Section J

Irrigation management for water quality protection

Irrigation efficiency

In order to manage irrigation water, one must understand the basic concepts of irrigation system **water application efficiency**. No irrigation system is 100% efficient in applying water to the field; part of the water applied will not be available for use by the crop. An estimated value of irrigation system efficiency must be used to calculate the gross amount of irrigation water that needs to be pumped or delivered to the field in order to apply a given net amount of irrigation water. Note that amounts of irrigation water are normally expressed as a depth, in inches. The net irrigation depth is the water which infiltrates into the soil *and* is stored in the root zone available for plant use. The irrigation system application efficiency is a measure of the amount of water that is made available for crop use by an irrigation event. Irrigation system efficiency is defined as:

$$\text{Application Efficiency} = \frac{\text{Net Irrigation Depth}}{\text{Gross Irrigation Depth}}$$

The major ways water is lost from an irrigated field are illustrated in *Figure J-1*. The primary losses from furrow-irrigated fields will be runoff and deep percolation with a small amount of direct evaporation from the flowing water. For sprinkler systems that throw water in the air, evaporation occurs while the droplets are in the air and after they reach the crop and soil surface. Evaporation from the crop surface appears to be the most significant loss. If the wind blows, droplets may be blown outside the land being irrigated, resulting in a “drift” loss. Runoff loss can also occur under a sprinkler system if water is applied at a rate greater than the infiltration rate of the soil. If good irrigation scheduling is practiced, deep percolation losses during the growing season should be minimal under sprinkler systems.

Typical system efficiencies are shown in *Table J-1*. Keep in mind that these are average application efficiencies and there can be a broad range of efficiencies in the field. The actual application efficiency of your systems will depend on system characteristics, management, soil conditions, crop conditions and the weather, especially precipitation. Irrigating when there is little storage space available in the soil will lower the irrigation system efficiency. More detailed efficiencies for sprinkler systems are given in Section K.

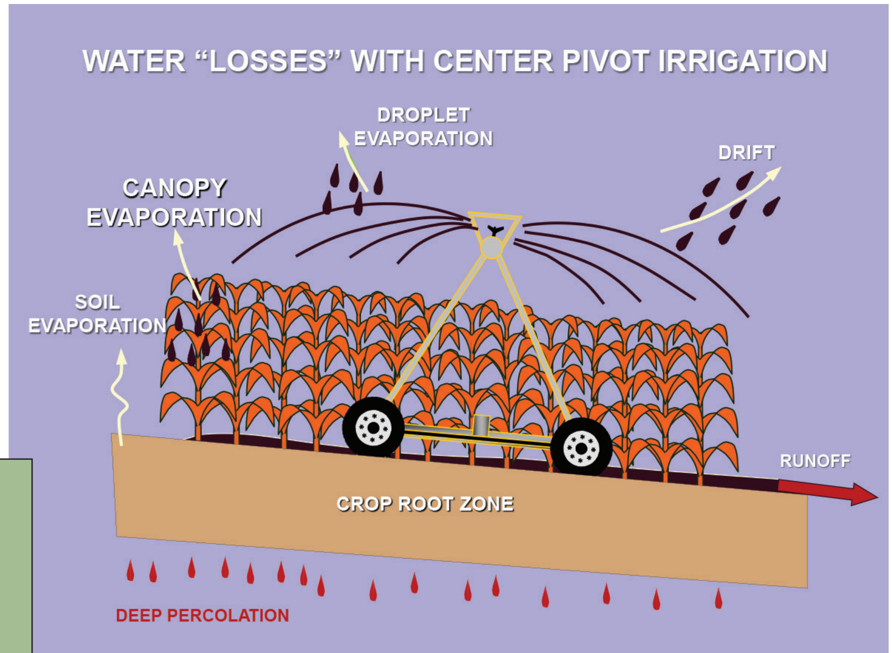

Figure J-1. Schematic drawing showing the major water losses that occur during a water application event using a center pivot irrigation system.

Water Application Efficiency is a measure of the fraction of the total volume of water that is pumped to the volume of water stored in the crop root zone and available for plant use.

Table J-1. Potential water application efficiencies of different types of irrigation water application systems (taken from EC732, Irrigation Efficiency and Uniformity and Crop Water Use Efficiency).

Irrigation System	"Potential" Application Efficiency (%)
Sprinkler Systems	
Low Energy Precision Application	80-95
Linear or Lateral Move	75-90
Center Pivot	75-92
Surface Irrigation Systems	
Conventional Furrow	45-70
Surge Flow	55-75
Furrow with tailwater reuse	60-80
Microirrigation Systems	
Bubbler (low head)	80-90
Microspray	85-90
Subsurface Drip	90-95
Surface Drip	85-95

Know how much water is applied

The inches of water applied per acre can be calculated if the irrigator knows the total volume of water pumped and the area irrigated. The total volume pumped is easily determined by using a water meter on the irrigation pipeline (*Figure J-2*). A water meter provides the most accurate means for determining the volume of water pumped. The application depth (in inches) is calculated by dividing the total acre-inches of water applied by the total acres on which the water was applied. Internet links to easy to use computer applications are available at: *water.unl.edu/cropswater/nawmdn*.

Without a water meter installed on the system, the water flow, or delivery rate from the irrigation pump or canal and the length (time) of the irrigation can be used to estimate the volume of water delivered to the field. The total volume applied to the irrigated area is calculated by multiplying the flow rate times the irrigation time. Flow rates from pumps are normally given in gallons per minute (gpm) and flows from canals in cubic feet per second (cfs). These flow rates will need to be converted to acre-inches per hour (ac-in/hr) to make the calculation.

Typical flow-measuring devices on open ditch systems provide a flow rate measurement. For a well not equipped with a flow meter, flow rates should be measured periodically with some type of measuring equipment. Many NRDs have ultrasonic flow meters and will measure irrigation pumping rates as a service for producers. It should be noted that flow rates may vary throughout the year and from year to year. When periodic water flow rate measurements are used to estimate total water applied during a period of time, an accurate record of irrigation time must be maintained by installing an hour meter on the power supply or irrigation system. The following example shows how the flow rate and irrigation time information is used to estimate total water pumped.

Figure J-2. Impeller flow meter commonly used to monitor the water flow rate in an irrigation pipeline.

Example: Use flow rate and time to estimate volume applied.

An ultrasonic meter indicates your pumping rate is 600 gpm (1.3 ac-in/hour). The hour meter shows you pumped for 84 hours.

The total volume pumped is 1.3 ac-in/hr x 84 hr = 109.2 ac-in.

It is highly beneficial to have a water-measuring device that provides the total volume of water delivered to the field. Water meters are also valuable tools to monitor changes in well output, indicate potential pump problems, and help monitor pumping plant performance. A meter is a management tool that provides the manager with the total volume of water pumped and an instantaneous flow rate. However, the most accurate estimate of the system flow rate is obtained by recording the time required for a set volume of water to be added to the accumulator box near the center of the meter dial.

Key relationships that you can use are:

453 gpm = 1 cfs = 1 acre-in/hr

1 acre-in = 27,154 gal

1 acre-ft = 325,851 gal

Since a volume of 1.0 acre-inch will cover a 1.0 acre land area with 1.0 inch of water, water from a 453 gpm pump will apply 1.0 inch of water to 1.0 acre in 1.0 hour. Similarly, a delivery of 1.0 cfs from a canal will apply 1.0 inch of water to a 1.0 acre land area in 1.0 hour. Using a measured flow rate determined by monitoring the flow meter, the average application depth may be calculated using the following equation:

$$\text{Gross Depth of Irrigation (in)} = \frac{\text{Flow Rate (ac-in/hr) x Time of Irrigation (hr)}}{\text{Acres Irrigated (acres)}}$$

Example: Determine the gross irrigation depth for one furrow irrigation set.

A 900-gpm well is pumping water for 12 hr through 40 open gates (every-other-row irrigation, 30-in row spacing and 1320 ft furrow length). What is the depth of irrigation?

The flow rate is converted from gpm to acre-in/hour.

$$\text{Flow Rate} = \frac{\text{900 gpm}}{\text{453 gpm/ac-in/hr}} = \text{2.0 ac-in/hr}$$

The area irrigated is:

$$\text{Area Irrigated} = \frac{40 \text{ gates x 2 rows per gate x 2.5 ft per row x 1320 ft}}{43{,}560 \text{ sq ft/acre}} = 6 \text{ acres per set}$$

The gross depth of irrigation is:

$$\textit{Gross Irrigation Depth} = \frac{2.0\ ac - \dfrac{in}{hr}\ x\ 12\ hr}{6\ ac} = 4\ \textit{inches}$$

Example: Determine the gross irrigation depth for a center pivot?

A center pivot irrigates 128 acres and is supplied by a flow rate of 750 gpm. If the system makes a complete revolution in 75 hr, what is the gross depth of irrigation water applied?

$$\text{Flow rate} = \frac{750 \text{ gpm}}{453 \text{ gpm/acre-in/hr}} = 1.65 \text{ ac-in/hr}$$

$$\text{Gross Irrigation Depth} = \frac{1.65 \text{ acre-in/hr x 75 hr}}{128 \text{ acres}} = 0.97\ \textit{inches}$$

Irrigation management and scheduling

To manage soil water we must first measure it to verify that soil water content is within the allowable bounds, when the next water application should occur, and how much water the soil can hold without deep percolation. It's easy to see crop stress that results if irrigation is delayed too long. Unfortunately, the losses of water and nitrogen that result from irrigating too much are not nearly as visible. Therefore, field checks of soil water content and irrigation scheduling play an important role in maintaining crop yields while protecting ground and surface water.

Yield reduction and other field and environmental effects due to over irrigation can be substantial. Hence, careful scheduling of irrigation water applications help to:

- Assure that plant water needs are met
- Conserve water supplies
- Avoid excess water application
- Reduce nitrate leaching losses
- Save pumping costs

A key input for making irrigation scheduling decisions is the amount of plant available water present in the soil. The plant available water remaining in the root zone, along with the expected ET, can be used to project the time remaining before the next irrigation begins. The crop's stage of growth must also be considered since, for most crops, water stress is more damaging during the reproductive growth stages. The amount of room left in the active root zone to store water determines how much water can be effectively applied and when the irrigation should be started. As a "rule of thumb," *irrigations should be scheduled so that the plant available soil water content remains above 50% of the total available water-holding capacity.*

To develop a good estimate of the current soil water content, soil water sensors such as tensiometers, granular matrix sensors, or capacitance probes can be installed in each field and/or crop. Soil water also can be estimated by using a "checkbook" or "water balance method," which starts with a good estimate of current soil water content and then subtracts crop ET and adds an estimate for *effective precipitation* and *net irrigation water* application. This process is like balancing your checkbook (*Table J-2*). Spreadsheets for personal computers and irrigation scheduling software have made this process easier, but it still requires gathering some basic information from the field to ensure the accuracy of crop ET, effective precipitation, and net irrigation estimates.

Measuring soil water content and matric potential

Feel and appearance

The feel method uses a soil probe to take samples of soil from different depths in the crop root zone (*Figure J-3*). The soil sample is crumbled into small pieces and squeezed by hand to form a ball. The cohesiveness of the ball and whether it leaves an imprint in the palm of the hand after squeezing is an indication of the soil's wetness. The soil is then ribboned out between the thumb and the forefinger. The soil water content is estimated based on the appearance and strength of the soil ball (*Table J-3*). The USDA-NRCS developed a guide for the characteristics different soils exhibit at different moisture contents.

The feel method requires experience, self-calibration, and a great deal of judgment to provide good estimates of soil water content. Nevertheless, it is widely used by crop consultants. This method allows rapid moisture measurements at multiple locations in the field during field scout visits. The feel method is relatively inexpensive but continuous monitoring of field conditions requires significant labor at a time when producers are very busy. Thus, other methods of monitoring soil water content are encouraged for accurately scheduling irrigation events.

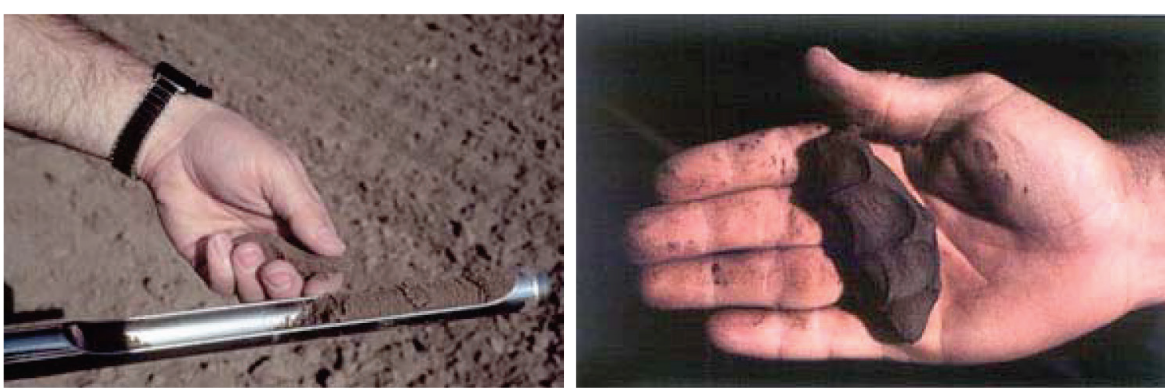

Figure J-3. Sampling and evaluation techniques for the feel method of soil water monitoring.

Table J-3. Feel and appearance for judging how much water is available for crops (taken from USDA, 1972).

Fraction of Available Soil Water Remaining	Loamy Sand or Sand	Sandy Loam	Loam and Silt Loam	Clay Loam or Silty Clay Loam
0 Wilting Point	Dry, loose, single grained, flows through fingers.	Dry, loose, flows through fingers.	Powdery dry, sometimes slightly crusted but easily broken down into powdery condition.	Hard, baked, cracked, sometimes has loose crumbs on surface.
0.25	Appears to be dry, will not form a ball with pressure.	Appears to be dry, will not form a ball.	Somewhat crumbly but holds together from pressure.	Somewhat pliable, will ball under pressure.
0.50	Appears to be dry, will not form a ball with pressure.	Tends to ball under pressure but seldom holds together.	Forms a ball somewhat plastic, will sometimes slick slightly with pressure.	Forms a ball, ribbons out between thumb and forefinger.
0.75	Tends to stick together slightly, sometimes forms a very weak ball under pressure.	Forms weak ball, breaks easily, will not slick.	Forms a ball, is very pliable, slicks readily, is relatively high in clay.	Easily ribbons out between fingers, has slick feeling.
At field capacity	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.

Sensing matric potential

Soil water content can be recorded by measuring the soil matric potential. There are two methods for measuring soil matric potential (*Figure J-4*). **Tensiometers** directly measure the soil matric potential. Tensiometers consist of a water-filled tube with a porous ceramic cup at one end and a reservoir and vacuum gauge at the other end (*Figure J-5*). It is installed with the ceramic cup at the desired depth below the soil surface. The cup must be in direct contact with the surrounding soil so that the water in the cup is hydraulically connected to the water in the soil. As the water content of the soil around the cup decreases, water flows through the porous cup. Since the other end of the tube is sealed, the water withdrawal creates a partial vacuum in the tube. Flow continues until there is equilibrium between the water in the tensiometer and the soil matric potential. The vacuum gauge is a direct indicator of soil matric potential. Usually the vacuum is registered in centibars and the scale reads from 0-100 centibars. As the tension or vacuum approaches 100 centibars, dissolved air in the water is released, breaking the partial vacuum. When this happens the readings are no longer reliable; thus, the practical operating range for this instrument is 0-75 centibars.

Figure J-4. Methods of measuring the soil matric potential.

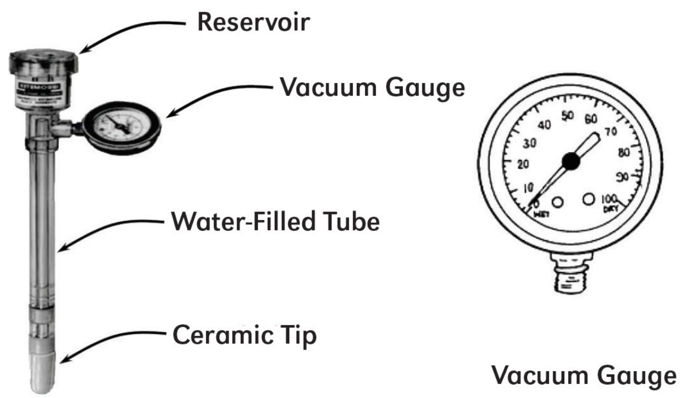

Figure J-5. Components of tensiometers used to measure soil matric potential.

Electrical resistance blocks indirectly measure the soil matric potential (*Figure J-4*). Electrical resistance blocks consist of a porous material, usually gypsum, with two embedded electrodes. The blocks are buried in the soil to the desired depth. As with tensiometers, good contact with the surrounding soil is essential. When the soil water equilibrates with the water in the block, an ohmmeter with an AC current source can be used to measure electrical resistance between the electrodes. There is a relationship between the resistance and the water content of the gypsum and therefore, the soil water potential and the resistance are related.

Electrical resistance in the soil is dependent on both soil water content and soil salinity. The gypsum buffers the effect of the salts on observed resistance in the soil. In saline soils, the effect of salts on the measured resistance cause inaccurate readings of matric potential. These sensors are inexpensive and easy to read. They work well in clayey soils but due to the particle size of gypsum, blocks are not sensitive in sandy soils.

Watermark Granular Matrix soil water sensors are another widely used version of a moisture block. Similar to gypsum blocks, these granular matrix sensors measure soil water potential indirectly through electrical resistance between two electrodes. However, Watermark Sensors use a matrix similar to fine sand with a porous ceramic external shell, surrounded with a synthetic membrane to protect against deterioration. This means that the matrix will dissolve slowly over time. The Watermark Sensors can be read by a handheld meter, or connected to a data logger (*Figure J-6*) for continuous measurement with remote access capabilities. The datalogger can set to record soil water content several times per day and the information can be downloaded to a computer using software provided by the company. Some private companies now offer the service of uploading watermark sensor readings to a Web page for easy access and viewing. *Figure J-7* presents a summary of soil water sensors recorded at a field site in 2007. Note that each sensor is displayed using a specific color so that it is easy to distinguish which depth the readings represent.

Figure J-6. **Pictures of the Watermark soil water monitoring system including the sensor, hand-held readout, and automated data logger marketed by Irrometer.**

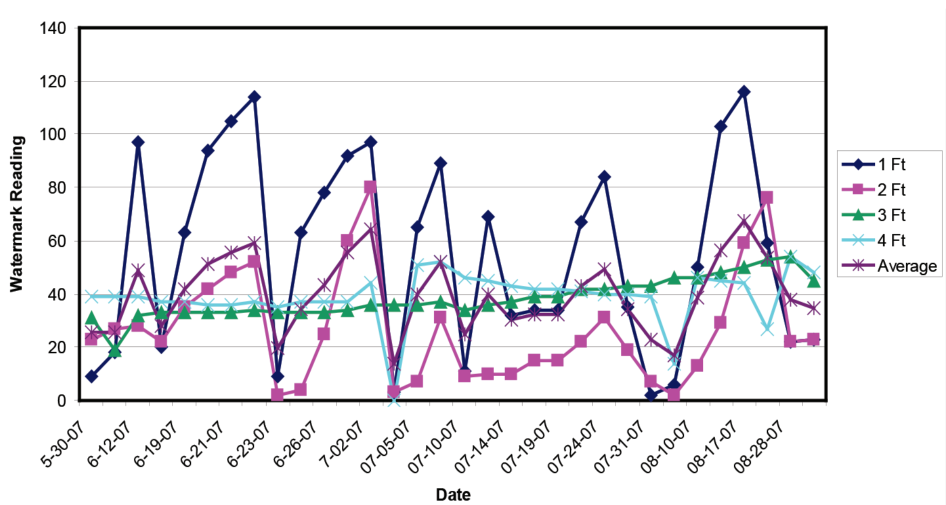

Figure J-7. **Watermark record of one growing season.**

Dielectric constant methods

Capacitance probes use the dielectric properties of the soil to determine the soil water content. The sensors pass a current through the soil between two electrodes. As the soil water content increases, so does the ability of the soil to transmit electrical current. *Figure J-8* shows examples of capacitance probes. Capacitance probes can be easily interfaced to a datalogger for continuous soil moisture monitoring and transfer to internet or wireless sites to allow producers to upload data without entering the field.

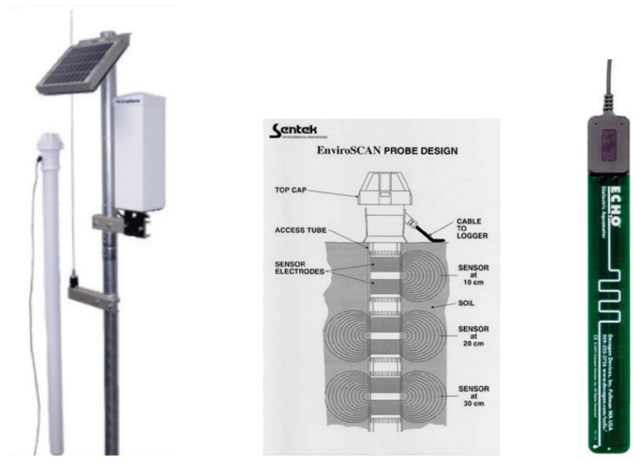

Figure J-8. **Examples of the AquaSpy, EnviroSCAN, and ECHO capacitance probes for soil water monitoring.**

Sensor placement

It is important to locate soil water monitoring equipment in locations that will give accurate and timely readings. This means that sensor locations must consider the variability in soils, the variability of water application, and the variability of plant populations within the irrigated area. The sensors should be placed under different spans of the pivot and in dominate soil textures. *Figure J-9* illustrates the concept of measuring the water content of the soil in the area of the field that has gone the longest since irrigation (start positions) and the area that was most recently irrigated (stop positions). A minimum of two depths, but preferably three or four depths are required to properly represent root zone moisture conditions.

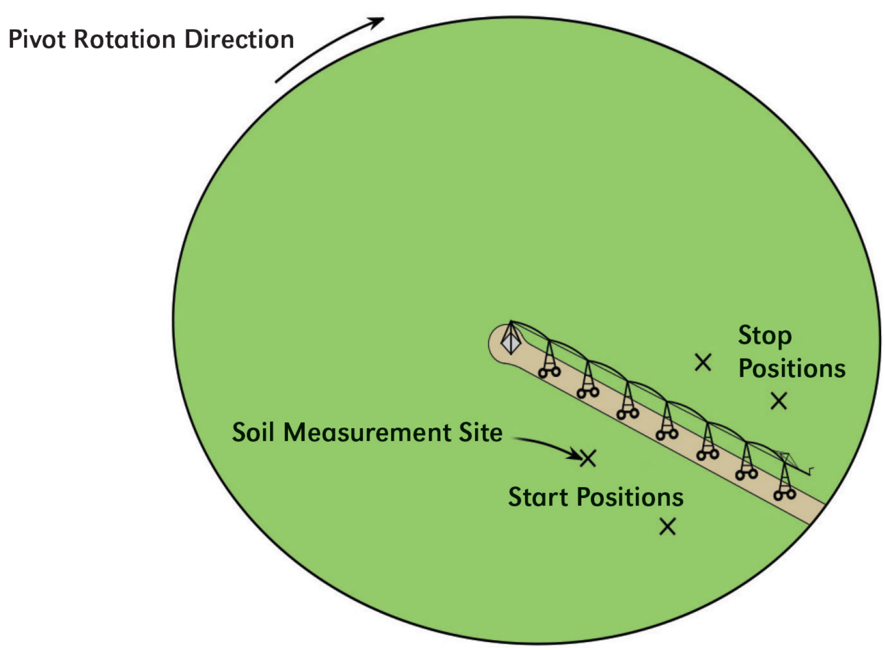

Figure J-9. **Sensor placement at starting and stopping positions in a center-pivot irrigated field.**

Web Soil Survey

A very useful tool for obtaining soil information needed for irrigation scheduling is the Web Soil Survey (WSS) (*Figure J-10*) from the Natural Resources Conservation Service (NRCS). Once WSS is launched by clicking on the Start WSS button, there are many options to locate the area to be studied, including the street address, the county, latitude and longitude, and the legal description (section, township, range). Once the area of interest (AOI) is selected the soil data is retrieved and available for viewing. The soils of a field located at the Agricultural Research and Development Center near Mead, Nebraska is illustrated in *Figure J-11*. First zoom into the field and select the area as your Area of Interest (AOI), (*Figure J-11*). Next, a soil map will be displayed when the Soil Map tab is clicked.

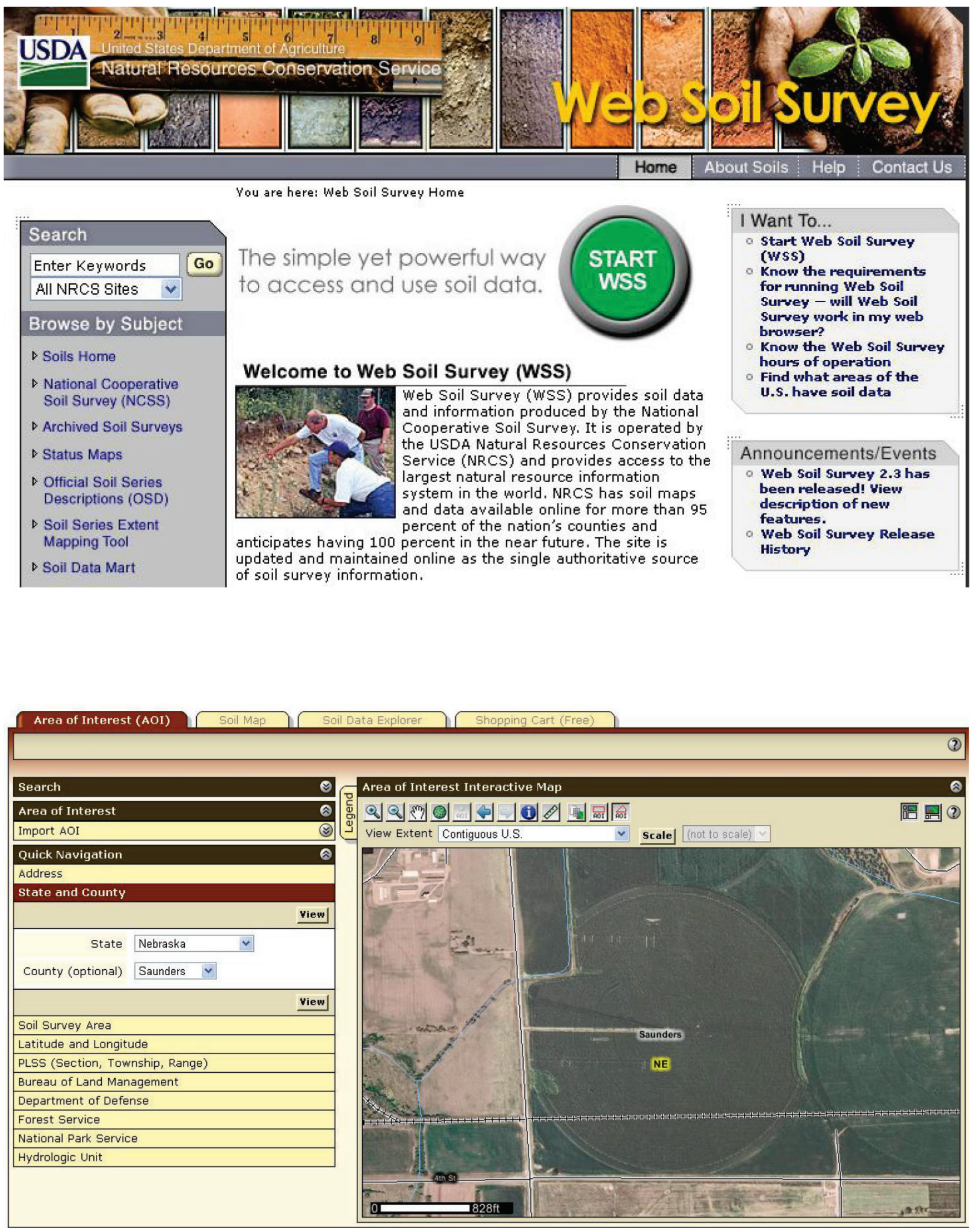

Figure J-10. Web Soil Survey webpage used to obtain soil mapping units, field slopes, and soil properties useful when scheduling irrigation events and for designing irrigation systems.

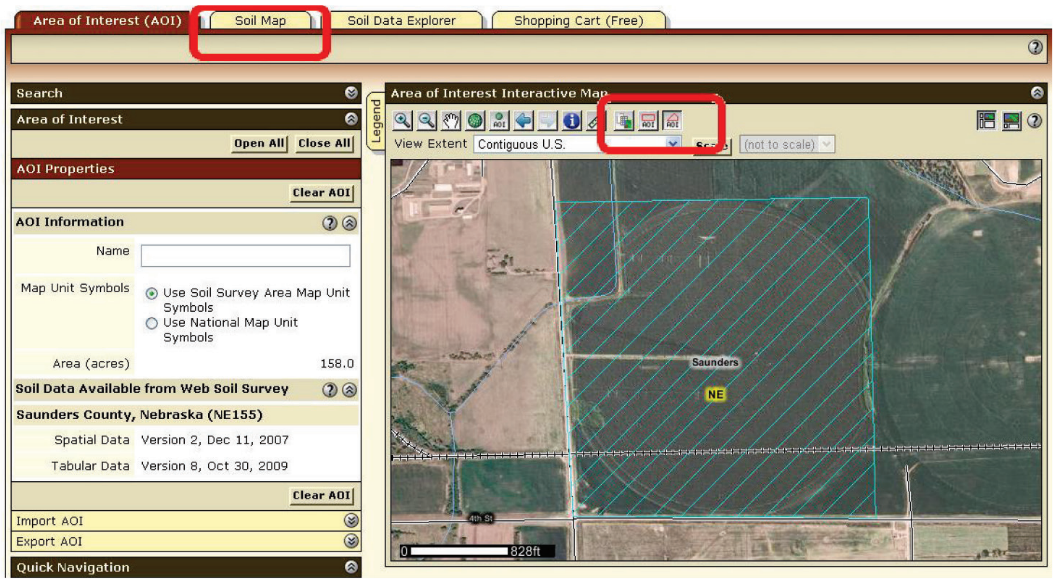

Figure J-11. Use of Area of Interest (AOI) tool on the web soil survey to delineate field area under irrigation. Red rectangles show location of AOI and soil map icons and cross-hatched shows the AOI under consideration.

Figure J-12 shows the soil map along with the map unit names and the areas of each map unit. Over half of this field is a Yutan silty clay loam. Another important soil is the Filbert silt loam, making up over 50 acres of this field. From the soil descriptions we can determine that the greatest slope will likely be 6%.

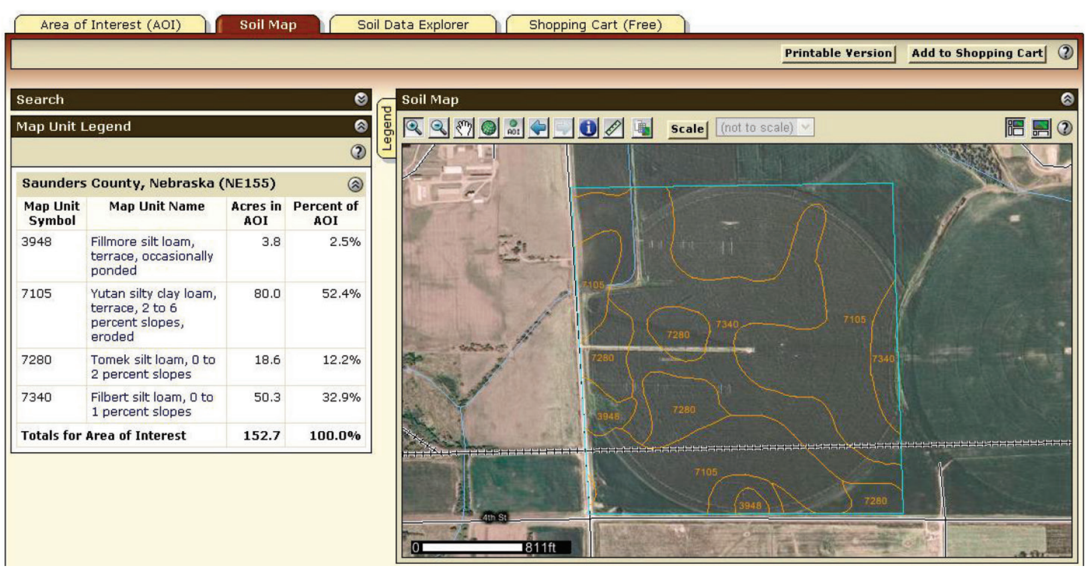

Figure J-12. Web soil survey soils map of a field area under irrigation as delineated using the AOI tool. Yellow lines delineate different soil mapping units, and the left hand panel provides area and basic soils information for each mapping unit.

Checkbook scheduling method

One way to schedule irrigation events is by using a "checkbook" or "water balance method." This starts with a good estimate of current soil water content, then subtracts crop ET and adds an estimate for effective rainfall and net irrigation water application. This process is like balancing your checkbook (*Table J-2*). Spreadsheets for personal computers and irrigation scheduling software have made this process easier. It still, however, requires gathering some basic information from the field to ensure the accuracy of crop ET, effective rainfall, and net irrigation estimates.

The irrigation timing is determined by considering two factors: 1) the amount of soil water remaining between the current soil water balance and the minimum allowable soil water balance (typically, 50% of the available water capacity) and 2) the projected estimated crop water use. Dividing the amount of usable water that remains in the soil by the estimated crop water use rate will give the days remaining before the next irrigation. Start irrigation early enough so no portion of the field drops below the minimum allowable soil water balance. The calculated water balance should be periodically updated by measuring the current soil water content.

$$\text{Estimated Days Before Next Irrigation} = \frac{\text{Remaining Available Water}}{\text{Forecasted ET}}$$

Table J-2. Template for using the checkbook method of irrigation scheduling.

Basic "checkbook" soil water balance calculation		
Beginning soil water balance	________	inches
Effective rainfall	+ ________	inches
Net irrigation	+ ________	inches
Crop water use	- ________	inches
Current soil water balance*	= ________	inches

*The current soil water balance can be no larger than the available water capacity of the active crop root zone.

Example: Determine when irrigation should begin.

$$\text{Estimated Days} = \frac{1.0\text{ inch}}{0.25\text{ in/day}}$$

$$\text{Estimated Days} = 4\text{ days}$$

The net irrigation amount or depth to apply should be no larger than the available soil water storage space in the active crop root zone, minus any allowance left for precipitation that may occur immediately following an irrigation event.

The net irrigation amount is divided by the estimated irrigation system efficiency to obtain the gross irrigation amount required. The following examples illustrate the effect of irrigation system efficiency on the gross irrigation amount. If storage space is available in the root zone for 1.5 in. of water, and you don't reserve some storage for precipitation, the net irrigation amount will be 1.5 inches. Gross irrigation amounts for different situations are shown in *Table J-3*.

Table J-3. Gross irrigation amounts for different irrigation system efficiencies.

	Irrigation System Application Efficiency			
	90%	75%	60%	45%
Net Irrigation, inches	1.5	1.5	1.5	1.5
Gross Irrigation[1], 1 inches	1.7	2.0	2.5	3.3

[1]Gross Irrigation Depth = $\dfrac{\text{Net Irrigation Depth}}{\text{Irrigation System Efficiency}}$

Scheduling the last irrigation

Applying a late irrigation, if not needed, will reduce the storage available for off-season precipitation by 1 to 3 inches. This is likely to result in more leaching loss of residual nitrate-nitrogen during the off-season, and will directly increase pumping costs by $5 to $15 per acre. On the other hand, failing to apply a needed irrigation could mean a loss of several bushels per acre in crop yield. Irrigation management near the end of the season should leave enough soil water to carry the crop to maturity, but at the same time deplete soil moisture as much as possible. This provides storage for off-season precipitation and can greatly reduce leaching loss of residual nitrogen. The need for the last irrigation can be predicted using the following information:

- Predicted crop water use before maturity
- Measured remaining available water in the root zone

The remaining usable water is the difference between the current remaining available soil water in the field and the minimum allowable soil water at maturity. In most cases the soil water at crop maturity can be depleted to the point that only 40% of the available water remains in the crop root zone without causing yield reduction. Subtracting the remaining available water from the crop's need for water gives the amount of irrigation needed to finish the growing season.

Normal water requirements to reach maturity for corn and soybean are shown in *Table J-4*. Since probabilities for significant precipitation are low during the later part of the growing season, precipitation is not usually considered in the last irrigation decision. Center pivot irrigators have more flexibility to consider precipitation since they can apply an inch of water in a three- to four-day period.

Table J-4. Average water requirements for corn, grain sorghum, soybean, and dry beans for various stages of growth and maturity in Nebraska.

	Stage of growth	Approximate days to maturity	Water use to maturity (inches)
Corn			
R4	Dough	34	7.5
R4.7	Beginning dent	24	5.0
R5	1/4 milk line	19	3.75
	1/2 milk line — Full dent	13	2.25
	3/4 milk line	7	1.0
R6	Physiological maturity	0	0.0
Grain Sorghum			
Stage 6	Half bloom	34	9.0
Stage 7	Soft dough	23	5.0
Stage 8	Hard dough	12	2.0
Stage 9	Physiological maturity	0	0.0
Soybean			
R4	End of pod elongation	37	9.0
R5	Begin seed enlargement	29	6.5
R6	End of seed enlargement	18	3.5
R6.5	Leaves begin to yellow	10	1.9
R7	Beginning maturity	0	0.0
Dry beans			
R5	Early seed fill	35	7.0
R6	Mid-seed fill	25	4.2
R7	Beginning maturity	15	2.0
R8	Harvest maturity	0	0

Smart phone applications

With advances in electronics and their applications to irrigation operations, smart phone applications or apps can also be used to determine in-season irrigation schedules as well as the last irrigation event of the season. The CropWater App, which is a product of soil water content and crop water use applications, can provide reasonable estimates of the last irrigation for corn and soybean based on soil water content and predicted crop water use information. The Crop Water App, developed for iPhone and iPad, provides an easy way to estimate soil water status based on Watermark soil matric potential sensors installed at soil depths of 1, 2, and 3 feet. With these sensor readings, the app will estimate the crop water used, as well as the available soil water remaining in the profile for typical Nebraska soils. The user can also see historic sensor readings and graph the data as the season progresses. For Apple smart phones, the CropWater App can be downloaded at *https:// itunes.apple.com/us/app/crop-water/id557926049?mt=8* or for Android smart phones go to: *https://play.google.com/store/apps/details?id=edu.unl.cropwater*.

More Extension Publications (available at ianrpubs.unl.edu)

EC732, Irrigation Efficiency and Uniformity and Crop Water Use Efficiency

G1850, Irrigation Management for Corn

G1579, Using Modified Atmometers for Irrigation Management

G1367, Irrigating Soybean

G1778, Irrigation Management and Crop Characteristics of Alfalfa

G2000, Tillage and Crop Residue Affect Irrigation Requirements

EC731, Producing Irrigated Wheat

G1328, Water Loss from Above-Canopy and In-Canopy Sprinklers

G1871, Predicting the Last Irrigation of the Season

EC709, Irrigation Scheduling: Checkbook Method

For More Information

Gardner, W.H. 1986. Water Content. In: A. Klute (ed). Methods of Soil Analysis, Part I, Physical and Mineralogical Methods, Second Edition. Agronomy Number 9, American Society of Agronomy, Madison, WI. pp. 493-544; and Ley, T.W. 1994. An In-Depth Look at Soil Water Monitoring and Measurement Tools. Irrigation Journal, 44(8):8-20.