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# Chapter 9

# Irrigation Water Management

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### 652.0900 General

Irrigation water management (IWM) is the act of timing and regulating irrigation water application in a way that will satisfy the water requirement of the crop without wasting water, soil, and plant nutrients and degrading the soil resource. This involves applying water:

- According to crop needs
- In amounts that can be held in the soil and be available to crops
- At rates consistent with the intake characteristics of the soil and the erosion hazard of the site
- So that water quality is maintained or improved

A primary objective in the field of irrigation water management is to give irrigation decisionmakers an understanding of conservation irrigation principles by showing them how they can judge the effectiveness of their own irrigation practices, make good water management decisions, recognize the need to make minor adjustments in existing systems, and recognize the need to make major improvements in existing systems or to install new systems. The net results of proper irrigation water management typically:

- Prevent excessive use of water for irrigation purposes.
- Prevent excessive soil erosion
- Reduce labor
- Minimize pumping costs
- Maintain or improve quality of ground water and downstream surface water
- Increase crop biomass yield and product quality

Tools, aids, practices, and programs to assist the irrigation decisionmaker in applying proper irrigation water management include:

- Applying the use of water budgets, water balances, or both, to identify potential water application improvements
- Applying the knowledge of soil characteristics for water release, allowable irrigation application rates, available water capacity, and water table depths
- Applying the knowledge of crop characteristics for water use rates, growth characteristics, yield and quality, rooting depths, and allowable plant moisture stress levels
- Water delivery schedule effects
- Water flow measurement for onfield water management
- Irrigation scheduling techniques
- Irrigation system evaluation techniques

See Chapter 15 for resource planning and evaluation tools and for applicable worksheets.

## 652.0901 Irrigation water management concepts

### (a) Irrigation water management concepts

Field monitoring techniques can be used to establish when and how much to irrigate. The long existing rule of thumb for loamy soils has been that most crops should be irrigated before more than half of the available soil water in the crop root zone has been used. It has also been demonstrated that certain crops respond with higher yields and product quality by maintaining a higher available soil-water content, especially with clay soils. Desired or allowable soil moisture depletion levels, referred to as Management Allowable Depletion (MAD), are described in Chapter 2, Soils, and Chapter 3, Crops. If the Available Water Capacity (AWC) of the soil, the crop rooting depth for the specific stage of growth, and the MAD level are known, then *how much water to apply* per irrigation can be determined. Part 652.0903 reviews measurement of soil-water content and describes tools, techniques, and irrigation scheduling. Part 652.0908, Water management, addresses the importance of measuring a predetermined quantity of water onto the field.

#### (1) Concepts of irrigation water management

The simplest and basic irrigation water management tool is the equation:

$$Q T = D A$$

where:

- Q = flow rate (ft<sup>3</sup>/s)
- T = time (hr)
- D = depth (in)
- A = area (acres)

For example, a flow rate of 1 cubic foot per second for 1 hour = 1-inch depth over 1 acre. This simple equation, modified by an overall irrigation efficiency, can be used to calculate daily water supply needs by plants, number of acres irrigable from a source, or the time required to apply a given depth of water from an irrigation well or diversion. Typically, over 80 percent of IWM concerns can be at least partly clarified by the application of this equation.

Quantity of water to be applied is often determined by available water capacity of the soil, planned management allowable depletion, and estimated crop evapotranspiration (ET<sub>c</sub>). When rainfall provides a significant part of seasonal plant water requirements, irrigation can be used to supplement plant water needs during dry periods resulting from untimely rainfall events.

Water should be applied at a rate or quantity and in such a manner to have sufficient soil-water storage, be nonerosive, have minimal waste, and be nondegrading to public water quality. Irrigations are timed to replace the planned depleted soil moisture used by the crop. Effective rainfall during the growing season should be taken into consideration.

#### (2) When to irrigate

When to irrigate is dependent on the crop water use rate, sometimes referred to as irrigation frequency. This rate can be determined by calculation of ET<sub>c</sub> rate for specific crop stage of growth, monitoring plant moisture stress levels, monitoring soil-water depletion, or a combination if these. Too frequently, crop condition is observed to determine when to irrigate. When plants show stress from lack of moisture, it is typically too late. Generally, crop yield and product quality have already been adversely affected. The over-stress appearance may also be from shallow roots resulting from overirrigation or from disease, insect damage, or lack of trace elements. Certain plants can be excessively stressed during parts of their growth stage and have little effect on yield. Part 652.0903 reviews measurement of plant moisture stress levels and describes tools, techniques and irrigation scheduling.

#### (3) Rainfall management

In moderate to high rainfall areas, managing the timing of irrigations to allow effective use of rainfall during the irrigation season is a common practice. The irrigation decisionmaker can attempt to predict rainfall events and amounts (which too often does not work), or the depleted soil water is never fully replaced with each irrigation. Instead, between 0.5 and 1.0 inch of available water capacity in the soil profile can be left unfilled for storage of potential rainfall. Rainfall probability during a specific crop growing period and the level of risk to be taken must be carefully considered by the irrigation decisionmaker. Applied irrigation water should always be considered supplemental to rainfall events.

#### (4) Water supply limitations

Where water supply is limiting, deficit or partial year irrigation is often practiced. Partial irrigation works well with lower value field crops. It does not work well with high value crops where quality determines market price, especially the fresh vegetable and fruit market. Typically, water is applied at times of critical plant stress (see Chapter 3, Crops) or until the water is no longer available for the season. Yields are generally reduced from their potential, but net benefit to the farmer may be highest, especially when using high cost water or a declining water source, such as pumping from a declining aquifer. An economic evaluation may be beneficial.

#### (5) Water delivery

Water supply and delivery schedules are key to proper irrigation water management. When water users pump from a well or an adjacent stream or maintain a diversion or storage reservoir, they control their own delivery. In some areas delivery is controlled by an irrigation district or company. Delivery by an irrigation district may be controlled by its own institutional constraints (management) or by canal supply and structure capacity limitations.

Flexibility in delivery generally is controlled by institutional restraints or capacity limitations on the downstream ends of irrigation laterals. Capacity limitations are primarily because required storage is not within or very close to farm delivery locations. Where water supplies are not limited and delivery is in open canal systems, irrigation districts often carry from 10 to 30 percent additional water through the system as *management water* to reduce district water management requirements. Low cost semi or fully automated controllers are available for water control structures that accomplish the same purpose with less water. (One large irrigation district discovered they had over 20 percent more water available to users when water measuring devices and semiautomatic gate controls were installed at each major lateral division.) The following schedules are widely used.

**(i) Fixed and rotation**—With fixed delivery time at fixed delivery rates, irrigation districts provide a single delivery point to an individual water user or to a group of neighbors that rotate the delivery among themselves. Generally the delivery schedule is the

easiest to use and the least costly. Turnout gates are adjusted to deliver a given share of water on a continual basis. This delivery schedule however, generally promotes the philosophy of **use the water (whether the crop needs it or not) or lose it**. This practice is not conducive to proper irrigation scheduling. Many project delivery systems have been designed based on this delivery schedule method because of the perception it allows minimum capacity sizing of all components. When in fact, only the lower end of laterals ( $\pm 5$  water users) is affected.

**(ii) Arranged**—The water user requests or orders water delivery at a rate, start time, and duration in advance. Most arranged schedules require a minimum of 24 to 48 hours advance notice for water to be turned on or turned off. Arranged schedules often require water be turned on or off at specific times; i.e., 7 to 9 a.m., to correspond to ditch riders' schedules. This delivery schedule requires good, advance communication between water user and irrigation company. Irrigation districts need to have flexibility in their delivery with this method. Temporary storage facilities are typically needed because water spills out the end of the delivery system.

**(iii) Demand**—A demand schedule is one that allows users to have flexibility of frequency, rate, and duration of delivery. A municipal water system meets this type of delivery schedule system. It also works best where the water user owns and maintains the water supply; i.e., well, storage reservoir, and stream diversion. On-demand schedules are technically feasible for most moderate to large irrigation districts. Except for downstream ends of supply laterals, canal and lateral sizes are the same whether demand, rotation, or arranged deliveries are used. Temporary storage is provided by main canals and laterals; however, canal appurtenances (diversions, turnouts, and flow measuring devices) must be sized accordingly. With smaller delivery systems, slight oversizing of main canals and temporary storage facilities can often be provided at a small increase in delivery system cost. Modifications to on-demand schedule can work well. For example, the rate may be limited, but frequency and duration made flexible. This method works quite well in many projects if the main canal capacity is increased slightly and if temporary storage facilities are provided within the delivery system.

Most onfarm irrigation delivery and distribution facilities are limited by their capacity. Therefore, variable frequency and duration are typically the best delivery schedule reasonably available. A good irrigation scheduling program can be developed around this type of delivery schedule.

### (6) Water measurement

A key factor in proper irrigation water management is knowing how much water is available to apply or is applied to a field through an irrigation application system. Many devices are available to measure open channel or pipeline flows. See Chapter 7, Farm Distribution Systems, for more details. Too many irrigators consider water measurement a regulation issue and an inconvenience. The importance of flow measurement for proper irrigation water management cannot be overstressed. Typically, less water is used where adequate flow measurement is a part of the water delivery system and a unit cost billing mechanism is used. In addition to chapter 7, the joint USBR, ARS, and NRCS water measurement publication should be consulted.

## 652.0902 Soil-plant-water balance

Detailed soil and crop characteristics were described in chapters 2 and 3 of this guide. Applying those characteristics and monitoring changes in soil-water content, plant moisture tension levels, canopy cover, root development, and water use rates provide valuable factors to implement proper irrigation water management. Generally, water budgets are a planning tool, water balance is the daily accounting of water availability. Both can be important irrigation water management tools.

### (a) Soil

Soil intake characteristics, field capacity, wilting point, available water capacity, water holding capacity, management allowed depletion, and bulk density are soil characteristics that irrigation consultants and decisionmakers must take into account to implement proper irrigation water management. Also see Chapter 2, Soils, and Chapter 17, Glossary.

**Field capacity (FC)** is the amount of water remaining in the soil when the downward water flow from gravity becomes negligible. It occurs soon after an irrigation or rainfall event fills the soil. Field capacity is generally assumed to be 1/10 atmosphere (bar) soil-water tension for sandy soils and 1/3 atmosphere (bar) tension for medium to fine textured soils. For accurate results these points should be measured in the laboratory, but can be measured (reasonably close) in the field if done soon after an irrigation and before plants start using soil moisture.

Free or excess water is available for plant use for the short time it is in the soil. With coarse textured soil, excess water can be available for a few hours because free water drains rapidly, but with fine textured soil it can be up to 2 days because free water drains more slowly. Laboratory results are typically good for homogenous soils, but results may be inaccurate for stratified soils because of free water movement being restricted by fine textured layers. In stratified soils, proper field tests can provide more representative data.

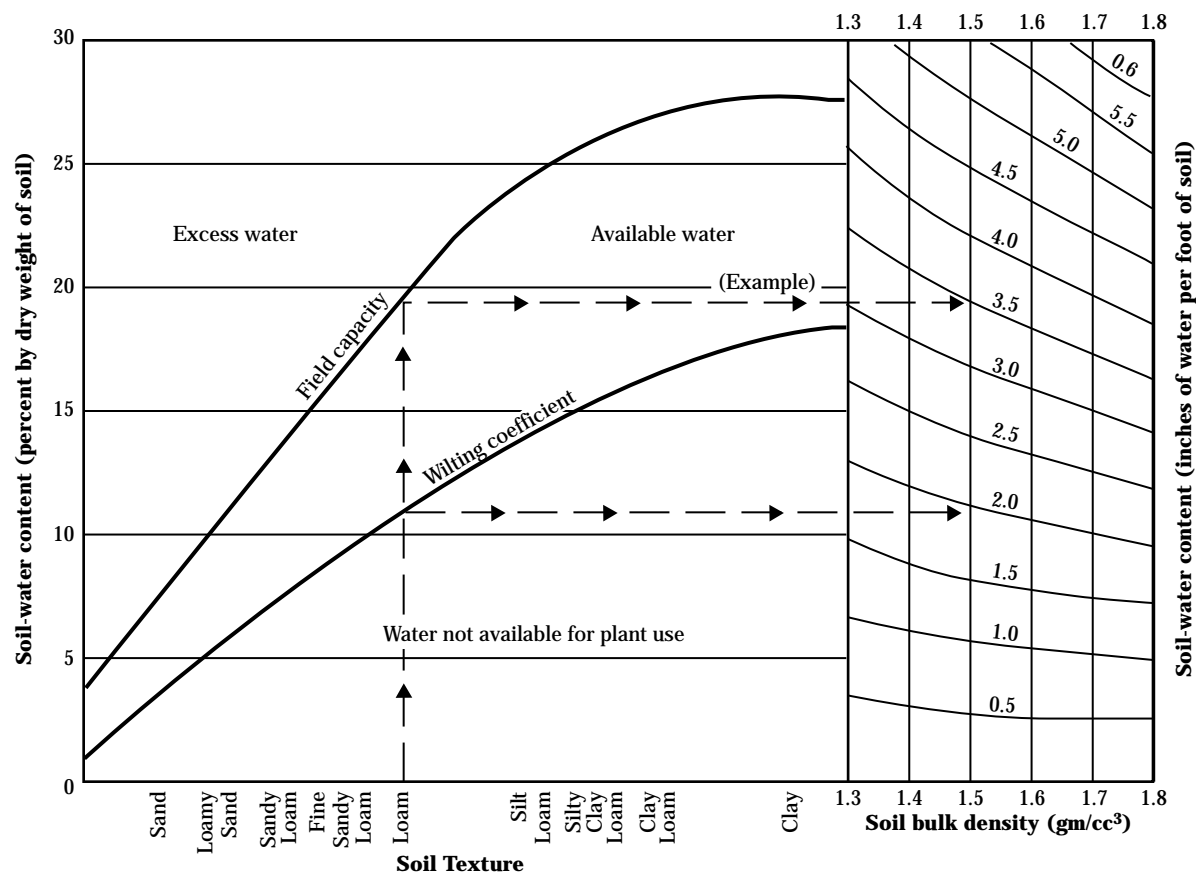
In stratified soils, a common perception that downward water movement is held up by fine textured soil layers is not entirely true. In fact, water enters fine textured soil layers almost immediately. However, because the fine textured soil has greater soil-water tension, downward water movement into a coarse textured soil below is restricted. A recently published NRCS video, *How Water Moves Through Soil*, demonstrates water movement in various soil profiles.

**Wilting point (WP)**, sometimes called wilting coefficient, is the soil-water content below which plants cannot obtain sufficient water to maintain plant growth and never totally recover. Generally, wilting point is assumed to be 15 atmospheres (bar) tension. It is measured only in the laboratory using a pressure plate apparatus and is difficult to determine in the field.

**Available water capacity (AWC)** is that portion of water in the soil (plant root zone) that can be absorbed by plant roots. It is the amount of water released between field capacity and permanent wilting point, also called available water holding capacity. Average available water capacities are displayed in table 9-1, based on texture in the profile. A specific soil series (i.e., Warden) can have different surface textures. Average soil-water content based on various textures and varying bulk density is displayed in figure 9-1.

**Soil-water content (SWC)** is the water content of a given volume of soil at any specific time. This is the water content that is measured by most soil-water content measuring devices. Amount available to plants then is SWC - WP.

**Figure 9-1** Total soil-water content for various soil textures with adjustment for changes in bulk density



**Management allowable depletion (MAD)** is the desired soil-water deficit at the time of irrigation. It can be expressed as the percentage of available soil-water capacity or as the depth of water that has been depleted in the root zone. Providing irrigation water at this time minimizes plant water stresses that could reduce yield and quality.

**Bulk density** is the mass of dry soil per unit bulk volume. It is the oven dried weight of total material per unit volume of soil, exclusive of rock fragments 2 mm or larger. The volume applies to the soil near field capacity water content. To convert soil-water content on a dry weight basis to volumetric basis, soil bulk density must be used. Bulk density is an indicator of how well plant roots are able to extend into the soil. See Chapter 2, Soils, for example of conversion procedure. Core soil samplers are most commonly used to collect in-place density samples. Commercial samplers available include the Madera sampler in which a 60 cc sample is collected. This sampler was developed for use with a neutron probe. The Eley Volumeter and the AMS core sampler are other examples. Other commercial push type core samplers use known volume removable retaining cylinders. These cylinders contain the core samples.

NRCS soil scientists use liquid saran to coat soil clods, and the volume of the clod is determined in a soils laboratory using a water displacement technique. This process provides the least disturbance to a soil sample; however, obtaining clods from sandy soils can be difficult. Techniques to determine density used in construction, such as using a sand cone, and balloon methods can also be used in soils with coarse rock fragments or with coarse sandy soils. Rock fragments cause disturbance of core samples when using a push type core sampler.

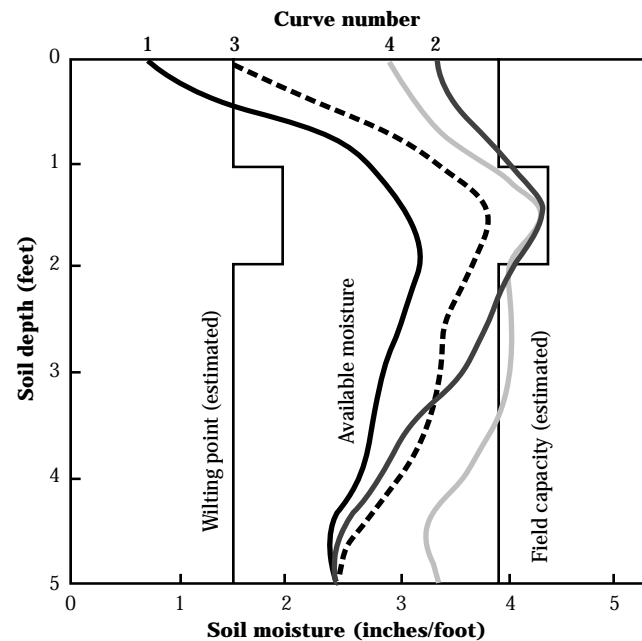
Soil-water profiles are a plot of soil-water content versus soil root zone depth. As a water management tool, this plot visually displays available water, total water content, or water content at the time to irrigate level (fig. 9-2).

The rate of decrease in soil-water content is an indication of plant water use and evaporation, which can be used to determine **when to irrigate and how much to apply**. This is the basic concept in scheduling irrigations.

**Table 9-1** Available water capacity for various soil textures

Soil texture	Estimated AWC	
	in/in	in/ft
Sand to fine sand	0.04	0.5
Loamy sand to loamy fine sand	0.08	1.0
Loamy fine sands, loamy very fine sands, fine sands, very fine sands	0.10	1.2
Sandy loam, fine sandy loam	0.13	1.6
Very fine sandy loam, silt loam, silt	0.17	2.0
Clay loam, sandy clay loam, silty clay loam	0.18	2.2
Sandy clay, silty clay, clay	0.17	2.0

**Figure 9-2** Soil-water content versus depth



An interpretation of data that soil moisture curves 1 through 4 on figure 9–2 represent includes:

- Curve #1—This curve shows the upper 6 inches of the soil profile is below wilting point. Shallow rooted plants are excessively stressed. Below a depth of 12 inches, soil moisture is still ample at 50 percent. If it is desirable to maintain soil moisture at 50 percent of total available moisture or higher (i.e., for plants with less than 10 inches rooting depth), it is time to irrigate, maybe even a little late to maintain optimum growth conditions. Deeper rooted plants are still drawing moisture from below a depth of 12 inches.
- Curve #2—This curve represents what soil moisture may be a day or two after an irrigation. The lower part of the soil profile did not reach field capacity. However, this situation may be desirable for crops with less than 25-inch rooting depth. For deeper rooted crops, additional water should have been applied.
- Curve #3—This curve represents moisture withdrawal from shallow rooted plants. There is ample moisture below 12 inches. A light application of water, to 12 inches depth, is needed for shallow rooted plants. A heavy application of water could put excess water below the crop root zone.
- Curve #4—This curve represents what soil moisture may be a day or two after an irrigation. The soil profile below a depth of 12 inches is nearly at field capacity, indicating a good irrigation application to approximately a 4-foot depth. Water is probably still moving downward.

## (b) Measuring soil-water content

To measure soil-water content change for the purpose of scheduling irrigation, several site locations in each field and each horizon (or if homogenous at 6 inch depth increments) at the site (test hole) should be sampled. Quite often, the experienced irrigation decisionmaker calibrates available soil water in the soil profile relative to one sample at a specific depth. Multiple sites in a field are used to improve confidence in determining when and how much water to apply.

Most commercial soil-water content measuring devices provide a numerical measurement range. This measurement range is an indication of relative water content. The range might be 0 to 100 percent AWC or 0

to 10. Readings represent different specific soil-water content depending on soil type. Most devices that indicate relative values are difficult to calibrate to relate to specific quantitative values. A calibration curve for each specific kind of soil and soil-water content (tension) should be available with the device or needs to be developed.

If the irrigator is only interested in knowing when to irrigate, a specific indicated value on the gauge or meter may be sufficient. The manufacturer may provide this information either prebuilt into the device or with separate calibration curves. Irrigators must know what number (value) on the meter represents what approximate soil-water content level for their field and soils. They then must associate a specific number on the gauge to when irrigation is needed for each soil texture. Irrigation system design and water management planning provide the **how much to apply**. Example worksheets are provided in Chapter 15, Planning and Evaluation Tools.

### (1) Methods and devices to measure or estimate soil-water content

*(i) Soil feel and appearance method*—This method is easy to implement and with experience can be accurate. Soil samples are collected in the field at desired depths, typically at 6 inch increments. Samples are compared to tables or pictures that give moisture characteristics of different soil textures in terms of feel and appearance. With practice, estimates can be obtained within 10 percent of actual. Typically the irrigation decisionmaker needs to learn only a few soils and textures.

Exhibit 9–1 displays the identification of soils and corresponding available water content when using feel and appearance method for determining soil-water content. The NRCS color publication, *Estimating Soil Moisture by Feel and Appearance*, is reproduced in chapter 15. Figure 9–3 is an example worksheet for determining soil-water deficient (SWD) in the soil profile.

Every operation can afford tools necessary to use this method of soil-water determination. Tools required are a push type core sampler, auger, or shovel. Care should be taken to not mix soil layers when sampling. Example forms for recording field data and calculating depleted or available soil-water content are in chapter 15.

**Exhibit 9-1** Guide for estimating soil moisture conditions using the feel and appearance method

Available soil moisture (%)	Coarse texture fine sand, loamy fine sand	Moderately coarse texture sandy loam, fine sandy loam	Medium texture sandy clay loam, loam, silt loam	Fine texture clay loam, silty clay loam
	0.6 – 1.2	1.3 – 1.7	1.5 – 2.1	1.6 – 2.4
0 – 25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure	Dry, forms a very weak ball <sup>1/</sup> , aggregated soil grains break away easily from ball	Dry, soil aggregations break away easily, no moisture staining on fingers, clods crumble	Dry, soil aggregations easily separate, clods are hard to crumble with applied pressure
25 – 50	Slightly moist, forms a very weak ball with well defined finger marks, light coating of loose and aggregated sand grains remain on fingers	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers grains break away	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers few aggregated soil pressure	Slightly moist, forms a weak ball, very few soil aggregations break away, no water stains, clods flatten with applied
50 – 75	Moist, forms a weak ball with loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon <sup>2/</sup>	Moist, forms a ball with defined finger marks, very light soil water staining on fingers, darkened color, will not slick	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, forms a weak ribbon between thumb and forefinger	Moist, forms a smooth ball with defined finger marks, light soil water staining on fingers, ribbons between thumb and forefinger
75 – 100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger	Wet, forms a ball with well defined finger marks, light to heavy soil water coating on fingers, ribbons between thumb and forefinger	Wet, forms a ball, uneven medium to heavy soil water coating on fingers, ribbons easily between thumb and forefinger
Field capacity (100%)	Wet, forms a weak ball, light to heavy soil water coating on fingers, wet outline of soft ball remains on hand	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil water coating on fingers	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil water coating on fingers	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil water coating on fingers, slick and sticky

1/ Ball is formed by squeezing a hand full of soil very firmly with one hand.

2/ Ribbon is formed by when soil is squeezed out of hand between thumb and forefinger.

**Figure 9-3** Available soil-water holding worksheet (feel and appearance)

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**Soil Water Holding Worksheet**

Field \_\_\_\_\_ Location in field \_\_\_\_\_  
 Year \_\_\_\_\_ By \_\_\_\_\_  
 Crop \_\_\_\_\_  
 Planting data \_\_\_\_\_ Emergence data \_\_\_\_\_  
 Soil name if available \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Factor	Season	
	1st 30 days	Remainder of season
Root zone depth or max soil depth - ft		
Available water capacity AWC - in		
Management allowed deficit MAD - %		
Management allowed deficit MAD - in		

(Note: Irrigate prior to the time that SWD is equal to or greater than MAD - in)

Estimated irrigation system application efficiency \_\_\_\_\_ percent

Data obtained during first field check					Data obtained each check		
(1) Depth range (in)	(2) Soil layer thickness (in)	(3) Soil texture	(4) Available water capacity (AWC) (in/in)	(5) AWC in soil layer (in)	(6) Field check number	(7) Soil water deficit (SWD) (%)	(8) Soil water deficit (SWD) (in)
					1		
					2		
					3		
					4		
					5		
					6		
					7		
					8		
					1		
					2		
					3		
					4		
					5		
					6		
					7		
					8		

Total AWC for root zone depth of \_\_\_\_\_ ft=  
 Total AWC for root zone depth of \_\_\_\_\_ ft=

AWC(5) = layer thickness(2) x AWC(4)

SWD(8) =  $\frac{AWC(5) \times SWD(7)}{100}$

SWD summary		
Check number	Check date	SWD totals
1		
2		
3		
4		
5		
6		
7		
8		

**(ii) Gravimetric or oven dry method**—Soil samples are collected in the field at desired depths using a core sampler or auger. Care must be taken to protect soil samples from drying before they are weighed. Samples are taken to the office work room, weighed (wet weight), oven-dried, and weighed again (dry weight). An electric oven takes 24 hours at 105 degrees Celsius to adequately remove soil water. A microwave oven takes a few minutes. Excessive high temperatures can degrade the soil sample by burning organic material. The drying oven can exhaust moisture from several samples at one time, but the microwave typically dries only one or two samples at a time. Percentage of total soil-water content on a dry weight basis is computed. To convert to a volumetric basis, the percentage water content is multiplied by the soil bulk density. Available soil water is calculated by subtracting percent total soil water at wilting point.

Tools required to use this method are a core sampler or auger, soil sample containers (airtight plastic bags or soil sample tins with tight lids), weighing scales, and a drying oven. Soil moisture will condense inside plastic bags, when used. This is part of the total soil moisture in the sample and must be accounted for in the weighing and drying operation. Standard electric soils drying ovens are commercially available. A much shorter drying time can be used with a microwave oven or infrared heat lamp, but samples need to be turned and weighed several times during drying to check water loss. Samples should be allowed to cool before weighing. These drying procedures are more labor intensive than using a standard drying oven at 105 degrees Celsius. Figure 9-4 displays an example worksheet for determining soil-water content of the soil profile.

**(iii) Carbide soil moisture tester**—A carbide soil moisture tester (sometimes called Speedy Moisture Tester) can provide percent water content of soil samples in the field; however, practice is necessary to provide satisfactory and consistent results. The tester is commercially available. Typically, a 26-gram soil sample and a measure of calcium carbide are placed in the air tight container. Some models use a 13-gram sample. When calcium carbide comes in contact with water in the soil, a gas (oxy-acetylene,  $C_2H_2$ ) develops. As the reaction takes place, the gas develops a pressure in the small air tight container. The amount of gas developed is related to amount of water in the soil sample (providing excess carbide is present).

**Caution:** If inadequate carbide is available to react with all of the water, indicated moisture content is low. The higher the water content, the higher the pressure. The tester provides a gauge that reads percent soil-water content on a wet-weight basis. A standard chart is available to convert percent soil-water content from wet weight basis to dry weight basis. Figure 9-4 displays an example worksheet for determining soil-water content of the soil profile. The worksheet shown in figure 9-5 can help determine soil moisture and bulk density using the Eley volumeter and carbide moisture tester. Table 9-2 displays oven dry moisture content,  $P_d$ , based on meter gauge reading,  $W_p$ . This instrument measures total water held in the soil sample. To obtain AWC, subtract water held at  $W_p$ .

**Figure 9-4** Soil-water content worksheet (gravimetric method)

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**Worksheet  
Soil-Water Content  
(Gravimetric Method)**

Land user \_\_\_\_\_ Date \_\_\_\_\_ Field office \_\_\_\_\_

Taken by \_\_\_\_\_ Field name/number \_\_\_\_\_

Soil name (if available) \_\_\_\_\_ Crop \_\_\_\_\_ Maximum effective root depth \_\_\_\_\_ ft

Depth range inches	Soil layer thickness inches d	Soil texture	Sample			Tare weight g Tw	Net dry weight g Dw	Volume of sample cc Vol	Moisture percentage % Pd	Bulk density g/cc Dbd	Soil-water content in/in SWC	Layer water content inches TSWC
			Wet weight g WW	Dry weight g DW	Water loss g Ww							

Dry weight (Dw) of soil = DW - TW = \_\_\_\_\_ g      Weight of water lost (Ww) = WW - DW = \_\_\_\_\_ g      Bulk density (Dbd) =  $\frac{Dw(g)}{Vol (cc)}$  = \_\_\_\_\_ g/cc

Percent water content, dry weight Pd =  $\frac{Ww}{Dw} \times 100 =$  \_\_\_\_\_ %      Soil-water content (SWC) =  $\frac{Dbd \times Pd}{100 \times 1} =$  \_\_\_\_\_ in/in

Total soil-water content in the layer (TSWC) = SWC x d = \_\_\_\_\_ inches

**Figure 9-5** Determination of soil moisture and bulk density using Eley volumeter and Speedy moisture tester

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**Determination of Soil Moisture and Bulk Density (dry)  
Using Eley Volumeter and Carbide Moisture Tester**

Farm \_\_\_\_\_ Location \_\_\_\_\_ SWCD \_\_\_\_\_  
Crop \_\_\_\_\_ Soil type \_\_\_\_\_ Date \_\_\_\_\_ Tested by \_\_\_\_\_

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Texture	Thickness of layer	Volumeter							Bulk density (g/cc)	Soil-water content (in)	Soil-water content at field capacity	Soil-water deficit (in)
		Reading before (cc)	Reading after (cc)	Volume (cc)	% Wet wt.	% Dry wt.	% Wilting point	% Soil-water				
	d			V	W <sub>p</sub>	P <sub>d</sub>	P <sub>w</sub>	SWC <sub>p</sub>	Db <sub>d</sub>	SWC	AWC	SWD
Totals												

Wet weight of all samples in grams unless otherwise shown.

$$Db_d = \frac{26}{V(1 + P_d)} \times 100$$

$$SWC = \frac{Db_d \times SWC_p \times d}{100 \times 1}$$

$$SWC_p = P_d - P_w$$

**Table 9-2** Oven dry moisture content based on 3-minute carbide moisture tester readings

Gauge reading <sup>1/</sup>	Oven dry moisture, P <sub>d</sub> (%)									
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9
2	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
3	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
4	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
5	5.1	5.2	5.3	5.4	5.5	5.7	5.8	5.9	6.0	6.1
6	6.2	6.3	6.4	6.5	6.6	6.8	6.9	7.0	7.1	7.2
7	7.3	7.4	7.5	7.6	7.7	7.9	8.0	8.1	8.2	8.3
8	8.4	8.5	8.6	8.7	8.8	9.0	9.1	9.2	9.3	9.4
9	9.5	9.6	9.7	9.8	9.9	10.1	10.2	10.3	10.4	10.5
10	10.6	10.7	10.8	11.0	11.1	11.2	11.3	11.4	11.6	11.7
11	11.8	11.9	12.0	12.2	12.3	12.4	12.5	12.6	12.8	12.9
12	13.0	13.1	13.3	13.4	13.5	13.7	13.8	13.9	14.0	14.2
13	14.3	14.4	14.6	14.7	14.8	15.0	15.1	15.2	15.3	15.5
14	15.6	15.7	15.9	16.0	16.2	16.3	16.4	16.6	16.7	16.9
15	17.0	17.1	17.3	17.4	17.5	17.7	17.8	17.9	18.0	18.2
16	18.3	18.4	18.6	18.7	18.9	19.0	19.1	19.3	19.4	19.6
17	19.7	19.8	20.0	20.1	20.3	20.4	20.5	20.7	20.8	21.0
18	21.1	21.3	21.4	21.6	21.7	21.9	22.0	22.2	22.3	22.5
19	22.6	22.8	22.9	23.1	23.2	23.4	23.5	23.7	23.8	24.0
20	24.1	24.3	24.4	24.6	24.7	24.9	25.0	25.2	25.3	25.5
21	25.6	25.8	25.9	26.1	26.2	26.4	26.5	26.7	26.8	27.0
22	27.1	27.3	27.4	27.6	27.7	27.9	28.1	28.2	28.3	28.5
23	28.6	28.8	28.9	29.1	29.2	29.4	29.6	29.7	29.9	30.0
24	30.2	30.4	30.5	30.7	30.8	31.0	31.1	31.3	31.4	31.6
25	31.7	31.9	32.0	32.2	32.3	32.5	32.7	32.8	33.0	33.1
26	33.3	33.5	33.6	33.8	33.9	34.1	34.3	34.4	34.6	34.7
27	34.9	35.1	35.2	35.4	35.5	35.7	35.9	36.0	36.2	36.3
28	36.5	36.7	36.8	37.0	37.1	37.3	34.5	37.6	37.8	37.9
29	38.1	38.3	38.4	38.6	38.8	39.0	39.1	39.3	39.5	39.6
30	39.8	40.0	40.1	40.3	40.5	40.7	40.8	41.0	41.2	41.3
31	41.5	41.7	41.8	42.0	42.2	42.4	42.5	42.7	42.9	43.0
32	43.2	43.4	43.5	43.7	43.8	44.0	44.2	44.3	44.5	44.6
33	44.8	45.0	45.1	45.3	45.5	45.7	45.8	46.0	46.2	46.3

1/ Carbide moisture tester—3-minute readings = W<sub>p</sub>

**(iv) Tensiometers (moisture stake)**—Soil-water potential (tension) is a measure of the amount of energy with which water is held in the soil. Tensiometers are water filled tubes with hollow ceramic tips attached on the lower end and a vacuum gauge on the upper end. The container is air tight at the upper end. The device is installed in the soil with the ceramic tip in contact with the soil at the desired depth. The water in the tensiometer comes to equilibrium with soil water surrounding the ceramic tip. Water is pulled out of the ceramic tip by soil-water potential (tension) as soil water is used by plants. This creates a negative pressure (vacuum) in the tube that is indicated on the vacuum gauge. When the soil is rewetted, the tension gradient reduces, causing water to flow from the soil into the ceramic tip.

The range of tension created by this device is 0 to 100 centibars (0 to 1 atmospheres). Near 0 centibars is considered field capacity, or near 0 soil water tension. Practical operating range is 0 to 80 centibars. The upper limit of 80 centibars corresponds to about: 90 percent AWC depletion for a sandy soil and about 30 percent AWC depletion for medium to fine textured soils. This limits the practical use of tensiometers to medium to fine textured soils with high frequency irrigation or where soil-water content is maintained at high levels. Tensiometers break suction if improperly installed and if the soil-water tension exceeds practical operating limits, typically 80 to 85 centibars. Once vacuum is broken, the tube must be refilled with water and the air removed by using a small hand-operated vacuum pump. A period to establish tensiometer-soil-water stability follows.

Tensiometers require careful installation, and maintenance is required for reliable results. They must also be protected against freeze damage. Maintenance kits that include a hand vacuum pump are required for servicing tensiometers. The hand pump is used to draw out air bubbles from the tensiometer and provide an equilibrium in tension. Tensiometers should be installed in pairs at each site, at one-third and two-thirds of the crop rooting depth. A small diameter auger (or half-inch steel water pipe) is required for making a hole to insert the tensiometer. Figure 9-6 shows a tensiometer and gauge and illustrates installation and vacuum pump servicing. Tensiometers are commercially and readily available at a reasonable cost.

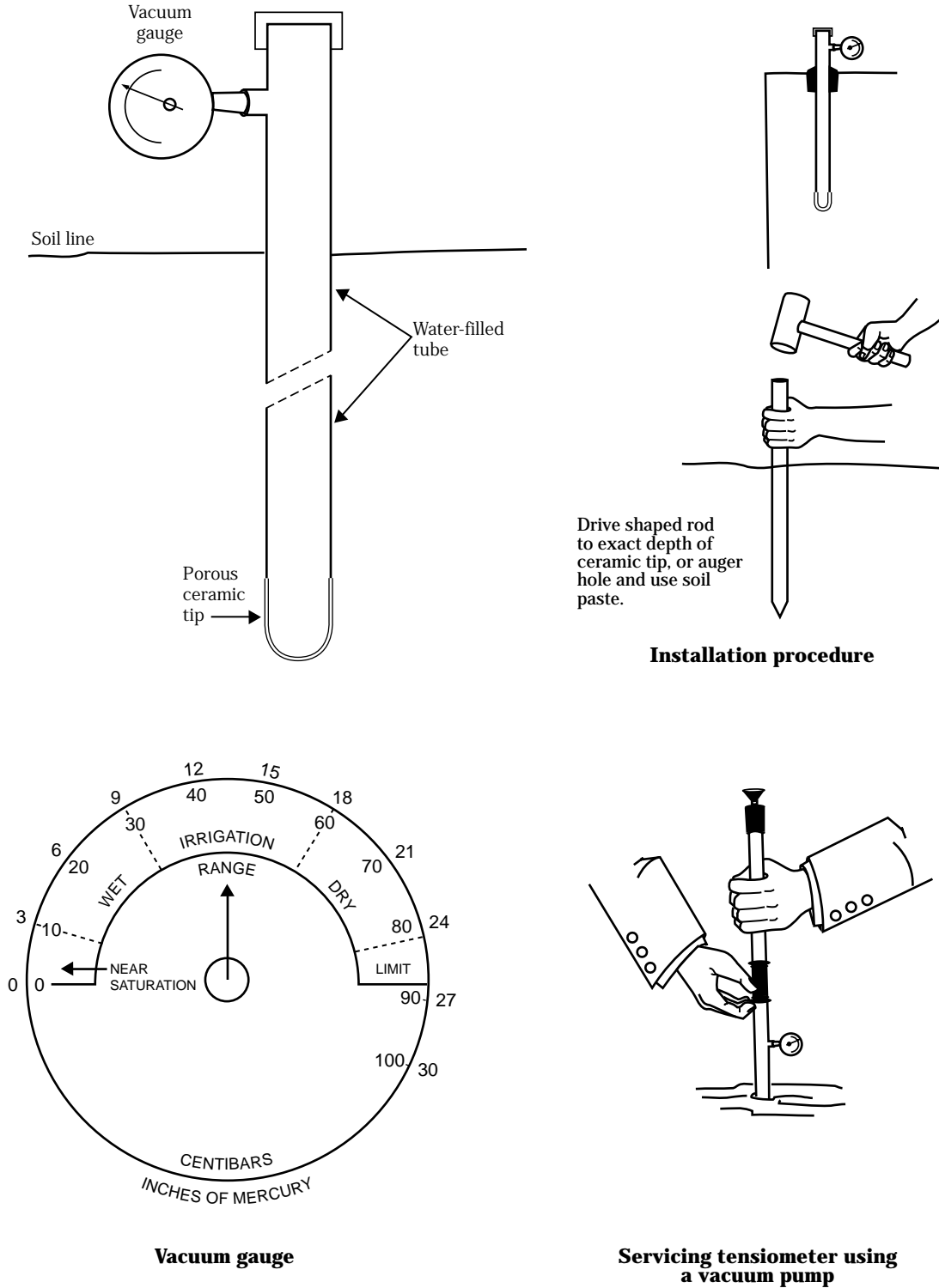
When installing tensiometers, make a heavy paste from part of the soil removed at the depth the ceramic tip is to be placed. When the hole has been augured about 2 inches below the desired depth of the ceramic tip, the paste is placed in the hole. As you install the tensiometer tube, move the tube up and down a few times to help assure good soil paste contact with the ceramic tip. Do not handle or touch the ceramic tip as contamination from material and body oil on the hands affects water tension on the tip. If the soil is wet at the desired ceramic tip depth, tensiometers can be installed by driving a rod or 0.5-inch diameter galvanized iron pipe to the desired depth. The end of the driving rod should be shaped the same as, but slightly smaller than the tensiometer tip. Pour a little water in the hole, move the driving rod up and down a few times to develop a soil paste at the bottom of the hole. Insert tensiometer tube, move the tube up and down a few times to help assure good soil paste contact with the ceramic tip.

Tensiometers installed at different rooting depths have different gauge readings because of soil water potential change in rooting depths. With uniform deep soil, about 70 to 80 percent of soil moisture withdrawal by plant roots is in the upper half of the rooting depth. Recommended depths for setting tensiometers are given in table 9-3.

**Table 9-3** Recommended depths for setting tensiometers

Plant root zone depth (in)	Shallow tensiometer (in)	Deep tensiometer (in)
18	8	12
24	12	18
36	12	24
> 48	18	36

**Figure 9-6** Tensiometer, installation, gauge, and servicing



**(v) Electrical resistance (porous) blocks—**Electrical resistance blocks are made of material where water moves readily into and out of the block. Materials are typically gypsum, ceramic, nylon, plastic, or fiberglass. When buried and in close contact with the surrounding soil, water in the block comes to water tension equilibrium with the surrounding soil. Once equilibrium is reached, different properties of the block affected by its water content can be measured. Electrical resistance blocks work best between 0 and 2 atmospheres (bars). Thus, they have a wider operating range than do tensiometers, but are still limited to medium to coarse textured soils.

Electrical resistance blocks are buried in the soil at desired depths. Intimate contact by the soil is essential. With porous blocks, electrical resistance is measured across the block using electrodes encased in the block. Electrical resistance is affected by the water content of the block, which is a function of the soil-water tension. Electrical resistance is measured with an ohm meter calibrated to provide numerical readings for the specific type of block. Higher resistance readings mean lower water content, thus higher soil-water tension. Lower resistance readings indicate higher water content and lower soil-water tension.

Gypsum blocks are affected by soil salinity, which cause misleading readings, and are prone to breakdown in sodic soils. They are best suited to medium and fine texture soils. Being made of gypsum, the blocks slowly dissolve with time in any soil. The rate is dependent upon pH and soil-water quality. Freezing does not seem to affect them. Blocks made from other material do not dissolve; therefore, have a longer life. Electrical resistance blocks are relatively low cost and with reasonable care are easy to install. Close contact with soil is important.

Installation tools required are a small diameter auger for making a hole for inserting blocks, a wooden dowel to insert blocks, and water and a container for mixing soil paste. (Multiple electrical resistance blocks can be installed in the same auger hole.) After the hole has been augered to about 2 inches below the deepest block installation depth, a soil paste is made from removed soil and placed about 6 inches deep in the bottom of the hole. Wet resistance block with clean water.

Handling or touching the electrical resistance block may affect soil moisture readings. With the electrical resistance block carefully held on the end of the dowel by the wires, place the block in the hole at the desired depth with a slight up and down movement to help assure soil paste contact with the block. Check for broken wires with an electric meter. Hold the electric wires along the side of the hole and carefully fill the hole with soil. Soil should be replaced by layers. It should be from the same layer from which it was removed. Repeat soil paste and block procedure at each electrical resistance block depth.

When electrical resistance blocks are located properly, almost anyone can obtain readings. One person with a meter can provide readings for many field test sites. Where farms are small, neighbors can share a single meter. Following each reading a report is developed and given to each farm irrigation decisionmaker. The irrigation decisionmaker must learn to interpret meter readings to decide the right time to irrigate.

Electrical resistance blocks and resistance meters (battery powered) are commercially and readily available. Table 9-4 displays interpretations of readings from a typical electrical resistance meter.

**(vi) Thermal dissipation blocks—**These blocks are porous ceramic materials in which a small heater and temperature sensors are imbedded. This 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 content. Thermal dissipation blocks must be individually calibrated. They are sensitive to soil-water content across a wide range. Meter readings can be used directly, or translated using manufacturer's charts to soil-water tension. Specific meters are to be used with specific type of blocks.

**(vii) Neutron scattering**—A neutron gauge estimates the total amount of water in a volume of soil by measuring the amount of hydrogen molecules in the soil. Hydrogen is a key element in water (i.e., H<sub>2</sub>O). The device is commonly called a neutron probe. The probe itself consists of a radioactive source that emits (scatters) high energy neutrons and a slow speed neutron detector housed in a unit that is lowered into a permanent access tube installed in the soil. The probe is connected by a cable to a control unit (neutron gauge) remaining at the surface. The control unit includes electronics for time control, a neutron counter, memory, and other electronics for processing readings.

Fast neutrons, emitted from the source and passing through the access tube into the surrounding soil, gradually lose their energy (and speed) through collisions with hydrogen molecules. The result is a mass of slowed or thermalized neutrons, some of which diffuse back to the detector. The detector physically counts returned neutrons. The number of slow neutrons counted in a specific interval of time is directly related

to the volumetric soil-water content in a sphere ranging from 6 to 16 inches. A higher count indicates higher soil-water content, and a lower count indicates lower soil-water content.

When properly calibrated and operated, the neutron gauge can be the most accurate and most repeatable method of measuring soil-water content. When plotted, count versus soil-water content is a linear relationship. The gauge as it comes from the manufacturer is calibrated to a general kind of soil (medium texture) and to a medium soil bulk density. A microprocessor calculates soil-water content in acre-inches or percent, dry weight basis. However, the gauge must be calibrated for in-place soils and type of access tube material being used; i.e., PVC, aluminum, or steel. Calibration is done using gravimetric sampling procedures. Also, for any soil texture other than what the device was calibrated to by the manufacturer, or with widely varying bulk density, the device must be recalibrated. This is a time consuming process in layered soils on alluvial sites where the texture and bulk density vary widely. Recalibration is generally not necessary in medium textured, medium bulk density, uniform soils.

**Table 9-4** Interpretations of readings on typical electrical resistance meter

Soil water condition	Meter readings <sup>1/</sup> (0 – 200 scale)	Interpretation
Nearly saturated	180 – 200	Near saturated soil often occurs for a few hours following an irrigation. Danger of water logged soils, a high water table, or poor soil aeration if readings persists for several days.
Field capacity	170 – 180	Excess water has mostly drained out. No need to irrigate. Any irrigation would move nutrients below irrigation depth (root zone).
Irrigation range	80 – 120	Usual range for starting irrigations. Soil aeration is assured in this range. Starting irrigations in this range generally ensures maintaining readily available soil water at all times.
Dry	< 80	This is the stress range; however, crop may not be necessarily damaged or yield reduced. Some soil water is available for plant use, but is getting dangerously low.

<sup>1/</sup> Indicative of soil-water condition where the block is located. Judgment should be used to correlate these readings to general crop conditions throughout the field. It should be noted, the more sites measured, the more area represented by the measurements.

The total volumetric soil-water content reading (count) of the neutron gauge should be translated into available soil-water content (AWC). Field capacity and wilting point levels must be known. It is more convenient if field measurements could be taken near those soil-water content levels. The neutron gauge method is highly accurate (1 to 2 percent of actual) if properly operated and adequately calibrated except:

- in the upper 6 inches of soil profile where fast neutrons tend to escape above the soil surface;
- in high clay content soil that contain tightly bound hydrogen ions that are not reflected in the detecting process;
- in soil with high organic matter content; and
- in soil containing boron ions.

These soil conditions all require recalibration of the gauge. Chapter 15 contains example worksheets, typical calibration curves, and sample displays for soil-water content by depth relationships.

Because a neutron gauge contains a radiation source and is a potential safety hazard to a technician using a gauge, special licensing, operator training, handling, shipping, and storage are required. The wearing of a radioactive detecting film badge is required by all technicians when handling and using a neutron gauge. The use of a neutron gauge is not to be taken lightly. NRCS operates under a site license held by the USDA Agricultural Research Service. Inspections of storage facilities are made periodically. Disposal of old neutron probes (radioactive source) is strictly controlled by U.S. Nuclear Regulatory Commission (NRC).

A neutron probe is recommended for large farms or farm groups where use efficiency and accuracy can justify high initial cost, maintenance, and operating under NRC requirements.

Tools needed are:

- Approved storage facility for the probe at the workshop and in the vehicle
- Small diameter soil auger
- Soil bulk density sampler
- Watertight access tubes that fit snugly against the soil
- Gravimetric soil sampling equipment (core sampler, auger, sample bags, weighing scales, drying oven) for calibration
- Neutron gauge

- Small square of canvas
- Tool box containing a variety of tools
- Film badges for everyone involved

**(vii) Dielectric constant method**—The dielectric constant of material is a measure of the capacity of a nonconducting material to transmit high frequency electromagnetic waves or pulses. The dielectric constant of a dry soil is between 2 and 5. The dielectric constant of water is 80 at frequency range of 30 MHz – 1 GHz. 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 developed for measuring the dielectric constant of the soil-water media (water content by volume) are time domain reflectometry (TDR) and frequency domain reflectometry (FDR).

For TDR technology used in measuring soil-water content, the device propagates a high frequency transverse electromagnetic wave along a cable attached to parallel conducting probes inserted into the soil. A TDR soil measurement system measures the average volumetric soil-water percentage along the length of a wave guide. Wave guides (parallel pair) must be carefully installed in the soil with complete soil contact along their entire length, and the guides must remain parallel. Minimum soil disturbance is required when inserting probes. This is difficult when using the device as a portable device. The device must be properly installed and calibrated. Differing soil texture, bulk density, and salinity do not appear to affect the dielectric constant.

FDR approaches to measurement of soil-water content are also known as radio frequency (RF) capacitance technique. 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. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes. Changes in soil-water content cause a shift in frequency. University and ARS comparison tests have indicated that, as soil salinity increases, sensor moisture values were positively skewed, which suggests readings were wetter than actual condition.

FDR devices commercially available include:

**Portable hand-push probes**—These probes allow rapid, easy, but only qualitative readings of soil-water content. Probe use is difficult in drier soil of any texture, soils with coarse fragments, or soils with hardpans. A pilot hole may need to be made using an auger. The probe provides an analog, color-coded dial gauge (for three soil types—sand, loam, and clay), or a digital readout. The volume of soil measured is relatively small (a cylinder 4 inches tall by 1 inch in diameter). Several sites in a field should be measured, and can be, because probes are rapid and easy to use. Proper soil/probe tip contact is essential for accurate and consistent readings.

**Portable device that uses an access tube similar to a neutron gauge**—The probe suspended on a cable is centered in an access tube at predetermined depths where the natural resonant frequency or frequency shift between the emitted and received frequency is measured by the probe. The standard access tube is 2-inch diameter schedule 40 PVC pipe. Installation of the access tube requires extreme care to ensure a snug fit between the tube and the surrounding soil. Air gaps or soil cracks between the tube and soil induce error.

The device is calibrated by the manufacturer to sand and to an average bulk density for sand. Recalibration is required for any other soil texture and differing bulk density. The volume of soil measured is not texture or water content dependent, and approximates a cylinder 4 inches tall and 10 inches in diameter. Accuracy can be good in some soils with proper installation and calibration, and there are no radioactive hazards to personnel such as when using a neutron gauge. Proper installation of the access tube is essential and can be quite time consuming. Accuracy of data is largely dependent on having a tight, complete contact between the access tube and the surrounding soil. Before making a large investment in equipment, it is highly recommended that adequate research be done on comparison evaluations that are in process by various universities and the ARS. Good sources of information are technical papers and proceedings of ASAE, ASCE, and Soil Science Society of America, as well as direct discussion with personnel doing evaluations.

**Other electronic sensors**—Numerous sensors are commercially available using microelectronics. Inexpensive devices sold at flower and garden shops measure the electrical voltage generated when two dissimilar metals incorporated into the tip are placed in an electrolyte solution; i.e., the soil water. Most of these devices are sensitive to salt content in the soil-water solution.

Factors to be evaluated for the selection and application of a soil-water content measuring program include:

- Initial cost of device, appurtenances, special tools, and training
- Irrigation decisionmaker's skill, personal interest, and labor availability
- Field site setup, ease of use and technical skill requirements
- Repeatable readings and calibration requirement
- Interpretations of readings—qualitative and quantitative needs
- Accuracy desired and accuracy of device
- Operation and maintenance costs
- Special considerations including licensing from NRC (private individuals do not operate under ARS licensing), storage, handling, film badge use, training required, disposal of radioactive devices, and special tools required for access tube installation

### (c) Crops

Crop characteristics are important for the irrigation planner and decisionmaker to know. Those characteristics necessary for implementing a proper irrigation water management program include purpose of crop, crop evapotranspiration, critical growth periods, and root development.

#### (1) Crop evapotranspiration

Crop evapotranspiration ( $ET_c$ ) is the amount of water used by the crop in transpiration building of plant tissue and evaporated from the soil or plant foliage surface. It is determined by using local climatic factors and stage of growth. Several equations can be used depending on climate data availability and degree of intensity of IWM program.  $ET_c$  provides one of the key ingredients in scheduling irrigations; i.e., how much water the crop uses or is projected to use.

## (2) Critical growth periods

Plants generally need sufficient moisture throughout the growing season. Most crops are sensitive to water stress during one or more critical growth periods during their growing season. If adequate moisture is not available during the critical period(s), irreversible loss of yield or product quality results. With many fruit and fresh vegetable crops, lack of available water at critical growth periods can result in a product that may be partly or totally unmarketable on the fresh market because of poor quality. See Chapter 3, Crops, for critical growth stages, and chapter 15 for IWM tools.

## (3) Root development

Roots develop as plants grow and mature. Major factors controlling root development are stage of plant growth, usable soil depth, soil compaction, soil condition, and amount of water in the soil. Irrigation should be planned to provide water only to the usable plant root zone unless leaching for salinity control is necessary.

Never assume a plant root zone depth. Observe and measure the actual depth roots penetrate a soil profile by digging a shallow pit and auguring. Notice the pattern of root development in the side of the pit. Check for roots in handfuls of augured soil. Generally 2 to 4 feet of total depth is adequate. If root development pattern depth is overestimated, an overirrigation recommendation is guaranteed. Plants will show unneeded stress between irrigations.

## (4) Yield (quality) versus water use relationships

Most crops respond to water availability and use to provide a given biomass or yield. Limited data are available for predicting specific yield versus water use relationships except for a few crops. With most crops, yield and product quality are reduced where excess water is applied. Too much water can also be detrimental to crop yield by leaching of otherwise available plant nutrients below the root zone. Water is also wasted. Tables or curves for several crops are in Chapter 3, Crops.

The following methods and devices are commercially available to measure plant moisture tension levels. They can provide indications of plant moisture stress.

*(i) Crop Water Stress Index (CWSI)*—The crop water stress gun measures plant canopy (foliage), temperature, ambient air temperature, relative humidity, and a range of solar radiation. The CWSI gun is commonly mistakenly called infrared gun or IR thermometer. In the CWSI gun a microprocessor calculates plant water stress and expresses it as an index from 0 to 1.0 or 0 to 10, depending upon the manufacturer. (The latter avoids using a decimal. Overall range is the same.) Threshold stress levels are developed for each crop for determining when to irrigate. Once developed, the stress index for a specific crop appears to be usable in all climate zones and for similar crop species. When first used in an area, it is best to affirm calibration based upon local conditions. When the canopy temperature in relation with other climate factors increases to a predetermined upper target level, the plants are considered stressed. A well watered plant has relative cool foliage because of the continual plant transpiration and has an index near zero. When plant canopy temperature reaches ambient temperature, the plant is not transpiring moisture and is probably beyond permanent wilting point. When following good water management practices, the irrigator can provide irrigations before upper target threshold stress levels are reached.

Periodic soil-water content checks should be made to relate plant water stress indexes and soil-water content levels. Observe and measure the depth of plant roots. Adequate soil moisture may be present below the plant root zone. CWSI readings can be observed over several days to predict the need for irrigation 3 to 5 days in advance.

This device is relatively easy to use and can provide rapid results at varied locations in a field. Proper techniques for use are important. Readings can be taken when the sky is clear or overcast, but not clouded over. The best time is midmorning to early afternoon, and the foliage must be dry. Readings must be taken only of foliage, not bare soil, landscape, sky, or other factors. Average several readings to improve accuracy. The gun is held at least 1 meter above the crop canopy, but not more than 10 meters. Direct the device more or less down onto the crop canopy. This creates a challenge with tall crops (corn, cotton, fruit, citrus, nuts). Caution must be exercised because apparent high stress levels may be from factors other than moisture, such as insects and disease. The user

should be able to observe field conditions and correctly interpret readings. Several models are commercially available. Different crops have different target stress levels.

Technology exists to provide CWSI readings from aircraft and satellite. Current limitations include getting information into the hands of the irrigation decisionmaker for timely irrigation water management decisions. Other uses of the CWSI gun include identification of plant stress before visual observation signs appear. Observing irrigation uniformity across the field and damage from crop insects, fungus (including root rot), and rodents are a few other uses.

**(ii) Leaf moisture stress (pressure chamber)**—This method involves encasing a part of the plant, such as a leaf, inside a pressure chamber, and checking the amount of pressure required to force the fluid stored in the sample back out the stem. Nitrogen gas is typically used. The pressure required to reverse the flow of plant moisture is interpreted to indicate plant moisture tension (stress). Target tension (stress) points must be developed for specific plants, after which it can be used as a reference for subsequent tests. Success of this method depends on standardization of the test protocol. It is desirable to take readings at predawn. Predawn plant water tension is controlled by soil-water tension, and daytime plant moisture tension is controlled by climate. Plant moisture stress can be several times higher during the heat of the day than at predawn and not be consistent at any specific time of day for each day. Sun angle, cloud cover, temperature, humidity, and wind all affect plant moisture tension levels during daylight hours.

**(iii) Evaporimeter (atmometer)**—An evaporimeter consists of a flat, porous ceramic disk (Bellani plate) in which water is drawn up by capillary action as water is evaporated from the disk. It is used to directly estimate crop evapotranspiration rate. Several commercial models can be easily installed near the edge of a field or on a roadway in a field. (The unit must be located far enough into the field to avoid field boundary effects.) One commercial model provides a green canvas-like material covering the ceramic disc to simulate crop leaf color. Reasonably good correlation has been found between field measurements and that calculated from Penman-type equations. Small difference in evaporation rates may be found between individual meters. Maintaining water levels and removal for freeze protection are necessary.

**(iv) Evaporation pans**—U.S. Weather Bureau Class A evaporation pans are standard sized, opentop metal water containers. Water is evaporated from a saturated source (water body) with solar energy. Coefficients must be applied to the evaporation rate representing pan coefficients and crop growth stage coefficients. Nonstandard pans have been tried with varying degrees of success. Materials range from galvanized metal wash tubs to PVC pipe (placed vertically). The devices are generally calibrated to a local Class A evaporation pan, and can be reasonably effective in determining when to irrigate. Coefficients are applied to the pan evaporation rate to represent crop evapotranspiration rate.

**(v) Infrared photography**—Aerial infrared photography can show current plant condition by the darkness of green vegetation. Red color intensity on photo prints displays dark green and lighter green patterns in the vegetation. Infrared photography is a valuable tool to visually observe local areas within an irrigation system or field(s) that receive either insufficient or excess irrigation water. Red color intensity differences can result from:

- Wrong sized or plugged nozzles or broken sprinkler heads giving poor distribution patterns
- Shallow or coarse textured soil areas (inclusions)
- Insect, fungus, or disease damage

Some skill is required to interpret color intensity on infrared photo prints. Plant canopy (foliage) temperature measured with a crop water stress gun may also be helpful.

**(vi) Visual**—Observation of plant condition is too often the only basis used for determining when a crop needs irrigated. By the time leaf color or degree of curl indicates the need of water, the plant generally is overstressed and yield and product quality are negatively affected. However, certain crops can be stressed at noncritical growth stages with little effect on yield. Some well-watered crops normally show visual signs of stress at or following solar noon on hot days. Overirrigation, especially early in the growing season, limits plant root development volume and depth, which limits the volume of soil containing water available for plant use. Often adequate soil water exists below existing plant root systems, but roots cannot grow rapidly enough to obtain adequate moisture to maintain plant evapotranspiration and growth.

Some irrigation decisionmakers randomly locate (or plant small areas in critical locations) a plant that shows moisture stress before the main crop. Corn is often used as a moisture stress indicator plant because it shows stress several days before many other crops. Many other indicator plants can be used. See Chapter 3, Crops.

#### (d) Upward water movement (upflux)

When a water table exists close to the root zone, crops extract water from the capillary fringe or water moving upward (upflux) into the crop root zone. The rate of upward flow depends primarily on the depth to the water table and soil texture. See Chapter 6, Irrigation System Design, for additional discussion.

## 652.0903 Irrigation scheduling

### (a) General

Irrigation scheduling is that part of proper irrigation water management involving the decision, when to irrigate and how much water to apply. Scheduling tools provide information that irrigation decisionmakers can use to develop irrigation strategies for each field on the farm. Such strategies may be based on long-term data, representing average conditions, or may be developed as the season progresses, using real time information and short-time predictions. In both cases information about the crop, soil, climate, irrigation system, water deliveries, and management objectives must be considered to tailor irrigation scheduling procedures to a specific irrigation decisionmaker and field condition. An irrigation scheduling tool needs only be accurate enough to make the decision when and how much to irrigate.

The need for proper irrigation water management, including irrigation scheduling, can best be demonstrated by identifying physical effects. To be most effective, identify the physical effects the irrigation decisionmaker is most concerned about, then show how proper irrigation water management will affect the concerns. The concerns include:

- Energy cost per season (fuel or electricity)
- Irrigation labor (kind of labor, timing, and amount)
- Wear and tear on irrigation equipment
- Plant response (yield) compared to potential
- Quality of product or crop
- Amount of irrigation water used
- Soil condition
- Plant response to fertilizer used
- Water quality onsite or offsite

Modern scheduling is based on soil-water balance or crop-water balance for one or more points in the field. By measuring existing and estimating future soil-water content or monitoring crop-water stress level, irrigation water can be applied before damaging crop stress occurs. Scheduling irrigation involves forecasting of crop water use rates to anticipate future water needs.

Figure 9–7 displays a flowchart for an irrigation scheduling process that uses soil-water content monitoring as the crop-water use indicator. Other techniques used to monitor current crop condition, such as infrared photography and leaf and plant moisture stress level index typically do not include a continual monitoring of soil-water content. Periodic checking of soil moisture status is generally sufficient to validate or update scheduling model.

The producer's management objective must be considered when developing a scheduling program. Maximizing net return is a common objective; other objectives may be to minimize irrigation costs, maximize yield, use less water, minimize ground water and downstream surface water pollution, optimize production from a limited water supply, use less energy for pumping, or to improve product quality.

Several scheduling techniques and levels of sophistication can be applied to track the amount of soil water in the crop root zone and crop water use. In some locations crop water use information is made available via newspapers, telephone call-in, television, or by computer modem systems. All irrigation scheduling programs should account for rainfall measured at the field site. Because of the spatial variation in rainfall, amount recorded at the farmstead or in town often does not represent precipitation at the field site. With precipitation (usually rainfall) at the field site known, accuracy for scheduling irrigations is improved. The amount available to meet plant water needs is called *effective precipitation*.

In addition to soil water to plant relationships, other factors are important in selecting a method of scheduling irrigations and setting up the scheduling procedures. Labor skill, availability, and personal interest dictate what type and level of intensity for readings and calculations can be made to make the scheduling procedure work. Irrigation district policies and capabilities often dictate when and for how long an irrigator will get water; i.e., delivery schedule. Cultural operations, such as hay cutting, over-canopy pesticide application, or row crop cultivation, have a major impact on scheduling. Some farmers do not like to keep written records; however, most have accepted the fact that they must for other purposes. Many farmers have a personal computer system. Some prefer to hire management services to give them information needed.

All these factors must be taken into account when determining what irrigation scheduling procedure will be best suited to a water user. A good rule to follow, **keep it simple and easy to understand**, even when a computer system is used. Adaptation requires maintaining the risk perceived equal to or less than the current way irrigation water is being scheduled.

## (b) Irrigation scheduling methods

Irrigations can be scheduled using methods varying from simple soil water monitoring using the feel and appearance method to sophisticated computer assisted programs that predict plant growth. Scheduling involves continual updating of field information and forecasting future irrigation dates and amounts.

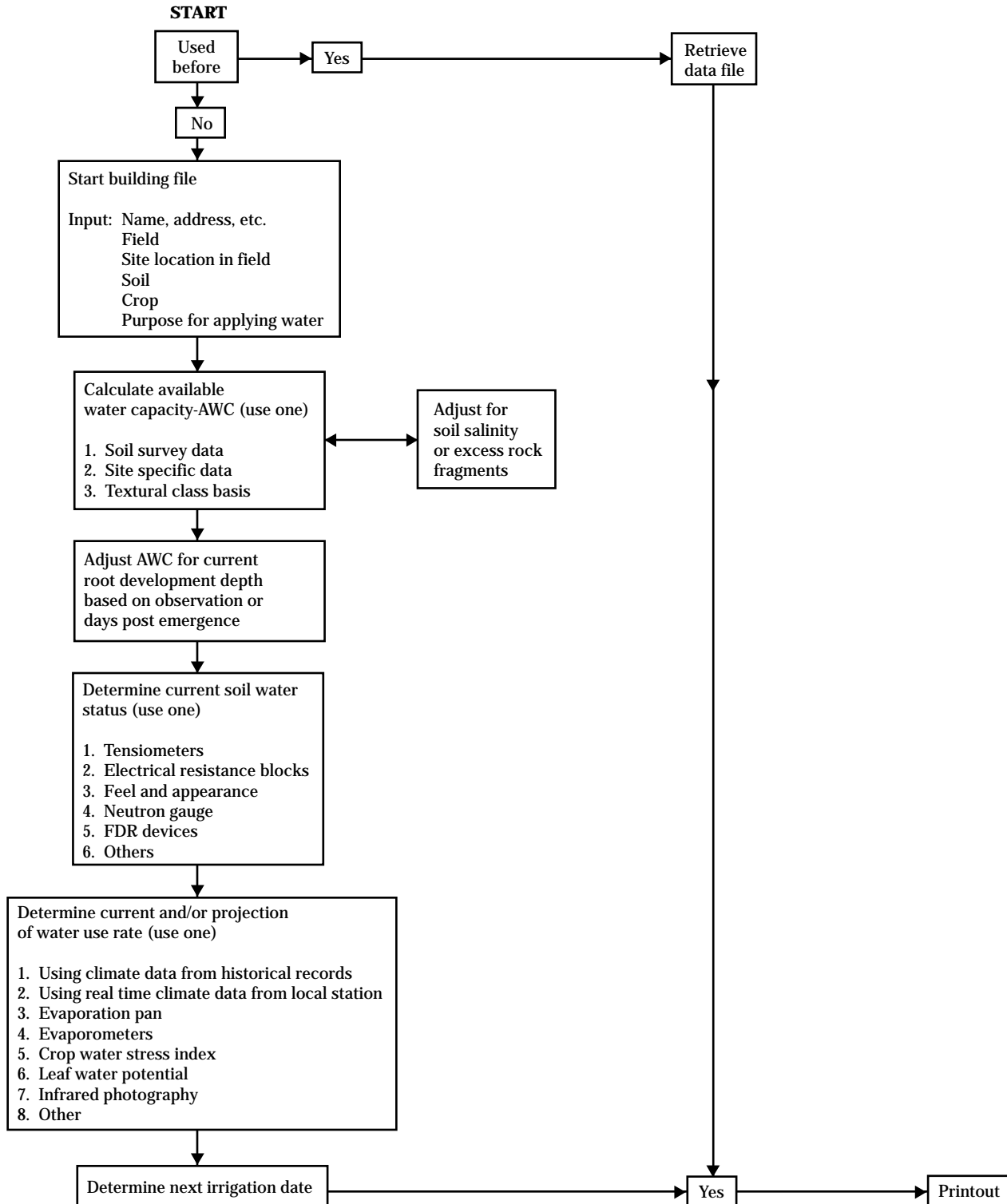
Crop yield and quality can be improved with most plants by maintaining lower soil-water tensions (higher moisture levels). Thus, it is wise to irrigate when the soil profile can hold a full irrigation. Waiting until a predetermined percent of soil AWC is used can cause unnecessary stress.

### (1) Soil and crop monitoring methods

Some scheduling practices are based solely on monitoring soil-water content or crop water use. Irrigations are needed when the soil-water content or crop water use reaches predetermined critical levels. Soil-water content and plant moisture tension measuring devices and procedures are described in section 652.0902(b). Using the monitoring data is briefly described in this section.

Accurate monitoring should provide the irrigation decisionmaker information at or soon after the time of measurement. The data must be available to ensure that the field can be irrigated before moisture stress occurs. Monitored data must be displayed so that the information is easy to understand and use to predict an irrigation date. When past data are projected forward, usually the future will resemble the past. Rapidly growing crops and weather changes must be considered. Local weather forecasts can provide a guide as to when to irrigate, but frequent field measurements are often necessary.

**Figure 9-7** Example irrigation scheduling program flowchart using soil water content for validation



**(i) Crop water use monitoring**—Monitoring crop conditions can be used to estimate when to irrigate, but it does not provide any information on how much water to apply. Crop water use can be measured, but it is usually calculated or estimated. The Crop Water Stress Index (CWSI) method measures plant condition and compares that status to a known reference for a well watered plant condition. Infrared photography indicates presence or lack of surface moisture, either on soil surface or plant leaf surface. Some skill is necessary to interpret color intensity on infrared photographs. What appears to be plant moisture stress may result from other causes, such as insect damage, lack of key nutrients, or from other toxic materials on leaf surfaces. Number of sets, days, and rotation or cycle time to get across a field should be considered when using a field monitoring method.

Some level of soil and crop monitoring is essential for efficient irrigation water management. Growing high value crops can support a sophisticated monitoring and scheduling program whether it be for optimizing water use and crop yield, maintaining desirable crop quality, minimizing use of fertilizer, or educing runoff, deep percolation, or both. Monitoring can be accurate where irrigators are adequately trained and personally interested. The monitoring schedule should fit into the pattern of irrigation. Monitoring dates before and after an irrigation should be flexible and adjustable to provide better management information.

**(ii) Soil moisture monitoring**—Monitoring soil-water content before, during, and after the crop growing season is the primary tool to schedule irrigations or calibrate other less labor intensive irrigation scheduling tools.

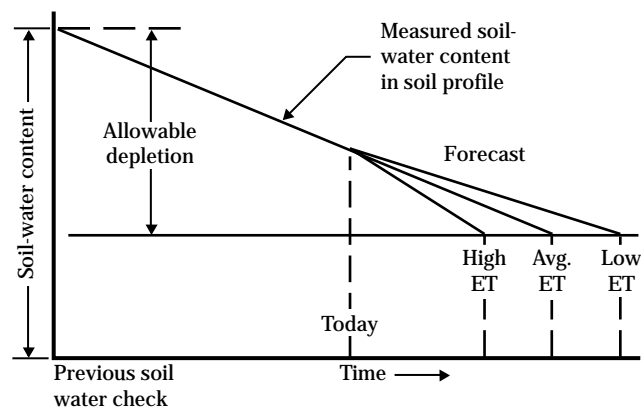
Soil moisture monitoring is perhaps the most accurate irrigation scheduling tool. With experience the feel and appearance method can be used to accurately determine soil moisture available for crop use. If other methods are used to determine soil moisture, the feel and appearance method should also be used to check the other method and to *experience* the fingers in determining soil moisture. At first three to five samples are examined at four or five sample sites in a field. Again with experience and a specific crop and soil, one soil sample at a depth of 12 to 18 inches can be sufficient per sample site. At this depth soil samples can be removed with a soil probe or small auger, typically under the growing plant. Displaying moisture

content at various depths may be desirable at each monitoring site. Too little or too much soil moisture in the profile becomes more apparent when displayed graphically.

Soil moisture monitoring is used to calibrate or affirm other irrigation scheduling methods that predict plant water use by measuring plant stress (crop water stress index, plant tissue monitoring) or calculate plant water use based upon climatic data. Examples are NRCS (SCS) SCHEDULER computer software or checkbook method. With these other methods, checking actual soil moisture is like receiving your bank statement from the bank. It affirms or cautions you when an error may exist or other adjustments are needed. See Section 652.0902(b), Measuring soil-water content.

Many computer scheduling programs use soil moisture measurements for updating methods based on computing the soil-water balance. Figure 9-8 provides a schematic of a basic soil-water content monitoring display to schedule irrigations. The same principal can be used regardless of units provided by a soil-water content or plant moisture tension level measuring device. Displaying may be desirable the various depths, if applicable, at each monitoring site.

**Figure 9-8** Soil-water measurements used to predict day to irrigate



## (2) Checkbook method

The checkbook irrigation scheduling method is similar in principle to using a checkbook to transfer money into or out of a home checking account. In this case, instead of a bank holding the money, the soil profile holds water available for plant growth in the root zone. If the amount of available water (bank balance) in the root zone at the end of day one is known and if the water losses (withdrawals) and gains (deposits) that occurred on day two are known or can be estimated, then the amount of soil water in the root zone at the end of day two can be calculated.

Deposits of water to the plant root zone are effective precipitation, irrigation, or water table contribution. Withdrawal of water from the root zone is primarily crop evapotranspiration ( $ET_c$ ) and soil evaporation. Manual, adding machine, hand calculator, or computer bookkeeping methods can be used. Checkbook crop use data can be forecasted crop ET, pan evaporation, or other data. Because of spatial variability, rainfall amounts should be measured at the field. Net irrigation or precipitation application amounts can be reasonably estimated. Soil-water content measurements should be made to calibrate calculations and other measurements.

Deep percolation cannot be directly measured in a field situation, but is accounted for in field application efficiency, which also includes improper irrigation timing (too much water too late). Irrigation depths applied under sprinkler systems can be measured by using catch cans (rain gauges) to determine application amounts, flow measuring devices to measure irrigation flows to laterals or from sprinkler heads, and estimates of evaporation losses. A water balance method, such as the checkbook method, is used by the irrigator to track crop water use and soil-water deficit.

Crop evapotranspiration reporting services are sometimes available. This community wide, private, or public service calculates daily crop evapotranspiration for selected crops and provides this information to irrigators through radio, newspaper, television, or by a special telephone service. The TV Weather Channel displays maps showing ET of well-watered grass for the preceding week.

The Water Balance Irrigation Scheduling Worksheet (fig. 9-9) may be used with the checkbook method.

## (3) Computer assisted methods

Computerized irrigation scheduling allows the storage and transfer of data, easy access to data, and calculations using the most advanced and complex methods for predicting crop ET. Many computer software programs are available to assist in scheduling irrigations. Most programs access data bases for soil characteristics, crop growth characteristics, climate, water supply, irrigation system, and economic data. The ability to directly access and process climate data from a regional network of local stations or an onsite weather station has greatly streamlined data entry and analysis for computerized scheduling. Scheduling programs are no better than the data used or the ability of the irrigator to interpret output data.

**(i) Daily crop evapotranspiration**— $ET_c$  is computed to the day of real-time climate data availability, then the method predicts crop ET for up to 10 days in the future. The data can be used by the irrigator to keep a water balance worksheet (fig. 9-9) for each field. This type program generally is used by a local agency or district, consultant, water company, or water district to provide information to local irrigators. Crop ET data are often available to the irrigation decisionmaker in local newspapers, telephone dial-up service, or television. Irrigation decisionmakers for large farms or farms growing high value crops often use onfarm weather station(s) and the farm computer to calculate daily plant water use. However, almost any size farm can support the use of a computer. The computer facilitates the management of all natural resource data as well as record keeping on the farm. The method is similar to the checkbook method.

**(ii) Local real-time climate data**—Climate data are retrieved by computer phone modem, soils data and crop growth characteristics are accessed, current crop ET is computed, monitored soil-water content is input if available, and a complete crop-soil water balance set of records is developed by computer software for each field being scheduled. Actual onsite, field by field, irrigation system performance is used as basis to determine net irrigation application values. This type program is used directly by the irrigator (or farm consultant) using their own computer and telephone modem.



A good irrigation scheduling program can be updated on a regular basis with soil-water content data to improve efficiency and accuracy of determining when to irrigate and how much water to apply. Following periods of excess rainfall when soils are probably at or near field capacity is an easy calibration point. Calculated available soil water should be near field capacity. When crop ET and water costs versus crop yield data are known, a true current economic evaluation can be presented to the irrigation decisionmaker. Improved predictions from computerized irrigation scheduling allow the irrigation decisionmaker to lengthen the period between field monitoring and reduce the uncertainty of the soil-water balance. Adequate and timely water can be provided to the crop and deep percolation losses minimized when following a good irrigation scheduling program.

Some currently available computer programs are briefly described in the following paragraphs. Documentation required to run the program must be available and easy to understand.

*NRCS (SCS) Scheduler (DOS Version 3.0 as of 6/96)*—This irrigation scheduling program was developed for NRCS by Michigan State University. It is usable nationwide and is applicable in most climates. Using onfarm characteristics and local real time climate data, a simple accounting process is employed to:

- Determine daily and monthly evapotranspiration of the crop.
- Determine seasonal irrigation requirement.
- Account for change in soil-water content since it was last measured.
- Predict rate at which soil water will decrease over the next 10 days.

This program works with any soil and may be applied to any number of crops as crop-specific growth data become available. Currently the program includes 42 crop curves. Climatic data and crop information necessary for local irrigation scheduling should be developed or adapted from local information. Accounting for onsite rainfall is essential. Climate data may be entered manually or transferred directly from a local real-time climatic data collection station via phone modem. To update the soil-water balance, soil-water content monitoring data can be input at anytime. Figures 9–10 and 9–11 display seasonal crop ET curves and soil-water content status using NRCS (SCS) SCHEDULER computer program.

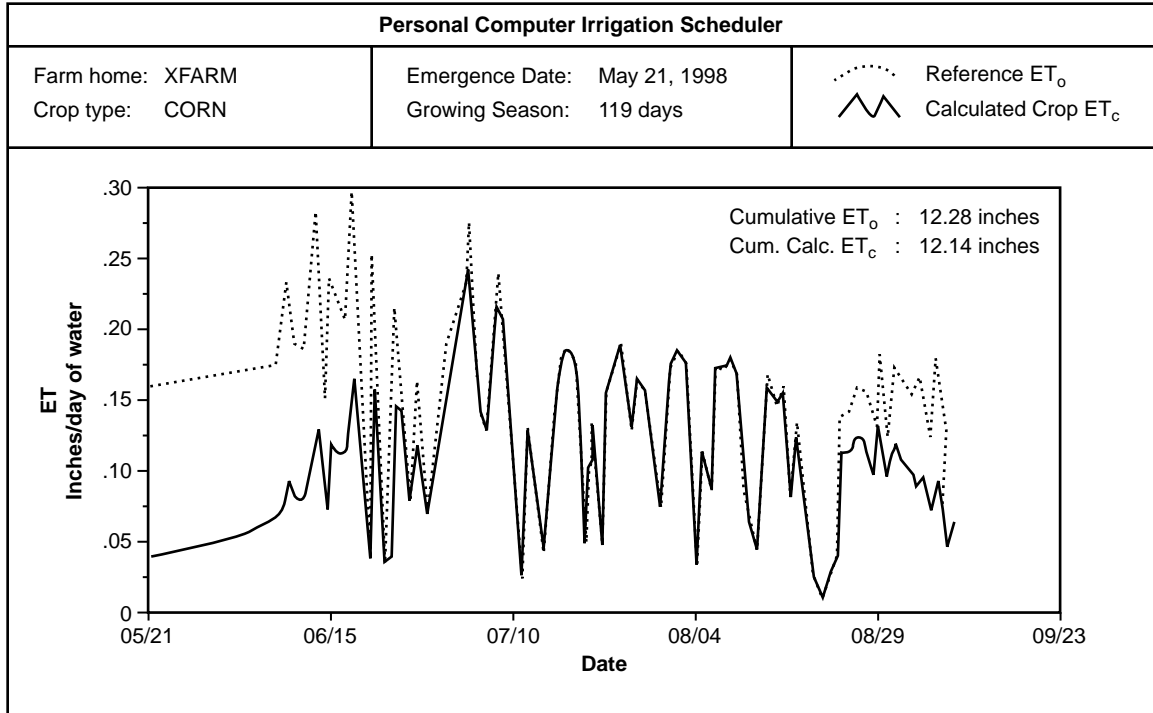
*US Bureau of Reclamation Scheduling program (Agrimet)*—Bureau of Reclamation has adopted and modified a computer scheduling program developed at USDA Agriculture Research Station at Kimberly, Idaho. Agrimet is the Northwest Cooperative Agricultural Weather Network. It is cooperatively sponsored by land grant universities, Cooperative Extension Service, NRCS, local soil and water conservation districts, ARS, local irrigation districts, and other state and local water resource agencies and organizations.

Sensors collect real time climate data (air temperature, relative humidity, solar radiation, precipitation, and wind run speed and direction). A data collection platform (DCP) interrogates the sensors at programmed intervals, every 15 minutes or hourly, depending on the parameter. The DCP transmits the data every 4 hours via the GOES satellite to a central receive site in Boise, Idaho. The recorded parameters are used to calculate a daily reference ET based on the 1982 Kimberly-Penman equation. Crop water use models are run daily to translate the local climatic data into daily ET information for crops at each weather station. Anyone with a computer, a modem, and an Agrimet user name can access Agrimet for weather data or site-specific daily crop water use information from throughout the Pacific Northwest Region. Other onfarm factors to be considered when using the published crop ET data include water used for environmental control, salinity control, and irrigation system application efficiency and uniformity.

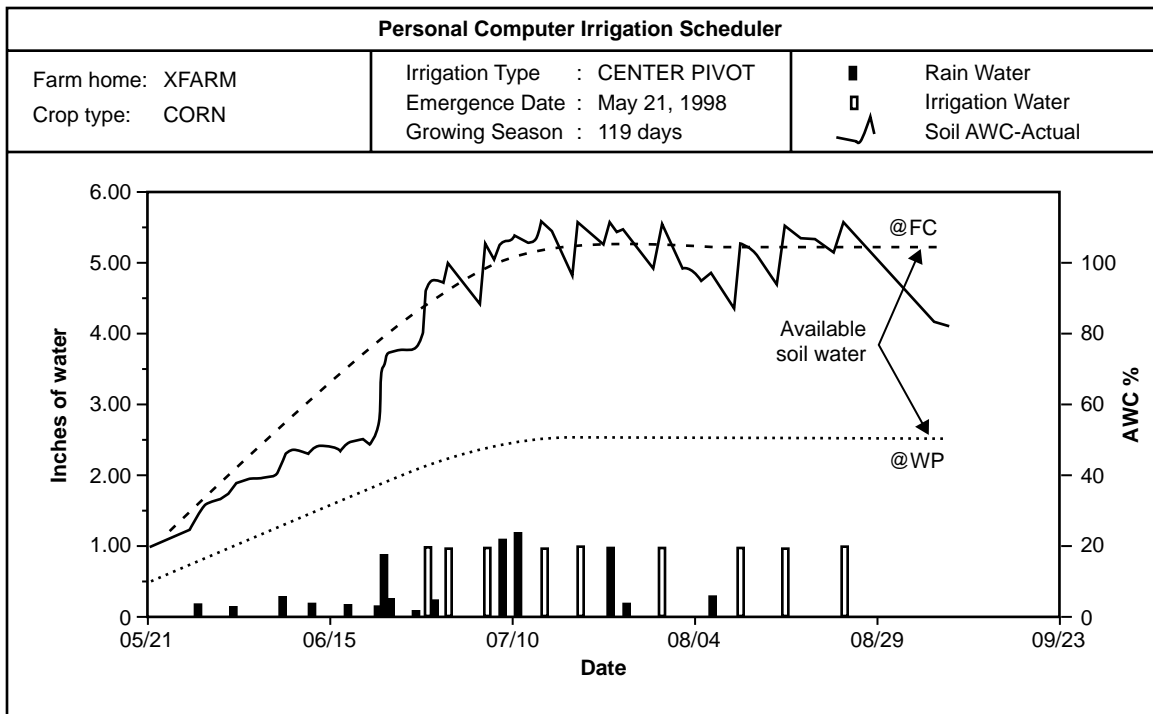
ARS personnel at Ft. Collins, Colorado, developed a computer assisted irrigation scheduling program. Program software uses minimum to optimum field data to predict when to irrigate. Default values replace measured data where necessary. In general, the better the field data input, the more precise the data output.

University scheduling programs—Several computer scheduling programs are available and supported by many local universities. Typically, these programs apply statewide or to more localized areas within a state. The State Supplement section at the end of this chapter gives additional information on programs available from local universities.

**Figure 9-10** NRCS (SCS) SCHEDULER—seasonal crop ET



**Figure 9-11** NRCS (SCS) SCHEDULER—seasonal soil moisture status



#### (4) Consultative irrigation scheduling services

Consultants are available who will (for a fee) provide irrigation scheduling services throughout the irrigation season. These consultants often offer other agricultural services including fertilizer and pest management programs.

The advantages of this type scheduling are:

- The consultant is generally well trained and professional.
- The latest techniques are typically used, including state-of-art soil-water content measuring devices and computers.
- Fine tuned management can be maintained.
- Water management integrated with fertilizer, pest, and other management programs can result in optimum plant growing conditions.
- The farm manager who is willing to pay for such services is probably going to follow the recommendations faithfully.
- The saving or proper timing of one irrigation often pays for the service for the entire growing season.

#### (5) Commercial service

Associated with crop growing contracts, many commercial companies provide field assistance to the irrigator to assure that expected crop yield and crop quality are obtained. Assistance from a field specialist, involving irrigation and fertilizer recommendations and insect control, is typically provided as part of the crop contract arrangement.

## 652.0904 Irrigation system evaluation procedures

### (a) General

The effectiveness of irrigators' irrigation water management practices can be determined by making field observations and evaluations. The results of these observations and evaluations are used to help them improve water management techniques, upgrade their irrigation system(s), or both. Improvements to operations and management can conserve water; reduce labor, energy, and nutrient losses; generally improve crop yields, biomass, and product quality; and reduce existing or potential water pollution. The following principles apply to all irrigation methods and systems.

- Irrigation should be completed in a timely manner to maintain a favorable soil-water content for desired crop growth. An exception may be made where the water supply is limited. In this situation, water should be applied in a manner that maximizes water use benefits.
- The amount of water applied should be sufficient to bring the crop root zone to field capacity minus allowable storage for potential rainfall events.
- Water should be applied at a rate that will not cause waste, erosion, or contamination of ground water and downstream surface water.
- Improving management of the existing system is always the first increment of change for improved water management. Each irrigation evaluation should consider a change in water management decisions only, and then a change in water management decisions and irrigation system performance.

Evaluation is the analysis of any irrigation system and management based on measurements taken in the field under conditions and practices normally used. An examination of irrigation water management practices should attempt to answer the following questions:

- Is the water supply sufficient (quantity and quality) and is it reliable enough to meet the producers objective?
- Are irrigations being applied in a timely manner?

- How is the need for irrigation determined? What is the planned soil-water deficit (SWD)? Is it dry enough to irrigate, too dry, or wet enough to stop irrigating?
- How much water is being applied by each irrigation? How is this amount determined?
- Is irrigation causing erosion or sediment deposition in parts of the field? Off the field?
- How uniform is water being applied over the irrigated area?
- How much water is being infiltrated into the area being irrigated?
- Is there excessive deep percolation or runoff in parts of the field?
- How much deep percolation or runoff? Are amounts reasonable?
- Does water applied for salinity management meet salt level balance needs throughout the soil profile? meet quality of water being used? for the crop being grown? during the desirable crop growth period? over the field?
- Does water applied for climate control meet uniformity and rate objectives?
- Are pesticides or fertilizers being applied through the irrigation system? (May require a high level of management, more or less water per application, and such additional safety devices as back flow prevention devices.)
- Is there a real or potential pollution problem being caused by irrigation?
- What is the overall irrigation application efficiency (mostly affected by management decisions) and irrigation system distribution uniformity of application (highly dependent on system flow rates and configuration)?
- On a sprinkle (or micro) irrigated field, is there translocation of water from the point of application to adjacent areas? How does this affect uniformity of application?

## (b) Irrigation efficiency definitions

Irrigation efficiencies are a measure of how well an irrigation system works as well as the level of management of the system. The definitions that follow are similar to standard definitions developed by ASAE and ASCE, and are used in NRCS.

### (1) Conveyance efficiency

Conveyance efficiency ( $E_c$ ) is the ratio of water delivered to the total water diverted or pumped into an open channel or pipeline at the upstream end, expressed as a percentage. It includes seepage losses, evaporation, and leakage inherent in the specific conveyance facility. With appropriate identification it could also include operational spills.

### (2) Irrigation efficiency

Irrigation efficiency ( $E_i$ ) is the ratio of the average depth of irrigation water beneficially used to the average depth applied, expressed as a percentage.

### (3) Application efficiency

Application efficiency ( $E_a$ ) is the ratio of the average depth of irrigation water infiltrated and stored in the plant root zone to the average depth of irrigation water applied, expressed as a percentage. Average depth stored in root zone (or intercepted by plants) cannot exceed soil-water deficit (SWD), but may be equal. If the entire root zone will be filled to field capacity during an irrigation, then average depth infiltrated and stored in the root zone is SWD.

### (4) Application efficiency low quarter

Application efficiency low quarter (AELQ or  $E_q$ ) is the ratio of the average of the lowest one-fourth of measurements of irrigation water infiltrated and stored in the plant root zone to the average depth of irrigation applied; it is expressed as a percentage.

### (5) Application efficiency low half

Application efficiency low half (AELH or  $E_h$ ) is the ratio of the average of the low one-half of measurements of irrigation water infiltrated and stored in the plant root zone to the average depth of irrigation water applied; it is expressed as a percentage.

**(6) Project application efficiency**

Project application efficiency ( $E_p$ ) is the ratio of the average depth of irrigation water infiltrated and stored in the plant root zone to the average depth of irrigation water diverted or pumped; it is expressed as a percentage. Project application efficiency includes the combined efficiencies from conveyance and application. It can be the overall efficiency of only onfarm facilities, or for community projects, it may include both on and off-farm efficiencies.

**(7) Potential or design application efficiencies**

Potential or design application efficiencies are usually those recommended in the irrigation guide and in various tables and charts in NEH, Part 623 (Section 15), Irrigation. These efficiencies are typically used for designing irrigation systems. The efficiency recommendations usually assume good management and maintenance of a well designed and installed system. If it is anticipated that a specific irrigator will not meet these criteria, then a lower potential application efficiency should be used than those recommended in references. Judgment by the designer is required. Overestimating the operator's level of management can result in an inadequate irrigation system design.

**(8) Uniformity of application**

How uniform an irrigation system applies water across the field is important. Within a range of physical conditions and management, any irrigation method can apply water in such a manner that over 90 percent of applied water is used by the plant. However, the range of physical conditions (topography, soils, water supply) in which this level of uniformity and management can be accomplished, can be narrow. Selection of a different irrigation method and system may provide a wider, more reasonable range of conditions; thus fewer management limitations.

**(9) Distribution uniformity**

Distribution uniformity (DU) is a measure of the uniformity of infiltrated irrigation water distribution over a field. DU is defined as the ratio of the lowest one-fourth of measurements of irrigation water infiltrated to the average depth of irrigation water infiltrated, expressed as a percentage. For low value crops, maintenance of vegetation, or areas of partial season irrigation, DU of low one-half may be more economical than using low one-quarter.

Sprinkler systems:

$$DU = \frac{\text{Average low - quarter depth received}}{\text{Average catch can depth received}} \times 100$$

Surface systems:

$$DU = \frac{\text{Average low - quarter depth infiltrated}}{\text{Average depth infiltrated}} \times 100$$

The average low-quarter depth of water received is the average of the lowest one-quarter of the measured values where each value represents an equal area. For calculation of DU of low one-half, substitute average low half depth received or infiltrated in place of low quarter.

**(10) Christiansen's uniformity**

Christiansen's uniformity (CU) is another parameter that has been used to evaluate uniformity for sprinkle and micro irrigation systems. DU should be used instead of CU. Thus, sprinkler and micro irrigation application uniformity can be directly compared to other irrigation methods and systems. Christiansen's uniformity is expressed as:

$$CU = 100 \left( 1.0 - \frac{\sum X}{m n} \right)$$

where:

- X = absolute deviation of the individual observations from the mean (in)
- m = mean depth of observations (in)
- n = number of observations

CU can be approximated by:

$$CU = \frac{\text{Average low - quarter of water received}}{m} \times 100$$

and the relationship between DU and CU can be approximated by:

$$\begin{aligned} CU &= 100 - 0.63 (100 - DU) \\ DU &= 100 - 1.59 (100 - CU) \end{aligned}$$

Some parameters that affect uniformity tend to average out during a series of irrigation applications. Other aspects of nonuniformity tend to concentrate in the same areas, either over or under irrigation during each application. See discussion in NEH, Part 623, Chapter 11, Sprinkle Irrigation, Sprinkle Irrigation Efficiency.

## (c) Irrigation system evaluations

### (1) First step

Many important factors concerning how well an irrigation system is operating and how well it is being managed can be determined with a few simple observations and evaluation procedures. These procedures are used for a simple, abbreviated, or detailed evaluation and are the first step in any system evaluation.

For any irrigation method or system, equipment needed to check soil moisture and compacted layers is a soil auger, push tube sampler, or soil probe. If the soil is rocky, a shovel (sharp shooter) is also needed

A pressure gauge with pitot tube attachment, drill bits to check nozzle wear, short piece of hose, and calibrated container to check nozzle discharge are needed for sprinkler irrigation systems. For micro irrigation systems, special fittings for pressure gauge and catch containers to check the head and emitter discharge are needed. Surface irrigation systems require measuring devices to check furrow and border inflow and outflow. Flow measuring devices are needed for sub-irrigation systems.

### (2) Evaluation procedures

**Step 1**—Determine basic data about the irrigation system and management from the irrigation decisionmaker. Some questions that might be asked include:

- How does the irrigation decisionmaker determine when to irrigate and how much water to apply?
  - How is length of time for each irrigation set determined?
  - For sprinkler and micro irrigation systems, what are the operating pressures at several locations along a selected lateral?
  - How is the time to shut water off determined?
  - How long does it take for water to reach the end of borders or furrows?
  - What is the irrigation water supply flow rate in early season? mid season? late season?
  - How is flow rate determined?
  - What is the rate of flow onto each border or into a furrow? into the system?
  - What problems (or concerns) have the irrigator experienced with the system?
- Are there dry spots in the field? wet spots? Are large areas of the field under irrigated? overirrigated?
  - Crop production:
    - What is the average production of each field irrigated?
    - Does it meet or exceed county or area averages?
    - Does production vary across the field? If so, what does the irrigation decisionmaker feel are the causes (irrigation system, field surface nonuniformity, water supply amount and location of source or delivery, soil, fertilizer, chemigation, pests)?
  - How much control does the irrigator have over when and how much irrigation water is available? delivery schedule?
  - What are farm manager's objectives?
  - What is the skill level, timing, and amount of labor available?
  - Can water be changed at night? during the middle of the day? at odd hours? If short set times are necessary, is a semiautomatic or complete automatic control system available?

**Step 2**—Observe the field in question. Look at other fields. Look at the supply system. Look for and ask:

- Are there erosion or sediment deposition areas?
- Are there indications of excessive runoff from part or all of the field?
- Are there problems (benefits) created by excessive irrigation tailwater or field runoff?
- Do leaky ditches and pipelines appear to have excessive water loss (seeps or leaks)? (1gpm=1 acre inch every 20 days)
- Are crops uneven or discolored? Do they show obvious stress?
- Are there water loving plants and weeds present? If so, is there an obvious wildlife benefit?
- Are there saline or swampy areas?
- Are there obvious signs of poorly maintained micro and sprinkler hardware, including leaky gaskets, weak or broken springs, plugged emitters, or worn nozzles?
- Are there poorly maintained diversion or turnout gates, leaks, uneven flows from siphon tubes or gated pipe gates, uneven irrigation heads, weeds, and trash?
- Are there measuring devices? Are they in satisfactory operating condition? Are they used to make onfield water management decisions?

**Step 3**—With the irrigation decisionmaker, auger or probe several holes at selected locations in the field. This is the best time to start talking to the farm manager or irrigation decisionmaker about proper irrigation water management. The feel and appearance method of moisture determination can also be demonstrated. Look for such information as:

- Is there evidence of an excessive high water table or indications of a fluctuating water table?
- Locate hard pans, compacted layers, mineral layers, or other characteristics that can restrict root growth and the movement of water in the soil. What is the apparent cause(s) of each restriction?
- Does soil texture change at various levels in the soil profile?
- Observe water content of each soil layer. Demonstrate the feel and appearance method of moisture determination to the irrigation decisionmaker. Is the location of wetted soil shallow (typically under irrigated) or deep (typically overirrigated) in the soil profile?
- Are root development patterns normal (unrestricted by soil compaction, overirrigation) for the time of year and stage of crop growth?
- Is soil condition favorable for plant growth?

**Step 4**—Discuss with the irrigation decisionmaker the findings and information so far obtained. Listen for management reasons. Make recommendations if enough information is available to do so. Make sure there is a true communication with the farm manager or irrigator. Use sketches and narratives, if appropriate. Are decisions based on tradition or field observations and measurements?

### (d) Simplified irrigation system and water management evaluations

Some simple evaluation items can be done by irrigation system operators that will help them make management and operation of irrigation equipment decisions. They include:

**Item 1**—For sprinkler and micro irrigation system, they can check:

- Operating pressures at pump, mainline, sprinkler heads, upstream and downstream of filters to assure they match design.
- Application depth for the irrigation set by using a few 3- to 4-inch random placed, straight sided, vegetable or fruit tin containers for catch containers. Measure water depth in catch containers with a pocket tape. Does it match design and what is desired?
- Discharge from a few microsystem emitters using a one-quart container and a watch. Do not raise emitter more than a few inches. Compute flow in gallons per hour. Do flows match design?
- Translocation and runoff from sprinkler systems.

**Item 2**—For all irrigation systems, simplified field checking by the operator can include calculation of depth of irrigation for a set using the basic equation,

$$QT = DA.$$

where:

Q = flow rate (ft<sup>3</sup>/s)

T = time of irrigation application (hr)

D = gross depth of water applied (in)

A = area irrigated (acres)

**Item 3**—Using a probe, shovel, soils auger, or push type core sampler, the operator can put down a few holes after an irrigation to determine depth of water penetration. Does it match plant rooting depths? Depending on the irrigation system and soil, checking on water penetration could be anywhere from an hour after the irrigation to the next day.

**Item 4**—Check runoff. Is it excessive? Does it contain sediment?

### (e) Abbreviated water management and irrigation system evaluations

An abbreviated evaluation can determine whether a problem(s) exists in a field and how serious it may be. Frequently, a simple evaluation provides enough information to make a decision. Such an evaluation should always precede a more detailed evaluation. With some guidance the irrigation decisionmaker can perform abbreviated irrigation evaluations themselves. Abbreviated management and irrigation system evaluations can be made by onfarm managers or NRCS field staff. Many times, needed changes can be identified in less than an hour.

#### (1) Sprinkle irrigation

Before irrigation, randomly place calibrated catch containers (or rain gauges) at plant canopy height. Containers should be straight sided with a reasonably sharp edge. When irrigation is complete, a pocket tape or graduated cylinder may be used to measure depth of water caught in each container. This provides an indication of average depth of application only. When sufficient number of containers is used with a uniform spacing pattern within all of the sprinkler lateral application area, pattern uniformity can be calculated (see section 3 in this section).

#### (2) Sprinkle irrigation (center pivot or linear move)

Using the design nozzle package, source pressure, and lateral size provided by the owner or dealer, a computer evaluation can be made in a few minutes if the computer program is readily available. Field observation of an operating system can identify improper (usually plugged or wrong nozzle size) nozzle operation. A computer equipment evaluation or field inspection of irrigation equipment in use (including lateral pressures and nozzles used) should always precede a detailed system evaluation.

#### (3) Sprinkle, surface, and micro irrigation

A portable or permanently installed flow measuring device can be used to evaluate gross irrigation water applied. By knowing the flow rate and kilowatt hours per hour energy used with electric powered pumps, the volume of water pumped can be determined using the common electric meter. When using gas or diesel, hours of operation can be determined by knowing the cubic feet, pounds, or gallons of fuel used and the rate

of fuel used per hour. Totalizing time clocks that operate from the engine ignition can also be used.

Irrigators try all too often to cover more acres than the water supply will adequately provide, or they overirrigate a large part of the field to satisfy a small area. Applying the formula  $QT = DA$  will solve four out of five IWM problems. Net irrigation depth can be calculated by multiplying gross depth by the overall irrigation efficiency expressed as a decimal.

Some irrigators estimate plant water need accurately then fail to measure flow onto the field, thus applying an unknown quantity of water. Flow measuring devices are one of the most valuable water management tools available to the irrigator. Accurate devices for pipelines and open channels may cost as little as \$50 to over \$1,000. Where water supply is not limited, farmers typically apply too much water, especially where plant water needs or water applied are not measured. This is also common with an irrigation delivery system where water is delivered on a rotation basis.

#### (4) Surface and sprinkle irrigation

The ball or tile probe is perhaps the most versatile and cheapest tool available to the irrigation decisionmaker. Following irrigation, the probe can be inserted in the soil at various points along the length of run (surface irrigation) or across the field (sprinkle irrigation) to measure the depth of water penetration. (Penetration is easy where water lubricates the soil.) By knowing the soil AWC, the effective irrigation water applied is calculated. Both management application efficiency and system distribution uniformity can be calculated. The ball or tile probe works best where there is an abrupt boundary between a wetted soil and a soil with moisture at less than field capacity. In rocky soil, a sound is emitted when the probe strikes a rock, otherwise no sound should be heard.

The ball or tile probe can also be used to detect excess moisture in lower portions of the soil profile even though soil at or near the surface appears dry, thus delaying irrigation and improving plant vigor.

**(5) Surface and sprinkle irrigation**

A soil auger or push type core sampling probe can be used at various locations in a field to determine depth of irrigation, extent of lateral movement, and available soil moisture. With experience the irrigation decision-maker can schedule irrigation applications based upon soil moisture at a relatively shallow depth. Application efficiency ( $E_a$ ) and irrigation system distribution uniformity (DU) can be calculated using soil auger or probe observations. An advantage in using the ball probe, soil probe, or soil auger is that you observe other field crop conditions when walking through the field, thus use the multiresource planning process. Many locations in the field can be quickly checked.

**(f) Water management and irrigation system evaluations****(1) Graded or level border (basin)**

**(i) Equipment**—Equipment needed for a graded or level border includes:

- Soil auger, probe, push type core sampler.
- Watch, 100-foot tape.
- Lath or wire flags for marking stations.
- Portable water measuring device, such as sharp crested weir, Replogle flume, Parshall flume, broadcrested weir, and pipe flow meter. Capacity needed depends on typical inflows used in the area.

**(ii) Procedures**—The following procedures should be followed.

**Before start of irrigation:**

- Estimate the soil-water deficit (SWD) at several locations down the border being investigated. Use feel and appearance method.
- Set flags or stakes at uniform distances down the border (generally 100-foot spacing).

**During irrigation:**

- Observe how uniformly water spreads across the border (basin) width. The soil surface should not have excessively high or low spots, and no intermittent ponding should occur.
- Observe and record the time when the water reaches each station. These times will be used later in plotting a simple advance rate curve.
- Record the time and location of the water front when inflow is turned off.

- Record the time when 90 percent of the soil surface area is no longer covered by water at each station. These times will be used later in plotting a recession curve. No long time ponding should occur.
- Measure or estimate the volume of runoff in terms of percent of inflow volume. (Duration of runoff is determined from the records mentioned above.)
- Probe approximately 24 hours following irrigation, the soil profile down the border strip to check uniformity of water penetration. Where soil and crops are uniform, a previously irrigated border strip may be used for this purpose.
- Determine adequacy of the irrigation with an additional simple check if the rate of inflow is known or can be estimated. Use the basic equation  $QT = DA$  to calculate the gross depth of irrigation application from the known rate of inflow, duration of irrigation, and length and width of border strip. An example to determine gross application depth,  $D$ , for a border strip 100 feet wide and 1,200 feet long, with 3 cubic feet per second inflow for a set inflow time of 4.5 hours, would be:

$$D = \frac{(Q \times T)}{A}$$

$$D = \frac{(3.0 \text{ ft}^3 / \text{s}) \times (4.5 \text{ hr})}{A} = 4.9 \text{ in.}$$

where:

$$A = \frac{(100 \text{ ft}) \times (1,200 \text{ ft})}{43,560 \text{ ft}^2 / \text{acre}} = 2.75 \text{ acres}$$

When the gross depth of application,  $D = 4.9$  inches, is multiplied by the estimated overall application efficiency (decimal), average net depth of irrigation can be estimated. The field technician needs to have experience in ranges of average application efficiencies for the farm or in the general area.

$$\text{Ave. net depth} = 4.9 \times 60\% = 3 \text{ inches (approx.)}$$

**(iii) Use of field data**—The following steps should be used with the field data:

Step 1—Using distance down the border (stations) and elapsed time in minutes, plot advance and recession curves for the border (fig. 9–12). Show the time when water was shutoff and location of water front at that time. The opportunity time is the time water was in contact with the soil surface (the interval between the advance and recession curves) at any given point (station) along the border. With basins, the water front at various times is plotted on an area basis, similar to topographic contour lines. Advance and recession curves can be plotted at select locations radiating away from the water supply onto the field.

Step 2—Compare probe depths at various locations down the border (basin) keeping in mind that water movement through the soil may not be complete. Does it appear that parts of the border (basin) have had too short an opportunity time?

Step 3—If information on accumulated intake versus time (intake characteristic [family] curve) for the particular soil is available, compare actual opportunity times throughout the length of the border to the opportunity time required for the net application as interpolated from intake characteristic curves.

Step 4—Large variations in opportunity times along the length of the border indicate changes need to be made in the rate of flow, duration of flow, or field surface conditions. Large variations between the opportunity time determined from the intake characteristic (family) curve and the actual opportunity times indicate that changes need to be made in the application or that the estimated intake characteristic (family) curve number is wrong. If it appears that the intake characteristic (family) curve number used is wrong, then a complete system analysis, including ring infiltrometer tests, may be required if more detailed recommendations are desirable.

Step 5—If possible, check the original design. Is the system being operated in accordance with the design (hours of each set, return frequency)? Should redesign be considered?

Step 6—Are irrigation water screening facilities needed?

Step 7—Are there water, soil, or plant management changes that can be made to reduce beneficial water use, fertilizer use, or water lost?

## (2) Graded or level furrows

**(i) Equipment**—The equipment needed includes:

- Soil auger, probe, push type core sampler, shovel.
- Portable flow measuring devices (broadcrested weir/flume, Replogle flume, Parshall flume, v-notch flume, v-notch sharpcrested weir, orifice flow plate, siphon tubes, flow meter in a short length of pipe, bucket).
- Watch with second hand or stop watch.
- Stakes or wire flags for locating stations.

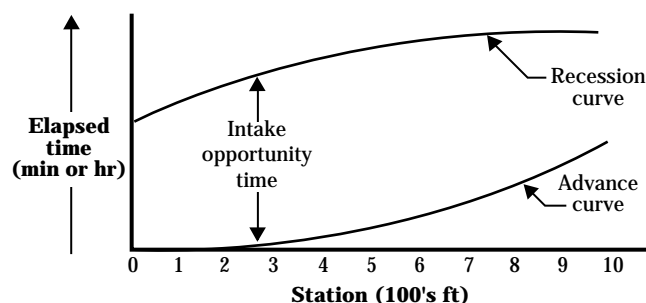
At least three furrows should be evaluated. Included should be the correct proportion of wheel rows, nonwheel rows, and guess rows. A judgment decision must be whether these few furrows adequately represent the entire field.

**(ii) Procedures**—The following procedures should be followed.

### Before the start of irrigation:

- Estimate the soil-water deficit (SWD) at several locations down furrows being investigated (use feel and appearance method). Check soil moisture in the root zone (not necessarily in the center of the furrow). Is it dry enough to irrigate?
- Note the condition of furrows. Has there been a cultivation since the last irrigation?
- Set stakes or wire flags at 100-foot stations down the length of each furrow evaluated.

**Figure 9–12** Plot of example advance and recession curves



**During an irrigation:**

- Measure (or estimate) the inflow rate (example 9–1). If siphon tubes are used, a siphon tube head-discharge chart can be used to estimate inflow. If total inflow is known, divide total inflow by the number of furrows being irrigated. Timing furrow flow catch in a bucket of known capacity or using a portable furrow flow measuring device are both accurate.
- Observe the time it takes water to reach each station (lath or wire flag) and to reach the lower end of each furrow evaluated.
- Measure furrow outflow with a portable flow measuring device periodically during the runoff phase to get an average outflow rate in gallons per minute, or estimate runoff rate in terms of percent of inflow rate (example 9–1).
- Check for erosion and sedimentation in the furrow or tailwater collection facilities.
- Dig a trench across a furrow (plant stem to plant stem) to be irrigated by the next set. The wetted bulb can also be observed following an irrigation. Observe conditions, such as:
  - Actual root development, location, and pattern
  - Compaction layers—identify cause (cultivation, wheel type equipment, plowing, disking)
  - Soil textural changes
  - Salt accumulation and location
- About 24 hours following irrigation, probe the length of a representative furrow to check uniformity of water penetration. Where soil and crops are uniform, a previously irrigated furrow set can be used for this purpose.

**(iii) Use of field data**—The following steps should be used with the field data:

Step 1—Was the soil dry enough to start irrigating? What was the soil-water deficit in the root zone at various points along the furrow before irrigating?

Step 2—Did water penetrate uniformly along the length of furrow? Good uniformity usually is achieved if the stream progresses uniformly and reaches the lower end of the furrow without erosion in about a quarter to a third of the total inflow time. Should furrow length be reduced? increased? Should inflow rate be changed?

Plot the advance curve for the furrow (see fig. 9–12). Plotting of the furrow advance curve is basically the same as the plot of the border advance curve. Shape of advance curve can indicate adequacy of inflow rates in relation to soil intake characteristics for that specific length of furrow. Estimates for adjustments in furrow irrigation operation values can be made using inflow and advance rate estimates.

Step 3—Was there runoff? How much? Water ponding with blocked end nearly level furrows or running off at the lower end of nonblocked furrows is essential for practical operation and a full, uniform irrigation. Runoff water can be collected and reused by using a tailwater collection and return-flow facility.

Step 4—Are the water supply and conveyance systems capable of delivering enough water for efficient and convenient use of both water and labor? Supplies should be large enough and flexible in both rate and duration. Furrow streams should be adjustable to the degree that flow will reach the end of most furrows in about a quarter to a third of the total inflow time. If appropriate, tailwater reuse, cablegation, cutback, or surge irrigation techniques can significantly increase distribution uniformity (see chapter 5).

**(iv) Observations**—Did soil in the crop root zone contain all of the irrigation water applied? Is there still a soil-water deficit in the root zone or is deep percolation below the root zone occurring? A simple before and after soil-water content check can provide data to estimate amounts before and after irrigation. However, this does not account for uniformity or nonuniformity in application depths throughout the length of the furrow. By simple soil probing or push core sampling throughout the length of the furrow the next day following an irrigation (or on a previous set), depth of water penetration along the furrow can be observed.

With some field experience, inflow rate and set time adjustments can be recommended to improve depth of water penetration and uniformity of water penetration along the furrow length. A detailed field evaluation is necessary for fine tuning recommendations. Often these measurements can be observed by the farm irrigation decisionmaker or irrigator. Until a field technician is experienced with furrow irrigation, a complete evaluation process with data should be used.

Was the soil dry enough to start irrigating? Was it too dry? Compare the SWD to application. How does the crop look? Is there evidence of under irrigation, salinity problems, overirrigation? Are there obvious dry spots? dry strips?

Is there soil erosion? water translocation? or runoff? Is it general or only at specific locations? A solution may be to improve irrigation water or tillage management.

**Example 9-1** Estimating furrow inflow and outflow depths

Use the basic equation  $QT = DA$  (altered to use common field units; i.e., conversion factor of 96.3 so flow can be shown in gallons per minute and furrow spacing and length in feet)

**Inflow:**      Depth,  $D = \frac{(\text{furrow flow, gpm}) \times (\text{set time, hr}) \times (96.3)}{(\text{furrow spacing, ft}) \times (\text{furrow length, ft})}$

**Field data:**    10 gpm per furrow inflow  
12 hours set time  
30-inch furrow spacing (with flow every furrow)  
1,000-foot furrow length, gives:

$$D = \frac{(10 \text{ gpm}) \times (12 \text{ hr}) \times (96.3)}{(2.5 \text{ ft}) \times (1,000 \text{ ft})}$$

**Outflow:**       $RO = \frac{(\text{average furrow outflow, gpm}) \times (\text{outflow time, hrs}) \times 96.3}{(\text{furrow spacing, ft}) \times (\text{furrow length, ft})}$

**Field data:**    3.5 gpm average outflow and 9.5 hours outflow time, gives:

$$RO = \frac{(3.5 \text{ gpm}) \times (9.5 \text{ hr}) \times (96.3)}{(2.5 \text{ ft}) \times (1,000 \text{ ft})} = 1.3 \text{ inches}$$

**Summary:**      Infiltration = 4.6 inches – 1.3 inches = 3.3 inches, or 72 percent

$$RO = \frac{1.3 \text{ inches}}{4.6 \text{ inches}} = 28\%$$

**(3) Sprinkler systems**

**(i) Periodic move laterals**—This type sprinkler systems include sideroll wheel lines, handmove, end tow, and fixed or solid set operations.

**Equipment**—The equipment needed includes:

- Soil auger, probe, push type core sampler.
- Bucket calibrated in gallons (2 to 5 gal).
- 5-foot piece of 3/4-inch garden hose.
- Set of new twist drill bits (1/8 to 1/4 inch by 64ths).
- Watch with second hand or stop watch.
- Pressure gauge with pitot tube attachment. Suggest using liquid filled pressure gauges for increased durability, plus the indicator needle does not flutter when making a reading.

**Procedures**—The following procedures should be used in the evaluation.

**Step 1**—Estimate the soil-water deficit (SWD) at several locations ahead of the sprinkler lateral. Check irrigation adequacy behind the sprinkler. Use the feel and appearance method.

Check uniformity of water penetration into the soil between sprinkler heads and laterals on the previous irrigation set using a probe or push core sampler. Properly overlapping sprinkler-wetted areas (pressure, discharge, sprinkler head, and lateral spacing) provides nearly uniform application. A detailed evaluation using a complete grid of catch devices can accurately determine application pattern uniformity.

**Step 2**—Using the IWM formula,  $QT = DA$ , determine depth of water applied by an irrigation. This is accomplished by first measuring nozzle discharge by placing the hose over the nozzle and then timing the flow into the calibrated container.

**Step 3**—To check nozzle discharge, fit hose over sprinkler head nozzle (two hoses for double nozzle sprinkler heads). A loose fit is desirable. Direct water into a calibrated bucket. Using a watch or timer, determine the time period it takes to fill the calibrated bucket. Check several sprinkler heads on the lateral. Calculate nozzle flow rate in gallons per minute. Calculate the precipitation rate from manufacturer tables or charts, or use the IWM equation (96.3 is units conversion factor when using gallons per minute and sprinkler head spacing in feet):

$$I = \frac{(96.3) \times (q)}{S_l \times S_m}$$

and

$$\text{Depth of water applied} = I \times H$$

where:

- I = precipitation (application) rate, in/hr
- q = nozzle flow, gpm
- H = set time, hr
- $S_l$  = spacing of heads along lateral, ft
- $S_m$  = lateral spacing along main, ft

**Step 4**—Take pressure readings at several locations along the lateral(s) using the pitot tube pressure gauge. If not in the critical position, measure elevations and calculate pressure differences if the lateral was moved to that location. Critical location is usually determined by elevation and distance from the mainline or pump. Pressure differences should not exceed 20 percent between any two sprinkler heads on the same lateral. This provides for less than 10 percent difference in discharge between heads on the lateral.

Desirable and design operating pressure should occur in the area that affects most sprinklers; i.e., about a third the distance from upstream end, on uniform diameter, level laterals. Excessive operating pressure produces small droplets, or fogging, and irregular turning of sprinkler heads. Small droplets are subject to wind drift and result in increased application close to the sprinkler head. Too low of a pressure causes improper jet breakup giving large droplet sizes. This typically produces a doughnut-shaped spray pattern, which if not corrected, results in a similar plant growth pattern. Larger droplets are less affected by wind. Very little water is applied close to the sprinkler head. Both conditions, excessive and too little pressure, result in poor distribution patterns.

**Step 5**—Using the shank end of a new, same size twist drill bit, check the orifice diameter of several sprinkler nozzles for appropriate size and wear. The twist drill shank should just fit into the orifice without wiggle. Excess wiggle indicates excessive wear (or too large nozzle diameter), which indicates nonuniform discharge from nozzles and poor distribution pattern between heads. Nozzles are considered worn if the next diameter bit fits into the orifice or the drill bit can

be moved sideways more than 5 degrees. Wear is typically caused from abrasive sediment in the water. Often excessive wear creates an oblong opening and is readily apparent.

**Utilization of field data**—The following steps should be used with field data:

Step 1—Was the soil dry enough to start irrigating? Was it too dry? What was the soil-water deficit at various locations in the field ahead of the sprinkler?

Step 2—Compare the SWD to application. How does the crop look? Is there evidence of under irrigation, salinity problems, overirrigation? Are there obvious sprinkler application pattern problems? dry spots? dry strips? donut-shaped patterns?

Step 3—Is there soil erosion, water translocation, or runoff? Is it general or only at specific locations? This indicates whether the application rate is too great. A solution may be to improve irrigation water or tillage management rather than changing hardware.

Step 4—Are sprinkler heads vertical and are self leveling risers on wheel lines operating properly? Are sprinkler heads rotating evenly and timely? (They should rotate at 1 to 2 revolutions per minute.) Do sprinkler head type, nozzle size, and pressure match spacing on lateral and along mainline and design? If it is apparent that sprinkler heads along the wheel line are not plumb, installation of self leveling heads should be recommended. Installing new, proper sized nozzles can be one of the most cost effective operational improvements.

Step 5—If possible, check the original design. Is the system being operated in accordance with the design (pressure, hours of each set, return frequency)? Should redesign be considered?

Step 6—Are gaskets in good condition with no excessive leaks? Are nozzles plugged or partly plugged? Are return springs broken? Is a screening system needed? If the nozzles are oversize, of varying size, or worn, they should be replaced. Replacement with new nozzles of uniform size generally is one of the most cost effective actions an irrigator can take.

**(ii) Continuous (self) move**—This type sprinkler system includes center pivot, linear, or lateral move.

**Equipment**—The equipment needed includes:

- Soil auger, probe, small diameter (1 inch) push type core sampler.
- Calibrated catch containers or rain gauges.
- Measuring tape (50 ft).
- Pressure gauge with pitot tube attachment. Suggest using liquid filled pressure gauges for increased durability, plus the indicator needle does not flutter when making a reading.
- Electrical resistance meter (tick meter) to check for stray voltage.
- Stakes to set containers or rain gauges above crop canopy.

**Procedures**—The following procedures should be used in the evaluation.

Step 1—Safety precautions should be followed before touching or climbing upon an electric powered self moving lateral system. Check for stray electric currents with a properly grounded tick meter or other approved equipment or methods, then use the back of the hand to briefly touch metal lateral components the first time. Don't grab any part of the system until it is checked. Muscles in the hand and fingers contract when subjected to electrical currents, causing the fingers to close and stay closed. If portable ladders are used to reach any of the sprinkler heads, it is advisable to use ladders made from OSHA approved nonconductive material. Hooks should be installed on the upper end of the ladder because the system moves during the evaluation.

Step 2—Uniformly place catch containers or rain gauges at or slightly above the crop canopy equidistant apart (the closer the spacing the more accurate the results, generally not greater than 30 feet apart) and ahead of the moving lateral so the lateral will cross perpendicular over them. For best accuracy, two rows of catch containers are set out and catch is averaged. However, one row is typically used to provide information needed to make general decisions. For center pivot systems, select representative spans near the middle and end of the lateral.

Catch containers or rain gauges are often omitted within 400 feet of the pivot point, as containers represent a small area (less than 3 acres). Uniformly space

containers or rain gauges within each test section. The nearer to the outer end of the lateral, the shorter time period required for the lateral to pass over the catch containers. Let the lateral completely cross the containers. The start-stop operation of self move systems, evaporation losses between night and day operation, and changing wind speeds and direction can cause nonuniformity in catch volume for a single spot. If this appears to be a problem, use two lines of containers or rain gauges at different lateral positions. Use the same container spacing and start distance from pivot point for both rows of catch containers. Water caught in containers positioned at the same distance from the pivot point represent the same area on the lateral. Averages should be used. Identify tower positions when laying out catch containers for later reference when presenting results to the irrigation decision-maker.

If containers are left for an extended time, a small amount of mineral oil placed in them will reduce evaporation effects.

Step 3—Calculate the average depth of water caught in all containers to find average application depth for the length of lateral tested. The longer the lateral length tested, the more representative the average depth of application. Testing the full length of the lateral would represent the total area, but requires more time. Operating pressure should be measured at several points along the lateral.

*Special and unique field catch devices and evaluation procedures must be used for low energy precision application (LEPA), low pressure in-canopy (LPIC), and low pressure systems using specialty heads.*

**(iii) Continuous (self) move**—This type sprinkler system includes the traveling gun sprinkler.

**Equipment**—The equipment needed includes:

- Soil auger, probe, push type core sampler.
- Calibrated catch containers or rain gauges.
- Pressure gauge with pitot tube attachment. Suggest using liquid filled pressure gauges for increased durability plus the indicator needle does not flutter when making a reading.

**Procedures**—The following procedures should be used in the evaluation.

Step 1—Uniformly space catch containers or rain gauges across the path of the traveling sprinkler. Catch should represent a cross section of the total application. When the sprinkler has completely passed over the catch containers, measure the depth of water in each can and record the distance from the sprinkler travel path. Combine sprinkler catch where lap would have occurred. Calculate the average irrigation application.

Step 2—With water shut off, use calipers (for improved accuracy) to check inside diameter of nozzles on big gun sprinkler heads. It is rather difficult and hazardous to check nozzle discharge with a hose and bucket or use nozzle pressure with a pitot tube on a pressure gauge. If attempted, hold the driving arm down to prevent sprinkler head rotation. An access plug that is often near the base of the big gun can be used to temporarily install a pressure gauge. Line pressure should be corrected for elevation of the nozzle. Manufacturer charts and tables should be referenced.

**Utilization of field data**—The following steps should be used with the field data:

Step 1—Was the soil dry enough to start irrigating? Was it too dry? What was the soil-water deficit (SWD) at various locations in the field ahead of the sprinkler? following the sprinkler?

Step 2—Compare the soil-water deficit (SWD) to the water application. How does the crop look? Is there evidence of under irrigation? salinity problems? overirrigation? Are there obvious sprinkler application pattern problems? dry spots? dry strips? donut shaped patterns? wet areas?

Step 3—Is there soil erosion, water translocation, or field runoff? Is it general or only at specific locations? These items indicate whether application rate is too great. A solution may be to improve irrigation water or tillage management rather than changing hardware. Increasing traveler speed to apply less water or changing tillage to increase soil surface storage are examples of low cost management changes.

Step 4—Are sprinkler heads positioned vertically? Are sprinkler heads rotating evenly and timely? Do sprinkler head type, nozzle size, pressure, and lane spacing match the design?

Step 5—If possible, check the original design. Is the system being operated in accordance with the design (pressure, speed, return frequency)? Should redesign be considered?

Step 6—Are gaskets in good condition with no excessive leaks? Are nozzles and equipment worn? Is a screening system needed? Should nozzles be replaced?

Step 7—Are there water, soil, or plant management changes that can be made to reduce beneficial water use, fertilizer use, or water loss?

#### (4) Micro systems

(i) **Equipment**—The equipment needed includes:

- Soil auger, probe, or small diameter (1 inch) push core sampler.
- Catch devices, graduated cylinder with 250 mL capacity. Devices used for catching discharge are generally home crafted so the catch device is fitted to the specific type of emitter device(s). Examples of catch devices are:
  - Troughs made from rain gutter (preferably plastic) or rigid plastic pipe (cut in half longitudinally) for line source emitters.
  - Single catch container for single emitters.
  - Cut and fit 2-liter plastic soda bottles for minispray heads (fig. 9-13)
- Watch with second hand or stop watch.
- Pressure gauge with special adapters to fit polyethylene pipe microsystem fittings.
- Manufacturer emitter performance charts.
- Measuring tape.

(ii) **Procedures**—The following procedures should be used for the evaluation.

Step 1—Set catch devices under selected drippers or over minispray heads and sprinklers, or both. Checking a few emitters can give an idea if a detail evaluation is necessary. Figure 9-13 shows a home fabricated catch device made from a 2-liter plastic soda bottle that can be used to catch flow from minispray heads and sprinklers. Check operating pressure at head and end of lateral or wherever possible and practical. Fittings may need to be installed. A low range reading pressure gauge (0 to 20 psi) may be necessary to obtain reasonably accurate pressure readings. Do not raise a micro irrigation emitter device more than a few inches. Raising the emitter reduces the operating pressure and discharge.

Step 2—Use a probe or push core sampler to determine wetted area and depth of water penetration for all types of emitter devices, including single and line-source emitters for both surface installed and buried laterals. Wetted width should reach the drip line of plants (perennials). Wetted depth should reach potential root zone depth. For annual plants, such as row crops, wetted width should be at a planned width, but generally not less than 50 to 65 percent of the total surface area.

(iii) **Utilization of field data**—The following steps should be used with the field data:

Step 1—Was the soil dry enough to start irrigating? Was it too dry? What was the soil-water deficit (SWD) at various locations in the field ahead of the emitter system? following irrigation? If soils are uniform, a previous irrigation can be used.

Step 2—Compare the soil-water deficit to application. How does the crop look? Is there evidence of under irrigation, salinity problems, or overirrigation? Are there obvious pattern or distribution problems?

Step 3—Are visible emitters operating properly? Are minispray heads and sprinklers rotating evenly and timely?

Step 4—If possible, check the original design. Is the system being operated in accordance with the design (pressure, hours of each set, return frequency)? Should redesign be considered?

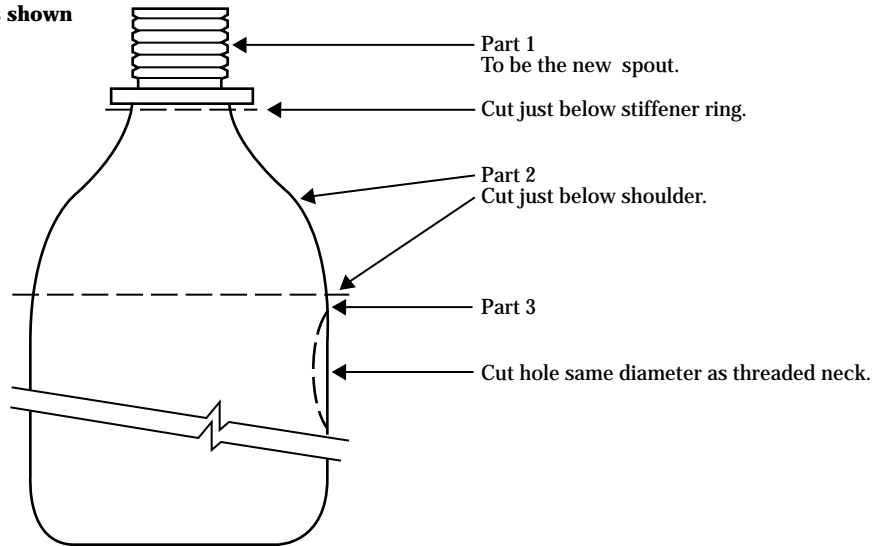
Step 5—Are there excessive leaks? Are emitters or nozzles plugged? Is the filter system appropriate and being operated satisfactory?

Step 6—Compare catch against manufacturer's flow rate chart. Discharge variation could be because of plugging, inadequate or excessive pressure, excessive main, submain and lateral head loss, or manufacturing discharge variation.

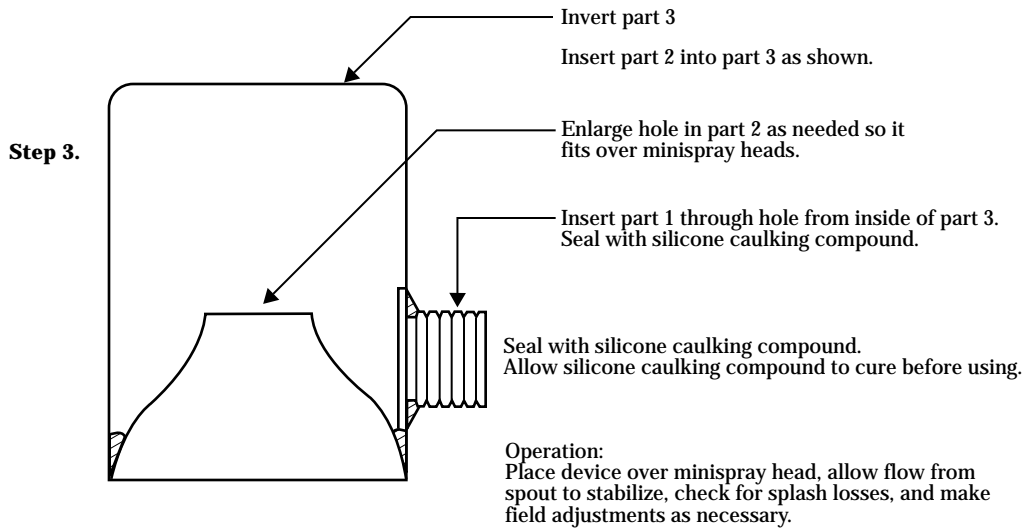
Step 7—Are there water, soil, or plant management changes that can be made to reduce water use, water lost to nonbeneficial uses, and fertilizer use?

**Figure 9-13** Minispray head catch device (made from a 2-liter plastic soft drink bottle)

**Step 1. Make cuts as shown**



**Step 2.**



### (g) Detailed irrigation system evaluation procedures

More detailed irrigation system evaluations are occasionally needed when complete field data, including pattern uniformity and distribution efficiency, are needed at a particular site. The first-step procedures described in 652.0904(c) should always be completed before deciding to expend the considerable time and effort required to do a complete irrigation system and management evaluation. Each detailed system evaluation consumes from one to five staff person days, depending on type of irrigation system. The objective of any evaluation is to improve irrigation system operation and water management.

The product for the irrigation decisionmaker would be an evaluation report and a comprehensive irrigation system operation and management plan. Depending on local concerns and priorities (i.e., water quantity or quality), it may be desirable to set up multi-agency sponsored IWM teams that have the necessary full-time staff and equipment to provide assistance to farm managers and irrigation decisionmakers. Irrigation decisionmakers should be present during the evaluation so they can observe measurements being taken. The weighted importance (or effect) of measured observations can also be discussed.

In addition to site specific benefits derived from a complete evaluation for the irrigation decisionmaker, collected field data can support or modify estimated values in the local irrigation guide. The data can be used as a basis for future irrigation system planning and design. Another benefit is local on-the-job training opportunities for NRCS irrigation personnel. The best way to learn about planning, designing, and operating irrigation systems is to closely observe and evaluate irrigation system(s) operation and management as they are taking place. Every person performing irrigation planning and design should occasionally go through a complete evaluation on each type of system being used in the area. It is a fantastic learning opportunity. To become adequately experienced in irrigation to where sound knowledgeable and practical recommendations can be made, typically is a long-term process. True communication takes place when the irrigation decisionmaker perceives the consultant's knowledge being equal to or expanded beyond their own.

Providing detailed field evaluations is time consuming and must be comprehensive enough to provide detailed recommendations for improvements to both management and system operations.

This part of chapter 9 describes procedures for performing detailed irrigation system evaluations. Included are detailed procedures for performing irrigation system evaluations for surface, sprinkle, micro, and subirrigation systems and for pumps. Examples and blank worksheets are included in chapter 15 of this guide.

#### (1) Graded border irrigation systems

Improving water use efficiency of border irrigation has great potential for conserving irrigation water and improving downstream water quality. A detailed evaluation can provide the information for design or help to properly operate and manage a graded border irrigation system. It can help the irrigation decisionmaker determine proper border inflows, lengths of run, and time of inflow for specific field and crop conditions. It should also be recognized that soil intake characteristics have the biggest influence on application uniformity. Intake rate for a specific soil series and surface texture varies from farm to farm, field to field, and throughout the growing season; typically because of the field preparation, cultivation and harvest equipment, and other field traffic.

To approximate the infiltration amount (intake rate) based upon advance and opportunity time for a border, a correlation is made using cylinder infiltration test data. A detailed irrigation system evaluation can identify soil intake characteristics for site conditions within that particular field. It can also provide valuable data to support local irrigation guides for planning graded border irrigation systems on other farms on similar soils.

**(i) Equipment**—The equipment needed for a graded border irrigation system includes:

- Engineers level and rod, 100 foot tape
- Pocket tape marked in inches and tenths/hundredths of feet
- Stakes or flags, marker for stakes or flags
- Measuring devices for measuring inflow and outflow
- Carpenters level for setting flumes or weirs.
- Cylinder infiltrometer (minimum of 4 rings) set with hook gauge and driving hammer and plate

- Equipment for determining soil moisture amounts (feel and appearance charts, Speedy moisture meter and Eley Volumeter, or Madera sampler and soil moisture sample cans)
- Water supply and buckets to provide infiltrometers with water
- Soil auger, push tube sampler, probe, shovel
- Graded border evaluation worksheet, clipboard, and pencil
- Soils data for field
- Stop watch, camera
- Boots

**(ii) Procedures**—The field procedures needed for this system are in two main categories: General and inventory and data collection.

### General

Choose a typical location in the field to be irrigated. The typical location should be representative of the type of soil for which the entire field is managed. Use standard soil surveys, where available, to locate border evaluation sites. Then have a qualified person determine the actual surface texture, restricted layers, depth, and other soil characteristics that affect irrigation. Soil surveys are generally inadequate for this level of detail. Almost all mapping units have inclusions of other soil. Extension of results to other areas also has more reliability. The site selected should allow measurement of runoff if it occurs. The evaluation should be run at a time when soil moisture conditions are similar to conditions when irrigation would normally be initiated. This procedure is described in the following steps.

**Step 1**—Obtain information from the irrigation decisionmaker about the field and how it is irrigated; i.e., irrigation set time; borders irrigated per set with typical inflow rates, advance rates (times), adjustments made during irrigation set time, and number of irrigations per season; and tillage and harvesting equipment.

**Step 2**—Record field observations, such as crops grown, crop color differences in different parts of the border or field, crop uniformity, salinity, and wet areas. Also make field observations concerning erosion and sediment deposition areas. The border to be evaluated should have uniform cross slope grade and uniform downslope grade.

Set stakes or flags at 50- to 100-foot stations down the center of the border to be evaluated. Mark stations so readings can be observed from at least 50 feet; i.e., border dike or adjacent border. Determine field elevation at each station and for a typical cross section of the border.

Record border width (center to center of border dike), strip width (distance between toes of border dikes), and wetted width (width to which water soaks or spreads beyond the edge of dike).

Set flumes, weirs, or other measuring devices at the upper end of the border and at the lower end if runoff is to be measured. Continuous water level recorders in the measuring devices may be convenient to use.

Part of the objective during a detail evaluation is to determine infiltration rate under actual field conditions using cylinder infiltrometers. Set three to five cylinder infiltrometers in carefully chosen typical locations within the border strip. Generally the most convenient location is a couple of hundred feet from the upper end of the strip (close to the water supply). Continuous water level recorders are convenient to use in the infiltrometers. USDA publications reviewing the installation of the cylinders are nearly nonexistent. See Part 652.0905(b) for additional information on installation and operation of cylinders.

**Step 3**—Estimate soil water deficit at several locations along the border. Use the feel and appearance method, Eley Volumeter/Speedy Moisture Meter, push type core sampler and gravimetric, or some other portable method. Pick one location as being typical for the border strip and record the data for that location on the worksheet.

**Step 4**—At the same time make note of soil profile conditions. With uniform soils, this can be done in an adjacent border during a later portion of the test when infiltration rates are typically slower. Soil conditions to consider include:

- Depth to water table
- Apparent root depth of existing or previous crop (to determine effective plant root zone)
- Restrictive (compacted) soil layers to root development and water movement; i.e., tillage pans
- Mineral layers
- Hard pans or bedrock
- Soil textural changes

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## Inventory and data collection

Steps to following during irrigation are:

Step 1—Irrigate with inflow rates normally used by the irrigator, and record starting time.

Step 2—Measure and record the inflow rate at 5- to 10-minute intervals until it reaches a constant rate. During the trial, periodically check inflow rate and record the values. More frequent checks are needed if the inflow rate fluctuates considerably.

Step 3—Observe and record how well water spreads across as water advances down the border strip.

Step 4—Record the time when the leading edge of the water reaches each station. If the leading edge is an irregular line across the border strip, average the time as different parts of the leading edge reach the station.

Step 5—Fill cylinder infiltrometers (rings) as the leading edge of the water flow in the border passes through the test site. An alternative to measuring infiltration while the border is being irrigated is to build berms (or install a larger ring) around infiltrometers being measured. Maintain water between the berm and infiltrometer ring at the same time water is poured into and measured inside infiltrometer rings. Using a hook gauge or other water level recording device, record water levels in each infiltrometer at times shown on the infiltrometer worksheet. See procedure and worksheets in section 652.0905, Soil intake determination procedure.

Step 6—If there is runoff, record the time when it starts. If outflow is being measured, periodically measure the flow rate and record the rate and time of measurement until it ceases.

Step 7—Record the time when water is turned off at the head of the border and the time water recedes past each station. This requires good judgment. On slopes of 0.5 percent or greater, a large part of the water remaining in the border strip when the supply is shut off may move downslope in a fairly uniform manner. On these fields, record recession time at each station when the water has disappeared from the area above it. If the recession line across the border strip is irregular, record the time when less than 10 to 20 percent of

the area is covered by water. Another method is to judge when there is about as much cleared area below the station as there is above the station.

Step 8—On slopes of less than 0.5 percent, a smaller proportion of the water moves down the strip. Some water may be trapped in small depressions and may not be absorbed for some time after surrounding areas are clear. The important thing is to determine when the intake opportunity time has essentially ceased. The recession time may be recorded for a station when 80 to 90 percent of the area between it and the next upstream station has no water on the surface.

Step 9—Immediately after recession, use a probe or auger to check depth of water penetration at several locations down the border. A check at this time will indicate the depth to which water has already percolated. A ball type probe (a 1/2-inch diameter ball welded onto the end of a 3/8-inch diameter push probe) is handy for this task. In the absence of rock, the probe inserts easily where soil has been lubricated by water, and stops abruptly when the wetted front (dry soil) is encountered.

Step 10—If possible, check for adequacy and uniformity of irrigation time when the soil profile has reached field capacity. Sandy soils can be checked 4 to 24 hours after irrigation. Clayey soils typically are checked about 48 hours after irrigation when most gravitational water has drained.

Step 11—If field capacity must be established, determine the soil water content when checking the adequacy of irrigation. With uniform soils, a previously irrigated border strip can be used for this purpose at the same time cylinder infiltrometer rings are being observed.

**(iii) Evaluation computations**—Information gathered in the field procedures is used in the detailed system evaluation computations. Example 9-2 outlines computations used to complete the Surface Irrigation System Detailed Evaluation Graded Border Worksheet (exhibit 9-2)