Soil Moisture Content and Tension

A volume of soil contains solid particles-sand, silt, and clay-and voids or pores. The pores contain air and water. Void or pore volume, which contains air and water, ranges from about 30 percent in sand to about 50 percent in clay of the total volume of soil. Clay has more pore volume than sand, but the pores are smaller because of the smaller particle sizes of clay. Sand has larger pore sizes because of larger particle sizes. Both pore volume and pore size play major roles in water movement and water retention or water-holding capacity of soil.

Saturated soil has pores completely filled with water. (In reality, complete saturation does not occur because some entrapped air exists in saturated soil.) No air can flow through the soil. Unsaturated soil has pores partially filled with water so that air can flow though the soil.

Soil Moisture Content

The amount of water in soil is the soil moisture content. Methods used to describe soil moisture content are gravimetric soil moisture content, volumetric soil moisture content, and depth of soil moisture per depth of soil. The section, *Soil Sampling*, contains detailed information on these descriptions. Both volumetric soil moisture content in percent and depth of soil moisture per depth of soil are most commonly used. Using gravimetric soil moisture content can underestimate the amount of soil moisture used or available by plants.

Gravity drainage and crop use of soil moisture drains water out of the pores after irrigation. This causes a saturated soil to become unsaturated. The largest pores empty first followed by progressively smaller pores as drainage continues. Thus, the remaining soil moisture occupies the smaller pores, and as drainage continues, the moisture is retained in progressively smaller pores.
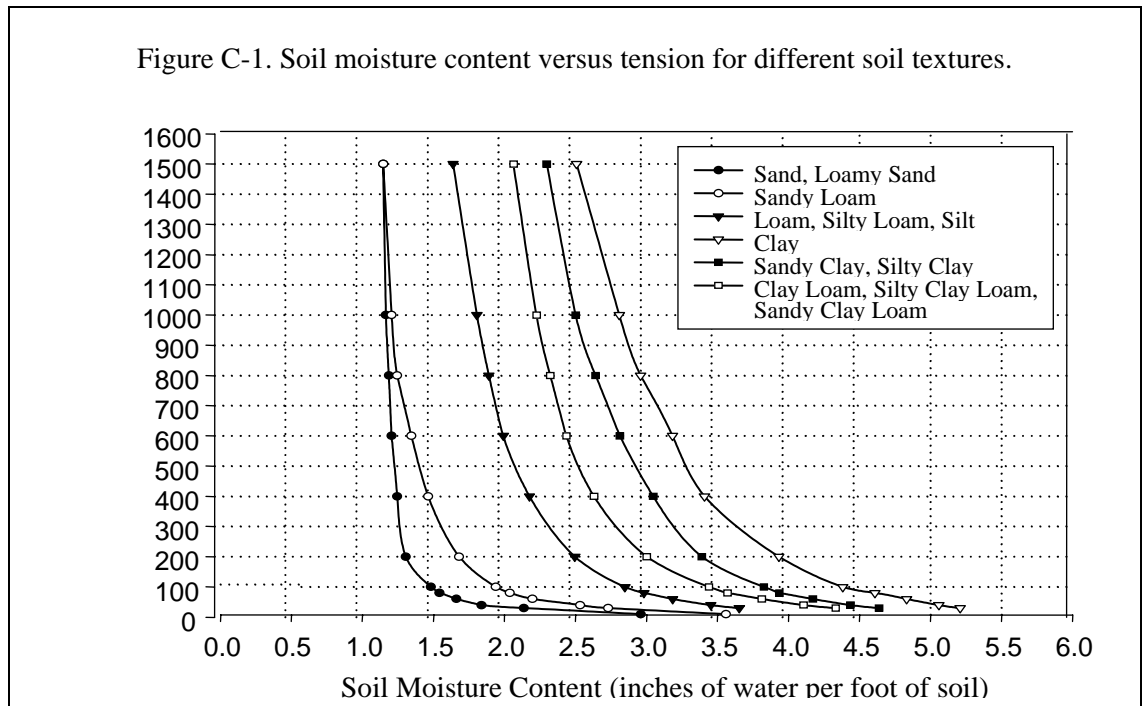
Soil Moisture Tension

The retained soil moisture is held in the soil by a complex phenomenon called surface tension. Surface tension generates a force that binds the water to the soil particles. The magnitude of the force depends on soil moisture content. The drier the soil, the larger the surface tension forces, and the larger the tenacity at which water is held in soil.

The soil moisture tension is a measure of the tenacity at which water is retained in soil. As soil dries, soil moisture tension increases, and the more the energy needed to extract soil moisture. Other terms used to describe this tenacity are soil suction, matric potential, matric suction, or soil water suction. Units commonly used for soil moisture tension are bars and centibars (1 bar = 100 centibars). Most tensiometers and electrical resistance blocks used for irrigation scheduling use centibars as the unit of measurement.

The relationship between soil moisture content and soil moisture tension depends on soil texture. For a given soil moisture tension, soil moisture content of a sandy loam will be less than that of clay loam. The relationship between soil moisture tension and soil moisture content is described by soil moisture release curves, shown in *Figure C-2* for various soil textures. Other terms used for these curves are water holding characteristic curves, water retention curves, and water release curves.

Soil Moisture Release Curves

Figure C-1 shows generalized soil moisture release curves for several soil textures. Sandy soil has the smallest amount of retained water for a given tension, and the clay soil the largest. From the figure, we see that as soil moisture tension increases, soil moisture content of sandy soil rapidly decreases, whereas the decrease is more gradual for loam soil. Thus, small changes in soil moisture tension result in large changes in soil moisture content for sandy soil, whereas, small moisture changes occur for a clay loam soil.

Figure C-1. Soil moisture content versus tension for different soil textures.

(Source: Ley, T., R. G. Stevens, R. R. Topielec, and W. H. Neibling. 1996. *Soil water monitoring and measurement*. PNW475.)

Available Soil Moisture

Available soil moisture is moisture that plants can use. It depends on soil texture. The upper limit of available soil moisture is the field capacity, defined as the soil moisture at which drainage ceases. Field capacity occurs at soil moisture tensions of 1/10 bar (10 centibars) for sandy soil and 1/33 bar (33 centibars) for other soil. The lower limit is the wilting point, defined as the soil moisture at which plants wilt permanently. Permanent wilting point occurs at 15 bars of soil moisture tension. Sandy soils have less available soil moisture than clay soils. *Tables C-1* and *C-2* list average values and ranges of available soil moisture for various soil textures.

Total available soil moisture in the root zone is available soil moisture obtained from *Table C-1* multiplied by root depth.

Table C-1. Soil moisture content in inches of water per foot of soil at field capacity, 15 bars, and available soil moisture for various soil textures.			
Soil Texture	Field Capacity	15 Bars	Available Moisture Content
Sand	1.2	0.5	0.7
Loamy Sand	1.9	0.8	1.1
Sandy Loam	2.5	1.1	1.4
Loam	3.2	1.4	1.8
Silt Loam	3.6	1.8	1.8
Sandy Clay Loam	3.5	2.2	1.3
Sandy Clay	3.4	1.8	1.6
Clay Loam	3.8	2.2	1.6
Silty Clay Loam	4.3	2.4	1.9
Silty Clay	4.8	2.4	2.4
Clay	4.8	2.6	2.2

Sometimes soil moisture content is expressed as percent of water in a volume of soil, listed in *Table C-2*. For example, a moisture content of 32 percent means that 32 percent of the soil volume is water. To convert from percent soil moisture content to inches of water per foot of soil, multiply percent content by 12 inches per foot and divide by 100. For example, 32 percent soil moisture content x 12 inches per foot / 100 = 3.8 inches of water per foot of soil.

Table C-2. Volumetric (%) soil moisture content at field capacity, 15 bar, and available soil moisture for various soil textures			
Soil Texture	Field Capacity (%)	15 bar (%)	Available Moisture Content (%)
Sand	10	4	6
Loamy Sand	16	7	9
Sandy Loam	21	9	12
Loam	27	12	15
Silt Loam	30	15	15
Silty Clay Loam	36	20	16
Clay Loam	32	18	14
Sandy Clay Loam	29	18	11
Sandy Clay	28	15	13
Silty Clay	40	20	20
Clay	40	22	18

Available moisture contained in the root zone, which will be extracted during the season, can be easily estimated using a quantitative moisture-measuring device. (See *Neutron Moisture Meters*) The amount of water contained in the root zone should be measured at bud break and again at the dry point, occurring at harvest for irrigated vineyards. The difference between these values equals the amount of water that typically is available for use during the period bud break through harvest. Figure C-2 shows the amount of available water measured in the same Lodi vineyard ove an eight year period. For this use, it is best to locate the access well away from a drip emitter's wetted area. It is necessary to measure the bud break soil water content each year since the amount of effective rainfall varies each year as well as residual post harvest irrigation amounts.

The amount of water remaining in the root zone is influenced by the irrigation strategy and any changes in the root zone over time by further root extensiveness. A deficit irrigation strategy results in a relatively dry root zone at harvest and works well in this scenario. However, a full irrigation regime will at harvest contain substantial quantities of water in the root zone with its distribution depending on the irrigation schedule and distribution of the irrigation water.

Figure C-2. Available water (inches at bud break)
in different years
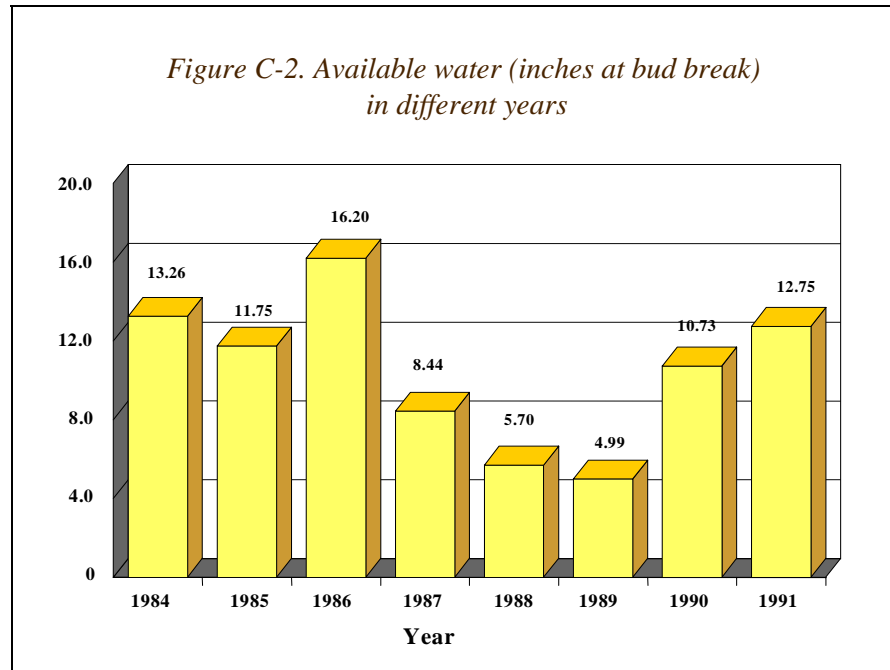
General References.

Ratliff, L. F., J. T. Ritchie, and D. K. Cassel. 1983. "Field-measured limits of soil water availability as related to laboratory-measured properties." *Soil Science Society of America Journal*, Vol. 47:770-775.

Measuring Soil Moisture

Many methods exist for measuring or monitoring soil moisture content. Methods that measure soil moisture content help determine when to irrigate and how much soil moisture was used. Methods that measure soil moisture tension help determine when to irrigate, but they require calibration to relate soil moisture tension to soil moisture content. Even though reliable calibrations may be unavailable, monitoring soil moisture tension provides useful information on trends of soil moisture content with time, patterns of soil moisture uptake by roots, and depths of wetting. In addition, simple observations correlating soil moisture content determined by soil sampling and the instrument's reading could help to determine those readings that indicate a need to irrigate.

Methods

These methods and their use, described in detail in the succeeding sections, are summarized as follows.

Soil probe/soil sampling. Soil samples are obtained using a soil probe or auger. Appearance and feel of the soil is related to soil moisture using an appropriate chart. Soil samples can also be dried in an oven to determine actual soil moisture.

Tensiometers. A tensiometer is a plastic tube with a porous cup attached to one end and a vacuum gauge attached to the other end. The porous cup is inserted into the soil, and the vacuum gauge

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measures the soil moisture tension. Tensiometers measure soil moisture tension. See "Tensiometers."

Electrical resistance blocks. These devices are two electrodes embedded in gypsum or a gypsum-ceramic mixture. Changes in soil moisture content cause changes in the water content of the block, which in turn changes its electrical resistance. An appropriate instrument is used to read the electrical resistance or conductance of the block depending on the manufacturer. Readings of resistance blocks are related to soil moisture tension. See "Electrical Resistance Blocks."

Neutron moisture meters or neutron probes. This method involves lowering a tube containing a sealed radioactive source and a detector into the soil. Fast neutrons are emitted by the radioactive source and then are converted to slow neutrons by hydrogen atoms in the soil water. The amount of slow neutrons is related to soil moisture content. This instrument measures soil moisture content over a volume of soil with a horizontal diameter of about 12 inches and a vertical diameter of about 6 inches. See "Neutron Moisture Meters."

Dielectric Soil Moisture Sensors. Dielectric moisture instruments measure the dielectric constant of the soil. This constant, an electrical property of the soil, depends on soil moisture content. Appropriate calibration equations relate dielectric constant to soil moisture content. A variety of instruments are available. See "Dielectric Soil Moisture Sensors."

No one method is the best. Each has advantages and disadvantages depending on the use of the measurement. Since the implementation of deficit irrigation strategies requires a quantitative measurement of soil moisture for use in the calculation of applied water volumes, neutron meters or dielectric sensors are preferred. Tensiometers, electrical resistance blocks, and the soil probe feel method however useful for soil moisture status are not appropriate for this use.

Soil Sampling

Soil sampling is commonly used to determine soil moisture content. Two types of soil sampling are gravimetric sampling and volumetric soil sampling.

Gravimetric Soil Moisture

Gravimetric sampling measures soil moisture content on a weight basis by dividing the weight of water in the sample by the dry weight of the soil sample. An auger for obtaining soil samples, an oven for drying the soil, and a balance or scale for weighing the samples before and after drying are needed.

Volumetric Soil Moisture

Volumetric sampling measures the soil moisture content on a volume basis by dividing the weight of water in the sample by the volume of the sample. A soil sampler that collects a sample of a known volume, an oven, and a balance are required.

Soil samples are collected at the desired locations, and then are weighed and dried to determine their moisture content. A step-by-step procedure follows:

Procedure

1. Collect a soil sample at the desired location and depth. This may require auguring or excavating to reach the required depth. Any one of a number of commercially available samplers or augers can be used. A volumetric soil sampler is required for measuring the volumetric soil moisture.

2. Remove the sample from the collection device, place it in a metal container of known weight, and then weigh the sample and container. If the sample cannot be weighed immediately, the can should be sealed tightly for later weighing.

3. After the weight of the can and wet soil sample has been measured, place the opened can containing the soil sample in an oven. Dry the sample for at least 24 hours (preferably 48 hours) at a constant temperature of 105°C (221°F).

4. When drying is completed, allow the can to cool, and then weigh the can and the dry soil sample. The weight decrease is the amount of soil moisture in the soil sample at the time it was collected.

5. Use the following formulas to calculate the moisture content and the bulk density of the sample.

   [1] Gravimetric soil moisture (GM)

   $$GM = (W_w - W_d) / W_d$$

   W_w = weight of the wet soil
   W_d = weight of the dry soil (weight of can must be subtracted from weight of dry soil + can)

   [2] Volumetric soil moisture (VM)

   $$VM = V_w/V_s = (W_w - W_d)/V_s$$

   V_w = volume of water in the sample
   V_s = volume of the soil sample.

   V_w equals $W_w - W_d$ where the weight is in grams. Units of measurement must be consistent for calculating the volumetric soil moisture. No conversion is needed for weight expressed in grams and volume expressed in cubic centimeters or milliliters because 1 cubic centimeter of water weighs 1 gram. If the weight is in ounces and the volume is in cubic inches, then divide the weight by 0.578 to calculate the cubic inches of water in the sample.

   The depth of water per depth of soil can be determined from the volumetric soil moisture content. Multiply the volumetric water content expressed as a decimal fraction by the depth interval over which the sample was collected to calculate the depth of soil moisture over that depth interval. For example, if the depth interval is 12 inches, multiply the volumetric water content by 12 to calculate the inches of water per foot of soil.

[3] <u>Soil bulk density (BD).</u> The soil bulk density of the soil is necessary to convert gravimetric soil moisture to a depth of water. The bulk density (BD) is as follows.

$$BD = W_d / V_s$$

Gravimetric moisture content is multiplied by bulk density to obtain volumetric moisture content.

Gravimetric sampling is the easiest because measuring the volume of the soil sample is not necessary. However, crop water use is expressed as a depth of water. This means that the volumetric moisture content must be used to estimate crop water use. For a given soil sample, the volumetric soil moisture content will be greater than the gravimetric soil moisture content.

Which is the best?

Soil Probes and Augers

Soil probes and augers can be purchased from the following:

Art's Manufacturing & Supply
105 Harrison
American Falls, ID 83211
Telephone: (800) 635-7330
Fax: (208) 226-7280

Ben Meadows Company
2589 Broad Street
Atlanta, Georgia 30341
Telephone: (800) 241-6401
Fax: (800) 628-2068

Tensiometers

A tensiometer—a device for measuring soil moisture tension—is a cylindrical pipe about one inch in diameter with a porous ceramic cup attached to one end and a vacuum gauge attached to the other *(Figure C-3)*. The porous cup allows water to flow in and out of the tensiometer as soil moisture content changes. The vacuum gauge readings, which measure soil moisture tension, change in response to this water flow. Units of gauge readings for commercially made tensiometers frequently are in centibars, with the vacuum gauge ranging between 0 and 100 centibars. A reservoir is located at the top of the tensiometer. The tensiometer must be sealed tightly to prevent air from entering to operate properly.

Figure C-3. Tensiometer

Cap

Reservoir

100 50 0

Vacuum Gauge

Water

Porous Ceramic Cup
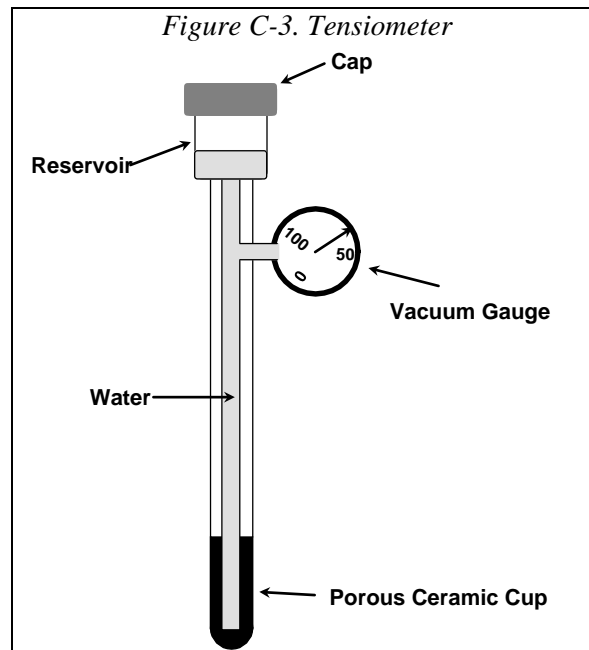
Tensiometers are easy to install, read, and maintain. They provide information on soil moisture tension, which helps irrigators determine when to irrigate.

Tensiometers do not directly measure soil moisture content. Relationships between tensiometer readings and soil moisture contents are needed to determine soil moisture depletions. These relationships depend strongly on soil texture, as shown in *Figure C-4* for sandy loam and silt clay. While generalized relationships exist for various soil textures, their accuracy is uncertain for any given site. Calibration for a particular site requires sending soil samples to a laboratory to develop a soil moisture release curve.

Figure C-4. Tensiometer reading versus soil moisture content for two soil textures.
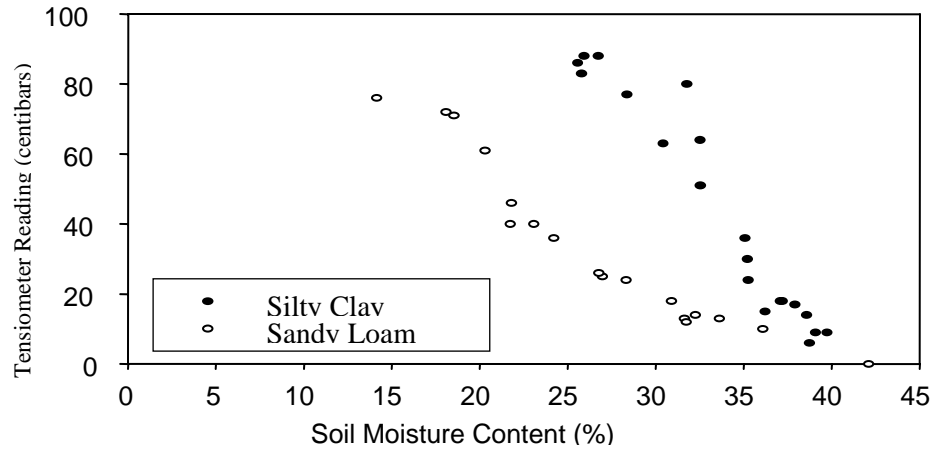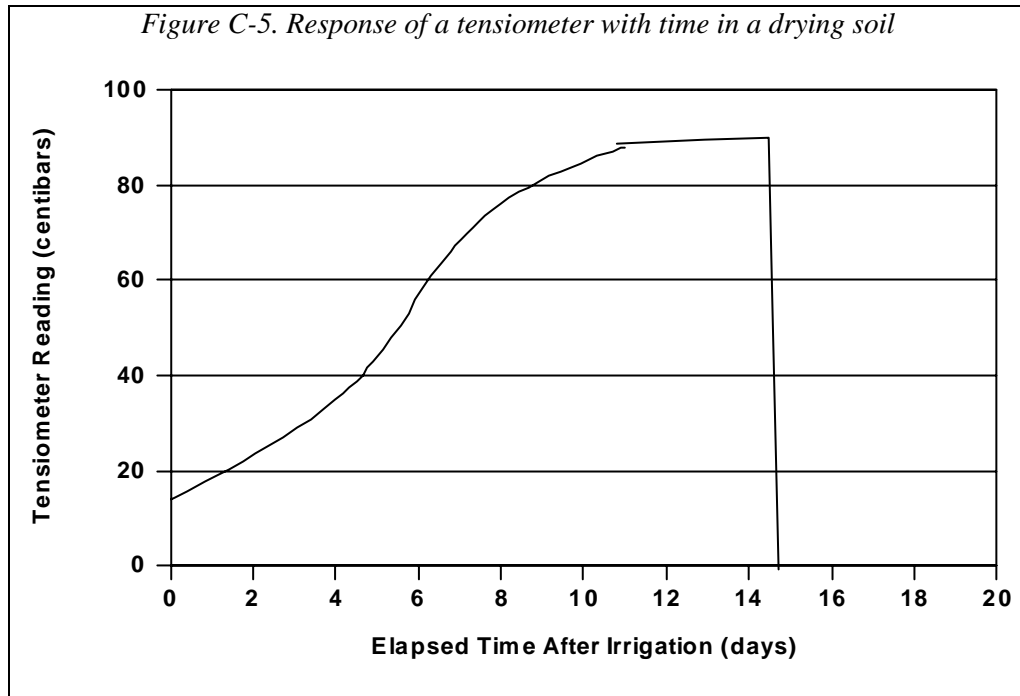
As soil dries, soil moisture content decreases and soil moisture tension increases. This decrease in soil moisture content causes water to flow out of the tensiometer through the porous cup, and the tensiometer gauge to read higher and higher. During irrigation, soil moisture content increases causing soil moisture tension to decrease and water to flow into the tensiometer. This causes tensiometer readings to decrease.

Water flows in and out of tensiometers only if the porous cup is saturated with water. If the cup de-saturates, then little or no flow occurs, and air enters the tensiometer. The tensiometer then stops operating.

Figure C-5 shows tensiometer readings with time in drying soil. Initially, the tensiometer reading increases with time. Eventually, readings become constant with time, even though drying continues, because the vapor pressure of water is reached, about 80 centibars at sea level. At that vacuum, water turns into vapor preventing any further increases in tensiometer readings. As soil continues to dry, tensiometer readings drop to zero because the porous cup de-saturates and allows air to enter the tensiometer.

Figure C-5. Response of a tensiometer with time in a drying soil

Chart: Tensiometer Reading (centibars) on the vertical axis (0 to 100) versus Elapsed Time After Irrigation (days) on the horizontal axis (0 to 20). The curve rises from about 14 centibars at day 0, passes through 40 at about day 5, 55 at day 6, 75 at day 8, levels off near 90 by day 11–14, then drops sharply to 0 at about day 15.

To restore proper operation, tensiometers must be re-saturated by filling the pipe and reservoir with water and flowing water through the porous cup for several hours before sealing the pipe. However, unless the soil is rewetted by an irrigation, the porous cup will rapidly de-saturate again. Thus, tensiometer readings that drop to zero in dry soil do not necessarily indicate faulty instruments, but rather dry soil with moisture contents likely to reduce crop growth and yield of water-stress sensitive crops.

Maximum Readings

Because of the vapor pressure of water, maximum tensiometer readings at sea level are 80-85 centibars. Maximum readings decrease with altitude because vapor pressure depends on altitude. At 3,000 feet, about 60 centibars is maximum for tensiometers.

Problems in Sandy Soil

A tensiometer may operate poorly in a very sandy soil. The coarseness of the sand may cause poor hydraulic contact between the porous cup and the soil. Thus, water will not readily flow in and out of the tensiometer resulting in a very slow response of the tensiometer to changes in soil moisture. One manufacturer markets a tensiometer that is designed to overcome this problem to some degree by using a relatively coarse porous cup.

Installing a Tensiometer

First, soak the tensiometer in water for several hours to saturate the porous cup. Next, make a pilot hole with a soil probe down to the desired depth. Pour a small amount of slurry of soil and water into the pilot hole before inserting the tensiometer to ensure good hydraulic contact between soil and porous cup. Next, insert the end of the tensiometer with the porous cup into the pilot hole. Then fill the tensiometer with water, seal it, and allow it to equilibrate for about 24 hours before making readings.

Install tensiometers at about one-fourth to one-third of the maximum root depth to schedule irrigations. Another tensiometer installed near the bottom of the root zone is recommended to monitor depth of wetting. Tensiometer readings at that depth that do not change after irrigation or continue to increase during the growing season indicate insufficient water applications.

Adjusting Tensiometer Readings

The number of tensiometer stations required depends on irrigation system type, soil uniformity, and cropping patterns. At least two stations should be established for every 40 acres. More stations may be needed depending on soil texture variability. In fields with different crops, monitor each crop separately because of different water use patterns.

Tensiometer readings will differ from the actual soil moisture tension (SMT) because of the tensiometer's length between porous cup and vacuum gauge. Some instruments can be adjusted for this length by filling them with water, standing them upright in a pan containing enough water to cover the cup, and adjusting the gauge. Otherwise, tensiometer readings are adjusted by the following equation.

$$SMT(centibars) = Tensiometer\,\mathrm{Re}\,ading(centibars) + Length(inches) \div 4$$

Maintenance

Periodic maintenance is required for tensiometers. Periodically fill the tensiometer with water and replace porous cups and O-rings as needed. A cracked cup prevents a vacuum from occurring in the tensiometer causing the instrument to always read zero. A saturated porous cup should not be exposed to the atmosphere for long periods of time. Such exposure evaporates water from the cup's surface causing salt buildup and clogging. Copper sulfate or an algaecide may be needed to prevent algae growth in the tensiometer.

Automation

Tensiometers can be used with automated irrigation systems. Soil moisture tension is measured with pressure transducers in addition to vacuum gauges. Solenoids attached to the instrument then turn water on and off based on soil moisture tensions measured by transducers.

Where can I purchase tensiometers?

Tensiometers are available through local irrigation equipment dealers. They come in standard sizes ranging from 6 to 72 inches. Manufacturers who supply tensiometers include:

Irrometer Co., Inc.
P.O. Box 2424
Riverside, CA 92516-2424
Telephone: (909) 689-1701

Soil Moisture Equipment Corp.
P.O. Box 30025
Santa Barbara, CA 93105
Telephone: (805) 964-3525

Electrical Resistance Blocks

Electrical resistance blocks, commonly called gypsum blocks or soil moisture blocks, measure the electrical resistance of the blocks' moisture content. This device uses two electrodes embedded in gypsum or a granular material (see *Figure C-6*). Wires extending to the soil surface connect the meter to the blocks.

Electrical resistance blocks are easy to install, read, and maintain. Because they are buried, damage by farming equipment, animals, etc. is minimal.

Figure C-6. Electrical resistance block

Wire

Display → 55

Electrical Resistance Block

Instrument
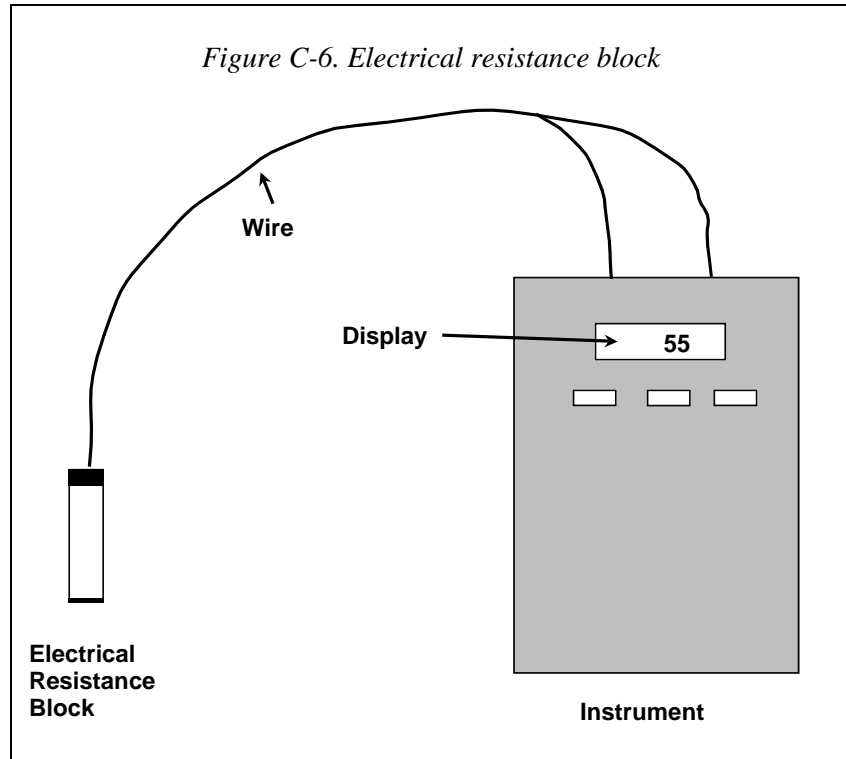
Most electrical resistance blocks are made of gypsum. Gypsum stabilizes the salinity of the moisture in the block, thus buffering the effect of salinity on electrical resistance or conductance.

The granular matrix sensor marketed as the Watermark block contains electrodes embedded in a ceramic-sand material. A wafer of gypsum installed in the granular material buffers salinity effects on the readings. The instrument provided for these blocks reads in centibars of soil moisture tension.

Drying soil causes water to flow out of the resistance block. Its electrical resistance is then increased because the conducting area for electrical current is reduced. This is analogous to increasing the electrical resistance between two electrodes attached to a wire by using a smaller and smaller wire. Rewetting the soil causes soil water to flow into the block, thus, increasing the conducting area and decreasing its electrical resistance.

Electrical resistance of blocks also depends on the salinity of the block water. Salinity effects are stabilized by the gypsum in the block dissolving or precipitating as the block water content changes. These reactions maintain a constant electrical conductivity of the block water. However, if the salinity of the soil moisture exceeds that of a saturated gypsum solution, block salinity can increase and affect the electrical resistivity of the block. Soil salinity can affect readings of resistance blocks if the electrical conductivity of saturated extracts of soil samples exceeds about 1 to 1.5 dS/m (mmhos/cm).

Figure C-7 shows responses of gypsum block readings to changes in soil moisture content for two soil textures. Block readings in sandy loam changed little for soil moisture contents greater than about 25 percent. Large changes occurred for smaller moisture contents. In silty clay, readings changed considerably for moisture contents smaller than about 40 percent. These behaviors show gypsum block readings not responding to changes in soil moisture content for moisture contents greater than some threshold value. This value depends on soil texture, with larger threshold values for fine-texture soil than for coarse-texture soil.

The response of the Watermark block for two soil textures, in *Figure C-8*, showed much more sensitivity to changes in soil moisture content in wet soil. Block readings increased gradually as soil moisture content decreased. This response reflects a wider range of pore sizes in the block material compared with the gypsum block. These devices operate over a wider range of soil moisture tensions than do tensiometers.

These results show that some resistance blocks may be insensitive to changes in soil moisture in wet soil. These blocks are more appropriate for use under low-frequency irrigation methods. Watermark blocks are more responsive to changes in moisture content, making them suitable for both low-frequency systems and micro-irrigation systems where frequent irrigations keep soil relatively wet.

First, soak blocks in water for a few minutes to saturate them. Then, make a small-diameter hole with a soil probe or a small-diameter auger to a depth slightly deeper than that desired. Next, add slurry consisting of water, a small amount of soil, and, if possible, gypsum to the hole to provide good contact between soil and block. Before installing a block, check the block reading to ensure that the block is working.

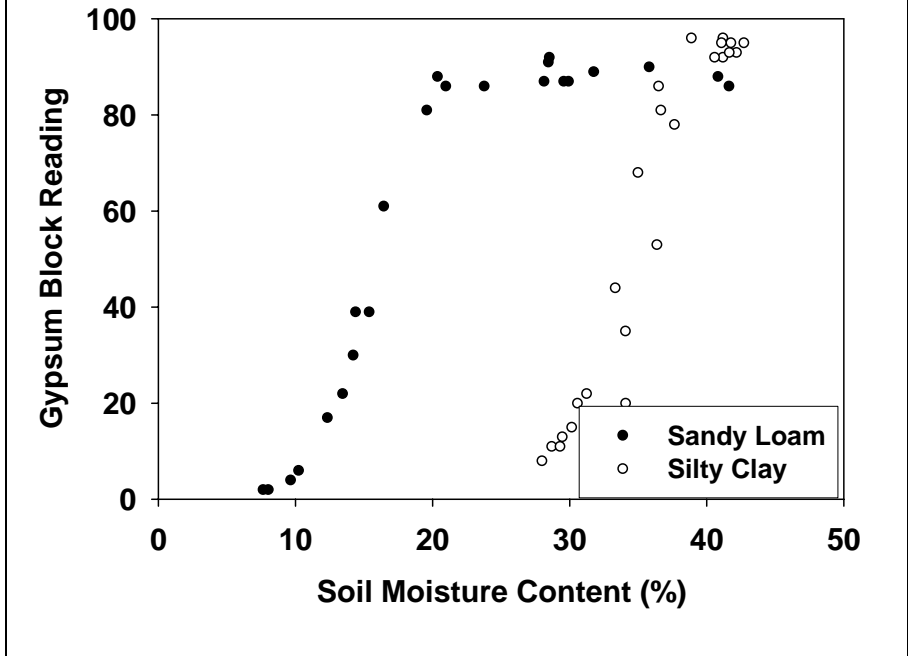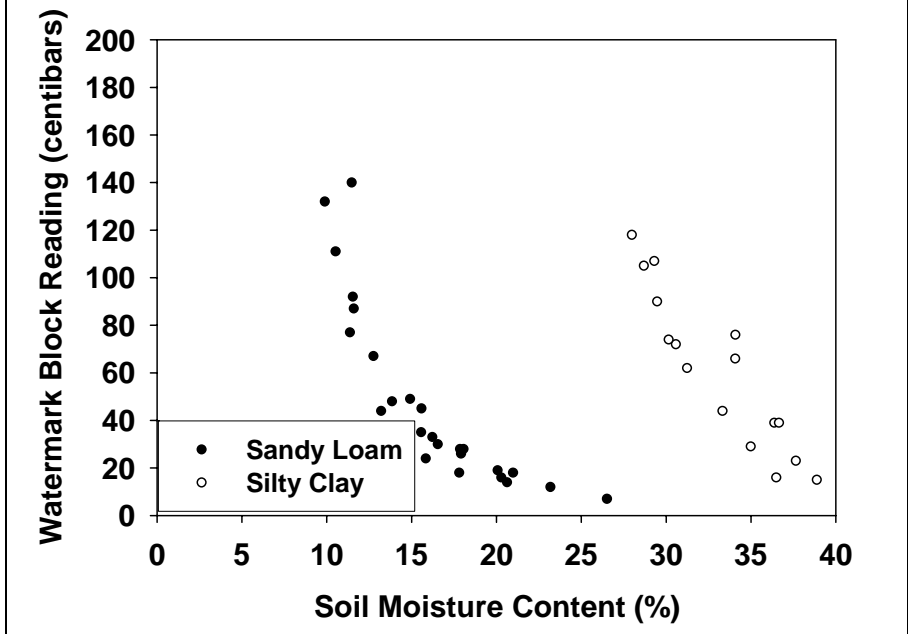*Figure C-7. Response of a gypsum block to soil moisture content.*

Figure C-8. Response of a granular matrix block to soil moisture content

Push the block into the slurry in the bottom of the hole with a length of PVC pipe (1/2", Schedule 80). Remove the pipe and backfill the hole with soil removed from the hole. Do not damage the wire leads during the backfilling. As the hole is filled, pack the backfilled soil in the hole with the PVC pipe. Be sure to identify each block with a tag or knots in the wire.

As a minimum, install one block at approximately one-fourth to one-third of the root zone to schedule irrigations and a block at the bottom of the root zone to monitor depth of wetting. Blocks installed at one-foot depth intervals, however, provide better information on depth of wetting and soil moisture uptake patterns. Little change in block readings at the lower depths after irrigation indicates insufficient water applications.

Install at least two sites of blocks for every 40 acres. More sites may be needed depending on soil texture variability. Separate stations for problem areas or for areas having different soil conditions are recommended.

Watermark blocks are read in a similar manner, as is a tensiometer.

What do readings mean?

For other resistance blocks, instrument readings must be correlated with soil moisture contents or soil moisture tensions to establish relationships between readings and need to irrigate. Even if no correlation exists, however, resistance blocks can help identify patterns of moisture uptake, depths of wetting, and trends of the soil moisture content with time.

Response in Sandy Soil

In very coarse-textured soils, the response of electrical resistance blocks may lag behind changes in soil moisture content caused be poor hydraulic contact between blocks and soil. Under these conditions, block readings may indicate little depletion of soil moisture even though severe drying of soil may occur.

Temperature Effects

The reading of an electrical resistance block also depends on the temperature of the soil. The electrical resistance decreases as the temperature increases. One manufacturer provides for adjustments for temperature while others do not.

Can an ohm meter be used?

A question frequently asked is, "Can an ohm meter be used instead of the manufacturer's meter?" The answer is no. Ohmmeters use DC voltage. Applying DC power to resistance blocks causes polarization at the electrodes and results in unstable readings. The manufacturers' meters convert DC to AC, which stabilizes the meter readings.

Maintenance and Block Life

Resistance blocks are relatively maintenance-free. Gypsum blocks may last one to three years, depending on soil moisture conditions. Constantly wet soil causes gypsum blocks to dissolve more quickly, thus shortening their lives. As gypsum dissolves, contact between block and soil may be lost. Longer life can be expected for blocks made of porous materials that do not dissolve. The wire leads may corrode and require occasional scraping to ensure good contact between wire and meter.

The cost of resistance blocks range from about $6 to $20 depending on the manufacturer. The meter used to read all blocks may range in cost from $200 to $400. Manufacturers of resistance blocks and meters include:

Irrometer Company, Inc.
(Watermark Block)
P.O. Box 2424
Riverside, CA 92516
Telephone: (909) 689-1701

Soil Moisture Equipment Corp.
P.O. Box 30025
Santa Barbara, CA 93105
Telephone: (805) 964-3525

Electronics Unlimited
3231 Riverside Blvd.
Sacramento, CA 95818
Telephone: (916) 448-2650

Delmhorst Instrument Company
51 Indian Lane East
Towaco, NJ 07082
Telephone: (201) 334-2557

Neutron Moisture Meters

What is a neutron moisture meter?

Neutron soil moisture meters (neutron probe) use radioactive material for measuring soil moisture. They contain an electronic gauge, a connecting cable, and a source tube containing both nuclear source and detector tube (*Figure C-9*). An access tube is installed in the ground, and the source tube is lowered into the tube to the desired depths of measurement.

Figure C-9. Neutron moisture meter.
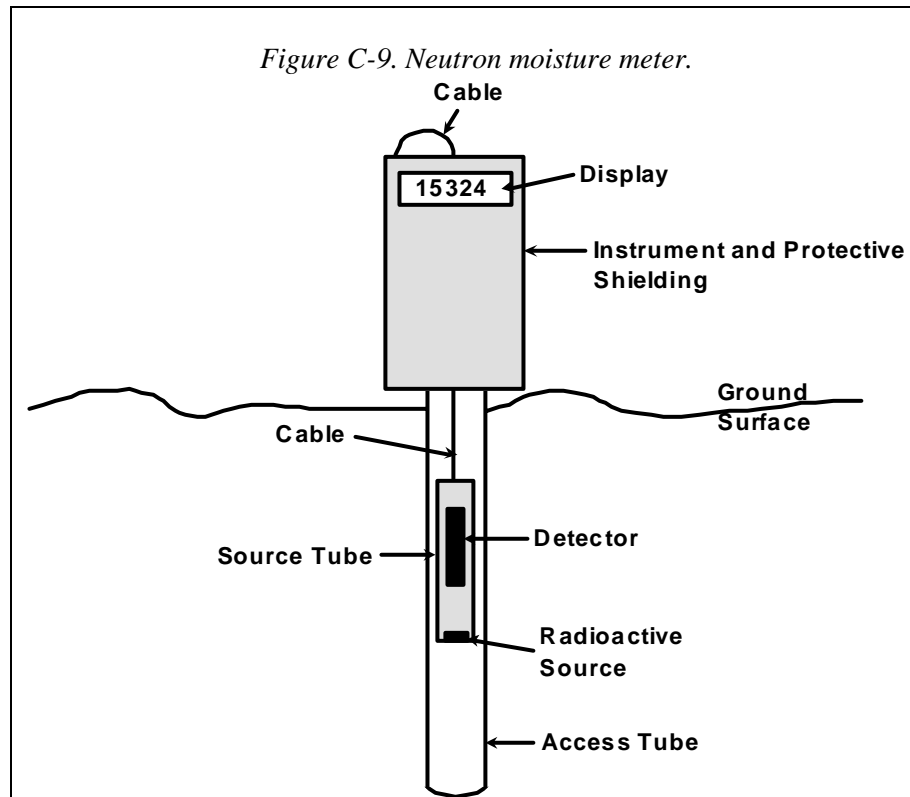
An Americium 241/Beryllium pellet emits high-energy neutrons. Lowering the source tube down in soil causes high-speed neutrons to collide with hydrogen atoms in water and soil. Their energy is then lost and low-energy or "slow" neutrons are created. Some slow

neutrons are reflected back to the source tube and counted by the neutron detector. These "counts" are transmitted to the gauge and displayed. Because soil moisture is the primary source of hydrogen atoms, neutron moisture meters indirectly measure soil moisture content.

An advantage of these meters is a volume of soil about the size of a volleyball is sampled. This more reflects soil moisture contents affecting plant growth compared with sampling volumes of other moisture sensors. Another advantage is that same depths can be measured each time. Measurements can be made at a given site in a few minutes.

One disadvantage of this device is that reliable measurements at shallow depths (less than six inches) may not be possible because some neutrons escape from the soil surface into the air instead of being detected. The main disadvantage of this method, however, is that because a nuclear source is used, operators must be trained in its handling, storage, and use. Licensing is also required with periodic inspections.

Installing a Neutron Moisture Meter

First, install an access tube to the desired depth. Aluminum pipe, PVC pipe, or electrical metal tubing (EMT) is commonly used for access tubes. Because meter readings are affected by access tubing material, the same material must be used for each site. Aluminum affects the readings the least, while PVC affects the readings the most because "slow neutrons" are absorbed by chlorine in PVC. Pipe 2 inches in diameter is commonly used. In high water table areas, the bottom of the access tubing must be sealed to keep out water. Water in the access tube can damage the source tube and cause very high readings.

Auger a hole about the same diameter as the outside diameter of the access tubing to a depth of about 6 inches deeper than that desired for the readings. A small gap between access tube and soil can be tolerated, but surface water should not flow down the side of the access tube. Cover the top of the access tube between measurements to keep water, frogs, and other foreign material out of the tube.

*Calibrating the Neutron Moisture Meter*

Calibrate neutron moisture meters for soil type for best results. A "universal" calibration curve is available for each instrument, but calibration curves can differ for various soil types. The calibration procedure is somewhat complex and should be done by someone who is familiar with the procedure and has the proper equipment.

The calibration curve relates count ratio (or actual count) to soil moisture content (see *Figure C-10*). The count ratio is the actual count divided by a standard count. The standard count is made with the source tube locked in the meter. Count ratios are recommended because actual counts can change with time due to deterioration of the radioactive source and electronic drift of the instrument.

A procedure for developing a calibration curve is:
1. Take volumetric soil samples at each measurement depth. Gravimetric sampling is not recommended. (See "Soil Sampling" for detailed information on sampling.)
2. Take readings with the neutron meter at each measurement depth. A standard count should also be made.
3. Measure the volumetric soil moisture content of the soil samples.

Figure C-10. Count ratio to soil moisture content.
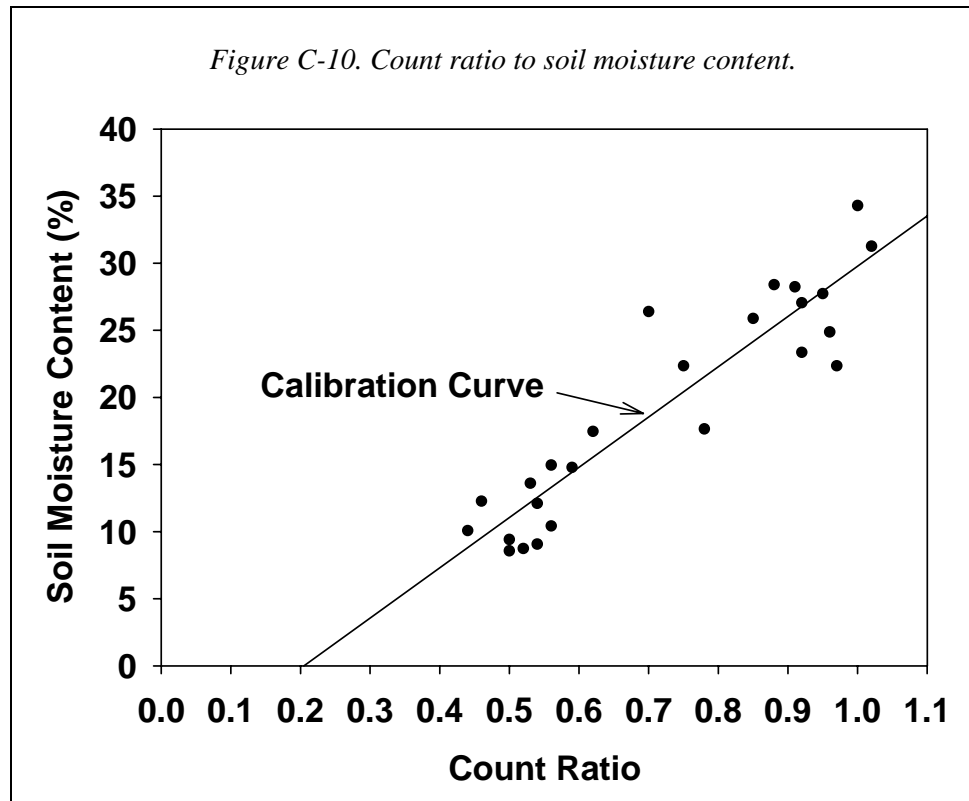
4. The equation for relating the count ratio to the soil moisture content is as follows.

$$SM = a + (b)(CR)$$

where:
- SM = volumetric soil moisture content
- CR = count ratio
- a = y-intercept of the calibration equation
- b = slope of the calibration equation

A hand calculator or computer spreadsheet software with a linear-regression program can be used to calculate the constants "a" and "b". Otherwise, plot the data on graph paper and draw a best-fit line through the data points. Determine the y-intercept and the slope of the drawn best-fit line.

Placement of Monitoring Sites

At least two sites for each 40 acres are recommended. More sites may be necessary depending on soil variability. Additional sites may be needed for problem areas or for areas with different soil or management conditions.

The maximum depth of access tubes should be at least the depth of the root zone. However, measuring moisture contents at deep depths may be desirable for monitoring percolation below the root zone.

25

Access tubes can be place in different locations depending on the purpose of the reading. If measuring the depth of irrigation water penetration, placement under the dripper or in the wetted area of a micro-sprinkler is best. For determining water extraction before irrigation begins, a berm placement 25 percent of the distance between vines on the berm is typical. This practice works well with deficit irrigation since the entire soil becomes quite dry before irrigation begins. For full potential irrigation or for young vines, several access tubes in the wetted zone may be needed. If determining available water content, by measuring soil moisture content at bud break and at harvest (dry point) placement in the root zone and away from the emitter gives a more reliable reading.

Actual counts are not very useful. Actual counts must be related to volumetric soil moisture contents expressed in inches of water per foot of soil using an appropriate calibration curve. Then, measured soil moisture contents can be compared with soil moisture contents at field capacity, and soil moisture depletion determined. Actual depletions can be compared with allowable depletions to determine when to irrigate and how much to apply.

Neutron meters can store multiple calibration curves in memory and can provide direct readouts of soil moisture content in a variety of terms, such as inches per foot and soil moisture percentage. Field readings can be stored for later retrieval or transfer to computers.

Neutron meters require little maintenance beyond checking to ensure proper operation. Access tubes should be checked for water or foreign materials in them. The most common failure is a broken or worn cable, which connects the source tube to the electronic readout device. Replacing cables will cost about $120 every two years. However, in the event that the access tube contains water, considerable damage can occur if the source tube is submersed. Repair costs could exceed $700. A repaired instrument may also require recalibration. Operator recertification is required every two years.

Some considerations in using neutron moisture meters are:

1. Access tubing material can affect counting rates. Highest counting rates occur in aluminum, lowest in PVC.
2. A standard count is made periodically to monitor performance of the meter and to calculate count ratios (actual count divided by standard count). When determining standard counts, place the instrument at least 2 feet above the soil surface and at least 2 feet from any material that can influence the count. At least five counts are recommended for calculating the average standard count to minimize errors in the count ratio.
3. A slight air gap between access tube and soil will not greatly affect count rate. However, prevent ponded water from flowing down the gap. Root density also might be affected by gaps.
4. Normally, one count per depth is sufficient for an error of one percent or less. At least two counts per depth should be made if counts are less than about 5,000 per 30 seconds of counting time.
5. A 30-second counting time is recommended for meters with standard counts less than about 15,000 per 30 seconds. A 15-second counting time is suggested for meters with much larger standard counts (25,000 to 30,000 per 30 seconds).
6. Use caution in interchanging neutron moisture meters. Meters with similar standard counts and their calibration curves can be interchanged as long as count ratios are

used which standardizes the meter's performance. Meters with very different standard counts should not be interchanged unless calibration curves for each instrument are available. Using standard counts may not standardize performances of very different meters.

7. Counts made six inches below the surface are affected by the soil-air interface. However, the slope of a calibration curve for the 6-inch depth is similar to the slope of the calibration curve for the deeper depths. Thus, calculating changes in soil moisture contents at the 6-inch depth are not greatly affected by the soil-air interface.

The current cost of a neutron probe is approximately $5,000 to $6,000. Suppliers include:

Manufacturers

Troxler Electronic Laboratories, Inc.   Boart Longyear CPN
P.O. Box 12057   2830 Howe Road
Research Triangle Park, NC 27709   Martinez, CA 94553
Telephone: (919) 549-8661   Telephone: (415) 228-9770

Dielectric Soil Moisture Sensors

Dielectric soil moisture sensors determine the soil moisture by measuring the dielectric constant of the soil. This constant is a measure of the ability of a dielectric material to establish an electrical field and is highly dependent on the soil moisture. The constant of a dry soil is between 3 and 5, about one for air, and is about 80 for water. Thus, changes in the soil moisture content change the dielectric constant of the soil. Calibration equations have been developed that correlate the soil moisture content and the dielectric constant. The most common dielectric methods are capacitance sensors and time-domain-reflectometry (TDR) sensors although other types of dielectric sensors exist.

Capacitance Sensors

The capacitance sensor (*Figure C-11*) consists of two electrodes separated by a material called the dielectric, a material that does not readily conduct an electrical current. Normally, cylindrical-shaped electrodes are used. Inserting the sensor into the soil results in the soil becoming part of the dielectric. An oscillator applies a frequency between 50 and 150 Mhz to the electrodes, which, in turn, results in a resonant frequency, the magnitude of which depends on the dielectric constant of the soil. The larger the soil moisture content, the smaller the resonance frequency will be.

Figure C-11. Enviroscan/Cprobe capacitance instrument.
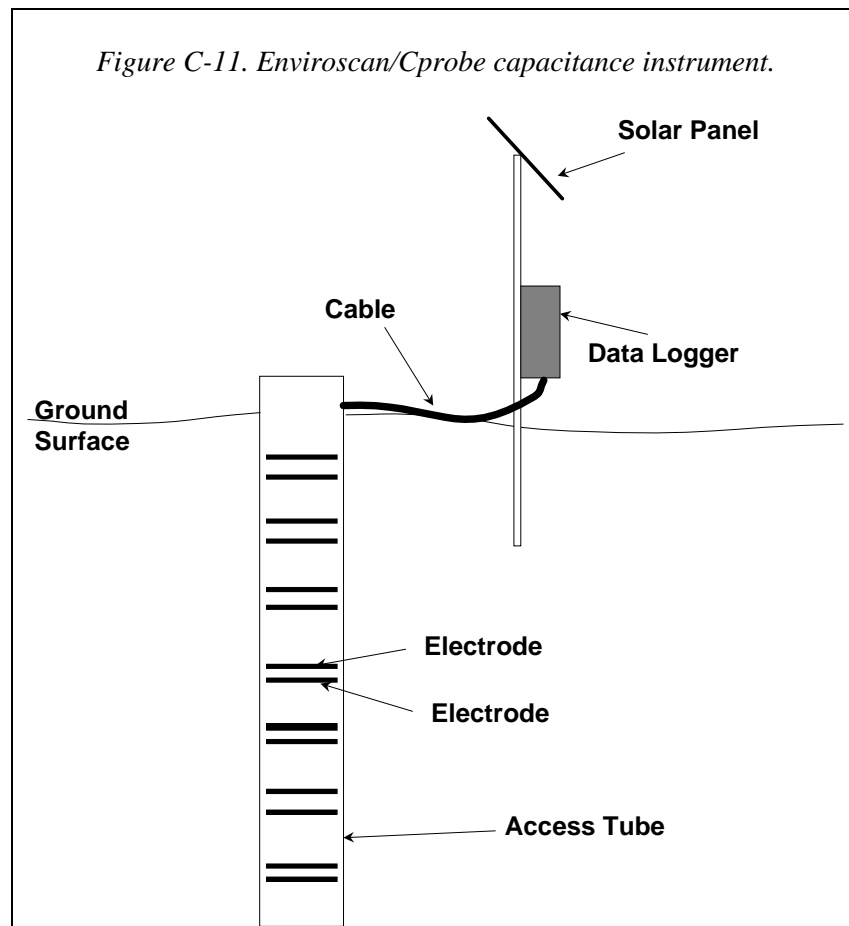
A calibration equation relating the dielectric constant and soil moisture content is necessary. Unfortunately, some uncertainty exists about the effect of soil texture and soil salinity on the calibration although the effect of soil salinity is thought to be small. Calibration equations may be necessary for different soil textures. Further research is needed on these topics.

The zone of influence of this sensor design is restricted to a narrow disk-shaped region surrounding the sensor and centered on the gap between the electrodes. Some uncertainty exists on the distance from the sensor over which the soil moisture content affects the sensor's reading. However, the sensor is most sensitive to the soil moisture content of the soil immediately adjacent to it. This sensitivity means that any air gap between the sensor and the soil will greatly affect the instrument's performance.

Advantages of capacitance probes include the ability to be left in place to continuously log soil moisture content; repeatability of measurements; sensitivity to small changes in soil moisture content; and their precise resolution with depth because of the narrow vertical zone of influence.

Disadvantages include the need for a calibration equation; the difficulty in developing the equation; the relatively small zone of influence; possible influence of soil salinity on

probe reading; and sensitivity to air gaps surrounding the sensor. Costs of these devices range from a few hundred dollars to many thousands of dollars.

Time-domain-reflectometry involves installing two or three steel rods, called waveguides, into the soil parallel to each other (*Figure C-12*). Components of a TDR system are a voltage pulse generator, a signal analyzer, the waveguides, and a cable connecting the waveguides to the instrumentation.

Figure C-12. Time-domain-reflectometry sensor.

Cable   **Instrument**

Probes or Waveguides
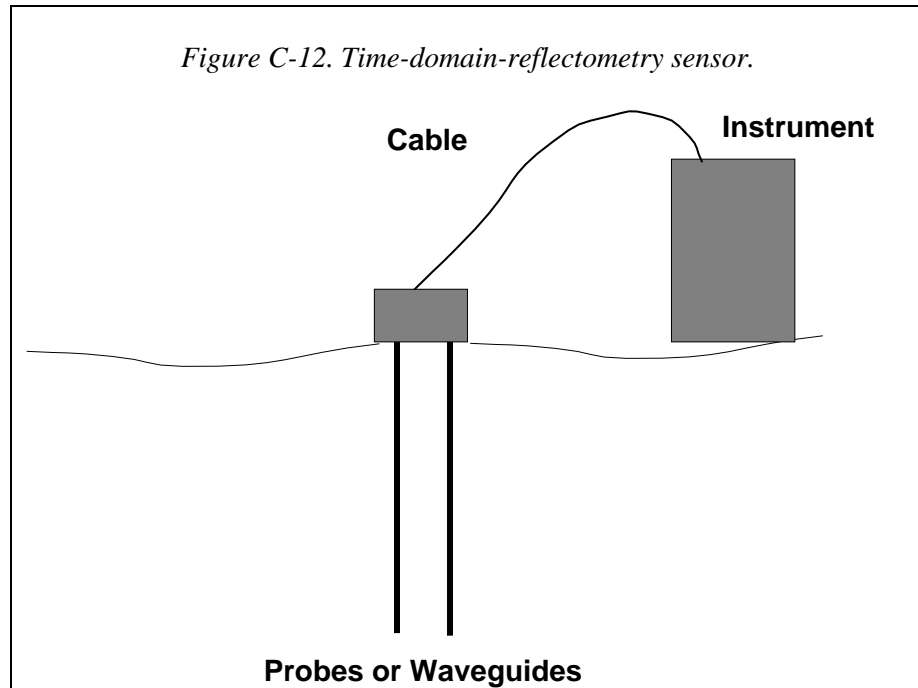
An electrical pulse applied to the waveguides travels its length, and then is reflected back as shown in *Figure C-13*. The travel time required for the pulse to reach the end of the waveguides and back depends on the dielectric constant of the soil. The larger the dielectric constant, the longer the pulse travel time.

Figure C-13. Behavior of electrical pulse along waveguides.
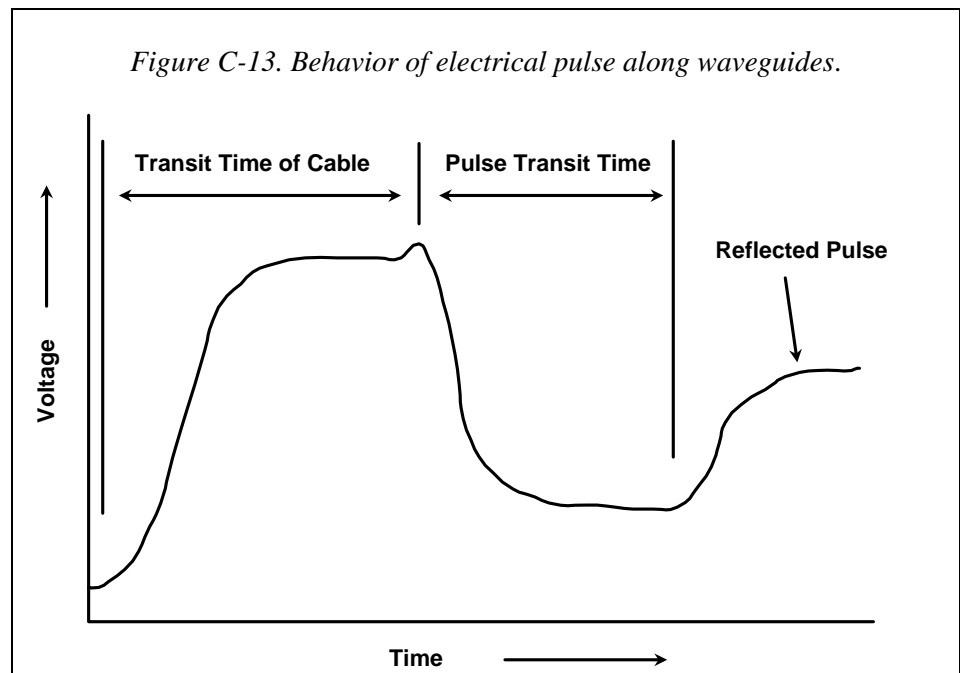
Most TDR sensors contain two to four waveguides. Lengths can range between a few inches to several feet. Keeping the probes parallel during installation may be difficult for lengths longer than two or three feet. The dielectric constant and thus the soil moisture is averaged along the waveguide's length. Measurements at specific depths can only be made by using very short waveguides, which may affect the accuracy of the measurement, or by installing longer waveguides horizontally into the soil, not practical for irrigation scheduling purposes.

A calibration equation has been developed for TDR systems that relate the dielectric constant and the soil moisture content. This equation has been found to be valid for a wide range of soil textures. Some discrepancies may exist between the calculated soil moisture content and the actual moisture content for values less than about 5 percent, generally too dry to be of little interest for irrigation scheduling purposes. Site-specific calibration may be required for soils with high iron contents or high organic matter content such as peat soils.

The zone of influence appears to be very small for a TDR sensor. Most of the response reflects the soil moisture within about one inch from the waveguide. Thus, the zone of influence of a one-foot long probe is a strip one-foot long extending about one inch beyond the waveguides. The width of the strip depends on the distance between the waveguides. Because of this small zone, an air gap between the waveguide and the soil can adversely affect its measurements.

The electrical conductance of a soil can affect the performance of a TDR system by attenuating the amplitude of the reflected TDR signal. Some studies have investigated using this behavior to measure soil salinity. However, relatively high levels of soil salinity may severely attenuate the reflected TDR signal such that the travel time cannot be measured. Under these conditions, TDR sensors cannot be used to measure soil moisture content.

Advantages of the TDR sensor are its ability to be left in place to continuously measure soil moisture content; its ability to make easy and rapid measurements; the use of a "universal" calibration equation; and its depth-averaged soil moisture content. Disadvantages include the relatively small zone of influence; its sensitivity to air gaps between the waveguide and soil; and signal attenuation caused by soil salinity.

Waveguides can be installed successfully from the surface to 18-24 inches. Deeper depths require digging a pit after which the waveguide pair or all-in-one sensor is inserted into the undisturbed pit wall or bottom. This necessary soil disruption can change both water movement and extraction patterns resulting in erroneous water use/recharge readings.

Some Types of Instruments

Costs of TDR systems may range from $500 to $600 to thousands of dollars depending on the system.

GroPoint (Environmental Sensors, Canada). This time domain sensor consists of a U-shaped electrode with a rod located within the U (see *Figure C-14*). A hole is augured to the desired depth of installation, the sensor inserted into the hole, and the hole is backfilled. The soil must be carefully packed around the electrodes to prevent any air gaps. This instrument can be used with a hand-held meter or with a low-cost data logger. The data logger can be downloaded into a shuttle, which then can be downloaded into a computer at some other time. Costs of the sensor are from $200 to $300, the data logger from $300 to $400, and the hand-held meter is $261. Advantages of this sensor are its relatively low cost and accuracy. Disadvantages are the need to disrupt the soil and roots to install the sensor.

Figure C-14. GroPoint dielectric soil moisture sensor.
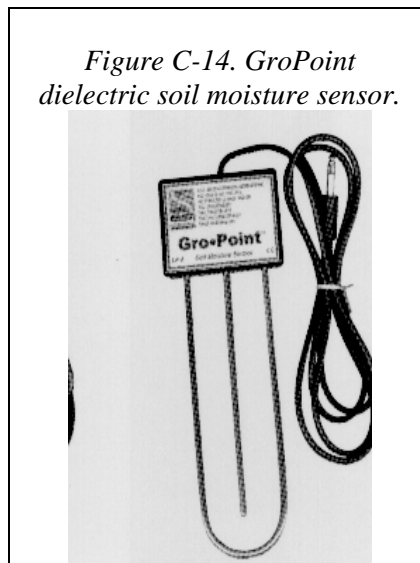
Aquaterr Moisture Meter (Aquaterr Instruments, Fremont, CA). This capacitance meter consists of a steel rod containing two electrodes at its tip. The rod is pushed into the soil to the desired depth of measurement. A pilot hole may be needed if the soil surface is too dry. This device provides a qualitative reading of soil moisture between 0 (dry soil) and 100 (water). A color-coded chart relates meter reading to degree of wetness for different soil types. Advantages of this soil moisture sensor are its low cost compared to other

dielectric instruments -- about $500 -- and its portability, thus allowing measurements to be rapidly made at many locations in a field. Its portability, however, can be a disadvantage for making measurements over time because of soil variability. In dry soils insertion to any meaningful depth is difficult.

Enviroscan (Sentek Pty Ltd) and *C-Probe* (Adcon Telemerty, Boca Raton, FL). These capacitance sensors consist of a series of cylindrical electrodes installed in a PVC access tube. The sensors are located at the desired depths of measurement, and are left in place for the irrigation season. A cable connects the sensors to a data logger powered by a solar panel and battery. The data can be downloaded to a computer via a data pod or through telemetry to obtain the measurements of soil moisture content. An advantage of this device is its ability to make continuous measurements at small time intervals. Disadvantages include its cost (about $1600 for the basic single station unit and up to 4000 for a full weather station including the soil monitoring probe) and the difficulty in installing the access tube without any air gaps.

Diviner 2000 (Sentek Pty Ltd). This capacitance sensor uses the same technology, as does the Enviroscan. However, this sensor is portable and uses one set of electrodes. Measurements are made by lowering the sensor down a PVC access tube. As the sensor is lowered, measurements of depth below the ground surface and soil moisture content are made and recorded in a small computer. After the measurements are made, the sensor is removed from the access tube, and measurements then can be made at another location. One sensor can be used at many different locations

Sentry (Troxler Electronic Laboratory, North Carolina). This capacitance meter consists of a probe containing two cylindrical electrodes. The probe is lowered into a PVC access tube (2-inch Schedule 40) to the desired depth of measurement. One instrument can be used for many different access tubes, similar to using the neutron moisture meter. Calibration is provided for sandy soils but an adjustment may be needed for finer-textured soils. Advantages of this instrument are its relatively low cost (about $3,000 to $4,000); its portability; and its flexibility in making measurements at different depths. Disadvantages included the difficulty in installing the access tube such that no soil compaction or air gaps exist, and its limited calibration.

TRASE System (Soilmoisture Equipment Corp., Santa Barbara, CA). This TDR instrument requires driving two steel rods parallel to each other into the ground. The soil moisture content is averaged over the length of the rods. Maximum recommended depth of installation is about three feet because of the difficulty of keeping the rods parallel for deeper installations. The waveguides can remain in place during the duration of the irrigation season. The advantages of this instrument are its relative ease of installation compared with other dielectric instruments; and it's averaging over the probe length which is desired for irrigation scheduling purposes. Disadvantages include the difficulty in removing rods and its cost.

ThetaProbe (Delta-T Devices Ltd, Cambridge, England; marketed by DYNAMAX, Houston, TX). This sensor contains four small steel rods installed at the end of a short section of PVC pipe. A cable connects the sensor to a hand-held readout instrument. A hole is augured down to the desired depth, and the instrument is pushed into the soil at the bottom of the hole. The probe can be left in place for the irrigation season or used to periodically sample at various locations or various times. The sensor can be connected to a data logger or read with a hand-held meter.

ECH$_2$O Aquameter (Decagon) Pullman,Washington; The *ECH$_2$O* sensor measures the dielectric constant of a medium by finding the rate of change of voltage on a sensor that is embedded in the soil at a specific depth. The sensors measure the area of the device, which is available in 10 and 20 cm lengths. For shallow installations they can be inserted directly into undisturbed soil. For deeper installations they are inserted permanently into the bottom of an auger hole. An installation kit provides the necessary tool to provide good soil contact. Auger hole should be carefully backfilled to minimize water movement from the surface. Handheld meters, data storage modules and telemetry are available. Prices are about $100 per sensor and $375 for a handheld sensor and $425 for a data logger.

Field evaluations of some of these dielectric sensors were conducted at six sites in the San Joaquin Valley. Three sites, located on the eastside of the valley, were loamy sand or sandy loam, while the other sites were silt loam and silty clay, located on the westside of the valley. The instruments' readings were compared with the soil moisture content measured with a neutron moisture meter calibrated for each site.

Results showed that the dielectric instruments were reasonably accurate in coarser-textured soil. However, in fine-textured soil, capacitance sensors can be very inaccurate. In some cases, they may not work at all.

The bottom line is, before investing money in dielectric sensors to monitor soil moisture content of fine-textured soils, be sure that the instrument will work under the particular conditions. Some calibration may be necessary for accurate measurements.

Sensor Placement and When to Measure

Moisture sensors vary in the volume of soil from which the measurement is made. The smallest include the resistance block and tensiometer. The soil contact with the sensor determines the volume of soil used for the determination, in this case, only a few cubic inches. Other devices such as the Neutron moisture meter and dielectric constant moisture meters average a larger area. A neutron probe, depending on soil moisture content, measures about a ten-inch diameter area at a single measurement location. The zone of influence of Dielectric sensors is restricted to a narrow disk-shaped region surrounding the sensor and centered on the gap between the electrodes. Some uncertainty exists on the distance from the sensor over which the soil moisture content affects the sensor's reading. However, the sensor is most sensitive to the soil moisture content of the soil immediately adjacent to it. This sensitivity means that any air gap between the sensor and the soil will greatly affect the instrument's performance. TDR methods measure between the waveguides to the depth installed as deep as 18 to 24 inches.

Single point devices require multiple instruments be installed at a number of placements in the root zone to adequately characterize the soil moisture. Typically, single point instruments are installed in the top third, middle third, and lower one third of the root zone. Devices that use an access well inserted to the bottom of the root zone or deeper can be set to measure at any soil depth.

Measurements can be made with all instruments at any time; however, the reading times should coincide with specific times of the year or irrigation events to be most useful. These times might be by date before irrigation begins to measure vine water extraction or by events such as bud break or harvest.

Measurements made at bud break are at a time when the soil moisture is evenly distributed horizontally in the root zone. Another way to visualize this is that a reading at a specific depth will be representative of the same depth over the entire area. A cover crop or resident vegetation can disrupt this even horizontal distribution leading to an overestimation of soil moisture if the measurement is measured in the clean berm area.

As the vine begins to use moisture, it first extracts from the shallow depths where the highest root densities exist. As the soil dries in these areas, extraction is switched to areas of lesser root density but higher water availability. This pattern continues without irrigation until the soil is quite dry with the remaining soil moisture at the deeper depths.

A measurement made when the soil is relatively dry prior to the first irrigation can be used to determine:
1) the volume of water used since bud break (bud break measurment – current measurement)
2) the amount remaining in the soil which can be removed by harvest (current measurement – harvest measurement).

Once irrigation begins by applying water to the soil from a non-full coverage irrigation system (drip/micro sprinklers) the soil is recharged non-uniformly. Measurements at this time are valuable to determine the depth of water penetration and size of wetted area if multiple wells are used. Readings to determine water use between two measurement times is not valid since the soil is not uniformly wetted (*Figure C-15*). In order to determine the soil water depletion under these conditions a number of measurements encompassing the entire root zone would be necessary to calculate the average root zone water content.

Figure C-15. Neutron meter access well placement.
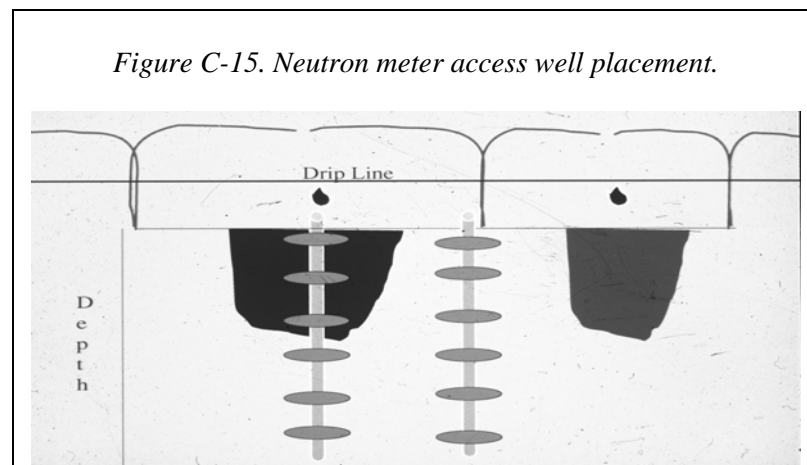
Measuring In-Season Rainfall

In-Season Effective Rainfall

In-season rainfall is that which occurs after bud break and before leaf fall. However, not all rainfall is stored in the root zone and is available for use by the vine. In irrigation scheduling, the term "*effective rainfall*" refers to that portion of rainfall, which infiltrates and is stored in the root zone. Effective in-season rainfall reduces the irrigation requirement. Since rainfall is spatially quite variable in during the growing season effective rainfall must be estimated for each field and rainfall event. This task however, is difficult since the climatic conditions during and after the event determine the volume of water, which will be stored in the root zone for vine use. Factors like the soil type the amount of surface mulch and cover crop, rainfall duration and intensity as well as evaporation conditions immediately after the event each influence the volume of effective rainfall. Effective rainfall occurring when the soil reservoir is full is lost to drainage or runoff.

Measuring effective rainfall using soil moisture devices is imprecise since the amount is usually small and is stored near the soil surface where devices such as neutron probe meters are ineffective. Using a deficit-threshold plus RDI irrigation method requires the estimation of effective rainfall from the irrigation threshold through harvest. This is a time with limited significant rainfall events. Soil sampling methods are best used after the surface has dried a few days; however, the vine can be using the moisture during this period leading to errors. Many complex methods exist for calculating effective rainfall, which requires many climate and soil variables. Most were developed for midwestern dryland agriculture.

The most practical method to estimate effective in-season rainfall for vineyards is using the formula:

$$\text{Effective Rainfall} = [\text{rainfall (in)} - 0.25 \text{ in}] \times 0.8$$

This method discounts the first 0.25-inch as lost to evaporation after the event and estimates 80% of the remainder is stored in the soil. Most scheduling programs only begin to account for effective in-season rainfall after irrigation begins the chance of significant rainfall during this period is low in most areas of California. *Table C-3* shows the calculation of effective rainfall for a one-week period of time.

Table C-3. Effective rainfall		
Day	Rainfall (inches)	Effective Rainfall (inches)
1	0.39	0.11
2	0.62	0.30
3	0	0
4	0	0
5	0	0
6	0	0
7	0.25	0
Weekly Total	1.26	0.41

Measuring Irrigation Water

Measuring the water delivered to an area of land can be done using water flowmeters, measuring individual emitter discharge and using estimates based on measured pump performance and power records.

Flowmeters

Flowmeters measure the volume of water moving through a full-flowing closed pipe and as such are one of the key components of a drip irrigation system. They are essential for managing irrigation efficiently and for monitoring the performance of the irrigation system. Managing irrigation efficiently requires: (1) knowing how much water the crop has used since the last irrigation (irrigation scheduling); and (2) operating the irrigation system to apply only the amount of water desired. A flowmeter gives the manager the information needed to apply only the amount of water required.

Monitoring the performance of a micro-irrigation system makes it possible to identify changes in flowrate during the season (measured at the same pressure), which may indicate problems such as clogging of emitters or filters, leaks in the system, or problems with the pump or well.

Propeller Flowmeters

Propeller flowmeters, consisting of a propeller linked by a cable or shafts and gears to a flow indicator and inserted into a pipeline, are frequently used to measure flowrates in pipelines. The indicators can report either the flowrate or the total flow volume, or both.

Propeller flowmeters can be installed in several different ways: by being inserted into a short section of pipe, which is then either coupled *(Figure C-16)*; bolted *(Figure C-17)* into the pipeline; clamped, strapped, or welded onto the pipeline as a saddle-type meter *(Figure C-18);* or inserted into the pipe discharge *(Figure C-19)* to measure flow from gates installed in canals and ditches.

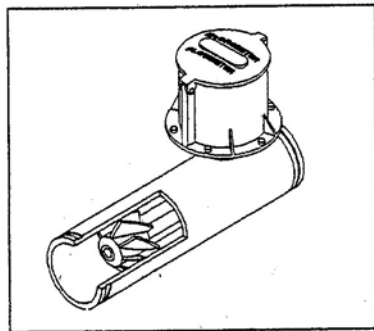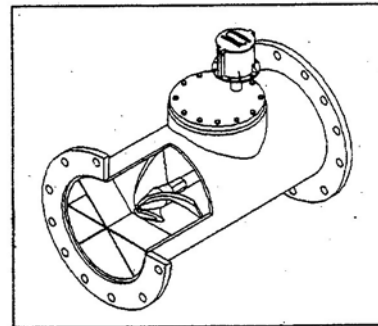*Figure C-16. Welded propeller flowmeter.*   *Figure C-17. Bolted propeller flowmeter*

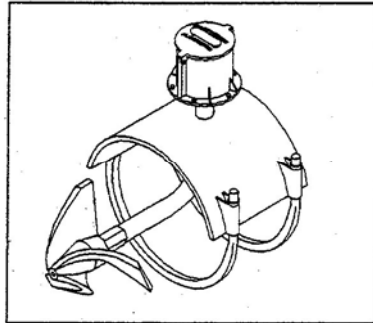*Figure C-18. Saddle-type propeller
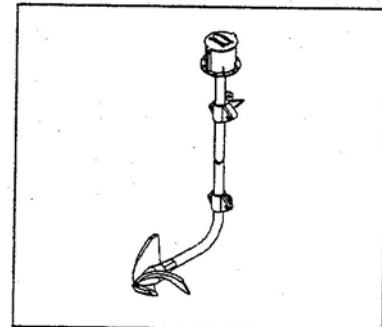flowmeter.*

*Figure C-19. Insertion-type
propeller flowmeter.*

Illustrations courtesy of Ketema/McCrometer Division, Hemet, CA 92545

Propeller meters can also be installed as in-line meters in a short section of portable pipe *(Figure C-16)*. Couplings are welded onto each end of the flowmeter pipe section to connect sections of the portable pipe. One flowmeter of a given size can be used for several sizes of portable pipe if a sufficiently long straight section of pipe of the same diameter as the flowmeter section is installed immediately upstream from the flowmeter.

Since clamp-on and strap-on saddle meters can be moved from location to location, one flowmeter can be used to measure flowrates for several pumping plants. The same pipe diameter must be used at each site, however. Dummy saddles can be installed at locations other than the one at which the meter is installed.

**Selecting Propeller
Flowmeters**

Propeller meters must be matched to the correct pipe size — since the gear mechanism connecting the propeller to the indicator is based on the pipe inside diameter — and to the desired flowrate. *Table C-4* gives maximum and minimum flowrates for various pipe diameters.

Most flowrate indicators report in gallons per minute or in cubic feet per second, while total flow indicators ("totalizers") report in gallons, acre-feet, or cubic feet. Some indicators report in metric units.

**Installation and
Operation**

The flowmeter should be installed at a location of minimal water turbulence, since too much turbulence will cause the flowrate indicator to oscillate wildly, preventing reliable measurement.

Manufacturers often recommend that a section of straight pipe, eight to ten pipe diameters long, be placed immediately upstream from the flowmeter, but field experience has shown that a longer pipe length may be required in locations where jetting may occur because of a partially closed valve. One manufacturer maintains, however, that reliable measurements can be made with even relatively short sections of pipe if straightening vanes are used.

Table C-4. Flowmeter maximum and minimum flowrates for various pipe diameters. (Courtesy of McCrometer Flowmeters)						
Meter and nominal pipe size	4	6	8	10	12	14
Maximum flow rate	600	1200	1500	1800	2500	3000
Minimum flow rate	50	90	108	125	150	250

Swirling

A centrifugal sand separator or a series of elbows in the pipeline may cause a swirl or rotation to develop in the flowing water. The swirls may still be present even one hundred pipe diameters downstream. The remedy is to place straightening vanes in the pipeline just in front of the flowmeter. One manufacturer recommends that a six-vane straightener be used.

A relatively stable propeller meter rate indicator means that turbulence is minimal, but wide variation in indicator readings signals turbulence in the pipeline. If the rate indicator shows erratic, violent behavior, air or gas may be present in the water.

Attaining Full Flow

Propeller flowmeters will operate properly only if the pipe is flowing full. If the pipeline is only partially full, the flowrate measurement will not be accurate. In pressurized irrigation systems, flow will usually be full at the pump discharge, but in pumps with an open discharge, as into an irrigation ditch, pipe flow may not be full. The problem can be remedied by creating a slight rise in the discharge pipe; by installing a gooseneck at the pipe discharge; by installing an elbow (discharge end pointing upward at the pipe discharge); or by installing a valve downstream from the meter.

Accuracy

Under ideal conditions, a propeller flowmeter operated within its recommended range can be accurate to within ± 2 percent, but if the flowrate is too slow, accuracy will be less.

Pressure/Head Loss

Inserting a propeller into the water flow can cause friction, resulting in pressure or head losses in the pipeline. The amount of pressure lost depends on the velocity or flowrate and on the pipe diameter. The higher the flowrate, the more pressure lost because of the flowmeter, but the larger the pipe diameter, the less pressure lost.

As *Figure C-20* illustrates, these pressure losses are generally small. With a ten-inch flowmeter, the pressure loss is less than 0.1 psi for flowrates less than 2000 gpm.

Figure C-20. Pressure loss caused by propeller flowmeters.
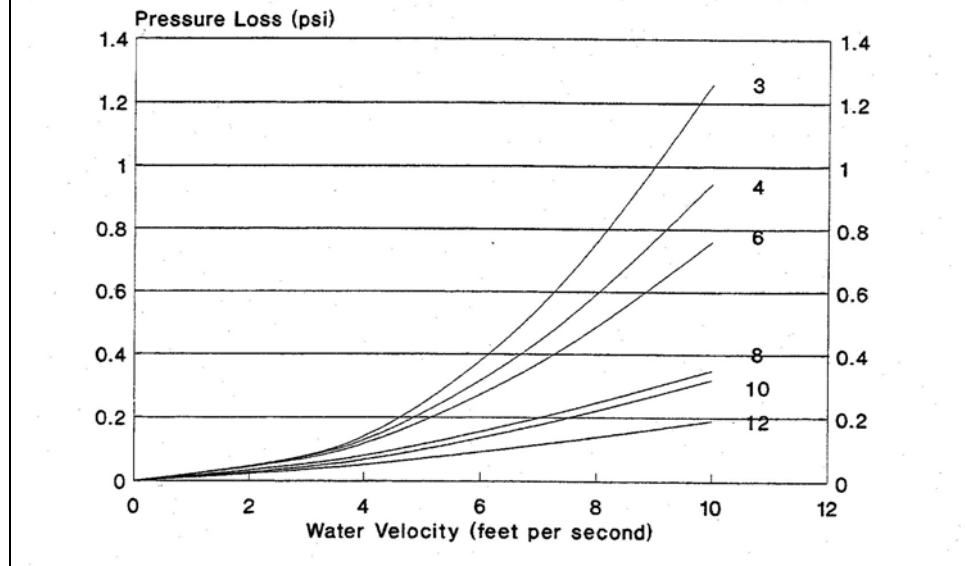
(Figure developed from data supplied by Water Specialties Corporation, Porterville, CA 93257.)

The recently introduced magnetic flowmeter has the advantage of not causing an obstruction in the pipe. This feature eliminates the problem of possible entanglement from debris in the water as well as any pressure loss across the device. Magnetic flowmeters also require less maintenance than propeller meters, have long-term accuracy, and can be installed only five pipe diameters of straight pipe upstream from the meter, but have the disadvantages of a higher initial cost and the need for an external power supply.

*Ultrasonic
Flowmeters*

Ultrasonic flowmeters measure flow velocity (and thus flowrate) by directing ultrasonic pulses diagonally across the pipe both upstream and downstream. The difference in time required for the signal to travel through the moving water is measured and converted to flow velocity. Ultrasonic flowmeters have accuracy comparable to that of propeller meters and, since they have no moving parts, require little maintenance. Because all attachments are external, these meters can be moved easily to different locations. Since the ultrasonic meters work by bouncing the ultrasonic pulses off particles in the water, irrigation waters, which don't have enough suspended particles in it, may not be appropriate for ultrasonic meter use. It has been found that high quality well waters may fall into this category. Ultrasonic flowmeters generally cost more than other types of meters.

*Turbine
Flowmeters*

Turbine flowmeters operate on the principle of a rotor assembly, turning at a rate proportional to the flowrate in the pipelines. The rotor is suspended near a magnetic pickup, which records a pulse on its readout unit as each rotor blade passes. Turbine flowmeters have an accuracy comparable to that of propeller flowmeters (within a few percent) under the correct flow conditions and require a ten-pipe diameter length of straight pipe upstream and a six-pipe diameter length downstream. The turbine flowmeter is more sensitive to non-uniform flow conditions, such as exist downstream of an elbow or constriction, than is a propeller flow meter. Some turbine flowmeters can be

installed in a range of pipe diameters, which provides flexibility in their use. The applicability and cost are comparable to that of a propeller meter.

Venturi flowmeters consist of a section of pipe with a restriction in a specific shape, across which pressure change is measured. The magnitude of this pressure change depends on the flowrate through the device. Venturi flowmeters offer the advantages of unobstructed water flow, no moving parts (meaning low maintenance requirements), little pressure loss across the device, and good accuracy. Venturi flowmeters cost slightly more than propeller meters and the meter readout is less convenient than that of some other flowmeters.

The readout from flowmeters can be in instantaneous flowrate in gallons per minute (gpm) or cubic feet per second (cfs), or in total flow in gallons, cubic feet, or acre-feet. For irrigation scheduling purposes, however, crop water use is given in inches or in inches per day. The following formulas can be used to convert flowmeter readout to inches per hour.

____ gpm ÷ area irrigated (acres) × 0.0022 = ____ in/hr (see also *Table C-5*).

____ cfs ÷ area irrigated (acres) × 0.992 = ____ in/hr (see also *Table C-6*)

____ gallons ÷ time period over which measured (min) ÷ area irrigated (acres)
    × 0.0022 = ____ in/hr

____ cubic feet ÷ time period over which measured (minutes) ÷ area irrigated
    (acres) × 0.0165 = ____ in/hr

____ acre-feet ÷ time period (minutes) ÷ area irrigated (acres) × 720 = ____ in/hr

From the flowrate measurement, the amount of water applied during an irrigation set can be calculated in inches using the following equation:
$$D = (Q \times T) \div (449 \times A)$$

where: D = inches of applied water
        T   actual hours required to irrigate the field
        A   acres irrigated
        Q   flowrate in gallons per minute

Calculate the inches of water applied if a flowrate of 300 gallons per minute is used to irrigate 40 acres in 16 hours.

$$D = (300\,gpm \times 16\,hours) \div (449 \times 40\,acres) = 0.27\,inches$$

References

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Measuring Emitter Discharge

Measuring individual emitter discharge can be easily done with a graduated container and a watch that displays seconds. The container can be a graduated cylinder (100 ml works best), a graduated measuring container (often used for spraying) or a 35 mm film canister. A number of emitters should be measured throughout the block to establish an average discharge rate. Flow rate varies with changes in pressure due to elevation changes, and friction loss in the system. Emitter clogging as well as manufacturing variation also will influence flow rate.

- Collect water for 30 seconds in a 100 ml graduated cylinder (see *Table C-5*) or time how long it takes to fill a 35 mm film canister (see *Table C-6*). Use either table to convert the amount of water collected from each sampled emitter to the discharge rate for that emitter

- For each irrigation block, average all your discharge rate measurements. This is the average emitter discharge rate (gph) of your emitters.

Table C-5. Drip emitter discharge rate (gallons per hour – gph) using a graduated cylinder)*			
ml of water collected in 30 seconds	Drip emitter discharge rate (gph)	ml of water collected in 30 seconds	Drip emitter discharge rate (gph)
10	0.32	26	0.82
12	0.38	28	0.89
14	0.44	30	0.95
16	0.51	32	1.01
18	0.57	34	1.08
20	0.63	36	1.14
22	0.70	38	1.20
24	0.76	40	1.27

$$\text{Drip emitter discharge rate (gal/hr)} = \text{Water (ml) collected in 30 seconds} \times 0.0317$$

* A 100 ml graduated cylinder works well

Table C-6. Drip emitter discharge rate (gallons per hour - gph) using a 35 mm film canister			
Seconds to fill 35 mm film canister	Drip emitter discharge rate (gal/hr)	Seconds to fill 35 mm film canister	Drip emitter discharge rate (gal/hr)
26	1.28	48	0.69
28	1.19	50	0.67
30	1.11	52	0.34
32	1.04	54	0.62
34	0.98	56	0.59
36	0.92	58	0.57
38	0.88	60	0.55
40	0.83	62	0.54
42	0.79	64	0.52
44	0.76	66	0.50
46	0.72	68	0.49

$$\text{Drip emitter discharge rate (gal/hr)} = 33.29 \div \text{Time to fill 35 mm film canister (seconds)}$$