla Walla, WA:	Instruments installed within dripline on southwest corner of 3 different vines in same vine row. Instrumented vines were in same relative position within sprinkler pattern and about 300 ft apart.	
	Soil type:	Catherine/Onyx silt loam-silty clay loam, > 5 ft deep
	Crop:	wine grapes
	Irrigation:	solid set overcrop impact sprinkler

Results

Weekly measurements at each site were averaged and grouped according to instrument output. The neutron probe, TDR, Troxler Sentry probe, and gravimetric sampling all ultimately yield volumetric soil water content. Tensiometers and Watermark blocks give readings of soil water tension in centibars. Readings of the gypsum blocks and the Aquaterr probe are on a scale from 0 to 100.

In general, methods which can be directly compared with each other compared fairly well, although the instrument response (sensitivity to wetting and drying) was more obvious for some instruments. The neutron probe and TDR compared well at all sites and both compared well with the gravimetric samples. The Troxler Sentry probe was calibrated using the gravimetric samples taken at all sites. The manufacturer's calibration (developed on sand) resulted in considerably higher soil water content values at all sites except the sandy soil at Paterson. Using the calibration developed in this study, the Troxler probe still generally yielded higher soil water content values than the neutron probe and TDR. It also showed less sensitivity to wetting and drying than the neutron probe or TDR. Some of the differences between these 4 methods can be attributed to volume of soil sampled in each measurement.

The tensiometer and Watermark blocks compared fairly well across all 4 sites, although the tensiometer readings showed considerably more movement at the 12-inch depth. The tensiometers at the 12-inch depth broke suction several times on the heavy silt loam soil at Walla Walla. At Granger and Paterson, where soil water content was maintained at even levels for most of the season, these two methods compared well, although the Watermark block readings tended to lag the tensiometer readings following wetting of the soil by irrigation. Watermark blocks required considerably less maintenance of the field installation than tensiometers.

Gypsum blocks showed very little sensitivity at both soil depths at Granger and Paterson, where higher soil water contents were maintained throughout most of the season. Considerably more sensitivity to the fluctuating soil water at the 12-inch depth at WSU-IAREC and on the heavy silt loam soil at Walla Walla was evident. Upon excavation to remove the gypsum blocks at the end of the field study, approximately half of them were found to have dissolved to the point of being non-usable. This effect was more apparent at Granger and Paterson where the soil water contents were higher.

All readings made with the Aquaterr probe were limited to the top foot of soil. The Aquaterr probe was difficult to evaluate due to difficulty in pushing the probe into the soil to the same depth, particularly once the surface 6 inches had dried. No effort was made to auger a pilot hole as recommended by the manufacturer. At Granger, where the surface layer was relatively moist all season, the Aquaterr was much easier to use. Readings obtained at the Granger site remained fairly even through the season, similar to the trends seen with the other methods. Only sporadic readings could be obtained at the other sites but in general, the readings tracked the wetting and drying of the soil. A more thorough and fair evaluation would require greater time and labor to auger pilot holes and ensure probe readings are obtained at the same depth at each sampling. The interpretation of readings and ranges could not be accurately verified (i.e., correlated against volumetric soil water percentages) in these field tests, thus the probe readings are qualitative.

Table 5 is a qualitative comparison of the methods evaluated, based on the conditions under which this study was conducted. Factors included in the table were rated on a scale from 1 to 10, with 1 being least favorable and 10 most favorable. The composite ratings are simple sums with equal weight placed on each factor.

Field site setup requirements includes factors such as time, labor, and equipment for site preparation and setup. In this study, the TD was used with permanently buried waveguides, requiring excavation of a pit, which resulted in a lower score. Portable TDR push probes are available which would result in a much higher score. Obtaining a routine reading considers the time and effort to obtain a single reading.

Methods giving readings which are **readily** interpreted in terms of soil water holding capacity and depth of water to refill the root zone received high scores for ease of interpretation of readings. Methods which give readings of soil water tension received medium scores. Accuracy includes comparison against a standard procedure such as gravimetric sampling (once an acceptable calibration is developed), repeatability, and adaptability across a wide range of soil types.

Maintenance includes activities necessary for routine operation (battery charging or replacement, frequency of calibration, field installation maintenance, etc.). Special considerations refer to licensing and storage requirements, specialized training needs, instrument longevity, amount of ancillary equipment required (soil augers, ovens, scales), permanence of field installations, etc.

Soil sampling and gravimetric analyses received the highest rating. It was assumed that a balance for weighing samples and an oven for drying were available. If this were not the ease, initial cost rating and the composite rating would be lower. The neutron probe and TDR were equally rated overall. The high cost of TDR offsets the regulatory requirements involved in owning and operating a neutron probe. The Sentry probe was ranked next. Accuracy improvements may be possible with this method as more calibration information is developed. Of the four methods most likely to be used by an individual grower on his/her own, tensiometers and Watermark blocks offer the best overall capabilities.

Table 5.
Qualitative evaluation of soil water monitoring devices. A score of 1 is least favorable while a score of 10 is most favorable.

DEVICE	NP	TDR	GS	AP	AQ	TM	GB	WB
INITIAL COST	3	1	8	2	7	8	8	8
FIELD SITE SETUP REQUIREMENTS	7	3	10	3	10	7	6	6
OBTAINING A ROUTINE READING	8	8	1	8	4	10	8	8
INTERPRETATION OF READINGS	10	10	10	10	3	5	3	5
ACCURACY	10	10	10	8	2	7	2	3
MAINTENANCE	9	9	8	9	7	3	9	9
SPECIAL CONSIDERATIONS	2	8	5	8	9	7	5	8
COMPOSITE RATING	49	49	52	48	42	47	41	47

NP	Neutron Probe
TDR	Time Domain Reflectometry
GS	Gravimetric Sampling
AP	Troxler Sentry 200-AP

AQ Aquaterr Probe

TM Tensiometer

GB Gypsum Block

WB Watermark Block

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SUMMARY AND CONCLUSIONS

Understanding soil water holding capacity and the factors affecting the plant available soil water are necessary for good irrigation management. Information is readily available from Cooperative Extension and the Soil Conservation Service to help growers assess the conditions specific to their own fields and crops.

Several different techniques are available which can be used to effectively monitor or directly measure soil water content. Some are extremely simple and are well worth the investment of time and labor. Many irrigation scheduling consultants are using these different methods.

The cost of keeping track of soil water on your own or by using a service can be paid back through the benefits of effective water management. Included among these benefits are energy savings, water savings, water quality improvement, and quite often improved crop quality and yields.

Successful implementation of any of the methods evaluated requires careful attention to the installation, operation, and maintenance requirements discussed. Soil type and irrigation regime are important parameters affecting the choice of a method or technique which will yield the best results.

A routine sampling schedule should be implemented to obtain the most information from any of these methods. The difference in soil water content at a given location from one sampling time to the next often provides more information than random space and time measurements. Soil water should be measured or monitored in at least two depths in the expected crop root zone at several locations in a field to obtain a field average. Subareas within fields having different soil textures or other characteristics should also be monitored.

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[2] The mentioning and use of commercially available equipment is for information and evaluation purposes only and does not imply endorsement by the authors or their respective universities, nor is discrimination against products not mentioned intended.

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